Piers Larcombe Consulting
Coastal and Marine Geoscience

Seashore Engineering

The past, present and future coastal dynamics relevant to the Eramurra Solar Salt Project, with implications for benthic habitats

Eramurra Solar Salt Project

for

Leichhardt Salt Pty Ltd

Report No. PL2025-001, Version 2.0.

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

Version and Quality Control

Report No. PL2025-001	Version	Author	Reviewer	Date
Draft - structure & formatting	0.1	Piers Larcombe	-	03/01/2025
Draft - structure & formatting	0.2	Piers Larcombe	-	19/01/2025
Draft - structure & formatting	0.3	Piers Larcombe	-	28/01/2025
Draft Final Report – internal review	0.4	Piers Larcombe, Matt Eliot	Steve Buchan, Matt Eliott	02/02/2025
Draft Report for client comment	1.0	Piers Larcombe, Matt Eliot, with contributions from Steve Buchan	Steve Buchan, Matt Eliot	04/02/2025
			LS - Regina Flugge, Alan Kerr	20/02/2025
Final Report	2.0	Piers Larcombe	Steve Buchan, Matt Eliot	25/02/2025

Leichhardt Salt Document No. ESSP-EN-14-TRPT-0051

This document should be referred to as:

Larcombe, P., Eliot, M. & Buchan, S. (2025) The past, present and future coastal dynamics relevant to the Eramurra Solar Salt Project, with implications for benthic habitats. Report to Leichhardt Salt Pty Ltd. Piers Larcombe Consulting, Report No. PL2025-001, Version 2.0. 25th Feb., 2025.

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
BOM	Bureau of Meteorology
CD	Chart Datum
Chl-a	Chlorophyll a
CPT	Cone Penetrometer Testing
DAWE	Department of Agriculture, Water and the Environment
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DEM	Digital Elevation Model (Topography + Bathymetry)
DTM	Digital Terrain Model (Topography)
DWER	Department of Water and Environmental Regulation
Deflated dunes	Sand dunes eroded by wind down to the level where they meet groundwater
EIA	Environmental Impact Assessment
ENSO	El Niño–Southern Oscillation
EPA	Environmental Protection Agency
ERD	Environmental Review Document
Erosion	Landward movement of the coastline
ESD	Environmental Scoping Document
ESSP	Eramurra Solar Salt Project
GA	Geoscience Australia
GIS	Geographic Information System
GBR	Great Barrier Reef
HAT	Highest Astronomical Tide
Hydroperiod	The frequency of inundation by tides
IOD	Indian Ocean Dipole
IUCN	International Union for Conservation of Nature
LAT	Lowest Astronomical Tide
Leichhardt Salt, or LS	Leichhardt Salt Pty Ltd
MHWS	Mean High Water Springs
MLWS	Mean Low Water Springs
MSL	Mean Sea Level
NGO	Non-Governmental Organisation

NWS	North West Shelf
Pa	Pascals, the unit of shear stress (same as Newtons/m^2).
Progradation	Seaward movement of the coastline
PSD	Particle Size Distribution
PSMSL	Permanent Service for Mean Sea Level
Qtz	Quartz
RFFE	Regional Flood Frequency Estimation
RSL	Relative Sea Level (relative to the land)
SLR	Sea-Level Rise
SME	Subject Matter Expert
SOI	Southern Oscillation Index
Subtidal	Below the level of LAT
Supratidal	Above the elevation of HAT
TC	Tropical Cyclone
TIM	Tidal Inundation Model
Vs:Vc ratio	Ratio of water volumes in a creek system at different tidal elevations. Vs = Storage Volume, at 2.5 m AHD, Vc = Creek Volume, at 1.7 m AHD for ESSP.
WA	Western Australia

NB - Directional convention.

- Wind and wave directions use the standard meteorological convention of ‘coming from’.
- Currents use the standard oceanographic convention of ‘flowing to’.

1. Introduction

1.1. Purpose

This report has two main purposes:

- To establish the best available understanding of the physical processes that control the coastline and associated habitats relevant to the Eramurra Solar Salt Project (ESSP) development area.
- To use that understanding to develop a defensible understanding of the possible future state(s) of the coastline and its associated key habitats, with and without the ESSP development.

This report is designed to provide physical context to Leichhardt Salt Pty Ltd's (LS) Eramurra Solar Salt Project (ESSP). It integrates relevant parts of existing reports, adds available new information and is designed to be a single document to inform the regulatory assessment of LS's ESSP proposal.

This document should be referred to as:

> *Larcombe, P., Eliot, M. & Buchan, S. (2025) The past, present and future coastal dynamics relevant to the Eramurra Solar Salt Project, with implications for benthic habitats. Report to Leichhardt Salt Pty Ltd. Piers Larcombe Consulting, Report No. PL2025-001, Version 2.0. 25th Feb., 2025.*

This report was led by Piers Larcombe (of Piers Larcombe Consulting) with contributions from Matt Eliot (of Seashore Engineering). Steve Buchan (MetOcean Consulting) contributed to some aspects of meteorology and oceanography. The contract was held by MetOcean Consulting.

The report draws on, adds to, builds on, integrates and re-interprets part or all of several previous reports relevant to coastal processes in the ESSP area, most notably (and in date order):

O2 Metocean 2022a. Coastal processes study to support BCH assessment. Final Report R210391 to Leichhardt Salt Pty Ltd. Rev. 2. 18 November 2022.

O2 Metocean 2023a. Eramurra Solar Salt Project - Coastal and Intertidal Processes Assessment, ESSP Scenario 7.2. Leichhardt Salt Pty Ltd. Report no. R220181, Rev 0. 04 July 2023.

Larcombe, P. 2024. Review of the interpretations and conclusions made by the CP-BCH Report, updating them using the latest pond scenarios and corrected hypsometric data - Eramurra Solar Salt Project. Report PL2024-001 to Leichhardt Salt Pty Ltd, 44 pp, Rev.1.1. 5th March 2024. Leichhardt Document No. ESSP-EN-14-TRPT-0031

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. Eramurra Solar Salt Project. Report for Leichhardt Salt Pty Ltd. Report No. PL2024-002, Version 3.1. 17 July 2024. Leichhardt Salt Document No. ESSP-EN-14-TRPT-0033.

Where there are differences in data, analysis or interpretation, this report takes precedence.

1.2. Sources of data and information

The report draws on a wide literature and is fully referenced throughout, with sources referred to in the relevant text, figures and tables. Sources include:

- The formal published literature, such as journal papers and government publications.

- Relevant unpublished grey literature.
- Measured processes from instruments deployed in the field, samples taken in the field and analysed, and relevant similar data obtained from elsewhere.
- Reputable websites, such as those operated by the Bureau of Meteorology and Geoscience Australia.
    - Of particular interest are documented changes in the physical environment, both qualitative and quantitative. Examples include qualitative measures such as assessments of past aerial photos, and quantitative or semi-quantitative measures such as the changing horizontal locations of mean sea level at the shoreline (MSL) as derived from satellite imagery combined with oceanographic model data and made available by Geoscience Australia (2022).
- Data and information supplied by LS, such as maps, and data on catchment volumes (noted below).

1.3. Data supplied

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

- Elevation contours at 1 m intervals between -19 m and +7 m AHD, and at 0.5 m intervals between -1 m and + 5 m AHD.
- Distribution maps of mangroves, samphire and algal mats (hereafter referred to as benthic mats)
- The proposed pond scenario 7.2.1.
- Creek catchment boundaries (watersheds) for a series of tidal creeks, with catchments boundary locations defined by the lead author.
- Volumetric data (hypsometry) between -1 m and +5 m AHD (in 0.5 m intervals) for the individual tidal creek catchments for pond scenario 7.2.1., and
- A variety of other associated GIS information.

2. Report structure

This report presents a series of broadly logical and sequential parts, first laying the basis for the study, presenting the evidence of the natural environment, then considering how it might change in the future, and how that future might be affected by the ESSP development.

As a result, after the introduction, there follow six main parts to the work, noted below:

PART ONE - KEY UNDERLYING PRINCIPLES AND FACTORS. (Sections 2 to 6).

This part deals with sea-level changes, the factors and key concepts of natural habitat change, the influence of sea-level rise on coastal geomorphology and associated habitats, and concludes noting the relevance of natural coastal change to the assessment of benthic community habitats.

PART TWO – THE ESSP REGION, PRESENT UNDERSTANDING. (Sections 7 to 12).

This part describes the key physical aspects of the ESSP region, including its physical processes, its marine and coastal landforms and the main sedimentary units. It then considers the relevant aspects of sediment transport, including quantifying some aspects of past change, and notes a series of tests that could usefully be applied to identify the sediment transport pathways and the significance of the various deposits.

PART THREE – THE ESSP REGION, NATURAL FUTURE CHANGE. (Sections 13 & 14).

This part focuses on the key elements involved in assessing future change, and the method of doing so.

PART FOUR – FUTURE CHANGE WITH THE ESSP DEVELOPMENT. (Sections 15 to 21).

This part notes some initial sedimentary concepts including sources, transport processes and evolution, and notes some basics about the ESSP project. It then examines in detail the tidal processes in the various creek catchments, considers river runoff and how it might affect habitats and the different constraints on coastal stability with SLR. Results of numerical models help indicate some areas of likely change. Qualitative descriptions are given for potential coastal changes over the next century.

PART FIVE - FUTURE CHANGE FOR KEY SITES. (Section 22).

This part integrates all available evidence and uses expert judgement to derive quantitative measures of potential future change. These are applied to a series of key sites in the ESSP area presented as detailed worked examples, to outline potential habitat changes at each site over the next century, with and without the ESSP development.

PART SIX – CONCLUSIONS AND SUMMARY. (Sections 23 to 25).

This part presents clear statements of the work’s caveats and uncertainties, highlighting the more significant aspects. Using defined levels of confidence, a series of conclusions are stated regarding the past and present natural system, natural future change, and potential change with the ESSP development in place.

2.1. Locations, names & key maps

A series of maps below show the main locations, their names and other key features:

- The regional location of the proposed ESSP development - Figure 1
- The pond scenario 7.2.1. and the previous scenario 7.2.0. - Figure 2
- The main named locations used in this report - Figure 3
- The regional bathymetry - Figure 4
- Detailed bathymetry - Figure 5
- The ESSP area with selected elevation contours - Figure 6
- The proposed pond locations of scenario 7.2.1. - Figure 7
- The nature and distribution of subtidal and intertidal habitats - (Figure 9 & Figure 10).

More detailed maps are included as appropriate within the main text.

The elevation of various tidal planes in the area (supplied by LS) is given in Table 2.

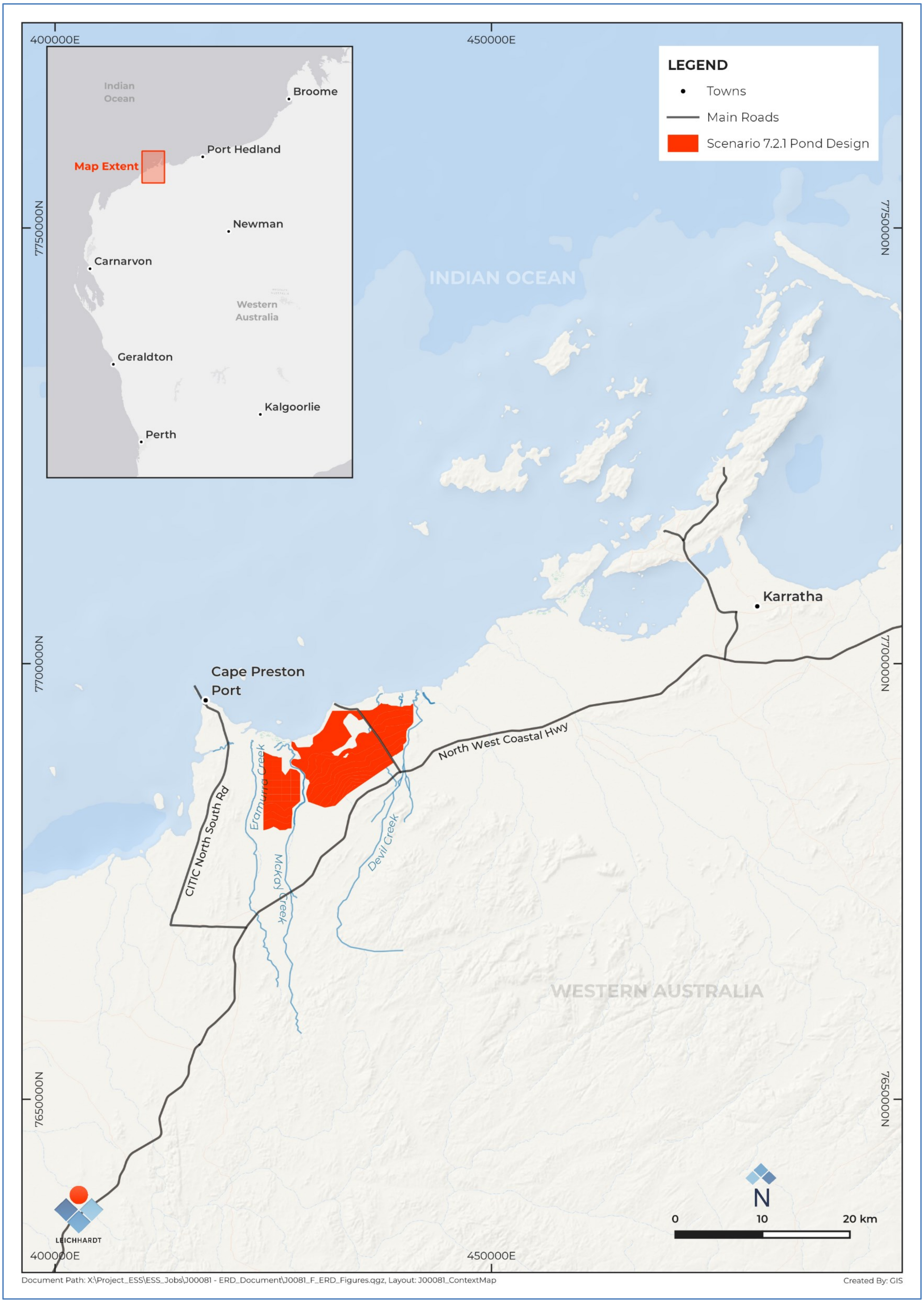


Figure 1. Regional location of the ESSP proposed development.

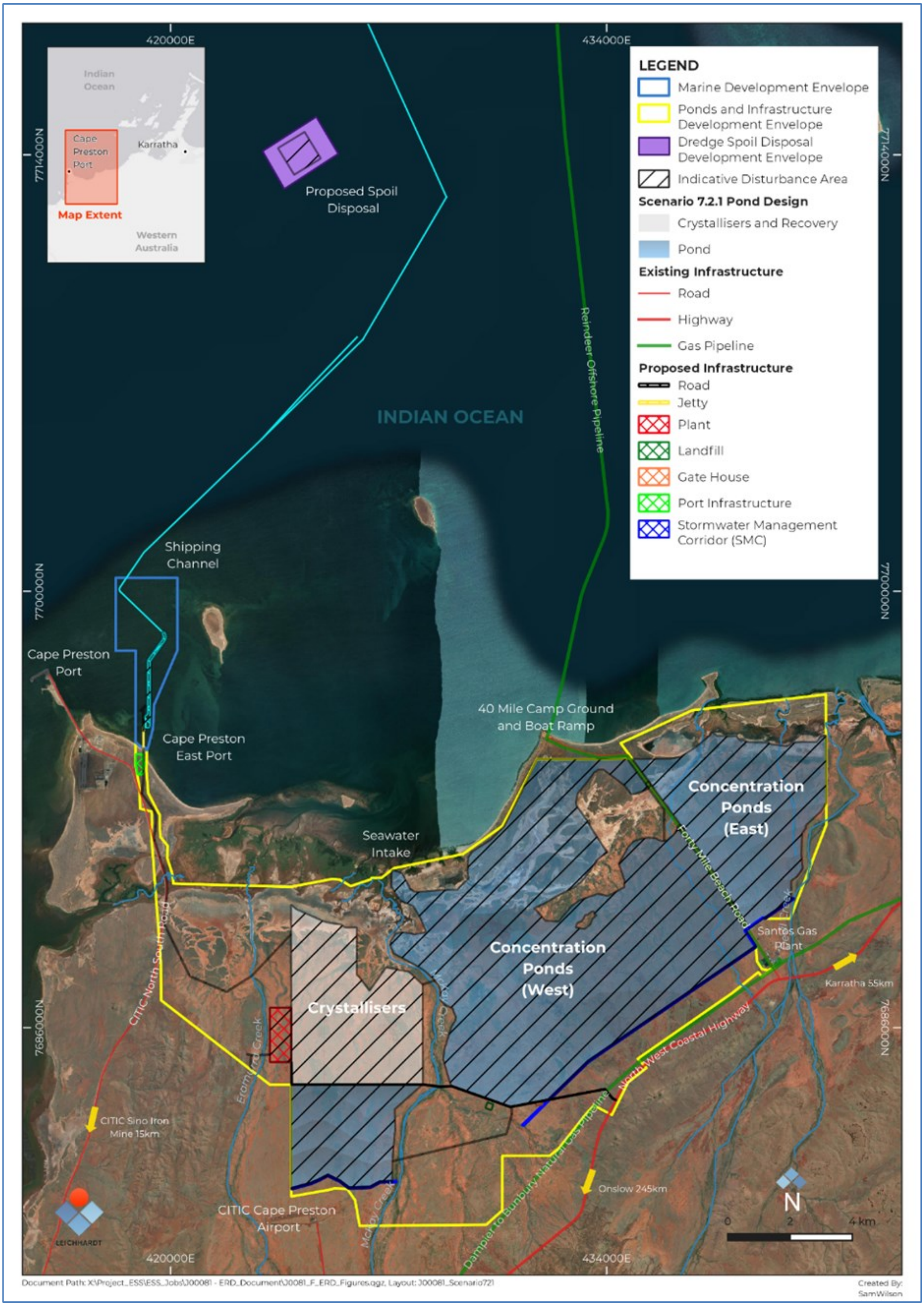


Figure 2. The ESSP proposed development envelope.

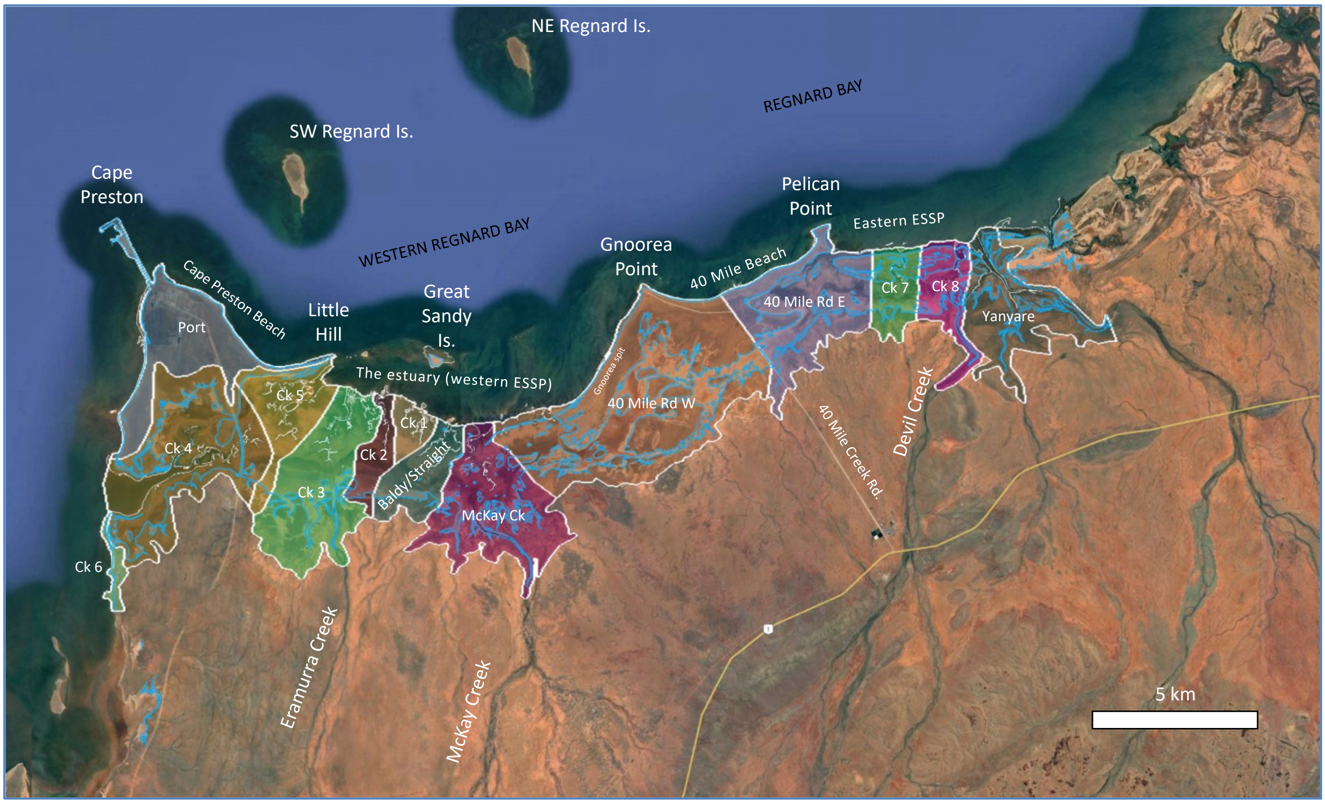


Figure 3. Main named physical features as used in this report, plus named tidal creek catchments (watersheds) taken landward to just beyond the 5 m AHD contour.

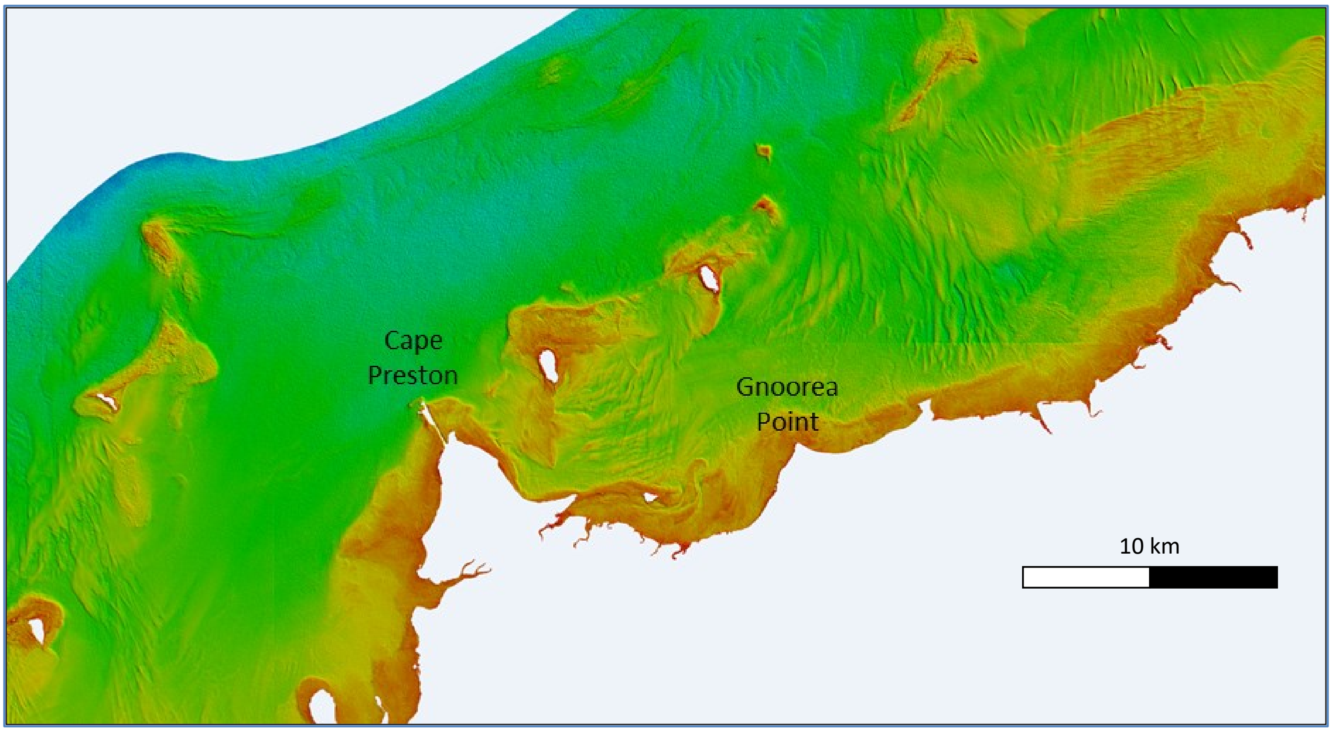


Figure 4. Regional bathymetry and seabed features (Lebrec et al., 2021).

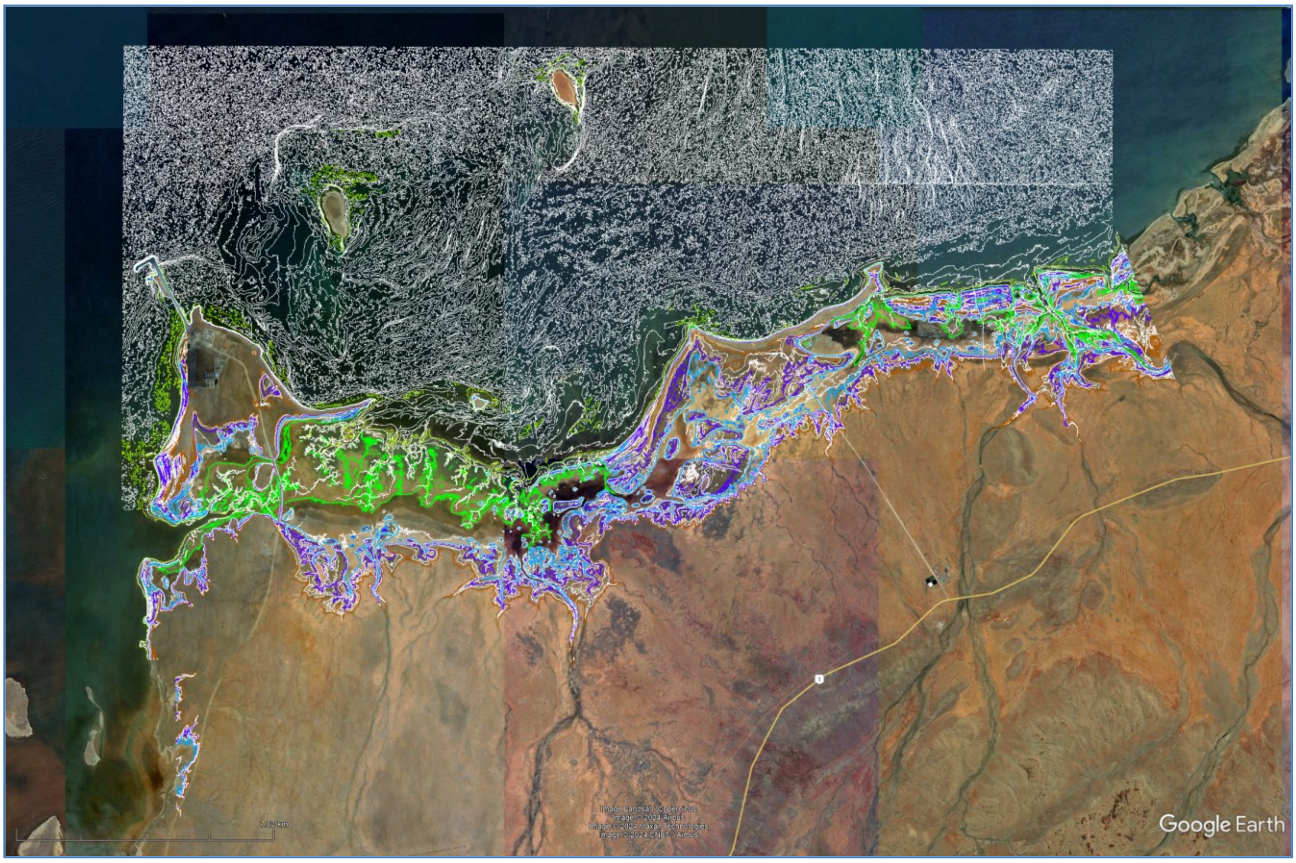


Figure 5. Aerial image of the ESSP area with elevation contours at 1 m intervals between -19 m and + 7 m AHD.

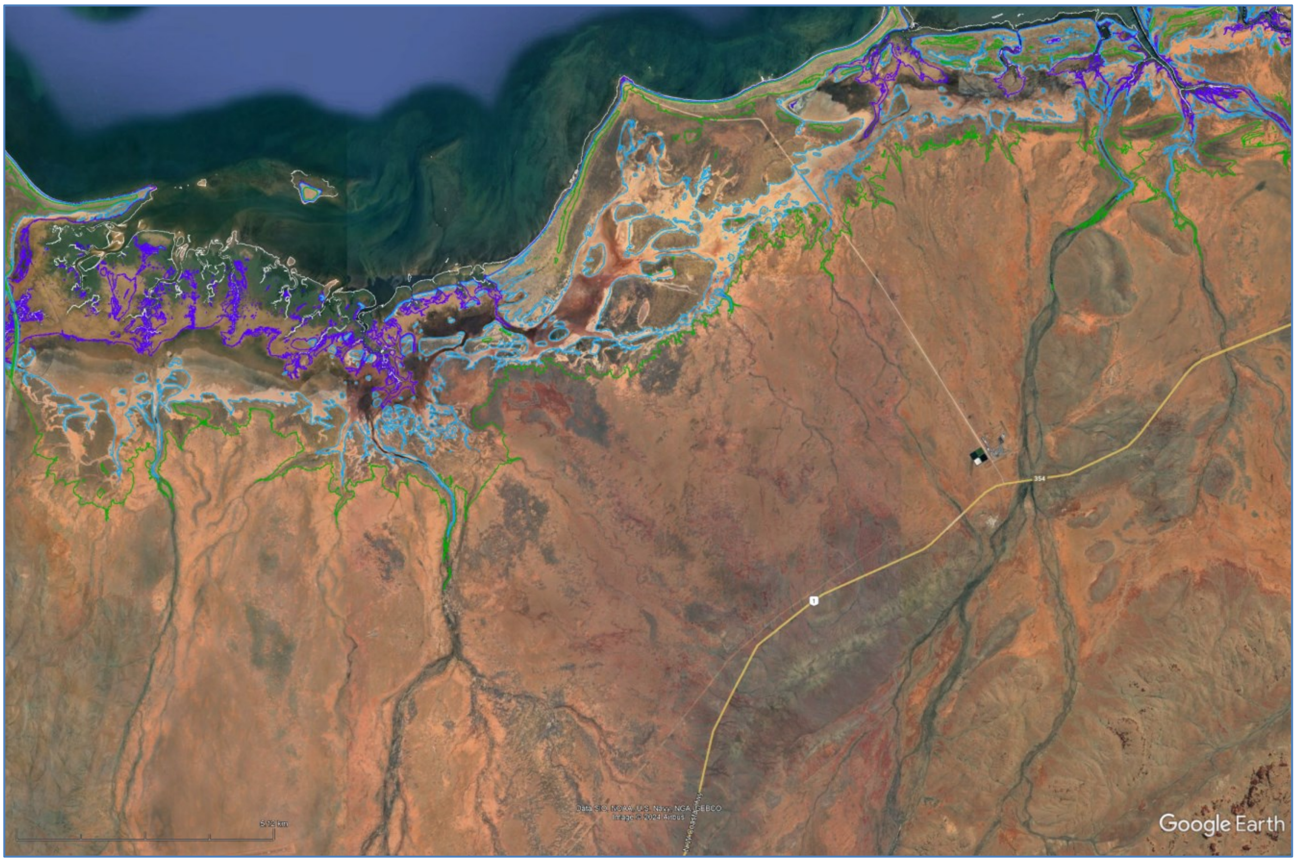


Figure 6. Aerial image of the ESSP area with selected elevation contours (AHD) at 0 m (white), +1.5 m (purple, approximating the top of the creek banks), +2.5 m (blue, mean high tide), and +5 m (green).

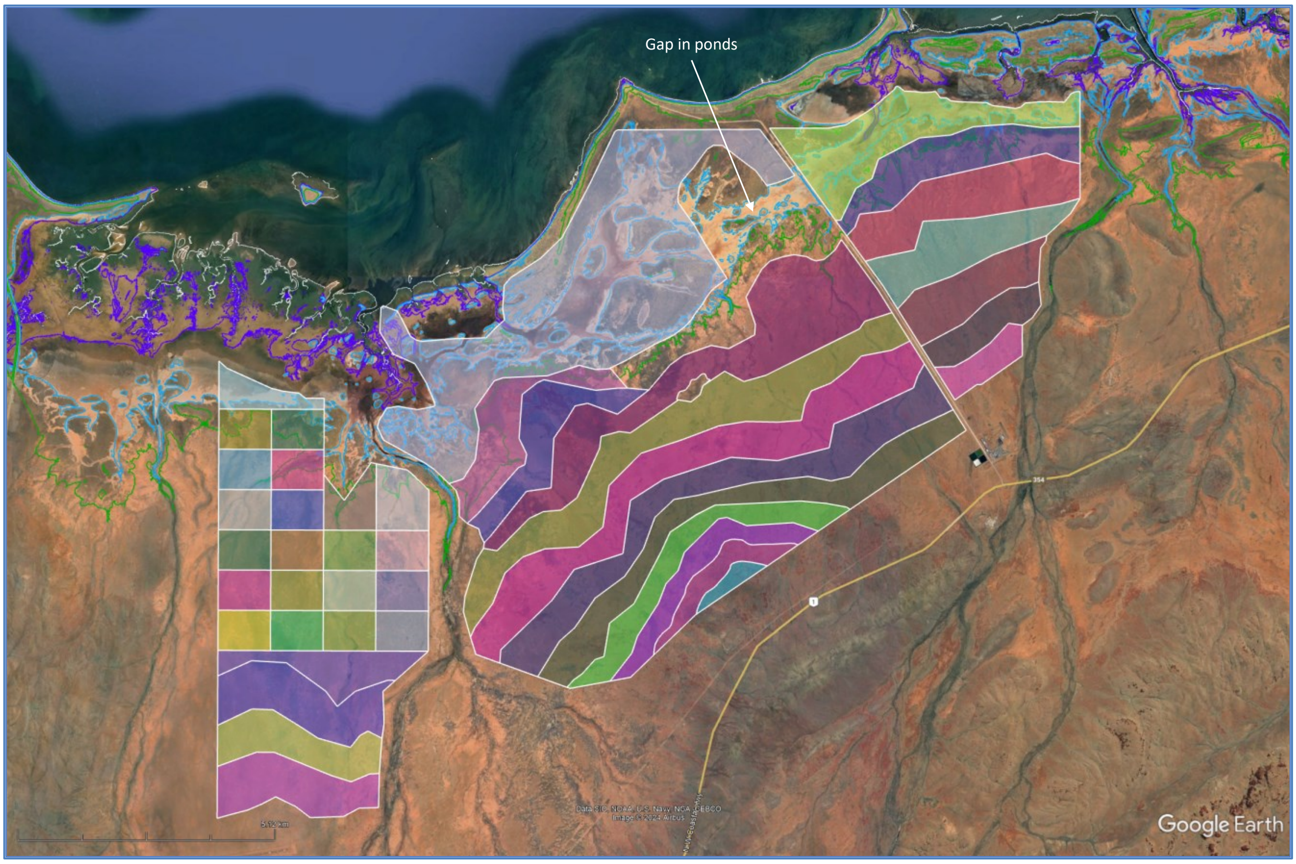


Figure 7. As Figure 6 plus the salt ponds of scenario 7.2.1. with internal bunds. (Colours of ponds not significant).

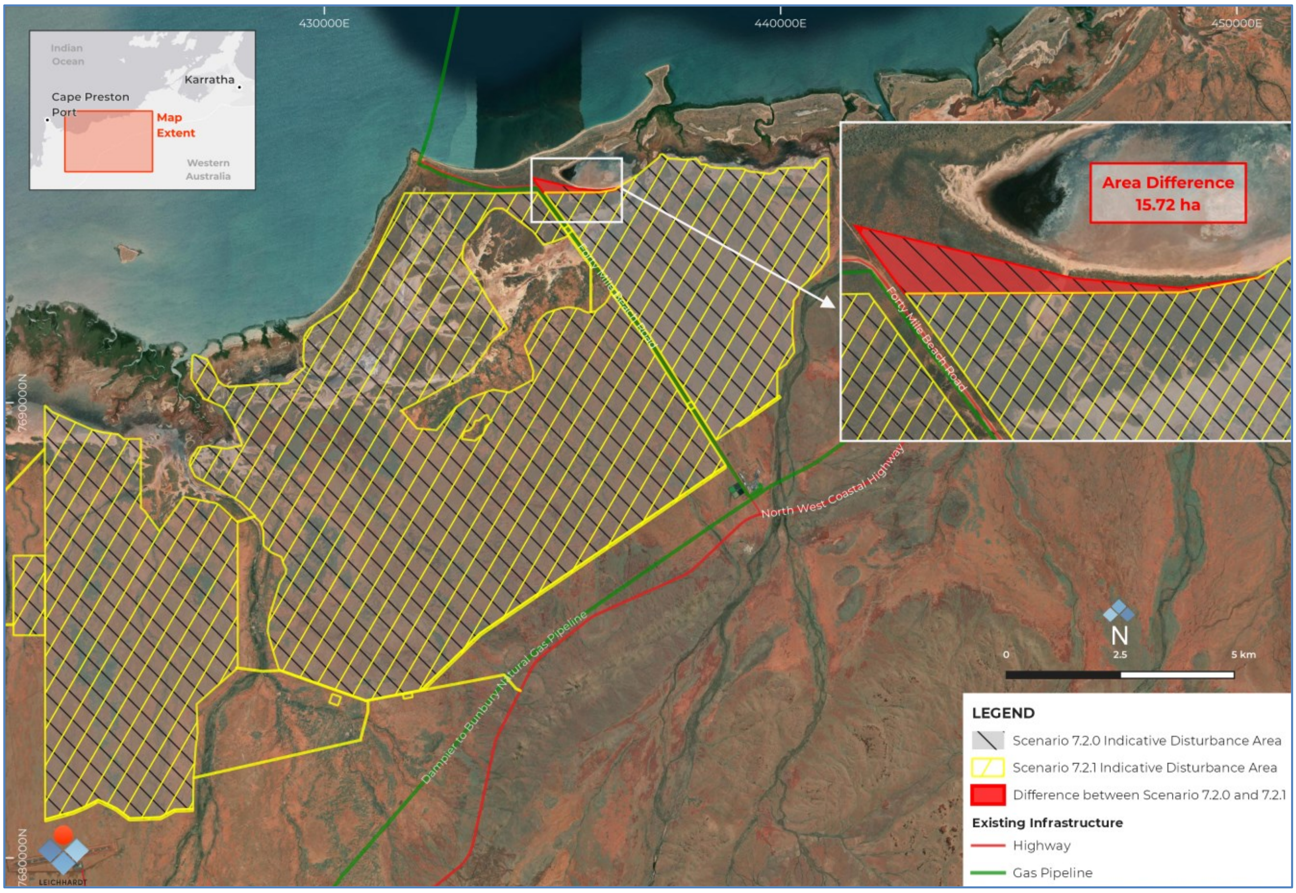


Figure 8. The outer extent of pond scenario 7.2.1. (yellow hachures) and its 16 ha smaller footprint than the superseded scenario 7.2.0. (The latter is used for some hydrodynamic modelling, with no substantive difference in outputs.)

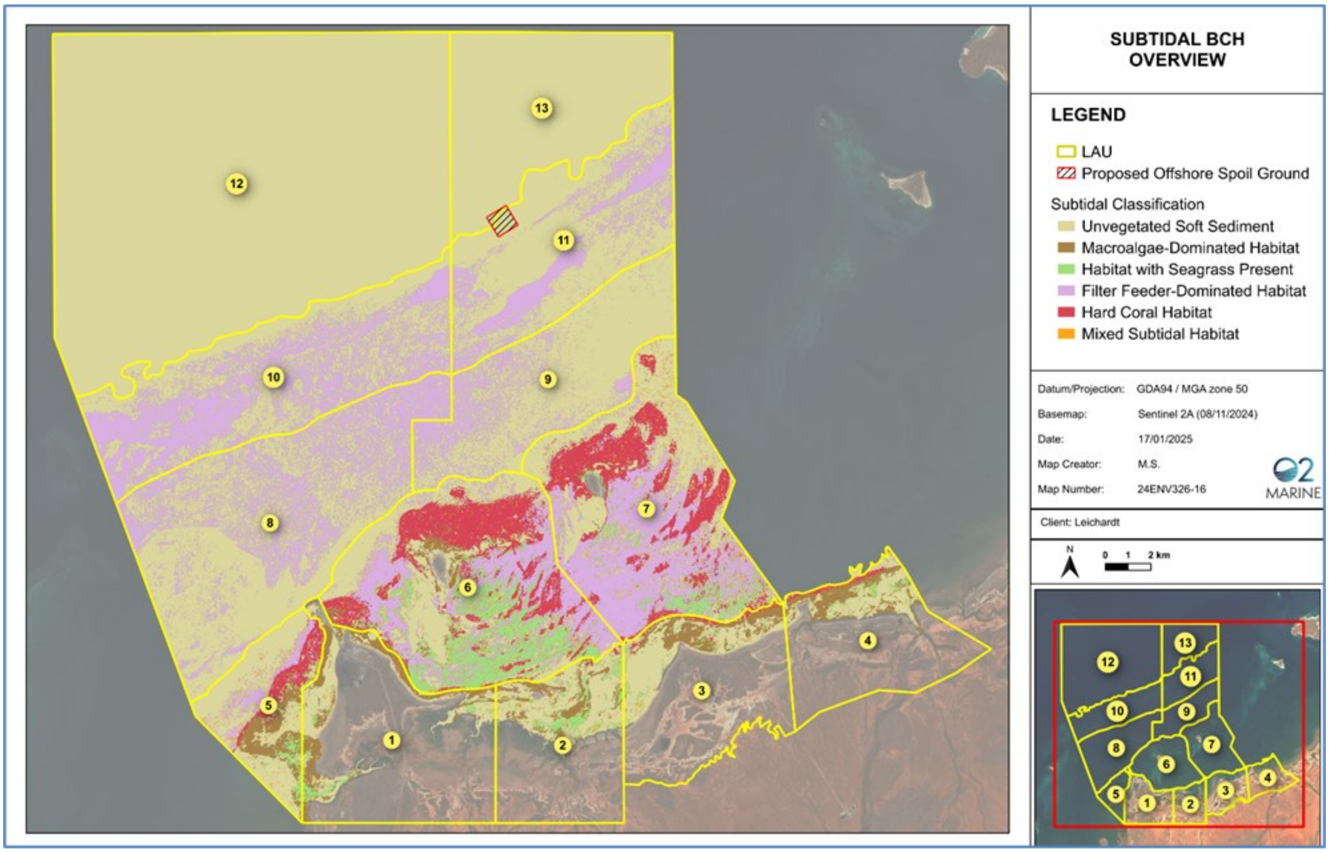


Figure 9. Compiled Subtidal BCH map for the study area within LAUs (O2 Environment 2025a)

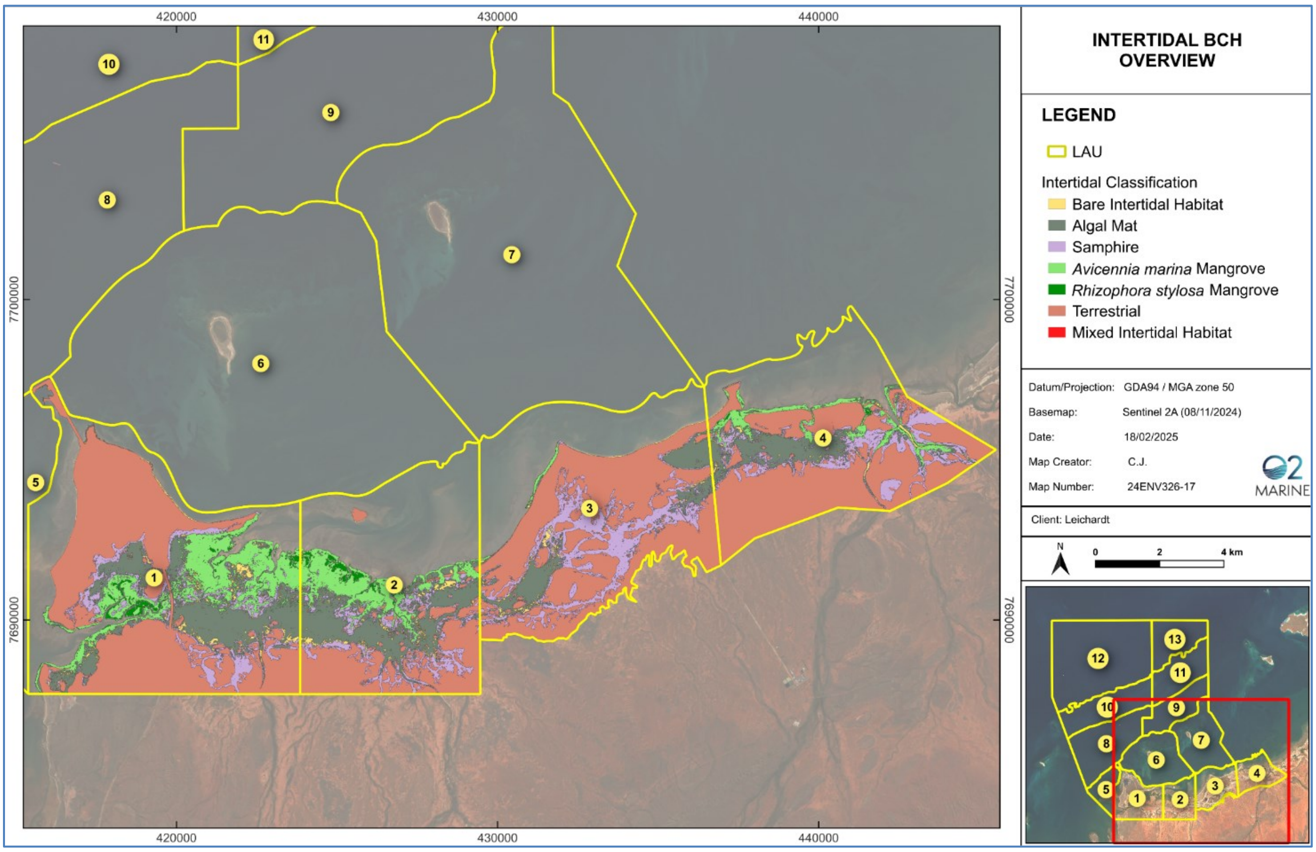
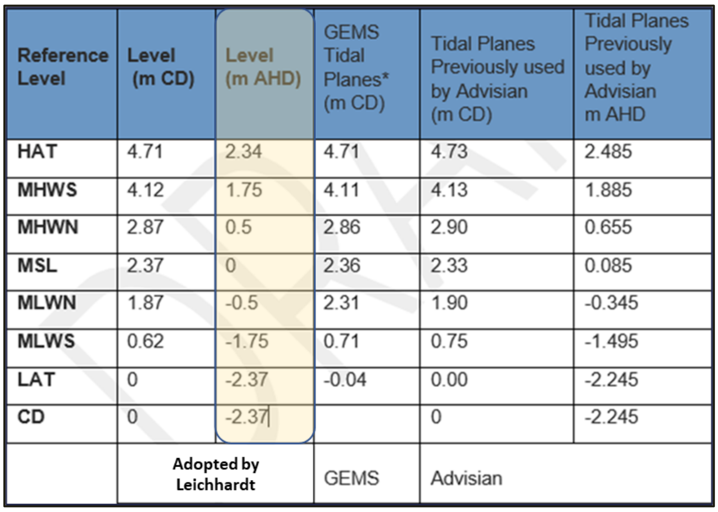


Figure 10. Intertidal BCH and Terrestrial vegetation classification within Proposed LAUs (O2 Environment 2025b).

Table 2. Tidal planes in the area (supplied by LS), with the shaded column adopted by LS.



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	

2.2. A note on sediment cells

Coastal sediment (littoral) cells are sections of the open coast that are considered to share a defined source, transport pathway and sink of sediment (Bowen & Inman 1966). In the 1990s a series of maps of sediment cells were developed around the UK, including by Motyka & Brampton (1993) for England and Wales and by HR Wallingford (1997) for Scotland. The essential concept was that of a series of sediment cells or compartments, where within each cell sediment may be transported by the longshore drift of beach material (sand, shingle etc.), but between adjacent cells there is limited sediment exchange. This concept was arrived at because most cases of severe coastal erosion around the UK coast had been caused by interruptions to the natural longshore transport of sediment.

Based on such concepts, Stul *et al.* (2014) used existing literature, aerial imagery, bathymetric data and digital datasets of rivers, shoreline position, geomorphology and geology propose a hierarchy of ‘sediment cells’ for much of WA, including the Pilbara (Figure 11). The hierarchy of primary, secondary and tertiary sediment cells was proposed to be relevant to coastal management timescales of, respectively, i) more than 50 years ii) inter-decadal and iii) seasonal to inter-annual periods. For much of the WA coast information is limited and available data places limitations on the location and nature of many ‘boundaries’, including whether the boundaries are ‘leaky’ or not, i.e., whether they allow transfer of sediment through them, and the conditions under which that might occur. The relevant cell boundaries of Cape Preston, Pelican Point, Little Hill and Regnard Bay were defined as ‘open’ (Stul *et al.* 2014) indicating that they are permeable to sediment transport between adjacent cells. Cape Preston, Pelican Point and Little Hill have a rock basement (Section 9.2, see also Figure 96 & Figure 64), indicating little sediment transport under fair-weather conditions.

Whilst these proposed cells are a helpful concept and are used by some management and regulatory agencies, it should be clarified that there has been almost no field testing of these compartments in WA - for example using sediment particle size and compositional data. Further, for some developments, these specific cells are unlikely to be useful because of cell size compared to the development. Relevant to the ESSP, the proposed cell boundaries are widely spaced (red dots on Figure 11) and together with the lack of field data, the concept is unable to usefully contribute to an assessment of the resilience of the coastline and associated habitats to anthropogenic changes in coastal sediment transport regimes. This sediment cell concept is not used in formal terms further in this report, but sediment sources and pathways of sediment transport are fundamental to the entire report.

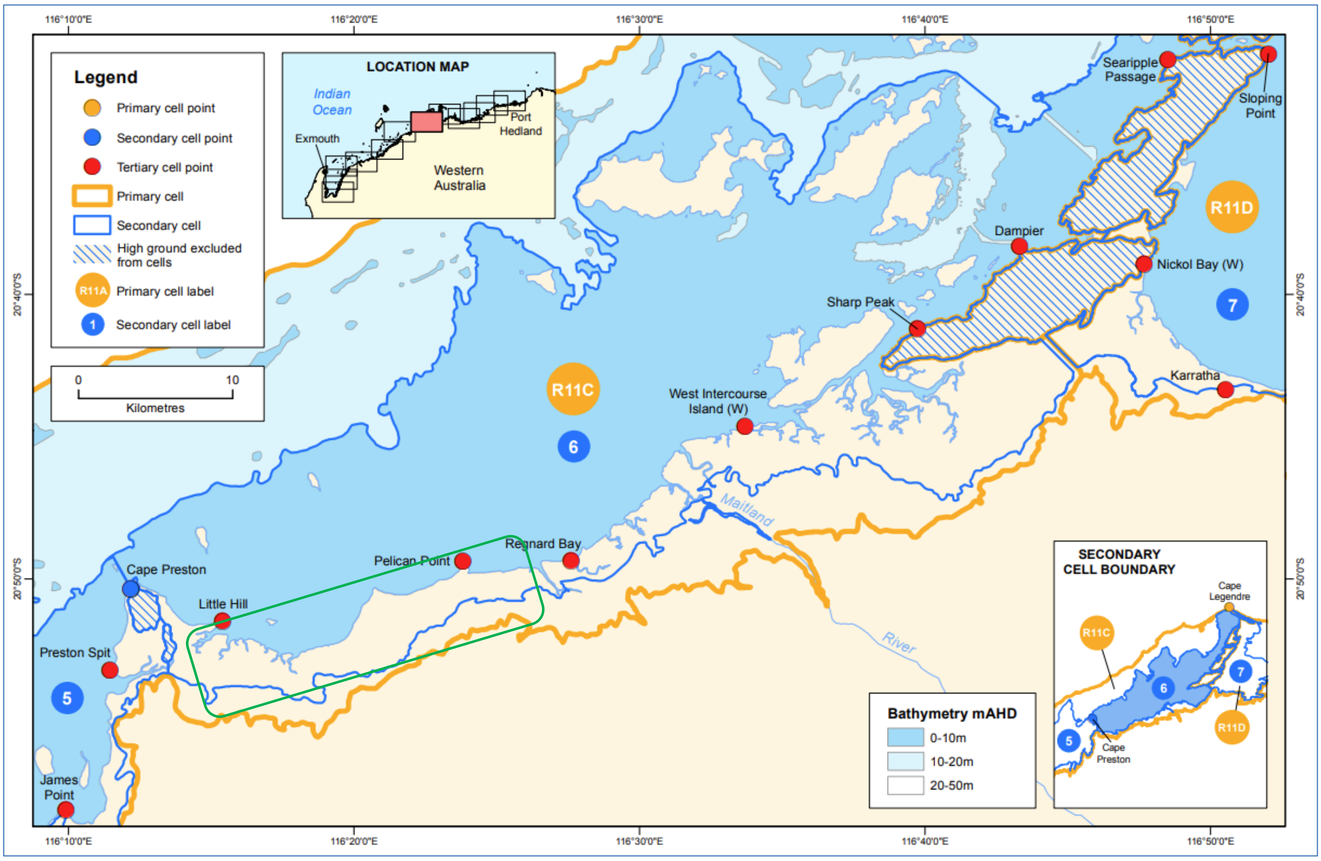


Figure 11. A hierarchy of regional sediment cells proposed by Stul et al. (2014) for the central Pilbara. Red dots indicate proposed boundaries, between which coastal cells or compartments occur. Green box marks approximate extent of ESSP coastal area.

PART ONE - KEY UNDERLYING PRINCIPLES AND FACTORS

3. Comments on levels of understanding about coastal change

As part of the remit, this report needs to assess the effects of future sea-level change (presumed net sea level rise SLR) over the next century on natural coastal physical change, then to consider the specific aspects of the ESSP area and possible effects of the proposed development. As background, it is necessary to consider key aspects of the coastline's geomorphology and processes.

A description specifically of estuarine change (Figure 12) is closely related to the ESSP setting and helpful to illustrate some issues. Of the four aspects below, the first is known relatively well and successive aspects are less well known than the previous:

- Trajectory – We know about the general direction of overall change. This includes various considerations, that are expanded below using the headings in Figure 12:
    - A basin structure is largely 'created' by SLR, i.e. the sea 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 type of consideration tends not to deal with episodic behaviour (such a Tropical Cyclones) and no rates of change 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 processes 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.
    - Various processes or controlling features are intermittent in nature and in their morphological effect are time-variable, also within the overall trend. An example here is the western 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 includes such aspects as:
    - What feature or set of features does the sediment form in the estuary?
    - What engineering intervention (if any) 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.

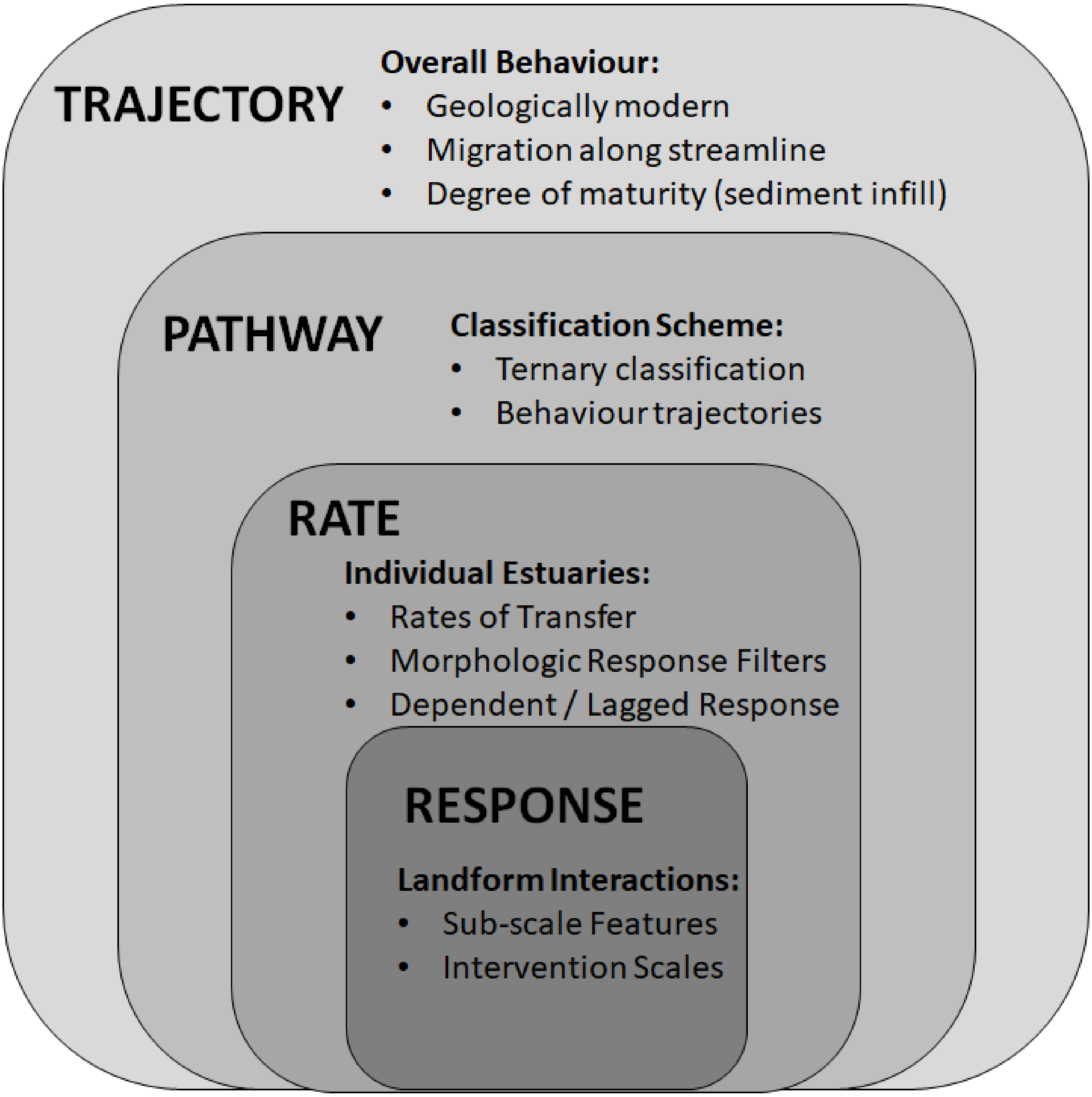


Figure 12. Conceptual differences in levels of understanding about several different aspects of estuarine change. The smaller the squares, the less knowledge.

4. 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. MSL is the mean level of the sea over a long period, preferably 18.6 years to account for a whole cycle of the moon's nodal cycle, often called the 'lunar wobble'. Put more simply, MSL is the mean level that would exist in the absence of tides. Whilst MSL is useful because measurements can form an indicator of long-term change, including over the last few decades or more where measurements are more accurate and better understood, MSL itself is 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 aspects include:

- **Tidal range.** The astronomical tide varies by up to 4.7 m or so (Section 7.2.2), 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 4.1);
- **'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 7.2.2). 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 7.3.4). These surges are generally associated with strong waves and may last several hours;
- **Coastal trapped waves.** These are ultra-long period waves (timescales of weeks to months) that propagate anticlockwise around the Australian continent, bringing with them coastal sea level fluctuations of up to +/- 0.5 m (though usually more of the order of +/- 0.2 m).
- **Geostrophic setup**. This can occur dur to persistent along-shelf currents such as the southward flowing Leeuwin Current, but this is generally poorly developed in the ESSP region, becoming more established south of North West Cape.
- **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 UNDERSTANDING THE PHYSICAL ASPECTS OF THE COAST, IT'S ABOUT FAR MORE THAN JUST A FUTURE RISE IN MEAN SEA LEVEL.

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

4.1. 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.* (2022). 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 13). 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 14) 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.

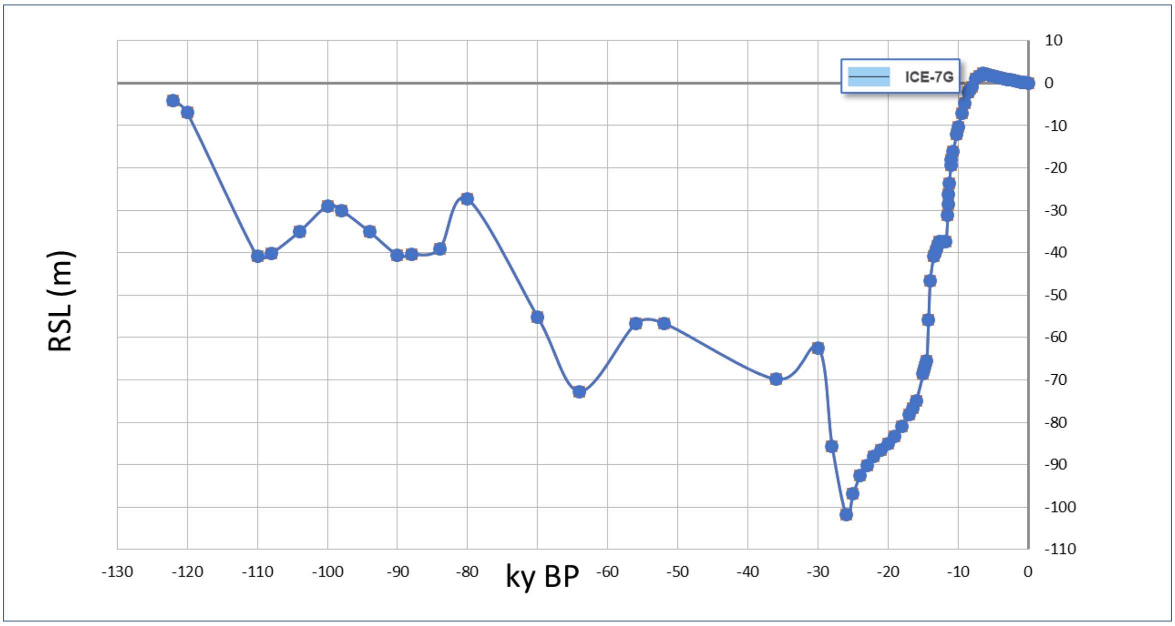


Figure 13. Simplified relative sea-level (RSL) curve for Barrow Island for the last 120,000 years derived from the Glacial Isostatic Adjustment model ICE-7G_NA (modified after Ward et al. 2022). Error bars in elevations have not been shown.

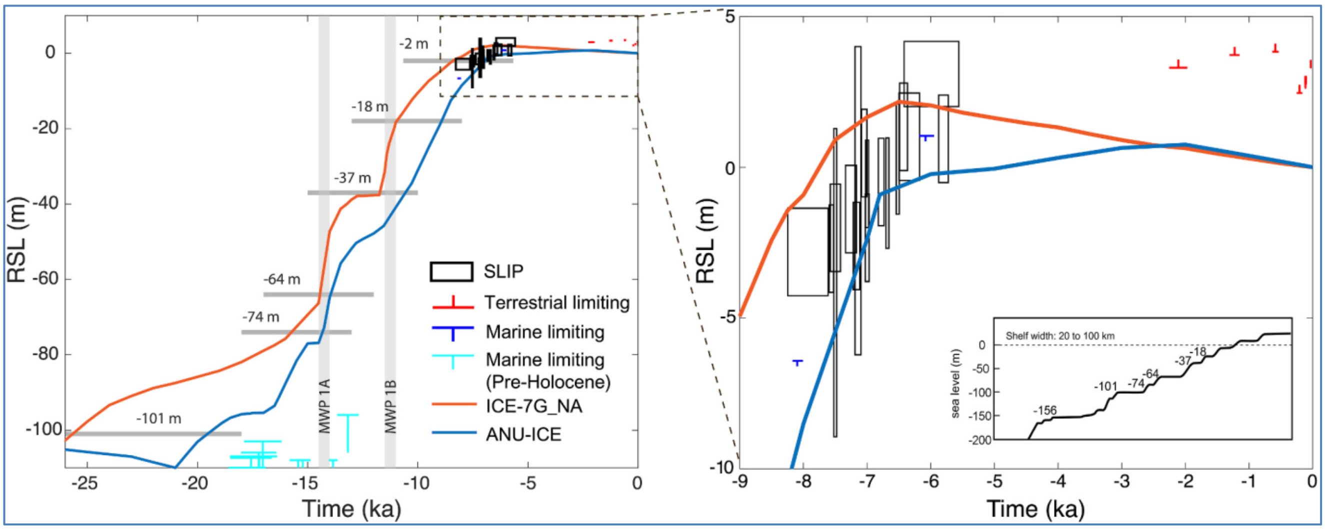


Figure 14. Deglacial relative sea-level (RSL) curves for Barrow Island derived from the Glacial Isostatic Adjustment models using the ICE-7G_NA and ANU-ICE ice models paired with the HetM-LHL140 3-D earth model (Ward et al. 2022)[1]. SLIP = Sea level index point.

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 changes in relative sea-level (RSL), i.e., the change in sea level relative to the land. Synthesis of regional or global MSL trends, variously incorporating models for isostasy (put simply, the changing land levels), have been developed. Over the 20th Century, once corrected for isostasy, most tidal stations have reported a rise in MSL, with rates of rise varying depending on data coverage, timescales, statistical methods and observational frameworks. On the whole, an accelerating rate of rise in MSL has been observed, 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.

---

[1] 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 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.

- 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 15) 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 generally available for the latter phase only.

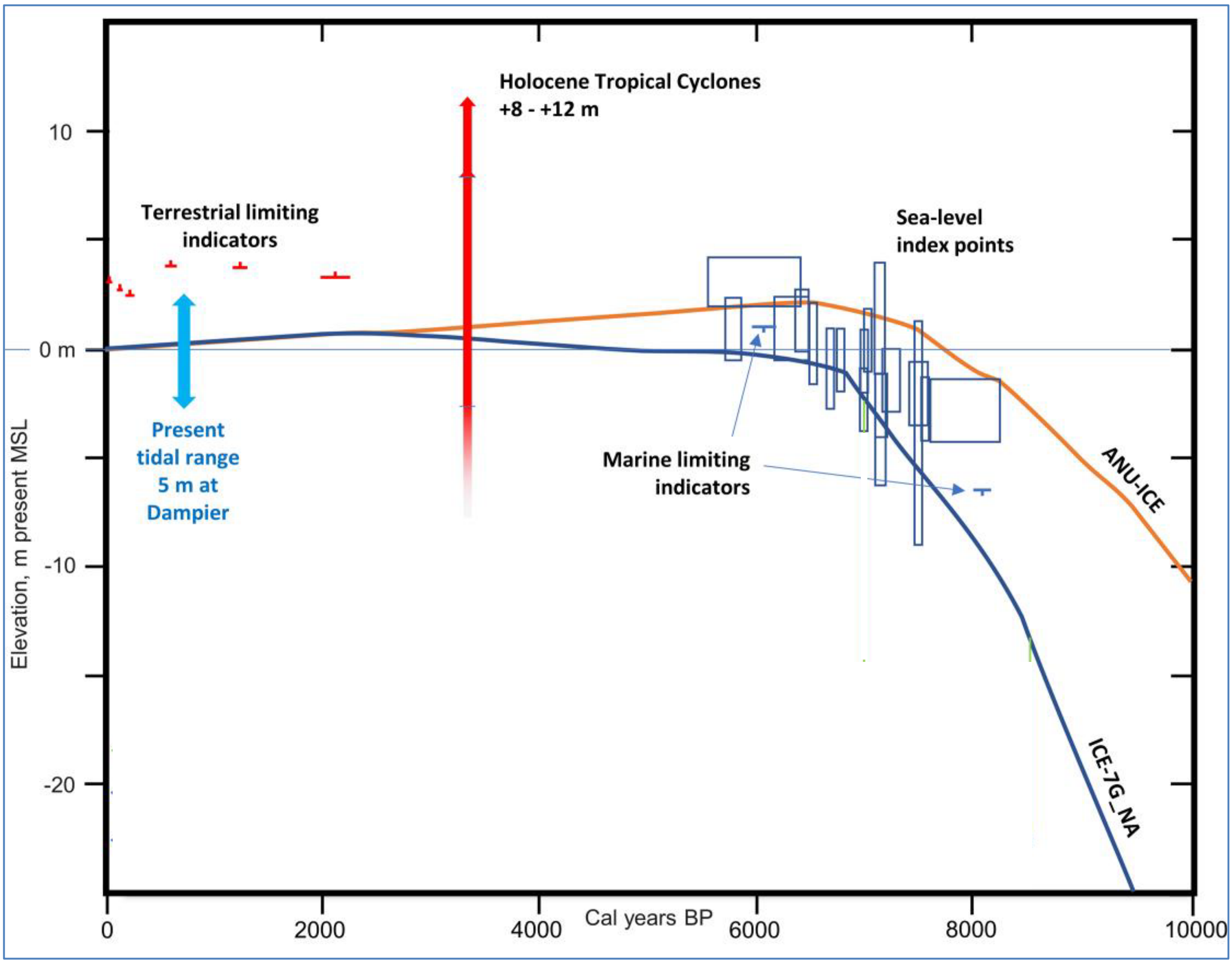


Figure 15. Regional relative sea-level change over the last 10,000 years (After Larcombe et al. 2025). Note the modern tidal range at Dampier (blue arrow) and the elevation of Holocene indicators of extreme sea levels in the Dampier Archipelago area (red arrow), assumed to be caused by cyclones.

Tide gauges around the world provide measurements 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 16, Figure 17) indicates high variability and a mean rate of SLR since 1985 of 2 to 4 mm/yr. For the ESSP area, 3 mm/year represents mean SLR for the period 1988-2020, relevant to the Geoscience Australia

(GA) data used to support an analysis of coastal change presented below (Section 11). Note though that BOM quote 1.7 mm for King Bay, Dampier.

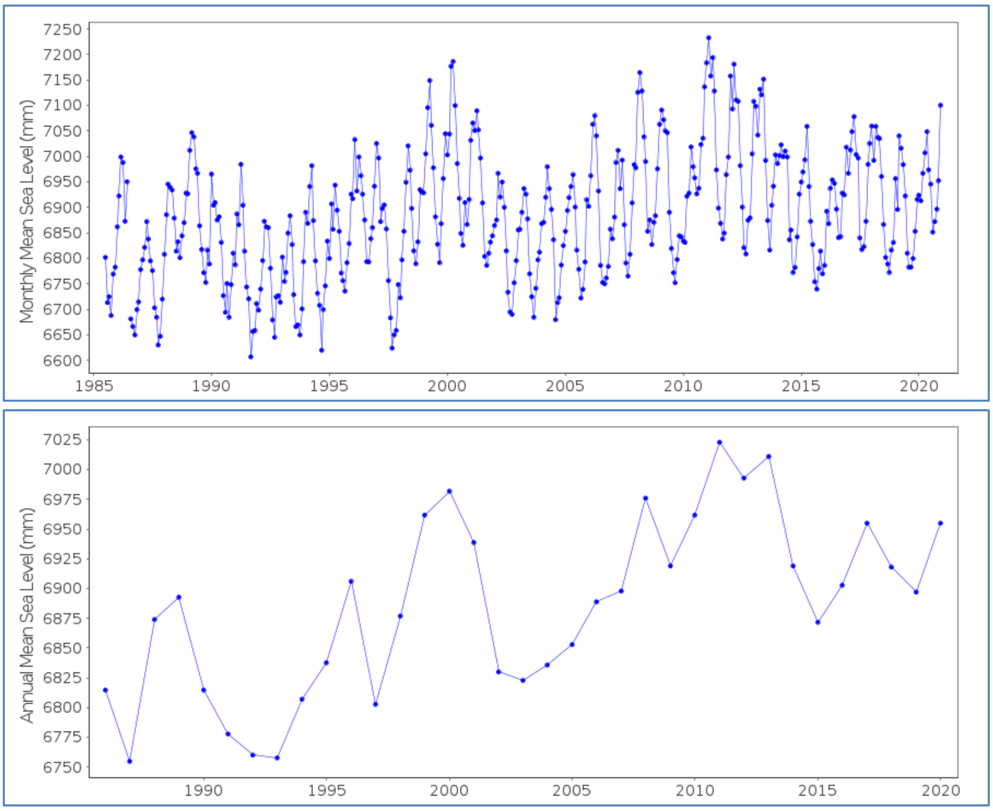


Figure 16. Onslow - monthly and annual sea level data since 1985 (PSMSL)

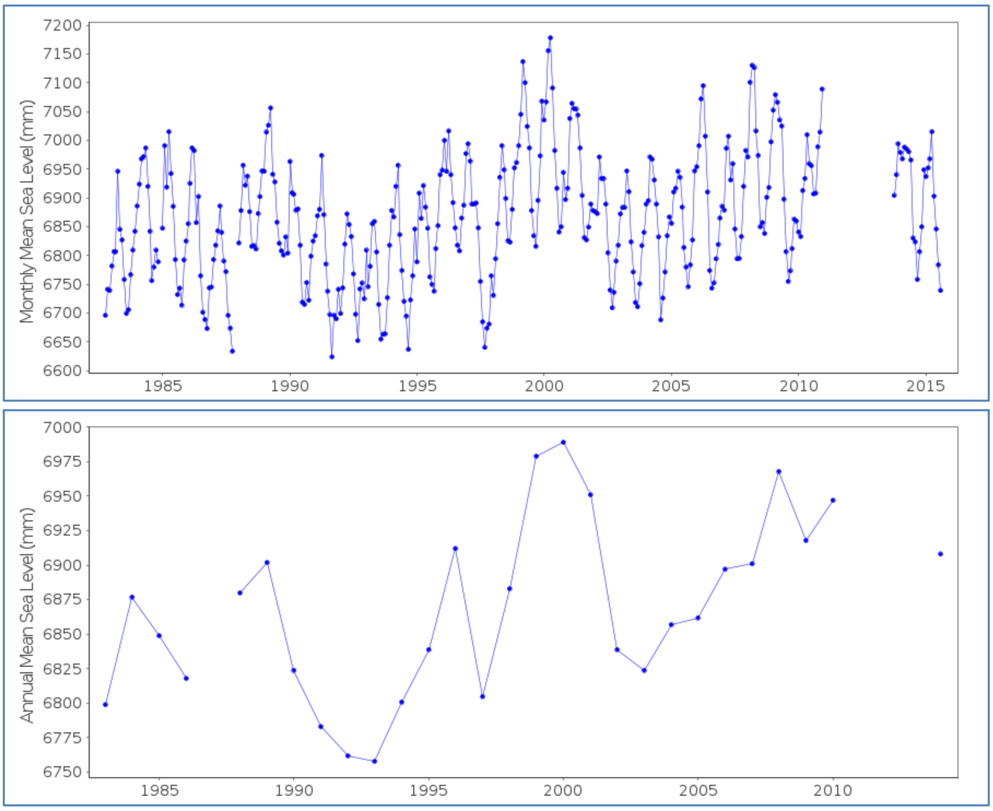


Figure 17. Dampier (King Bay) - monthly and annual sea level data since the early 1980s (PSMSL). This includes data from Withnall Bay (prior to 1985) which data should not be included in the SLR estimate, as the comparative datums are not well-established.

4.2. 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 (Figure 18). However, for stations with continuous records, a rise occurred over this period, e.g., for 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), but this is very different to the ESSP area because of the importance of the Leeuwin Current there at Fremantle. Changes in MSL are important for interpretation of coastal and habitat response to SLR but can be difficult to assess.

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 23). 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

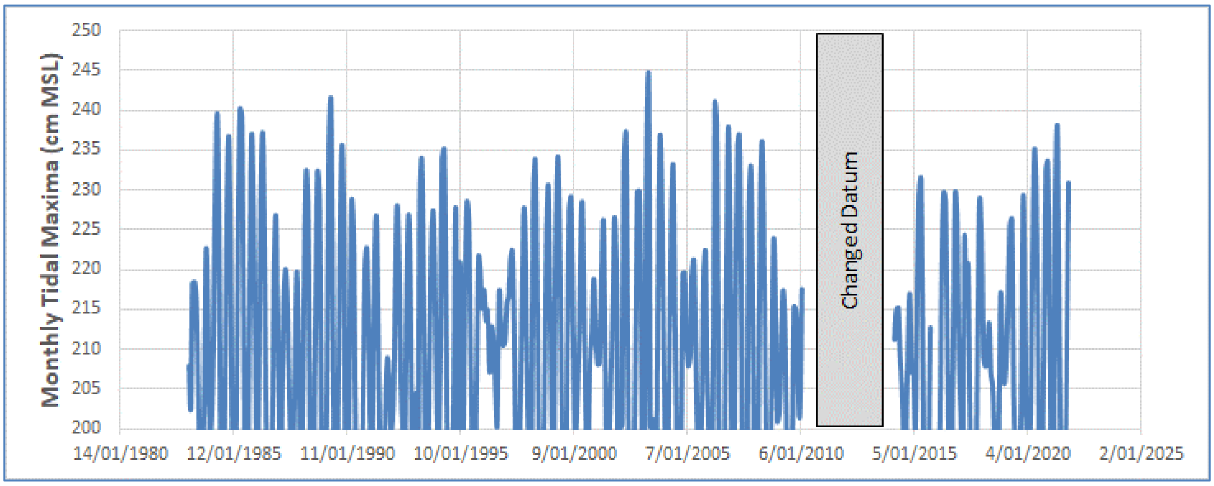


Figure 18. Monthly tidal maxima measured at Dampier. The datum changes was deliberate and well-controlled and shouldn't obfuscate measures of sea level change.

4.3. Projected future change

Future changes in MSL are unknown, but there are some relevant scientific projections, 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 19). Further, previous informal feedback from DWER (O2 Metocean 2022a) 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.

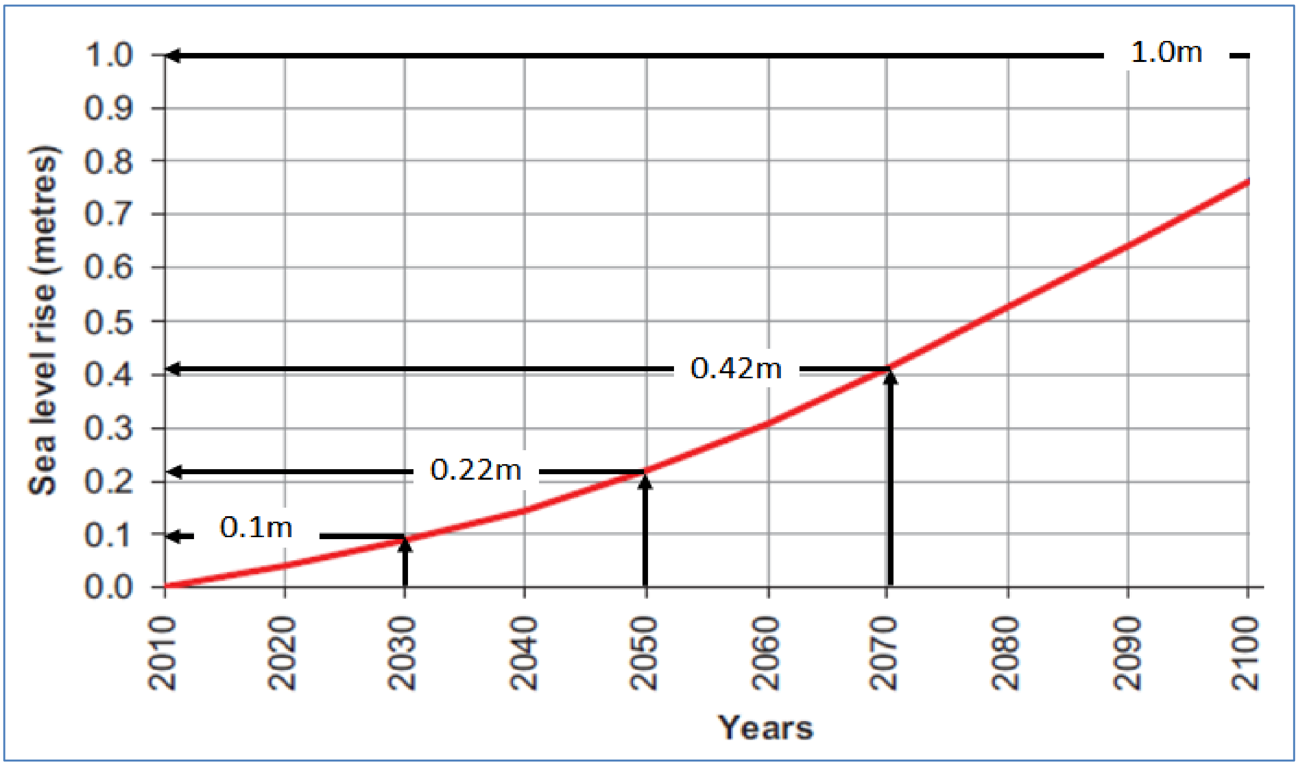


Figure 19. Future SLR trajectory used by the WA Department of Transport (DOT, 2010).

5. Natural habitat change - main factors and conceptual models

5.1. 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 focuses 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 with 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 3).

Table 3. 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 the 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).

5.1.1. Mangrove environments

5.1.1.1. General setting

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).

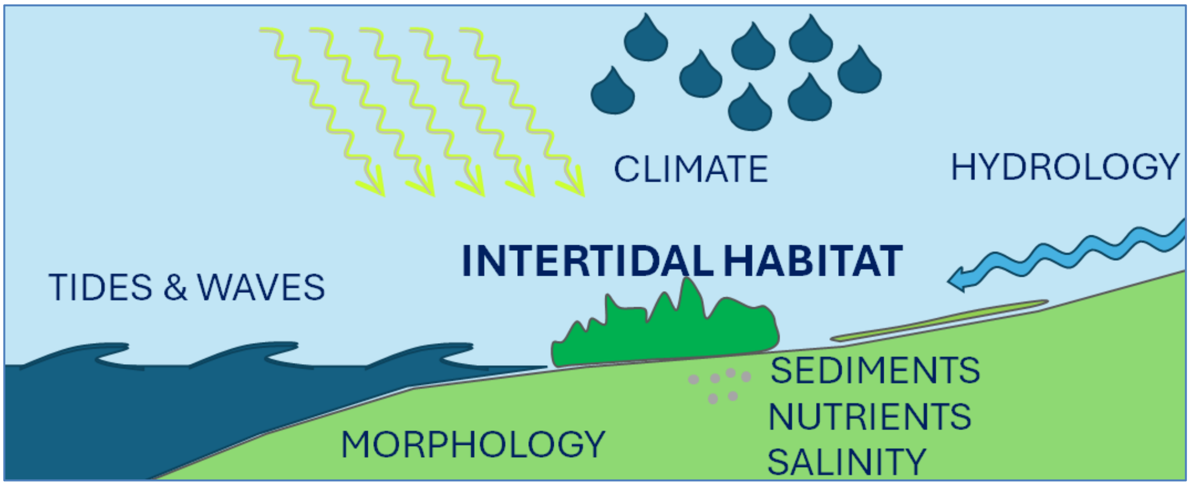


Figure 20. The main factors influencing intertidal habitats, including those occupied by mangroves.

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.

Within the coastal margin, steep and often dynamic ecological gradients limit the viable habitat for any single mangrove species. In response, mangrove systems typically develop species zonation, or an array of sub-habitats (Figure 21) 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 environments provide a critical habitat for diverse species, including key habitat for invertebrates, breeding and juvenile areas for fish stock, and foraging areas for marine turtles and birdlife. Mangroves have high bioproductivity and often play a significant role in contributing to coastal resilience (Alongi 2008).

5.1.1.2. Sub-habitats

The transition from marine to terrestrial conditions, including tidal creeks, supports the development of different sub-habitats (Figure 21) which can reflect the nature of varying hydrodynamic stresses, different sediments and changing salinity.

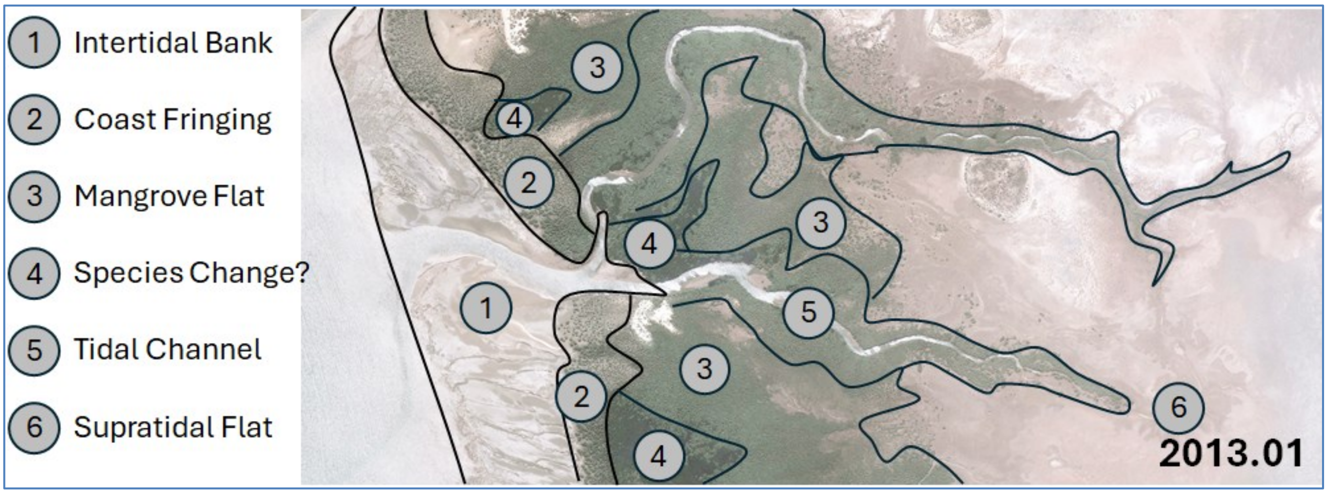


Figure 21. Mangrove sub-habitats characterised by their main physical control.

Simply, this provides three distinctive zones (bulwark, forest, & channel), characterised by the physical process which most influences the presence and abundance of mangroves (Figure 22). Here, bulwark means those mangroves that are influenced by waves and the direct exchange of material across them between the land and the sea, e.g., the mangroves of the nascent mangrove fringe of the western ESSP shoreline and the long narrow fringe seawards of the barrier in the eastern ESSP. Mangrove environment further landward reflect sediments derived from various sources (Figure 24).

In zoned heterogeneous systems, each zone may be occupied by a different mix or abundance of species, such as the red-black-white mangrove sequence occurring on many well-established mangrove communities in Florida and the Caribbean. For the western Pilbara region, which is dominated by *Avicenna marina*, the zonation reflects pressures, and often mangrove health or abundance, but less often results in significant species change. Mangrove species identified at the ESSP include *Avicenna marina, Rhizophora stylosa* and *Ceriops australis*, with *Avicennia* the dominant species (O2 Marine 2023a). Details of the mangroves in the ESSP area are provided in Section 9.3.1. and Appendix Section 33.

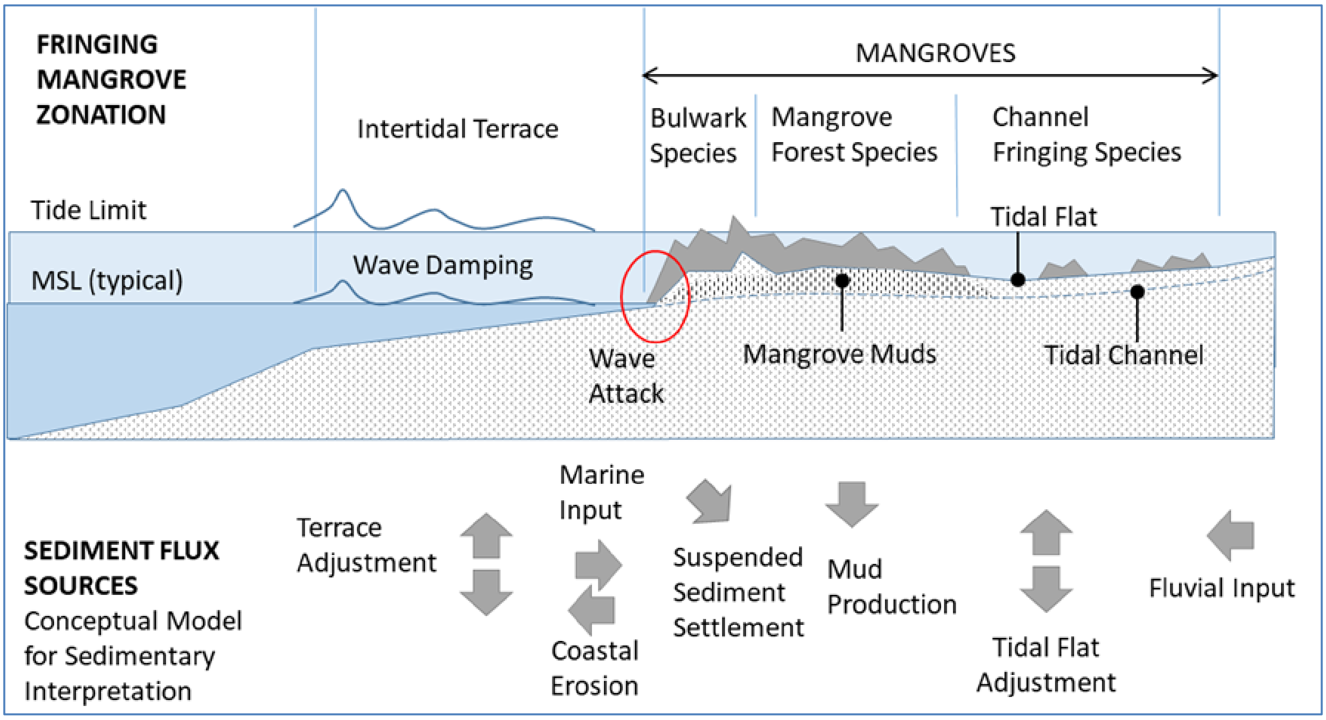


Figure 22. Notional mangrove zonation and sediment fluxes (Seashore Engineering 2021).

In a purely morphological sense, it is often convenient to distinguish:

- fringing mangroves that occur along open coastlines exposed to waves;
- estuarine mangroves that occur along the banks of estuarine channels and tidal creeks (and between adjacent tidal creeks where thicker muds1s - and older individual plants - may occur, i.e., the forest mangroves noted above;
- island-fringe mangroves, that occupy the often rocky and narrow margins of islands (See Appendix Section 33.3).

This report will generally use the terms fringing and estuarine mangroves, being specific where necessary. It is of importance that for estuarine 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 control on the zonation. Thus, a different spectrum of environmental conditions may induce a different relationship of mangrove zonation with elevation.

5.1.1.3. *Mangroves and tidal 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.

5.1.2. 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 23). 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.

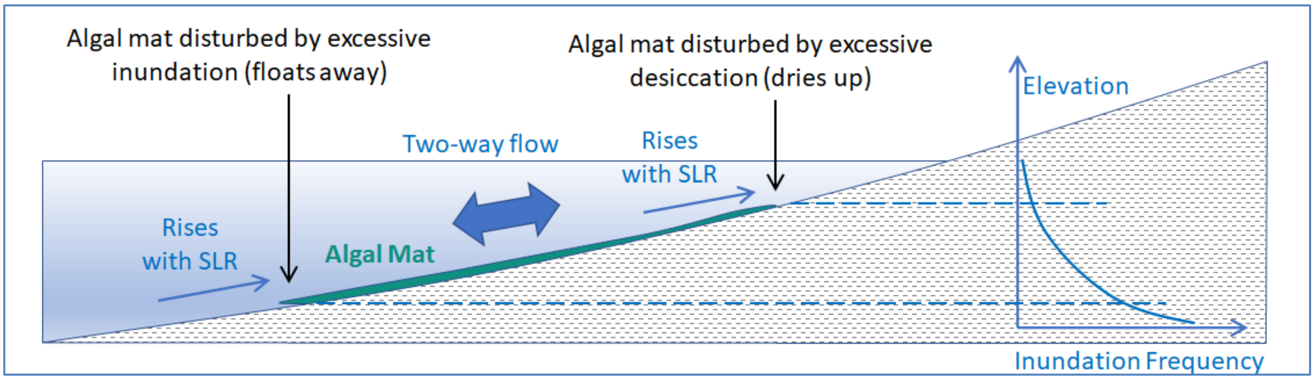


Figure 23. Conceptual uneven asymmetric distribution of algal mats under conditions of a rising sea level, whereby they are more prevalent towards the base of their distribution.

Details of the benthic mats in the ESSP area are provided in Section 9.3.2.

5.1.3. 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 9.3.3.

5.2. Influence of SLR upon geomorphic dynamics and habitats

5.2.1. 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 24). 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.

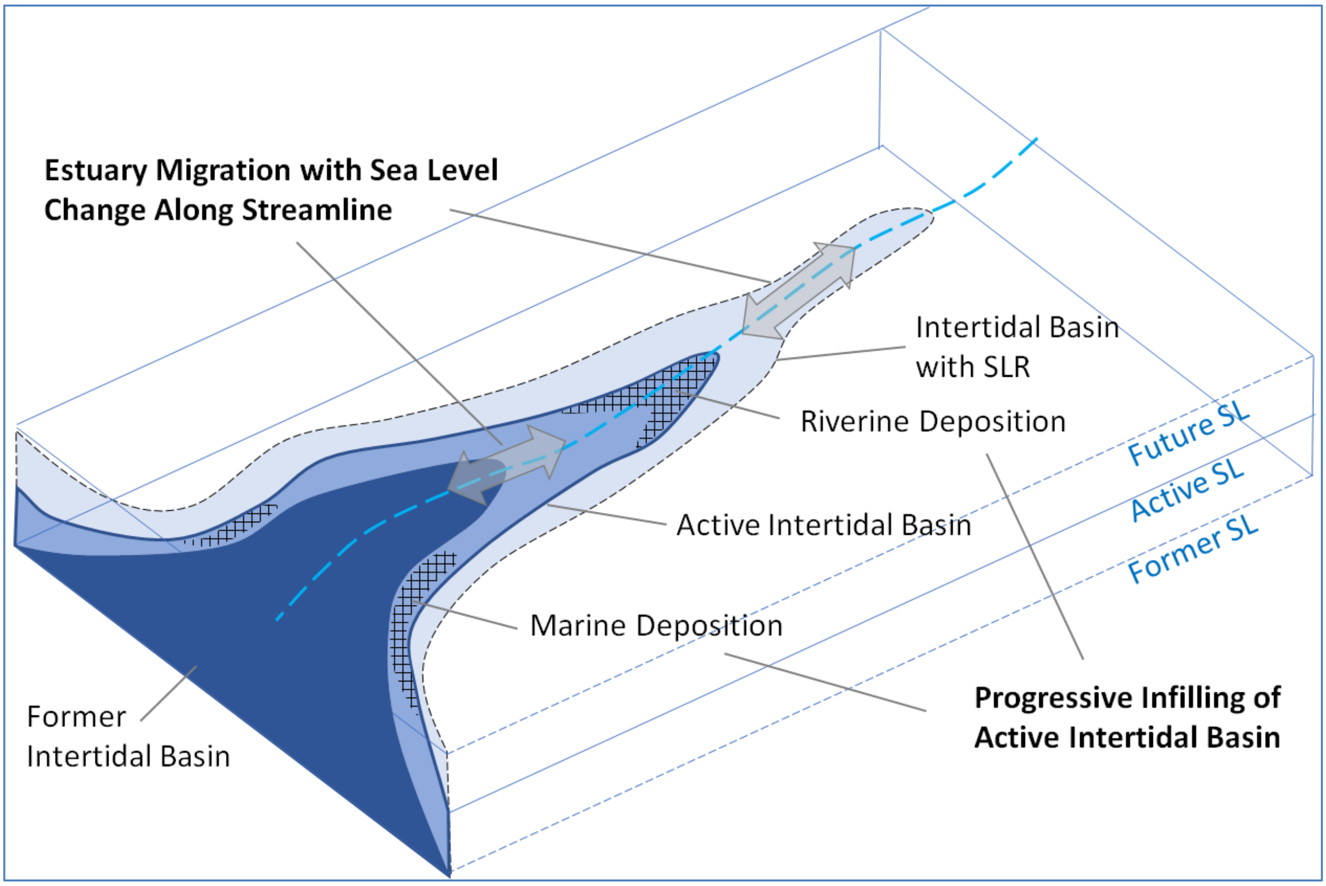


Figure 24. The coastal response in tidal systems subject to SLR can include accumulation of sediment input from the sea and from the land.

5.2.2. Dynamics of habitats

Temporal and spatial changes in sedimentary environments create challenges for their associated biological assemblages, which use an array of adaptive characteristics to support 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 25). 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.

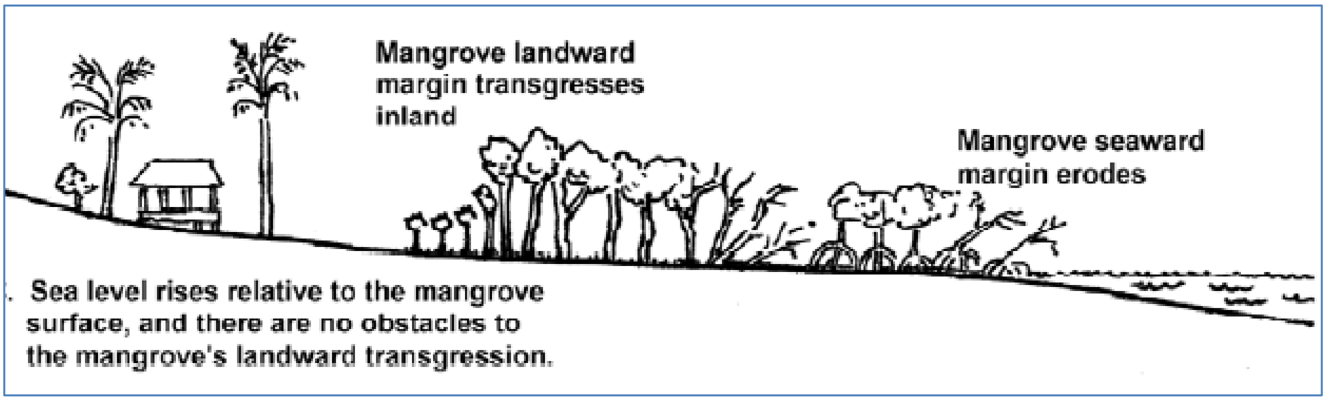


Figure 25. Concept of unrestricted mangrove evolution with SLR (from Gilman et al. 2007).

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 26). 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-term 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 roll-over 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.

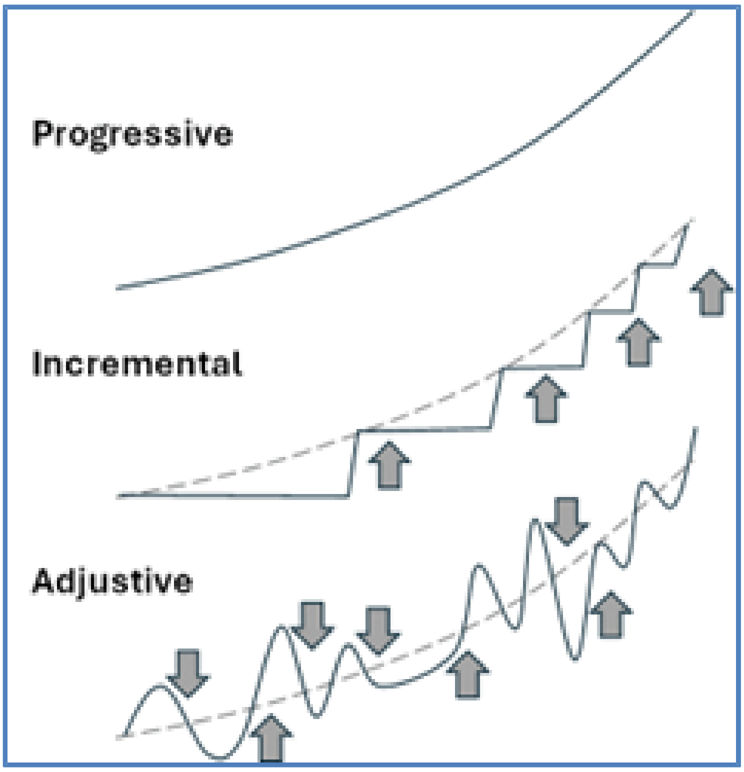


Figure 26. Conceptual diagram of the three main types of estuarine geomorphic response to change. These can apply to the whole system and each of its components. This can be applied to the ESSP area, with a century-scale perspective, and also shorter timescales.

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[2]. 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).

---

[2] The hypsometry of each creek is the vertical distribution of the bed elevations.

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 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.

5.2.3. Changes to hydrodynamics associated with SLR

Here, the word ‘hydrodynamics’ includes aspects of tidal currents, waves and wind-driven currents. Whilst a general consideration of hydrodynamics is provided later (Section 6.1), here are noted only those hydrodynamic aspects likely to change with SLR, and for ease of initial understanding, specifically an ‘instantaneous’ SLR without any sedimentary adjustments. Conceptually, the changes are relatively simple in the habitat-forming environments (Table 4) – details are developed in later sections where various options are considered.

Table 4. 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. Brown 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	-

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. For the tidal creeks, the essentials of

---

[3] See sections 7.2.2 and 7.2.3.

tidal creek dynamics that underpin some of the generic changes noted here are described in Sections 7.2.2 and 7.2.3.

Using the estuary as an example of different types of coastal and shallow marine morphology (Figure 27), 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 112 and Section 22.6). 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 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 change along nearby 'soft' sedimentary coastlines.

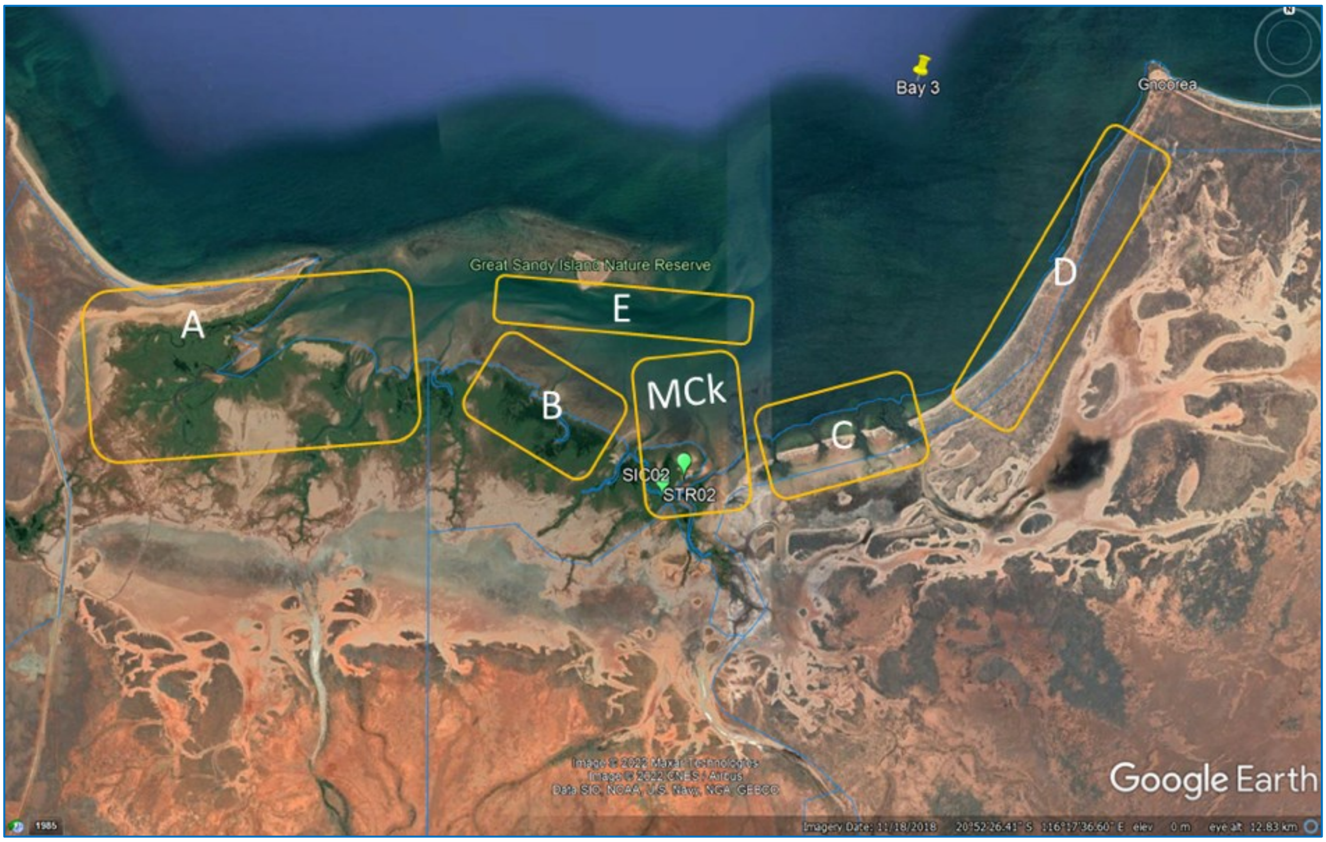


Figure 27. Distinct types of coastal and shallow marine geomorphology along the ESSP proposal frontage, i.e., the southern margin of the estuary (O2 Metocean 2022a).

6. Natural coastal change

6.1. Relevant factors and 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).

Note that sea level change is not on the list, because by itself it changes nothing, rather it changes the physical location at the coast of the other active physical processes.

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.

6.2. 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 arrive at indications 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 5.1).

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 closely associated with sediments, whether located in areas 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.

PART TWO – THE ESSP REGION, PRESENT UNDERSTANDING

7. ESSP Physical processes

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, 2025; Ward *et al.* 2022). 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.

7.1. Shelf oceanographic processes

Dufois *et al.* (2017) provide a useful summary of the regional oceanographic processes relevant to sediment transport, and this forms the basis of the material presented here. At daily time scales, the currents over the shelf are dominated by tidal motions. The semi-diurnal tidal amplitudes and velocities vary strongly along the NW shelf, increasing northward. The tidal range can reach up to ~2 m near the North West Cape, ~4.5 m off Dampier, and ~9 m in Broome (Holloway, 1983). Most peak tidal currents flow across depth contours over the deeper parts of the shelf, but on the inner shelf are increasingly influenced by the bathymetry and the coastline orientation (Condie & Dunn, 2006; Holloway, 1983). This coastal constraint means that the inner shelf includes some areas of complex flow directions and some strong along-shelf tidal flows. Tidal current speeds can reach >1 m/s in the Pilbara region (Condie *et al.* 2006; Porter-Smith *et al.* 2004), but generally in localised areas of constricted flow, or in regions of strong internal tide at the shelf edge.

At the coastline itself, tidal and other flows at the coastline can vary greatly, depending upon the dynamics of the estuaries and tidal creeks. There is little publicly available data on tidal flows in the estuaries and the creeks of the NW shelf, but there are data from comparable systems elsewhere, including on the Great Barrier Reef shelf and elsewhere across northern Australia (e.g., Friedrichs *et al.* 1990, Wolanski & Ridd 1990; Larcombe & Ridd, 1996; Pethick, 1984; Horstman *et al.* 2021), which can inform the support the interpretations made in this study.

7.2. 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.

7.2.1. Tides in Regnard Bay

There are various stations that have produced oceanographic information specific to the ESSP region (Figure 28), 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 29). 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/s. 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 28. 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.

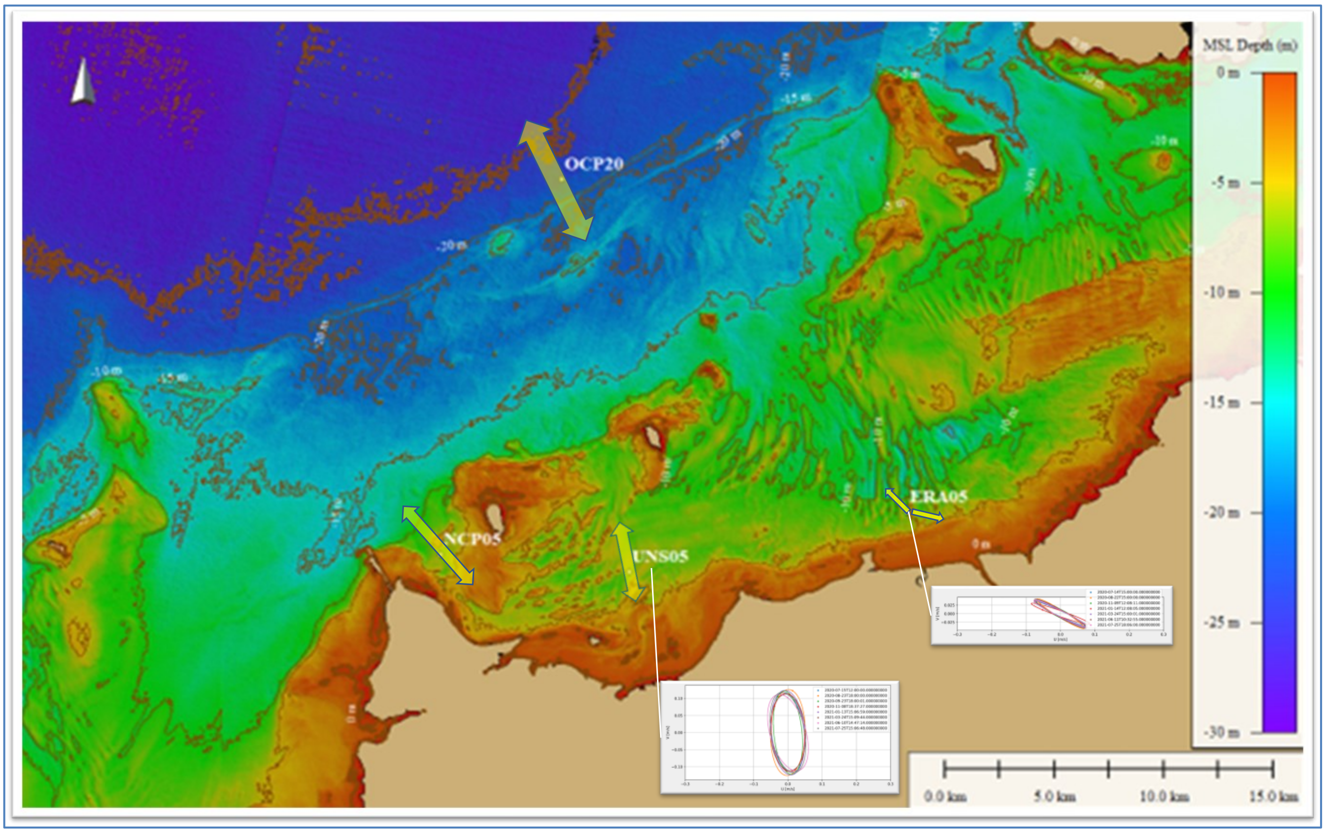


Figure 29. M2 tidal ellipses at the measured sites, with the ellipses illustrated for the two inshore sites.

Measurements at UNS-05 in western Regnard Bay show that even the fastest measured currents and largest waves produce only moderate turbidity. With a rising flow speed, turbidity rises in tandem, but beyond a moderate flow speed, faster currents do not further raise the turbidity, i.e., turbidity becomes limited by a factor other than flow speed. This effect happens during individual tidal flows, and also when viewed across a series of flows of different maximum speeds. (A similar phenomenon occurs in McKay Creek, when not influenced by intense rainfall events).

This indicates that resuspendable sediment is limited in its local availability and is further evidence that muddy and silty sediment is thin and patchy on the bed of western Regnard Bay.

7.2.1. Tides in the estuary

No measurements are available, but modelled currents for present conditions (Section 19, simulation 1 of Table 30) in the estuary indicate depth-averaged tidal currents peak at 0.3 to 0.35 m/s, with the flood tides stronger than the ebb (Figure 30, Figure 31). As noted elsewhere, currents of such speeds can move fine sand, and with additional waves, many tides will do so. The lack of vegetation on the low intertidal flats is also clear physical evidence of regular sediment mobility.

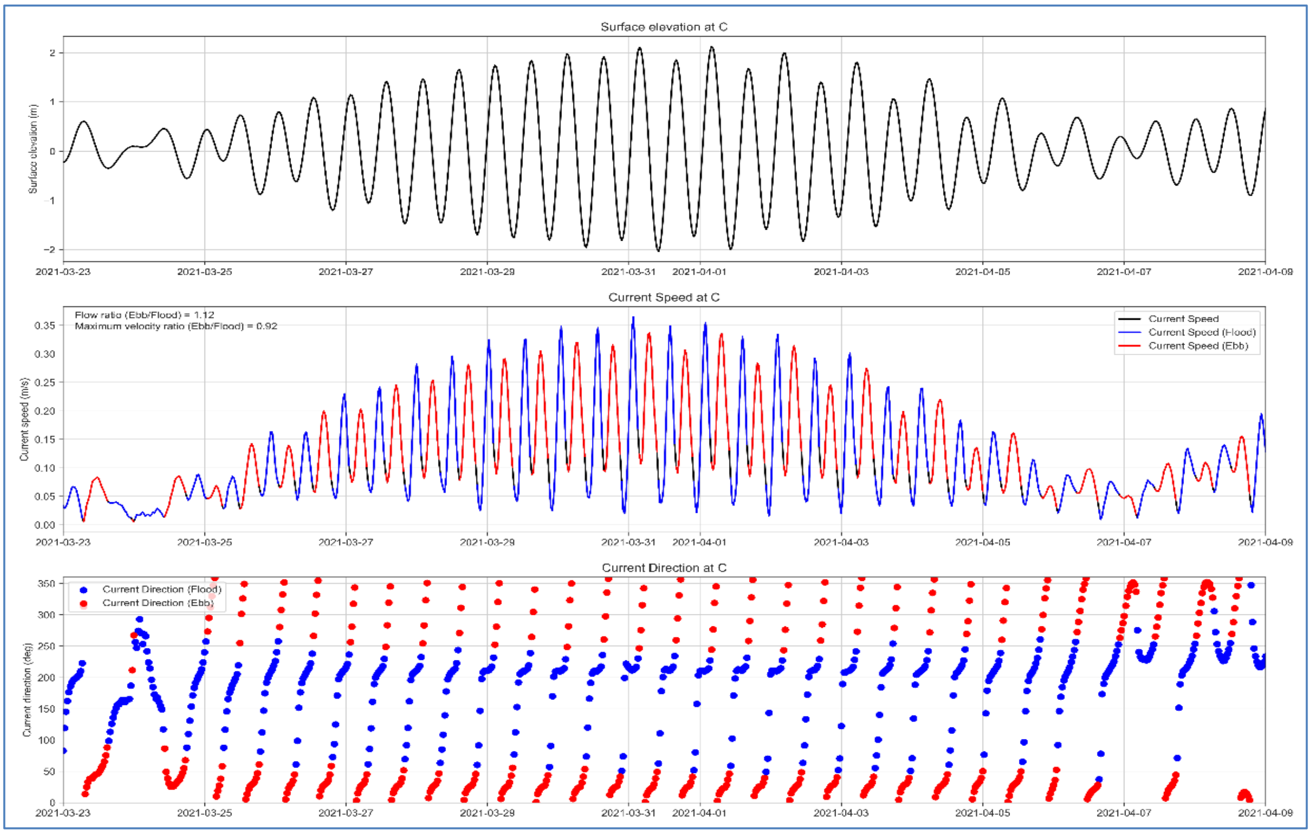


Figure 30. Modelled currents of existing tidal flows at location C, 850 m NW of the mouth of Baldy/Straight Creek and 500 m NE of Creek 1, for the period of large spring tides of March-April 2021. Flood tide in blue, ebb tide in red.

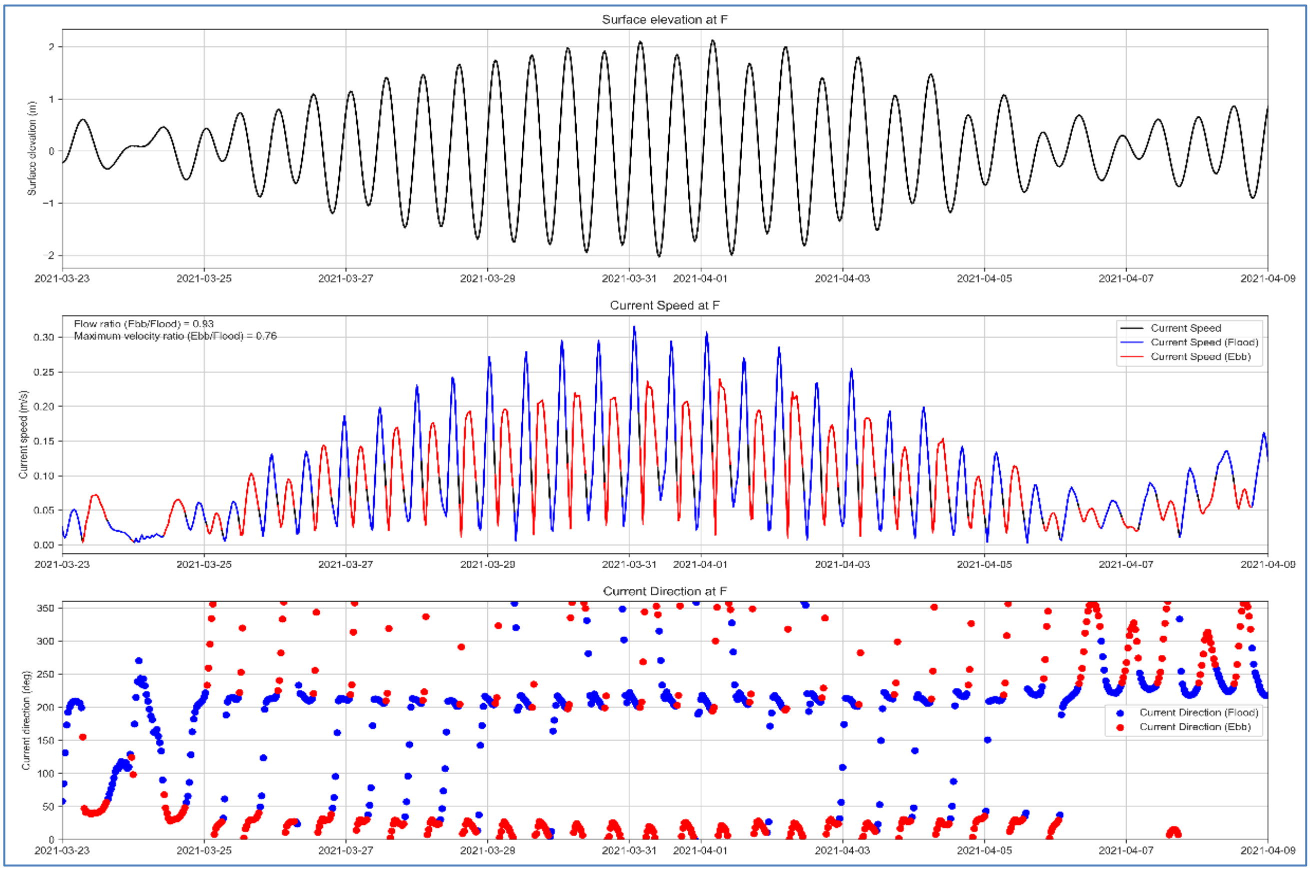


Figure 31. Modelled currents of existing tidal flows at location F, 350 m seawards of the nascent fringing mangroves, for the period of large spring tides of March-April 2021. Flood tide in blue, ebb tide in red.

7.2.2. Assessing tidal flow in unmeasured tidal creeks - flows are controlled by the elevations of high tide

As noted elsewhere (Section 7.3.2), rainfall in these environments can be very seasonal and sporadic, such that freshwater flow down many rivers and tidal creeks is rare, rapid to start and generally of short duration (termed ‘flashy’ in the fluvial literature). Hence, on a day-to-day basis, these arid systems are controlled by the ever-present tides, and the dynamics of the currents induced within the creeks and within the surrounding associated estuarine mangroves and high intertidal flats.

The tides in the ESSP area generally exhibit 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. For the tidal creeks, there are three categories of tides, Overbank tides, Intermediate tides and Within-creek tides, distinguished by their water elevations at high tide and the associated nature of flows in tidal creeks. Examples of these tides and the associated flows measured in the creeks are shown in Figure 32 for a tidal creek in Queensland, and in Figure 33, Figure 34 and Figure 35 for McKay Creek, discussed below.

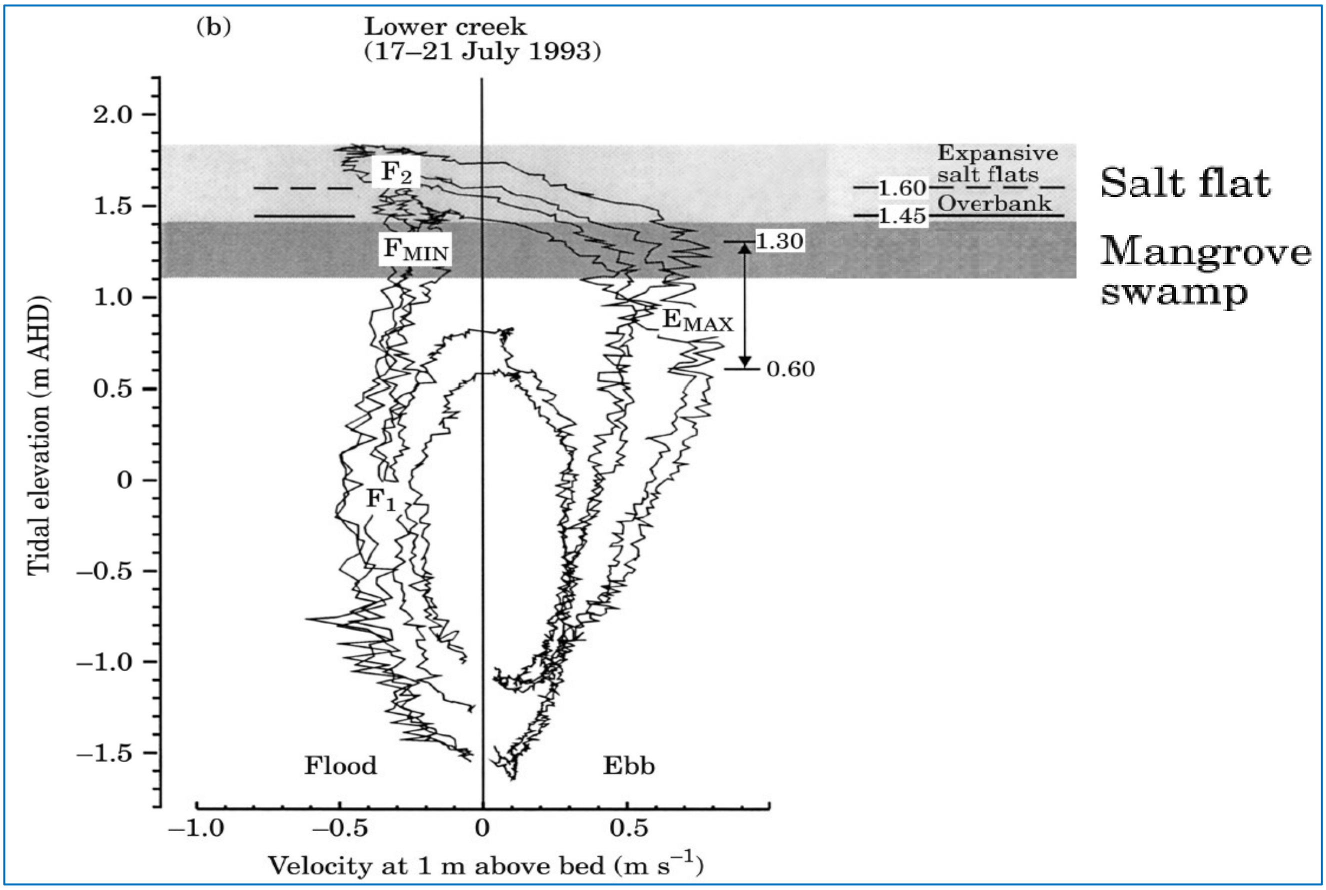


Figure 32. Velocity-stage diagrams for lower Cocoa Creek, Townsville, during a spring-tide period with strong semi-diurnal inequality. For the three overbank tides illustrated, the ebb speeds were far faster than the flood. For the two within-creek tides illustrated, the flood and ebb were largely similar 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).

7.2.2.1. Measured tidal flows in the creeks

The report uses the tidal planes adopted by LS (Table 2). Tidal flows were measured near the mouth of McKay Creek from July 2020 to October 2021. Below are designated three types of tide, overbank, intermediate and within-creek tides. Whilst primarily related to the different elevation of high tide, these are also based on the characteristics of the creek’s flood and ebb flows, involving some judgement. For example, the measurements show that some individual 'overbank' tides that exceeded 2.5 m AHD did not generate a strong ebb tide, but a series of successive tides of such elevation generally did. Further, there is some uncertainty in the precise elevation values used to designate overbank, intermediate and within-creek tides, because:

- the elevation of the instruments used for measurements in McKay Creek were not surveyed in, so that there is some uncertainty (estimated at ±0.2 m, possibly more) on the water levels in the creek;
- uncertainty is increased by the instrumental data showing evidence of movement within deployment periods and difference in instrument elevation between successive deployments; and
- it is common along the WA coastline for there to be sustained non-tidal contributions of up to 0.3 m to local water levels (i.e., a residual, whether positive or negative)[4]. This is well documented by measurements (https://www.transport.wa.gov.au/imarine/storm-surge-comparison-chart.asp) such as the sustained storm surge for Onslow. Therefore, at the ESSP coastline, water levels higher than 2.5 m AHD will definitely occur.

Nonetheless, the key aspects of the tidal flow within McKay Creek are clear and are illustrated here (Figure 33, Figure 34, Figure 35). The three key types of tides in McKay Creek are as follows.

1. Overbank tides - where high tide ≥ ~2.5 m AHD[5]
    - 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 flows that are faster 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.
        - A clear example is shown in Figure 33. Note the brief flood peak at 09:00 on 16/03/22, lasting 1.5 hours and reaching a peak speed of 0.8 m/s, compared to the ebb characteristics, which included a peak speed of 1.15 m/s, speeds of 0.8 m/s exceeded for 2 hours, and which lasted a total of 7.5 hours. Sand transport is a cubic function of current speed (i.e., speed^3), so that sand transport during this tide will have been overwhelmingly ebb-dominated. Indeed, with currents so fast and sustained, it is possible that the true rate of sand transport might have been limited by the local availability of sand on the bed, i.e., all available sand was being mobilised. If this occurred, then underlying material would have been prone to scour.
        - Note too that towards the end of the ebb fall in tidal elevation, the ebb current speeds remain significant. Thus, the water outflowing rapidly from the creek mouth and moving across the emerging intertidal zone is likely to have also scoured the channel seawards of the creek. In this way, the overbank ebb tidal flows are a key factor in influencing some aspects of sedimentation on the intertidal zone seawards of the creek mouth.

---

[4] Due to continental shelf waves, Ekman adjustment to longshore currents, etc.

[5] Note the uncertainty in this elevation.

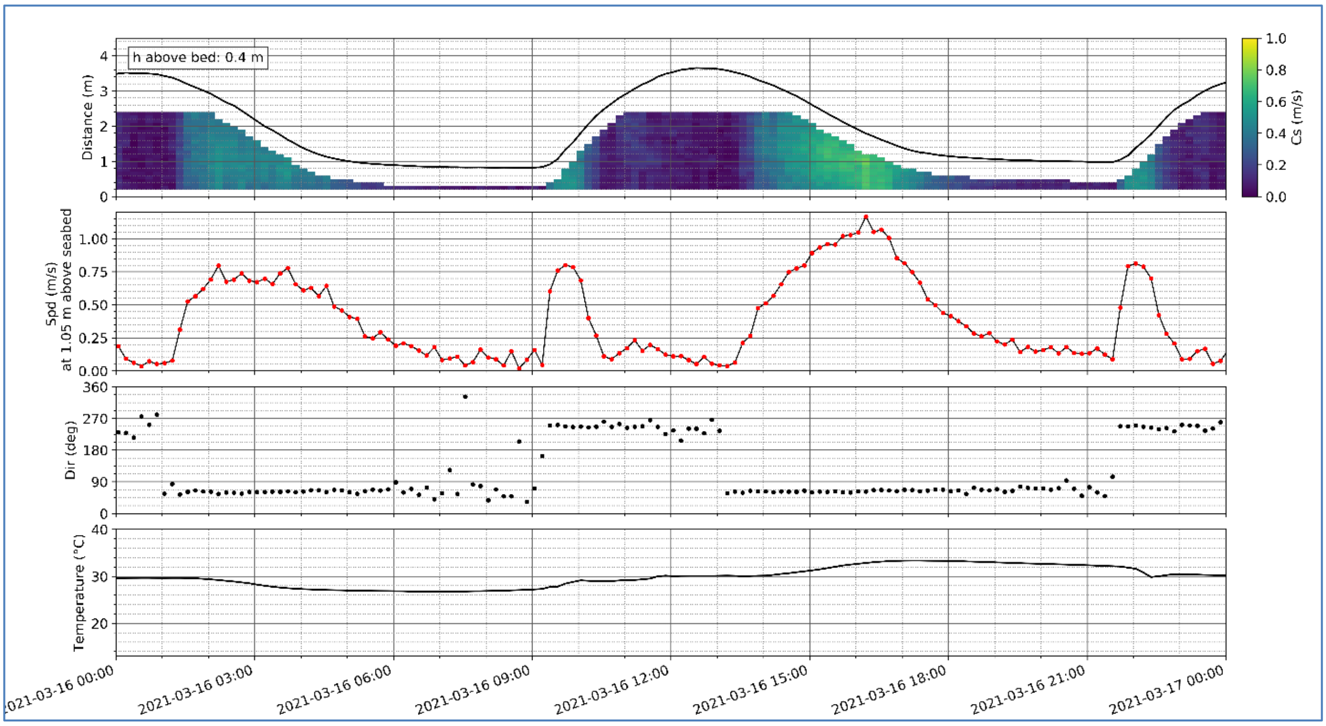


*Figure 33. Time-series data over a 24-hour period, showing ebb dominance in peak speed and duration of an **Overbank Tide**. The four time-series plots show: tidal height above the depth sensor with vertical distribution of speed, current speed 1.05 m above the bed, current direction 1.05 m above the bed, and water temperature at the bed (O2 Metocean 2022a).*

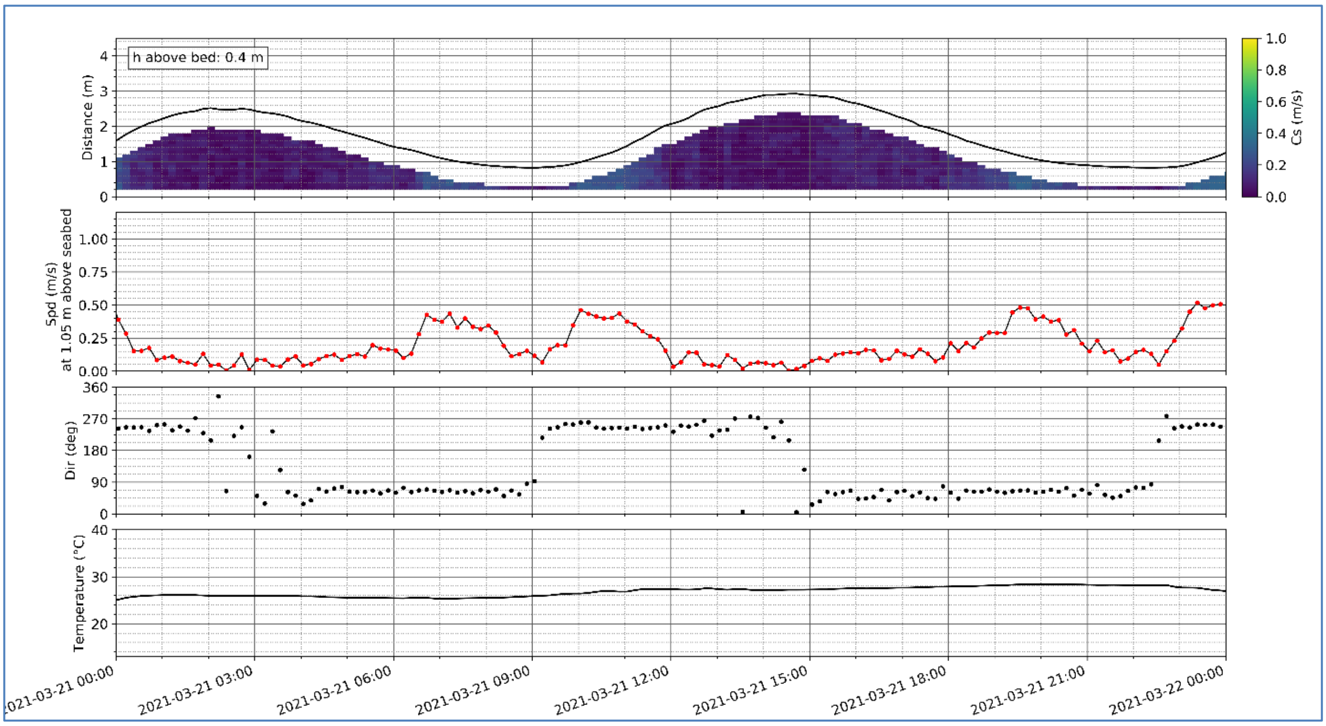


*Figure 34. Time-series data over a 24-hour period, showing characteristics of an **Intermediate Tide**. (Plots as described in Figure 33).*

2. Intermediate tides – where high tide is 1.7 to ~2.5 m AHD[6]
    - 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 (e.g., Figure 34).
3. Within-creek tides - where high tide ≤ 1.7 m AHD[7]
    - 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 (e.g., Figure 35).

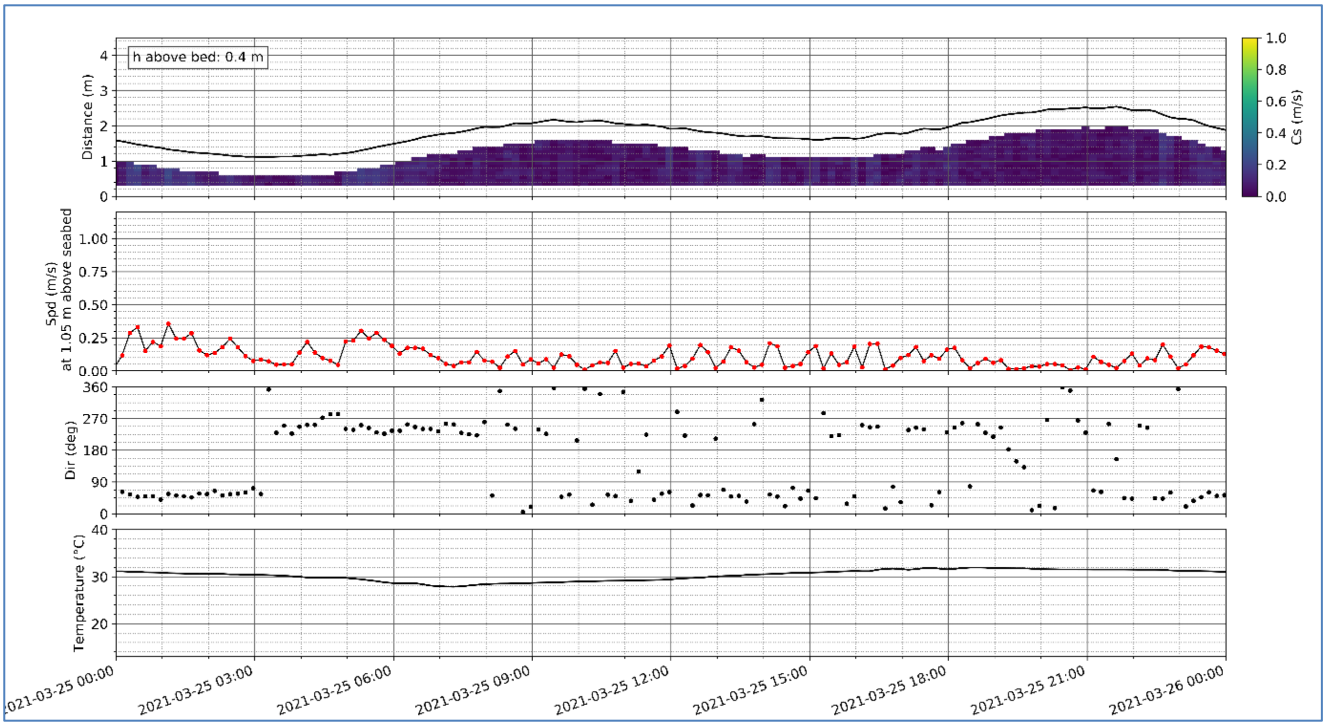


*Figure 35. Time-series data over a 24-hour period, showing characteristics of a **Within-Creek Tide**. (Plots as described in Figure 33).*

Further, it is notable that McKay Creek is regularly isolated from the sea by a mouth bar, with isolation having been noted to occur when low tides fall below about -0.1 m AHD (O2 Marine 2020), although there is some uncertainty in this precise figure due to survey uncertainties and natural physical changes. The presence of a mouth bar is visible on aerial images, and it is likely controlled by the local interaction of waves and tides but there is little clear information on its past variations, especially regarding its elevation.

7.2.2.2. Tidal creek hypsometry

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 36). This can be used to define the storage volume Vs (in this case, the volume at 2.5 m

---

[6] Note the uncertainty in this elevation range.

[7] Note the uncertainty in this elevation.

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.

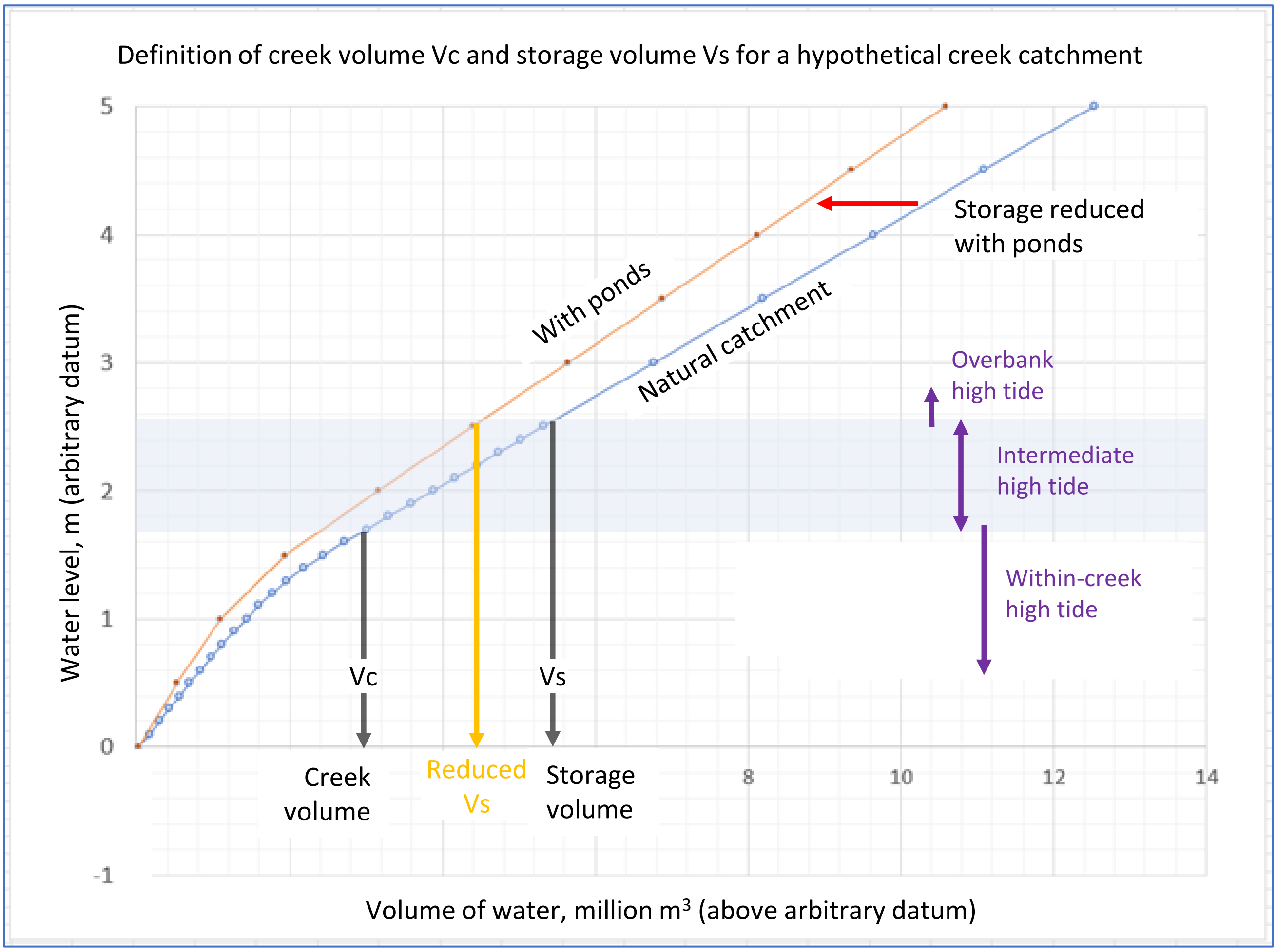


Figure 36. Generic hypsometric curve of a hypothetical tidal creek catchment (blue line) with definitions of Vc and Vs related to the creek morphology. If ponds are emplaced on the upper intertidal zone, the system will have reduced volumes (orange line), and ratios of Vs:Vc at each tidal elevation are reduced.

In the ESSP project creeks, there are some uncertainties to note[8]:

- Current measurements are only available for McKay Creek, and the characteristics of the tidal flows were used to derive the key tidal elevations derived in O2 Metocean 2022a and used below.
- The elevations of high tides given in Table 2 are slightly lower (perhaps by 0.2 m) than derived in O2 Metocean (2022a) and used below. This is probably a result of some remaining uncertainty about the precise 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).

Noting the fast, extended flow speed of overbank tides, and the fact that sand transport rate is a cubic function of flow speed (i.e., speed^3) the most critical tides to understand are thus the largest overbank tides because they

---

[8] Whilst these uncertainties exist, 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 of greater impact regarding arriving at defensible conclusions on creek dynamics.

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 tides, 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 8.4) allows moderate to high confidence that the relationship will be similar within the catchments in Areas A, B and McKay Creek of Figure 27, and this can be assessed comparing each catchments hypsometry.

7.2.2.3. Tidal types help predict flows in unmeasured creeks

The three types of tidal flows described above are strongly related to the ratio of water volume ‘stored’ in overbank areas Vs to the volume in the creek Vc (e.g., Table 5). Hence the ratio Vs:Vc can be used as a first-order indicator of possible tidal flows in those tidal creek systems where:

- there have been no measurements, and
- there are proposed changes to these volumes, e.g., caused by the emplacement of solar salt pond walls.

Although poorly documented in this particular region of Australia, there is well established research in support of the above relationship between morphology to tidal flow. The physical dynamics of such systems are very well known and effectively described by their basic physics. The tidal controls on flows and on coastal sediment transport in such systems have been known since the 1990s (e.g., Friedrichs *et al.*, 1990, Wolanski & Ridd, 1990; Larcombe & Ridd, 1995, 1996; Bryce *et al.*, 1998; Bryce *et al.*, 2003; Horstman *et al.*, 2021, Guo *et al.*, 2022), building on knowledge from their temperate equivalents, tidal saltmarsh systems (e.g., Pethick, 1980; 1984).

Wolanski *et al.* (1992b) associated faster ebb tidal speeds in mangrove creek systems to a high ratio of Vs:Vc, and for seven mangrove creek systems that, with one extreme outlier, ratios of Vs:Vc generally ranged from 2 to 7, i.e., a range that is comparable to Cocoa Creek (Table 5). This indicates that the intertidal storage capacity of overbank tides at Cocoa Creek should have been sufficient to repeatedly induce a relatively fast and brief ebb tide, but this was not always the case. Bryce *et al.* (2003) concluded that the tidal asymmetry of Cocoa Creek was dependent on the interaction between at least two controls: the offshore forcing of a shorter and faster flood tide, and the internal forcing of a faster ebb tide imparted by the intertidal storage effect. This conclusion may also be appropriate for McKay Creek, as evidenced by the short fast flood tide of many tides in June, July and August 2021 and other months too (Figure 37). As noted above, McKay Creek is largely isolated from the sea at elevations below -0.12 m AHD, so the flood tide is already steep and rising quickly when it breaches the creek mouth and enters the creek. The caveat on this interpretation is that this has not been directly observed as occurring in McKay Creek, and there is the chance that this is a shallow-water effect on the instrument.

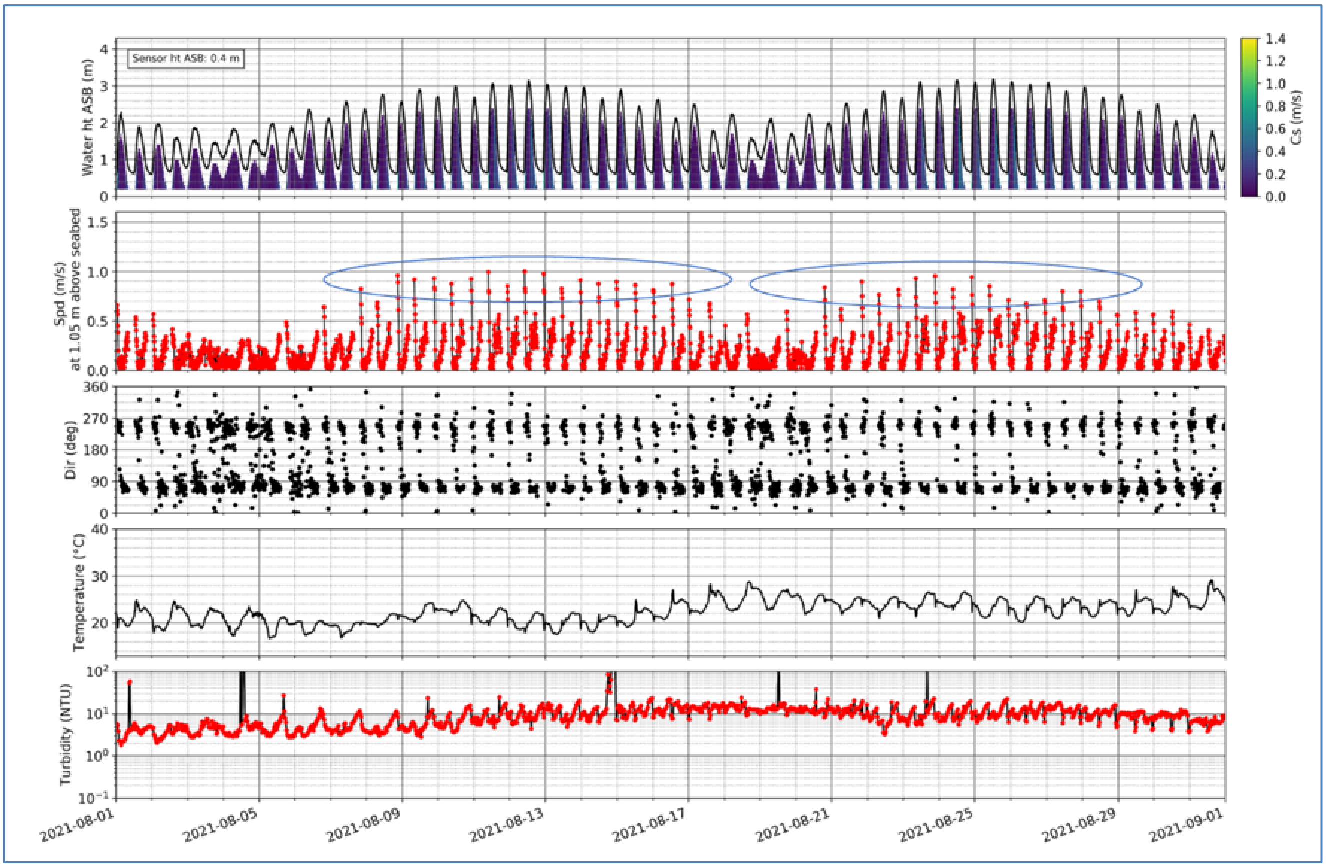
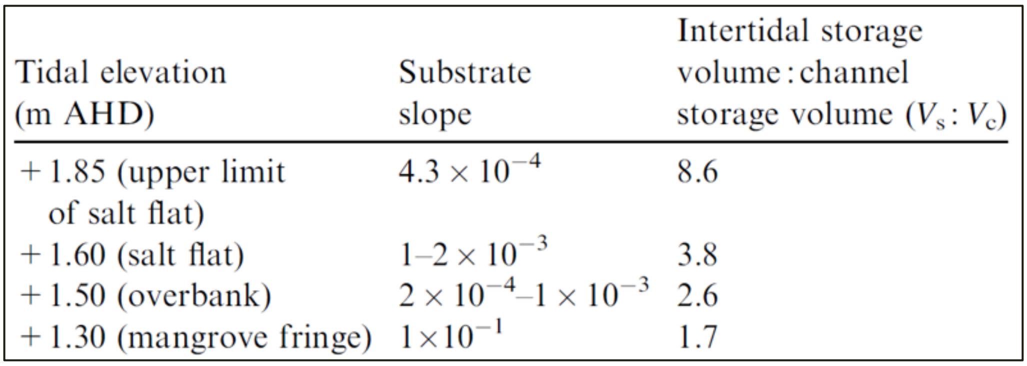


Figure 37. Examples (August 2021) of the short-fast flood tide (blue ovals) at SIC-02 during spring tides.

Table 5. Measured substrate slopes and calculated estuarine intertidal storage ratios (Vs:Vc) at significant tidal elevations, Cocoa Creek, Townsville (Bryce, 2003). Wolanski et al. (1992b) generally found ratios of 2 to 7.



Tidal elevation (m AHD)	Substrate slope	Intertidal storage volume : channel storage volume ($V_s : V_c$)
+ 1.85 (upper limit of salt flat)	4.3×10^{-4}	8.6
+ 1.60 (salt flat)	$1–2 \times 10^{-3}$	3.8
+ 1.50 (overbank)	$2 \times 10^{-4}–1 \times 10^{-3}$	2.6
+ 1.30 (mangrove fringe)	1×10^{-1}	1.7

This report uses the bed elevations of the various creek systems, tidal volumes and such ratios to help assess the nature of tidally controlled flows in McKay Creek (and others), especially flows associated with overbank tides compared to within-creek tides and draw inferences regarding sand transport processes in the creeks and transport of finer sediment sediments more generally. Data from McKay Creek was used to define the relevant tidal elevations, which were then applied across the area to define volumes for all creeks:

- Vs (volume stored in overbank areas) was defined using a tidal elevation of 2.5 m AHD, the highest astronomical tide HAT.
- Vc (volume of the creek) was defined using a tidal elevation of 1.7 m AHD, below which all data indicate tidal flows had characteristics of within-creek tides.

Results of this analysis are presented below. (They are also expanded upon in Section 16 as part of considering the potential effects of the ESSP on the tides in creek systems.)

7.2.3. Methods

7.2.3.1. Hypsometry of the tidal creek catchments

The catchment boundaries (Figure 3) associated with each tidal creek mouth were designed using the aerial images and DTM topography and expert judgement to ensure that they were logical with respect to the natural drainage. The analysis below addresses how each tidal creek might function as a single unit, i.e., it considers that each creek or catchment unit extends landward from the creek mouth. The logic is that the mouth is where the fundamental changes in flows are likely to be measurable, and changed sediment transport is likely to be most evident, especially in terms of the exchange of sand into and out of the tidal creeks. Hence, for this purpose:

- The hypsometries of Baldy W Creek & Straight Creek were combined into one creek, called "Baldy/Straight", because they have a common creek mouth.
- The Yanyare tidal catchment, although not directly impacted by having ponds located within it, might be affected by changes in tidal and riverine flow elsewhere on the coastal plain, and was thus included in the analysis. Its eastern margin was drawn to follow the line of the highest elevations between Yanyare and the next creek to the east.

The hypsometric curves (Figure 38) can help compare some catchment characteristics[9] and from these curves are derived the Vs:Vc ratio for each catchment (Figure 39).[10]

Dealing here with the natural Vs:Vc ratios, it is notable that the Vs:Vc ratios are low for Creeks 5 & 1, at 2.2. The other tidal creek systems in the western and central estuary (Creek 2, Baldy/Straight and McKay) have a similar ratio of 3.0 to 3.3, like those catchments fronting the eastern ESSP area (Creeks 7 & 8).

It is notable that 40 Mile Road W and E are markedly different from 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. Further, the shallow slope of the hypsometric curve for 40 Mile W (Figure 38) cuts across many other curves, indicating that it is not at a similar stage of physical equilibrium to the 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.

Flow measurements are only available for McKay Creek, so it is logical to examine some other indicators of the potential natural tidal flow regime in the other tidal creek systems. Below we note relevant outputs derived from the numerical modelling of tidal inundation of the ESSP area.

---

[9] Although the general pattern in the results is strong and logical, at the highest tides some of these catchments will clearly exchange some water, so each individual number should not be taken as definitive.

[10] The hypsometric curves for individual catchments are presented in detail elsewhere (section 16) when considering the potential effects of the ESSP ponds. Full curves for all catchments without ponds, plus with ponds of the present scenario (7.2.1.) plus those of the previous pond scenario (6.2.1.) are given in the Appended Section 29.

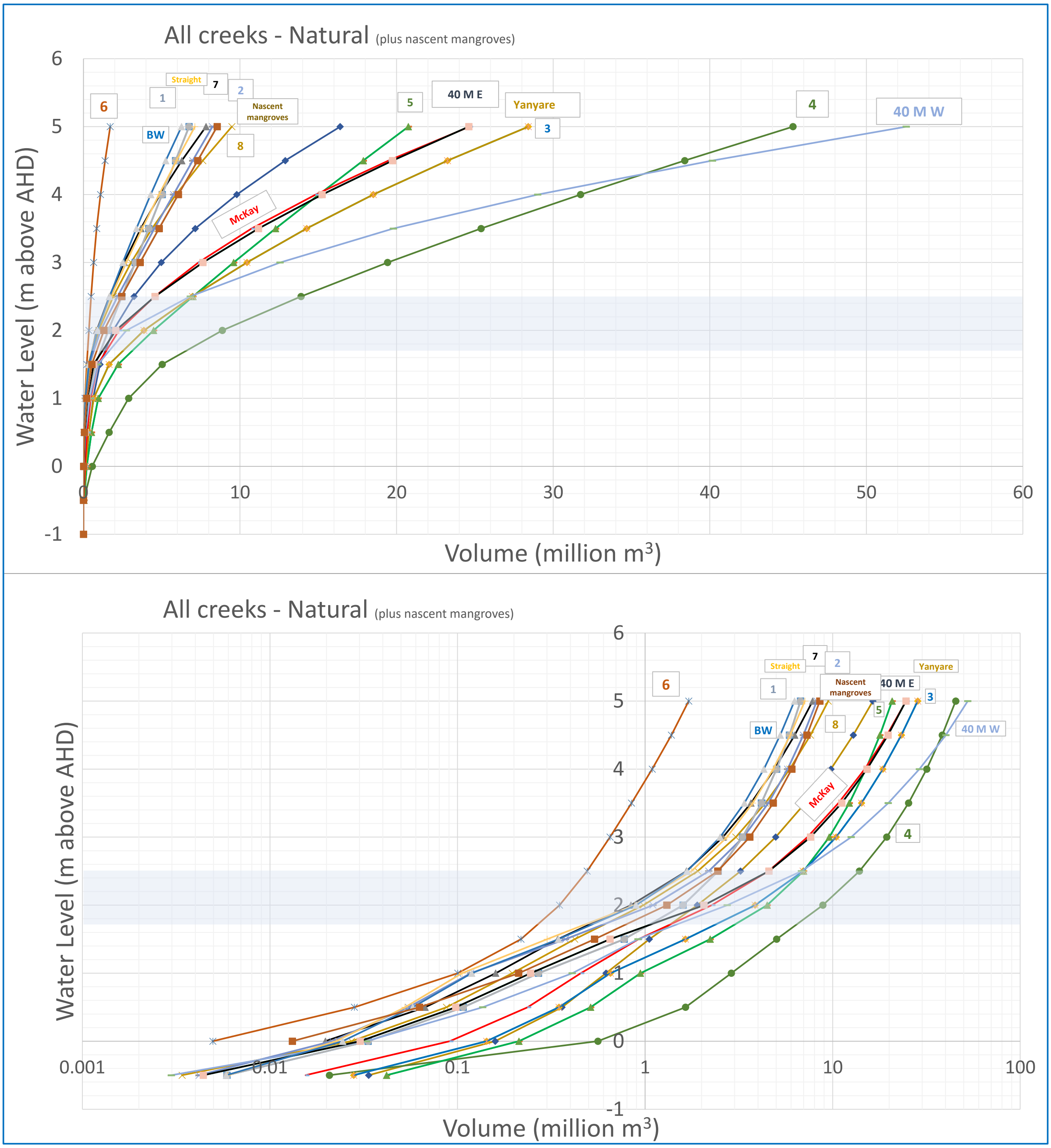


Figure 38. Hypsometric curves for all natural catchments (plus the artificial scenario 7.2.1 catchment of the nascent mangroves). Note the shallow slope of the curve for 40 Mile Road W, that it cuts across many other curves, indicating that it is not at a similar stage of physical equilibrium to those other catchments. The blue bar highlights the elevation range 1.7 to 2.5 m AHD.

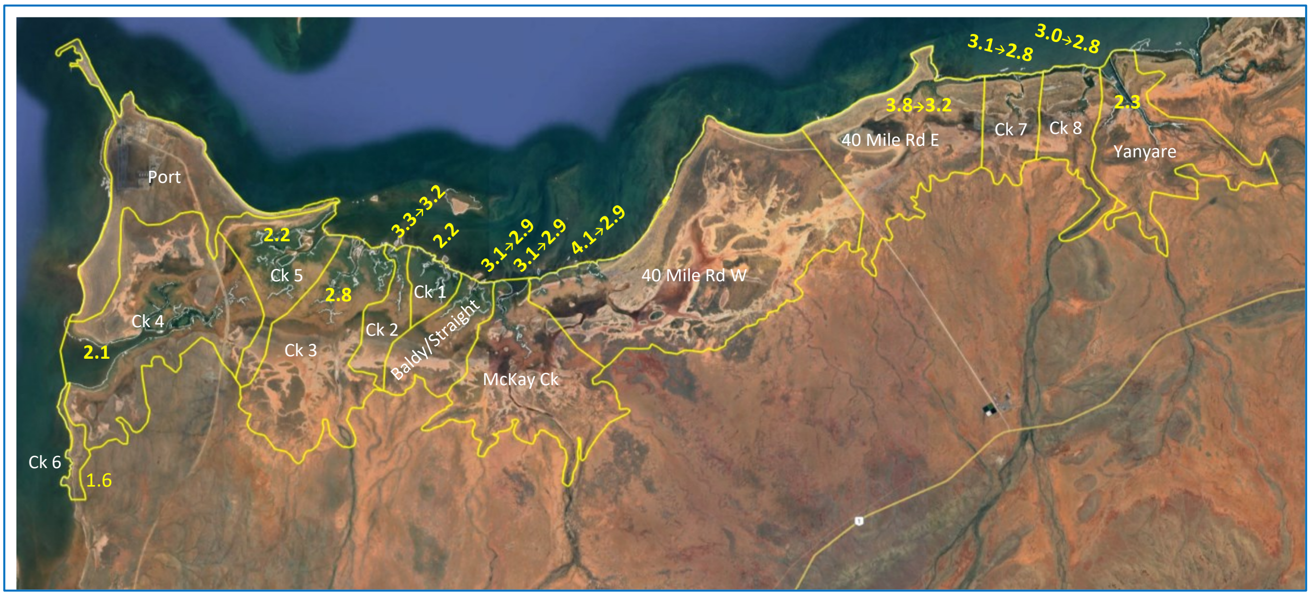


Figure 39. Calculated Vs:Vc ratios for the natural catchments (yellow text). For those catchments affected by the ponds of scenario 7.2.1, the first number is the natural ratio (noted below), and the number after the arrows is the ratio with the ponds emplaced (discussed later in Section 16). (Repeated as Figure 167 for convenience)

7.2.3.2. Relative Ebb:Flood ratios from the numerical model

Data were extracted from the model outputs (Section 19) to produce current speed and direction time-series data for a series of locations (Figure 40, Figure 41, see also Appendix Section 30). Note that the modelled current speeds have not been calibrated with field measurements and that the model outputs represent depth-averaged currents, so that they need to be treated with some circumspection. Nonetheless, given this is the best information presently available, these time series were split into ebb and flood periods based on analysis of the water surface elevation data at each site (Appendix Section 28). Two ratios were then produced:

- The flow ratio - The current speed time series corresponding to both ebb and flood periods was integrated to produce a measure of the total distance travelled in or out by water at that point, and the ratio between ebb and flood data results in the flow ratio - i.e., a distance ratio.
- Maximum speed ratio - Noting that sediment transport is a function of flow speed, a ratio was also formed based on relative maximum speed of ebb and flood current at each location - i.e., a speed ratio.

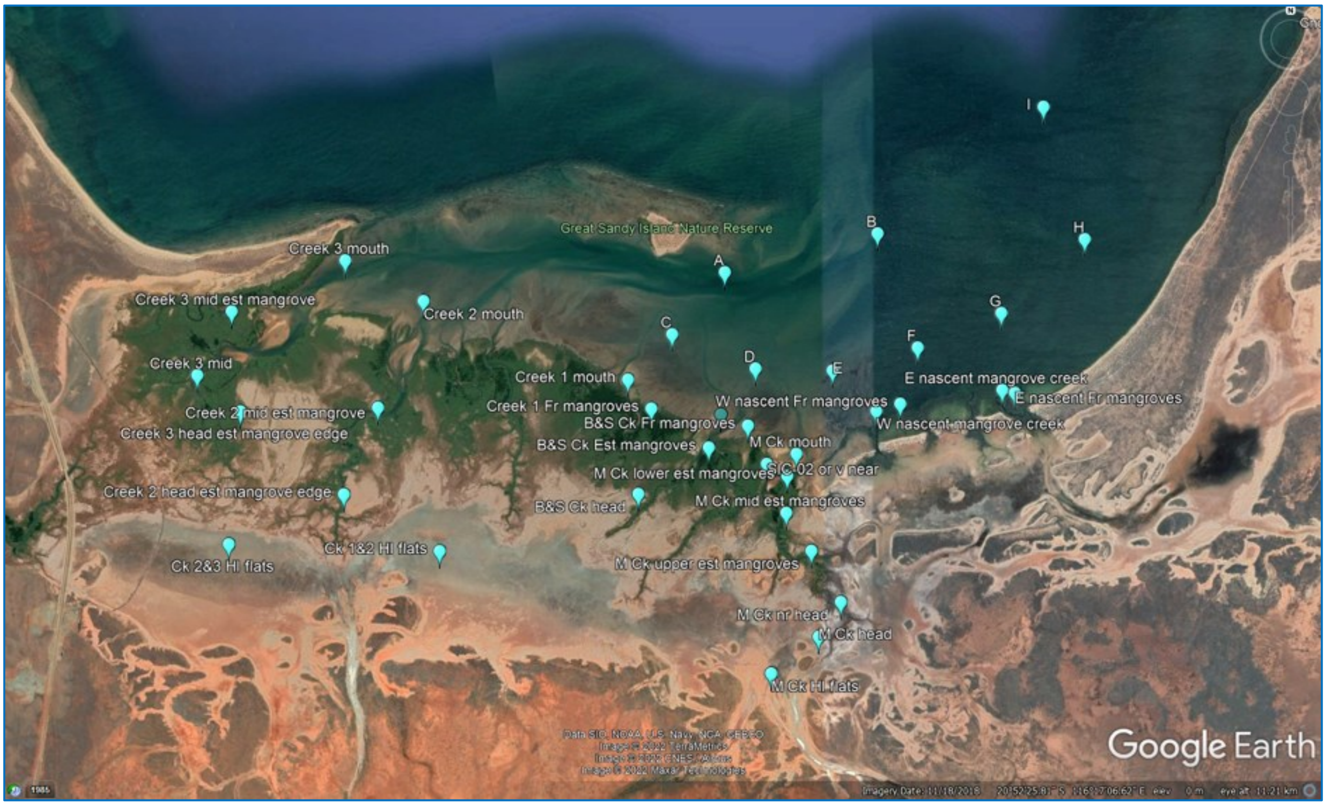


Figure 40. Locations in the estuary (named) and away from the coastline (letters, in upper right) where data was extracted from the tidal inundation model.

Figure 41. Locations in the eastern ESSP area where data was extracted from the tidal inundation model.

As useful context, the sites in the outer estuary have ratios generally close to 1 (Table 6), indicating as might be expected, a tidal wave less distorted compared to that at the tidal creek mouths.

Table 6. Flow ratio and Maximum velocity ratios for sites away from the shoreline (locations shown in upper part of Figure 51). Higher number is a relatively greater ebb.

Sites	Flow Ratio (Ebb:Flood)	Maximum Speed Ratio (Ebb:Flood)
A	1.02	0.84
B	1.1	0.98
C	1.12	0.92
D	1.07	0.9
E	1.03	0.88
F	0.93	0.76
G	1.12	0.93
H	0.96	0.82
I	0.96	0.87

7.2.4. Analysis

The variation in natural Vs:Vc along the ESSP coastline and adjacent areas varies from 1.6 for Creek 6 and the Port, to 4.1 for 40 Mile W (Figure 39). The pattern in the Vc:Vs ratios broadly matches that of the flow ratio and maximum speed ratio, together indicating the tidal creeks that are likely to have strongly ebb-dominated tides in the creeks themselves (Table 7). In contrast, the westernmost nascent mangrove creek mouth is flood dominated (flow ratios of 0.67 and max. speed ratio of 0.83), interpreted as the very small catchment being insufficient to reverse the flood tidal dominance of the incoming tide in the small creek entrance channel.

Table 7. Hypsometric Vs:Vc ratio, flow ratio and Maximum Speed Ratio for coastal locations and natural conditions. (For the flow ratios, a higher number is a relatively faster ebb). Brown shaded rows have strongly ebb-dominated ratios.

Sites	Vs:Vc ratio	Flow Ratio (Ebb:Flood) (ratio of distance)	Maximum Speed Ratio (Ebb:Flood) (ratio of max. speed)
Creek 3 mouth	2.8	1.14	0.81
Creek 2 mouth	3.3	1.19	0.91
Creek 1 mouth	2.2	1.09	0.97
Baldy/Straight Ck mouth	3.1	1.27	1.13
McKay Ck mouth	3.1	1.51	1.59
W nascent mangrove creek (West end of Area C in Figure 27)	n/a	0.67	0.83
E nascent mangrove creek (East end of Area C in Figure 27, i.e., part of 40 Mile W)	n/a	1.72	1.36
40 Mile E (Barndar Ck of O2 Metocean 2022a)	3.8	1.49	1.23
Creek 8 (Devil Ck mouth of O2 Metocean 2022a)	3.0	0.7	0.67
Yanyare (~Cooglegong Ck mouth of O2 Metocean 2022a)	2.3 NB - represents a side creek not the main mouth	1.5	1.92

7.2.4.1. Catchments fronting the ponds

Along the southern estuary bank, the systems Creek 2, Baldy/Straight and McKay Creek have very similar ratios, at 3.0 to 3.3, like those catchments fronting the easternmost ponds (Creeks 7 & 8). Considering the hypsometric curves, McKay Creek is much larger in relative terms at and above high tide level (2.5 m AHD) than Baldy West and Straight Creek (Figure 42). At elevations above ~2 m AHD, Baldy West increases in volume at a lower rate than Straight Creek, indicating that Baldy West might be constrained in its high tidal and supratidal area, and likely has a tidal regime less ebb-dominated than Straight Creek itself. However, they are combined at the mouth so purposes of coastal dynamics should be considered together, and indeed their combined hypsometry (Figure 42, right) indicates that, above 1.5 m AHD, the combined curve is of similar shape to adjacent McKay Creek.

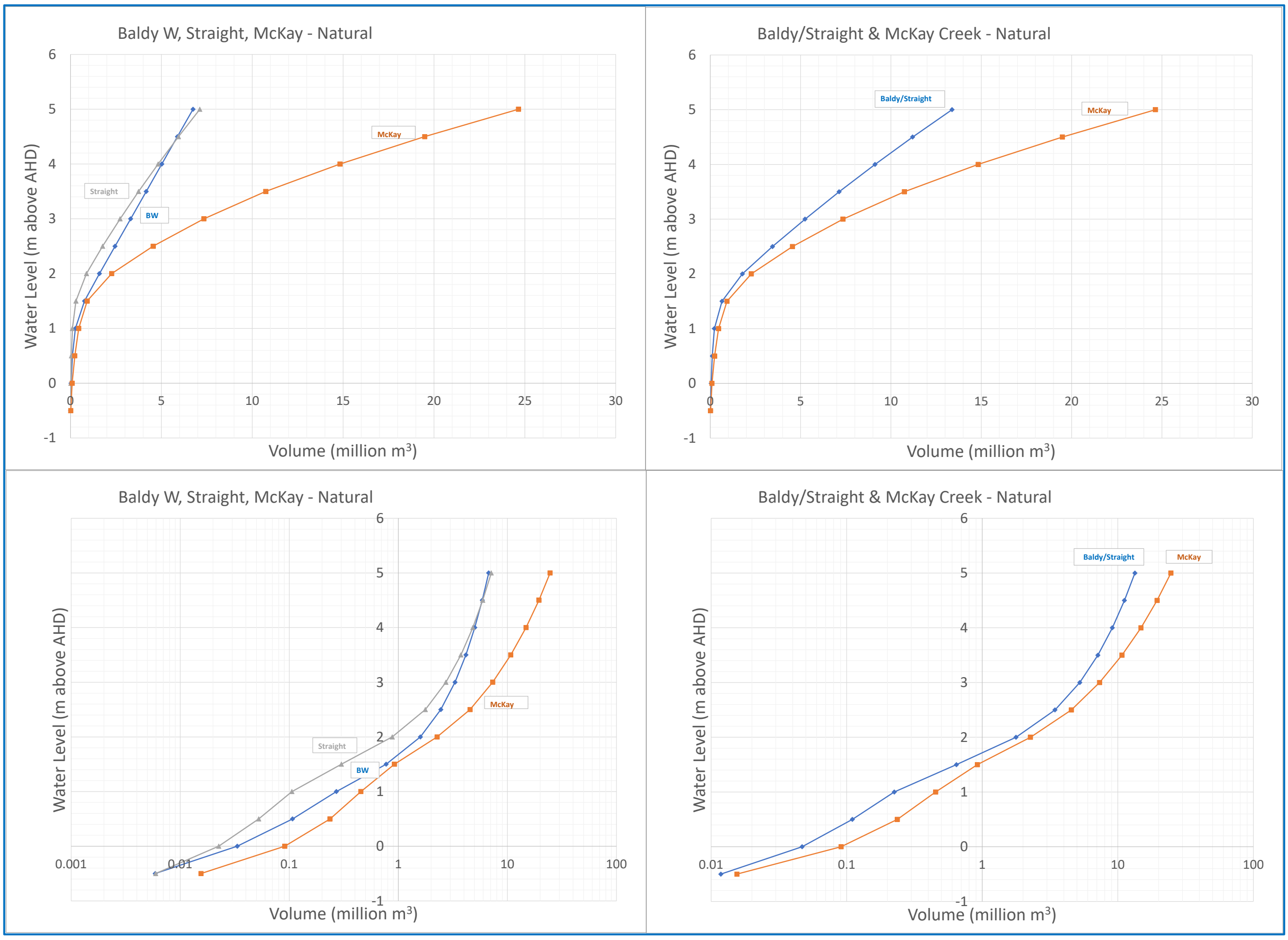


Figure 42. Hypsometric plots for: Left - Baldy, Straight and McKay creeks all considered separately, with Straight Creek notably smaller than Baldy Creek in the lower estuary (elevations 0 – 2 m AHD) and Right – with Baldy & Straight creeks combined. Upper - volume plotted on linear scale. Lower – volume plotted with log scale.

Further east, 40 Mile West and East have the largest Vs:Vc ratios for the entire ESSP region. They are similar in overall hypsometry, as perhaps might be expected for linked catchments (Figure 43), and both curves are relatively shallow across the elevation range 1.7-2.5 m AHD, the tidal range between overbank tide and HAT, tending to indicate a relatively strong hypsometric effect on tidal flows for high tides. In particular, the shallow slope of the hypsometric curve for 40 Mile W (Figure 43) cuts across many other curves, indicating that it is not at a similar stage of physical equilibrium to those other catchments.

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 & Water Consulting, 2023, their Appendix C). Taken together, these geological and human factors tend to indicate that their Vs:Vc ratios might not 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 shape of 40 Mile West's hypsometric curve (and its flow ratio and maximum speed ratio) is consistent with the presence of nascent mangroves at their mouths. Large areas of young mangroves on an accumulating coastline 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, as part of a process of coastal advance.

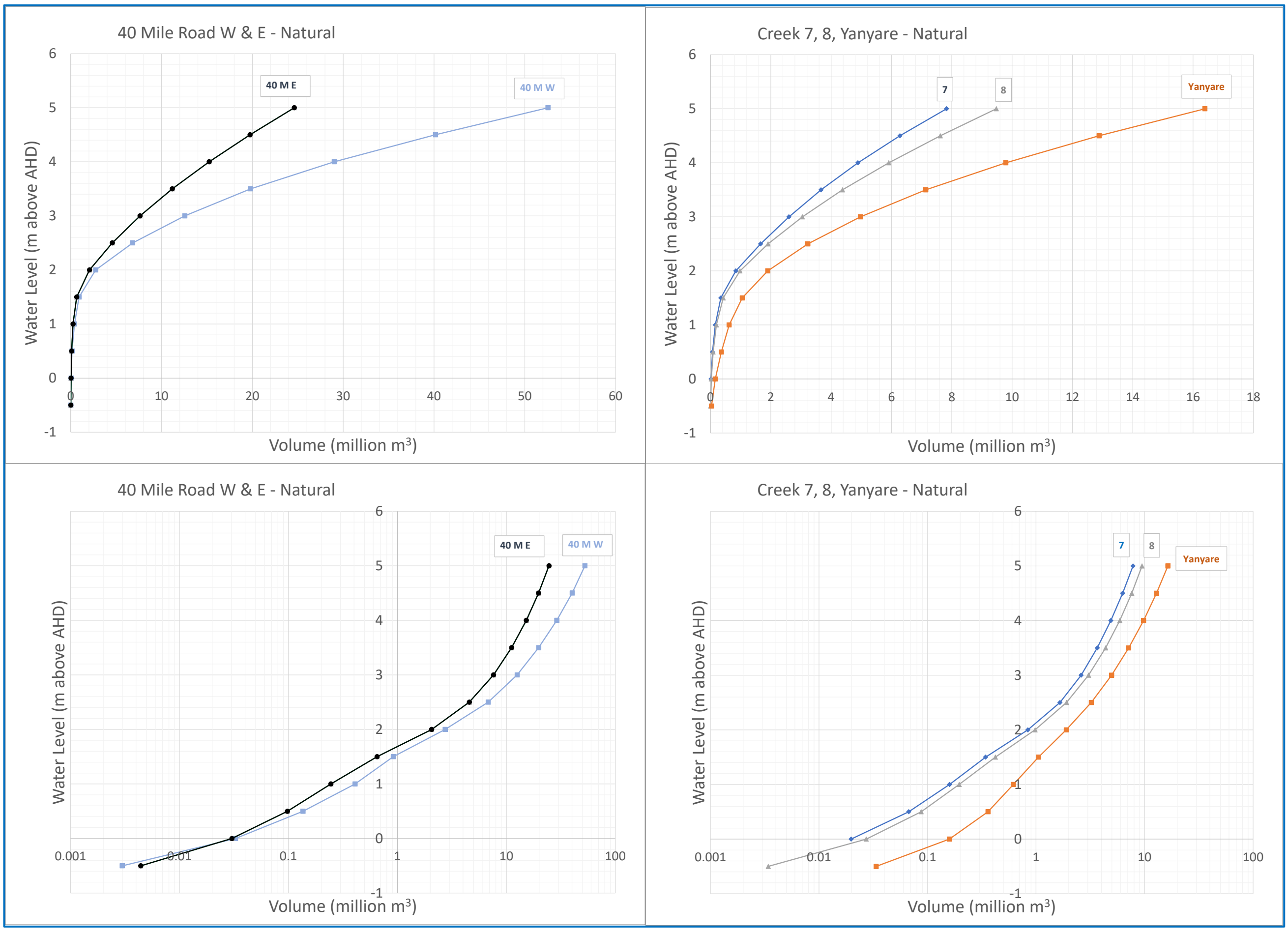


Figure 43. Hypsometric plots for: Left - 40 Mile West and 40 Mile East, and Right – creeks 7, 8 and Yanyare. Upper - volume plotted on linear scale. Lower – volume plotted with log scale.

Further, there is a sand spit based at Gnoorea Point that affects the 40 Mile W catchment. The spit's morphology indicates that it extended SW toward the nascent mangroves (Figure 44) with previous splays extending into the tidal flat area, and a small number of breaches in the feature at its SW end. 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 two nascent mangrove creeks.

It is important to note that there are no dates on this sand spit and splay features, nor others in the intertidal or supratidal zones, nor on their surrounding sediments. If these features might be a past coastline, which seems likely, it is unknown whether it is ~120,000 yrs old or just ~5,000 yrs old (the 2 most likely possibilities). Such uncertainty is significant, because it makes a considerable difference in our understanding of past coastal changes, and therefore what range of future possibilities there may be.

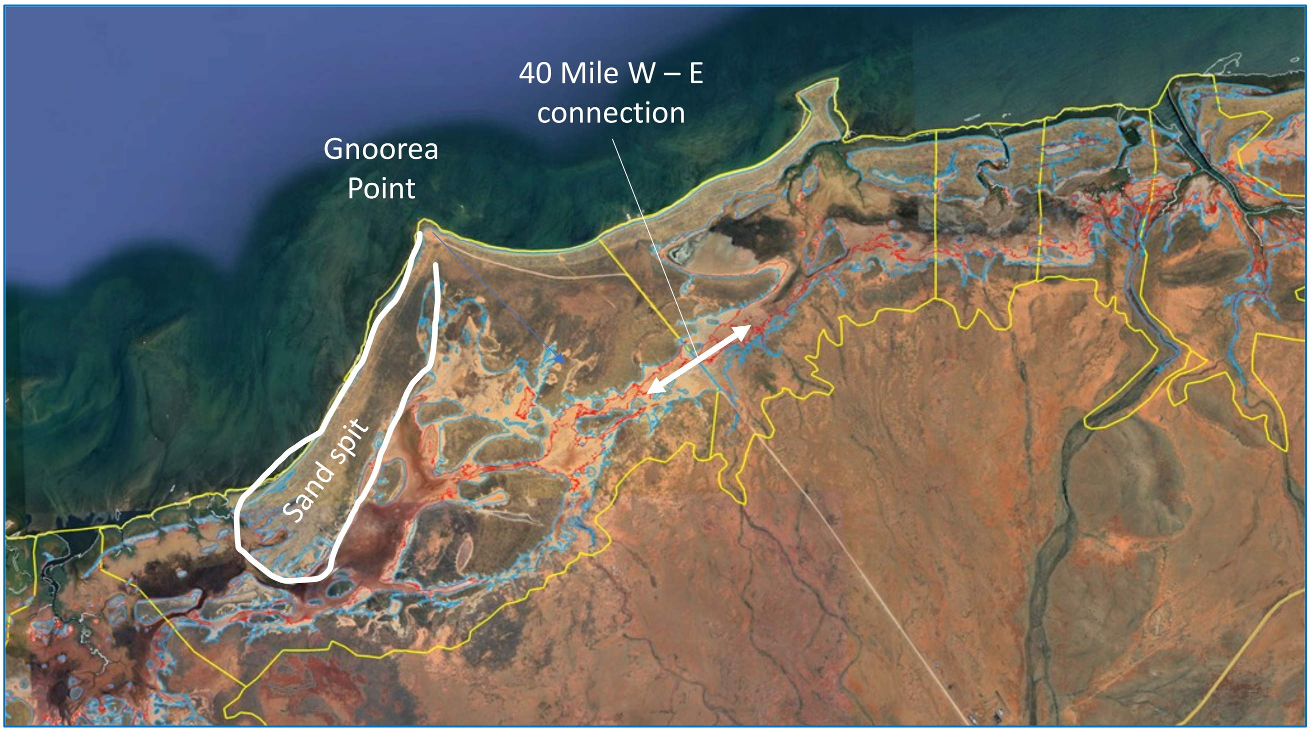


Figure 44. The sand spit SW of Gnoorea Point that fronts the western part of the 40 Mile West catchment, and the connection (before road construction) between the 40 Mile W and 40 Mile E catchments.

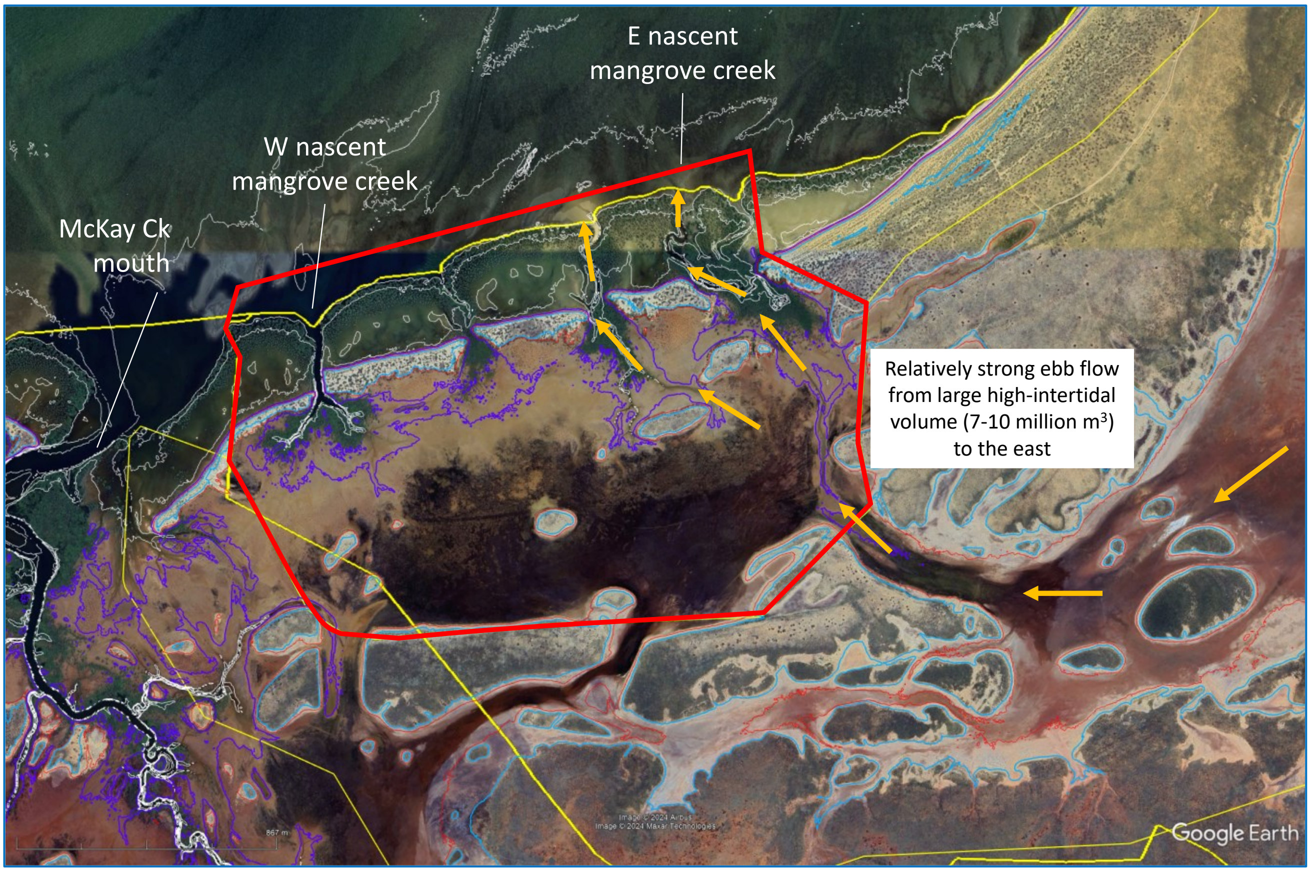


Figure 45. The possible flowlines (orange arrows) of strong ebb flows and/or runoff from the catchment to the east of the present nascent mangrove creeks east of McKay Creek. Elevation contours are at 0.5 m intervals from -1.0 m upwards, including +1.5 m (purple), +2 m (red) and to +2.5 m AHD (light blue, at approximately high spring tide). The bulk of the isolate area lies at +1.5 - +2 m AHD. Finally, note that with pond scenario 7.2.1, an area becomes isolated to seawards of the ponds (red outline).

Overall, for 40 Mile West and East, it can be concluded that the natural Vs:Vc ratios for 40 Mile West and East may well reflect active modern tidal processes, but perhaps including a contribution from fluvial runoff at the creek mouths, and perhaps too a relative lack of past sediment supply to the high intertidal zone and supratidal zone. In geological terms, these catchments might have some remaining accommodation space compared to those around them.

Further east, creeks 7 & 8 are very similar in their hypsometric shape (Figure 43), with the lines on the log plots strongly parallel – these systems are likely to operate in a similar way. Just beyond the proposed ponds to the east, Yanyare is similar in shape above high tide level (i.e., > 2.5 m AHD).

7.2.4.2. The western estuary

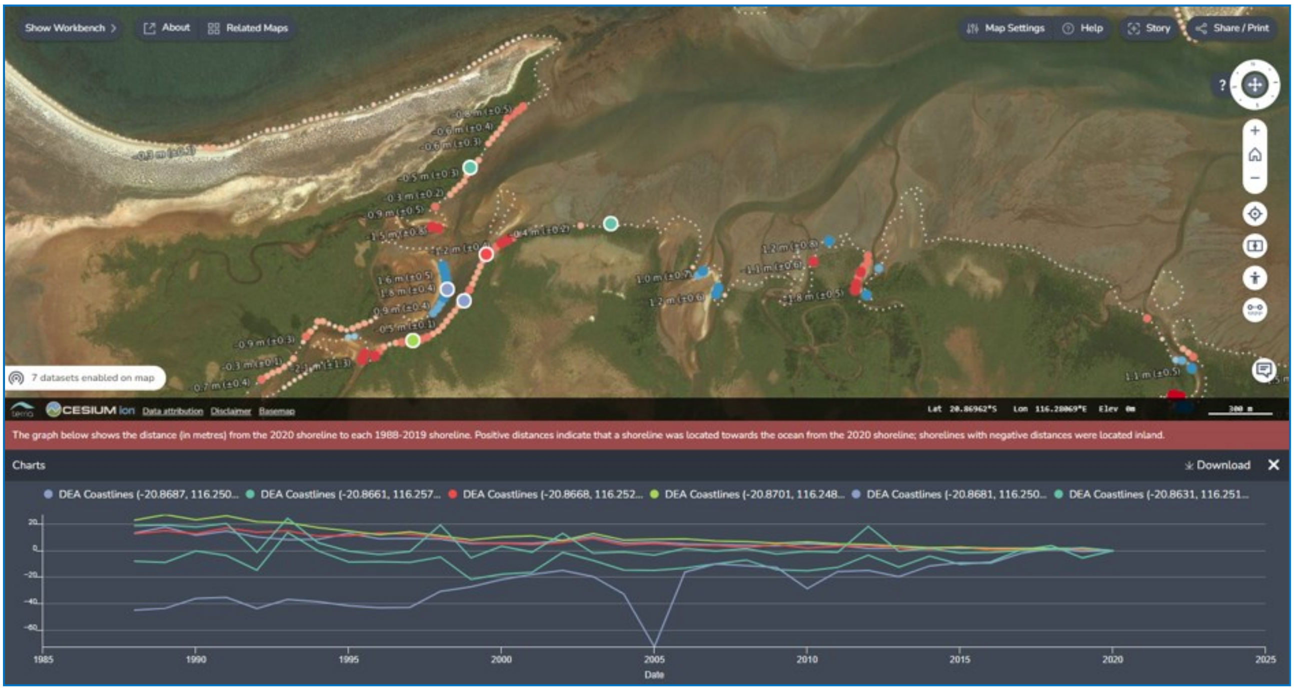
Although not directly associated with the ponds, it is notable that the Vs:Vc ratios are low for Creeks 5 & 1, at 2.2, and see also the steep slopes of the curves on Figure 38 through the elevation range shaded blue. For creek 5, this is consistent with the presence of large wide creeks containing mobile sandbanks. This tends to indicate that these systems are prone to silting up, because they have relatively low capacity for ebb-tidal-scouring of their channels.

The Geoscience Australia data on past shoreline change (Figure 46 - Creek 5 is on the left) (Geoscience Australia, 2023; see also Bishop-Taylor *et al.* 2021) indicates a general pattern over the last 32 years of little change along the fringing mangrove shoreline itself, with most change concentrated i) in the tidal creeks, being related to lateral movement of the channels, and ii) near the creek mouths. Further, the data indicate relatively continuous change through time, with no major events of coastline migration. This tends to support the interpretation of tidally dominated processes in this sheltered environment with relatively little influence from episodic events.

The dominance of erosion on creek 5's banks since 1988 tend to indicate landward migration of the creek system, but the data cannot inform on sedimentation patterns above or below MSL. Above MSL, and especially in the overbank areas, other factors may come into play. In the north of the creek 5 catchment, the overbank area may be constrained by the active sand barrier, and to the west there is uncertainty in delineating the catchment boundaries because of the active link at 1-1.5 m AHD with the west-facing Creek 4. The road to Cape Preston might also have had an effect since construction, despite its 90 m-wide culvert, and there is little information on subsequent sediment accumulation or erosion in this area (except some aerial images noted later (Section 10.5, Table 20, Figure 124). Thus, the above interpretation of dominant tidal processes in the Creek 5 system might be expanded to include the uncertainties of:

- the (presumed) southward-migrating sandy back-beach barrier along Cape Preston Beach east reducing the catchment area from the north;
- the linkages across catchments in the high intertidal area; and
- the possible effect of Cape Preston Road.

These issues are returned to in Section 10.5.



The graph below shows the distance (in metres) from the 2020 shoreline to each 1988-2019 shoreline. Positive distances indicate that a shoreline was located towards the ocean from the 2020 shoreline; shorelines with negative distances were located inland.

Figure 46. Time-series of erosion (red, -ve) and progradation (blue, +ve) for selected points since 1988 in the western estuary. Creek 5 is at the far left (image from CP-BCH report). White dots indicate areas of little net change since 1988. Channel banks within creek 5 are mostly eroding, and near the mouth are migrating laterally at around 0.5 - 2 m/year, with little net change just seawards of the mouth. There is a total of ~10 m horizontal erosion over 32 years outside the estuary mouth along the open coast (2 x dark green lines), i.e., 0.3 m/year.

7.2.5. Seasonal waves

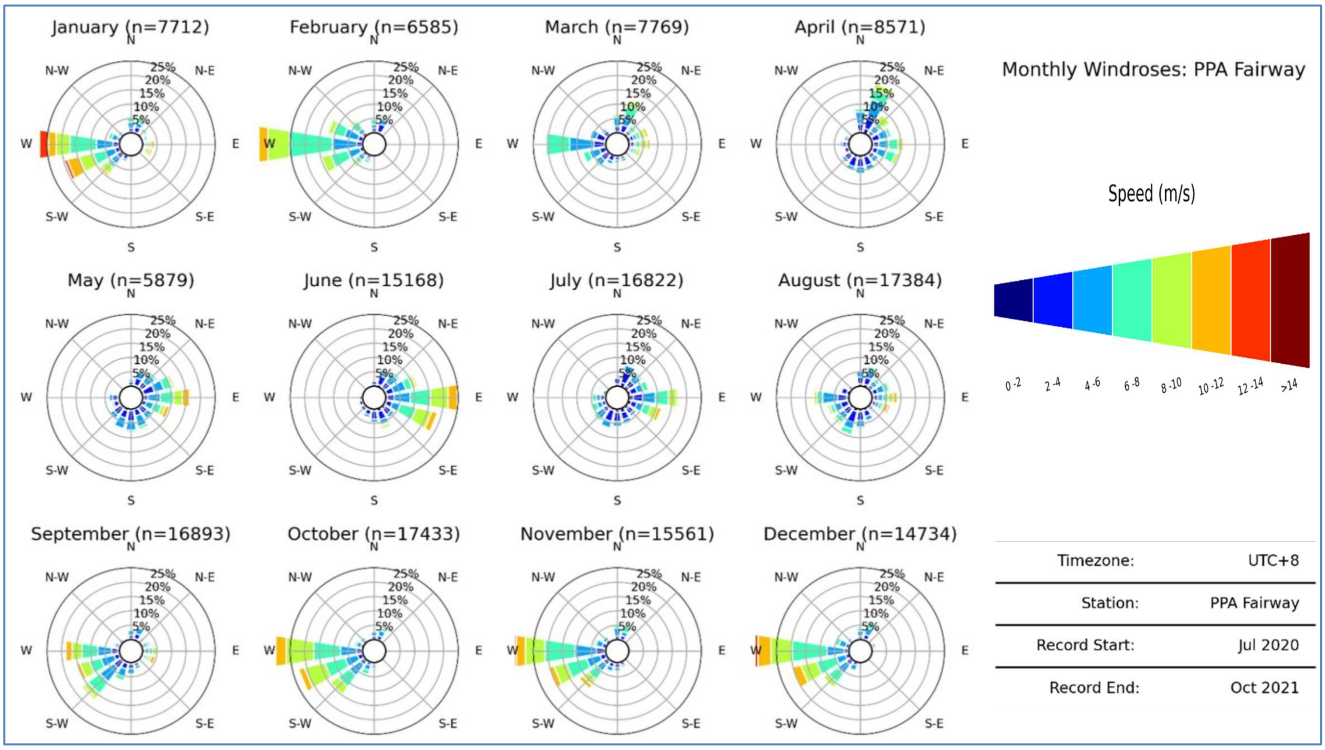
The sea state of the southern NWS comprises contributions from Southern Indian Ocean swell, Winter Easterly swell, 'West Coast' swell, tropical cyclone swell, local wind-generated sea and 'old sea' (O2 Metocean 2022b). Of these, several are notably seasonal in nature. (NB – cyclonic conditions are dealt with as an episodic driver, in Section 7.3.3). 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. Whilst synoptic offshore winds can drive swell on the outer shelf, this will not directly affect the ESSP area, rather arriving as 'old sea'; and
- 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; and
- 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 all swell 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.



Timezone:	UTC+8
Station:	PPA Fairway
Record Start:	Jul 2020
Record End:	Oct 2021

Figure 47. 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.

7.3. Episodic drivers

7.3.1. Meteorology & rainfall

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 48). 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.

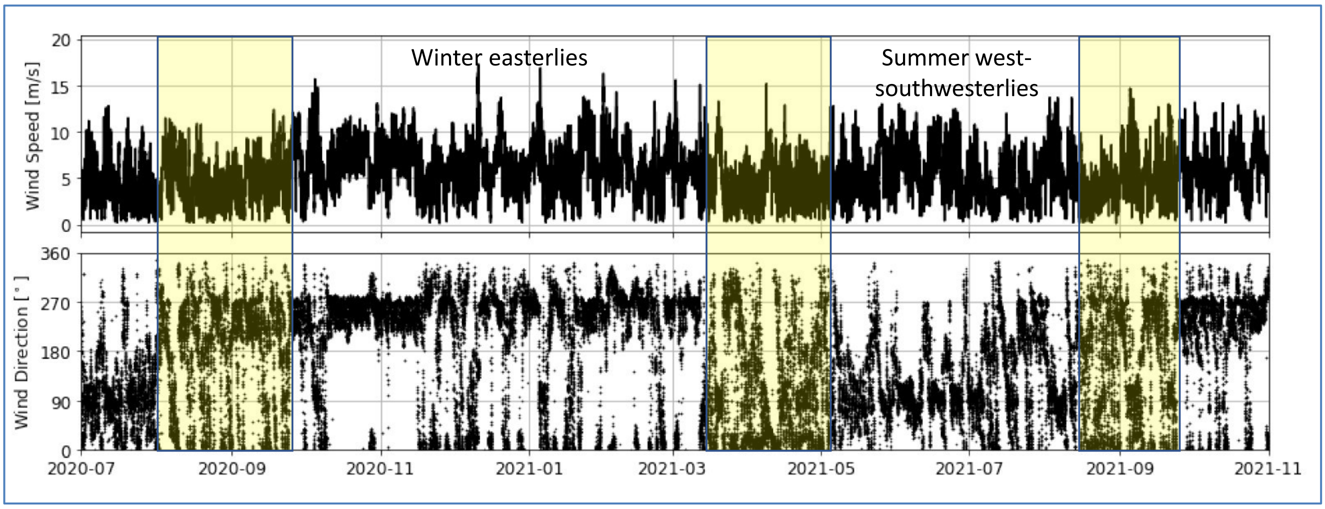


Figure 48. Dampier Fairway winds for July 2020 to Oct 2021. Note the seasonal shift from winter easterlies to summer west-southwesterlies. Yellow panels = Transitional seasons.

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 49), 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.

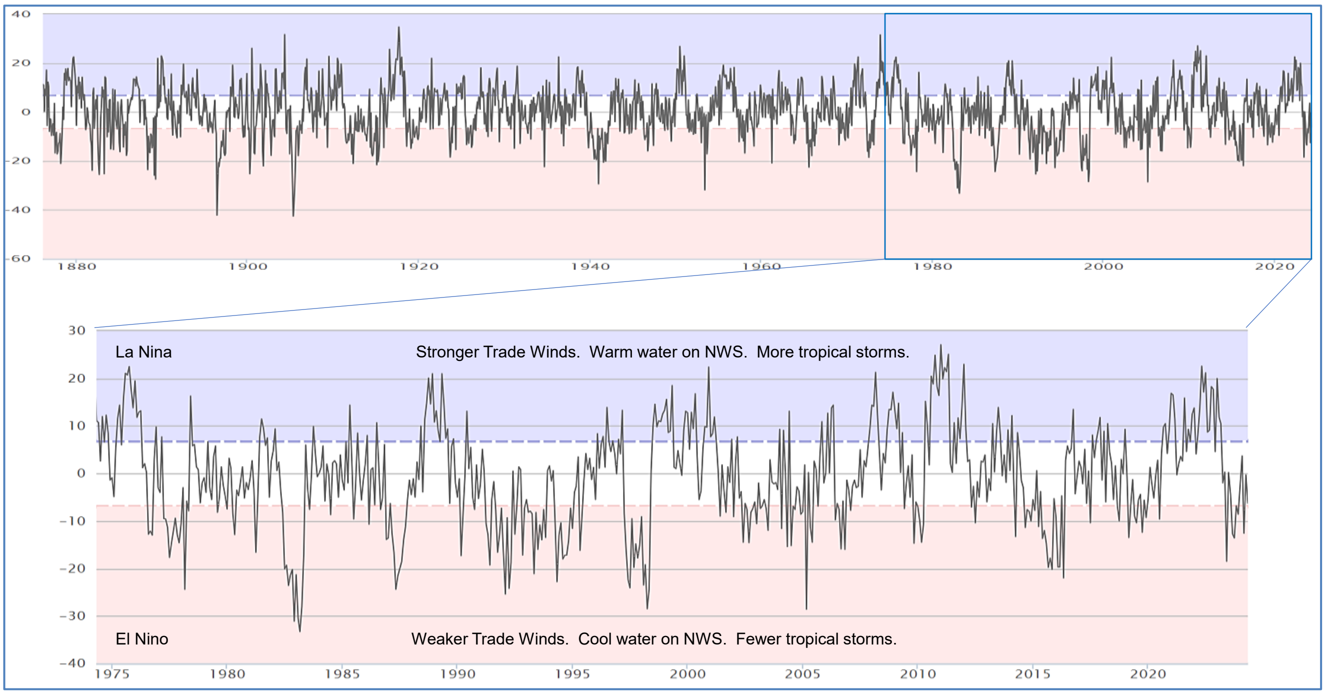


Figure 49. Monthly measures of the Southern Oscillation Index (SOI) since 1880, with detail for the period since 1975. The SOI is a monitor of the ENSO, so can inform on the El Nino and La Nina conditions. SOI above +ve 8 = La Nina = stronger Trade Winds, warmer water on the NWS and more tropical storm activity. SOI below -ve 8 = El Nino = the opposite.

7.3.2. Rivers & freshwater runoff

In the Pilbara region, the mean annual rainfall is only ~300 mm (Lough, 1998); however, extreme rainfall during tropical cyclones and other tropical storms can induce flash flooding within the coastal zone, sometimes providing most of the river discharge in a given calendar year (Semeniuk, 1993). Rainfall in the western Pilbara region has decreased over the past 40 to 60 years (Sudmeyer, 2016). The ESSP area's rainfall regime shows significant variability between years, with episodic events generating high rainfall (e.g., Figure 50).

Mean rainfall data for the area is around 290 mm/yr with most rainfall occurring in the period January to June (Figure 51). Some significant rainfall events may not be associated with identified tropical lows (as per the BoM database). Annual pan evaporation rates average around 3,200 mm/yr (SILO station number 004083), far exceeding precipitation for every month of the year (Land and Water Consulting, 2023a, 2023b). The period of current measurements in McKay Creek (Figure 54) was markedly different to the mean monthly pattern.

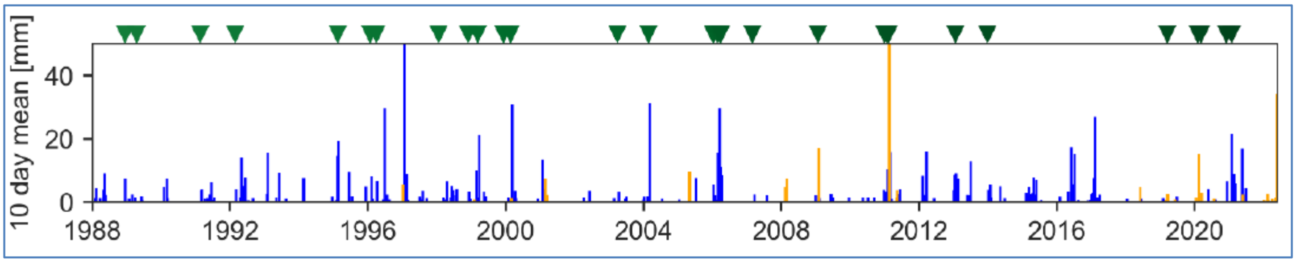


Figure 50. 10-day average rainfall since 1988 as recorded at Eramurra weather station (O2 Metocean 2022a). Blue data represents 'good' and orange 'suspect' data, as per BoM quality control. Green triangles indicate the occurrence of cyclones.

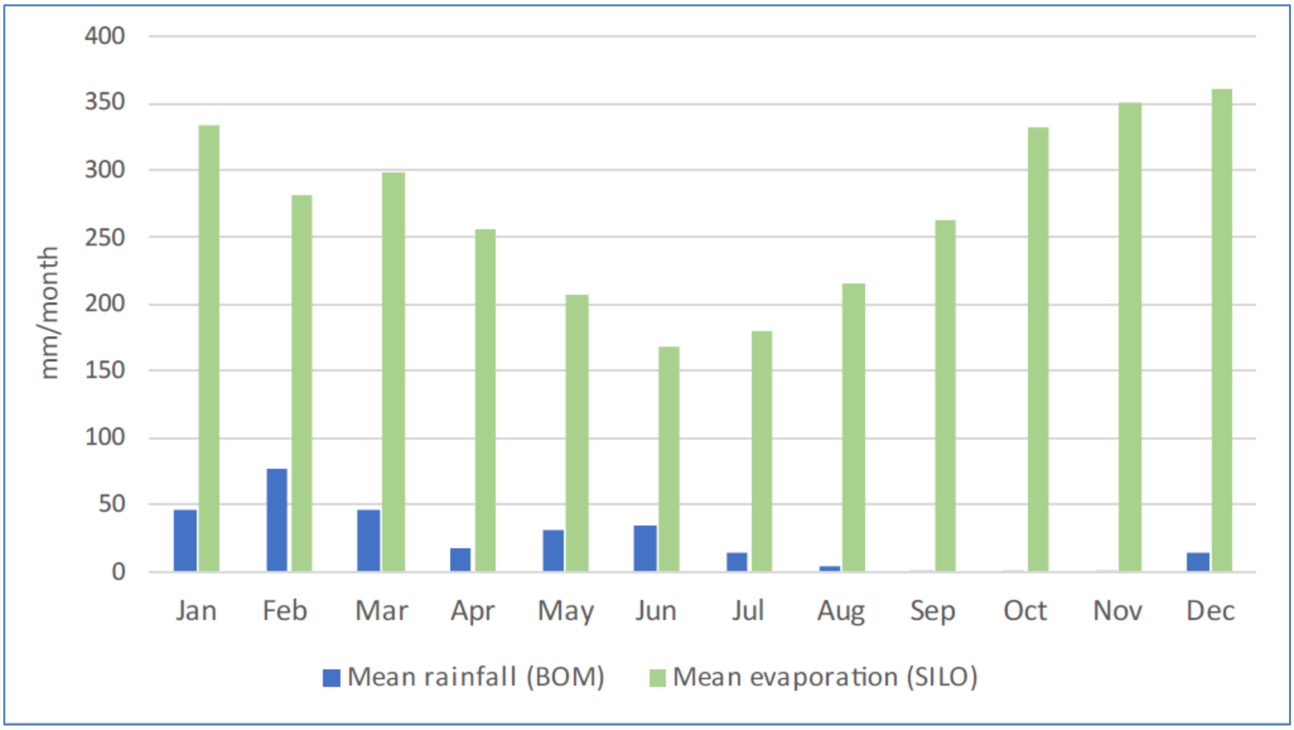


Figure 51. Mean monthly rainfall and evaporation data for the ESSP area (Land and Water Consulting 2023b).

As well as the major creeks (Eramurra, McKay and Devil; Figure 52), there are several minor creeks that can contribute freshwater and sediment to the ESSP coastal systems, notably between Eramurra and McKay creeks, and another that enters the 40 Mile Road W catchment (Figure 53, see also Section 16).

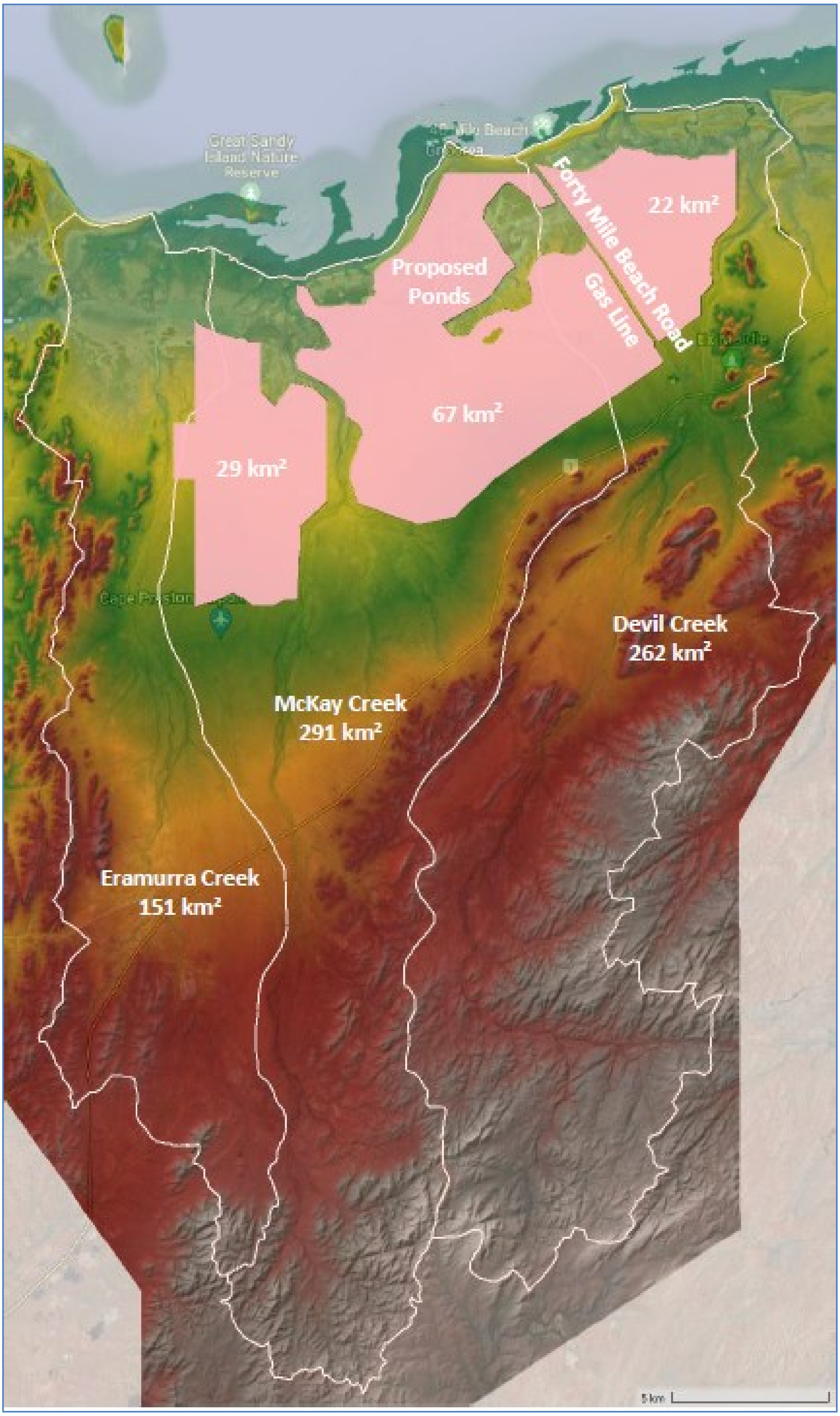


Figure 52. The ESSP and contributing river catchment areas (Land and Water Consulting, 2023a). The ponds mostly affect the McKay and Devil Creek catchments.

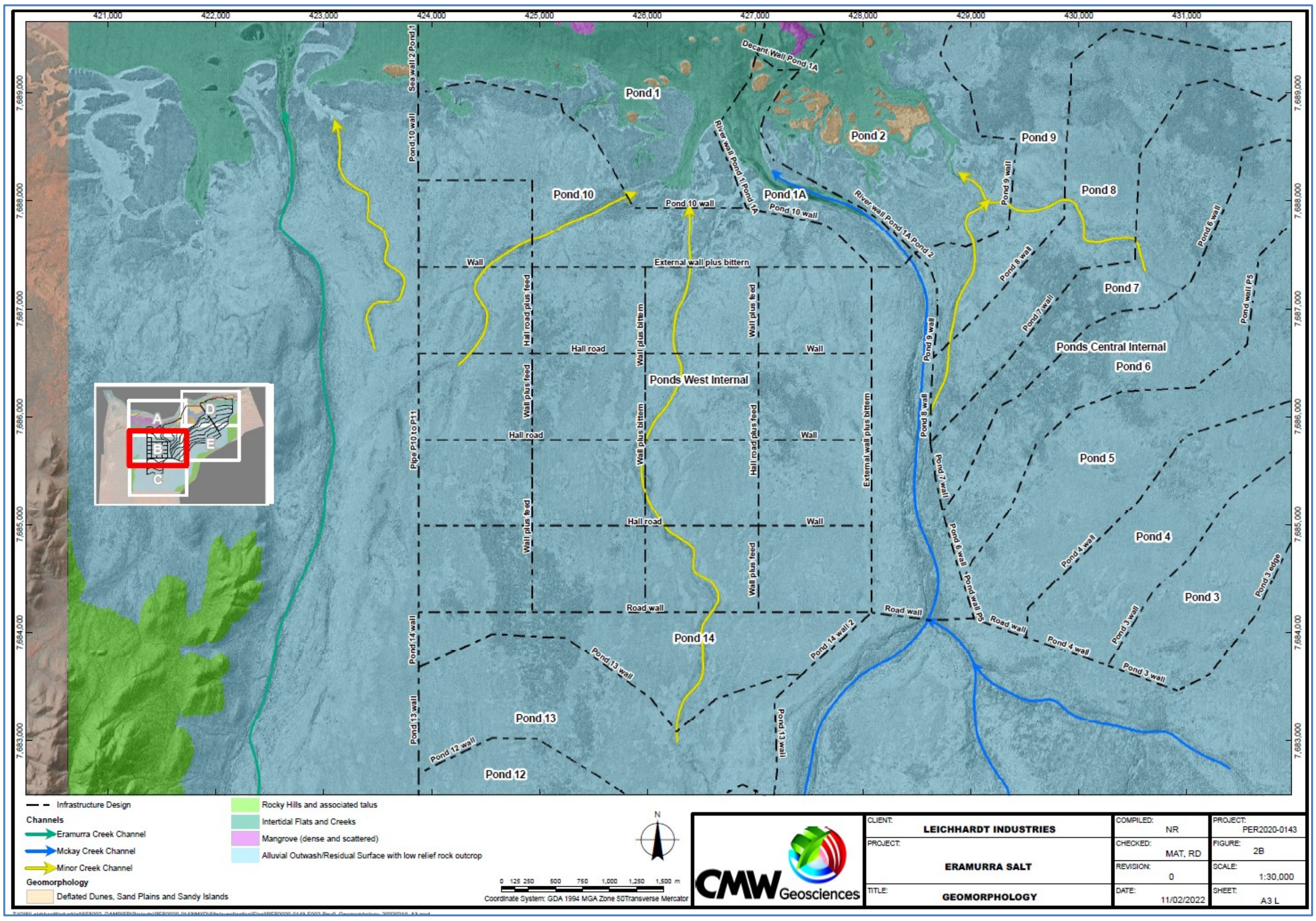


Figure 53. Minor drainage channels west of the uppermost tidal area of McKay Creek (CMW Geosciences 2022). Note that several minor channels are covered by the proposed ponds.

Tidal flows were measured in McKay Creek for 15 months, from July 2020 to October 2021 (Figure 54). The 2020-2021 wet season was characterised by mild La Niña conditions and a neutral IOD, while the 2021 dry season was characterised by neutral ENSO conditions and a mild negative IOD. Despite the presence of La Niña, cyclone impacts in the Pilbara region were very mild for the 2020-2021 cyclone season (Table 8). The only storms reaching cyclone classification were TC Marian (21 February – 9 March 2021), and the interacting systems TC Seroja (3 – 12 April 2021) and TC Odette (3 – 10 April 2021), although each of these reached full intensity far to the west of Cape Preston. In addition to these extreme events there were numerous other weaker tropical storms in the region (e.g., TL02U 6 – 12 December 2000; TL08U 15 – 23 January 2001, and; TL12U 28 January – 5 February 2001 – these are the last three unnamed events in Figure 50 and Table 8).

An intense rainfall event on 11-12 December 2020 generated intense runoff, such that, measured at the mouth of McKay Creek, both flood and ebb tides flowed seawards, with maximum speeds occurring at successive low tides (Figure 55). Maximum measured turbidity occurred at low tide too, unlike all other measured periods that lacked rainfall. This indicates export of sediment during these events, but also that the sediment flux is very small compared to day-to-day tidal processes and unlikely to be significant over periods of weeks to months.

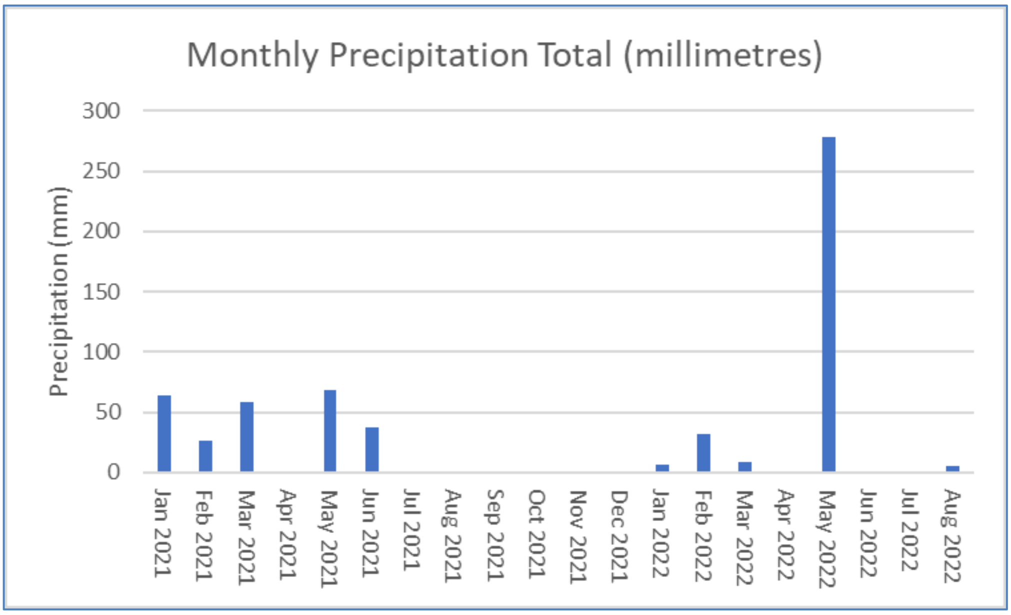


Figure 54. Monthly rainfall totals for Jan 2021 to Aug 2022.

Once such an intense rainfall event occurs, if the next follows soon after, say several weeks to several months, some of those processes that that might help produce sediment in the catchment (e.g., bioturbation & weathering) may not have had time to recharge available surface sediments to the previous level. In this way, a second equivalent event might carry less sediment. However, on the contrary, between events, vegetation cover might form over some eroded areas thus reducing potential availability again. In this way, the ‘groupiness’ of heavy rainfall events and associated modulation of processes in catchments introduces uncertainty into projections of the sedimentary effects of runoff events.

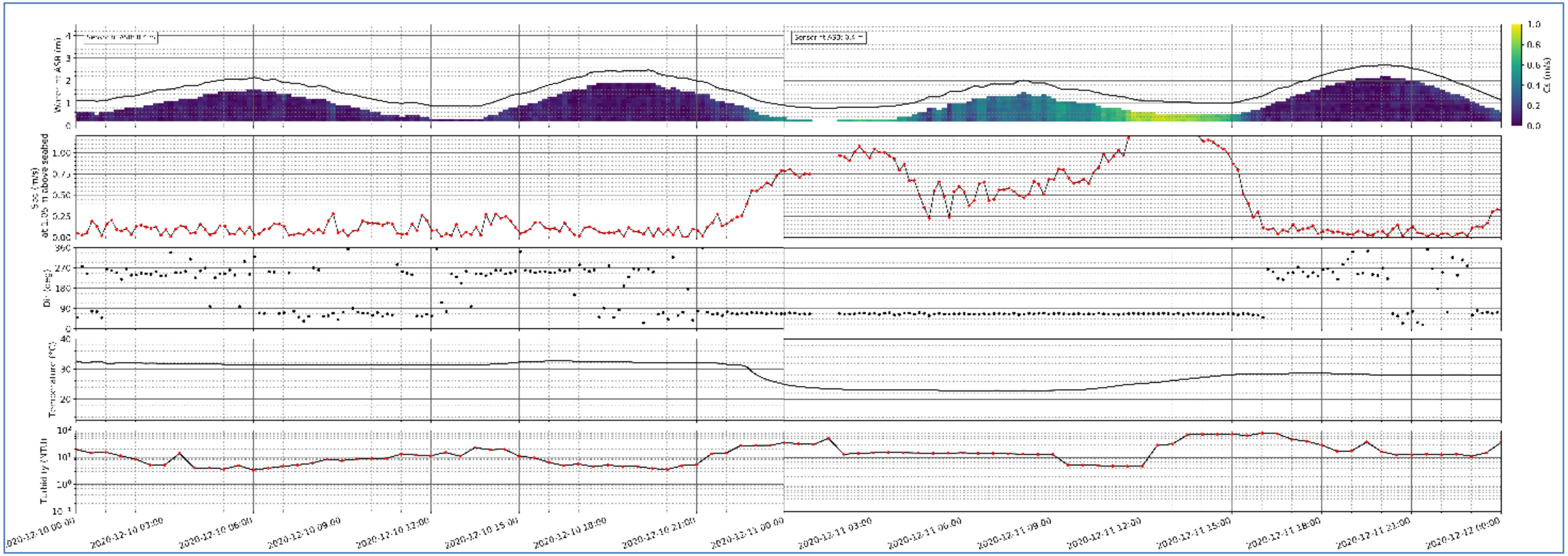


Figure 55. Period of persistent seawards-directed flows associated with a major rain event on 11-12 December 2020. Rows of data are, top to bottom: Water height (m above the measurement point) with currents speed measured at various heights within the water column (m/s, colour scale on right), current speed at 1.05 m above the bed (m/s),current direction (degrees), water temperature (Celsius) and turbidity (NTU, on a log scale). Note the speed (data on second row) reaches 1m/s and >1.25 m/s on successive low tides. The direction (third row) is persistently in the ebb direction.

7.3.3. 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 7.3.4) are generally associated with very strong onshore winds, creating the opportunity for wind and wave 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, whereby setup further north propagates poleward (to the SW) along the coast (Fandry & Steedman 1994). Wind setup itself is usually too transient to be significant, but it does add to surge magnitude.

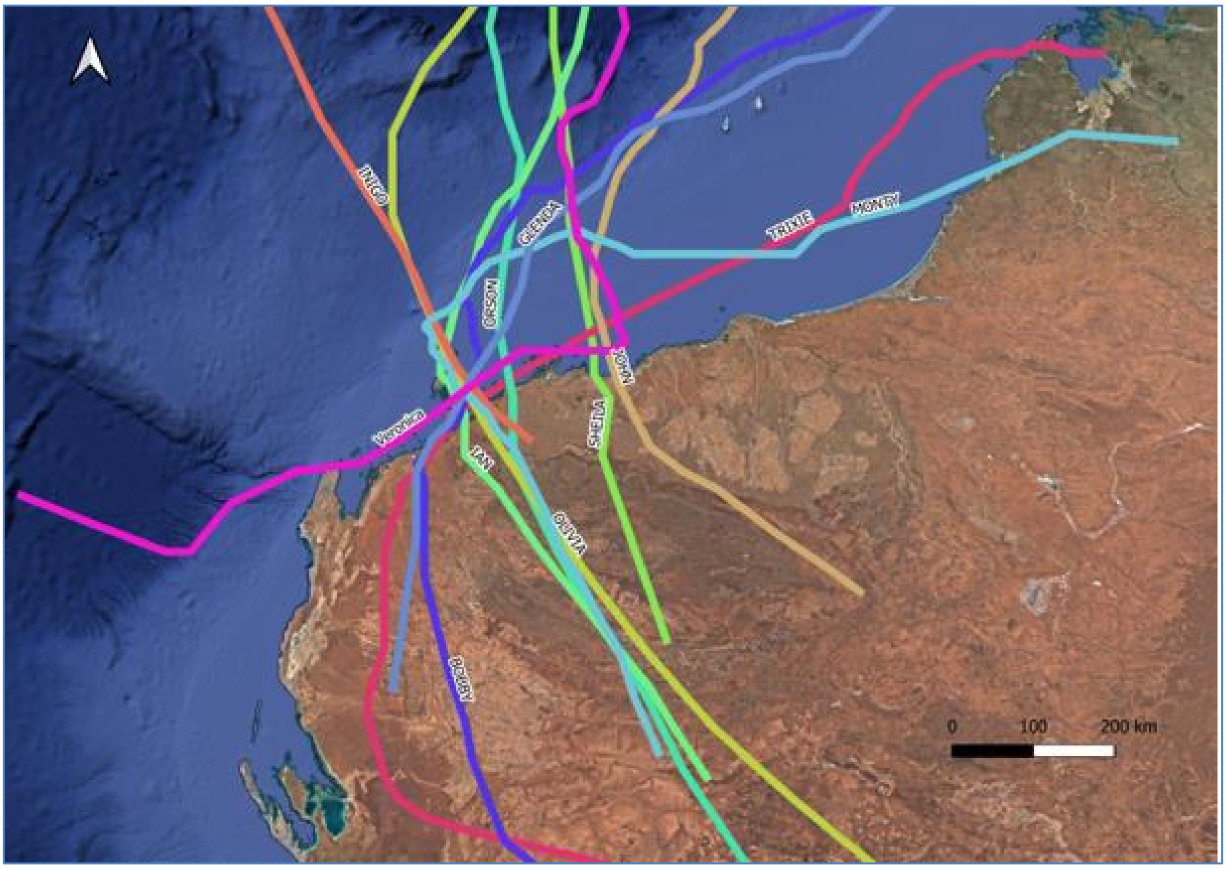


Figure 56. Tracks of notable cyclones impacting Cape Preston from the last 30 years (O2 Metocean 2023a).

A total of 31 cyclonic events passed within 150 km of the ESSP site since the beginning of 1988 (Table 8). The track passage was categorised as a NW passage (passing to the north and/or crossing land to the west), a SE (crossing land east of the site) or a direct hit (passing within 20 km). Most (20 of 31) passed the site to the NW, with most of those making landfall to the west. For most cyclones, winds are likely to be offshore until the storm passes the site, when winds turn to onshore.

Table 8. Cyclones passing within 150 km of the ESSP area[11], 1988 to early 2021, derived from the BoM cyclone database and comprehensive information in Wikipedia (e.g., 1974–75 Australian region cyclone season - Wikipedia). Rainfall data measured at the BoM's Eramurra site, 15 km inland and at 50 m elevation.

Cyclone name	Month-Year	Central Pressure [hPa]	Distance* [km]	Passage (NW/SE)	Assoc. rainfall [mm]
ILONA	Dec-88	960	31	NW	74
ORSON	Apr-89	923	13	Direct	0
DAPHNE	Feb-91	976	96	NW	37
IAN	Feb-92	965	72	NW	40
BOBBY	Feb-95	940	60	NW	176
JACOB	Jan-96	960	185	NW	82
OLIVIA	Apr-96	930	66	NW	67
TIFFANY	Jan-98	945	187	NW	0
BILLY	Dec-98	1000	123	NW	22
VANCE	Mar-99	920	187	NW	192
JOHN	Dec-99	940	132	SE	0
STEVE	Feb-00	975	14	Direct	185
INIGO	Mar-03	997	40	NW	31
MONTY	Feb-04	965	47	NW	280
CLARE	Jan-06	968	2	Direct	44
DARYL	Jan-06	980	128	NW	20
EMMA	Feb-06	990	62	NW	122
GLENDA	Mar-06	932	56	NW	100
HUBERT	Apr-06	990	78	NW	84
JACOB	Mar-07	995	150	SE	0
Dominic	Jan-09	976	106	NW	103
noname	Dec-10	993	194	NW	18
Bianca	Jan-11	979	173	NW	73
Carlos	Feb-11	980	9	Direct	216
Peta	Jan-13	994	94	SE	90
Christine	Dec-13	965	86	SE	38
Veronica	Mar-19	993	55	NW	3
Damien	Feb-20	955	49	SE	150
noname	Mar-20	995	156	NW	29
noname	Dec-20	992	190	SE	46
noname	Jan-21	992	116	SE	64

**At closest distance to site.*

- Cyclones travelling a NW passage are more likely to generate strong alongshore currents (to the SW), which will usually generate a higher coastal surge (due to Ekman Adjustment).
- Cyclones travelling a SE passage generate strong offshore winds and there is a much smaller storm surge.
- Cyclones that pass directly over the site generate a more complex (time-dependent) wind field at the site.

Cyclone-associated rainfall is highly variable, with measured rainfall at Eramurra ranging from 0 to 280 mm, with an average of 85 mm (Figure 57). The spatial distribution of cyclone-associated rainfall is variable along the nearby coast, with large differences between the weather station at Eramurra and nearby stations to the SW (Mardie, 33 km SW) and NE (Karratha Airport, 65 km NE).

---

[11] The list notes those where information indicates likely coastal change and those since ~1988, to help with interpretation of the GA dataset on coastal erosion and progradation, to illustrate the episodic nature of the environments and the associated BCHs, as well as inform considerations of the range of potential ages of the existing coastal habitats. Reference to key events and cyclones is made in the main text.

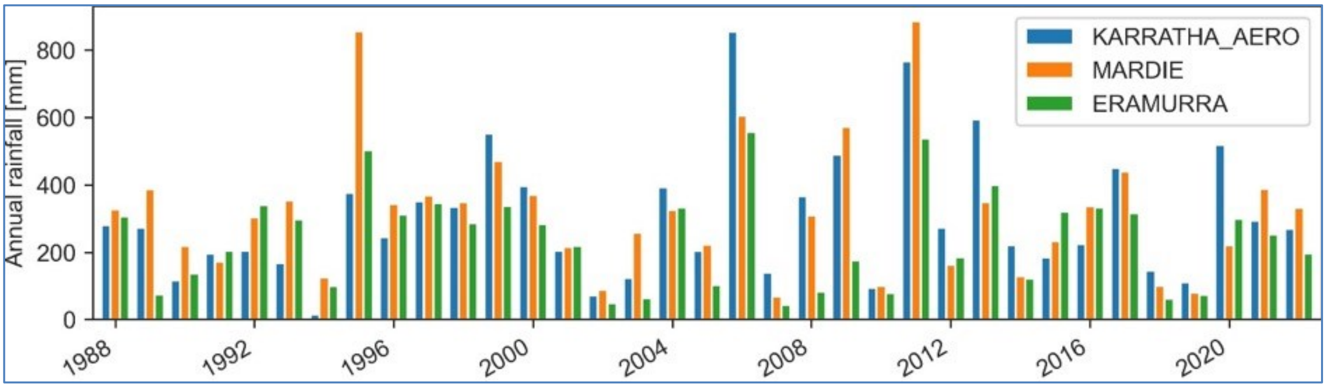


Figure 57. Total rainfall associated with each cyclone passing within 200 km of the site since 1988 for three BoM weather stations.

7.3.3.1. Cyclone seasons of 1998-1999 and 1999-2000

The 1998-1999 and 1999-2000 cyclone seasons saw four named cyclones pass within 200 km of the site. The events were: TC Billy in December 1998; severe TC Vance in March 1999; TC John in December 1999; and a direct hit by TC Steve which reached the site in March 2000 (Figure 58). Measured at Karratha Airport (50 km ENE of the ESSP site) all four events generated 3-hr average wind speeds of at least 60 km/h. The latter two events resulted in peak daily precipitation of nearly 100 mm (Figure 59). The strongest winds generally came from the West during the 1998-1999 cyclone season (Figure 60) and the 1999-2000 season was similar. This reflects the enhanced NW Monsoon, which is predominantly WSW at these latitudes.

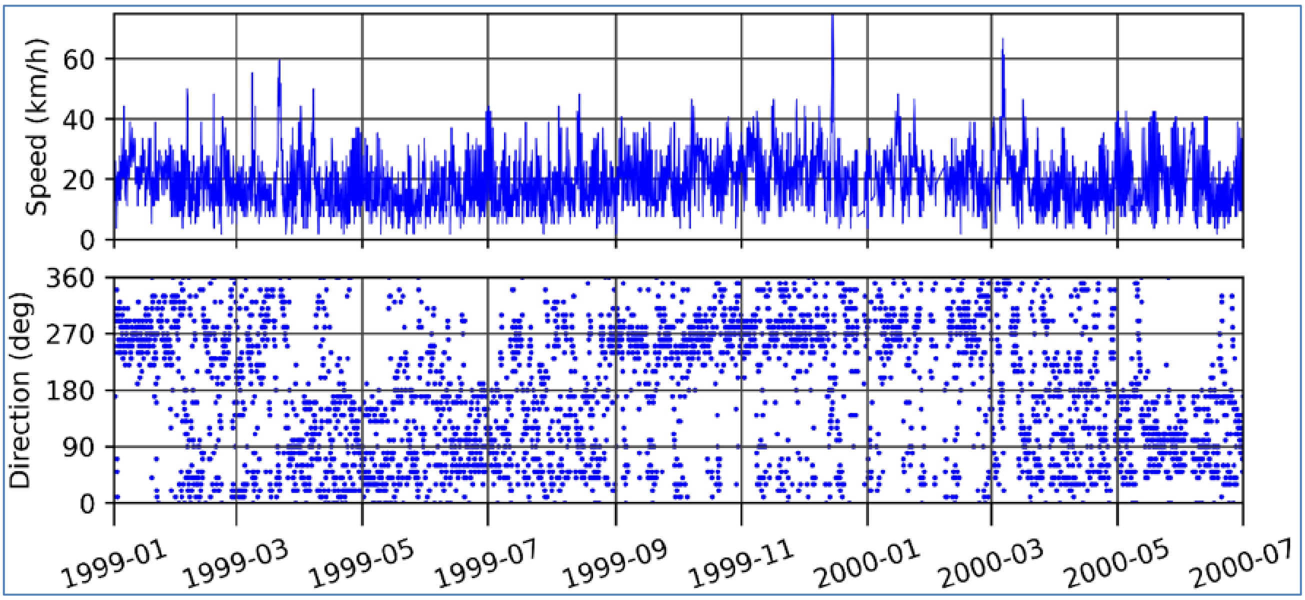


Figure 58. Wind speed and direction as observed at Karratha airport, Jan. 1999 – July 2000.

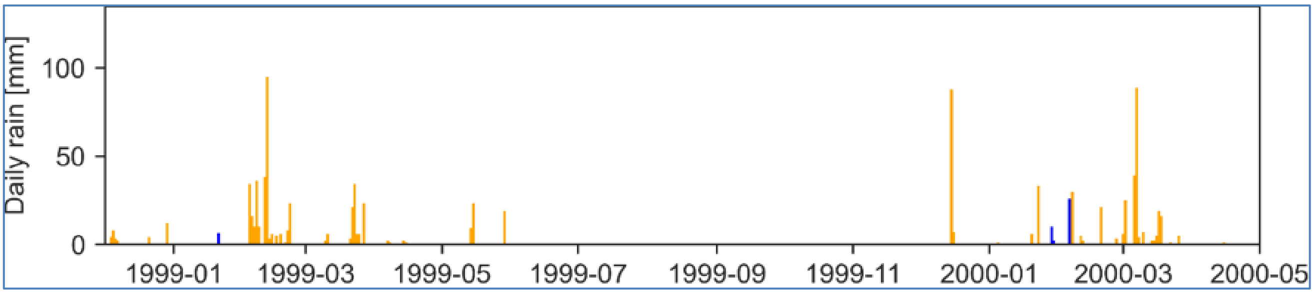


Figure 59. Daily rainfall as observed at Karratha airport.

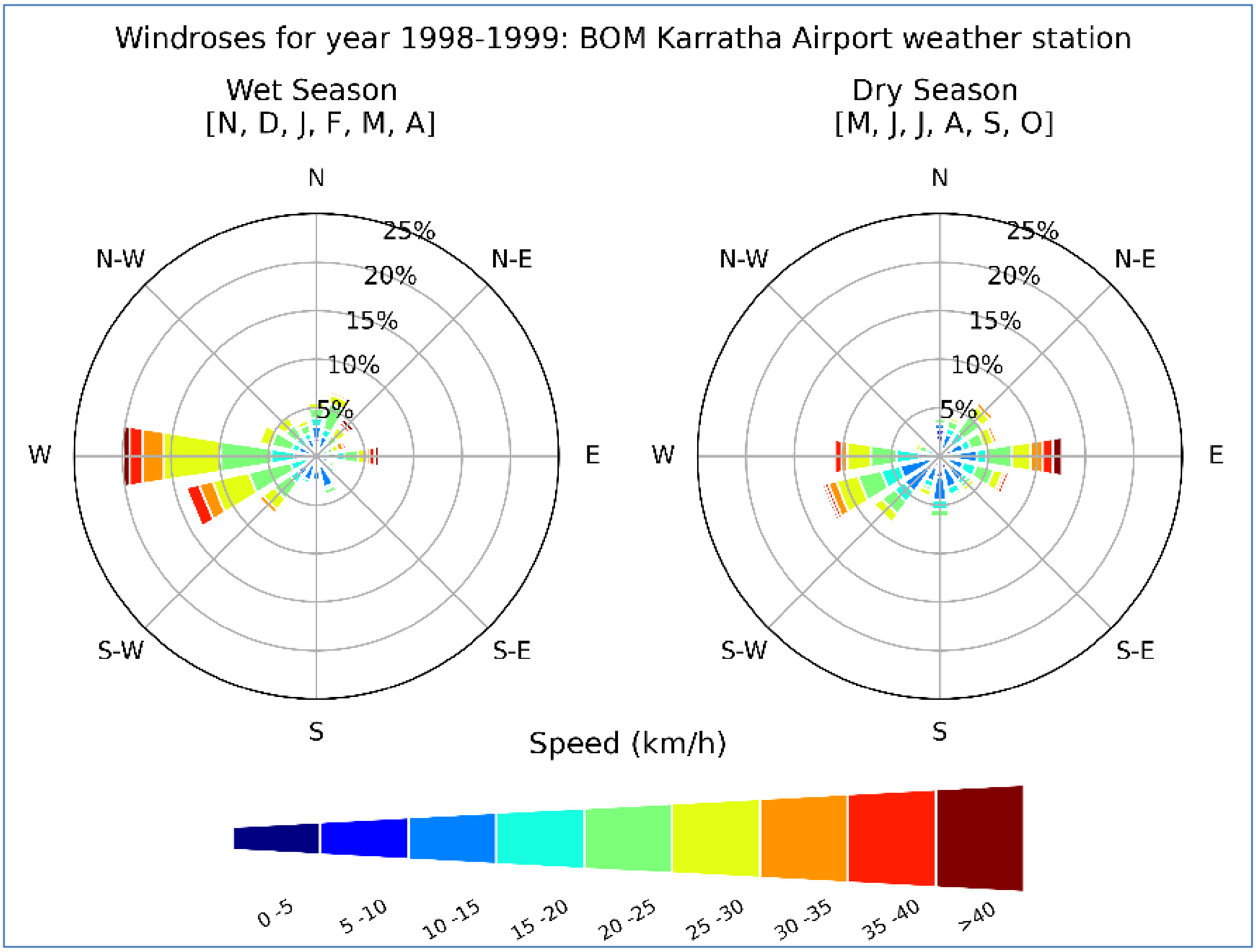


Figure 60. 1998-1999 wind rose as observed at Karratha airport.

For Tropical Cyclone Vance, the wind speed and direction during was highly variable, with strong offshore and shore-parallel winds prior to the passage of the peak (Figure 61), as measured at Karratha Airport. Winds shifted from Easterly through to Westerly, reaching a maximum speed when winds were from the North as the cyclone passed. Such events passing to the North of the site can generate strong onshore winds near and after the peak that may generate significant storm surges. The storm surge generated by TC Vance was estimated at up to 3.5 m as the storm moved towards the west along the Pilbara coast and down into the Exmouth Gulf.

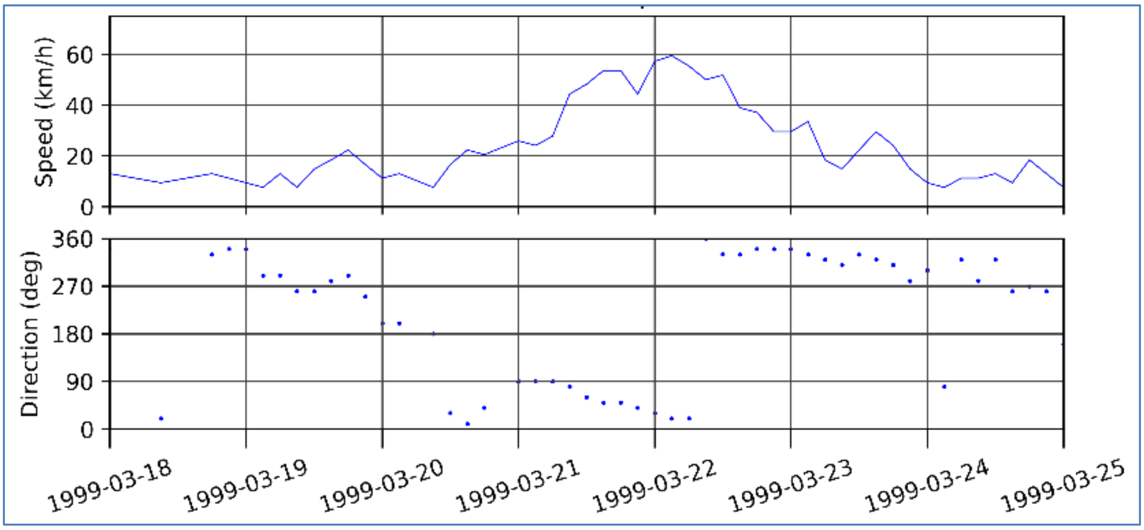
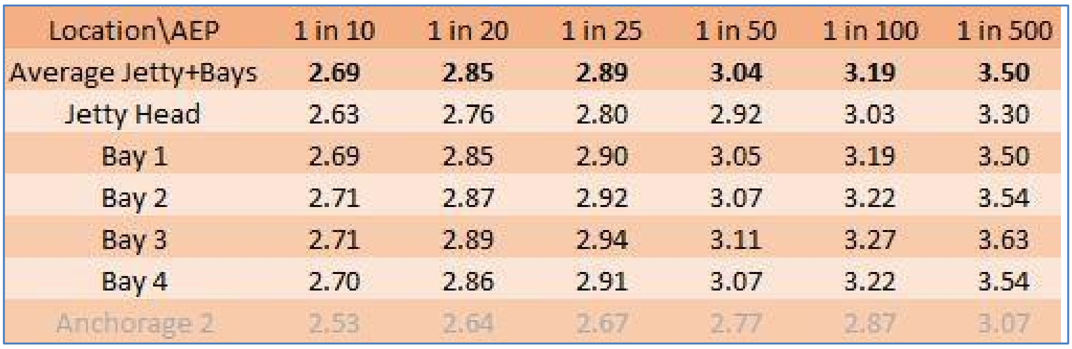


Figure 61. Wind speed and direction during TC Vance as observed at Karratha airport.

7.3.4. 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 9, Figure 62).

Table 9. 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

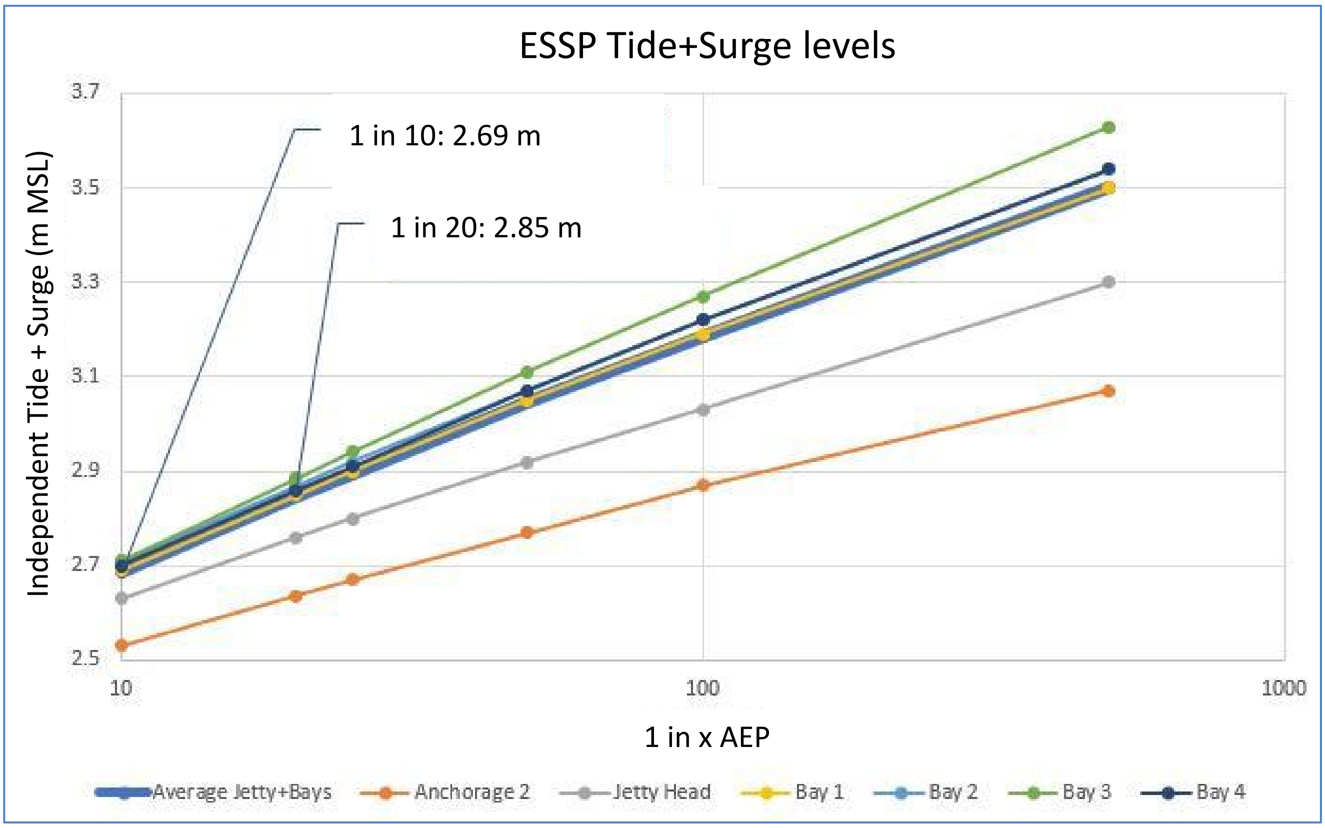


Figure 62. Tide and storm surge level interpolation (replotted from Table 9).

The Dampier tide gauge record has been analysed to describe a series of positive storm surges (Table 10). 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.

Table 10. 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[12]	Cat 5, N, 55 km SW of Dampier	Main 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[13]	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[14]	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[15]	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[16]	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[17]	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[18]	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.

Despite this record of potential episodic events, the associated record of coastal advance or retreat is not clearly related. For example, the western coast of Gnoorea spit (Area D of Figure 27) 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 to date that these generated major change in the eastern estuary nor indeed elsewhere along the ESSP shoreline. In part, this might be because TC Orson's surge peaked near the time of low tide, minimizing its effects. Cyclonic effects on coastline change are addressed in Section 11.

---

[12] http://www.bom.gov.au/cyclone/history/pdf/orson.pdf

[13] http://www.bom.gov.au/cyclone/history/olivia.shtml

[14] http://www.bom.gov.au/cyclone/history/pdf/damien2020.pdf

[15] http://www.bom.gov.au/cyclone/history/pdf/clare.pdf

[16] http://www.bom.gov.au/cyclone/history/pdf/ilona.pdf

[17] http://www.bom.gov.au/cyclone/history/glenda.shtml

[18] http://www.bom.gov.au/cyclone/history/bobby.shtml

7.3.5. 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.

8. Regional marine and coastal landforms

8.1. General features and their ages

Recent bathymetric data show seabed features (Lebrec *et al.*, 2021, 2022) indicative of a complex array of past sedimentary processes and products, including palaeoshorelines and marine and coastal sand bodies (Figure 4, see also Section 11.2). The modern seabed within the 20 and 30 m isobaths represents the approximate location of the shoreline at around ~8000 BP, before island formation (Wilson, 2013). With postglacial sea-level rise and throughout the mid-Holocene sea-level highstand, the regional coastal plain is likely to have changed from housing estuarine mangrove systems behind coastal barriers, towards the present mixed shorelines of rocky and sandy beaches, and subtidal and intertidal flats incised by tidal creeks. In places, there are associated carbonate reefs and marine and coastal sand bodies, especially on the southern and western sides of the islands.

There are very few numerical ages for coastal landforms in the Pilbara region, with relative ages largely determined from interpretations of geomorphic evolution in relation to sea-level changes (e.g., Eliot *et al.*, 2013; Semeniuk, 1996). Most unconsolidated coastal landforms (such as active dunes or beach ridges) in the Pilbara overlie or are perched on older sedimentary rocks, such as Pleistocene limestone, last interglacial coral platforms and Holocene beachrock ramps (Semeniuk, 1996; Unno & Semeniuk, 2019; see also Semeniuk & Searle, 1987). Numerical ages from unconsolidated dune, chenier, spit and other shoreline deposits are highly variable and range from modern to a few thousand years old, reflecting their ongoing reworking (Dodson *et al.*, 2014; Ward *et al.*, 2022a).

As noted by Dufois *et al.*, (2017), seabed sediments across the NW shelf tend to be relatively coarse and composed primarily of sands and gravels, with a slight increase of the mud fraction along the shelf break and some nearshore areas (Jones, 1973). The sediments are considered mobile over most of the shelf in response to the local hydrodynamic environment (James *et al.*, 2004; Jones, 1973; Porter-Smith *et al.*, 2004). The sediment dynamics on the shelf are also influenced at times by the terrigenous sediment supply (Gingele *et al.*, 2001) but little sandy material leaves the shoreline itself, being held there by marine processes.

8.2. Geomorphological setting

The Pilbara coast is one of the most geologically and geomorphologically diverse and complex arid coasts in the world (Semeniuk 1996). The region immediately east of Cape Preston, which would house the proposed ESSP development, is a microcosm of this complexity. The region harbours a major tidal estuary, which along its ~15 km long southern margin contains tidal creeks of various forms and sizes, and within which are extensive areas of subtidal and intertidal flats, fringing and estuarine mangroves. The coastline immediately seawards of the proposed solar salt ponds is about 18 km long, and contains a variety of coastal morphologies, inferred sediment transport regimes and sediment transport pathways. At the eastern margin of the ponds are located several tidal creeks, again of various forms and sizes. Further east are the wave-dominated deltas of some relatively small rivers - the Yanyare and Maitland – beyond which is the complex array of islands of the Dampier Archipelago. The area is described in more detail below.

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 ESSP is located along the coast east of Cape Preston and west of Yanyare Creek, within the western part of Regnard Bay (Figure 63). 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 8.6). The eroding and/or heavily weathered bedrock forms very flat land, with the McKay Creek catchment having a slope of only 0.7% (Figure 68, upper), and to the SE the slope averages only 2.5% (Figure 68, lower).

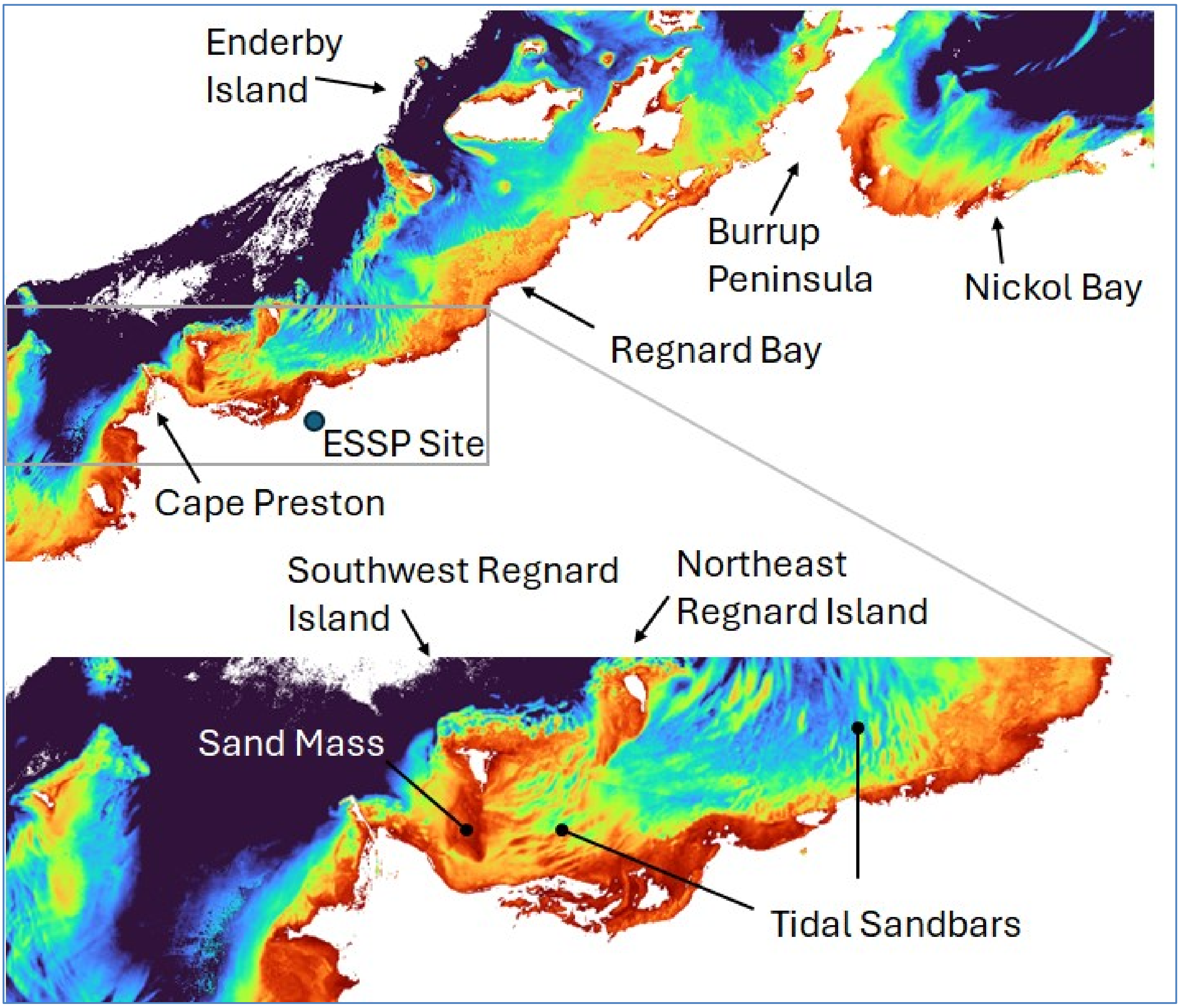


Figure 63. Western Regnard Bay Satellite Derived Bathymetry. Bathymetry derived by Dr Sam Blake (Neptune Remote Sensing).

8.3. Marine geomorphology

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.

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 body of sand extending southwards from Southwest Regnard Island. The sand body has appeared to have changed little since 2001 (no older imagery is available at present).

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 64, Figure 66), 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 64 and Figure 66 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.

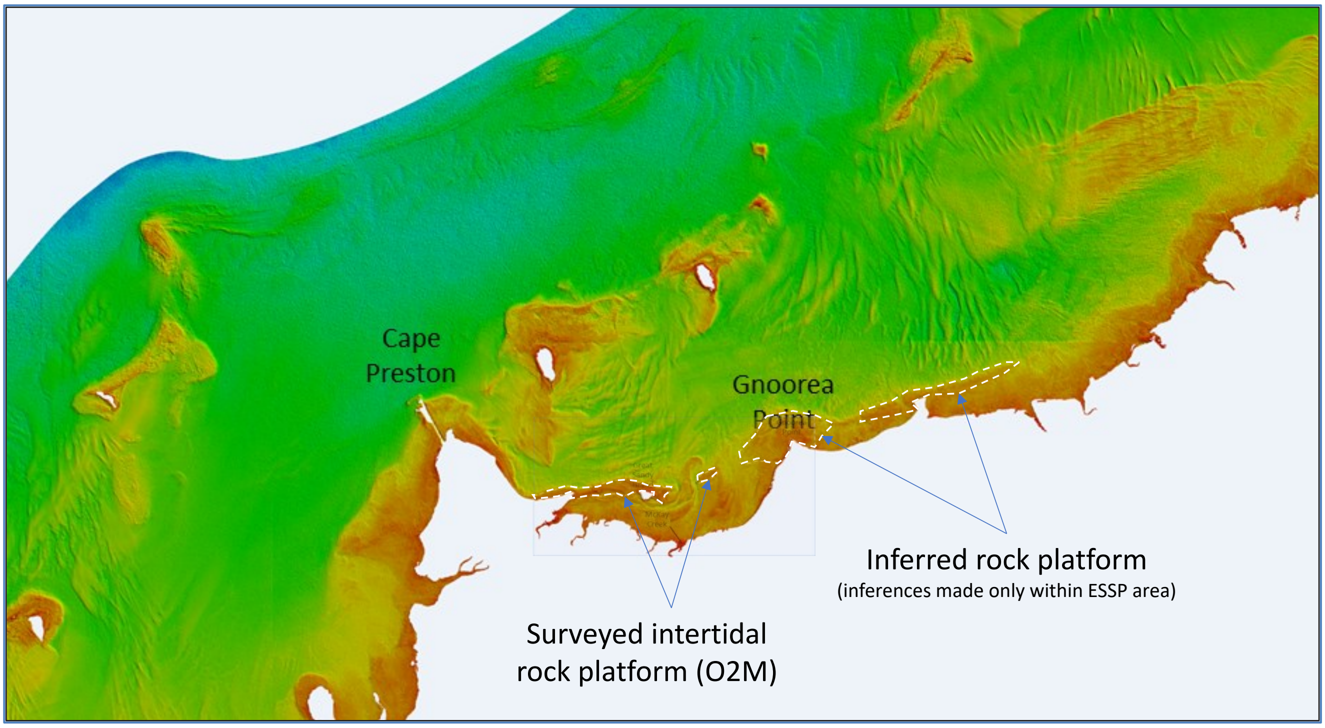


Figure 64. Regional bathymetry and seabed features (Lebrec et al., 2021). Islands occur in the west and centre of the figure, each with likely rocky and/or sedimentary aprons and associated relict and/or active sedimentary bedforms. Dashed lines indicate intertidal rock platform identified by survey (O2M 2023) from which can be inferred similar rock platforms off Gnoorea and further east.

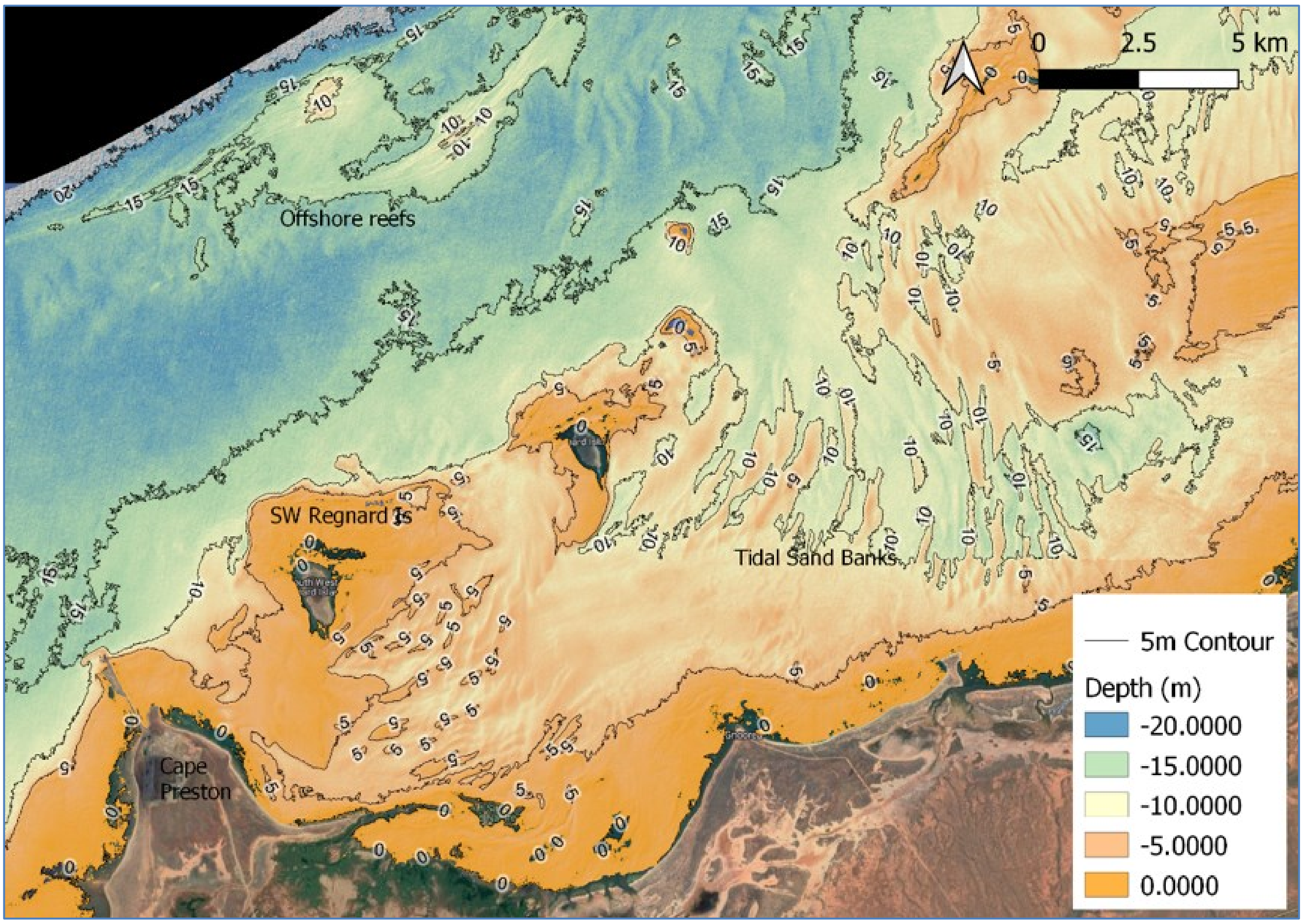


Figure 65. Bathymetry of Regnard Bay (O2M, 2022a, based on satellite bathymetry of LeBrec et al. 2021, relative to LAT). Image from Google Earth. Note that the label 'Tidal Sand Banks' appears to be based on surface features only – there are no data to indicate whether these features are active or relict, and/or are a result of tidal action.

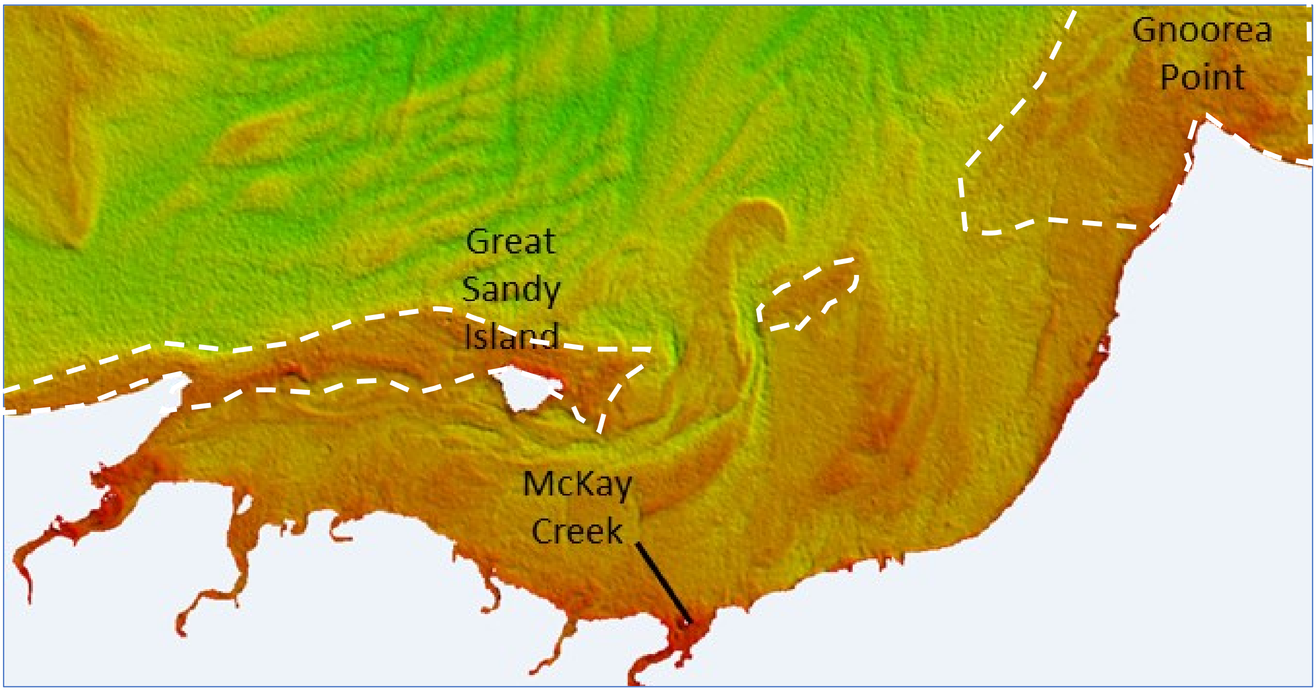


Figure 66. Local bathymetric and seabed features (Lebrec et al., 2021). Note the incised tidal channels within the greater estuary, and their termination east of Great Sandy Island between seabed outcrops of bedrock (see Figure 64).

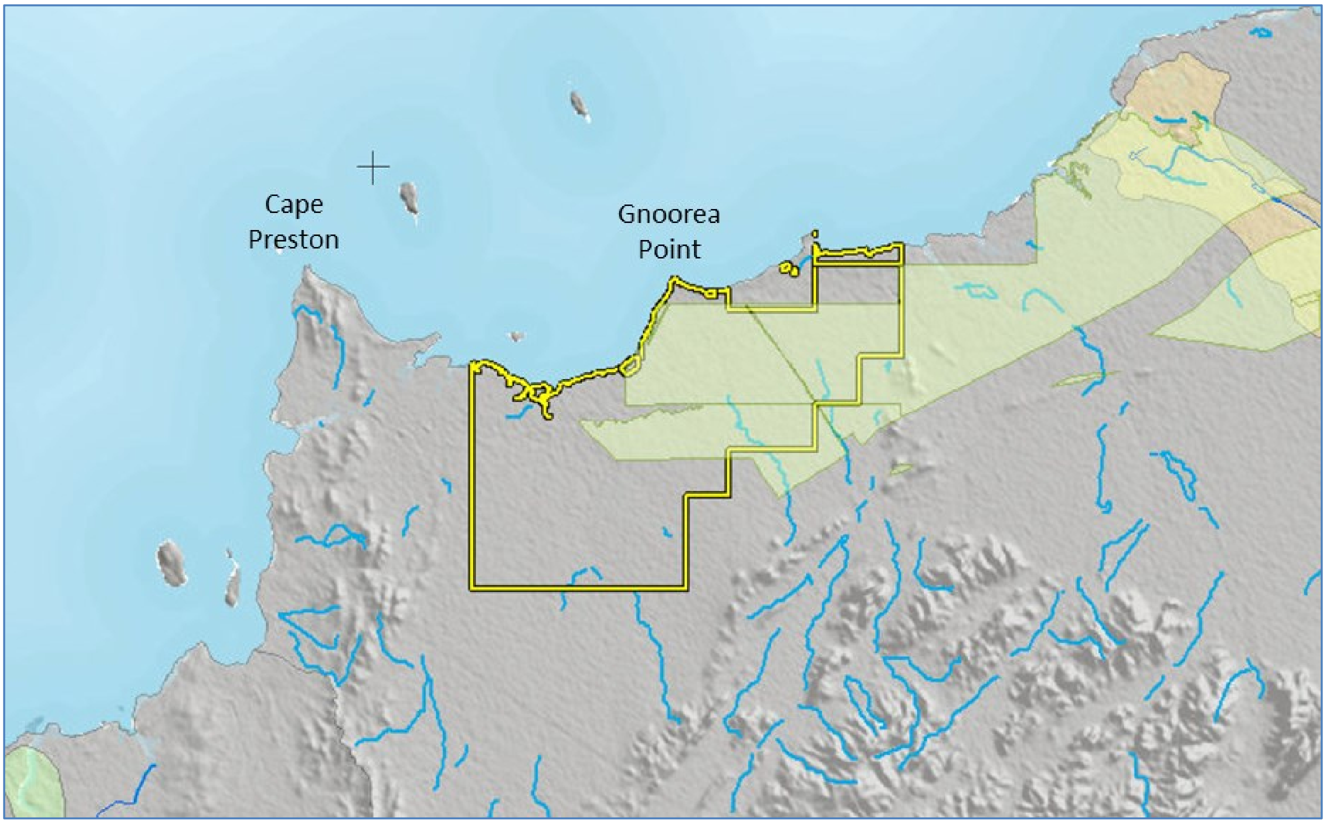


Figure 67. Regional topography (Phoenix Environmental Sciences, 2018). Note the rocky ridges of igneous rocks that lead to Cape Preston and the minor rise at Gnoorea.

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 69) 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 contains 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.

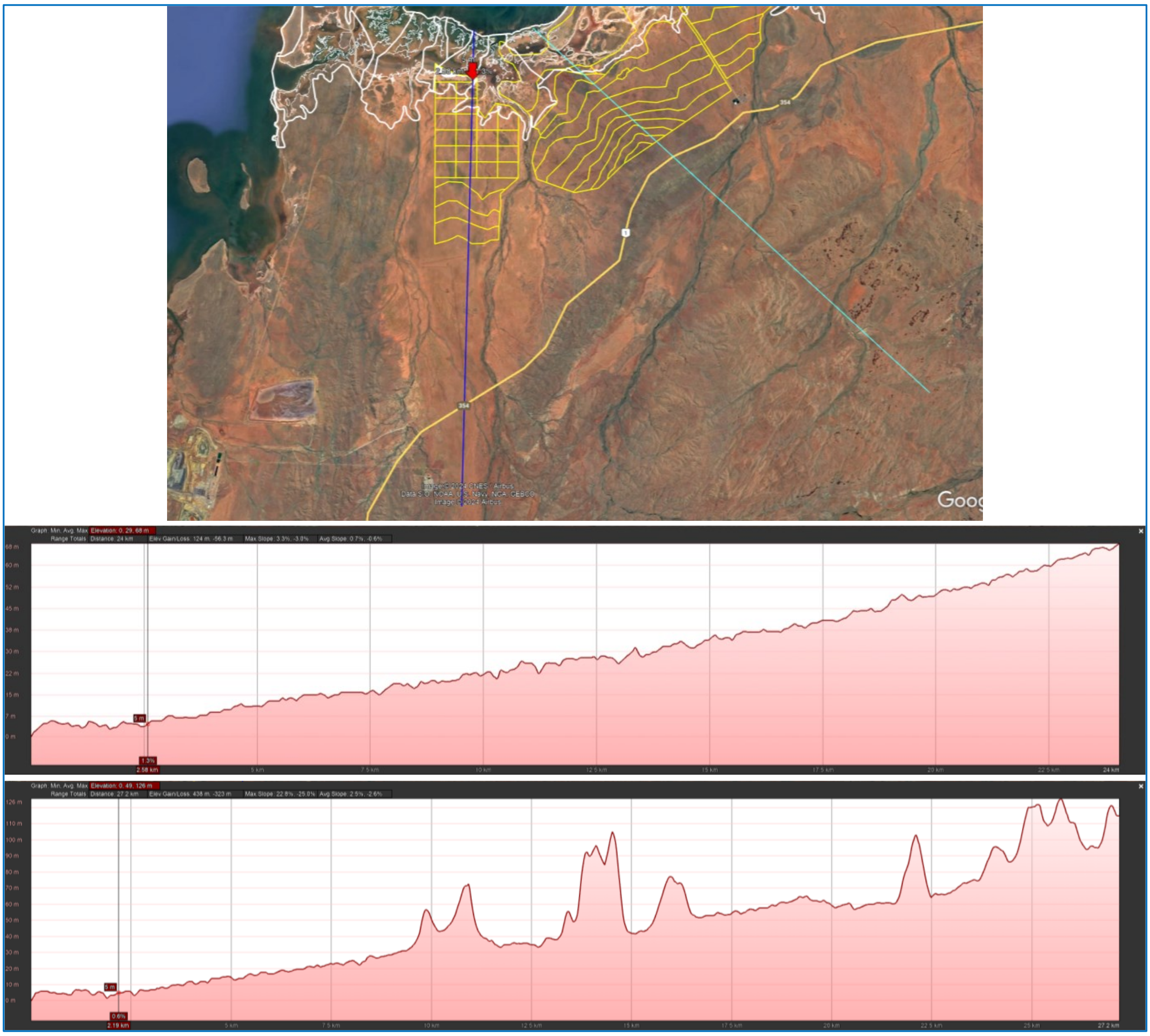


Figure 68. Vertical profiles across the coastal plain and hinterlands: Upper – 24 km long profile up the McKay Creek catchment (dark blue) from an elevation of 0 to 68 m. Lower – Profile 27 km long profile across a series of creeks (light blue) from an elevation of 0 to 126 m. Red arrow on map and vertical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

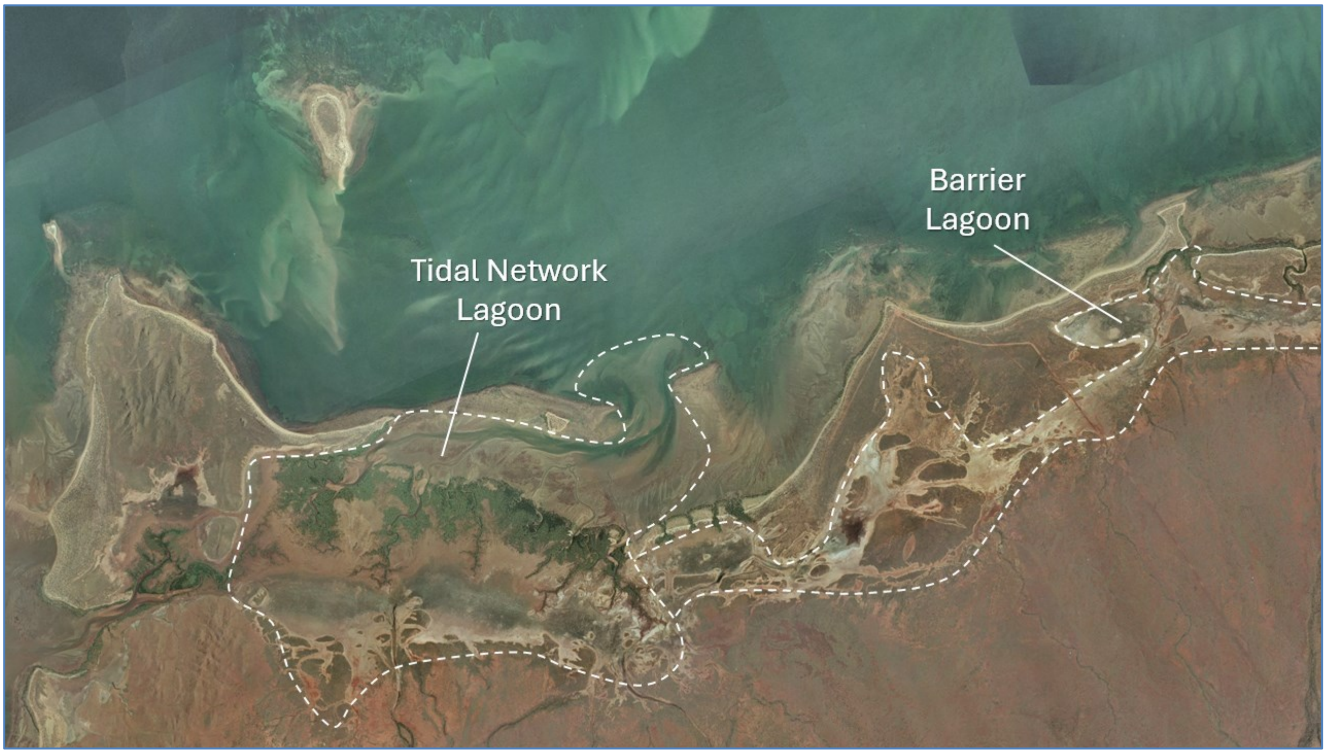


Figure 69. Aerial images for low tide (2001) showing the main coastal lagoon structures in the western and central ESSP area, i.e., the modern 'estuary' to the left and the joined tidal catchments of 40 Mile Road W, 40 Mile Road E and Creeks 7 & 8.

8.4. 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 11). 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). Ponds emplaced in the intertidal zone thus reduces the Vs:Vc ratio. The capacity of scenario 7.2.1. to cause impacts is likely to be significantly reduced from the earlier pond scenario 6.2.0 (Figure 70), especially because of the smaller area of ponds fronting catchments Creek 1 and Creek 2, and also Baldy West and Straight Creek (Figure 71).

Table 11. Range of topographic slopes (1:200 is shallow, 1:7 is steep) across the intertidal zone (-1 to 3 m) for the areas A, B, C & D of Figure 27. (The McKay Creek catchment is discussed separately in Section 22).

Elevation range (m AHD)	Approximate topographic slopes			
	Area in Figure 27			
	A & B	**C**	**D (south)**	**D (centre & north)**
2 - 3	1:20 - 1:250 Impinging on river delta deposits, restricted potential landward migration	1:6 - 1:7 Upper storm beach	1:6 - 1:7	1:6 - 1:7
1 - 2	1:800 - 1:2400 High tidal flats, incl. benthic mats	1:10 – 1:30 Lower beach	1:14 - 1:17 Active beach	1:10 - 1:20 Lower beach above sparse mangroves
0 - 1	1:200 Fringing mangroves, half sparse, half dense. (Estuarine all dense)	1:110 - 1:250 Sparse mangroves backed by bare sand flats	1:8 - 1:10 Active lower beach (toe)	1:70 - 1:140 Mangrove seaward limit at 0 m
-1 - 0	1:700 Unvegetated intertidal flats	1:250 - 1:600	1:330 - 1:650 Vegetated intertidal flats (seagrass)	1:500 - 1:700 (100 near tip)

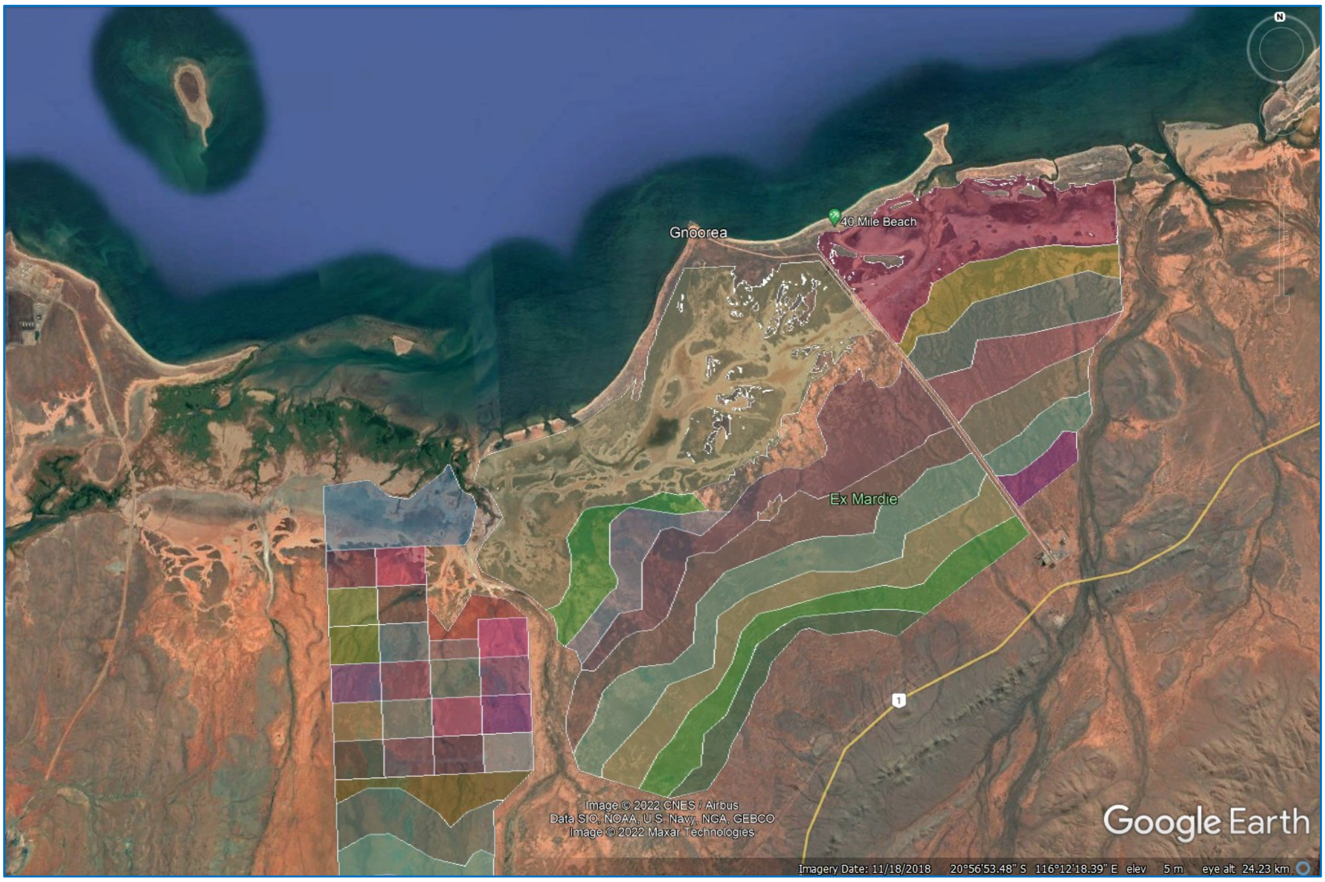


Figure 70. Ponds of superseded pond scenario 6.2.0. Specific colours of the pond segments are of no significance.

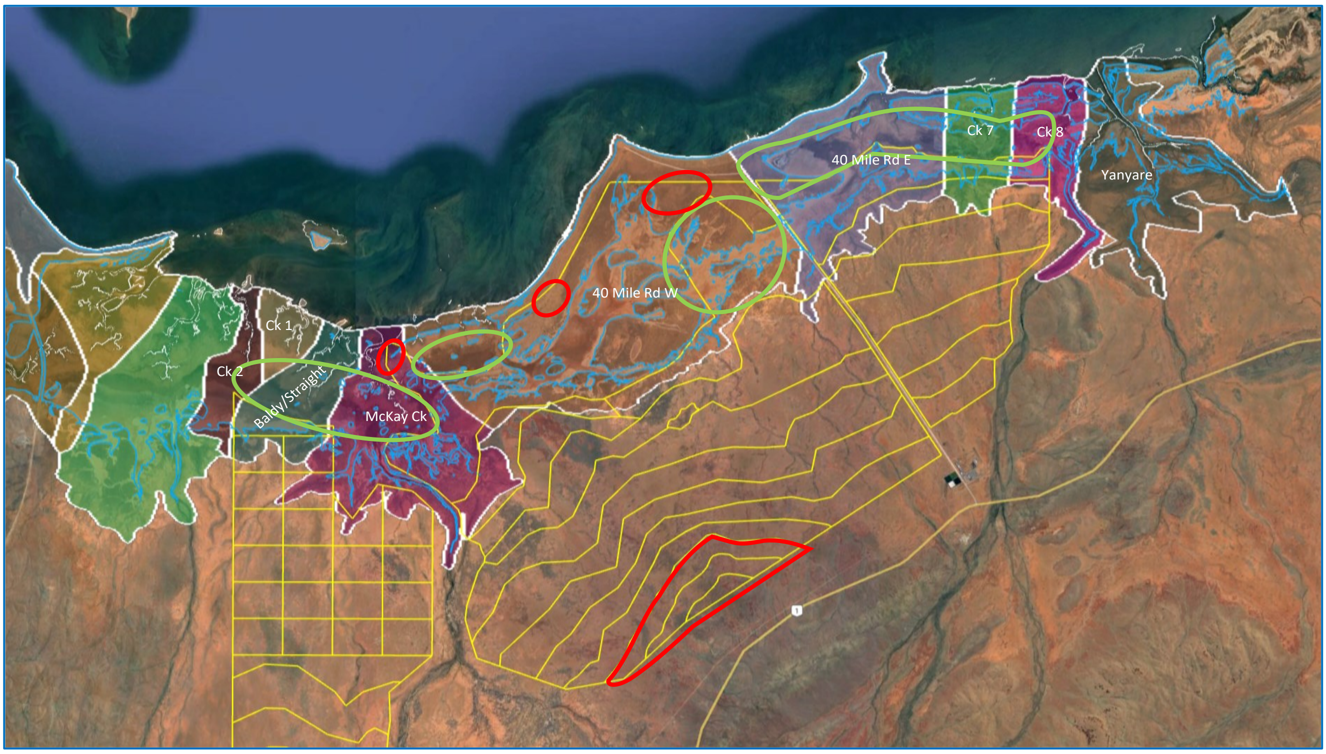


Figure 71. Pond scenario 7.2.1(yellow lines) overlain with main areas of change from superseded scenario 6.2.0. Pond areas added by 7.2.1 = Red outline. Pond areas removed from 6.2.0 = Green outline.

8.5. Basins in the coastal plain

Some of proposed pond areas are located in a very flat area of the coastal plain. Shallow basins in the coastal plain (Figure 72, see also Section 9.3.2) 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 72. Location of topographic basins in the coastal plain, with depths in m below their surroundings. Most basins deeper than 0.2 m are 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).

8.6. Implications for BCH

From the above, the ages of the sedimentary deposits that house BCHs along the coastline at the ESSP are unknown. Given the sea-level curve for the area for the last 8,000 thousand years (Figure 15) it is likely that the coastal stratigraphy is highly condensed, meaning that i) there may be a short sediment column covering a wide range of ages back to perhaps as much as 7,000 or 8,000 years, and/or ii) the existing active sedimentary systems may sit atop a hard granitic, calcrete and/or ferricrete basement so that the entire sediment column is very young, perhaps only a few centuries.

Further, it is notable that the ESSP coastal system is not overly muddy, and any general changes to the coastal system might be expressed most in environments where the sediments are mostly muddy and more mobile. Seawards of the shoreline, there are large areas of “intertidal mudflat” displayed on maps of the designated BCHs but the available evidence is that they have relatively little mud on or within them (in terms of the coastline as whole). The evidence to date, although sparse in the local area, is that these areas are largely very fine sand, perhaps with a surficial drape of silt and clay at times of neap tides and small waves. Seawards of the western and eastern ESSP areas, there is no evidence for an inner-shelf sediment wedge formed of mud, such as that occurs in some other areas of northern Australia where mud is more prone to accumulation. This indicates a limited availability of mud in the system, at least seawards of the shoreline. To landward, there is some evidence for a thickness of up to 2 m of muddy sediments (e.g., the lagoonal muds and soft intertidal muds described in Section 9).

As an example of relatively muddy systems, the embayments of north Queensland (Upstart Bay, Cleveland Bay etc.) are fed by catchments draining some wet tropical muddy soils that supply a high proportion of mud to the coastline during the episodic large flows (Belperio, 1983; Orpin & Woolfe, 1999; Lewis *et al.*, 2014). The mud delivered to the shelf, plus mud eroded from the mid-shelf seabed during cyclones, becomes trapped in north-facing embayments in the indented coastline, forming extensive muddy deposits several metres thick. By contrast, the catchments of the NW shelf, including the Pilbara, drain relatively hard rocks, the coastal plain soils are thin and not muddy, and thus even though muddy plumes can appear dramatic to the eye, relatively little muddy sediment is delivered to the coastline down the rivers. Further, indentations to trap sediment are few and far between, and even where these indentations occur, such as at the western base of the Burrup Peninsula, the mud is relatively thin or even absent. To conclude some of the changes resulting from pond emplacement at Eramurra may be less, in terms of changed surface sediments, than those that might occur in more muddy areas of sub-tropical northern Australia.

9. Main sedimentary units & key features

On land, geotechnical survey work 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 proposed ponds and along some pond walls using field samples, Multichannel Analysis of Surface Waves seismic profiling (MASW) and Cone Penetrometer Testing (CPT) data, followed by interpretation of the results. Note that their work 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 at 1 to 1.5 m below the surface.

The main relevant units for this work (Table 12) inform an understanding of past coastal evolution and processes. A map has been derived (Figure 73), 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 multiple low ‘islands’ occur, 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 Section 9.1.7 and O2 Metocean 2022a).
- 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 12. Sedimentary units in rough order from landward to seaward (modified from CMW Geosciences, 2022 and O2 Metocean (2022a)

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[19] 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.

---

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

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 88) but the areas are described by O2 Marine (2023a) as 'mudflat', so the areas is marked here as 'soft silty sands' on Figure 73.	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

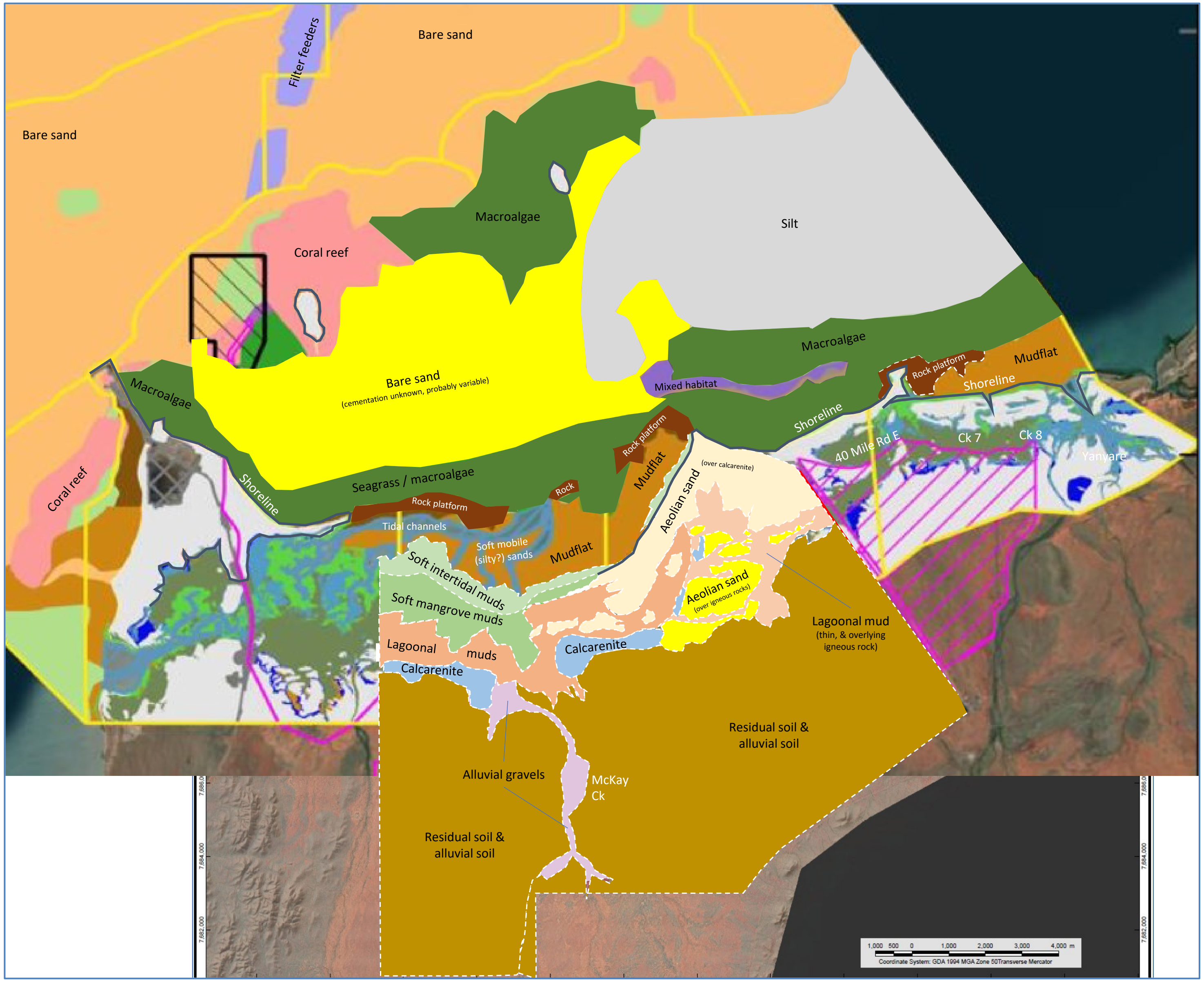


Figure 73. Interpretative map of surface sediments and main associated coastal units (after CMW Geosciences 2022 & Land and Water Consulting 2022) and incorporating the habitat map of O2 Marine (2022 & 2023). Seawards of the present shoreline, there is little sedimentary information, so that as well as variable spatial coverage, there is i) uncertainty in some designations and ii) inconsistency in naming of sediment types between terrestrial and marine surveys.

9.1. 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 worked examples (Section 22).

9.1.1. 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 74) 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 sulphates (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 75) so there is ample supply in the catchment of clays, silts and sands (see PSD curves of Figure 117).

Figure 74. Sheetwash gravels occurring as a thin veneer. Particle size varies from sand (0.2 mm) to cobble (< 200 mm). (CMW Geosciences, 2022)

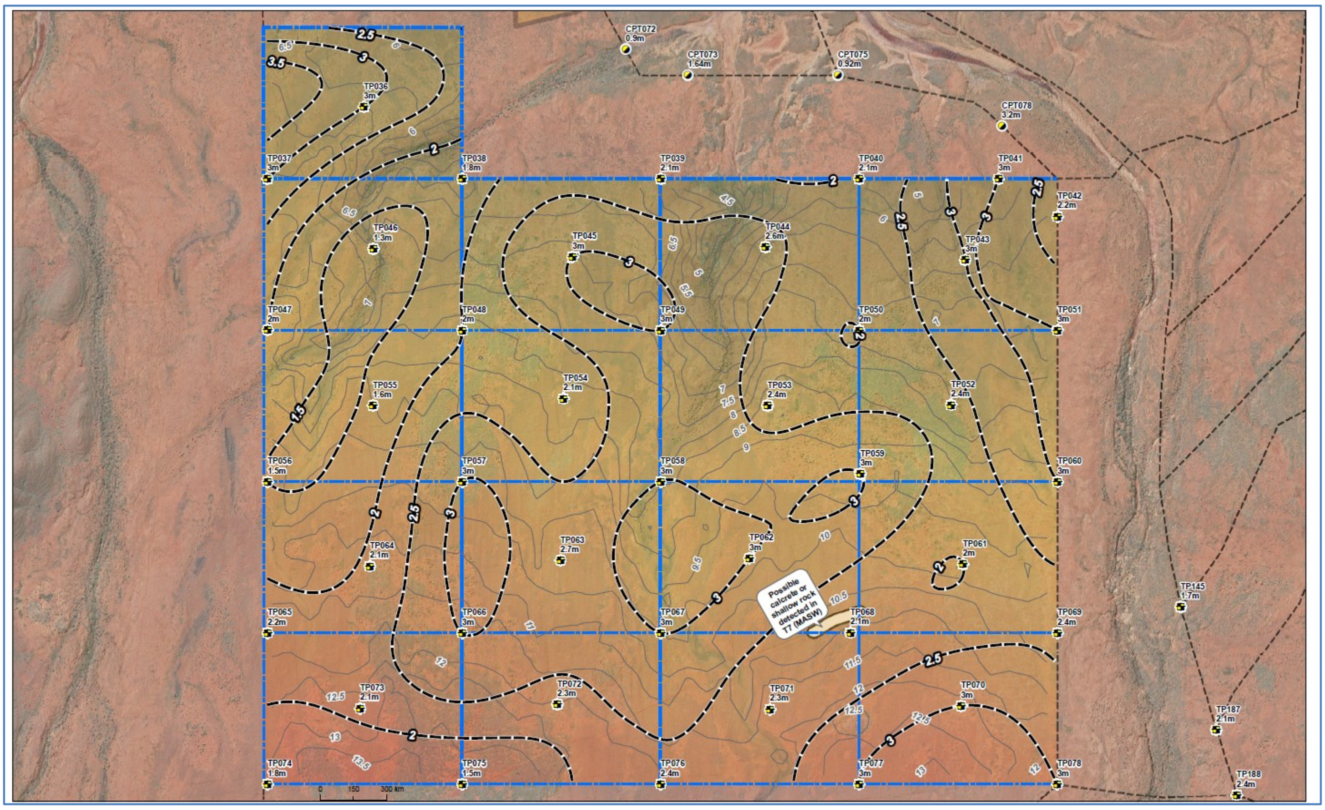


Figure 75. Thickness of residual soils above the bedrock in the higher ground between Eramurra and McKay creek (CMW Geosciences 2022). The bulk of the residual soil unit is 2 to 3 m thick. Note that these ponds occupy two drainage features that feed into the delta front area of McKay Creek.

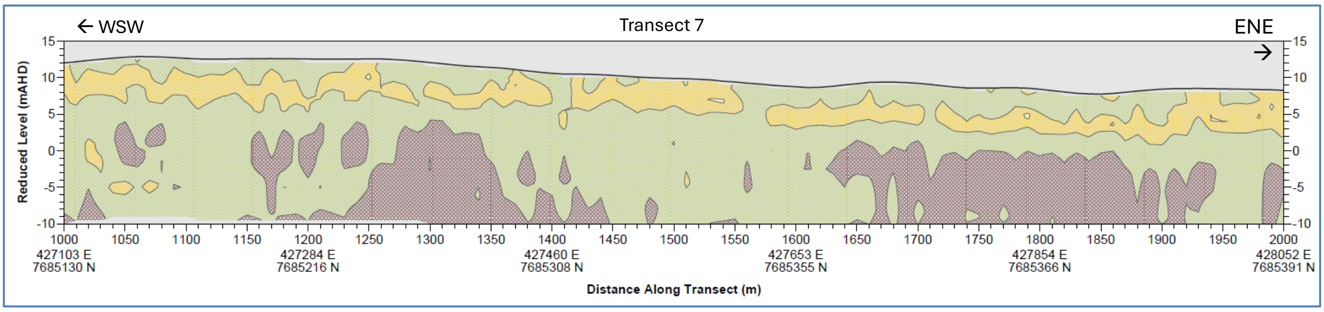


Figure 76. Interpreted material classification for Transect T7 of Figure 97, on the interfluve between Eramurra and McKay creeks. Key shown in Table 13.

Table 13. Key to shear wave velocity classification shown in Figure 76.

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

9.1.2. 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 77).

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 77. 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).

9.1.3. 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 78) 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 79).

Figure 78. Sheet calcarenite (left and top right) and weathered nodular calcarenite (bottom right) along the edge of the river delta front (CMW Geosciences 2022).

Figure 79. Sands washed out onto the tidal flats the river mouth (CMW Geosciences 2022).

9.1.4. Lagoonal muds

Landward of the mangroves, the extensive tidal flats house large areas of lagoonal muds (Figure 73, Figure 80, Figure 81). (These are marked ‘very soft clay’ in the sections across the nascent mangrove flats, Figure 101, and through lower McKay Creek and Baldy/Straight creek, Figure 103). 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 80. Lagoonal muds (high tidal flats) above the normal tidal limit with some dried benthic mats (CMW Geosciences 2022).

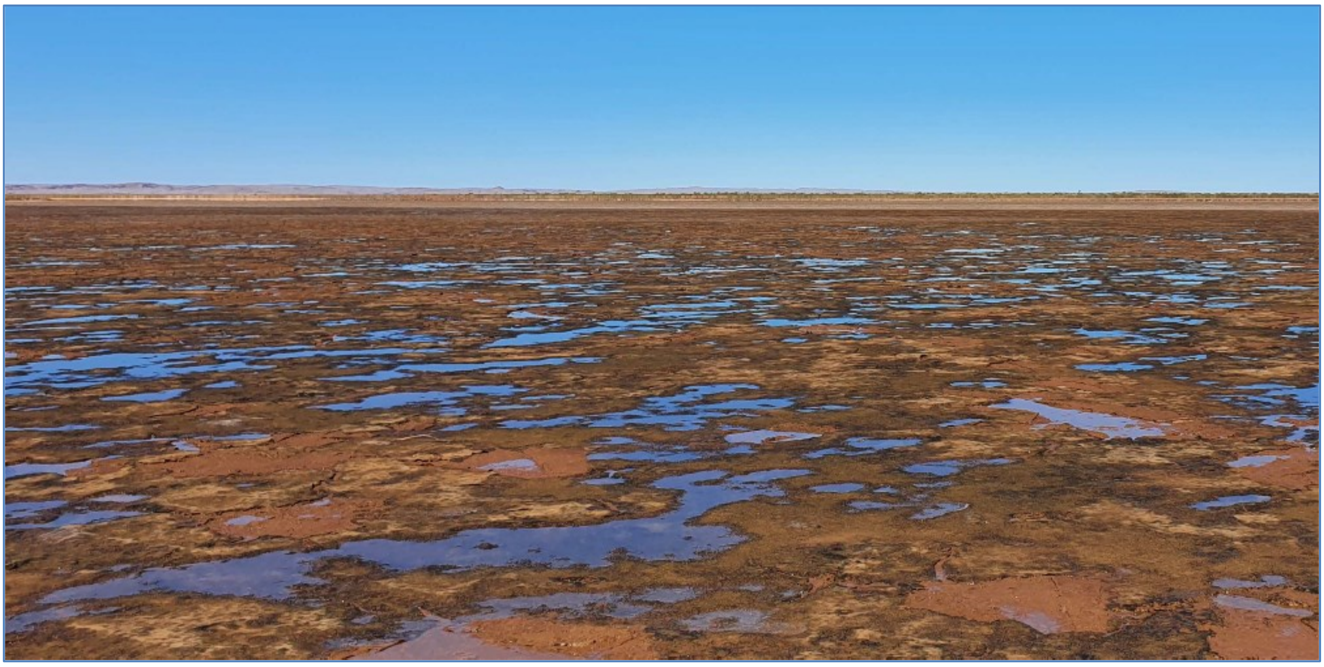


Figure 81. Lagoonal muds (high tidal flats) lower than Figure 80 and more frequently wet (CMW Geosciences 2022).

9.1.5. Soft intertidal muds

Further seawards are two units of soft muds, the 'soft mangrove muds' and 'soft intertidal muds' (Figure 73, Figure 82, Figure 83), 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 83 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 84) 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 82. The upper part of the incised tidal creek and the transition to adjacent tidal flats (CMW Geosciencse 2022).

Figure 83. Top - Mangroves with accumulating mangrove mud at a creek edge. Bottom - Exposed mangrove root systems in an area of recent erosion (CMW Geosciences 2022).

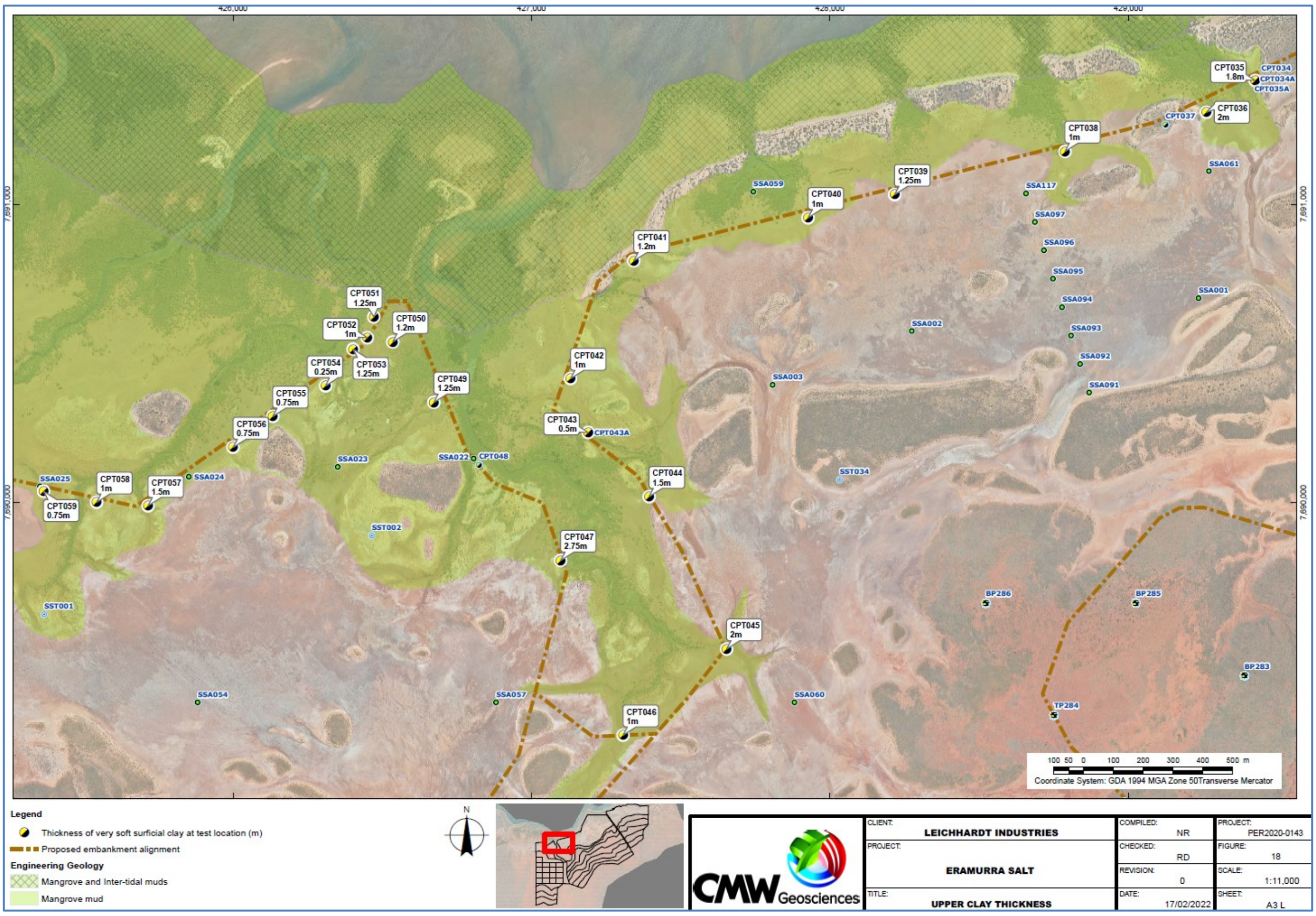


Figure 84. Thickness of very soft muds in lower McKay Creek and at the nascent mangroves (see also Figure 101 & Figure 103) (CMW Geoscience 2022).

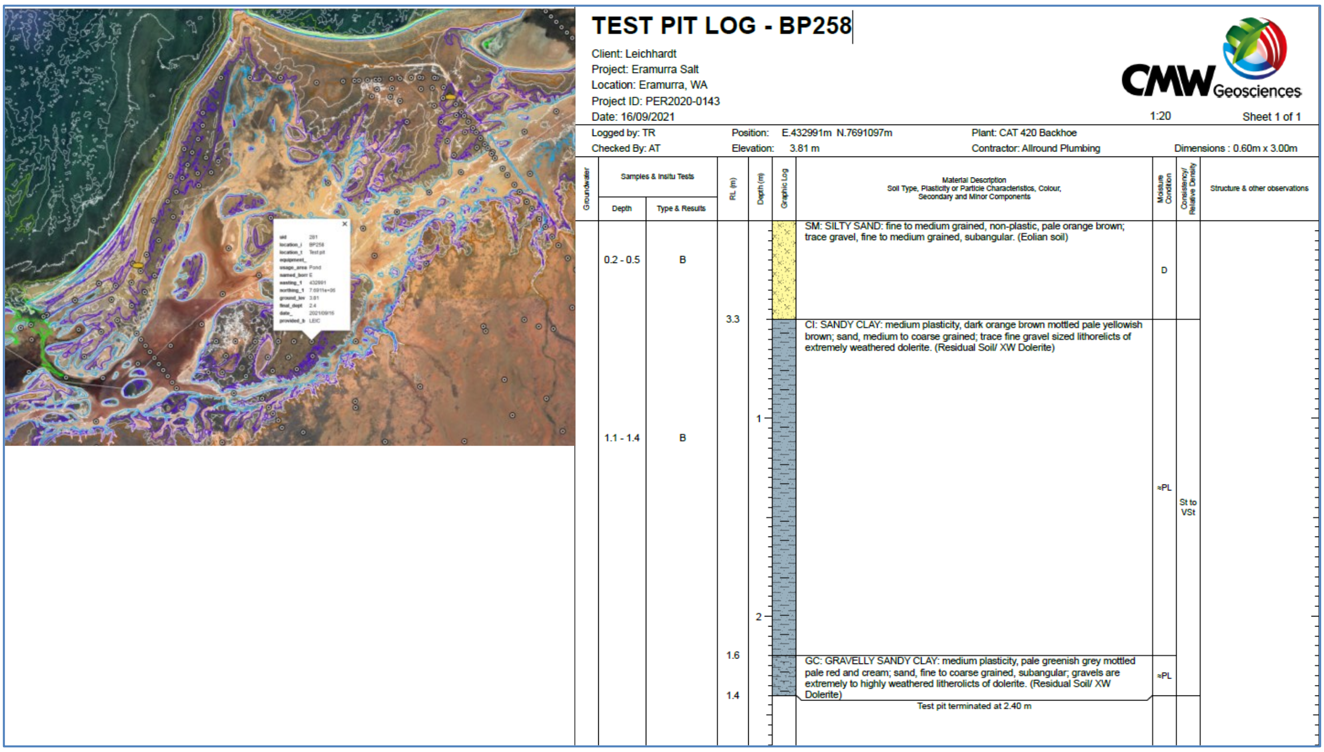
9.1.6. Dunes and deflated dunes

In the east of the area surveyed by CMW Geoscience (2022, i.e., bounded by the 40 Mile Road) are various sandy units[20]. 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 99) whereas in the northern road section and along the SW-orientated spit, they lack the interbedded clays (Figure 100, and Figure 101 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 73). Their thickness is generally a few decimetres (Figure 85, Figure 86, Figure 87) and they can be large, and sometimes termed sandplains (Table 12). 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.

---

[20] Coastal sands also occur at Cape Preston (section 9.2) 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
Checked By: AT
Position: E.432991m N.7691097m
Elevation: 3.81 m
Plant: CAT 420 Backhoe
Contractor: Allround Plumbing
Dimensions : 0.60m x 3.00m

Groundwater	Samples & Insitu Tests		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
	Depth	Type & Results							
	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 85. 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).

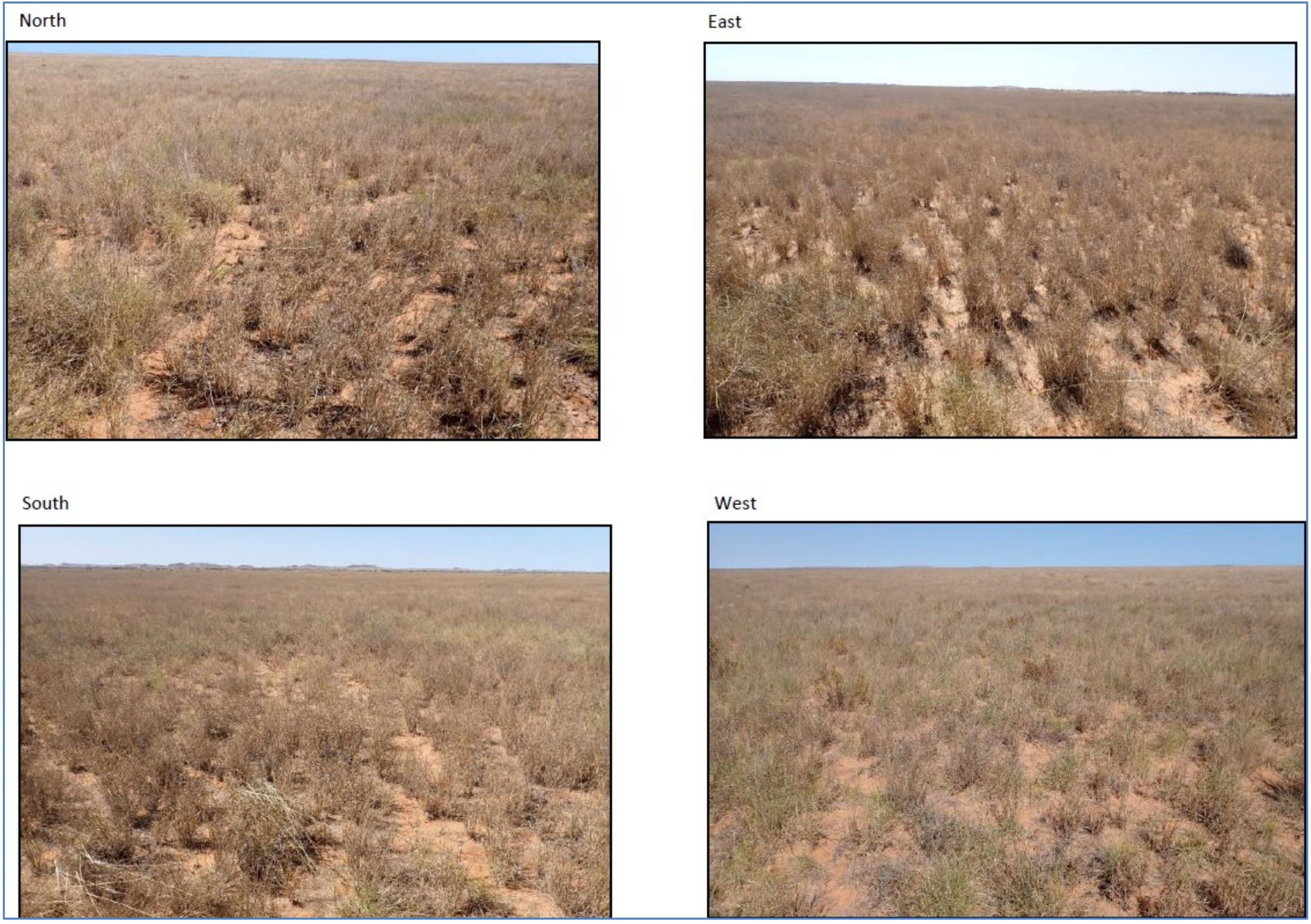
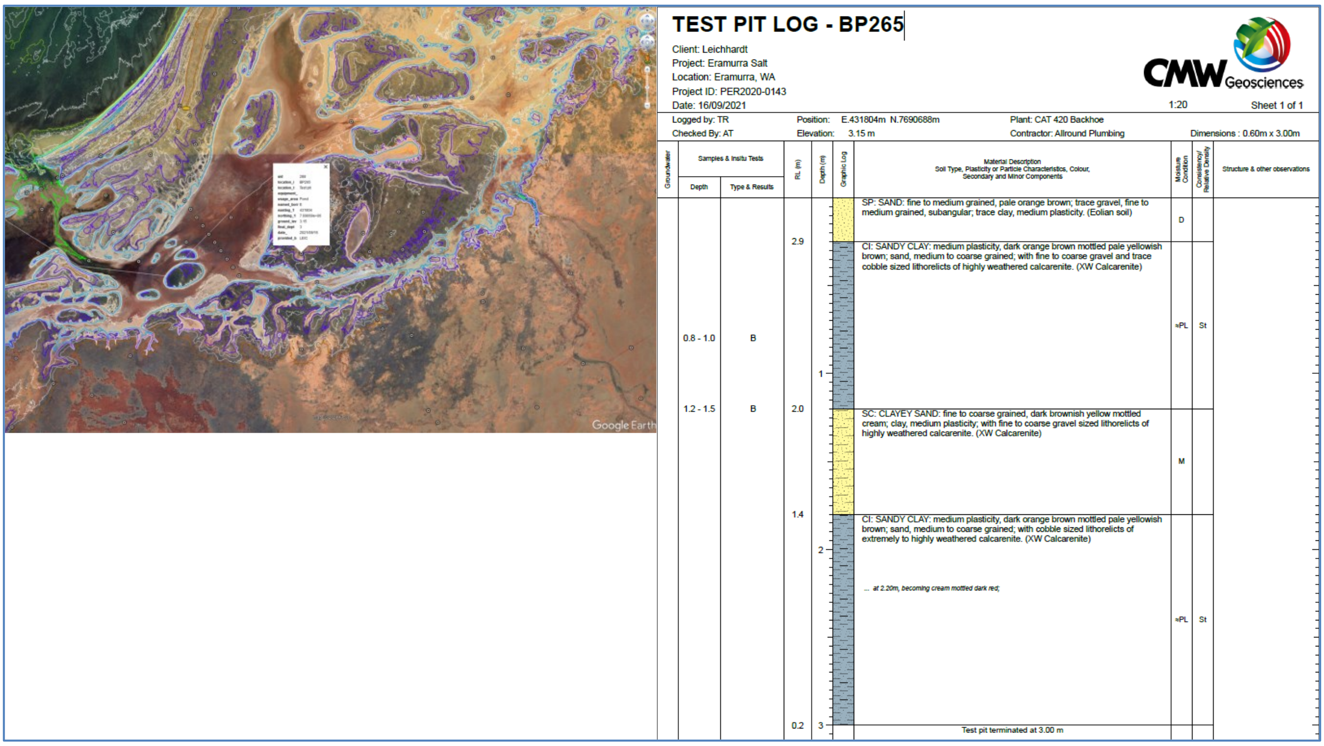


Figure 86. View in each direction from the test pit BP258 on a deflated dune (CMW Geosciences).



TEST PIT LOG - BP265

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

CMW Geosciences
1:20
Sheet 1 of 1

Logged by: TR
Checked By: AT
Position: E.431804m N.7690688m
Elevation: 3.15 m
Plant: CAT 420 Backhoe
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
						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	2.9	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 87. 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).

9.1.7. 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 (O2 Marine 2023a) as 'mudflat' but clean sands occur a few hundred metres 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 (Section 4.4.1 of O2 Metocean 2022a) was assessed by hand lens, and found to be a dark-brown loose slightly calcareous medium quartz sand (size range 250 to 500 um) with no silt or clay component (Figure 88). 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.

A further sample was opportunistically collected at 0837 am on 31/8/2020, from ~3.9 m below water level from the subtidal area a few hundred metres SSW of SW Regnard Island. The sample comprised a coarse sand of similar composition to that within McKay Creek, plus containing a few bivalve valves. Both sediment samples are clean, containing no silt- or clay-sized grains.

Figure 88. 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.

9.1.8. 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 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 little information on the thicknesses and volumes of mobile sediment on the inner shelf, with the exception of grab samples taken from the Cape Preston area where dredging is proposed (Figure 89) and analysed by laser particle sizer.

Together, the limited set of bed samples cannot be considered representative of all the sedimentary environments in the area, but their PSD results (Figure 90, Table 14) can be used to help identify the size of the grain size modes likely to be present in the region. Overall, nearly all these samples are well sorted medium to coarse sands. There is one sample that contains 15% silt (IG3 near Cape Preston) and 1 sample with more than 20% silt (IG4) but even this is a silty sand in sedimentary terms. Further, the six vibrocore sites (Prefix V in Figure 89) near Cape Preston resulting in little penetration and refusal of the core within the first horizon, i.e., between 0.25 m and 0.5 m below the seabed, indicating a thin surface layer of mobile sediments.

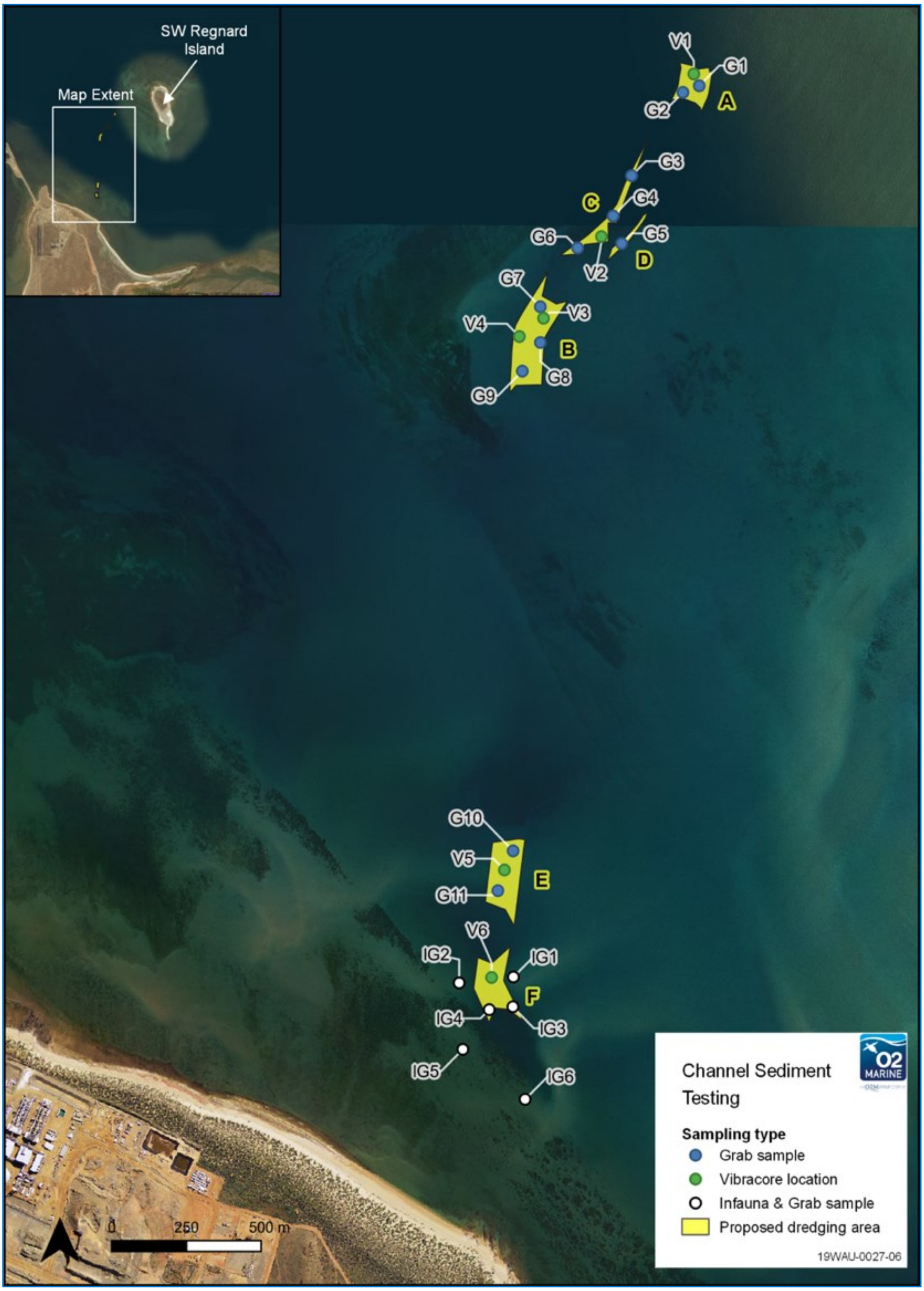


Figure 89. Sediment sampling locations at Cape Preston (O2 Metocean 2023b).

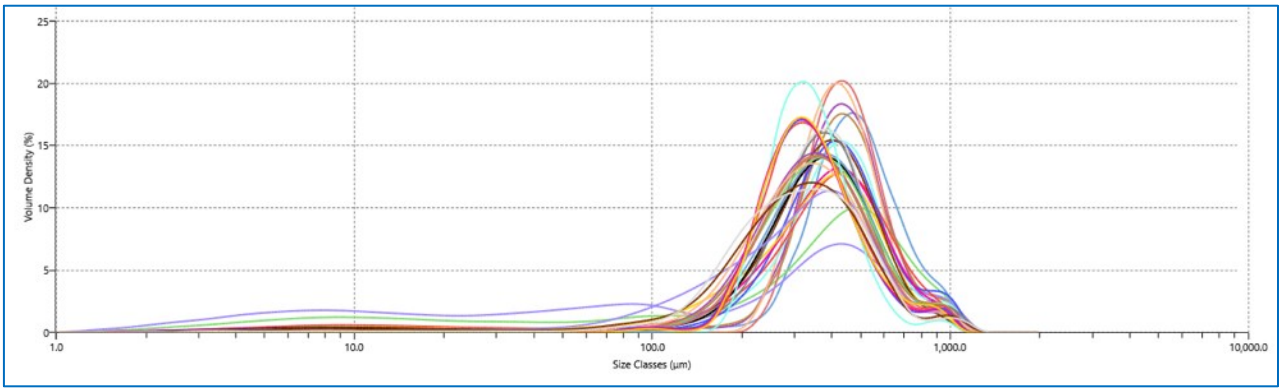
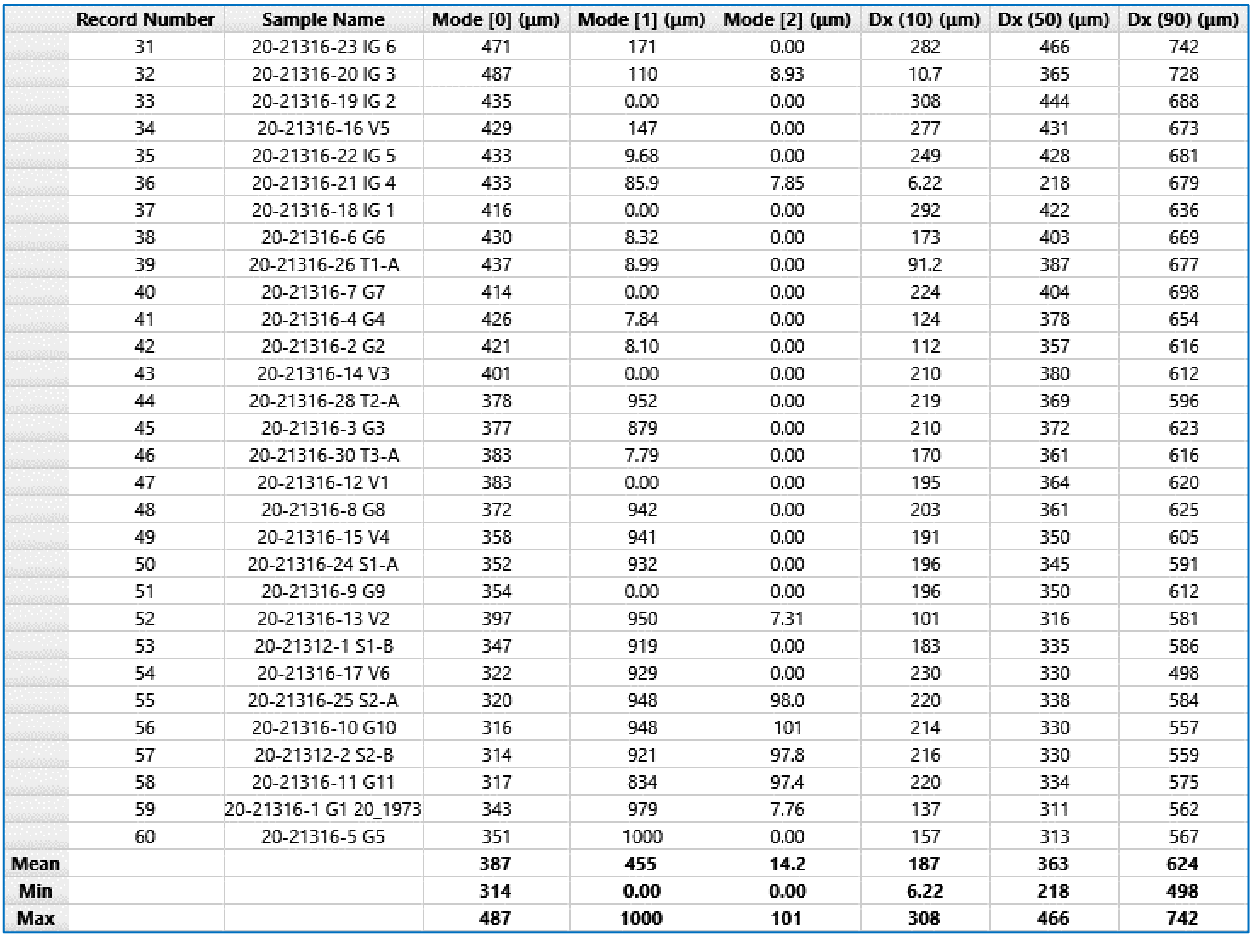


Figure 90. PSD data from laser sizer analyses of all samples taken by O2 Marine for the ESSP in the Cape Preston area. Nearly all samples are clean medium-coarse sands. Results have been processed to enhance the discrimination of grain size modes. These data are not representative of all the environments in the project area, but are useful in helping to identify the size of the likely grain size modes present.

Table 14. Tabulated modal grain sizes (primary mode named mode 0, secondary mode 1, third mode 2) from laser sizer analyses of all samples taken for the ESSP in the area (mostly the Cape Preston area). (In passing, note that the sizes D10, D50 and D90 shown here are not useful for sediment transport purposes.)



	Record Number	Sample Name	Mode [0] (μm)	Mode [1] (μm)	Mode [2] (μm)	Dx (10) (μm)	Dx (50) (μm)	Dx (90) (μm)
	31	20-21316-23 IG 6	471	171	0.00	282	466	742
	32	20-21316-20 IG 3	487	110	8.93	10.7	365	728
	33	20-21316-19 IG 2	435	0.00	0.00	308	444	688
	34	20-21316-16 V5	429	147	0.00	277	431	673
	35	20-21316-22 IG 5	433	9.68	0.00	249	428	681
	36	20-21316-21 IG 4	433	85.9	7.85	6.22	218	679
	37	20-21316-18 IG 1	416	0.00	0.00	292	422	636
	38	20-21316-6 G6	430	8.32	0.00	173	403	669
	39	20-21316-26 T1-A	437	8.99	0.00	91.2	387	677
	40	20-21316-7 G7	414	0.00	0.00	224	404	698
	41	20-21316-4 G4	426	7.84	0.00	124	378	654
	42	20-21316-2 G2	421	8.10	0.00	112	357	616
	43	20-21316-14 V3	401	0.00	0.00	210	380	612
	44	20-21316-28 T2-A	378	952	0.00	219	369	596
	45	20-21316-3 G3	377	879	0.00	210	372	623
	46	20-21316-30 T3-A	383	7.79	0.00	170	361	616
	47	20-21316-12 V1	383	0.00	0.00	195	364	620
	48	20-21316-8 G8	372	942	0.00	203	361	625
	49	20-21316-15 V4	358	941	0.00	191	350	605
	50	20-21316-24 S1-A	352	932	0.00	196	345	591
	51	20-21316-9 G9	354	0.00	0.00	196	350	612
	52	20-21316-13 V2	397	950	7.31	101	316	581
	53	20-21312-1 S1-B	347	919	0.00	183	335	586
	54	20-21316-17 V6	322	929	0.00	230	330	498
	55	20-21316-25 S2-A	320	948	98.0	220	338	584
	56	20-21316-10 G10	316	948	101	214	330	557
	57	20-21312-2 S2-B	314	921	97.8	216	330	559
	58	20-21316-11 G11	317	834	97.4	220	334	575
	59	20-21316-1 G1 20_1973	343	979	7.76	137	311	562
	60	20-21316-5 G5	351	1000	0.00	157	313	567
Mean			**387**	**455**	**14.2**	**187**	**363**	**624**
Min			**314**	**0.00**	**0.00**	**6.22**	**218**	**498**
Max			**487**	**1000**	**101**	**308**	**466**	**742**

So, there is no evidence (yet) of silt in the subtidal and intertidal area inshore of Gt Sandy Island, and no evidence of silts or clays (seawards of the coast at least).

From these results, the sizes 60 μm, 380 μm and 460 μm have been chosen to help represent the likely grain size modes present in the region, and which might be accumulated at the bed where conditions are i) able to transport grains there and then are ii) favourable to accumulation[21]. Note that these are similar to modes present in sampled terrestrial sediments, of ~50 to 110 and ~320 to 370 µm (Section 10.4.1).

9.2. Stratigraphy

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 91), which is exposed in places in creek beds and encountered in boreholes.

9.2.1. Cape Preston

The regional bedrock geology and boreholes from Cape Preston (Figure 91, Figure 92, Figure 94, Figure 95, Table 15) 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 is 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 96) and previous reports (e.g. O2 Metocean 2022a).

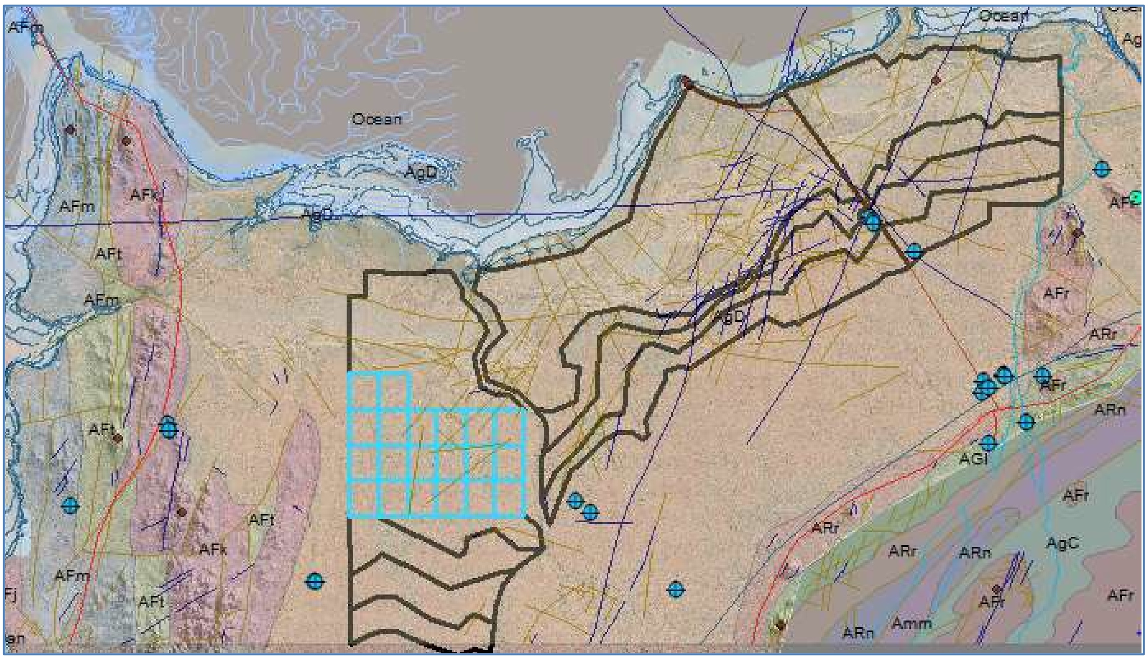
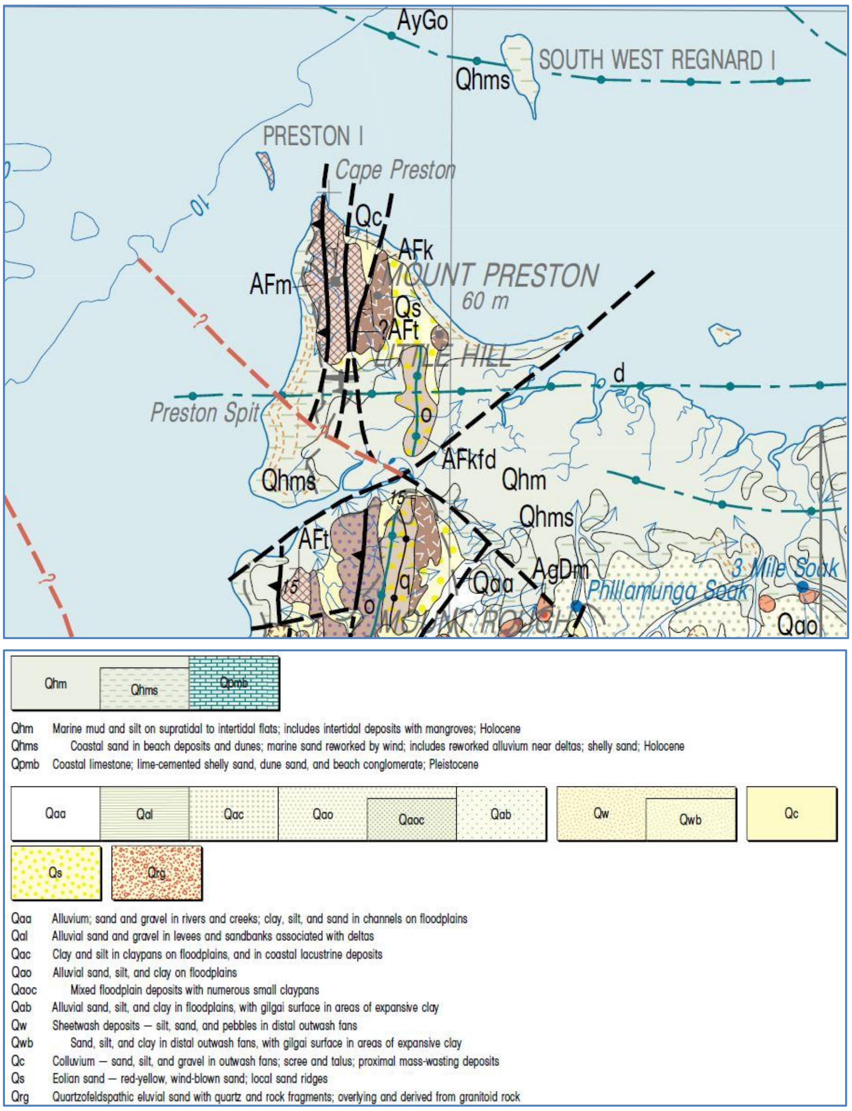


Figure 91. Bedrock geology (Geological Survey of Western Australia).

---

[21] These sizes have been converted into critical bed shear stresses that might move such grains (Chris Sherwood, USGS, pers. comm.) as part of a possible future potential assessment of sediment transport using results of numerical modelling, respectively 0.123, 0.037 and 0.034 Pa.



Qhm	Marine mud and silt on supratidal to intertidal flats; includes intertidal deposits with mangroves; Holocene
Qhms	Coastal sand in beach deposits and dunes; marine sand reworked by wind; includes reworked alluvium near deltas; shelly sand; Holocene
Qpmb	Coastal limestone; lime-cemented shelly sand, dune sand, and beach conglomerate; Pleistocene

Qaa	Alluvium; sand and gravel in rivers and creeks; clay, silt, and sand in channels on floodplains
Qal	Alluvial sand and gravel in levees and sandbanks associated with deltas
Qac	Clay and silt in claypans on floodplains, and in coastal lacustrine deposits
Qao	Alluvial sand, silt, and clay on floodplains
Qaoc	Mixed floodplain deposits with numerous small claypans
Qab	Alluvial sand, silt, and clay in floodplains, with gilgai surface in areas of expansive clay
Qw	Sheetwash deposits — silt, sand, and pebbles in distal outwash fans
Qwb	Sand, silt, and clay in distal outwash fans, with gilgai surface in areas of expansive clay
Qc	Colluvium — sand, silt, and gravel in outwash fans; scree and talus; proximal mass-wasting deposits
Qs	Eolian sand — red-yellow, wind-blown sand; local sand ridges
Qrg	Quartzofeldspathic eluvial sand with quartz and rock fragments; overlying and derived from granitoid rock

Figure 92. 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).

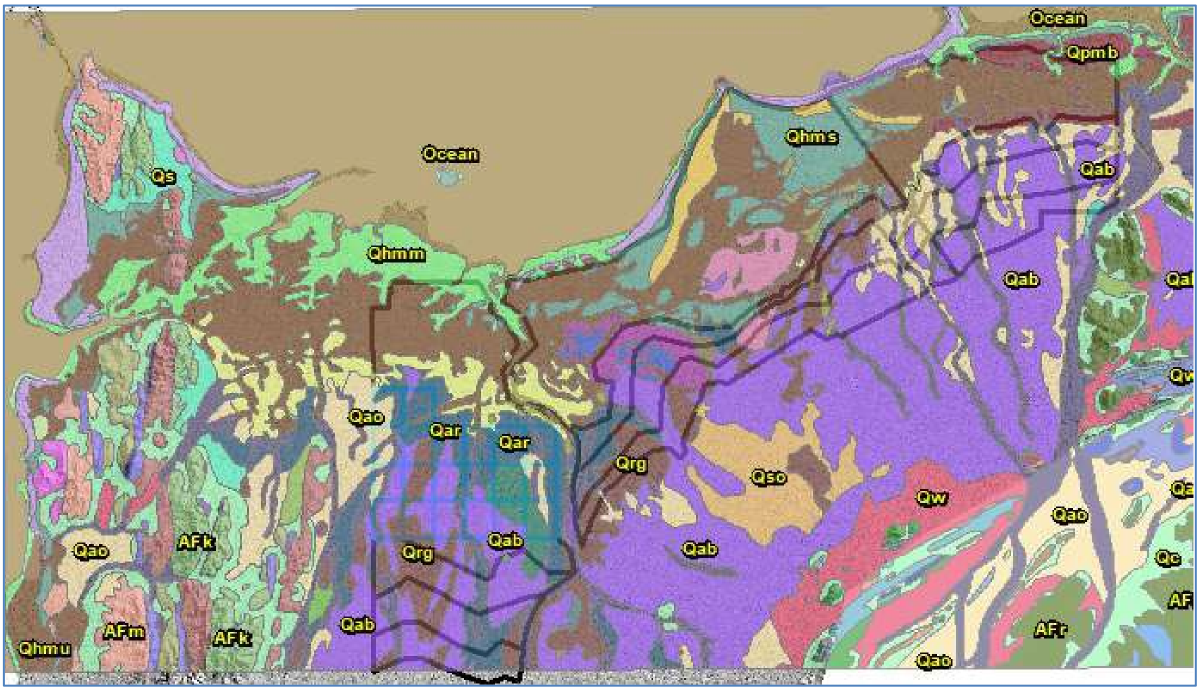


Figure 93. Surface geology (Geological Survey of Western Australia). (Legend to the letters on Figure 92).

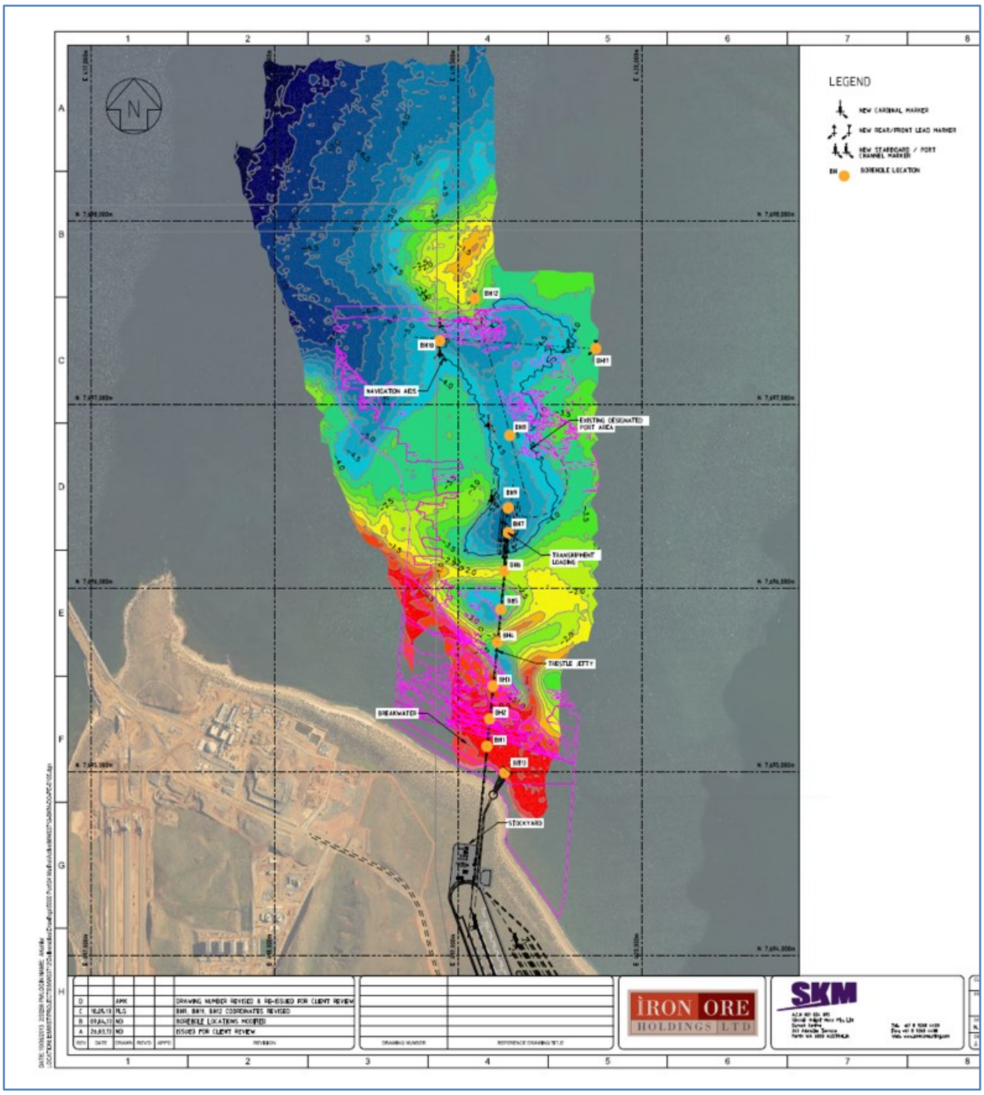


Figure 94. Location of boreholes at Cape Preston (SKM, 2013b).

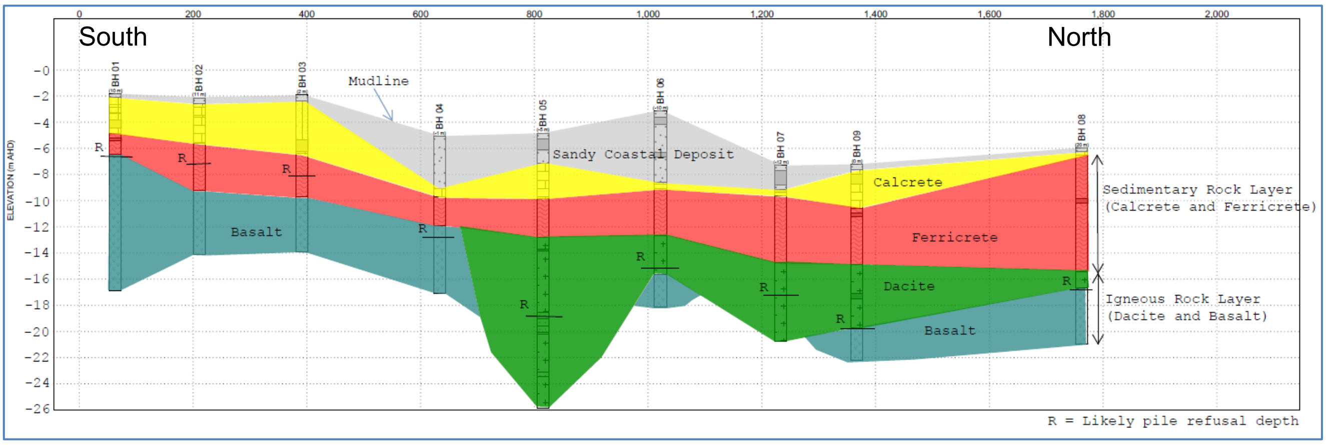


Figure 95. Geological cross-section at Cape Preston (S – N). (SKM, 2013b). The coastal sand unit was present in all boreholes, varied from 0.5 to 6 m in thickness, and is formed poorly sorted, sub-rounded dark brown and grey fine to coarse sands, with some silt and sub-angular gravel, shells, corals and rootlets.

Table 15. 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 96. 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.

9.2.2. The main ESSP area

Key units have been described above in Section 8.6., 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 97) are described briefly below and summarised in (Figure 98).

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 98), 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.

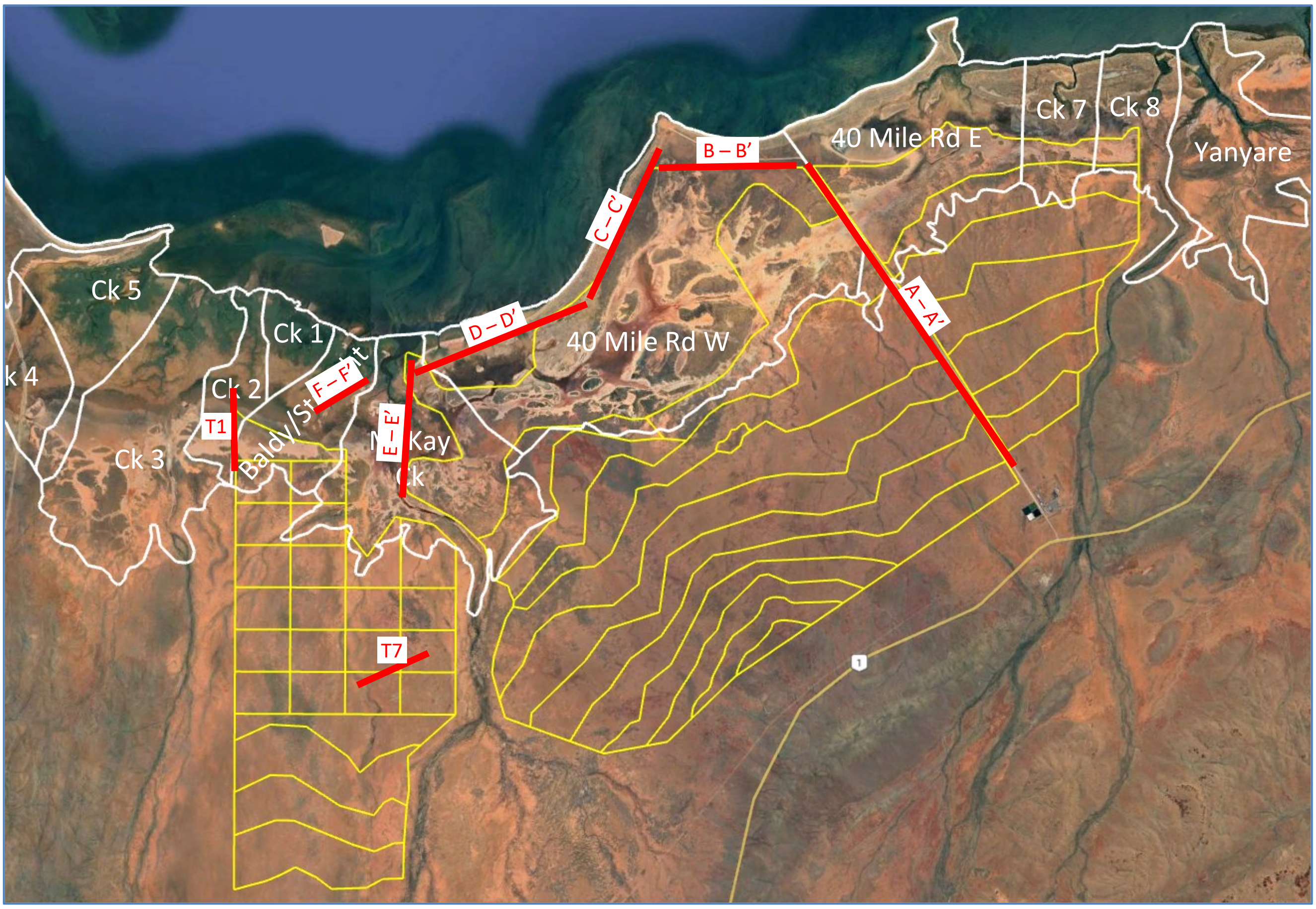


Figure 97. Location of interpreted stratigraphic sections in the area (after CMW Geosciences 2022).

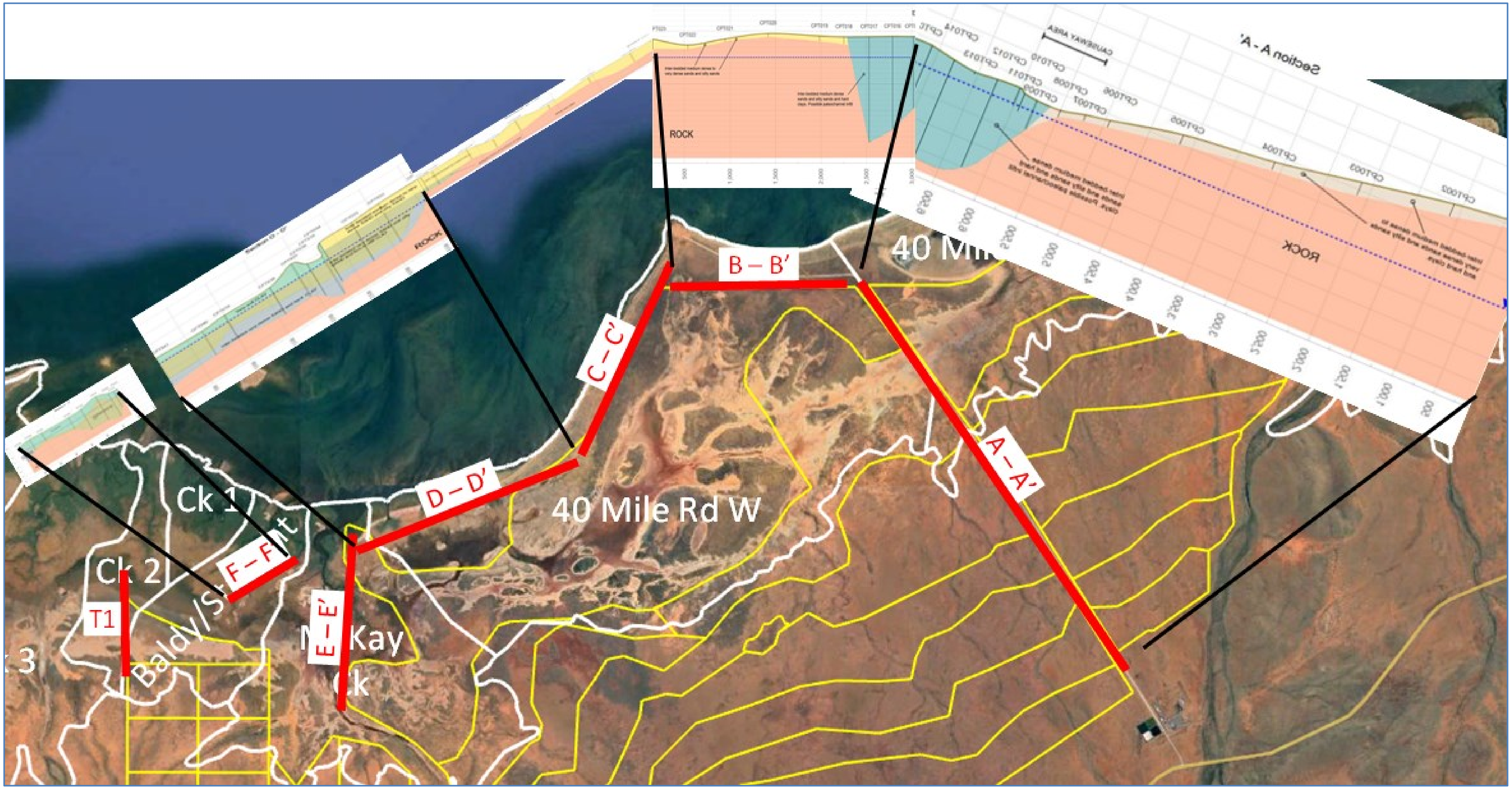


Figure 98. Ribbon diagram illustrating the overall stratigraphy of the area as defined by sections A, B, C, D & F. (Individual sections in Figure 99 to Figure 103 inclusive).

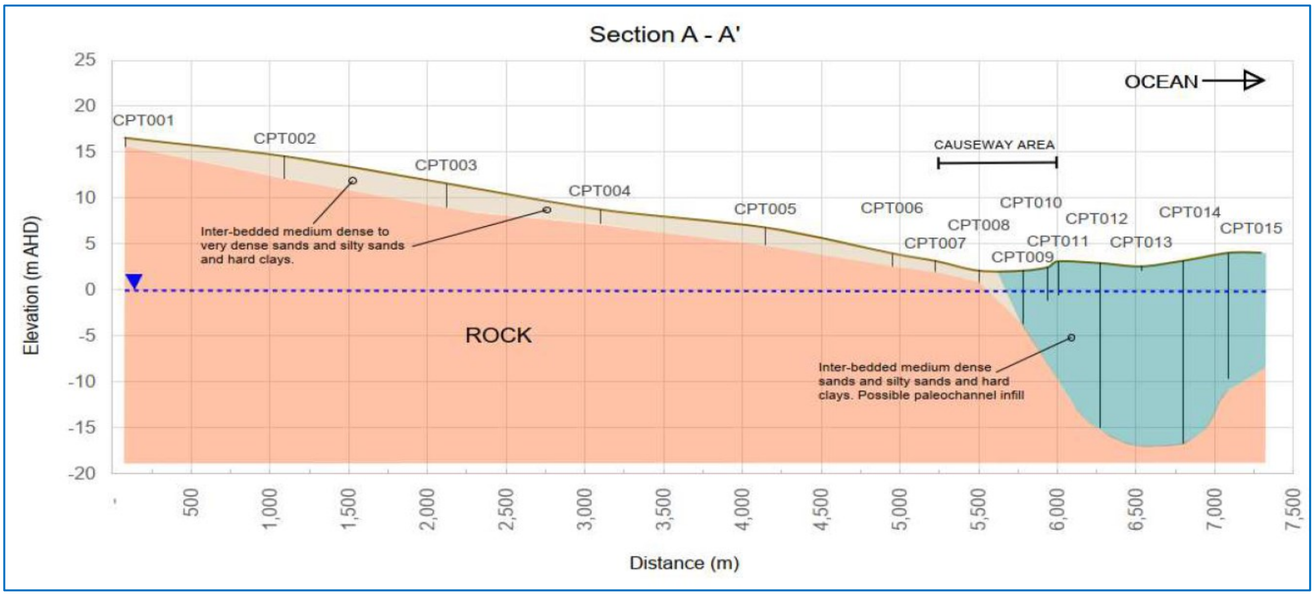


Figure 99. Interpreted stratigraphy along 40 Mile Road, A-A' (CMW Geosciences, 2022). Note the 1 to 2 m of dense sands along the road section, and the interpreted channel infill beyond the causeway towards the coast.

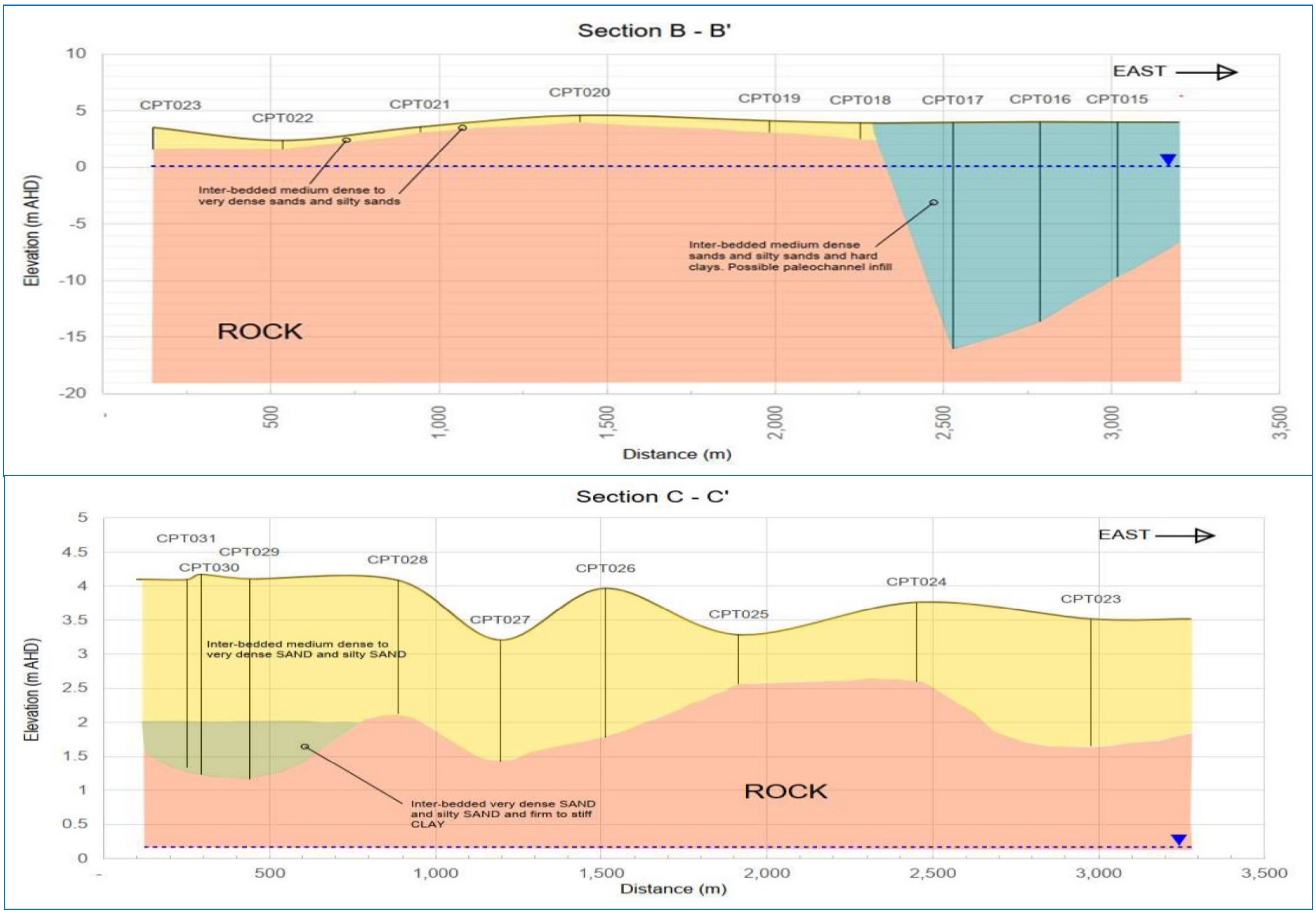


Figure 100. Interpreted stratigraphy (CMW Geosciences, 2022). UPPER – B-B', east of Gnoorea Point. Note the similar stratigraphy to the 40 Mile Road section (Figure 99), with 1 to 2 m of dense sands (no clays) along the road section, and the interpreted channel infill beyond the causeway towards the coast. LOWER – C-C', along the spit west of Gnoorea Point. In the west are buried deposits (green) of a possible palaeo-inlet.

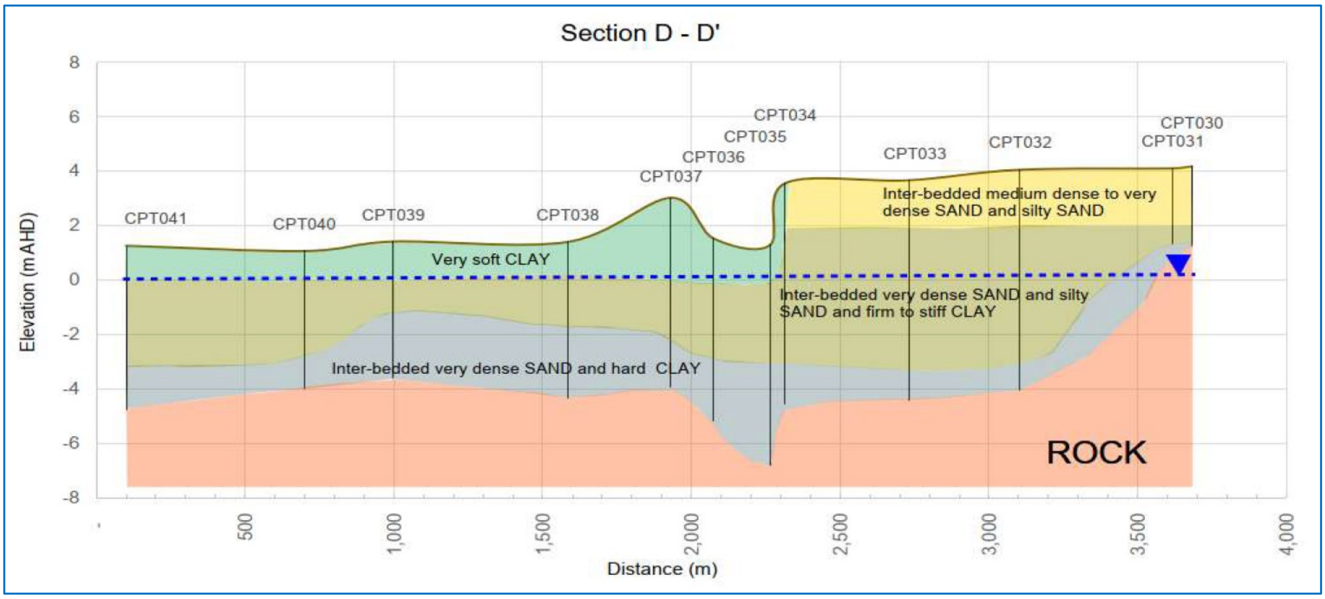


Figure 101. Interpreted stratigraphy in front of the nascent mangrove area (CMW Geosciences, 2022), along line D-D'. Note the barrier spit sand is replaced by soft mangrove muds at the location of the eastern, dominant tidal creek. Both sand and mangrove mud are probably Holocene (but not dated). They overlie very dense sand, silty sand and clay, interpreted as probably pre-Holocene.

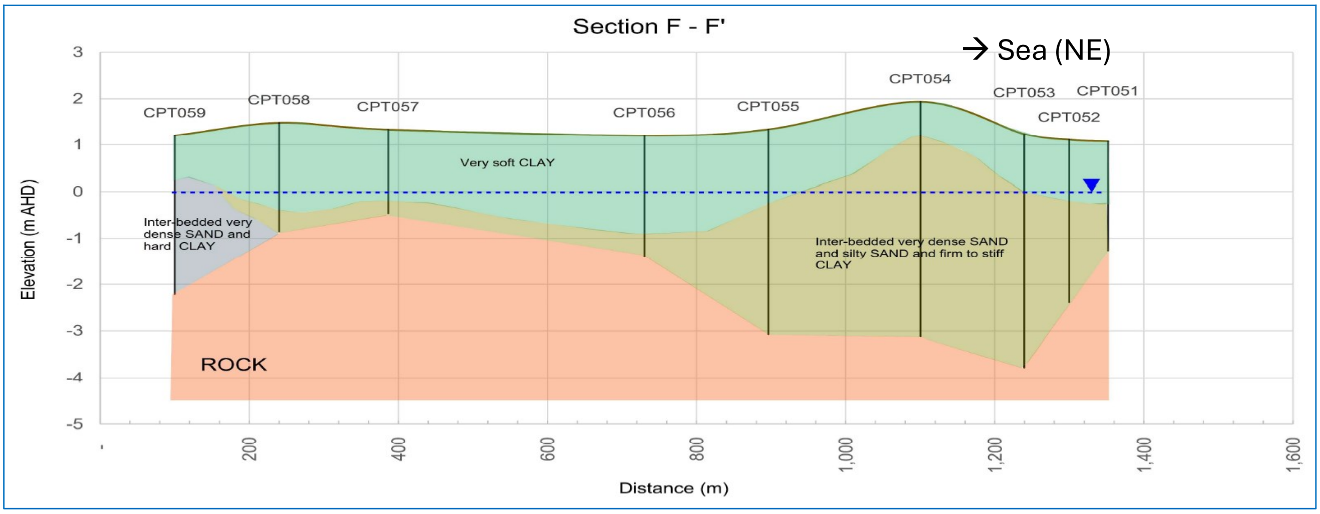


Figure 102. Interpreted stratigraphy: Section F-F', a shore-normal section though the mangroves of Baldy/Straight Creek catchment (CMW Geosciences, 2022).

Along the banks of McKay Creek, the section line E (Figure 103) 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 104), 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 102) and McKay Creek (Figure 103) 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.

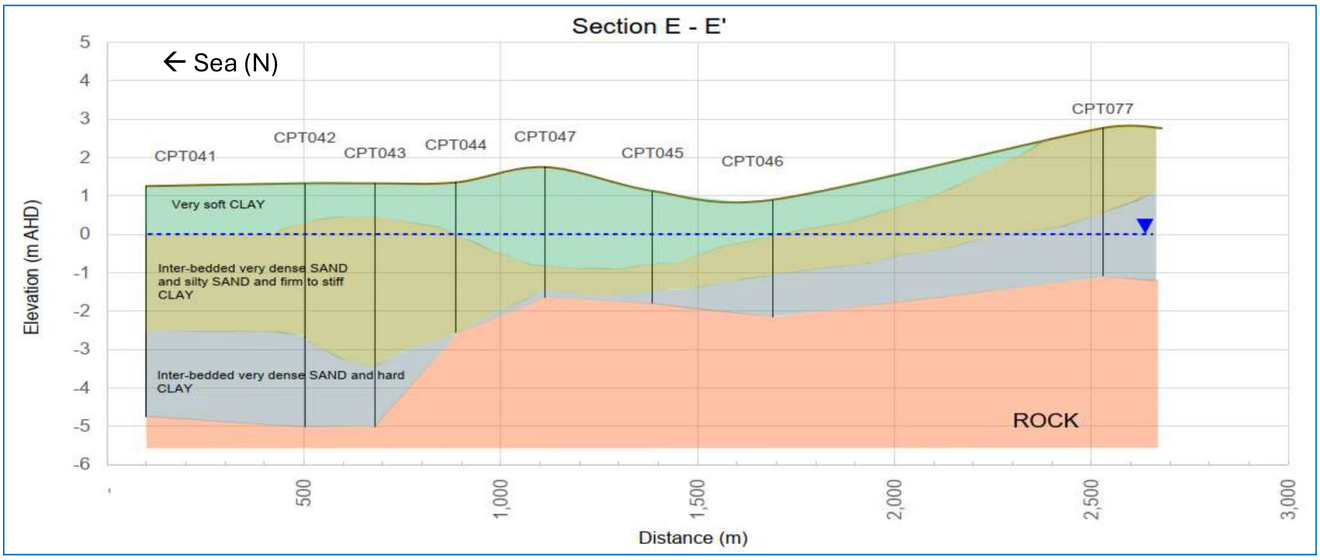


Figure 103. Interpreted stratigraphy: upper – E-E, along the eastern bank of McKay Creek from the sea landward to the delta mouth (CMW Geosciences, 2022). Note the seawards slope (i.e., northwards) to the three units above the bedrock – this tends to indicate that they might be diachronous, i.e., of different ages along their length. This gentle seawards dip of their base is also shown for Eramurra Creek (Figure 104).

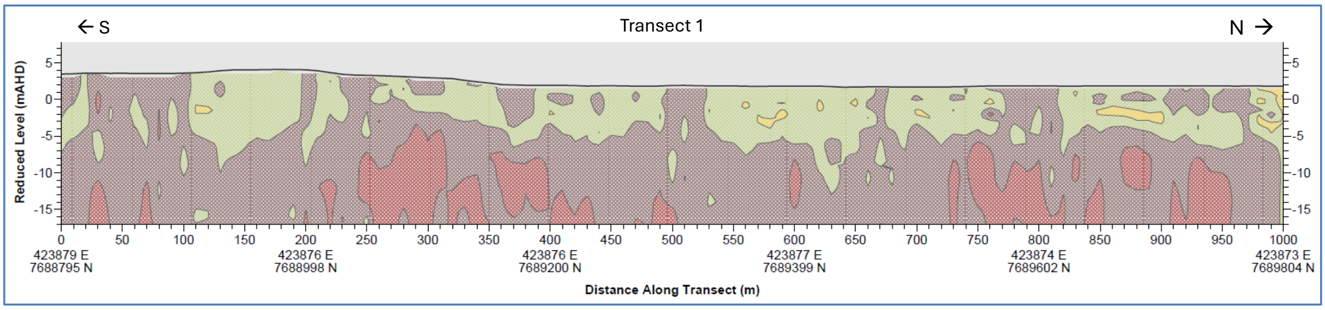
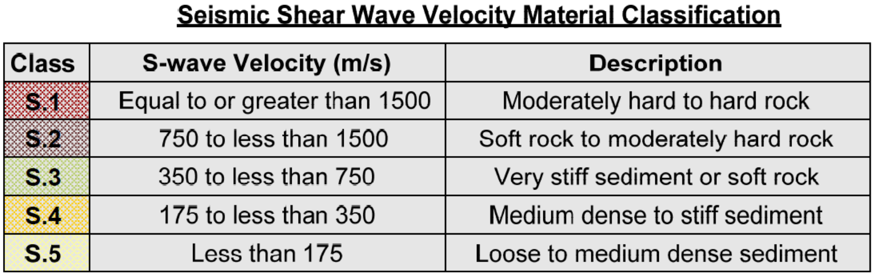


Figure 104. Interpreted material classification for Transect T1 of Figure 97, west of the other transects, perpendicular to the shoreline in the Creek 2 catchment, from the upper intertidal zone southwards across the eastern delta front of Eramurra Creek. Without core control, interpretation of this 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 103), there is a gentle northward dip of the likely sedimentary units (green). Key shown in Table 16. (CMW Geosciences 2022)

Table 16. Key to shear-wave velocity classification shown in Figure 104 & Figure 105 (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

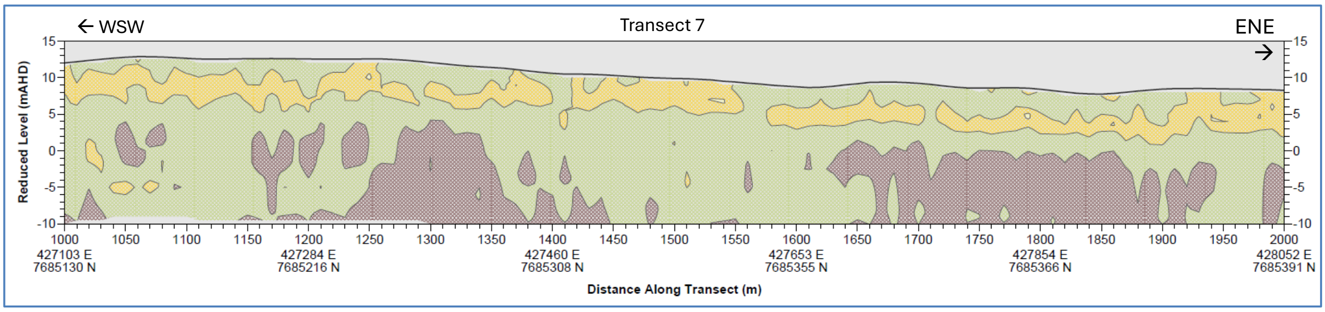


Figure 105. Interpreted material classification for Transect T7 of Figure 97, on the interfluve between Eramurra and McKay creeks. Key shown in Table 16. (CMW Geosciences 2022)

A conceptual cross-section through the coastal geology and sedimentary units (Figure 106) 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.

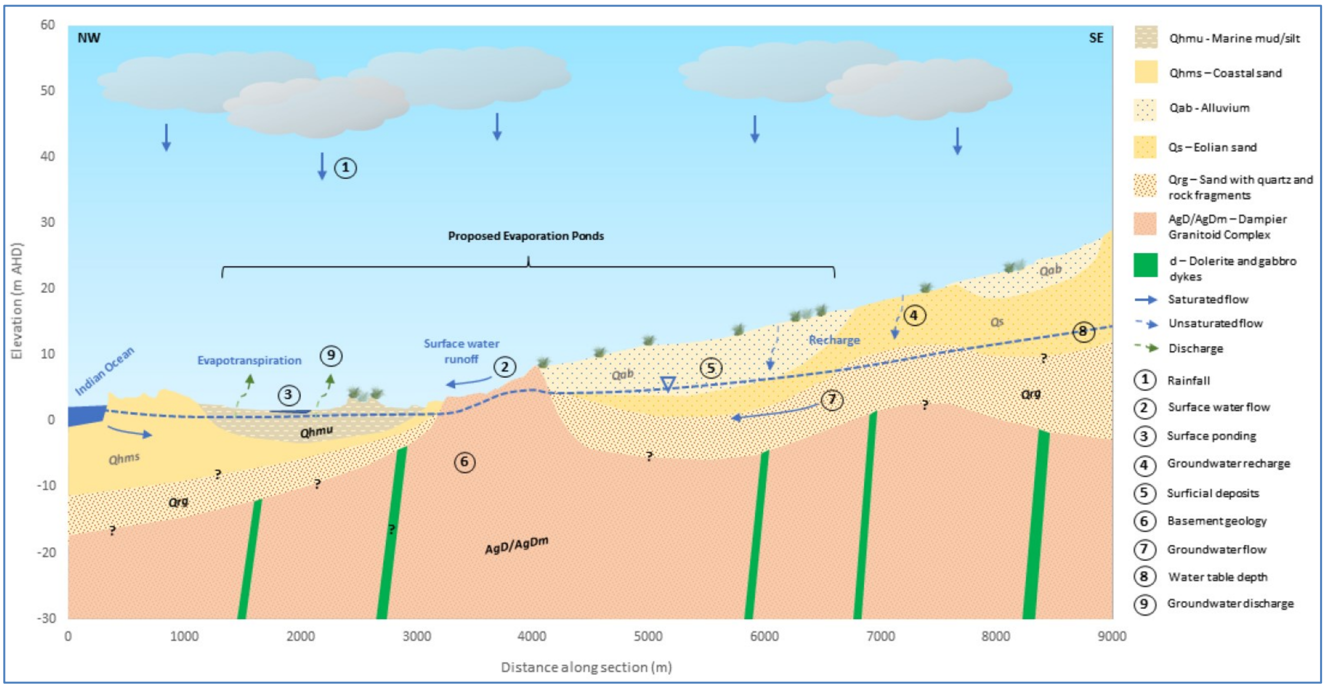


Figure 106. NW-SE vertical section of the geology and sedimentary units across the ESSP project area, showing a conceptual hydrogeological model (Land and Water Consulting, 2023b).

9.3. Physical aspects of key intertidal habitats

A key control upon most sub-tropical coastal and marine benthic habitats is the presence, nature, distribution and dynamics of bed sediments. Given the relevance of natural coastal processes to the BCHs in the area (Section 6.2), plus the need to meet EPA criteria and expectations, an internal exercise was designed and conducted to help ensure nothing significant might be missed. This exercise and its results are described in Appendix Section 31.

The intertidal habitats identified within the ESSP area include tidal creeks, intertidal rock platforms, mudflats (although some are not actually muddy – see Table 12 and associated text), mudflats with algal mats, beaches, mangroves and samphire (Figure 9, Figure 10, Figure 107). Of these, the key benthic habitats associated with coastal processes include mangroves, benthic mats and samphire communities. The coastline also forms potential or used habitats for key fauna, including various species of turtles (Flatback, Green and Hawksbill) and the Green Sawfish (*Pristis zijsron*).

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 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).

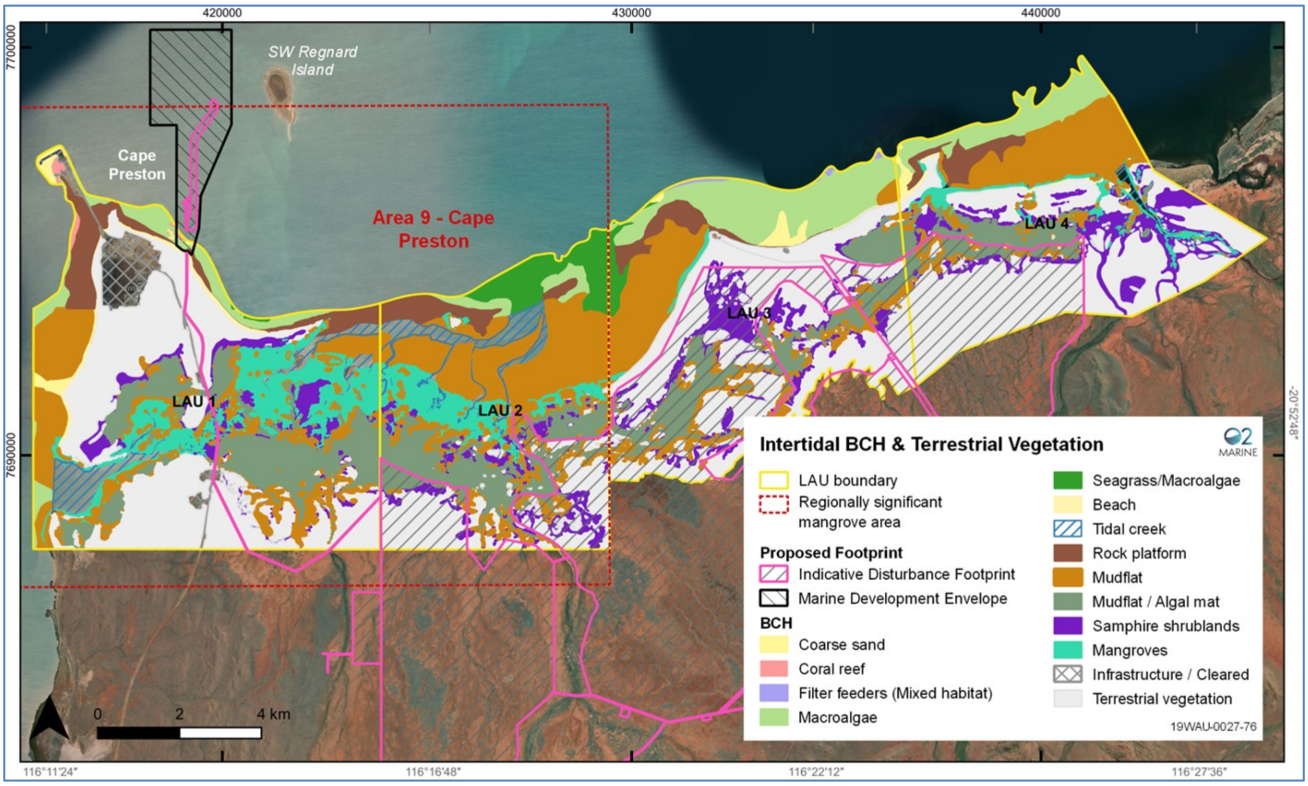


Figure 107. The mapped intertidal Benthic Communities and Habitats in the study area (O2 Marine 2023). (Note this usefully combines distributions of some habitats and some sediment bodies. For habitats, Figure 9 & Figure 10 are up to date and take precedence.)

Mapping of intertidal habitats has been conducted using hyperspectral remote sensing, supported by limited field checking. Comparison of mapped habitats (Figure 108) with aerial imagery indicates strong linkages to tidal creek networks, although this differs within the project area.

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 34) 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.

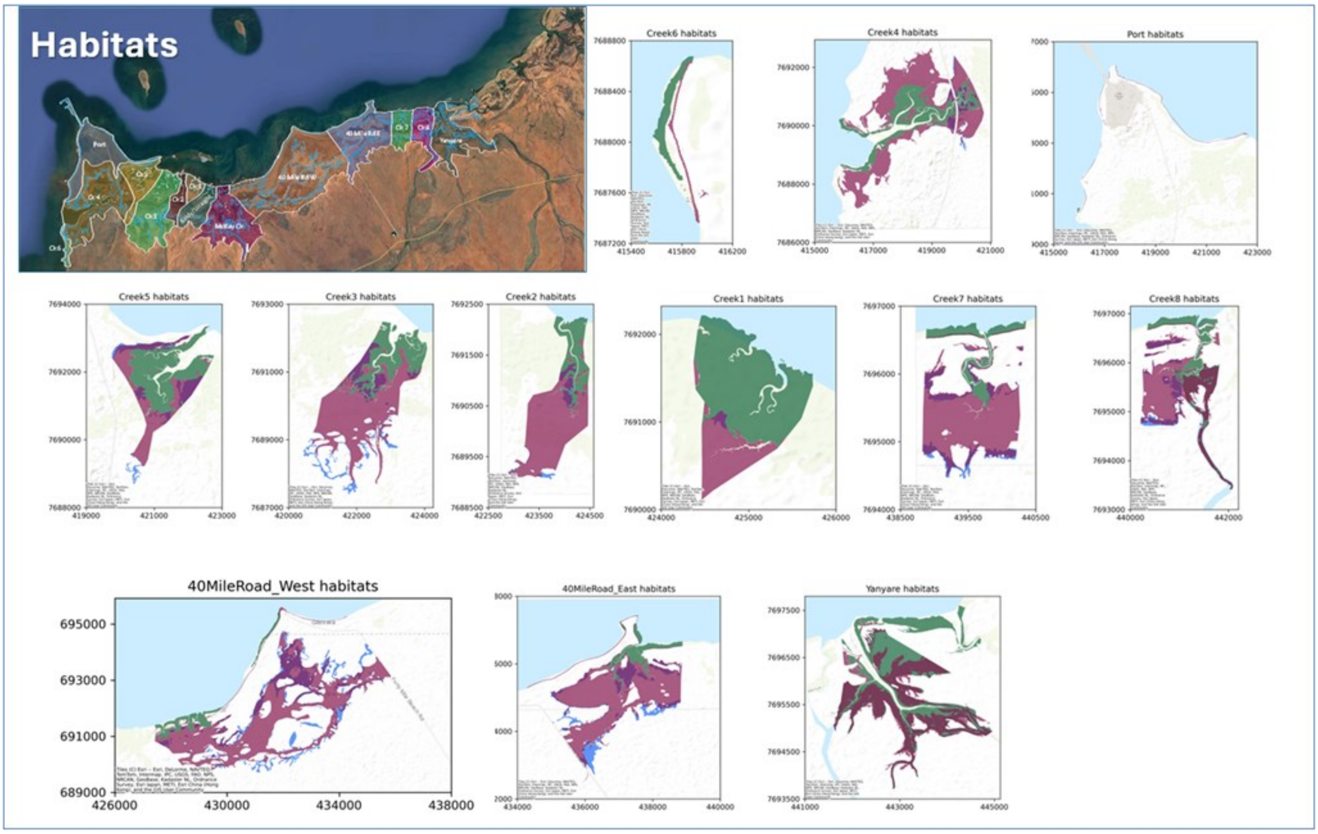


Figure 108. Mapped intertidal habitat areas in various ESSP tidal catchments.

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 17), 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 17). 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 17), 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 17. Modal elevations of key intertidal habitats (m AHD). (Full elevation details in Appendix Section 34).

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	

9.3.1. Mangroves

Although there are three types of mangrove environment in the ESSP area (Appendix Section 33.3), for practical purposes regarding coastal processes, 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 17). 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 109), 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 major local change of state, such as experiencing a meander cut-off. These are both relatively small fluctuations in an estuarine environment of relatively longer-term stability.

Figure 109. Top – Tidal creek with water levels below overbank, and exposed horizontal mangrove root systems on the banks, indicating 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).

9.3.2. 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 110), 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.

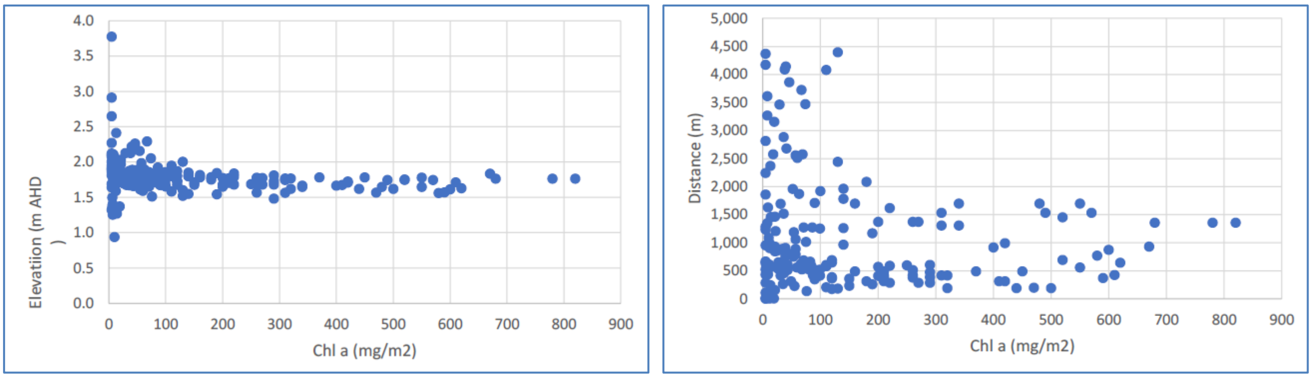


Figure 110. Chlorophyll-a content for all samples, measured as rewetted mats, plotted against bed elevation (upper) and distance from nearest landward mangrove fringe (lower) (Actis Environmental Services, 2023).

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 111). Other larger areas (i.e., most of the red areas of Figure 111 & to the centre left of Figure 112) 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.

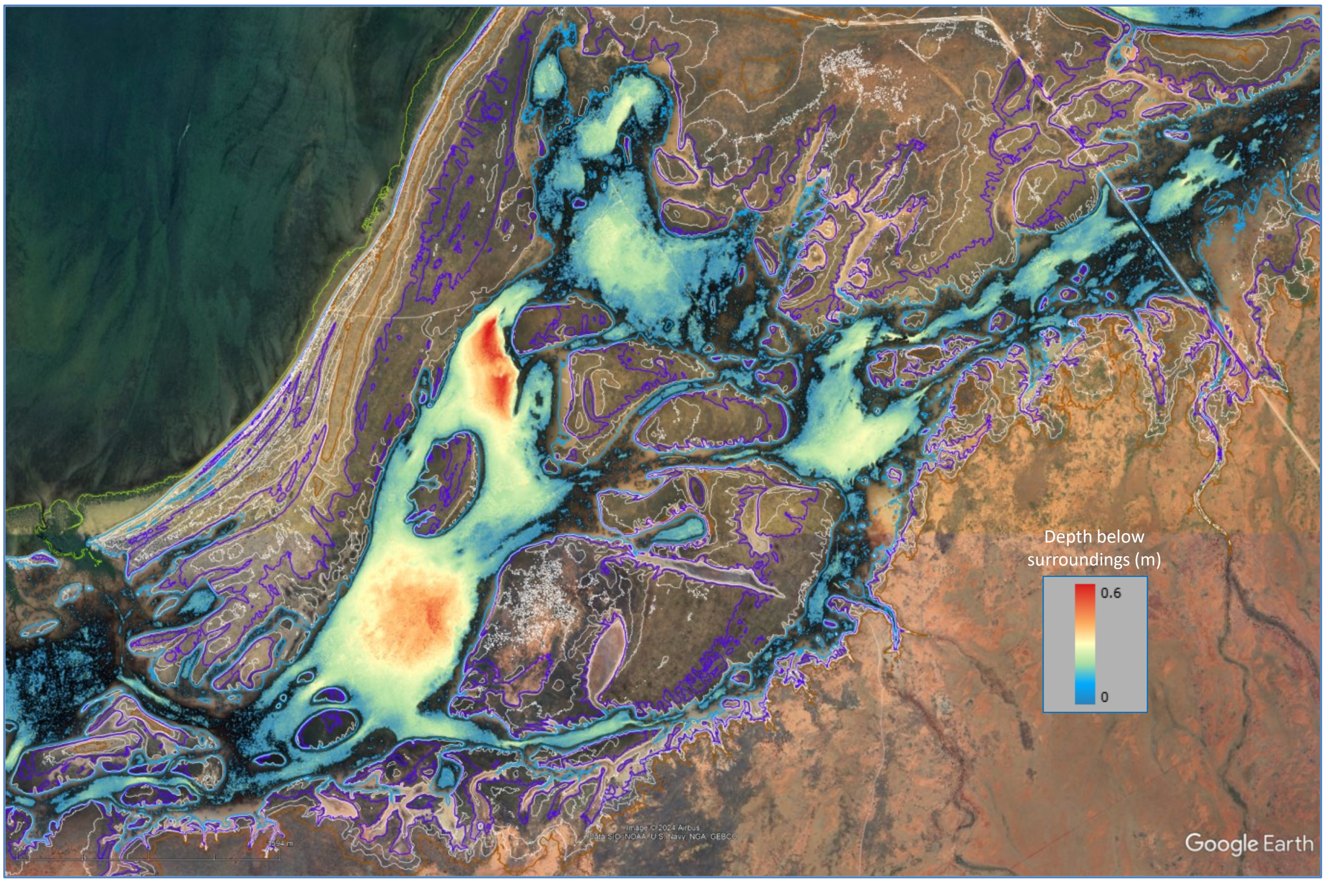


Figure 111. Basins in the 40 Mile Road W catchment are up to 0.6 m deep. The deepest area is behind (SE of) the spit, and together form an area 3 km by 0.8 km.

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.

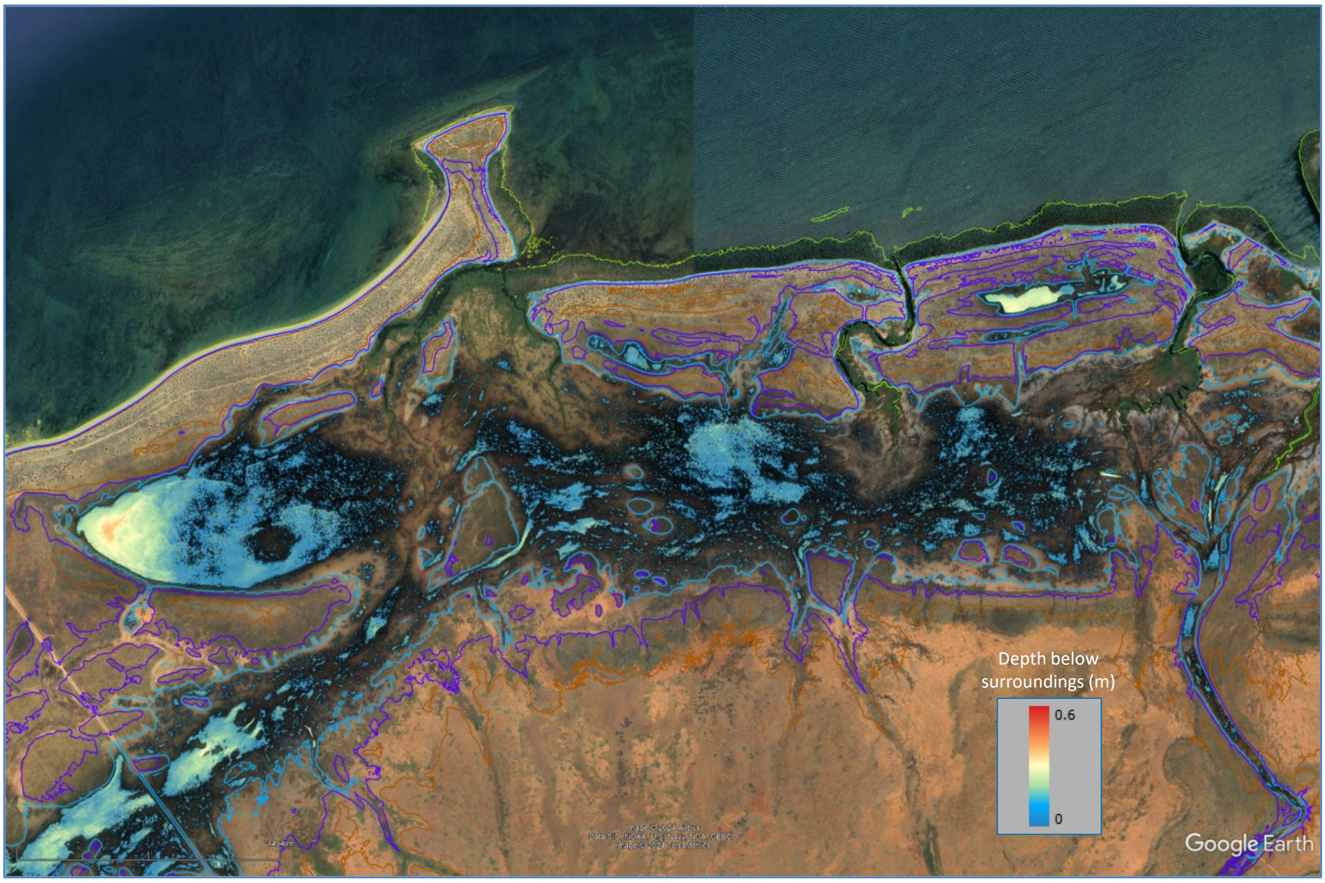


Figure 112. A smaller shallower basin ~1.5 km x 0.6 km occurs in the western part of the 40 Mile Road E catchment, as the extension of the low area landward of the barrier. A raised basin occurs in the coastal barrier to the east, 0.8 km long and 0.13 km across (light green area to upper right), with its lip at ~2.5 m AHD.

9.3.3. 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 samphire occurs in several general settings (Figure 113), 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.

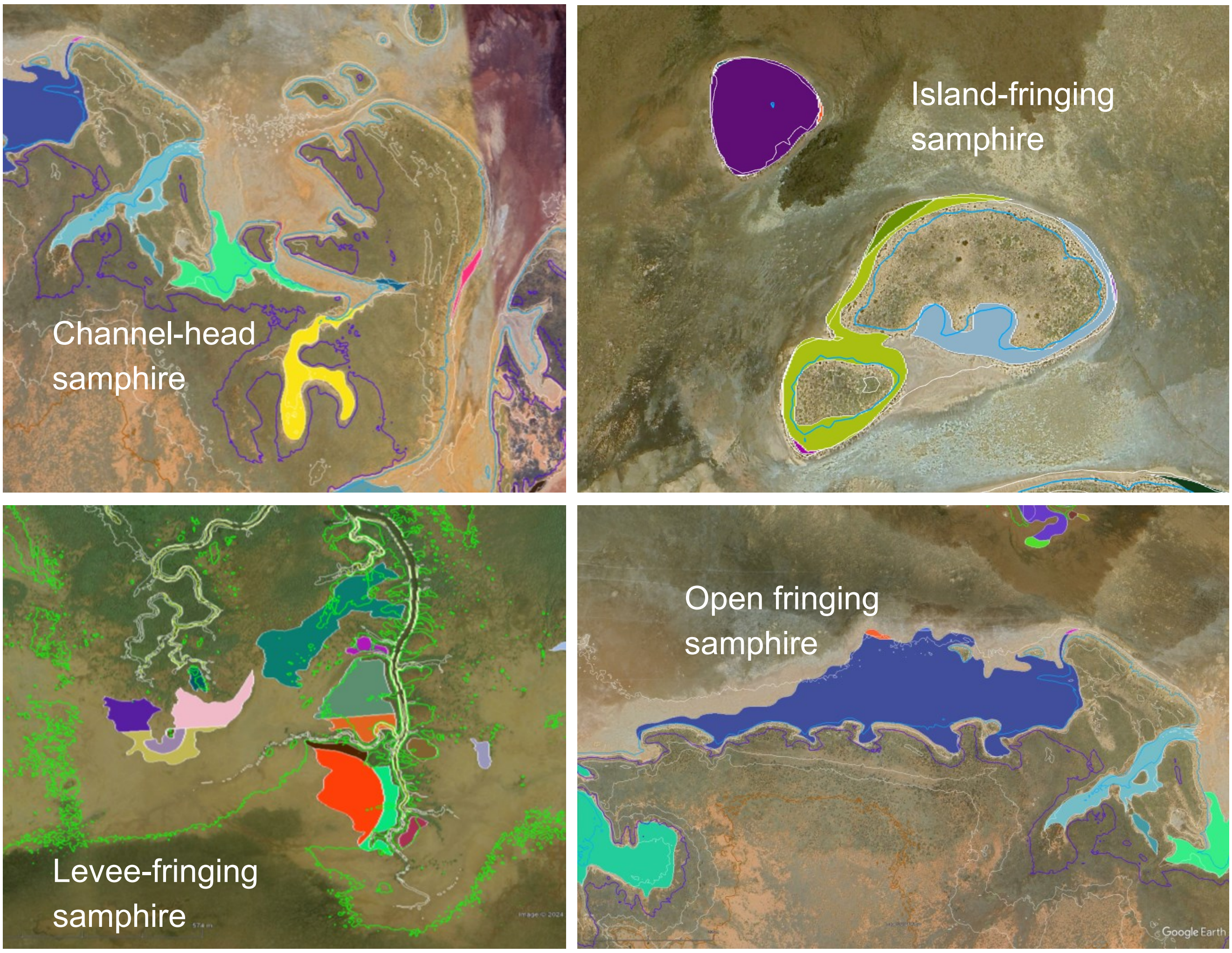


Figure 113. Four designated settings for samphire species, based on their geomorphological setting and different potential to migrate or persist with SLR. (Different colours are of no consequence – all indicate the presence of samphire).

9.3.4. Turtles

The Pilbara region provides an important habitat for marine turtles, which are protected under the Commonwealth EPBC Act and WA Biodiversity Conservation Act. Understanding potential impact to turtle habitats and developing an appropriate management plan is required for environmentally significant marine projects. Flatback, Green and Hawksbill turtles are the three most common species identified along the Pilbara coast. Identification of their presence, habitats and susceptibility to disturbance is subject to ongoing scientific assessment, with an extensive body of work developed for the Pilbara since the 1980s, including academic studies, NGO investigations and EIA studies for resource development proposals. It is part of a global effort to better manage human interactions with marine turtles, with an overall strategy to reduce the endangerment of turtle species (IUCN 1995).

Marine turtles are migratory, with dispersed habitats for breeding, foraging, migration and basking (Whittock *et al.* 2014). Biologically important areas have been mapped where marine turtles are known to be active, including extensive nearshore foraging areas southeast of Barrow Island, and west of the De Grey River (DAWE 2020). Habitats considered critical for species survival have been mapped based on nesting site observations and tagging, with the spread of turtles during the inter-nesting phase (between nesting attempts) used as a buffer from identified nesting sites (60 km for flatback turtles and 20 km for green or hawksbill turtles).

The importance of effective nesting for species survival, as well as greater relative ease for land-based observations, has prompted consideration of 'optimal nesting areas' as a means of characterizing habitat impacts from human activities (Chevron 2016). Attributes such as elevation, sediment composition, sediment depth, terrain steepness, nearshore gradient and artificial light have been related to nesting viability, for different studies and management plans (Mortimer 1982, Johannes & Rimmer 1984, Wood & Bjorndal 2000, Kikukawa *et al.* 1999, Chen *et al.* 2007, Kamrowski *et al.* 2014). It is important to highlight that geospatial evaluation of nesting viability is only a proxy, using indicative 'rules' based on relative nest abundance, as turtle nests are occasionally observed in areas that might be classified as less viable. It is further acknowledged that characteristics such as nest temperature and inundation occurrence have been scientifically linked to hatching effectiveness (Hewavisenthi & Parmenter 2002, Sahmblott *et al.* 2021), and have been used in interpretation of nesting observations, but are not typically included in delineation of viable nesting areas.

A fundamental characteristic of nesting viability is the presence of sediment that a turtle can access and dig a suitably deep nest. This usually occurs in the upper beach flat (beach platform) and lower foredune area, seaward of dense dune vegetation, although nesting has been observed on the lower beach flat, and very occasionally landward of coastal dunes. The size differences between species influences their preference for nesting sites (Pendoley *et al.* 2016; Fossette *et al.* 2021), with green turtles more typically nesting on higher energy beaches, with a deep approach and deeper foredune sediments, whereas the smaller hawksbill turtles are more tolerant of a shallower approach and shallow, rockier sediments (i.e., more frequently nesting at offshore sites).

Observations of turtle nesting in the Cape Preston area have been undertaken to investigate the impacts of development for Cape Preston and proposed development for Cape Preston East (EPA 2020) and Eramurra Solar Salt:

- Initial investigations were focused on the beaches on either side of Cape Preston (Kendrick 2000, DEC 2006). These identified a dead green turtle and nesting from at least two species in 2000, and nesting in 2006 was inferred to be by flatback turtles. Nesting occurred along the beaches east and south of Cape Preston, concentrated away from the Cape itself. Low-density nesting activity was identified, with 22 and 24 nesting tracks identified over 7.5 km of beach.
- Subsequent investigations have extended the area of survey coverage east of Cape Preston, including the Regnard Islands and Gnoorea (O2 Marine 2022b, Pendoley Environmental 2024). Investigations were timed to cover anticipated flatback nesting (O2 Marine 2022) and multiple surveys to cover flatback, green and hawksbill nesting seasons (Pendoley Environmental 2024). Moderate-density nesting activity was observed on SW Regnard and Steamboat islands, with low-density nesting on NE Regnard Island and Cape Preston East. One nesting track was identified along Forty Mile Beach in 2024, with no activity during other surveys, although 4WD activity along this section of coast may limit the capacity to identify nesting activity.

Surveys conducted have primarily identified the presence of hawksbill and flatback turtles, with most nesting activity found on the offshore islands. Identification of green turtle activity has been at a low level, but they are present in most surveys, including nesting activity along Cape Preston east. The relative abundance of annual nesting populations near the ESSP site has been estimated as a small fraction of the overall genetic stock, with ~0.6% of hawksbill, ~0.05% of flatback and ~0.01% of green turtles (Pendoley Environmental 2024).

Although nesting activity is used as an indicator of marine turtle presence, proposed activities should also be considered with respect to other habitat phases. Following a generalized description of turtle species diets (Commonwealth of Australia 2017), the proposed ESSP site is adjacent to areas characteristic of foraging habitat (O2 Marine 2022b, Table 18).

Table 18. Diet and foraging habitats for the main turtle species in the ESSP area.

Species	Generalised diet	Foraging habitat
Flatback turtle	Primarily carnivorous, feeding on soft-bodied invertebrates. Juveniles eat gastropod molluscs, squid and siphonophores. Limited data indicate that cuttlefish, hydroids, soft corals, crinoids, molluscs and jellyfish are also eaten.	Soft sediment habitats that support benthic invertebrates.
Green turtle	Primarily herbivorous, foraging on algae, seagrass and mangroves. The pelagic juvenile stage feeds on algae, pelagic crustaceans and molluscs.	Tidal/sub-tidal habitats with coral reef, mangrove, sand, rocky reefs and mudflats.
Hawksbill turtle	Omnivorous, feeding on algae, sponges, soft corals and other soft-bodied invertebrates.	Tidal and sub-tidal coral and rocky reef habitats.

Depending upon future design of the facilities, the ESSP may need to consider impacts to marine turtles through:

- Light overspill (to be managed);
- Disturbance of nesting areas through 4WD traffic (to be managed); and
- Alteration of nesting or foraging habitats due to modification of coastal processes, including effects of pond construction, intake/outfall systems and navigation works for offloading facilities, such as jetties, dredged channels and dredged spoil disposal sites.

This report only considers potential impacts to turtle habitats associated with coastal processes, and specifically those associated with the presence of the ponds.

Coastal process impacts due to human activities are developed where actions modify coastal morphodynamics, either through changing the physical structure of the coast and/or altering the hydrodynamics such that sediment transport patterns are changed. Coastal process changes may modify turtle habitat by affecting (i) areas used for nesting activity, through erosion, accretion or scarp formation; (ii) foraging areas, by smothering, scour, or otherwise changing the ecological character of the habitat.

The dredging of the ESSP development needs to be evaluated, due to their capacity for plume dispersal to affect large areas of habitat (Mills & Kemps 2016).

9.3.5. Green Sawfish

Of the four species of sawfish in NW Australia (Figure 114), the ESSP area houses the Green Sawfish (*Pristis zijsron*) (Morgan *et al.* 2025) which is mainly found in coastal marine, mangrove and estuarine habitats, and where the seabed consists of sand, mud or silt. It is important to understand the timing of key phases in the sawfish life cycle, compared to the potential timing and duration of changes at the creeks. For example, with the ESSP's ponds emplaced, seasonal river flood events may change potential effects on the creek morphology, including their mouths, and it is also possible that during dry season, pond-associated changes in tidal flows may lead to some creek mouths being more constrained.

As they grow, adult Green Sawfish extend their home range to several tens of km, and adults go offshore to depths of >70 m, and can live several decades. Monitoring studies of tagged individuals (Ingelbrecht *et al.* 2024) indicate more sightings in the larger rivers, such as the Ashburton and Fortescue. They leave the rivers during major river flows (such as in March 2011 in NW Australia, D. Morgan, pers. comm. 2024) but return later with reduced river input.

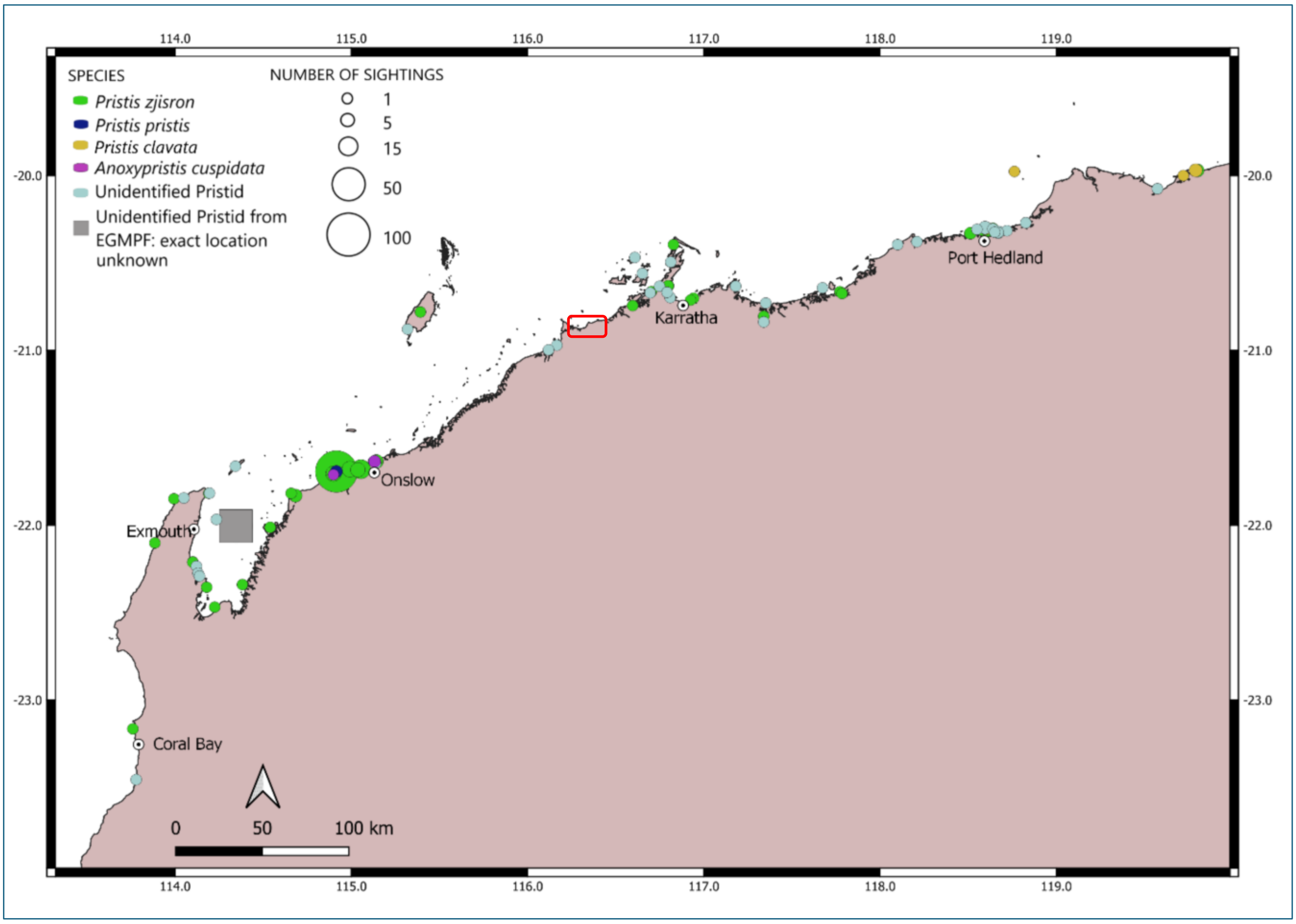


Figure 114. Sawfish sightings along the Pilbara coastline (adapted from Bateman et al., 2024). Note few sightings have occurred in the ESSP area (red box).

Female Green Sawfish return to the same creek to pup. Pups are produced in the period November to January and are around 60-108 cm long at birth. New-born and young pups of the year stay relatively in shallow water near the coast in very shallow water (<50 cm deep) and within perhaps 700-800 m upstream of creek mouths for foraging and avoiding predators. As they grow, they use deeper water, but only larger individuals (>2.5 m total length) appear to pass structures or dredged areas (Morgan *et al.* 2017, Lear *et al.*, 2024). In this way, physical barriers in shallow waters such as rock outcrops or harbour walls and areas of deep water at the coast such as dredged channels can deter migration along the coast of smaller individuals (Lear *et al.* 2024). Hence, changes to coastal configuration associated with SLR and/or pond emplacement might affect sawfish migration along the coast, including annual migration of females back to their home creek.

In the ESSP study area, a single Green Sawfish has been documented in the surveys of 2022-2024, within McKay Creek (Figure 115) in October 2023. Species with similar geographical distributions (sympatric species) are distributed within the greater estuary (i.e., the sampled area of Figure 114) so it is possible that these marine environments form part of a network of ‘stop-over’ sites that support long-distance movement of green sawfish along Western Australia’s coastline (Morgan *et al.* 2025).

Figure 115. Locations of seine netting (SN), gill-netting (GN) and acoustic receivers (orange crosses) used in the ESSP sawfish study (Morgan et al. 2025). Acoustic receivers record transmissions from any sawfish previously implanted with an acoustic tag. (Some place names in this figure differ from used elsewhere in this report, e.g., “Intake Creek” labelled here is the same as McKay Creek used throughout this report. Names used in this report are given in Figure 3.)

10. Sediment transport

This section summarises the controls and indications of past and present sediment transport. This is necessary to help understand the mechanisms that maintain the coastal system and inform the assessment of the system's resilience. This includes mechanisms that acted long ago in the past and those acting today.

10.1. Controls on sediment transport

In such subtropical environments, a variety of physical factors are relevant to coastal dynamics, such as the six 'drivers of change' in Section 6.1, which are fluvial sediment delivery, shelf sediment availability, shelf bathymetry, waves, tidal range and currents, and cyclones. In particular for the ESSP's tidal creek systems (O2 Metocean 2022a) we can note three aspects of special relevance:

- Underlying geology.
    - The location and morphology of the tidal creeks might be controlled in part by resistant rock beneath them. As noted above, the fluvial creek and tidal creek systems are 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.
    - 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 actually takes place – there needs to be sediment available for transport. For coastal features to migrate seawards or landwards requires sediment 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.

It is also clearly relevant how much sediment might be introduced into the coastal system from the emplacement of the solar salt ponds, where and what rate, and what its fate might be. 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 the range of available evidence.

10.2. Indicators of sediment transport

10.2.1. Bedforms - active and/or vegetated

A variety of (mostly) sandy bedforms are observed in fieldwork-associated photos and from aerial images. These may be regularly active and hence susceptible to mobilisation, vegetated or stabilized to some degree (e.g., with seagrass, benthic mats or terrestrial plants), or cemented and therefore immobile. The observed bedforms in the ESSP area 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 8.2)
    - 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 69).
    - Longitudinal bars and point bars in many of the active tidal channels, most with superposed tidal small dunes (e.g., Figure 109, Figure 207).
    - 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 22.6) and uppermost McKay Creek (Figure 209).
- 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 22.6)
    - Deflated dunes of the intertidal sandplains (Section 9.1.6)
- Some bedforms 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 8.2 and 9.1.8).

Therefore, from the bedforms alone, almost every sedimentary environment along the ESSP coastline appears either regularly, partially or episodically active in terms of sediment transport. Further, this suite of bedforms is largely consistent with the modern mix of hydrodynamic processes along the ESSP coastline. This indicates a degree of resilience in the coastal system. However, as noted above, uncertainties occur because where bedforms are not clearly presently active, such as when they are vegetated or of very low relief, information on their age (and thus sedimentary setting) is needed to help them support an interpretation of shoreline response to SLR and other factors. Relevant aspects of these bedforms are covered in the worked examples of Section 22.

10.2.2. Flow data

Tidal currents have been described and discussed in detail in O2 Metocean (2022a) with the key elements presented in this report (Section 7.2). There is little applicable data on waves regarding their potential influence on sediment transport at the coast itself. Relevant information on fluvial runoff is presented in Section 7.3.2.

10.3. Sediment transport – the key sedimentary units

The nature and disposition of the main stratigraphic units are described in Sections 8.6 and 9.2, 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 19). Across the whole ESSP coastal zone, there appears no obvious limitations on sediment availability. However, there are some local areas where there is limited sediment available because past processes acting over many centuries and longer have partitioned the sediments into specific locations. Therefore, in some areas even fast surface flows may generate limited rates of sediment erosion and transport.

Table 19. Key sedimentary units relevant to sediment erosion, transport and accumulation (see also Table 12).

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’ & ‘Sandy islands’**	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
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	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.

Unit name	Location and key characteristics	Thickness	Significance wrt sediment availability
~Soft mangrove muds			
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

10.4. Evidence of past sediment transport pathways

10.4.1. Sedimentary particle size and compositional trends

Different size particle modes can have different transport pathways and directions because of the different variety of processes affecting them. This concept has been widely tested and is effective in i) helping discriminate different sedimentary environments and ii) revealing sediment transport pathways (e.g., Bryce *et al.* 1998, 2003; Woolfe *et al.*, 2000, Orpin *et al.*, 2004; Reef at al 2023). Should modal sizes be present, readily identified and their composition is consistent, then gradual decreases in their modal size across an area can indicate the presence of a net transport pathway. Put simply, the grains get worn down and slightly smaller as they travel along the long-term sediment transport pathway.

Some available PSD data from the ESSP area has been tested for the possibility of using such particle tracing through the system. To date, in the ESSP area, relatively few samples have been analysed for PSD using laser-sizing, which along with their uneven distribution within the river catchments (Figure 116) unfortunately does not yet 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 22, in Section 12).

Nonetheless, selected results of tested samples were assessed to see if such an analysis might assist. These samples included samples in the interfluve between Eramurra and McKay creeks, in the McKay Creek catchment, and lower Devil Creek into Creek 8. The results are shown in Figure 117, Figure 118 and Figure 119. Even this small group of results shows 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. This is further supported by the size modes identified in grab samples at Cape Preston (Section 9.1.8) which showed size modes around 60 µm, 380 µm and 460 µm.

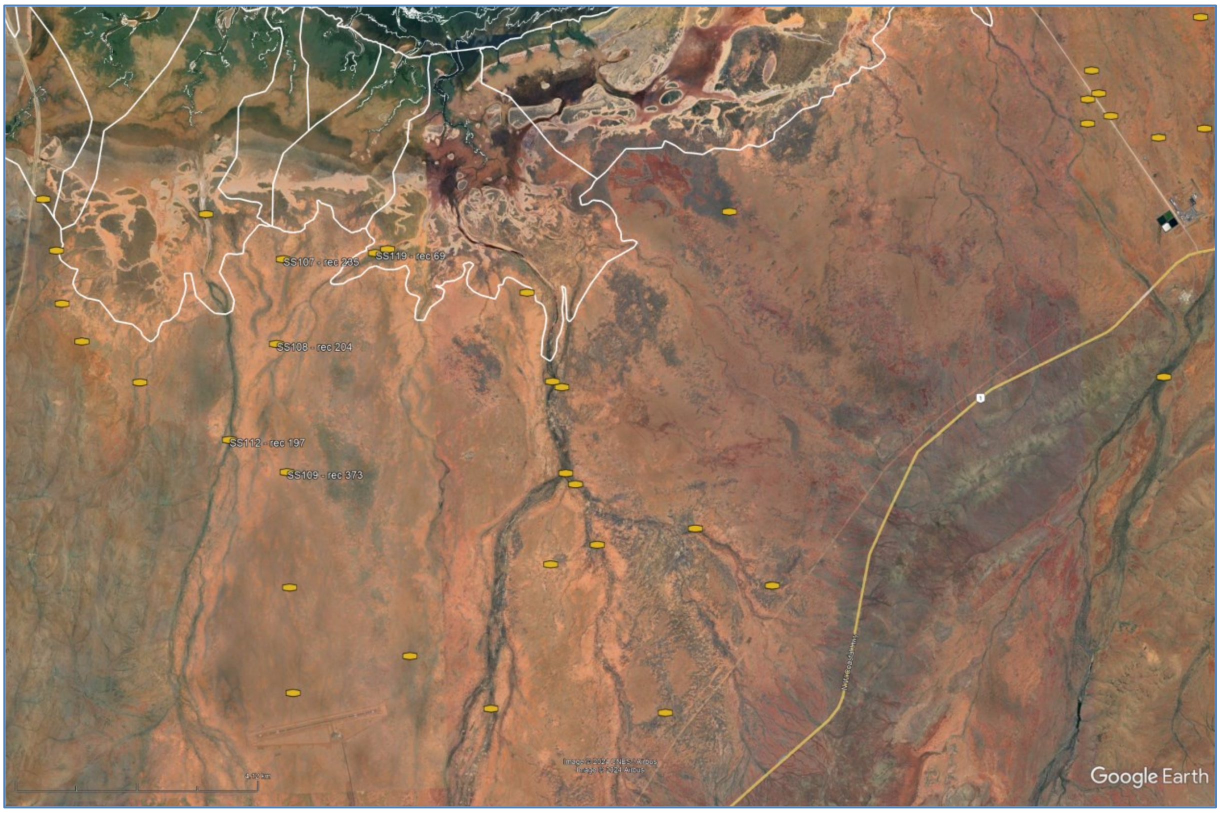
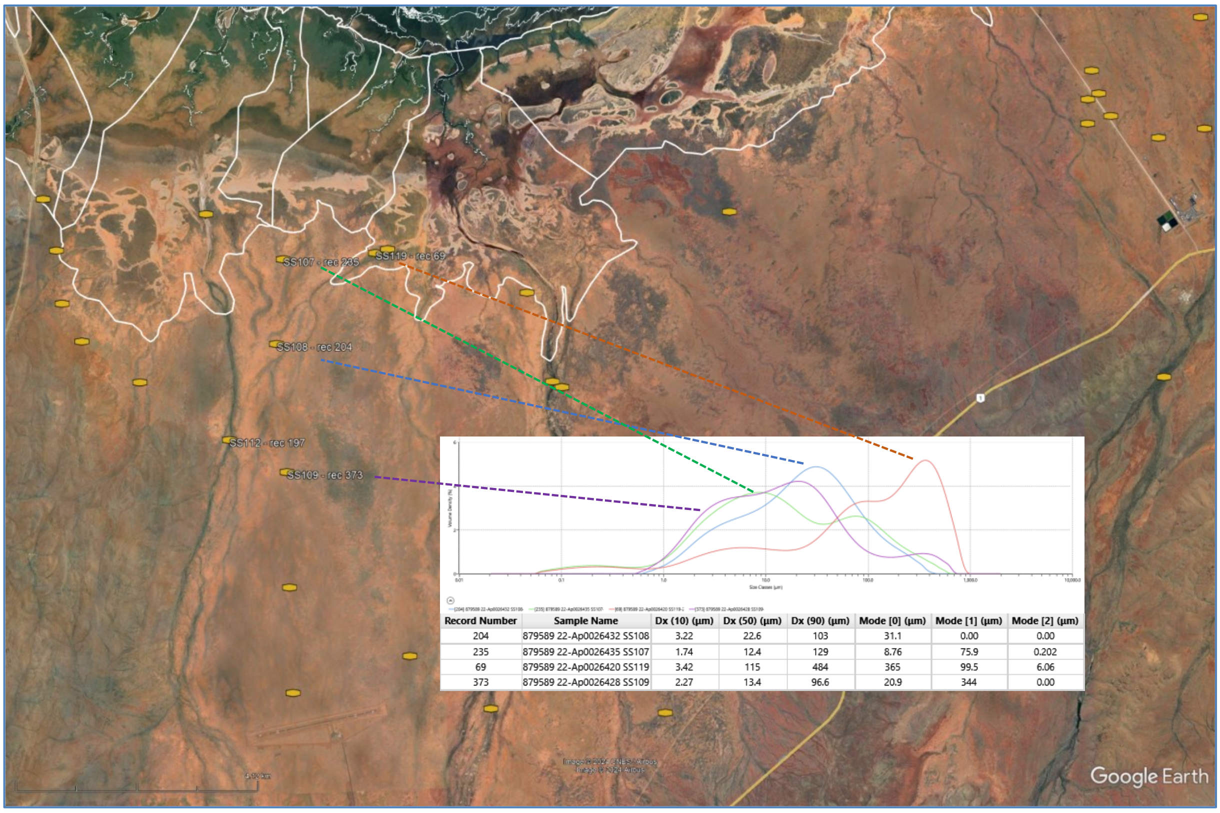
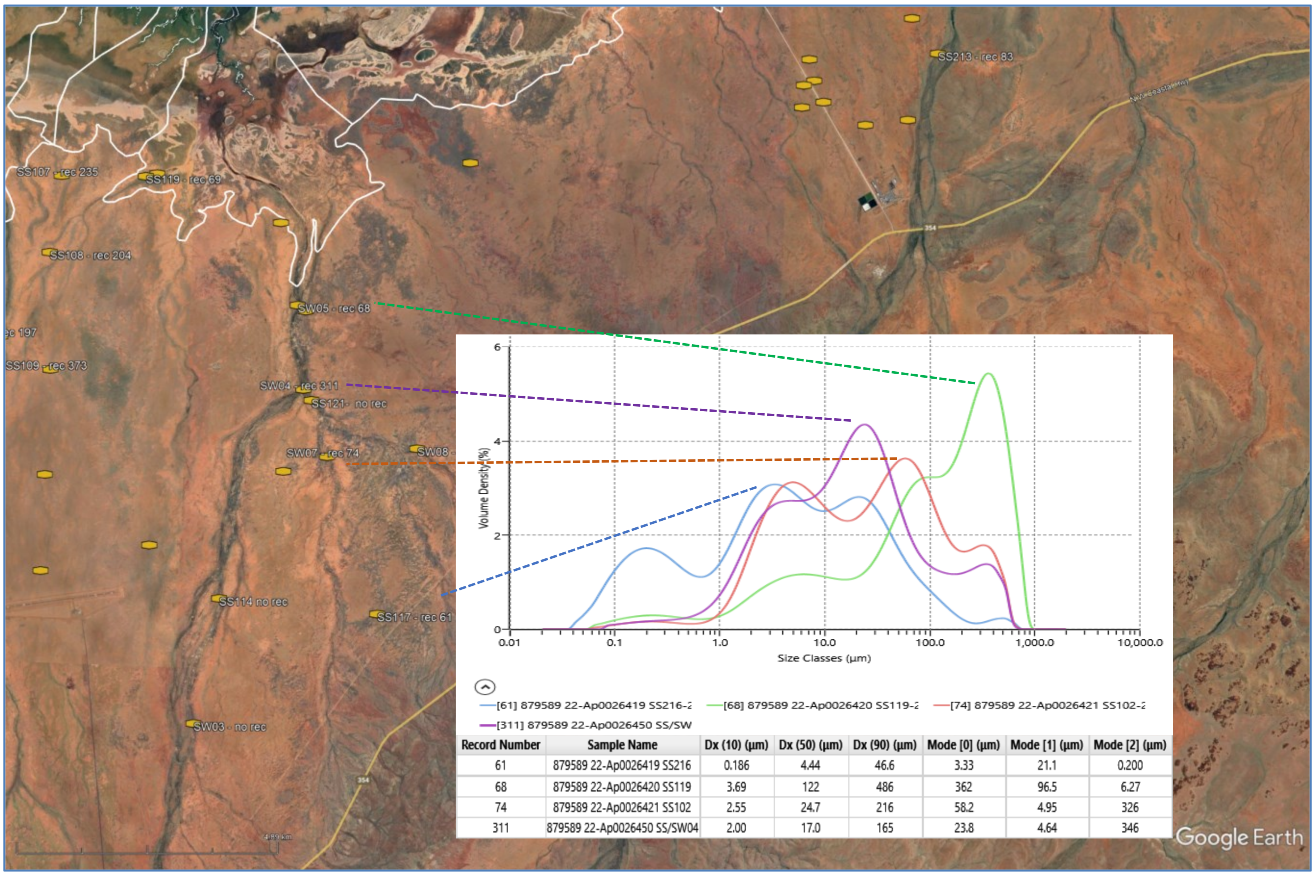


Figure 116. Distribution of surface sediment samples in the ESSP area that have had laser PSD analysis performed. No samples remain to check composition.



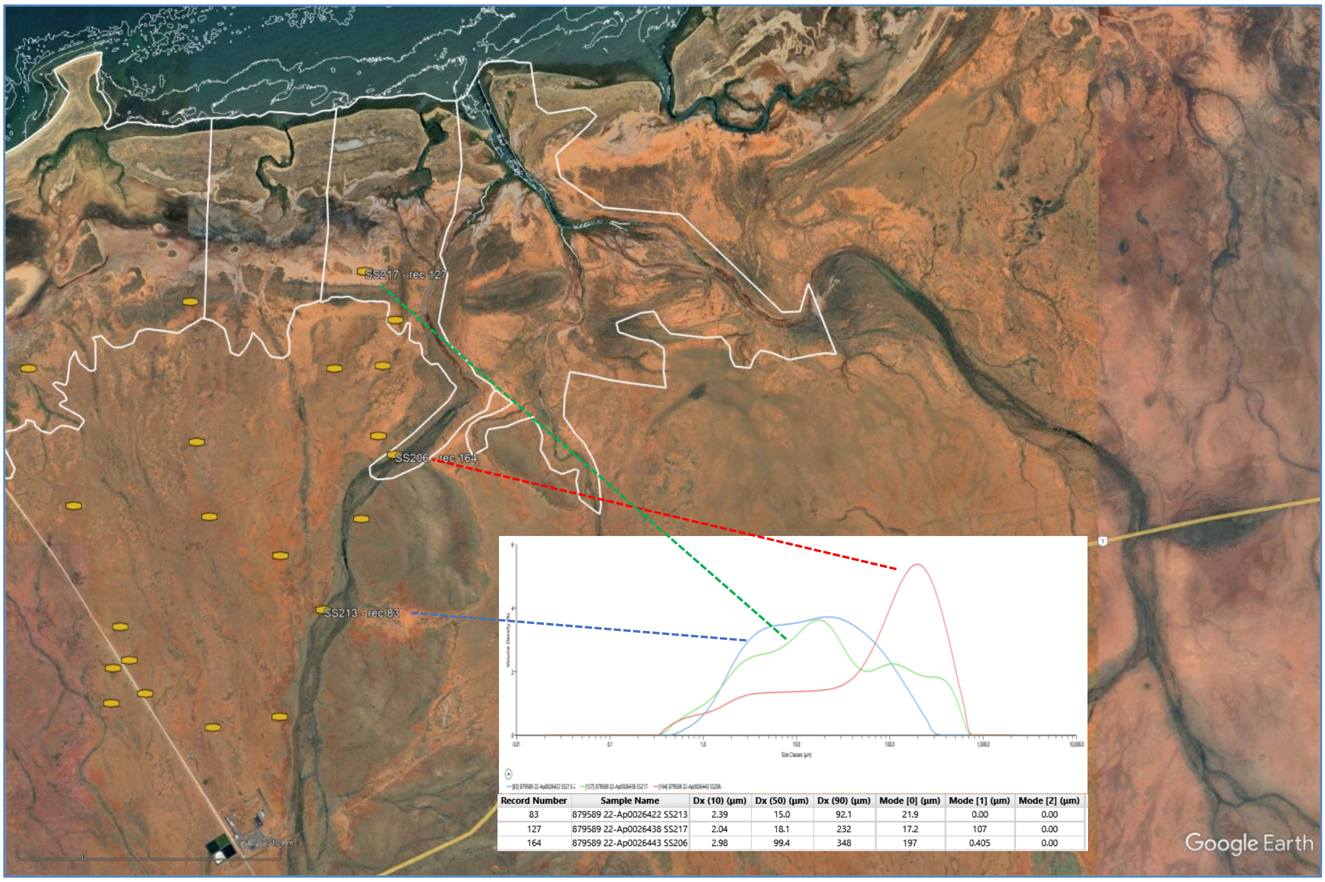
Record Number	Sample Name	Dx (10) (μm)	Dx (50) (μm)	Dx (90) (μm)	Mode [0] (μm)	Mode [1] (μm)	Mode [2] (μm)
204	879589 22-Ap0026432 SS108	3.22	22.6	103	31.1	0.00	0.00
235	879589 22-Ap0026435 SS107	1.74	12.4	129	8.76	75.9	0.202
69	879589 22-Ap0026420 SS119	3.42	115	484	365	99.5	6.06
373	879589 22-Ap0026428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

Figure 117. 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 118. PSD curves for samples in McKay Ck catchment.



Record Number	Sample Name	Dx (10) (µm)	Dx (50) (µm)	Dx (90) (µm)	Mode [0] (µm)	Mode [1] (µm)	Mode [2] (µm)
83	879589 22-Ap0026422 SS213	2.39	15.0	92.1	21.9	0.00	0.00
127	879589 22-Ap0026438 SS217	2.04	18.1	232	17.2	107	0.00
164	879589 22-Ap0026443 SS206	2.98	99.4	348	197	0.405	0.00

Figure 119. 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.

On the basis of the above, LS have collected a large suite of surface samples from across the ESSP area, designed to test the potential sediment transport pathways (Table 22), help reveal the active connections within the area and thus inform the resilience of the physical system to change. Laboratory analysis is underway[22] and interpretation of these samples is anticipated to follow.

10.5. Evidence of present processes

10.5.1. 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 120, Figure 121) for each relevant tidal catchment. A series of locations (shown in Figure 122) have been identified as indicative of significant change, and the key features are illustrated in Figure 123 to Figure 136 inclusive. Results are summarized in Table 20.[23]

In the estuary, aerial images tend to indicate a general increase in channel incision (Figure 123), but this cannot be definitive from aerial images alone.

Overall, between 1968 and 2022, almost all observed geomorphic change has occurred in the tidal creek systems, and its nature is consistent with expected 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:
    - 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.

Note that despite the clear geomorphic changes, there is a relatively small associated habitat response.

---

[22] As of early Feb. 2025.

[23] Table 14 contains links to the key Figures

- 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 eastern-most creek.

The smaller scale of the habitat response might indicate a time lag following 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 22.2).

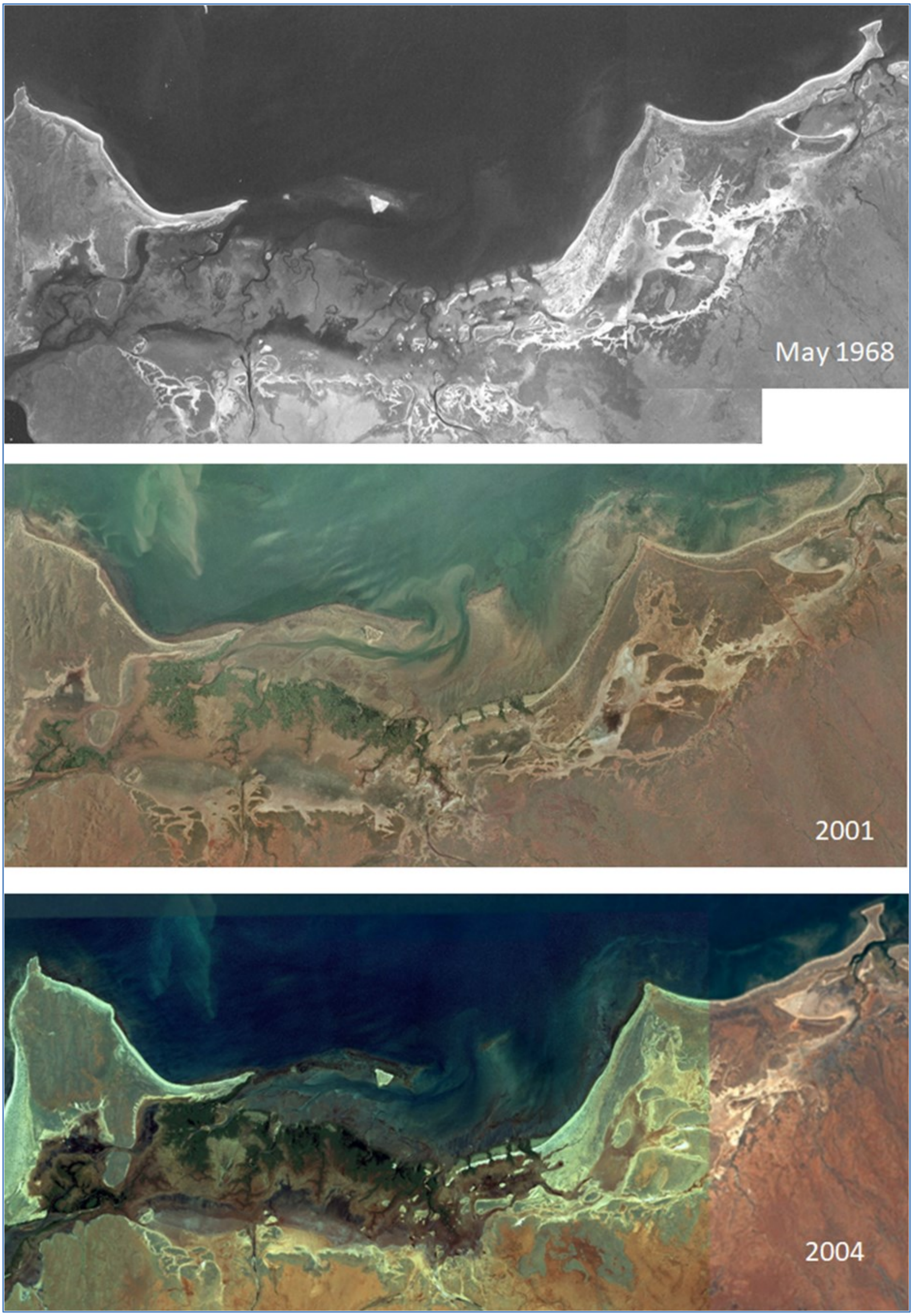


Figure 120. Historic Aerial Imagery 1968, 2001, 2004.

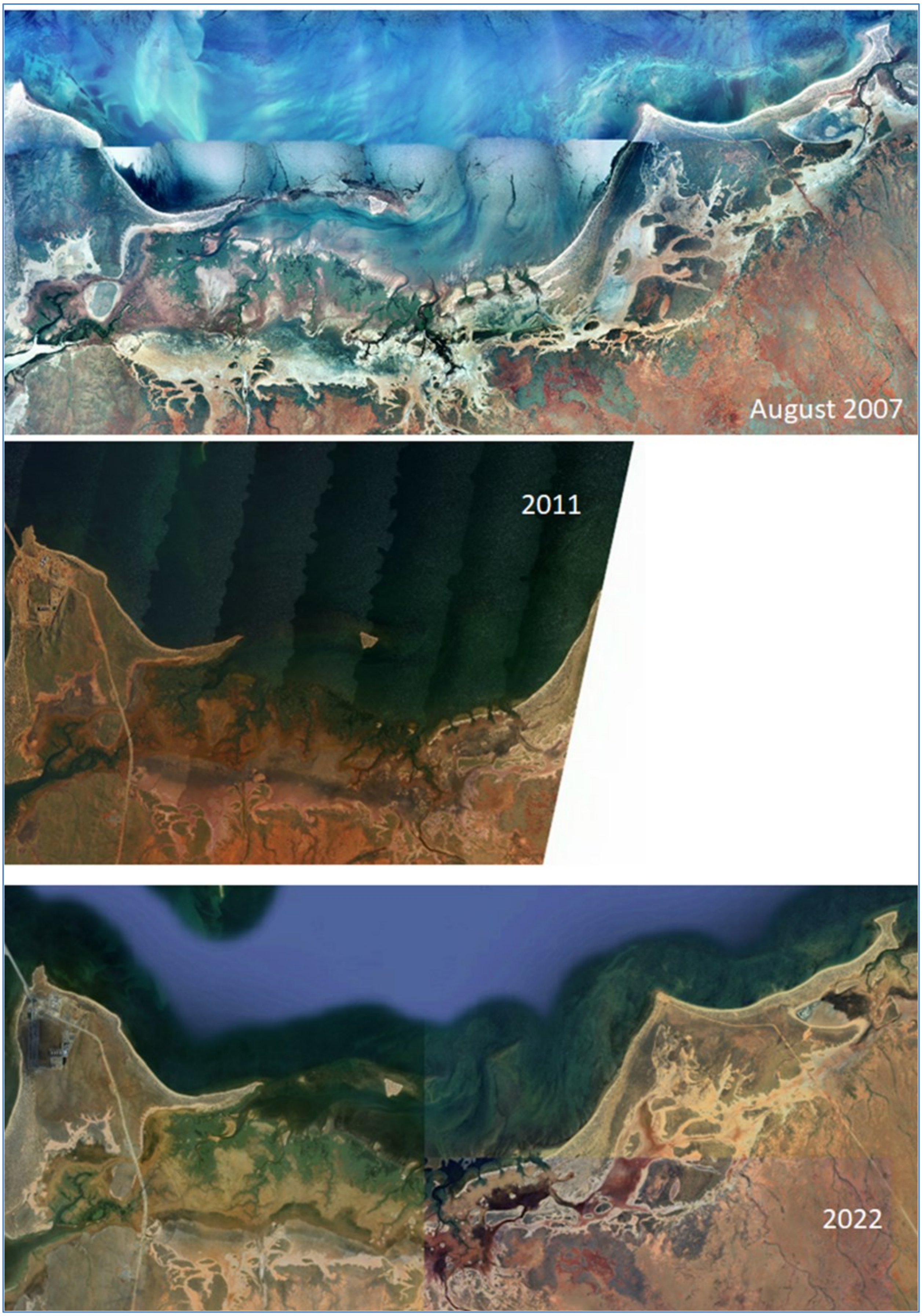


Figure 121. Historic aerial imagery 2007, 2011, 2022.

Figure 122. Locations of Figure 123 to Figure 136 inclusive.

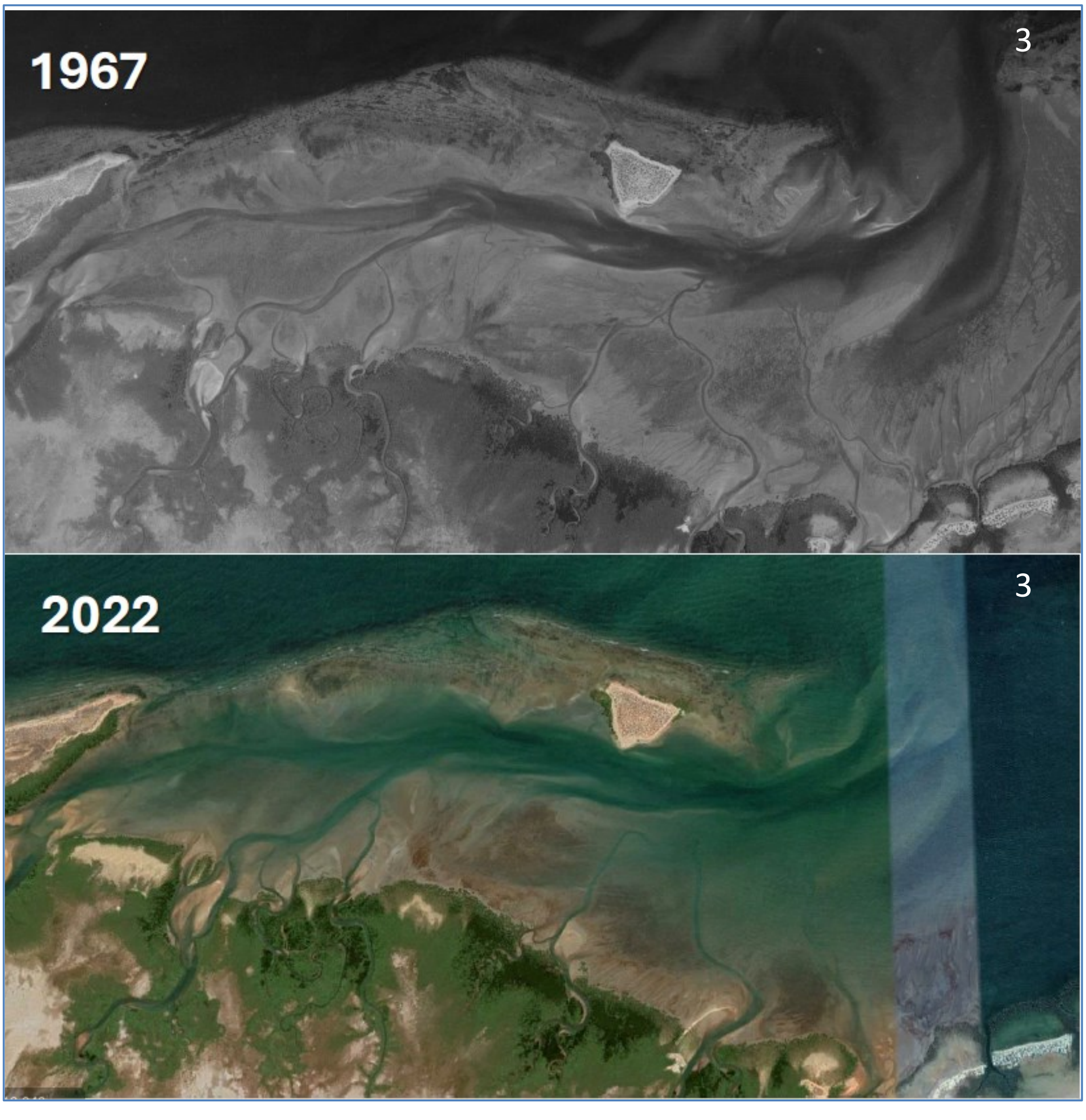


Figure 123. Changes in intertidal and shallow subtidal channel structure of the main estuary area, with most changes indicating a degree of channel incision.

Table 20. 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 124)
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 125)
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 126) • 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 134) apparently replaced by muddy sediment
Straight	Negligible change identified
McKay	• Extensive sediment fan apparent (over previous benthic mat) (Figure 132) • 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 131, Figure 133)
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 127), 4. Easternmost creek – landward edge of the estuarine mangroves fluctuates by 100 m landward (Figure 128) and channel incursion (Figure 129) Benthic mat coverage appears increased overall.
40 Mile E	• Extensive sediment fan apparent (over previous benthic mat) (Figure 130) • 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 sediment accumulation providing increased restriction to entrance

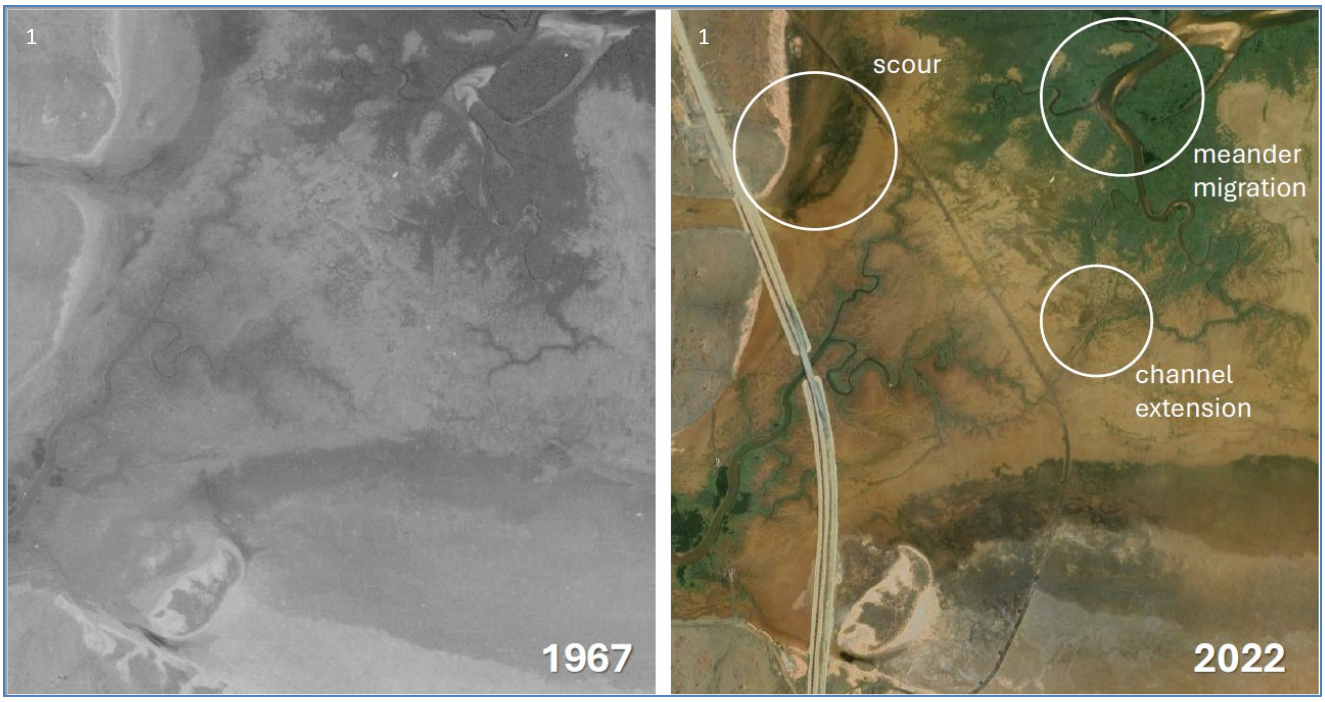


Figure 124. Differences in tidal creek characteristics for Creek 4 (scour at top left) and Creek 5 between 1967 and 2022 (after the construction of the Cape Preston road), including scour, meander migration and headward channel extension.

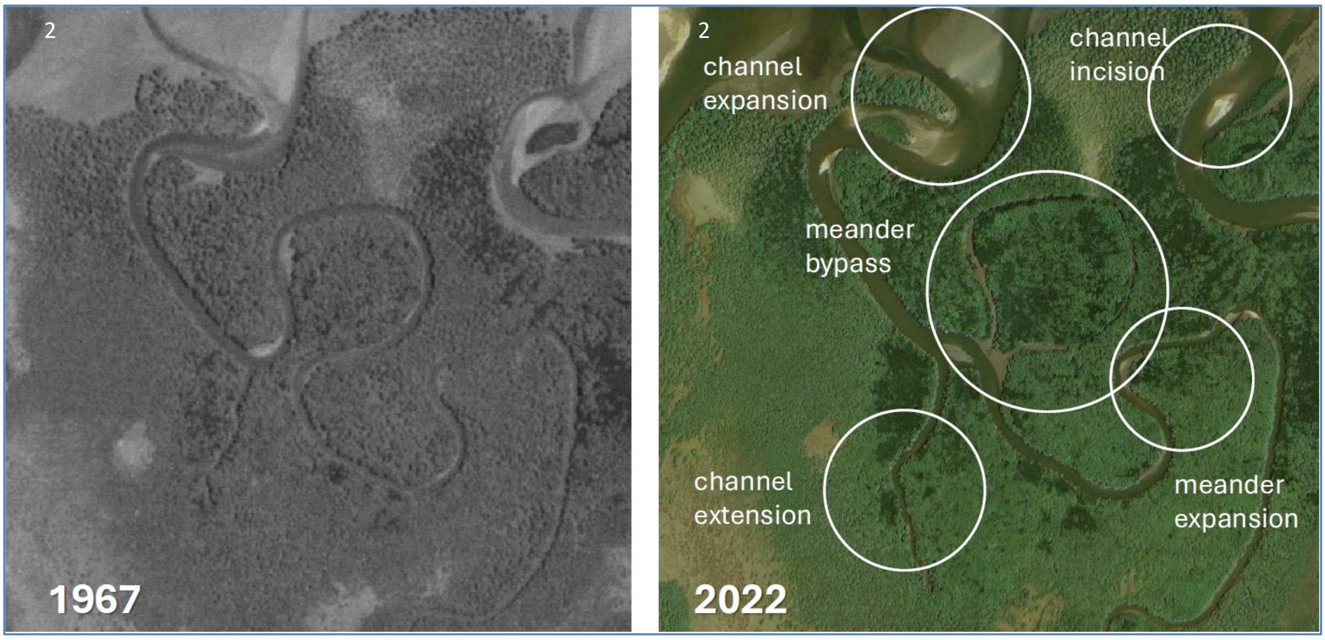


Figure 125. Various changes in the meandering eastern tidal creek of the Creek 3 catchment, including headward channel extension, the cut-off of a meander loop and channel expansion at the mouth (also for Creek 2, top right).

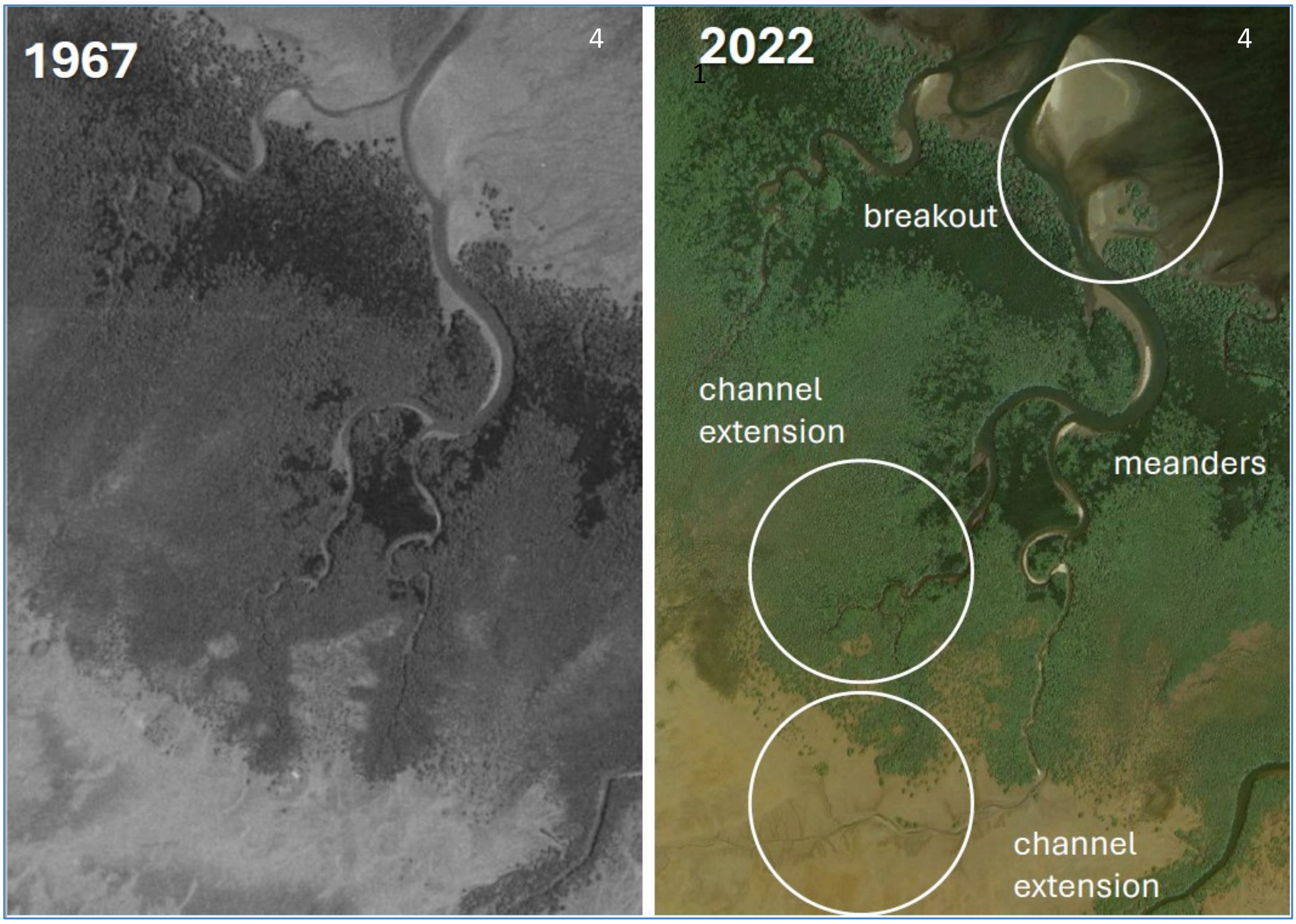


Figure 126. Headward channel extension in Creek 1, but note whilst the incised channels have extended landward, an increase in the extent of mangroves is far less apparent – they appear to have lagged the channel change.

Figure 127. Landward creek extension seawards of the central eastern barrier segment, nascent mangroves.

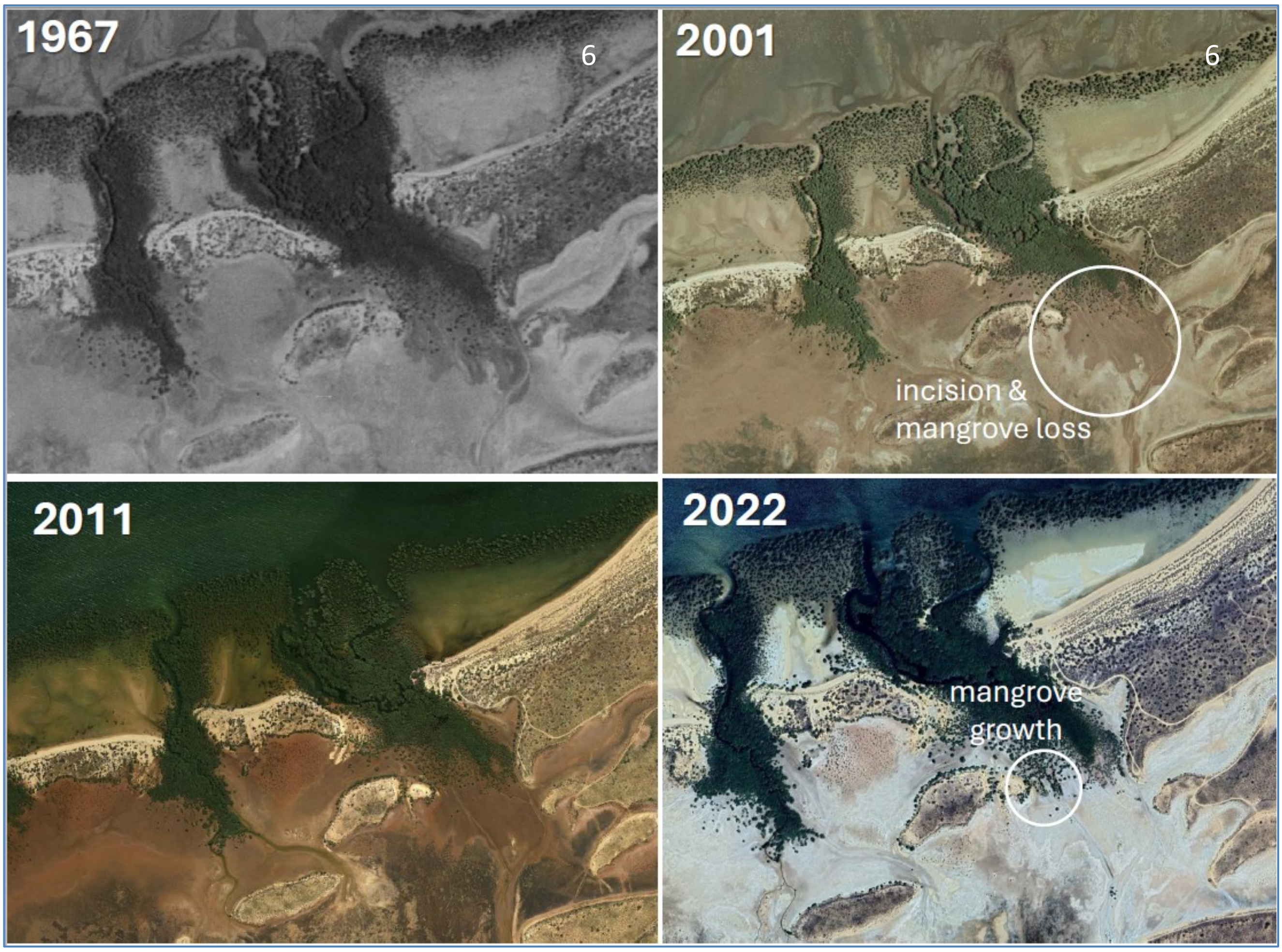


Figure 128. Fluctuations of channel incision with associated mangrove loss (2001) and subsequent regrowth (2022) at the head of the easternmost nascent mangrove creek.

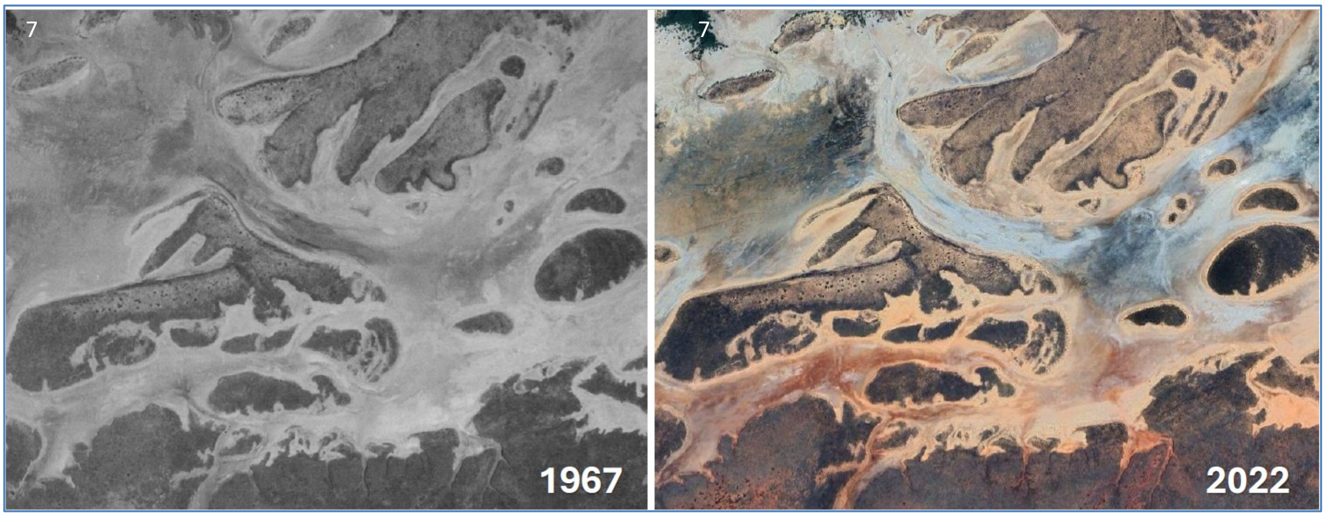


Figure 129. Numerous examples of channel incursion and expansion, SE part of 40 Mile Road W, behind the nascent mangroves.

Figure 130. 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 131. Landward channel extension to the east, with some pioneering mangroves. 1 km inland from McKay mouth, adjoining the SW nascent mangrove area.

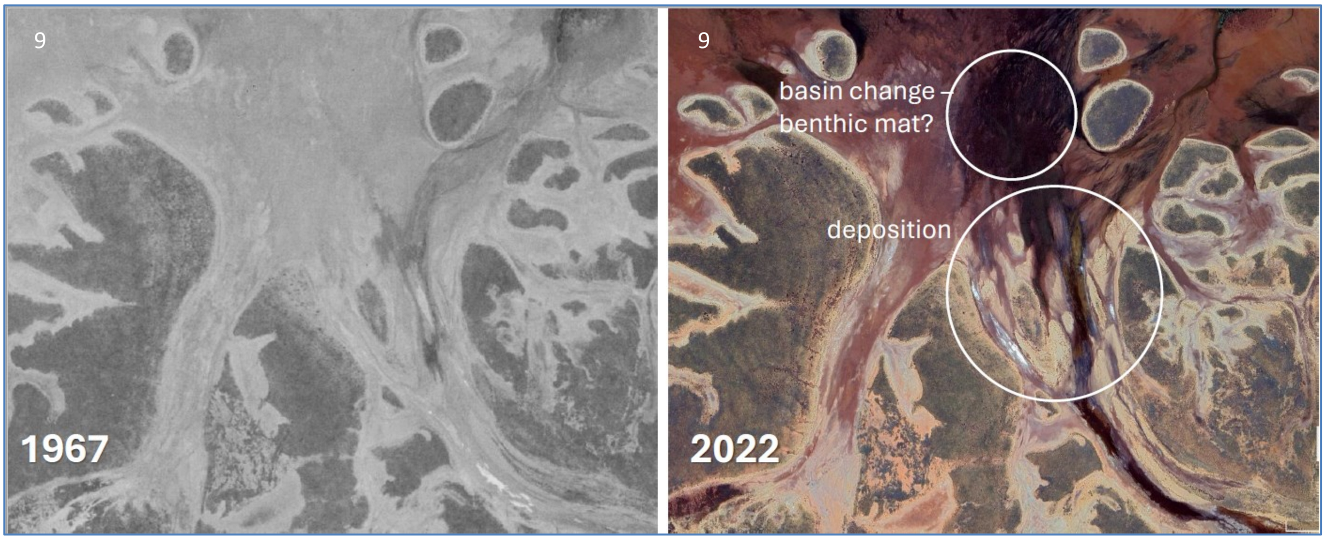


Figure 132. Sediment accumulation at the mouth of McKay Creek delta and associated apparent change in the benthic mat coverage to seaward on the tidal flats.

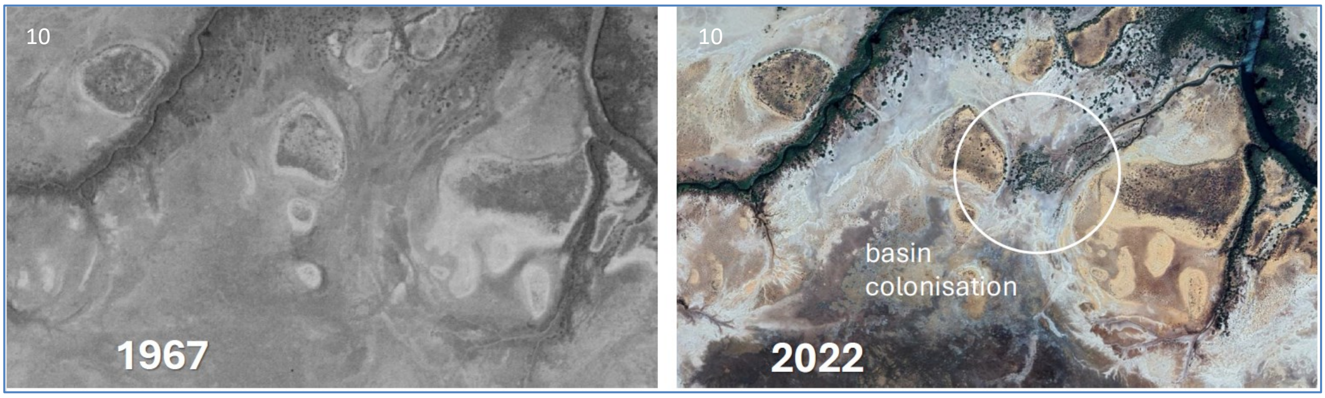


Figure 133. Creek extension to the SW and associated colonisation of a shallow basin on the western flank of the active tidal creek section of McKay Creek.

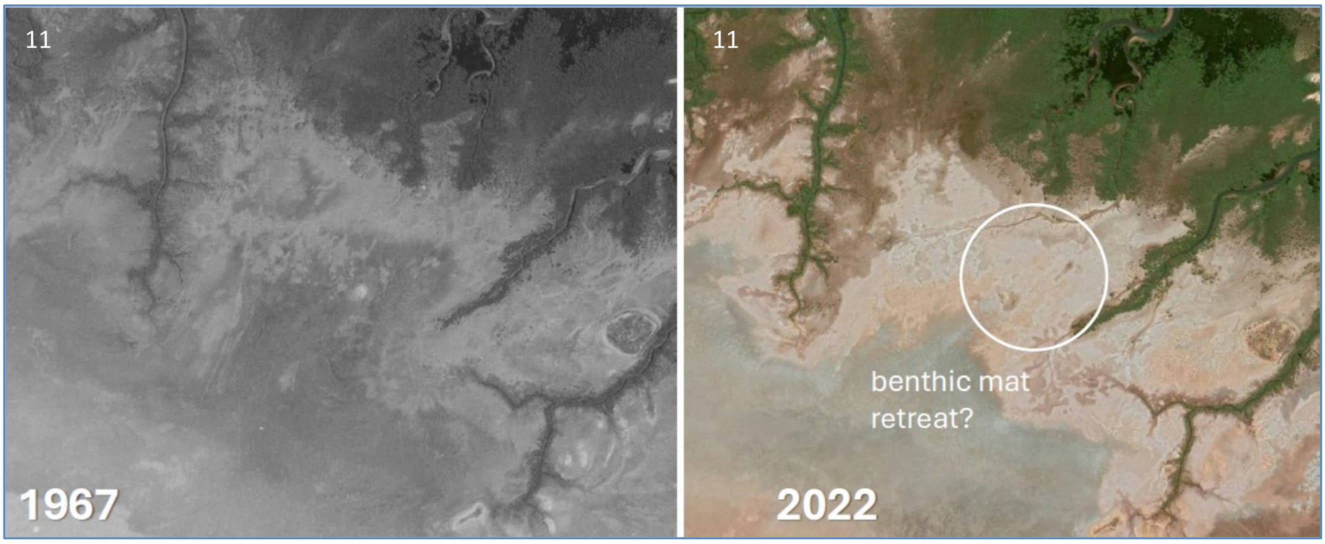


Figure 134. Landward (southward) advance of sediments associated with headward creek expansion and consequent benthic mat retreat (McKay Creek tidal flats).

Figure 135. Location of basin shown in Figure 136.

Figure 136. 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.

10.5.2. 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 elevation and other factors on 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 level, which has accelerated since the 1960s.

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

11. Quantitative past changes in coastal erosion and progradation

The online array of past aerial photos for the area was viewed using Nearmaps, but photos are of low quality and only go back to 2011 and are thus unsuitable for use. Hence the primary source of information on past changes at the coast itself is the data on horizontal movement of MSL, using the information presented by Geoscience Australia (2022) that provides data from 1988 to 2020, i.e., 32 years, during which time there was a mean SLR of 3 mm/year but with significant fluctuations (Section 4.1). It is important to understand that these data present an annualised view of the location of MSL, whereby all the fluctuations in the locations of MSL each year's data are reduced to a single measure at each point along the coastline, so this data cannot reveal fluctuations on timescales less than a year, and inevitably smooth out the data, reducing the extremes. Hence, it is vital to interpret the data by considering patterns shown by many points, and to analyse the data after grouping them into meaningful similar coastal features and environments.

Further, note that this dataset begins in 1988, and 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 in the eastern estuary nor indeed elsewhere along the ESSP shoreline and no data are available to know whether these did or didn't reset the shoreline in any significant physical way. Hence, the start here baseline of 1998 used in the analysis below is one dictated purely by the start of the available data, and is not physically significant.

Regionally, change averaged for each point along the coastline over the 32-year period is highly variable (Figure 137). There are some clear areas of high rates of change, such as at the coastal erosion at the proposed Mardie Solar Salt development zone (on the mainland coast SE of Barrow Island), and accumulation in the southernmost Dampier Archipelago. More locally, covering the estuary area, the average movement over 32 years has been highly variable (Figure 138). East of Cape Preston, the open coastline has some relatively low average rates of net erosion or net progradation, and some more complex patterns in the estuary itself.

Figure 137. General pattern of coastal progradation (blue) or erosion (red) along the region's coastline.

Feature Information

No data is available here - try another location.

Lat / Lon 20.90158°S, 116.32369°E

Figure 138. Changes in coastline position at Cape Preston and along the coastline affected by the project. Major changes have occurred along the west coast of Cape Preston, but the coast is relatively stable immediately to its east. Greater change has taken place in the mangrove-fringed areas seawards of the proposed ponds, and less variation in the extreme east near Gnoorea.

11.1. Cape Preston Beach

East of Cape Preston itself is a long NE-facing beach with its western portion appearing to be controlled by many intertidal and shallow subtidal outcrops of calcrete (and possibly ferricrete) (Section 9.2.1). This western part of the beach houses the Cape Preston port infrastructure and the proposed location for the ESSP jetty. The eastern part of the beach is set back to the south and curves around to the rocky outcrop of Little Hill, indicating that it is probably headland controlled at both ends.

The Geoscience Australia (2023) data indicate that between 1988 and 2021, most of this beach has remained stable or eroded slightly, with most mean erosion over that period less than 0.3 m/year (Figure 9). Noting that the GA data represent the best estimates of the horizontal location of MSL at the shoreline, this beach's relatively high exposure to waves from the NE sector might result in natural changes in beach steepness and shape, so that the plotted data probably include a degree of variation.

Figure 139. Mean rate of shoreline change (m/yr) between 1988 and 2021 for Cape Preston beach to Little Hill (O2 Metocean 2023a using data from Geoscience Australia 2023). The western part of this beach, at the proposed jetty site and to its west, appears to be controlled by underlying hard rock.

11.2. The estuary – the western ESSP area

This section describes some key features and gradients in, defined by a set of discrete areas (Figure 27) defined to help illustrate the sedimentary processes in the estuary. Note that the area named “M Ck” covers the lower portion of McKay Creek and much of the adjacent subtidal zone of Straight and McKay Creeks.

Below these areas are described in turn, using the Geoscience Australia time-series data on the horizontal movement of the location of MSL (Figure 140).

Figure 140. Mean rate of shoreline change (m/yr) between 1988 and 2021 for the southern bank of the estuary (O2 Metocean 2003 using data from Geoscience Australia, 2023).

Some available historical images indicate a key feature in the eastern estuary. This is a large area of shallow water, presumably of soft sediments, located immediately south of the rock outcrop in the central estuary mouth, and thus seawards of the McKay Creek mouth and directly to seawards of Areas D, the nascent mangroves (Figure 141). This feature appears in aerial images back to at least 2004 (Figure 142) and so appears at least a semi-permanent feature of the lower intertidal and shallow subtidal zone. When present, it will reduce the exposure to waves of the area to seawards of the nascent mangroves and will also act to reduce the exposure to waves of McKay Creek mouth.

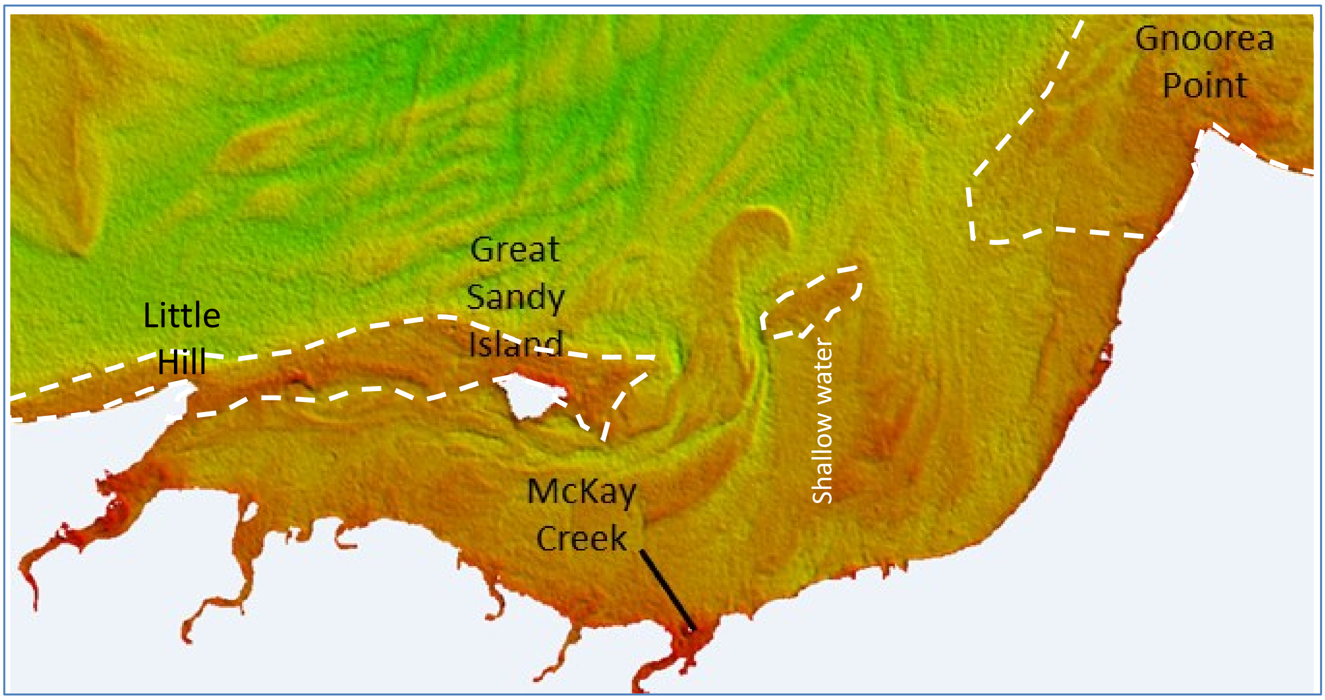


Figure 141. Local bathymetric and seabed features (after Lebrec et al., 2021). Note the incised tidal channels close to the southern coast, within the greater estuary, and their termination east of Great Sandy Island, between seabed outcrops of bedrock to the west and east (white dashed areas). These exposed and shallow submerged rock exposures control the adjacent coastline, including to the south within the estuary. Note the shallow water immediately south of the central marked rock outcrop.

Figure 142. Google Earth images of the estuary seawards of the nascent mangroves indicating the presence of shallow water (if sediment accumulation then it is an incipient tombolo) south of the seabed rock outcrop.

11.2.1. Area A – the western estuary coastline

This area (Figure 143, Figure 144) is strongly sheltered from waves, tidally dominated with strong tidal currents and sediment transport parallel to the main tidal creeks and channels. The main tidal channel is probably maintained by the scour of the spring ebb tides. The general pattern over the last 32 years is of little change along the fringing mangrove shoreline itself, with most change concentrated i) in the tidal creeks, being related to lateral movement of the creeks' channels, and ii) near the creek mouths. The data indicate relatively continuous change through time, with no major events of coastline migration. This tends to support the interpretation of tidally dominated processes with relatively little influence from episodic events. It is interpreted that the coastal sedimentary environments are probably largely stable through time, affected mostly by local changes in the tidal channels, banks and bars, with little net change overall.

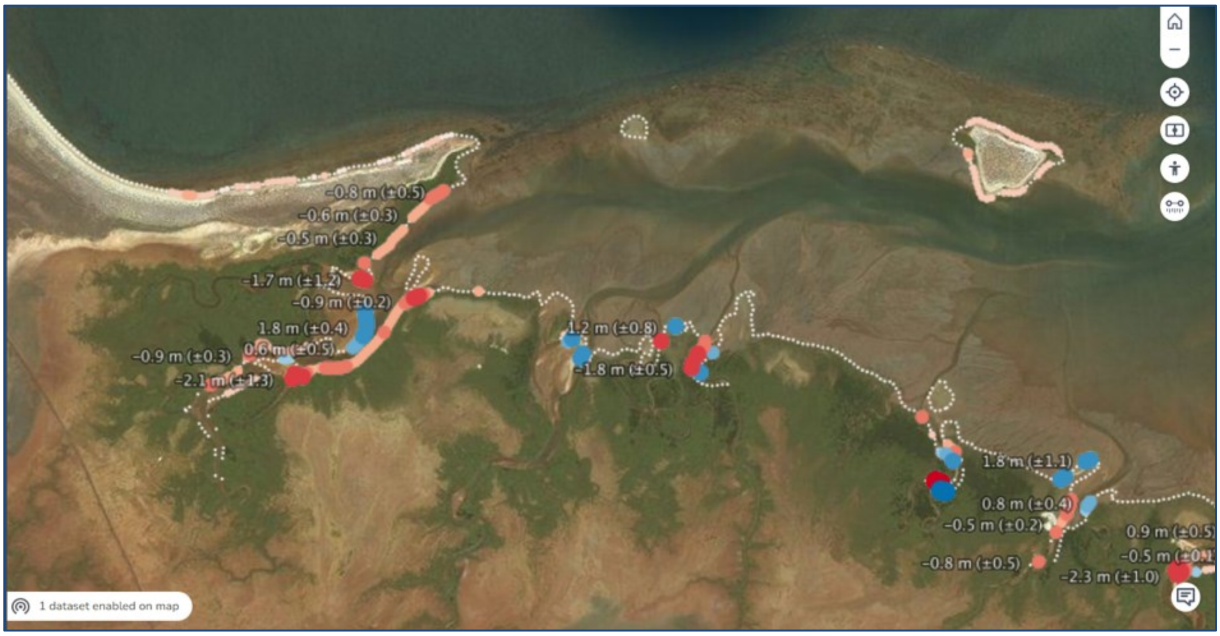
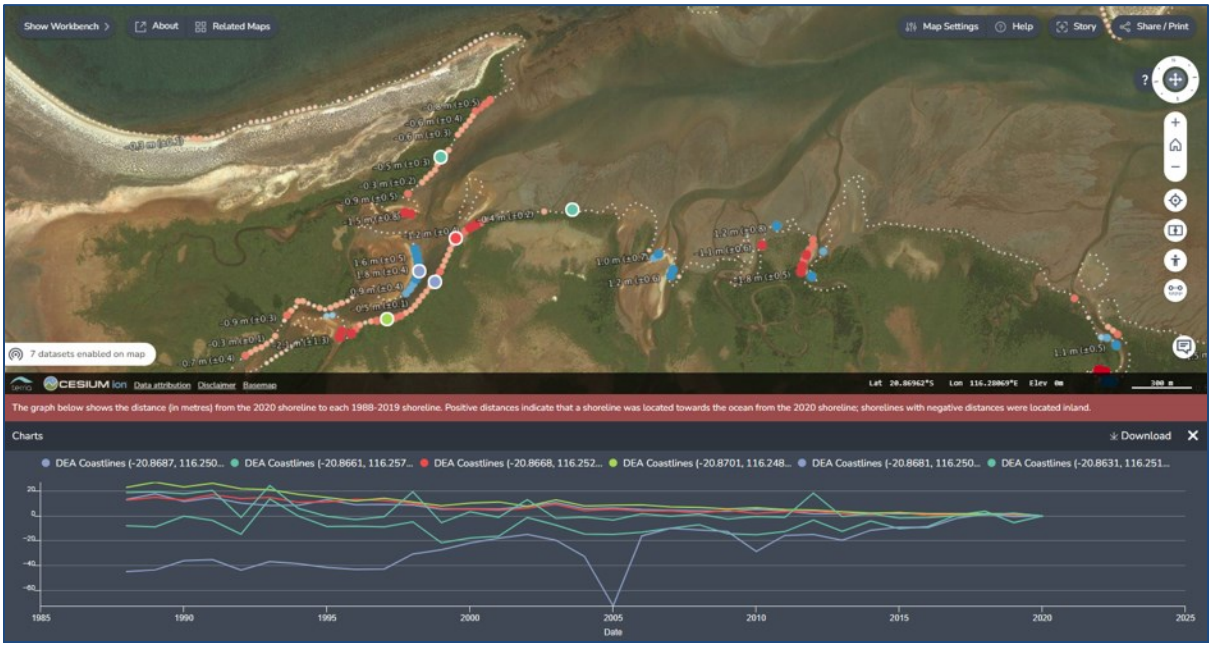


Figure 143. Area A - General pattern of erosion (red) and progradation (blue) since 1988. White dots indicate areas of little net change since 1988.



The graph below shows the distance (in metres) from the 2020 shoreline to each 1988-2019 shoreline. Positive distances indicate that a shoreline was located towards the ocean from the 2020 shoreline; shorelines with negative distances were located inland.

Figure 144. Area A - Time-series of erosion (-ve) and progradation (+ve) for selected points since 1988. Channel banks within the creek are mostly eroding, near the mouth are migrating laterally at around 0.5 - 2 m/year, with little net

change just seawards of the mouth. Total of ~10 m horizontal erosion over 32 years outside the estuary mouth along the open coast (2 x dark green lines), i.e., 0.3 m/year.

11.2.2. Area B – the central estuary coastline

This area (Figure 145, Figure 146) is relatively sheltered, tidally influenced, with a largely progradational coastline with few creeks. Episodes of erosion are probably minor, with relatively little along-coast transport of material. Sedimentary environments are probably largely stable through time.

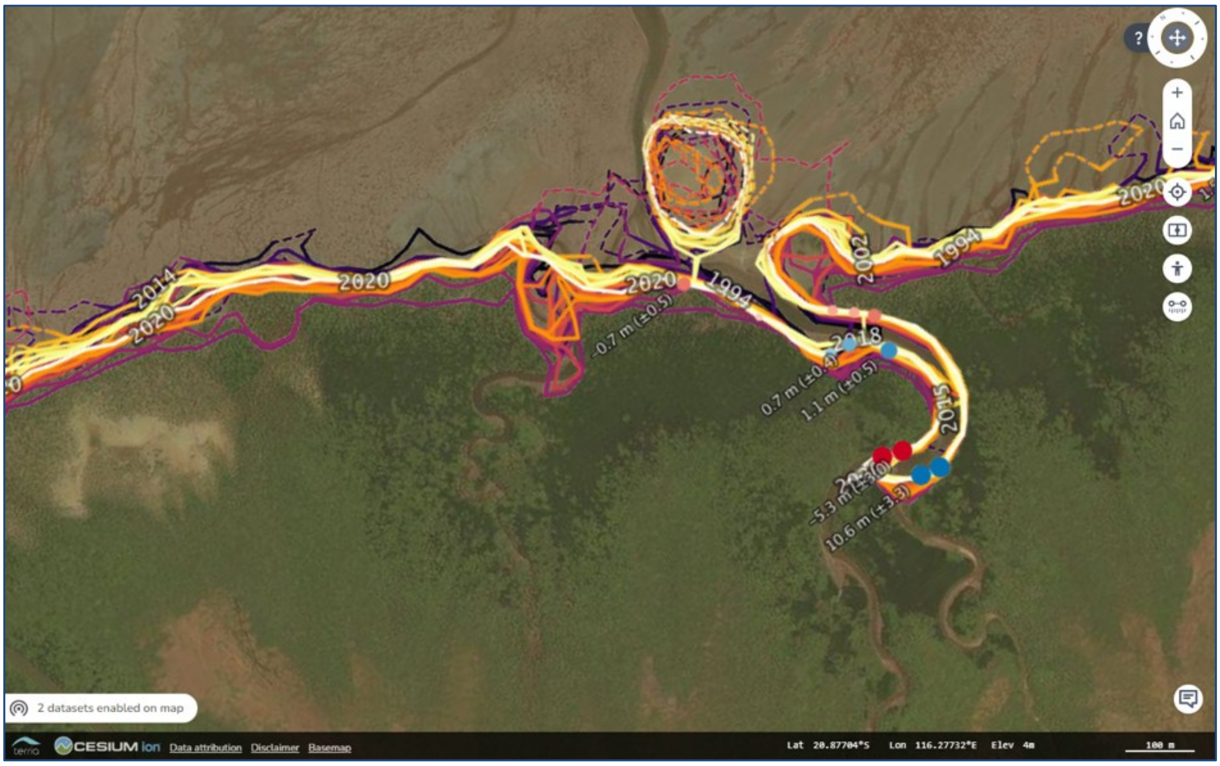


Figure 145. Area B - General pattern of erosion (red) and progradation (blue) since 1988. White dots indicate areas of little net change since 1988.

The graph below shows the distance (in metres) from the 2020 shoreline to each 1988-2019 shoreline. Positive distances indicate that a shoreline was located towards the ocean from the 2020 shoreline; shorelines with negative distances were located inland.

Figure 146. Area B - Time-series of erosion (-ve) and progradation (+ve) for selected points since 1988. Note the apparent erosional event in 1998 with recovery over the subsequent 4-5 years. (Spikes in the red line probably represent changes in the mouth bar and are not significant). Total of ~10 m horizontal erosion over 32 y, i.e., 0.3 m/year.

11.2.3. The designated area named MCk

This area contains a mix of modern processes, combining influences from the E-W tidal action of Area E, of N-S tidal action in and out of Straight and McKay creeks, of resuspension by waves and possibly alongshore flow driven by winds. The open coast shows almost no net migration (Figure 147, Figure 148) over the last 32 years. Immediately east of McKay Creek mouth the data show a spread of past coastline positions, indicating large changes including much apparent erosion and progradation. However, the seabed here is of shallow gradient so the ‘coastline’ data represent only normal and minor vertical variability of the shallow intertidal sandbars.

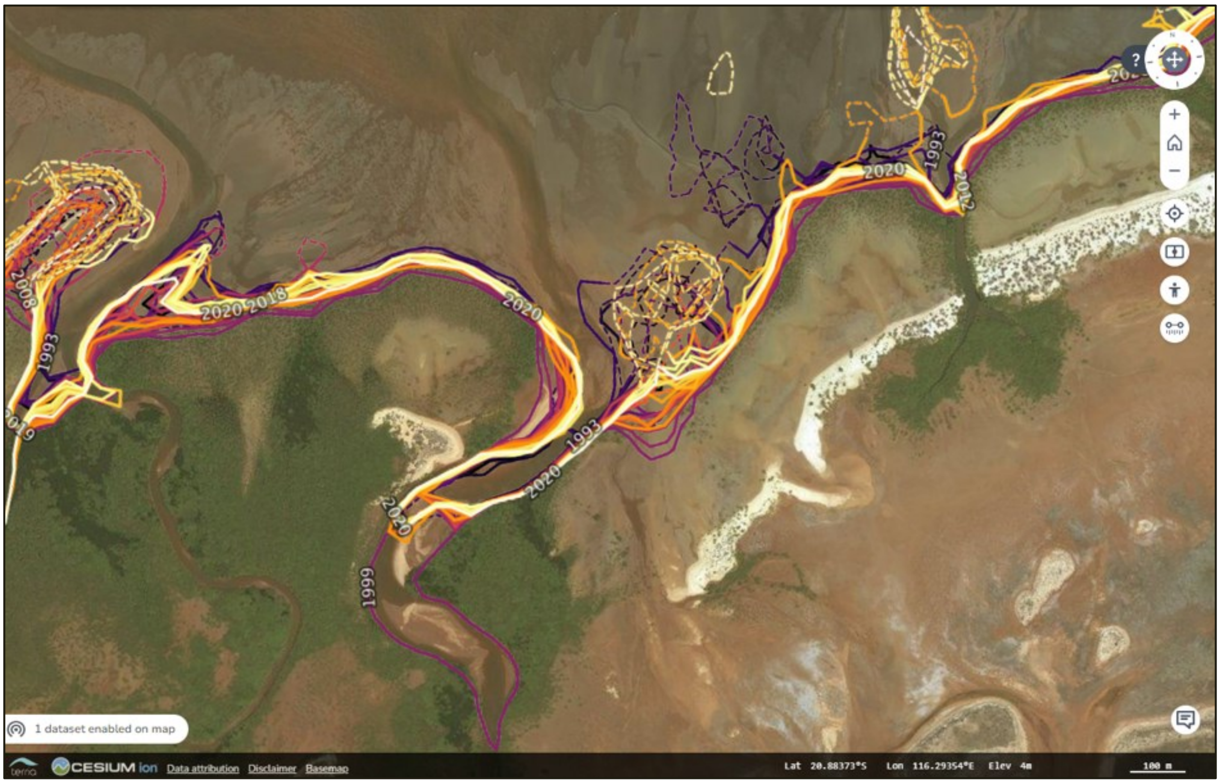


Figure 147. Area MCk - General pattern of erosion (red) and progradation (blue) since 1988. White dots indicate areas of little net change since 1988.

The graph below shows the distance (in metres) from the 2020 shoreline to each 1988-2019 shoreline. Positive distances indicate that a shoreline was located towards the ocean from the 2020 shoreline; shorelines with negative distances were located inland.

Figure 148. Area MCk - Time-series of erosion (-ve) and progradation (+ve) for selected points since 1988. Note the very large changes immediately east of the creek mouth (spikes in the uppermost green line), where there has been net erosion of 0.7-1.2 m/year since 1988, mostly reflecting the changing presence and absence of a large sandbar seawards of the mouth. The open coast (smoother dark green line and the purple line) shows almost no net migration.

11.2.4. Area C – the nascent mangroves

This area (Figure 149, Figure 150) appears semi-exposed to waves, and appears to be a relatively 'episodic' coast, with periods of erosion and landwards transport of sand (and presumably shelly material from erosion of intertidal flats) indicated by the presence of relatively steep storm beaches (white) and fronted by nascent mangrove fringes that represent periods of progradation between erosive events. There appears some sediment export from small tidal creeks, and probably some minor alongshore transport, variable in direction. The sedimentary environments close to the coast will be variable through time with significant episodes of erosion and subsequent progradation.

There was a major erosional event of 1998-9, where the location of MSL moved landward by 20-40 m, with recovery occurring over the subsequent 4 years. This may have been related to the effects of TC Gwenda and/or TC Vance (Figure 151). Here, the seawards margin of the nascent mangrove fringe is located 220-290 m seawards of the white storm beach. The timing of beach formation is unknown.

Figure 149. Area C - General pattern of erosion (red) and progradation (blue) since 1988. White dots indicate areas of little net change since 1988.

The graph below shows the distance (in metres) from the 2020 shoreline to each 1988-2019 shoreline. Positive distances indicate that a shoreline was located towards the ocean from the 2020 shoreline; shorelines with negative distances were located inland.

Figure 150. Area C - Time-series of erosion (-ve) and progradation (+ve) for selected points since 1988. Note the major erosional events of 1998-9, where the location of MSL moved landward by 20-40 m, with recovery over the subsequent 4 years. Total of ~8 m horizontal erosion over 32 y, i.e., 0.25 m/year.

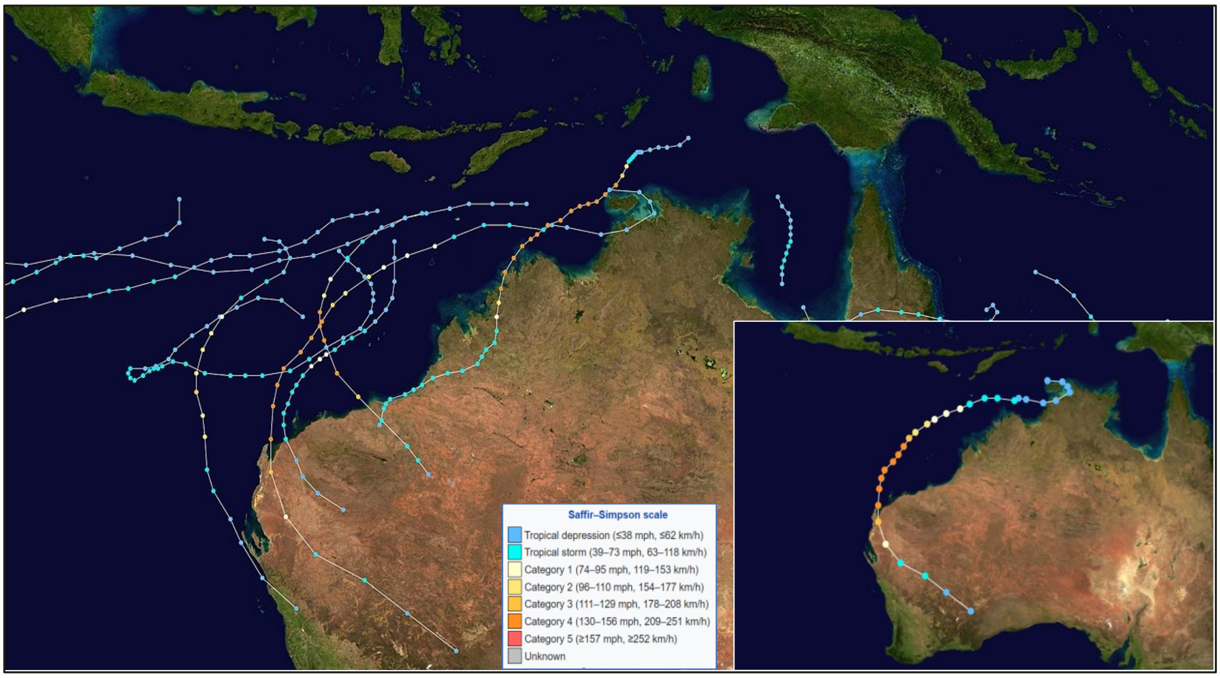


Figure 151. Cyclone tracks for the 1998-9 TC season in northern Australia (Wikipedia, 2007). Inset - Track and intensity of TC Vance, 16-23 March 1999.

11.2.5. Area D - the eastern estuary coastline

This area of the eastern estuary (Figure 152, Figure 153) is a wave-exposed sandy shoreline, with sediment movement erosive or translational alongshore (to E or W, probably variable) and progressively more exposed to waves to the NE. Transport at the coast is probably a combination of day-to-day transport and episodic events. A narrow band of *Avicennia* mangroves occurs along the coastline itself, but it is absent in SW part of the area where the coastline has been most erosive since 1988. To seawards there are wide tidal flats, probably highly mobile. There was a major period of erosion between 1995 and 1999, especially in the north, but with little overall change over 32 years.

Figure 152. Area D - General pattern of erosion (red dots) and progradation (blue dots) since 1988 (image rotated for clarity).

The graph below shows the distance (in metres) from the 2020 shoreline to each 1988-2019 shoreline. Positive distances indicate that a shoreline was located towards the ocean from the 2020 shoreline; shorelines with negative distances were located inland.

Figure 153. Area D - Time-series of erosion (-ve) and progradation (+ve) for selected points since 1988. Note period of erosion all along the area between 1995 and 1999, especially great in the north, but there has been little overall change, with a total of ~4 m horizontal erosion over 32 y, i.e., 0.12 m/year.

11.2.6. Area E – Great Sandy Island

The mangroves on the island (Figure 154) display a variety of changes, as might be expected from the different faces of an island. Nonetheless, all sites show erosion between 1993 and ~2000, and subsequent general stability. The southern boundary of the deep tidal channel of the main estuary is marked by a large eastward-pointing sediment tail (bottom centre of the aerial image of Figure 154), stemming from the edge of the shallow banks to the south, indicating long-term net easterly (ebb) sand transport in the channel.

The graph below shows the distance (in metres) from the 2020 shoreline to each 1988-2019 shoreline. Positive distances indicate that a shoreline was located towards the ocean from the 2020 shoreline; shorelines with negative distances were located inland.

Figure 154. Area E – General pattern and time-series of erosion (-ve) and progradation (+ve) since 1988 for points distributed around the island in the north of the image. Note the complex pattern, possibly because of the very different facing directions of the coastline. Nonetheless, all sites show erosion between 1993 and ~2000, and general overall stability since then. Total of ~6 m horizontal erosion over 32 y, i.e., 0.18 m/year.

11.2.7. Preliminary conclusions for the estuary

- Areas A, B, MCk, C & D together form a general W-E gradient of decreasing tidal influence and increasing fair-weather wave influence on the shoreline environments, with the detail that Area D in front of the nascent mangroves is probably more protected by the sediment accumulated to seawards.
- Area D – This is a wave-exposed sandy shoreline, with sand transport erosive or translational alongshore (to NE or SW, probably variable), and progressively more exposed to day-to-day waves towards its NE end. Locked at its northern end by the bedrock of Gnoorea Point, it is probably controlled by a combination of day-to-day and episodic waves. There are wide tidal flats to seawards, probably highly mobile. A narrow band of *Avicennia* mangroves occurs in front of the beach ridges but is absent in the southern part where GA data indicate the coast was subject to most erosion since 1988. Sedimentary environments close to the coast are variable through time with significant episodes of erosion and subsequent progradation.

- Area E – Apart from the island itself, this area is highly likely to be tidally dominated, with strong ebb flows scouring and maintaining the main channel. The distribution of sedimentary environments is likely to be relatively stable.
- Area MCk – This area is likely to be a combination of all the above, perhaps making it difficult to predict. McKay Creek is located broadly in the middle of the above-described spatial gradients, including:
    - The E-W gradient in coastal morphology, tidal influence and relatively exposure to episodic weather events (e.g., waves from tropical cyclones and lows)
    - Combining the E-W tidal currents action of area E with the N-S tidal flows in and out of Straight and McKay creeks.
    - Likely resuspension of intertidal sediments by waves
    - The general distribution of sedimentary environments is likely to be relatively stable but locally highly variable through time.
    - For the period 1982 onwards, the open part of the coastline at McKay Creek is an exception to the regional net erosion – it experienced no net erosion in this period (Table 21). One possibility is that the McKay Creek mouth, located at the southernmost point of the coastline, and SW of the shallow water behind the estuary-mouth rock outcrop (Figure 64, Figure 66, Figure 142), is a site of preferential net sediment accumulation within the bay. There appear few coastal processes able to remove sediment from the intertidal zone there, and so it might have accumulated sediment at a rate broadly equivalent to the erosion elsewhere. This is a working hypothesis only but is consistent with the basic geomorphology.

11.3. Forty Mile Beach

Forty Mile Beach extends between the bedrock headlands of Gnoorea Point and Pelican Point, with rock outcrops also common along the beach (Short 2005) including in the central section (Figure 155). Much of this coastline remained stable between 1988 and 2021, with mean changes of less than ± 0.3 m/year. The exception is near Pelican Point at the eastern end of the beach, where annualised erosion was 0.40 m/year, landward of a gap in the subtidal platform, where waves from the NW sector are most likely to erode the beach. Overall, this long beach is likely to exchange relatively sediment around its rocky headland, and the rocky shallow subtidal zone along much of the bay has a steep face to seawards into Regnard Bay (Figure 64, Figure 65) so that most sediment exchange is likely to be limited to shoreward or seaward transfer from the bay, and this is unlikely to occur at any significant rate.

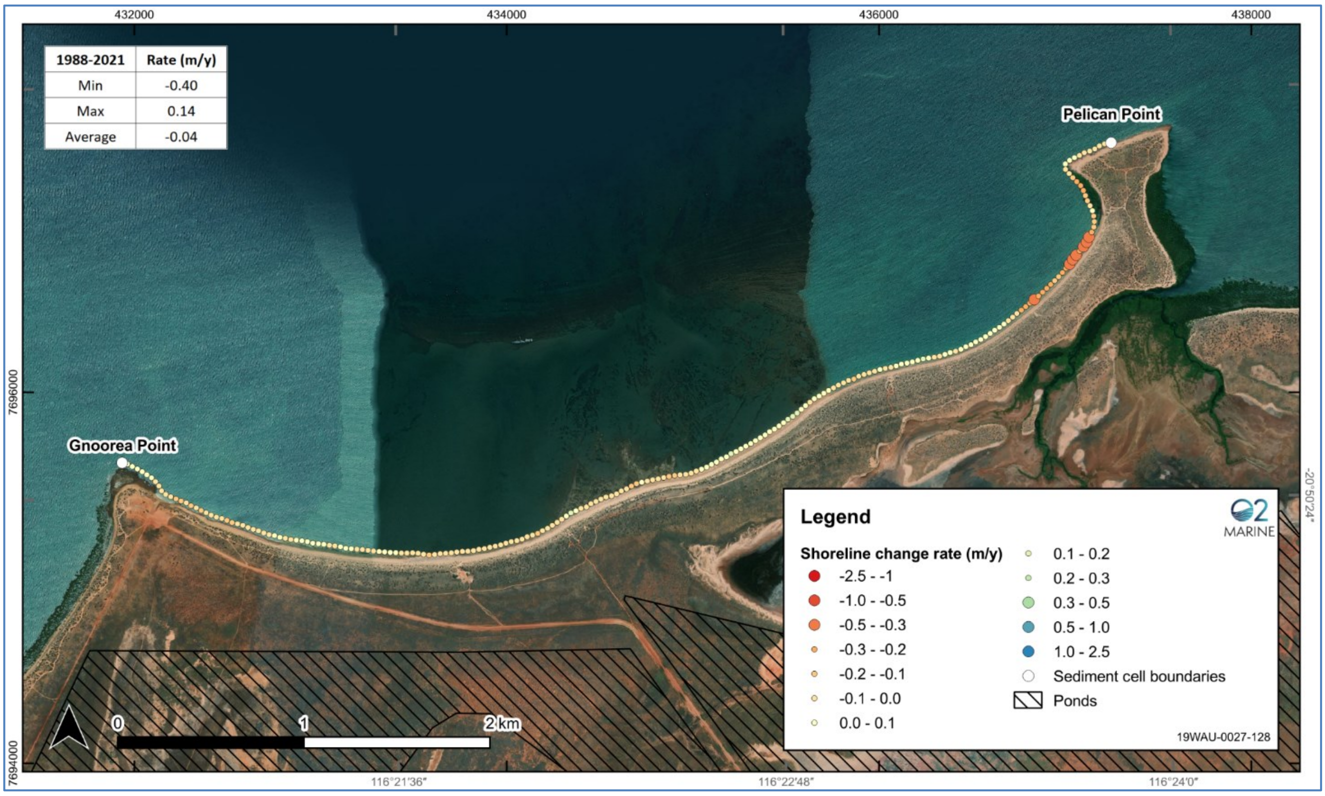


Figure 155. Rate of shoreline change 1988 and 2021 for Forty Mile Beach (O2 Metocean 2023a).

The largest erosion event occurred in 1999 and generated a maximum shoreline retreat of ~10 m in the central section of the bay W of Pelican Point, where higher rates of changes compared to the rest of the beach were also noted. Most of the beach recovery occurred in the first year following the erosive event (up to ~7 m and average of 1.9 m) and the pre-erosion status was achieved in three years in the eastern section of the beach and in four years in the western section of the beach.

11.4. The eastern ESSP area

The coastline at the eastern end of the ponds (Figure 71) has four creeks each containing estuarine mangroves. Between creek mouths, fringing mangroves occur along the open coastline, and shallow intertidal flats occur to seawards. Note that the lines from different sites are broadly parallel, indicating that all sites on the open coastline tend to move together, probably indicating a common driver. Like some other areas further west, all sites show erosion between 1993 and ~1999, with later stability.

The graph below shows the distance (in metres) from the 2020 shoreline to each 1988-2019 shoreline. Positive distances indicate that a shoreline was located towards the ocean from the 2020 shoreline; shorelines with negative distances were located inland.

● DEA Coastlines (-20.8265, 116.4344) Distan... ● DEA Coastlines (-20.8280, 116.4271) Distan... ● DEA Coastlines (-20.8288, 116.4180) Distan... ● DEA Coastlines (-20.8296, 116.4109) Distan... ● DEA Coastlines (-20.8298, 116.4052) Distan...

Figure 156. Area at the eastern end of the ESSP area – General pattern and time-series of erosion (-ve) and progradation (+ve) since 1988 for five points along the open shoreline. Note that these tend to advance and retreat in unison. All sites show erosion between 1993 and ~1999, and general overall stability since then. Total of ~8 m horizontal erosion over 32 y, i.e., 0.25 m/year.

11.5. Regional patterns of coastal change

As shown above, between 1993 and 1999, there was a sustained 6-year period of erosion for all ESSP areas, which lasted a year longer for Great Sandy Island. For all areas, rates of erosion were particularly high for 1998-9, so that the coastline[24] everywhere was located farthest landward in 1999. After this widespread erosion, there was a regional period of recovery lasting 3 years (4 years for Area B).

This 1993-1999 phase of erosion and subsequent 1999-2003 recovery is a regional signal, present for many 10s of km in either direction along the coast. 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 (O2 Metocean 2022a). The question is what might be responsible for these changes. Two main options are considered below, episodic cyclones and long-term (multi-annual) changes in MSL.

11.5.1. Tropical cyclones

Since 1988, many cyclones have passed the ESSP area (Table 8), and during the broad 6-year long 1993-1999 period of coastal erosion these include TCs Bobby (Feb. 1995), Olivia (April 1996) and Vance (1999). For example, in April 1996, TC Olivia passed NW of Eramurra (Figure 158), exposing the coastline to a period of

---

[24] Remember that this refers to the estimated location of MSL.

winds from the stronger eastern side of the wind field, and associated waves. In March 1999, TC Vance passed west of the area creating a surge at Onslow that flooded several houses, and at Tubridgi Point there was severe coastal erosion and widespread denudation of vegetation (BOM, 2000). (Note that the specific effects of these or other cyclones on winds and waves in the Eramurra area have not been analysed.)

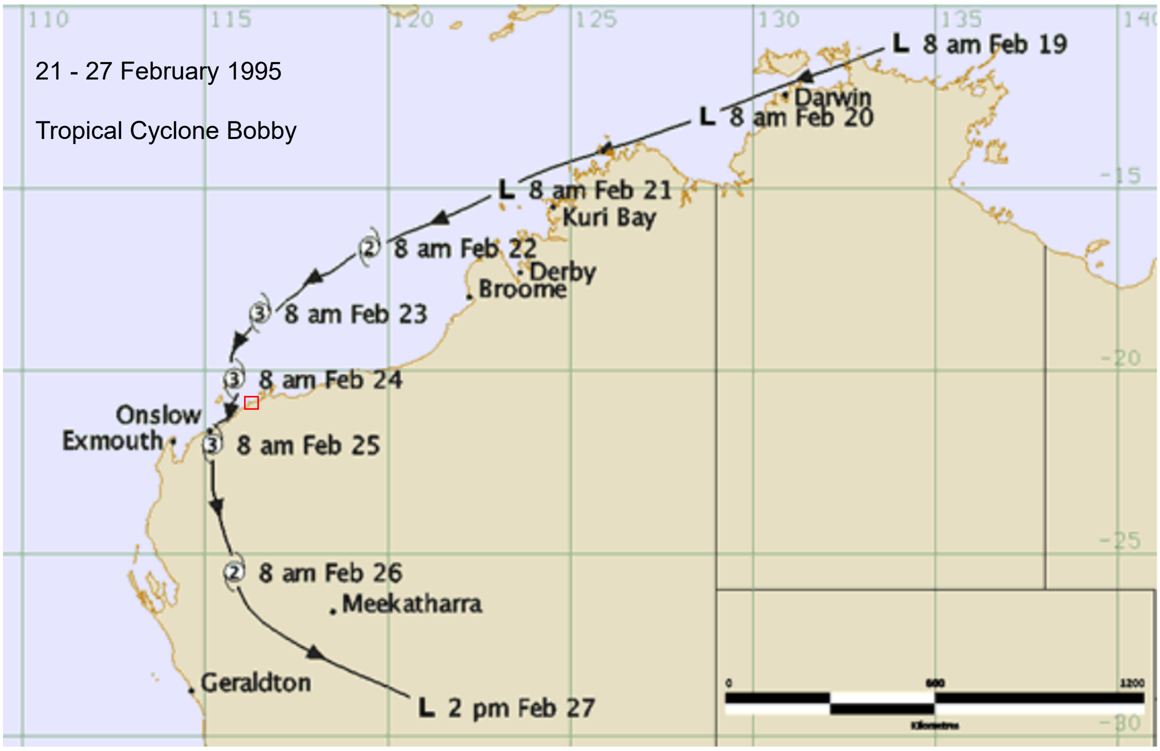


Figure 157. Track of TC Bobby in 1995 (BoM, 2000). The cyclone passed NW of Eramurra (red box), so exposing the coastline to the stronger eastern side of the wind field and associated waves.

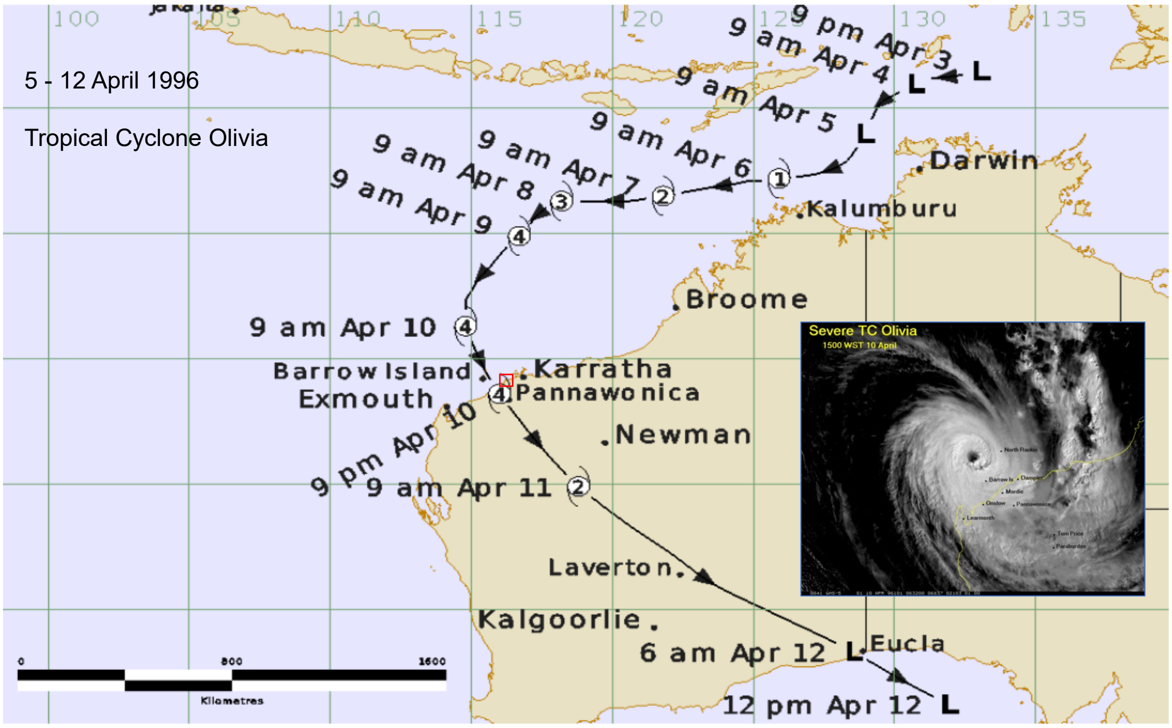


Figure 158. Left - Track of Severe TC Olivia in 1996. The cyclone passed NW of Eramurra (red box), exposing the coastline to the stronger side of the wind field and associated waves, with the largest waves likely to have been generated by the (weaker) northwesterlies in the wake of the storm. Inset - Satellite image of Severe Tropical Cyclone Olivia, 10 April 1996 (BoM, 2021).

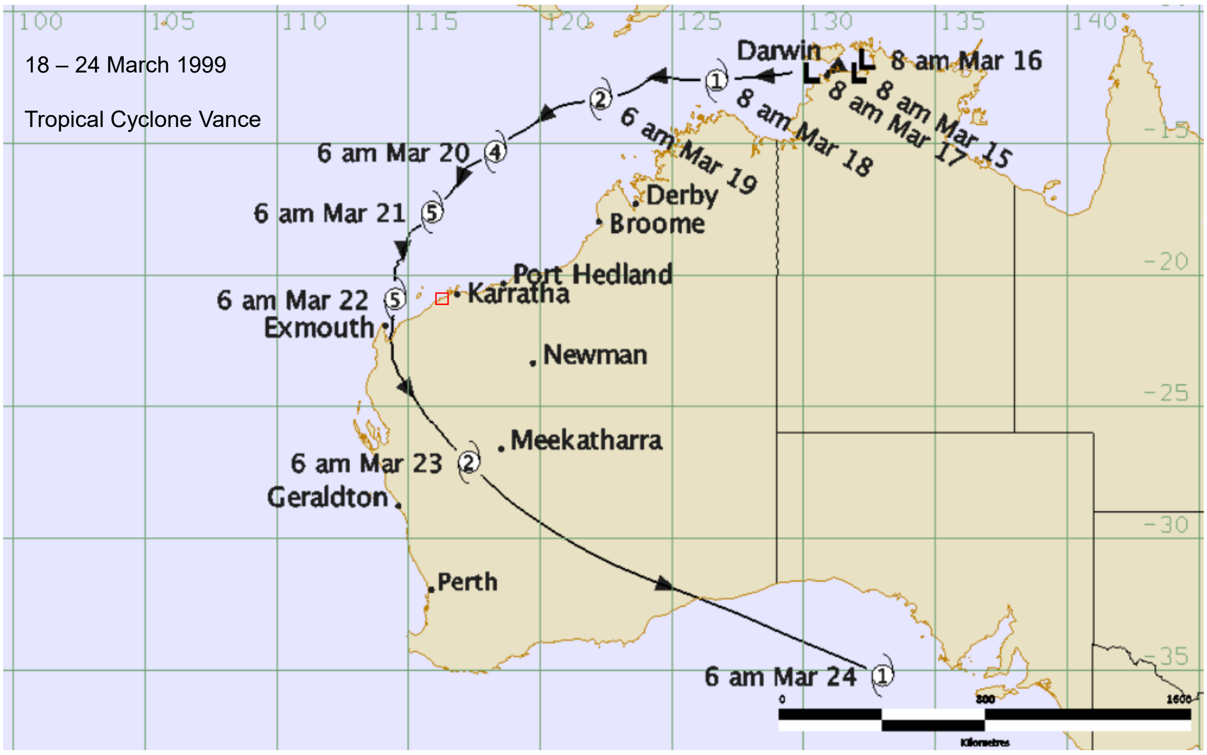


Figure 159. Track of Severe TC Vance in 1999 (BoM, 2000). The cyclone passed NW of Eramurra (red box), so exposing the coastline to the stronger eastern side of the wind field and associated waves.

Figure 160. Coastal erosion resulting from the storm surge associated with TC Vance west of Onslow (BoM, 2000). It was estimated that the surge reached 6-7 m AHD at the coast and that the water was up to 2 m deep about 200 m inland (Nott & Hubbert, 2004). The erosion and the resulting coastal morphology indicate severe wave action at the coast.

Whilst local variations occur along the project area's coastline so that this 1993-1999 signal of erosion and 1999-2003 recovery is not ubiquitous, it is consistent with the regional signal, which is present for many tens of km in either direction. Further, since 2003 (i.e., post-recovery), there has been the nearby passage of five cyclones, during which time most of the Eramurra coastline has experienced relatively little movement in the location of MSL, except for some fluctuations in Area C in 2011-2. The effect of individual cyclones on coastal erosion in the area is thus highly variable, with many showing no discernible effect in the annualised dataset.

The data on coastal erosion in the project area have been collated in Table 21 with some estimates of the rates of post-erosion 'recovery' in each area. All data therefore represent minimal magnitudes and annual rates of change. These estimates concentrate on the open coast, ignoring data spikes caused by local sandbar movements and migration of creek channels. Recovery rates are the focus because they will tend to be slower than the erosion rate, because erosion might relate to a short-lived episodic event, unable to be captured by annualised data. It is concluded that:

- On the open coast, periods of recovery from erosion commonly occurred at rates of annualised rates of 10-25 m/year (of progradation).
- Maximum annualised rates of erosion can be at least 2-3 times as fast.

As context for these conclusions, the riverine sediment load to the coastal zone is generally considered relatively low across the region, averaging ~0.3 Mt/year along the ~300 km of coastline between the North West Cape and Dampier, with the Ashburton River being the main contributor, representing about half of the total solid discharge (Margvelashvili *et al*., 2006). Using a grain density of 2.6 this is equivalent to 0.12 x 10^6 m^3/year, equivalent to only 0.4 m^3/year averaged for each km of shoreline.

Table 21. Estimated rates of horizontal change across the western area indicated by GA data using changed locations of yearly mean horizontal locations of MSL.

Area	Rates of change since 1988 (open coast) Erosion -ve	Date of period of uniform change across the area	Magnitude of Erosion -ve Progradation +ve	Duration for '**recovery**'	Rate of 'recovery' Range (& ~mid-range)
	m/year		m	year	m/year
A	-0.3	None	-	-	-
B	-0.3	1990-2	-20 to -40	2	10 – 20 (15)
		1998-9	-40 to -50	4	10 – 12 (11)
		2002-5	-20 to -30	-	-
		2011-12	+15 to +35	1	15 – 35 (25)
MCk	~0	1991-2	-8 to -30	1	10 – 30 (15)
		1998-9	20	3	7
C	-0.25	1998-9	-20 to -40	3	7 – 13 (10)
		1991-2	-10 to -20	1	10 – 20 (15)
		1992-3	5 - 40	1	5 – 40 (22)
		1997-9	-20 to -40	3	7 - 13 (10)
		2011-12	8 - 50	1	8 – 50 (21)
D	-0.12	1991-2	-5 to -25	1	5 – 25 (10)
		1998-9	-5 to -45	3	0.6 to 15 (8)
		2009-11	-5 to -28	1	5 to 25 (10)
E	-0.18	2001-2	4 - 9	1	4 to 9 (6.5)
Eastern end of ponds	-0.25	1991-2	-8 to -25	2	8 to 18 (13)
		1998-9	-15 to -25	3	15 to 38 (27)

For the eastern estuary coastline, i.e. the western flanks of Gnoorea sipt, 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 158), and whilst local variations occur along the project area's coastline, there is a local and regional signal of coastal advance (1999-2003).

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 (O2 Metocean 2022a).

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.

11.5.2. Mean sea level (MSL)

As noted in Section 2, MSL itself is not the key or sole controlling factor upon the coastline, however because it affects the location of every daily process, it can have a gradual effect in the long term. Indeed, over a period of the last 30 years or so, the time-series data on coastal changes appears to be broadly synchronous with changes in MSL (Figure 161). 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 this signal in coastal erosion is a regional one, so does indicate a potential relationship worthy of further investigation.

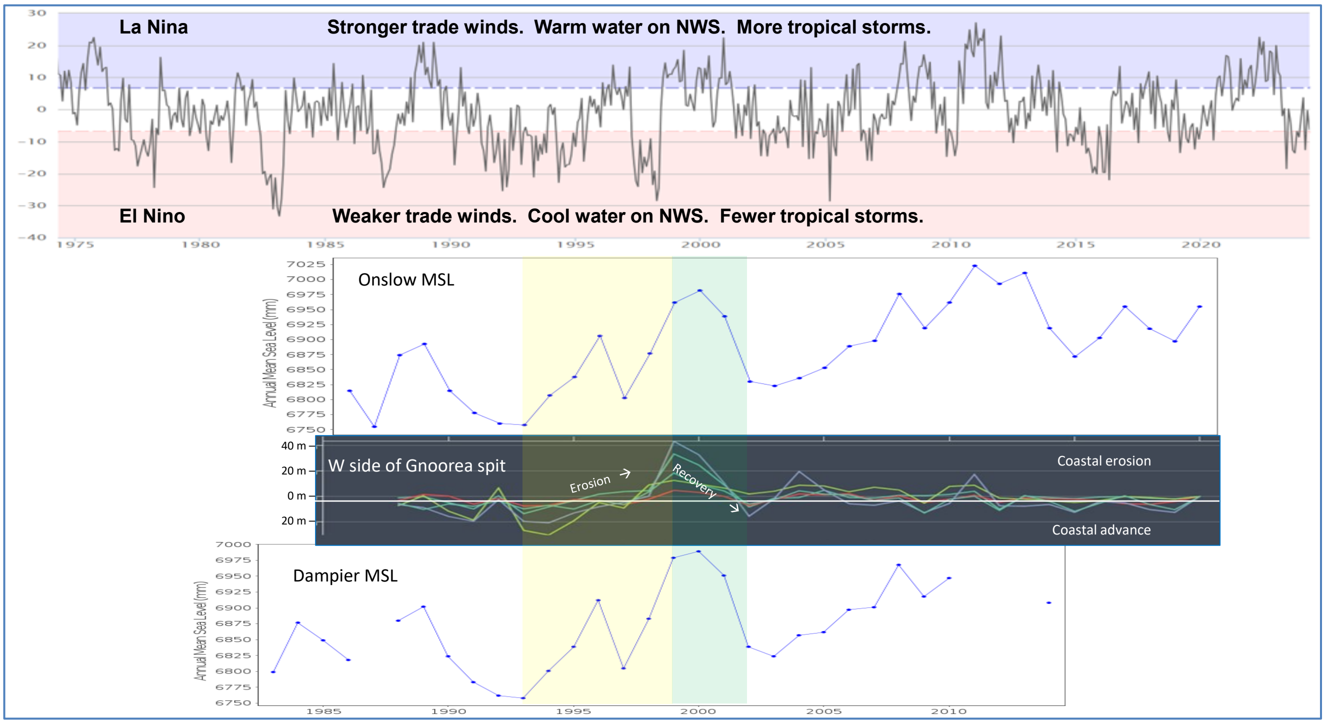


Figure 161. The SOI, plus data on mean annual sea level at Onslow and Dampier overlain with the mean annualised erosion or advance of the coastline along western Gnoorea spit (vertical scale inverted to aid comparison with SOI & MSL). Yellow bar = Erosional phase 1993-1999. Green bar = Recovery phase 1999-2002. (SOI from http://www.bom.gov.au/climate/enso/soi/).

11.6. Summary of past quantified coastal change

From the above, we can note that cyclones and MSL both might play a role in past coastal changes, but that their relative role is yet to be clarified, and especially for cyclones, it is likely to be event specific.

As noted above (Section 4.1), this report has adopted 3 mm/year to represent mean SLR for the period 1988-2020 for the ESSP. Over the full 32-year GA dataset on coastal change, there is slight net erosion indicated in almost all areas, at 0.25-0.3 m/year on shallow gradient sediment-rich coasts (Areas A, B, C and the eastern end of the ponds), and around half that (0.12 - 0.18 m/year) on steeper coastlines such as Areas D and E. Whilst there are some indications that this may reflect a signal related to long-term SLR (Figure 161), it could also be associated with the occurrence of tropical cyclones. Few data are available to test this further, and it is unknown whether the coastal sedimentary system was in a state of near-equilibrium with sea level in 1988 when the GA data begins.

Importantly, it is possible to quantify some relevant rates of change:

- Assuming sufficient sediment is available, 10-25 m/year of coastal progradation appears a general measure of the ability of sedimentary processes to restore an open sediment-rich low-gradient coastline after a period of erosion.
- For a slope of 1:1000, along the total of 7 km of the western and central estuary's southern shoreline, this represents a total of 35-90 m^3/year of sediment accumulation.
- For Areas D & E, that may have steeper shorelines at the coast itself, i.e., a different shape across the intertidal zone, the equivalent progradation rates are lower, at perhaps 6-10 m/year. For example, if the slope was 1:200, for the total of 4 km of the eastern portion of the estuary's southern shoreline, this progradation rate would represent a total of 60-100 m^3/year of sediment accumulation.

These rates are considered the best information available to support estimates of future rates of coastal progradation relevant to BCH areas at, and seawards of, the present ESSP coastline.

12. 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.

12.1. 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 the data allows testing of postulated modern active sediment transport pathways. A series of specific sediment transport pathways (Table 22) 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 22.

Table 22. 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

12.2. Ages of sedimentary units

12.2.1. 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 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 low ability of the coastline to adapt to change in the past, 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.

12.2.2. ESSP units

The main units were outlined in the main text in Section 8.6. and illustrated in simple form in Figure 73. No age dates exist. Based on their modern relationships to RSL, and the RSL curve in the last 120,000 years (Figure 13 to Figure 15), 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.

PART THREE – THE ESSP REGION, NATURAL FUTURE CHANGE

13. Assessing sedimentary resilience

The text below deals with coastal changes over the new few decades and out to a century ahead, specifically in the absence of the proposed ESSP development.

To repeat, in this report, sedimentary resilience refers to the capacity of natural processes to maintain the presence and integrity of those sedimentary environments that house the BCHs. The aim is to assess **sedimentary resilience over several decades into the future.**

First, the relevant factors on sedimentary processes and sedimentation on subtropical shelves and shorelines have been described elsewhere, in brief, they are shelf bathymetry and peritidal topography, fluvial sediment delivery, shelf sediment availability, waves, tidal range and currents, and cyclones. It is important to note the wide range of factors involved, and especially the mix of periodic and episodic factors. Note that sea-level change is not by itself a factor that drives coastal change (Larcombe *et al.*, 2018), but rather it can contribute towards altering some of the key driving factors involved and their location, with consequences for the coastline that are sometimes unclear.

Secondly, as noted elsewhere in this report (Section 5), coastal change might not occur smoothly nor maintain a particular coastal morphology. In those areas of relatively unchanging sediment availability, simple coastal morphology and invariable driving processes, it might be a defensible first-order estimate to assume landward migration of sedimentary environments and their associated habitats over the next few decades. Locally this might include the area around Gnoorea (Figure 162) and towards Pelican Point. Here, the morphological features are most likely to migrate in a single direction, at least on timescales of a decade or two.

Figure 162. Example areas (yellow boxes) in the region for which an assumption of future simple landward migration of morphology and associated habitats might be a reasonable initial estimate. Left box - the coastline north of the Mardie solar salt development zone. Right box - the coastline near Gnoorea.

In contrast, where the coastal system is more complex, which is the case for most of the ESSP coastline, assuming simple future change is not a reasonable option, especially over periods of decades. For example, a tidal creek mouth might become closed permanently, so that a small tidal delta with weak tides and ample sediment supply might be changed into a barrier-lagoon system. Potential candidates are those nascent mangroves and small associated tidal creek systems located immediately east of McKay Creek (Figure 27). Such natural state changes can occur on a coastline, including repeatedly, and such state changes might occur either through gradual adjustments that lead to the system being flipped into a different state, or through the results of one or more episodic events. Hence, the future possible trajectory of some parts of the coastline associated with the ESSP might contain one or more branches, increasing the uncertainty in making any prediction about the future associated habitats.

As an example, for the tidal creeks alone, the available field data on sediments and sedimentary processes is insufficient to allow a quantitative assessment of sedimentary processes over such a complex area as the ESSP and over a century ahead. In particular, the sediment budget of the existing coastal system is unknown, especially limited by the lack of age-dated deposits. Further, whilst the tides dominate day-to-day processes in the ESSP's tidal creek systems, several other factors are especially relevant when considering the possible future response of the coastline to sea-level rise and to the additional factor of the emplaced ponds of development 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.

These factors naturally interact with each other in complex fashion so that each of their specific contributions towards coastal dynamics may not be clear. Whilst this decreases the ability to make firm projections about the future, a broad evidence-based and expert-judgement approach can arrive at useful results.

13.1. Migration of sedimentary habitats

Part of natural coastal dynamics is that the sedimentary environments themselves, and their associated habitats, might move to landward, to seaward and/or along the coast. For the sedimentary environments to remain functional as benthic habitats requires two main things:

- Space for the habitats to move into.
    - In the ESSP area, space is generally available. As an example, for the ESSP's high intertidal flats there are large open spaces to landward, especially in the western part of the development bordering the estuary. Space is limited for a few locations, such as Gnoorea, where the present coastline is backed by higher ground.
- A suitable sedimentary regime.
    - As detailed throughout this report, many factors are involved in sediment transport in the ESSP region, but **the essential logic regarding why sediments are so important for future habitat resilience is simple**[25].
        - Many coastal habitats are closely linked to elevations relative to the tides, and habitats are more likely to persist if bed elevations are able to track broad sea level changes through time.
        - With a presumed future rise in RSL over several decades or more, vertical accumulation of sediment at rates equivalent to RSL rise would be needed to maintain the elevation of benthic habitats without a significant overall change in their area.

---

[25] To make the logic easiest to follow, here it is assumed that there is ample available space for migration, that the bed gradients are like today and that the sediments are dominantly mineral grains.

  - Therefore, the future rate of sediment accumulation is a major control upon whether the sedimentary environments at a particular location will become more suitable or less suitable for the associated benthic organisms.
  - The potential for sediment accumulation greatly enhances the prospect of habitat resilience (or persistence).
  - Sediment accumulation is possible if i) there is sufficient sediment available, ii) there is sufficient energy to transport it there, and iii) the sedimentary processes integrated over several decades act to retain the sediment there.

However, as detailed throughout this report, present levels of data and understanding for the ESSP's coastal sedimentary system, the upper intertidal habitats and most other habitats mean that we have not established:

- the **past** rate(s) of sediment accumulation
- the **present** rate(s) of sediment accumulation

and we cannot begin to predict **future** rates of sediment accumulation. This hinders the ability to determine future natural sedimentary resilience. Clearly, the past can provide key information about the future. Aerial photographs can be used to document past changes in the ESSP coastline, including potential state changes. However, such snapshots rarely provide sufficient understanding of the system dynamics to assess with confidence whether some areas might be close to a future state change or have experienced one in the past few centuries or so. Whilst some tidal creeks, such as McKay and Straight creeks, have shallow mouths and multiple mobile mouth bars, there is no information on the age and thickness of the sediments immediately offshore so that is it unknown whether they might have been blocked at some stage in the past.

13.1.1. Migration of mangrove environments

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).

Table 23: Dynamics Associated with Mangrove Sub-Habitat Boundaries

Boundary	Dynamics
Bank-Coastal Fringe	Mangrove growth limited by undercutting and storm damage Root structure & depth variation provide balance
Coastal Fringe-Forest	Forest species abundance due to sediments & low stress Boundary linked to migration of coastal sand mass
Channel-Forest	Channel margins have high water supply, but bank stresses Migration with channel bank instability
Forest-Flat	Mangrove growth limited by sediments, water supply & salinity Extent linked to tidal channel networks
Channel-Flat	Mangrove growth limited by water supply & salinity Creek structure affected by runoff or tidal head-cutting

Variation of stresses at each of the sub-habitat boundaries commonly influences the mechanisms for mangrove habitat migration (Table 23, see also Figure 21 in Section 5.1.1.2). Therefore, the general nature of mangrove habitat migration associated with SLR varies across the different sub-habitats. From seaward to landward:

- The coastal margin is expected to undergo some mangrove loss, with relative depth increasing such that storm erosion can undermine juvenile mangroves or damage mature mangroves. This behaviour can be offset if there is a large intertidal bank, capable of evolving upwards to match SLR, but mangrove loss will be exacerbated where the bank becomes less stable with SLR.
- Landward migration of the coastal fringe depends on the response to overtopping during increasingly high relative sea levels. For some parts of the Pilbara, coastal deposition during events (e.g., cyclones), particularly of coarse sand and shell fragments, has formed coastal chenier ridges. The ridges represent the winnowing of the bioturbated mixed intertidal sediments, export of suspended fine sediment and the landward transport of the remaining exposed coarse sands and shells. The elongate coarse ridges are relatively resistant to landward migration, and can thus form semi-permanent or permanent barriers between the ocean and the more mature mangrove forests to landward.
- The mature mangrove forest areas are subject to increasing inundation with sea level rise. Their capacity to keep pace with sea level rise is determined by the litter production, as well as suspended sediment input from tidal channel networks, river input and reworking of material from the high tidal flats. For mangroves without active sediment input, there is increased capacity for ‘drowning’, where sustained inundation limits the capacity for mangrove seedlings to establish, as part of the forest regrowth cycle. Examination of the record of past fossil mangrove systems indicates an apparent limiting rate of sustained SLR associated with mangrove vertical development, beyond which the ecosystem fails to keep up with the change (Saintilan *et al.* 2020).
- Landward extension along tidal creek systems, including smaller channels within the mangrove forest, is strongly influenced by channel dynamics. With SLR, tidal head-cutting provides a major mechanism for creek extension to landward and expansion of the overall creek catchment (Figure 163). Channel expansion can typically be related to increased tidal prism and can be significantly enhanced where higher sea levels cause more overbank tides over increasingly large areas of the upper intertidal flats.
- The extension process is staged in time, with the physical change first and the biological afterwards, i.e., headward channel extension occurs and later new areas of mangrove occupy parts of the tidal flats. In this way, mangrove forest expansion is a much smaller and slower response than tidal creek head-cutting. This is clearly shown in the ESSP region where aerial photographs covering the 54-year period 1968 to 2022 show some clear changes in creek down-cutting and extension but far fewer and smaller ones for forest expansion (Section 10.5.1, Table 20).
- Channel dynamics may also occur where there is a significant, generally episodic, runoff flow capacity.

- Finally, the landward boundary of both mangrove forest and creek-fringing mangroves is potentially influenced by water supply, with opposite spatial gradients of porewater salinity for runoff dominant or evaporation dominant situations (Figure 164).

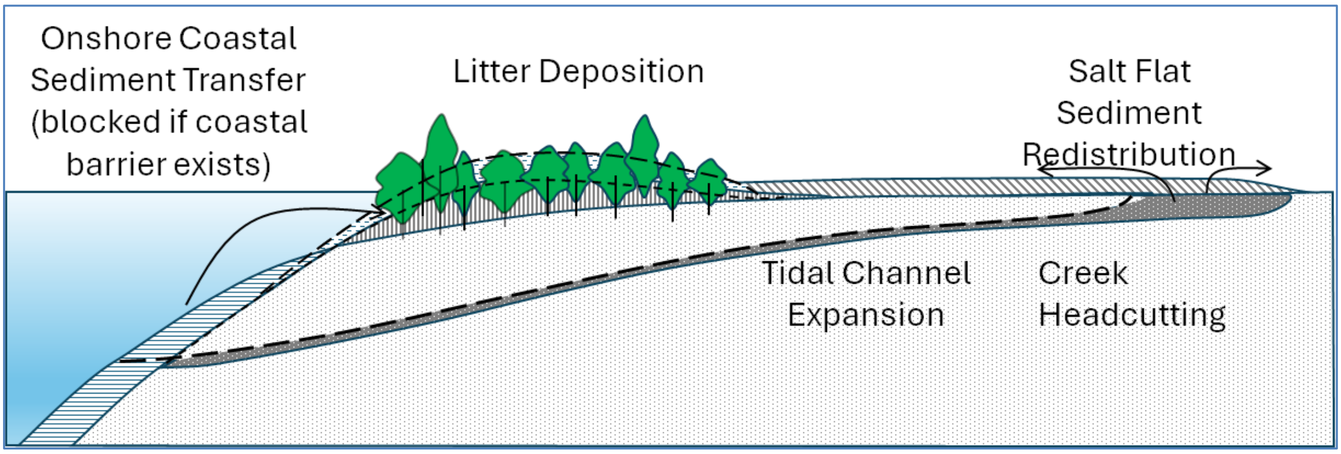


Figure 163. Downcutting at the head of tidal creek systems and redistribution of sediment onto the high tidal flats.

The capacity for increasing marine inundation to modify the spatial gradient of porewater can cause substantial rapid habitat change in situations where seawater can more frequently spill into a discrete sub-basin. As an example, on the South Alligator River, NT, salinisation extended across a distance of 15 km inland over a 40-year period (Cobb *et al.* 1997). Equivalent behaviour, albeit with the opposite salinity gradient, is apparent on parts of the Pilbara coast, where a large part of a sub-basin (200-400 m) adjacent to a tidal creek becomes occupied by mangroves over several years.

13.1.2. Regional patterns of tidal creek 'migration'

Headward channel extension of tidal creeks has been prevalent across the Pilbara region over the last 60 years. The SLR of ~0.2 m in that period has been associated with tidal channels typically extending by 60-200 m, and sometimes 400-600 m (Eliot & Eliot 2012), i.e., up to 10 m/year. There are also examples of greater extension where the higher tide levels have provided connection to large basins to landward.

In the western ESSP area, this study (Table 20) has noted headward extensions of 80 - 100 m over 20 years (Creek 3), up to 300 m extension (Creek 2), up to 350 m extension (Creek 1) with up to 300 m of scattered forest expansion, and 300 m landward migration of mangroves on a secondary creek (part of the McKay Creek system). In the eastern ESSP area, a tertiary creek extended 100 m in the 40 Mile Road E catchment and other changes took place. Although these changes are consistent with what we might expect from a rise in MSL, locally the period 2001-2020 had highly variable MSL (Figure 16, Figure 17) and it is difficult to see and and whether these horizontal rates of physical change can be related in a meaningful way to MSL.

WE CAN CONCLUDE THAT IN THE LAST TWO DECADES, THE HEAD OF SOME TIDAL CREEK SYSTEMS IN THE ESSP AREA HAVE MIGRATED LANDWARD AT MEAN RATES OF BETWEEN 4 AND 17.5 M/YR, AND THE ASSOCIATED MANGROVE FORESTS AT GENERALLY SLOWER RATES[26]. HOWEVER, DIFFERENT CREEK SYSTEMS VARY, WITH SOME SHOWING NEGLIGIBLE CHANGE.

From the above, the common general statement that sea-level rise will drive coastal erosion appears an over-simplification. The overall response to SLR must be coastal retreat, however, it is not uniform, let al.one inevitable at all locations along the coast. The specifics of each location are critical, especially at a local scale.

---

[26] These horizontal migration rates have not been corrected for the specific slopes concerned.

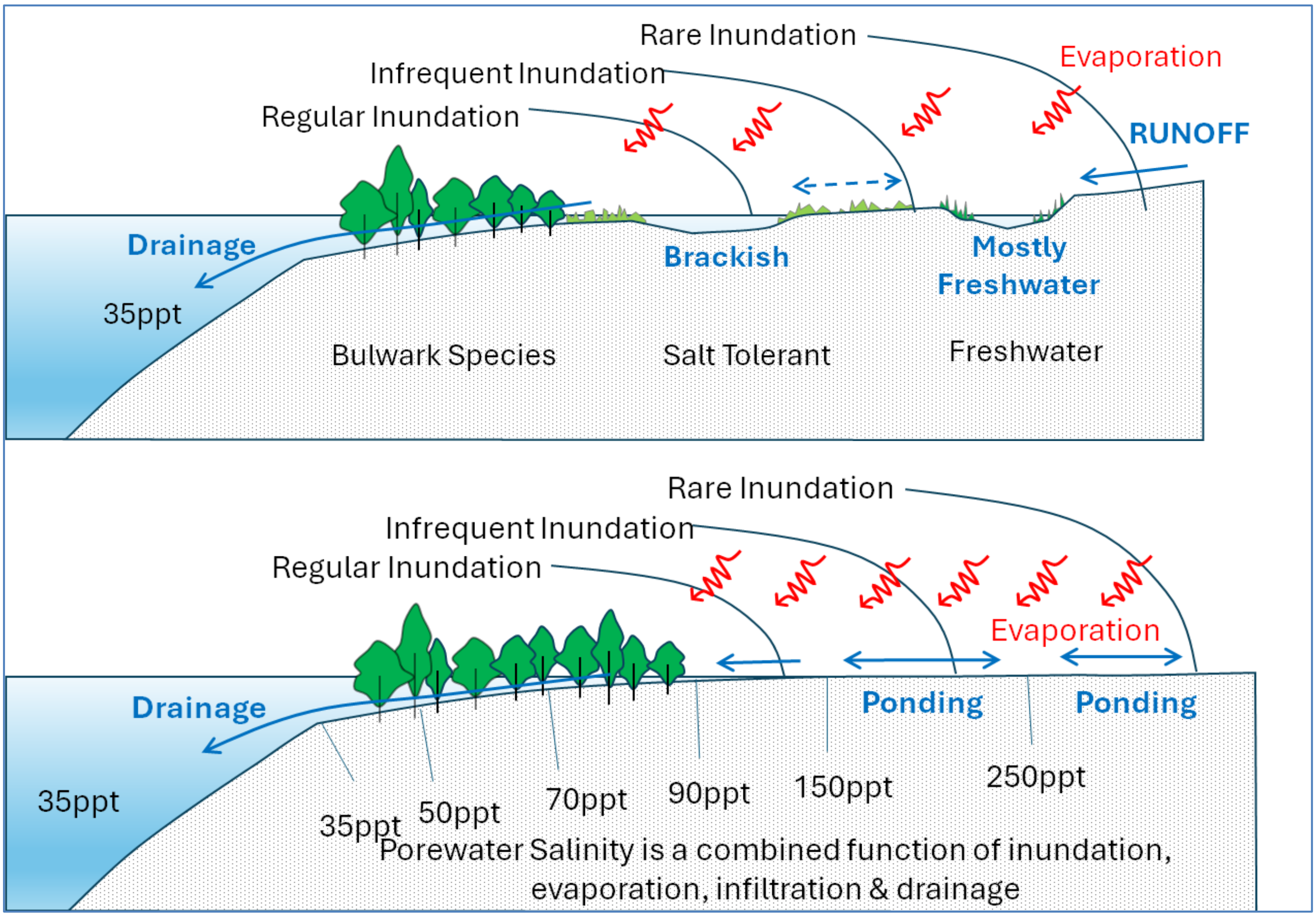


Figure 164. Patterns of porewater salinity gradients: TOP – salinity increases seawards, i.e., runoff is dominant; BOTTOM - b) salinity increases landward, i.e., evaporation dominant.

14. Assessment method

The above series of complexities and unknowns mean that it is not possible to **predict** the future changes in sedimentary environments and associated BCHs, and especially not in a quantitative sense. It might therefore appear tempting to use a computer-based morphological model to predict future change - or more realistically to help constrain the possibilities - but for the area of the ESSP the unknowns are so many, so fundamental and so varied that the basis of a model (including the volume of the sediments themselves, their physical nature and their dynamics) cannot be established. Any plotted and quantitative result risks would risk providing a false sense of reality.

Thus, the approach taken here is a practical and realistic one. It is to try and constrain the possibilities, by drawing on all available information present in the report and in associated material. First, expert judgement is used to develop a set of scenarios, carefully noting the uncertainties involved, and then these potential changes are placed into their regional context.

14.1. Scenario generation – the future without the ESSP development

The expert judgement here attempts to account for possible changes over a period of several decades, considering factors such as which parameters might be limiting and the possible range of variation in each parameter, using an assumption that the rise in RSL occurs at a rate of 0.1 m/decade (i.e., 10 mm/yr). It is possible to comment on the general range of potential changes and thus help assess the environments most and least likely to be resilient. Of the various factors involved, the key limiting factors include the frequency and magnitude of erosive events, and the availability of sediment to allow coastline to re-establish dynamic equilibrium. Additional but lesser factors are the rate of coastal roll-over and any geological restriction on landward migration of sedimentary environments.

This exercise is documented[27] and the results presented in Table 24. NB - this is general across the ESSP area, and not applicable to all areas. Relevant details and exceptions are dealt with in the worked examples of Section 15.

The potential changes to the main sedimentary environments are variable (Table 25). In brief, there are likely to be few changes in those shelf environments outside the estuary and in the areas landwards of the mangroves – these areas are relatively resilient in terms of physical sedimentary factors. However, within the more complex areas on the coastline itself, i.e., the intertidal zones, the beaches, the creeks and mangroves, there is the potential for geomorphic change. The possible changes are variable, e.g., some tidal creek systems and their areas of associated mangroves may either contract or expand. Much depends upon the tidal dynamics that influence these systems in various ways, and how the dynamics will be changed by the future (and unknown) relationship of sediment accumulation to the relative rise in sea level.

14.2. Placing these potential natural changes into context

Where likely, the above potential changes are of relatively low magnitude and may be variable in their sedimentary trajectory. There is no likely tendency for major changes in one direction, e.g., widespread contraction or expansion of sedimentary environments. The ESSP development is in a region with a wide variety of shelf and coastal sedimentary environments morphology that have developed over thousands of years and have been continuously dynamic. Overall, whilst there is a high chance of some local changes in the next few decades to a century, there appears no likelihood of natural changes of regional significance.

---

[27] One result of this exercise was to emphasise that there is little known about most key factors and far too little to undertake any defensible numerical analysis, so that none has been undertaken and no specific scenarios have been designated.

Table 24. Factors involved in considering scenarios to determine overall natural sedimentary resilience over several decades in the future, without the ESSP development.

Factor	How well known?	Potential factor limiting resilience	Potential factor maximising resilience	Are these factors limiting? Where?	Scenario of low resilience	Scenario of high resilience
Shelf bathymetry & peritidal topography	Well known	Steep bathymetric and topographic contours	Shallow contours and space for landward migration	Practically, almost nowhere	Use present bathymetry and topography	Use present bathymetry and topography
Waves (non-cyclonic)	Measured data available	Too small to transport sediments or modify coastline (not true)	Constantly able to contribute to sediment transport and coastal change (mostly true)	Mostly no, but at the coast and to seawards they are probably subordinate to episodic events (noted below)	Waves smaller and/or less frequent than at present	Waves larger and/or more frequent than at present
Fluvial sediment delivery	Unknown but sediment flux presumed to be minimal	None	Some local delivery onto high tidal flats, supporting algal mats etc	Mostly not, because there is room for most environments to migrate landwards	Assume zero	-
Shelf sediment availability	Poorly known	None (not true)	Unlimited (not true)	KEY FACTOR - Possibly limiting at the coast in providing sediment onto the high tidal zone	Assume none	Sufficient to supply migration of sedimentary habitats
Tidal range and currents	Range known & currents measured in places	Currents too weak to transport sediments (not true)	Currents can transport some sediments in all locations (mostly true)	Practically, almost nowhere	Use present conditions	Use present conditions
Cyclones	Unknown but presumed broadly similar to present	Unknown – cyclones will erode some sedimentary environment and their habitats, but also transport sediments to other areas		KEY FACTOR - e.g., wrt erosion, sediment transport, morphological change, state change, etc.	Less cyclonic reworking	More intense cyclonic reworking

Table 25. Assessment of natural physical changes to the main sedimentary environments over several decades, i.e., without the ESSP development.

Sedimentary Environment (or BCH name)	Potential change after several decades	Comment on cause(s)	Main unknowns	Level of confidence in the interpretation
Subtidal coral on rocky substrate	None	No regional changes in relevant factors	-	Very high
Subtidal seagrass beds	None	No regional changes in relevant factors	-	Very High
Intertidal seagrass beds	No change – Negligible	Sediment dynamics	Availability of sediment to accumulate	High
Intertidal flats (seawards of the coast)	No change – Erosion & deepening	Sediment accumulation relative to SLR	Availability of sediment to accumulate	High
Nascent fringing mangroves	Removal – Expansion	Removal by erosion or infilling of associated tidal creeks	Erosion	Moderate
Estuarine mangroves – Small systems	Transition to saltflats – System expansion	Changes in tidal dynamics and associated sediment transport. Small size & local factors result in lower resilience.	Rate of sediment accumulation, erodibility of substrates	Low to Moderate
Estuarine mangroves – Large systems	Minor reduction – Large expansion across high tidal flats	Reduction if tidal creek banks steepen. Expansion of mangroves if volume of tidal creeks does not increase or creeks do not migrate landward	Rate of sediment accumulation, erodibility of substrates	Moderate to High
Tidal creek channels	Decrease or increase in length, width & depth	Changed tidal flows, especially ebb tides	Rate of sediment accumulation, erodibility of substrates	High
Beaches	Slightly greater extent and mobility	Deeper intertidal zone might lead to more active beaches	Response of subtidal and intertidal zone seawards of the coast	Low
Algal mats	No change – Negligible	Migration possible with little geological limitation	-	High
Samphire	No change – Negligible	Migration possible with little geological limitation	-	High

PART FOUR - FUTURE CHANGE WITH THE ESSP DEVELOPMENT

15. The ESSP region

15.1. Initial statements

From the information reviewed above and associated reports, a series of general statements can be made, designed to be helpful when considering the following sections.

15.1.1. Sediment sources

- There is no major source of muddy sediment in this area nor the wider region. For example, the Maitland River catchment doesn't produce much mud – mostly sand.
- The local bedrock on the shelf contains little mud – it's mostly cemented clean carbonate or terrigenous sand or gravel, or igneous, so its erosion produced no mud.
- Bioturbators are not a huge factor in the bay's surface sediments, so that not much fine sediment is likely to get mixed into and stored in the inner shelf sediment body.
- And similarly, whilst there is some biological shell production, it is unlikely to produce much fine sediment even when broken down.

15.1.2. Sedimentary processes

- Cape Preston is a promontory, and tidal currents are stronger there than in bays or along the open coastline, and will have been so for around 8000 years, repeatedly mobilising fine material.
- The turbidity data in western Regnard Bay and elsewhere indicates that resuspendable sediment is limited in its local availability, because even the fastest measured currents and largest waves produce only moderate turbidity.
- Tropical Cyclones, in the long-term, will probably tend to drive a setup within Regnard Bay which will be relieved through currents flowing to the SW past Cape Preston, exporting any resuspendable sediment in Western Regnard bay to the west out an open and well-flushed inner shelf.
- The estuary and the coastline fronting the western ESSP area is a tidally dominated environment but also influenced by waves at times.
- At the coast itself, water movements are dominated by tidal flows, especially landwards of the shoreline.
- Based on tidal processes, muddy sediments are preferentially transported into the fringing and estuarine mangrove environments by flood-currents and sandy sediments are preferentially exported from the system down the incised creeks.
- High intensity rainfall events can enhance flows down the tidal creeks but possibly contribute relatively little to the overall sediment budget at the coast.
- Episodic events can cause rapid erosion of the coastline at horizontal rates up to several tens of m/year, but historical evidence indicates that post-erosion 'recovery' takes only about 3-4 years, at typical rates of 10-25 m/year in areas with shallow coastal slope, and 6-10 m/year on steeper slopes.

15.1.3. Sedimentary evolution

- Geological sediment accumulation rates on the Holocene inner shelf are very low, as evidenced by the large areas of patchy sediment and cemented rocks at or near-surface.
- The same is the case for the mid-shelf to seawards – it does not appear to be a source of sediment to the inner shelf.
- All the above will have been true for 8000 years and longer.

- Parts of the ESSP coastal system are probably close to a long-term dynamic equilibrium with the driving (tidal) processes and available sediments, but some parts are not.
- As the creek channels migrate through time, the system functions to accumulate some fine sediment (what little there is) in some intertidal basins, and to export sandy sediment to the coastline.

15.2. Generic physical effects of solar salt developments

For over a decade the Pilbara region has been a focus for solar salt projects. In their review of the impact of ports in the Pilbara region, Brocx & Semenuik (2015) commented on solar salt projects

> *"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 & Semenuik's (2015) work is useful in setting the scene, noting that

> *"the significance of tidal creeks along a coast where solar salt production is in operation is that the intentional discharge of effluents from solar salt production activities or the unintentional subsurface discharge of liquors from solar salt production activities (the latter via subterranean plumes emanating from under evaporation ponds) intersects tidal creeks and, hence, is short-circuited and channelled to the open sea."*

and noting that the construction of ponds, aqueducts and causeways can cause

> *"alteration of tidal flat hydrodynamics, hydrochemistry and geochemistry, due to the construction of ponds, aqueducts and causeways, and operating-phase maintenance of hydraulic heads. This results in alteration of any nearby tidal creek discharge/recharge rates and, hence, alteration in patterns of erosion/sedimentation*

Thus, the significance has long been recognised of those physical surface sedimentary processes that maintain tidal creek systems, and the potential disturbances of infrastructure to the natural interactions of flow and morphology. This report addresses such issues directly, because 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 with 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, runoff and relevant geomorphological factors are given in the sections below.

15.3. The nature and disposition 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 165), 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. Note that the central area of ponds has a gap within it located SE of Gnoorea Point (Figure 165).

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 166) 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.

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 16 and 0). Further their presence in the intertidal zone affects tidal processes.

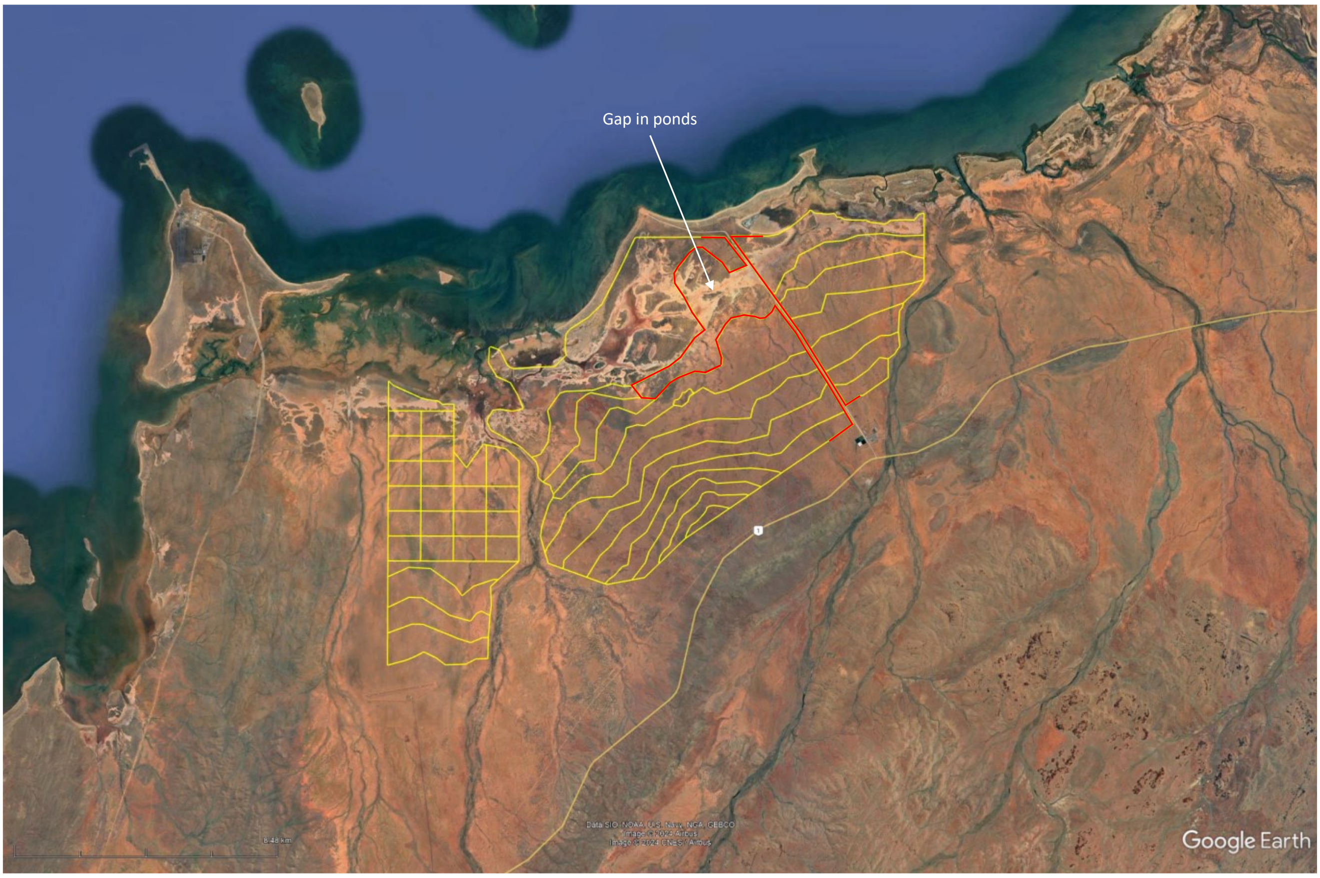
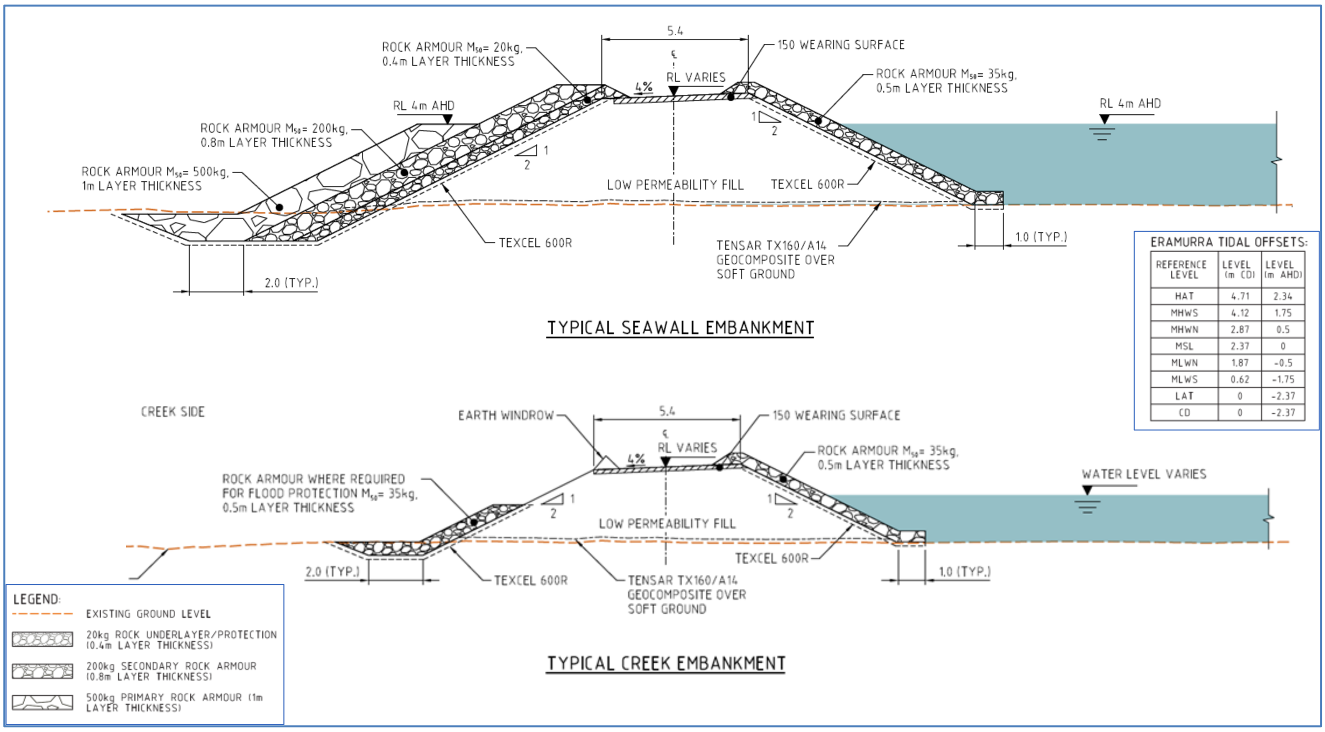


Figure 165. The ponds of scenario 7.2.1. Note the open-ended gap in the ponds SE of Gnoorea Point.



ERAMURRA TIDAL OFFSETS:

REFERENCE LEVEL	LEVEL (m CD)	LEVEL (m AHD)
HAT	4.71	2.34
MHWS	4.12	1.75
MHWN	2.87	0.5
MSL	2.37	0
MLWN	1.87	-0.5
MLWS	0.62	-1.75
LAT	0	-2.37
CD	0	-2.37

Figure 166. 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.

16. Potential changes to the tides in tidal creek systems

This section considers the potential effects of the ESSP on the tides in creek systems, specifically in terms of the potential effects on tidal flows, mostly as assessed at creek mouths. Full hypsometric curves for all catchments without ponds, plus with ponds of the present scenario (7.2.1.) plus those of a previous pond scenario (6.2.0.) are given in the Appendix Section 29. Selected examples are presented and discussed below, also using the results shown in Figure 167 and Table 26.

Table 26. Storage ratios of the relevant intertidal catchments for natural conditions and pond scenario 7.2.1 (data supplied by LS). Brown cells are those affected by the ponds of scenario 7.2.1.

Catchment / Creek Name	**Natural Systems**			**With ponds Scenario 7.2.1**	
	Storage Volume at 2.5 AHD (~HAT)	Creek Volume at 1.7m AHD	Storage Ratio	Storage Ratio	Ratio reduction from natural
	Vs	Vc	Vs:Vc	Vs:Vc	%
	m3 x 106	m3 x 106	-	-	
Port	2	1.04	1.6	1.6	-
6	0.57	0.35	1.6	1.8	-
4	14	6.6	2.1	2.1	-
5	7	3.1	2.2	2.2	-
3	7	2.5	2.8	2.8	-
2	2.2	6.7	3.3	3.2	3
1	2.5	1.1	2.2	2.2	-
Baldy W	1.7	0.57	3.0	2.7	10
Straight	1.8	0.53	3.3	3.2	3
Baldy/Straight combined	3.4	1.1	3.1	2.9	6
McKay	4.5	1.5	3.1	2.9	6
Nascent Mangroves (Area in red of Figure 201)	n/a	n/a	n/a	2.9 Vs = 2.4 m3 x 106 Vc = 0.8 m3 x 106	n/a
40 Mile W	6.8	1.6	4.1	2.9	29
40 Mile E	4.6	1.2	3.8	3.2	16
7 (Pimbayna)	1.7	0.54	3.1	2.8	10
8 (Devil)	1.9	0.64	3.0	2.8	7
Yanyare	3.2	1.4	2.3	2.3	-

Should tidal flows be decreased by pond emplacement and if those changes are also dominant in controlling creek morphology, the possible generic changes in tidal creek systems include:

- Less sediment transport, both landward through the fringing and estuarine mangrove areas of what fine sediment is available, and of all sediment sizes, including sand, to seawards through the creek channels. This would tend to indicate likely increased sediment accumulation in all affected areas, so that there will be vertical accumulation of sediment in parts of the overbank areas, and certainly within the incised creek channels. So, the morphology of some of these systems would alter, probably involving a reduction in overall size.

- Eventually, the systems will attain a new dynamic equilibrium, but the timescale(s) involved are unclear because there is no information on sediment transport rates or accumulation rates in the system. At present, the only quantitative information regards horizonal migration rates of the modern coastline. Analysis of the last 32 years of data has led to estimates of recovery rates for the natural open coastline over the last 32 years of 10-25 m/year of coastal progradation for a low-gradient coastline and 6-10 m/year for steeper coastlines (Section 11.5). However, the location of the sandy open shoreline is not a key control or indicator of actual or potential future sediment accumulation rates elsewhere in the overall coastal system.

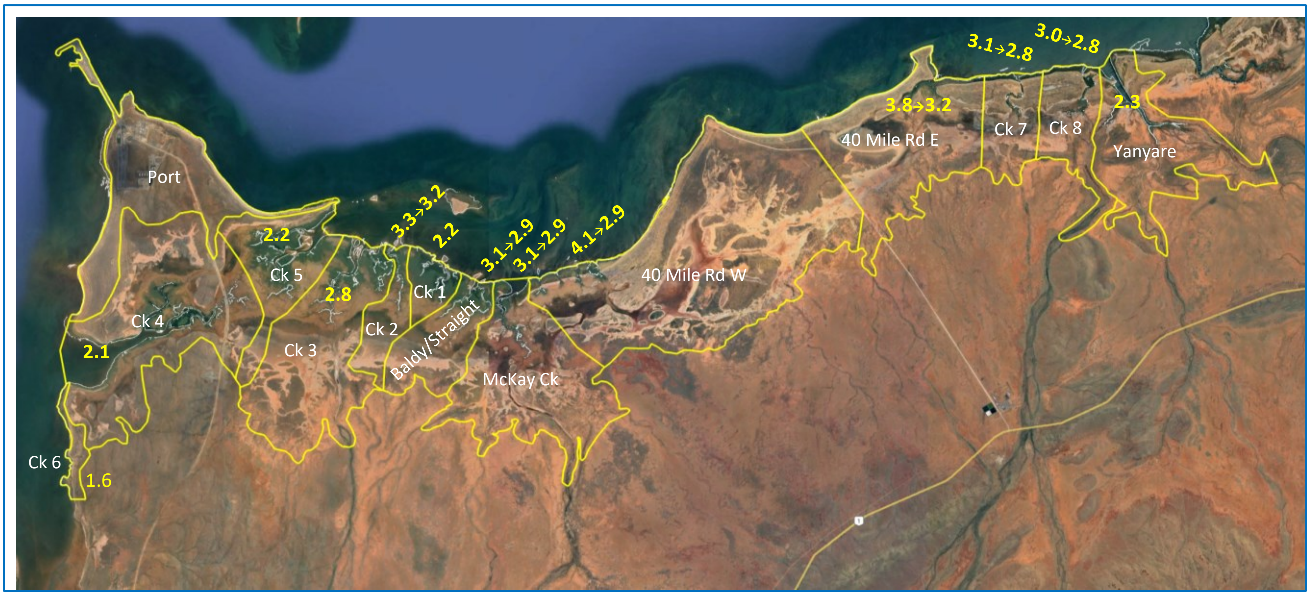


Figure 167. Calculated Vs:Vc ratios for the natural catchments (yellow text). For those catchments affected by the ponds of scenario 7.2.1, the first number is the natural ratio (noted below), and the number after the arrows is the ratio with the ponds emplaced.

16.1. Catchments fronting the ponds

For the combined Baldy-Straight catchment, the Vs:Vc ratio is slightly reduced, from 3.1 to 2.9 (Table 26), a minor change that is unlikely to cause a great change in the creek mouth or the system overall, although the greater relative change for the Baldy West sub-catchment means it might be subject to a little more sediment accumulation in the creek.

McKay Creek catchment displays a smooth hypsometry under scenario 7.2.1 (Figure 168) and whilst some changes are likely, tidal processes alone are unlikely to cause major change. The more significant issues are likely to be the new flow and sediment transport regime, from tides and runoff in the narrowed catchment between the eastern and central ponds, and the associated physical sedimentary consequences immediately seaward of this narrowed section (addressed in the worked examples of Section 22).

For 40 Mile W, the catchment changes of scenario 7.2.1 are sufficiently large (Figure 169) that changes in the overall Vs:Vc ratio are not relevant regarding potential associated physical changes. Of particular importance is the resulting isolation of the small group of fringing creek systems that house nascent mangroves (Figure 201). Taking this potential nascent creek area as a unit, the Vs:Vc ratio is 2.9 (Table 26), a figure that tends to indicate a reasonable degree of ebb dominance on overbank tides. That said, some modelling might provide supporting information regarding this interpretation, and we can note that this new area will no longer have the potential source of runoff or sediment from the higher intertidal and supratidal zones of the large 40 Mile W catchment.

Further east, in front of the eastern ponds, scenario 7.2.1 decreases storage ratios, such as for 40 Mile E (16%), creek 7 (10%) and creek 8 (7%), so that for these catchments, we might expect a slight reduction in system size, including some sediment accumulation in the creeks. According to the hydrodynamic modelling outputs, creek 8 had a flood-dominated flow regime (i.e., flow ratios <1 in Table 7), but there are some uncertainties about model resolution here, especially given the narrow creeks in the area.

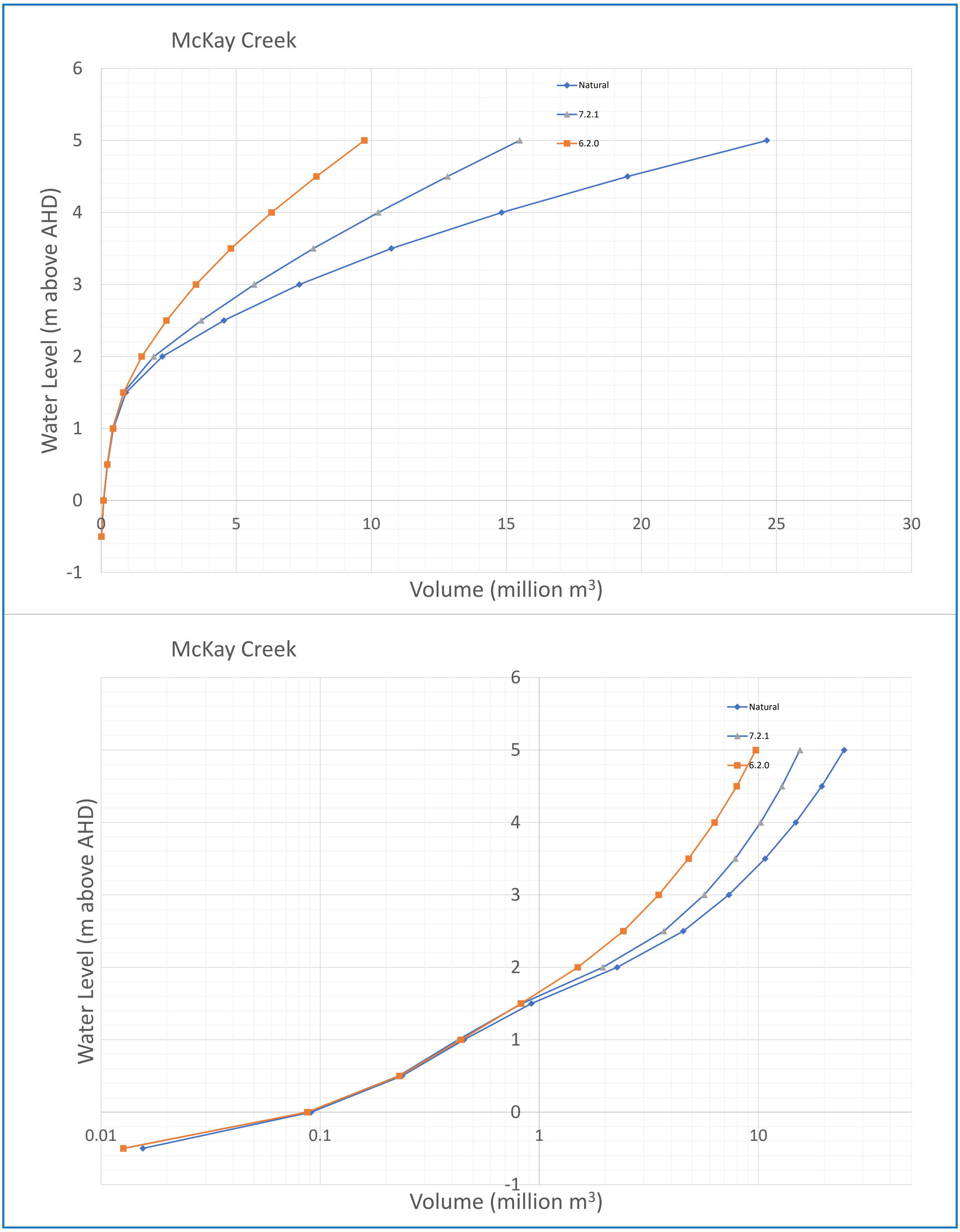


Figure 168. Hypsometry of McKay Creek for natural conditions (blue) and scenario 7.2.1 (grey). (The curve for the superseded scenario 6.2.0 is also shown - orange).

16.2. The western estuary

The western estuary is largely unchanged by scenario 7.2.1 in terms of the individual catchment hypsometric curves (Appendix 29), but there are some comments of note. As noted above (Section 7.2.4.2), the catchments might have been affected for many centuries or more by the barrier beach presumably migrating southwards reducing the catchment size, and more recently by the road to Cape Preston that may have had an effect on flow and sedimentation. Such effects, if any, are mostly unknown to date, but there are some geomorphological indications consistent with adjustment (Section 10.5, Figure 124).

It is also notable that the westernmost ponds project northwards to an elevation between 1.5 and 2 m AHD (Figure 165), and there may be an influence on the E-W exchange of water along these flats during periods of high tides and/or freshwater inundation.

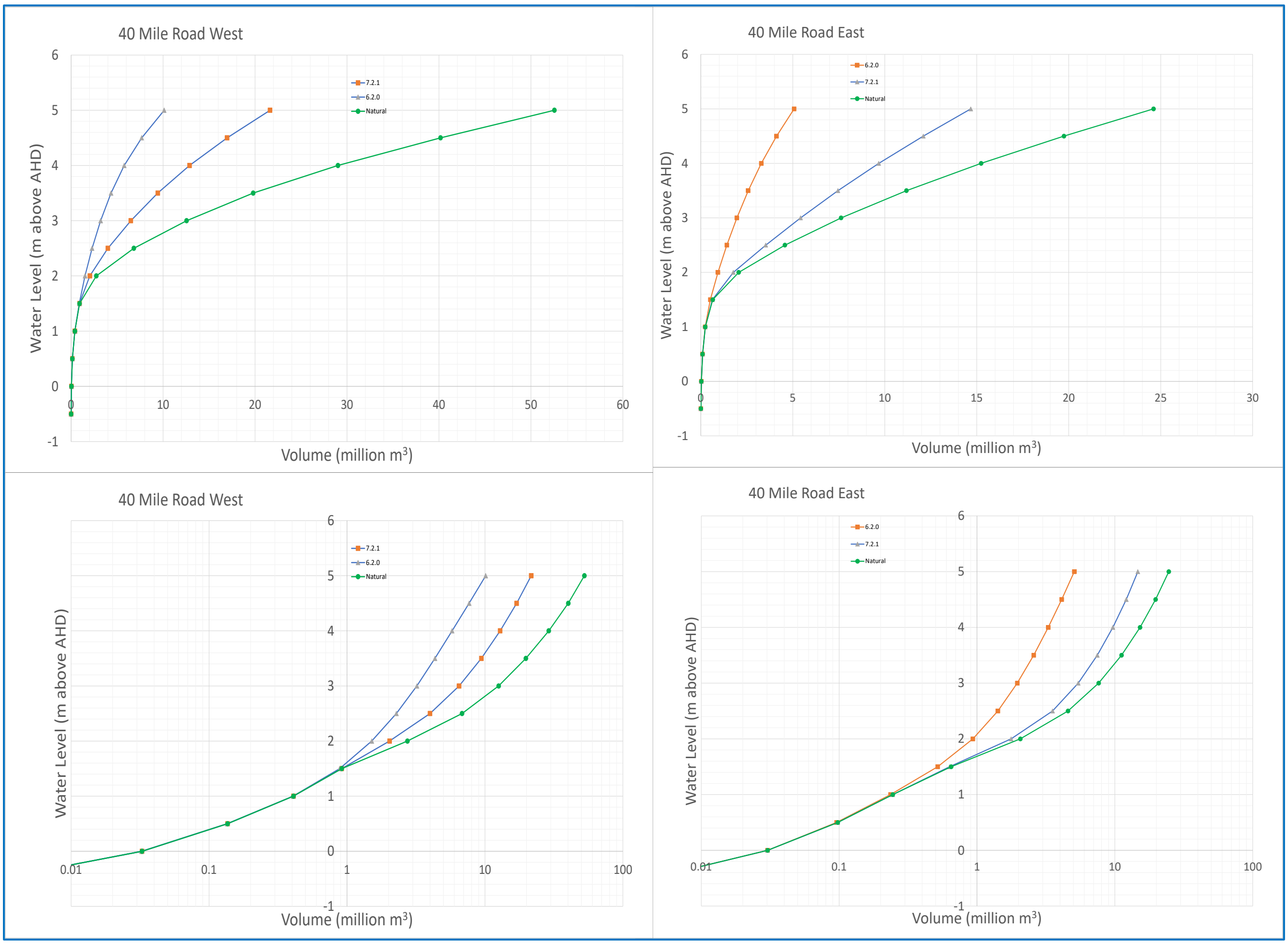


Figure 169. Hypsometry of catchments 40 Mile Road W and 40 Mile Rod E McKay Creek for natural conditions (green) and scenario 7.2.1 (blue). (The curve for the superseded scenario 6.2.0 is also shown in orange).

16.3. Might there be greater or lesser vulnerability to future erosive events?

In general, future change can take place if there is sufficient energy and sediment available to maintain a dynamic equilibrium with the hydrodynamics. In the natural system, the evidence is that there is ample tidal energy, and in some locations, ample wave energy, but there is some restricted sediment availability. With pond emplacement, tidal energy decreases in some elements of the coastal system, sometimes to an extreme level[28].

---

[28] Some possible morphological changes and potential causes are summarised later in this report (Table 31).

Some features, e.g., nascent fringing mangroves and beaches, may be subject to changes that both increase or decrease vulnerability, because of the along-shore variations of potential response. Further, over a century timescale, SLR as currently predicted (0.9 m in 100 years) will act to exacerbate some potential issues while ameliorating others. In general, SLR will begin to ameliorate the issues directly related to reduced tidal flows, by increasing the number of overbank tides. However, such amelioration will probably be small compared to the signal from the ponds.

16.4. Summary

Without the ponds, and for arid weather conditions, the interpretation is clearly of ebb tidal dominance for most tidal creek systems, especially regarding sand transport in the creek channels. With the scenario 7.2.1 ponds emplaced, some catchments will experience some change in their tidal conditions, especially 40 Mile Road W and 40 Mile Road E. That said, for most affected catchments, the Vs:Vc ratio under scenario 7.2.1. remains 2.8 or more, i.e., at a ratio only 10% below the unaltered ratio for McKay Creek (ratio is 3.1) for which flow measurements show that the tidal control on flow is strongly dominant (Figure 33, Figure 34, Figure 35). Given this level of reduction in the Vs:Vc ratio with pond scenario 7.2.1, it is not expected that tidal processes alone are likely to cause great physical change in these systems. Some hydrodynamic modelling plus samples of bed sediment to determine sand transport thresholds would inform this interpretation.

Where there are episodic or seasonal weather events, the ponds' presence will mean additional influences on sediment transport require particular consideration, such as the 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.

It is notable that for all the creeks where the Vs:Vc is reduced by the emplaced ponds, the effects on tidal processes will be ameliorated to some degree by future presumed higher sea levels that will increase the frequency and magnitude of overbank tides, i.e. increasing Vs and thus raising the Vs:Vc ratio again.

These issues are included elsewhere in Section 15 and in the worked examples of Section 22.

17. Changes through river runoff

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, might be stored for a period or accumulate more permanently in other coastal sedimentary environments. In all cases, the key question is whether the volume, nature and rates of such changes are significant.

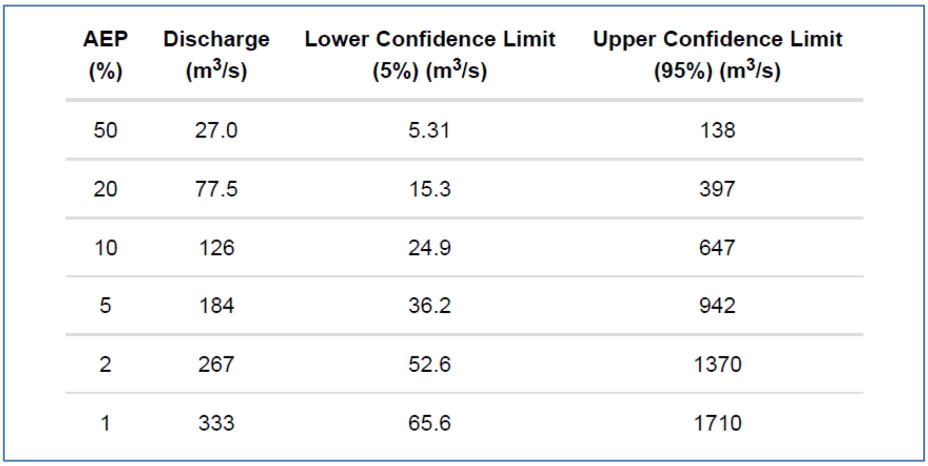
As indicated by the bedforms in some of the creek beds (e.g., in McKay Creek near the upper tidal limit) and on the bed in some catchments (e.g., 40 Mile Road E and Creeks 7 and 8) runoff appears to have caused significant sediment transport, including causing bed erosion and forming sediment tails behind some bed features, features sometimes termed ‘comet marks’. Below is an assessment of runoff as a factor in changing sedimentary environments and habitats for the ESSP area, and the possible influences 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 52). 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.

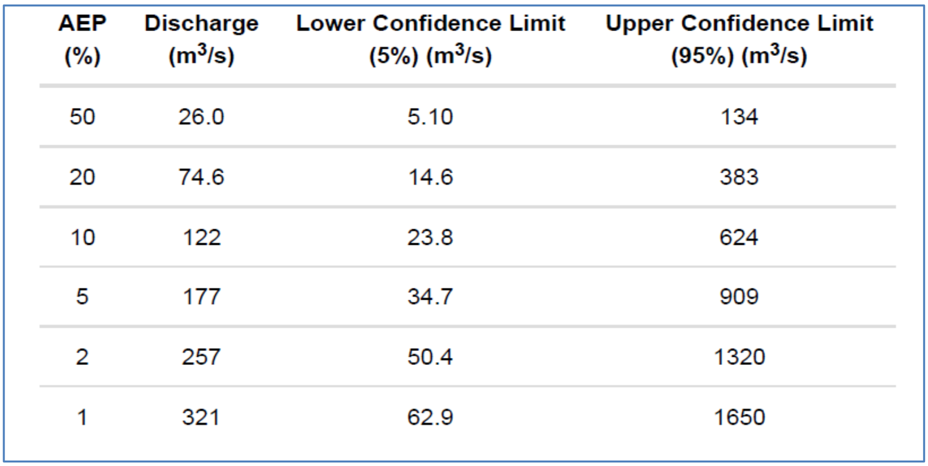
Severe Tropical Cyclone Damien (Feb. 2020) delivered substantial rainfall across the catchments feeding the ESSP area. The maximum recorded 24-hour rainfall of 150 mm was found to be equivalent to the 1 in 10 AEP event, which allowed some calibration of results. The RFFE results have substantial uncertainty, with peak flow estimates from 5% and 95% confidence limits varying by greater than an order of magnitude (Table 27, Table 28, Table 29). 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 27. Results of the Regional Flood Frequency Estimation for Eramurra Creek



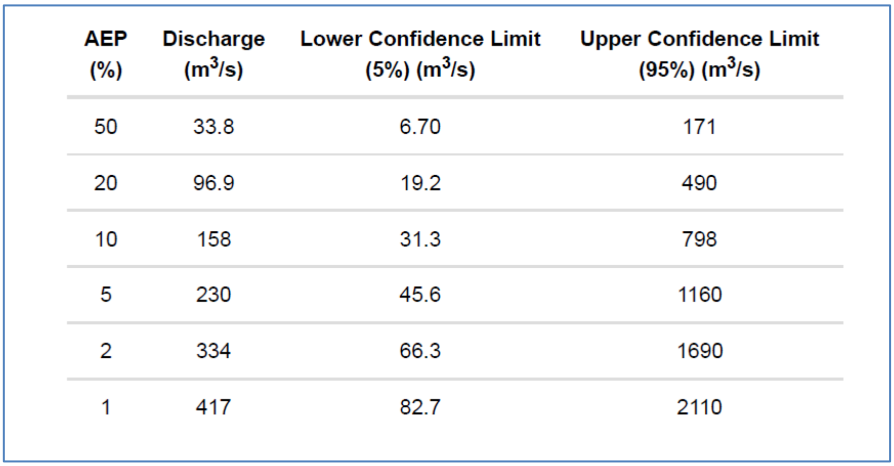
AEP (%)	Discharge (m^3/s)	Lower Confidence Limit (5%) (m^3/s)	Upper Confidence Limit (95%) (m^3/s)
50	27.0	5.31	138
20	77.5	15.3	397
10	126	24.9	647
5	184	36.2	942
2	267	52.6	1370
1	333	65.6	1710

Table 28. 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 29. 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 lengthy sections of all three main creek systems (Figure 170) and the lower part of a minor creek that flows into the 40 Mile Road W tidal catchment.

17.1. The main fluvial systems

For the 10% AEP, Eramurra Creek, McKay Creek and Devil Creek all display long reaches where modelled flow speeds attain up to 1 m/s (Figure 170). 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.

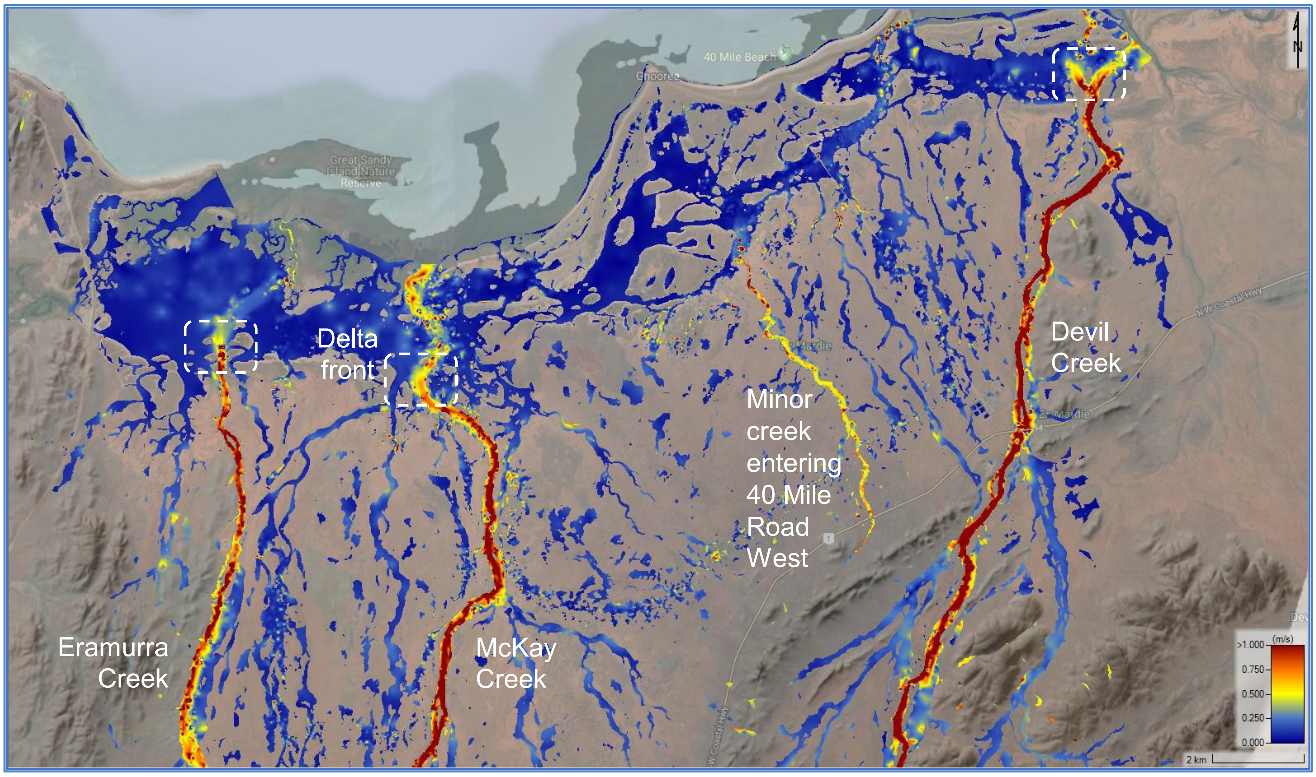


Figure 170. Natural conditions: 10% AEP existing conditions maximum velocity (m/s; Land and Water Consulting, 2023a).

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 171) 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 added 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, and although probably not major, it raises a degree of caution on using these outputs to inform the possible sedimentary response to river floods. As a separate comment, to have time-series of flow speeds for these events would help 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 172, Figure 173, Figure 174). 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.

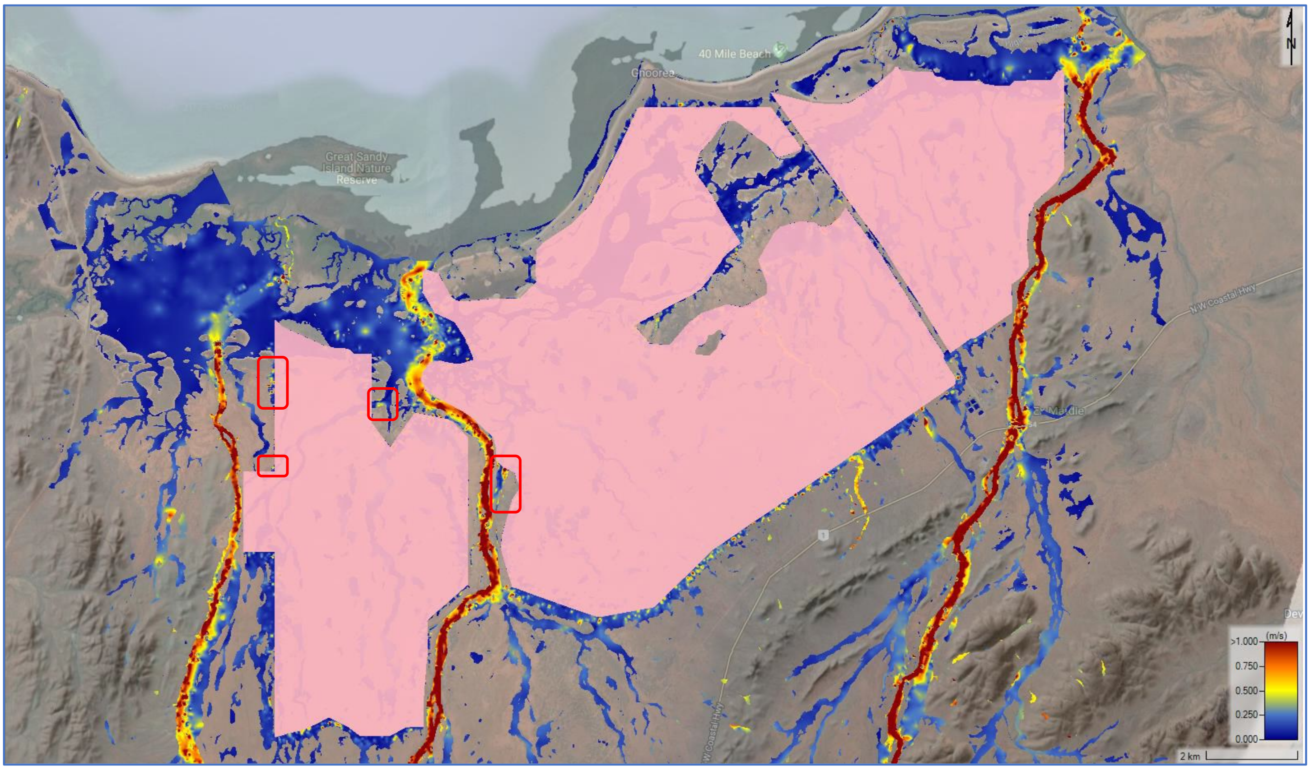


Figure 171. Pond scenario 7.2: 10% AEP existing conditions maximum velocity (m/s; Land and Water Consulting, 2023a). Red boxes indicate areas that appear suspect regarding flows. (No other events were presented in this form so that checking of these issues was not possible).

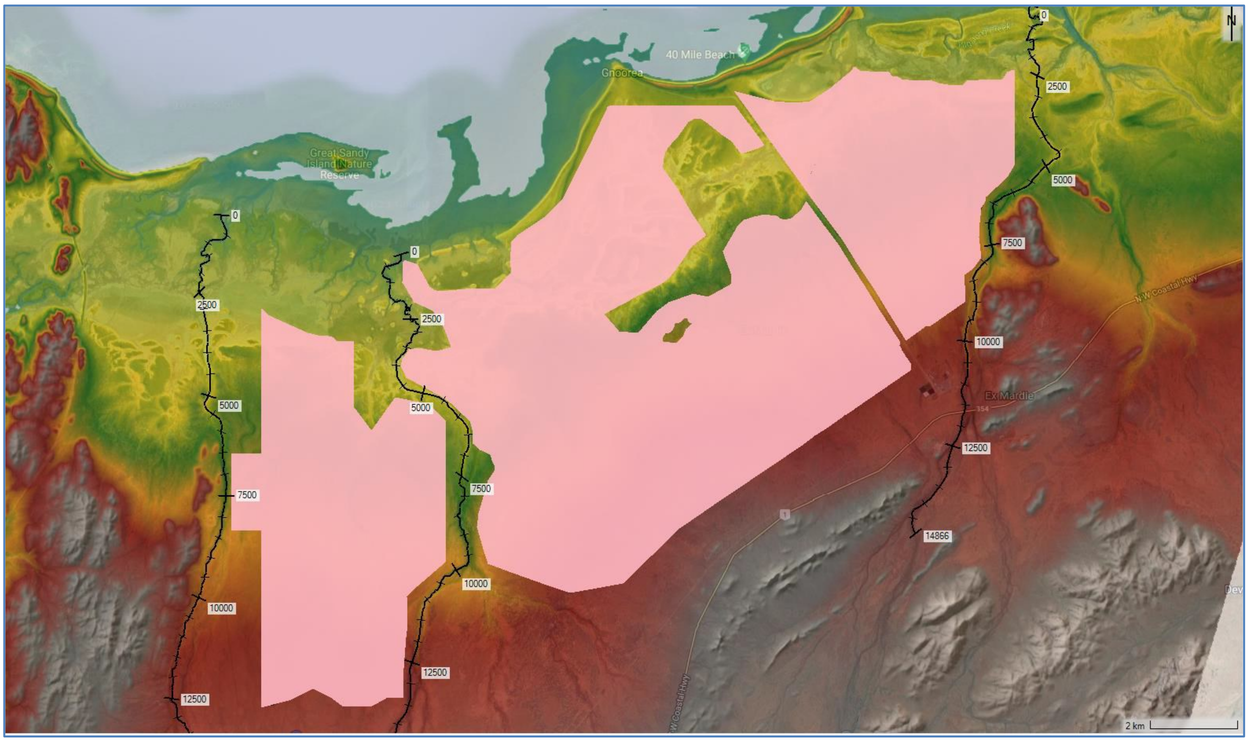


Figure 172. Chainage reference for Figure 173 and Figure 174.

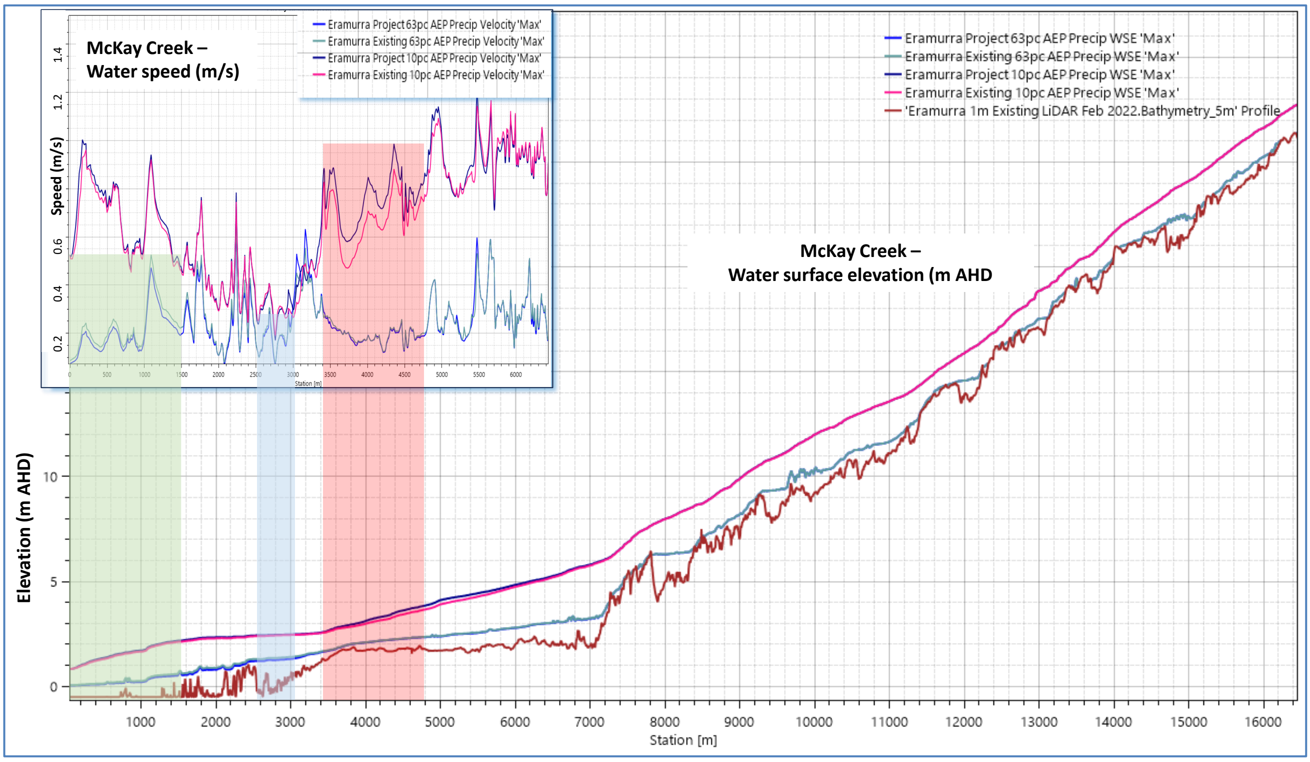


Figure 173. Overlay of 10% AEP flood water slope and speed for McKay Creek for natural conditions and scenario 7.2 (modified from Land and Water Consulting, 2023a). Red bar shows potential zone of enhanced erosion during the 10% AEP event. Blue bar shows zone of river flow speed below 0.3 m/s (i.e., 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 because of decreased fluvial input from the east (i.e., the effect of the presence of the central ponds). Details expanded in Figure 174.

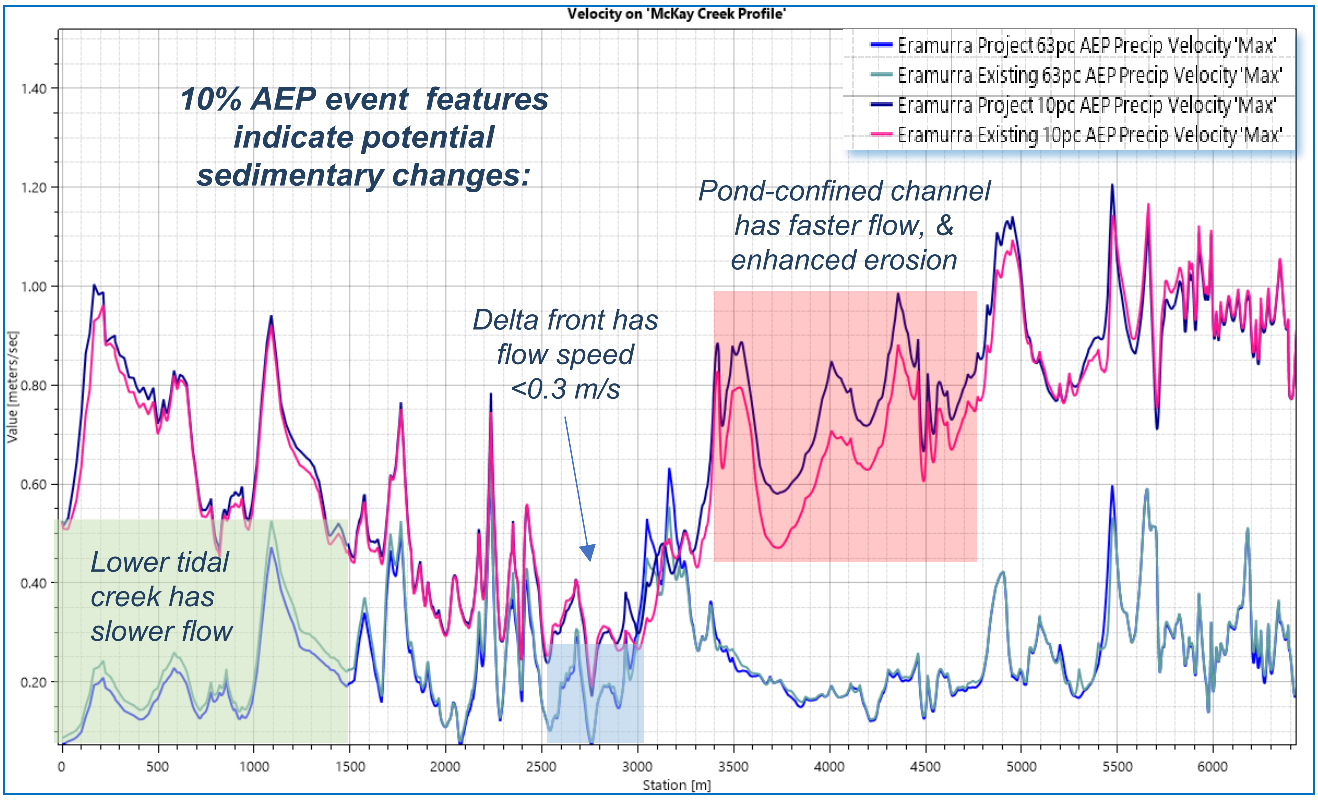


Figure 174. McKay Creek velocity profile (m/s; Land and Water Consulting, 2023a), expanded from Figure 173, indicating that changed flow speeds have the potential to generate changed sedimentary response.

17.2. Implications for changes in habitats

17.2.1. 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 22).

17.2.2. 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 with the ponds emplaced (Figure 175) 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 165).

Given the net evaporation rates are far greater than rainfall (Figure 51), 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 5.1.3 and 9.3.3), 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 113) 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.

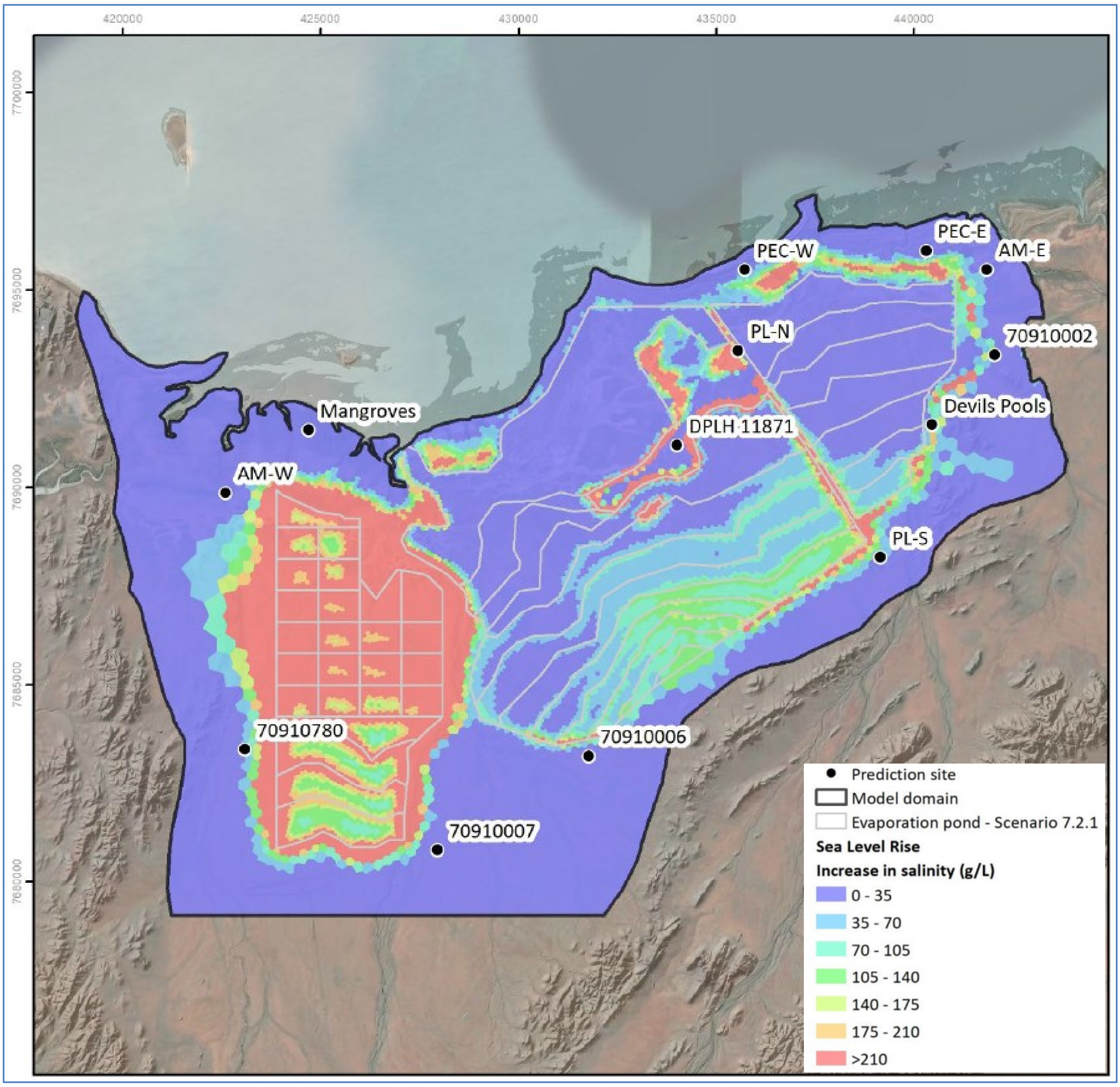


Figure 175. Predicted salinity change in the upper layer of groundwater after 100 years operation of the ponds with a sea level rise of 0.9 m (Land and Water Consulting, 2023b).

18. 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 aids the development of back-barrier 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. General assessments of barrier stability and regional evaluation of the magnitude of storm bite have led to the conclusion that barrier stability is likely with widths of >100 m (Seashore Engineering 2018, see also Sallenger 2000, Donnelly *et al.* 2006, Larson et al. 2009, Mariani et al. 2012). 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.

19. Numerical Modelling Simulations

As an additional assessment of the potential for future change with the ponds emplaced, a series of numerical model simulations were conducted. The aim was to investigate the potential changes in local hydrodynamic processes associated with the presence of the ponds. Regarding coastal processes, the model outputs were to:

- Support interpretations of existing sediment transport processes in areas where observed data is sparse or unavailable; and
- Support interpretations of possible future changes in tidal flows and sedimentation once the ponds are emplaced.

The general model setup and results are detailed elsewhere (O2 Metocean 2022c & d and see also the Appended Section 30). Model outputs were produced as maps and as time-series plots for specific chosen locations (locations shown on Figure 40).

The Tidal Inundation Model (TIM) was run with several different forcing conditions (Table 30). First, model simulations without pond emplacement (existing bathymetry) were compared to observed data. Second, the model simulations with pond emplacement were compared to the model simulations without ponds. This allowed for inference on changes to coastal processes spatially and temporally across the model domain (i.e., far from observed data) while still utilising the sparse observations to comment on the performance of the underlying model. In addition to the two simulations described above, four model simulations were run with synthetic wind fields (constant winds of 12.86 m/s, i.e., 25 knots, from a single direction) and constant 2 m surge. These models were used to assess the flooding and draining of tidal flats and areas above HAT, and the potential for wind-generated waves across the model domain. Model setups with synthetic forcing data were not compared to any observations.

Current speed and direction outputs from the TIM shown here are depth averages, and the exercise also output bed shear stress, calculated using a quadratic friction law as per the MIKE scientific documentation (MIKE 21 and MIKE 3 Flow Model FM Hydrodynamic and Transport Module Scientific Documentation). All models used a spatially constant bed roughness length, k_s, of 5 cm. With no measurements in shallow waters or within the mangrove forests, the model was not able to be validated, and it is likely that mangrove forests and tidal flats have a greater bed roughness than used here. This probably caused current speeds to be overestimated in these areas and may have resulted in overestimation of the landward extent of flooding. The influence of this model set up on bed shear stress calculations could not be determined. This setup likely also resulted in the over-estimation of wave height within and behind the mangrove forests and in areas above HAT.

NB - maps of bed shear stress are not available for the pond scenario 7.2.1., so the maps of bed shear stress presented below for the 'ponds' use scenario 7.2.0. The very minor difference between them (Figure 8) makes no substantive difference in model outputs.

For reference, the bed shear stresses estimated to move the modal grain sizes of 60 µm, 380 µm and 460 µm are approximately 0.12, 0.037 and 0.034 Pa. Hence most areas experience bed stresses exceeding these values on a large spring tide, in fact there are few areas of the natural system where on a spring tide these stresses are not exceeded. Note that there are a range of factors that affect the magnitude of the calculated shear stresses, and their practical applicability. First, the roughness lengths across the system are unknown, so that it was estimated at 5 cm everywhere, but roughness length is a significant contributor to calculated bed shear stress, and bed stresses are highly sensitive to changing roughness length. Second, it is not yet clear what grain sizes are present in most of the intertidal and high tidal environments. Third, mangrove areas can become bioturbated which alters the size of the sediment grains available at the surface. Further, especially in environments that are subject to desiccation, and/or that have semi-permanent or ephemeral biological mats across their surface, the bed surfaces can become bound together such that their undisturbed surface is more resistant to flows than would be loose non-cohesive sediments, but the environments can also be disturbed by surface sheets being stripped away once currents lift their edges. A similar but generally smaller effect of sediments being bound by surface organic films can occur in low intertidal and shallow subtidal zones.

Table 30. TIM simulations for sedimentary study (modified after O2 Metocean 2022d).

Simulation no.	Purpose	Ponds	Description	Simulation period
1	Assess effect of ponds on tides	Present-day conditions. No ponds	Tide. ERA5 winds. No waves.	14-day period centred on large spring tides (23/03/21 – 08/04/21)
2		Ponds scenario 7.2	Tide. No winds. No waves.	
3	Assess effect of ponds on tides at future higher RSL (NB - with no sedimentary adjustment in bed elevations)	No ponds	Tide. ERA5 winds. No waves With 0.9 m SLR	
4		Ponds scenario 7.2	Tide. ERA5 winds. No waves With 0.9 m SLR	
5	Compare effect of wind direction when surges elevations are present	Ponds scenario 7.2	Tide. Constant SW winds at 12.86 m/s Waves +2 m surge	4-day period centred on large spring tides (30/03/21 – 03/04/21)
6			As above but W winds	
7			As above but E winds	
8			As above but SE winds	

In addition, O2 Metocean (2023a) mentioned an additional simulation (9), using NW winds.

19.1. The western ESSP area’s coastline and creeks

At the coarse scale plotted, the model results for current speeds plotted as time series indicate relatively little change in current speeds (e.g., Figure 176) but perhaps with slower ebb tidal speeds in spring tidal periods. Maps of the model outputs indicate minor changes in maximum speeds (Figure 177) but the colour scale prevents accurate assessment of the changes in magnitude. Note that these plots present a model output of the present-day compared to a model output with pond emplaced, i.e., model output v model output. These indications of little change in current speeds appear difficult to reconcile with the maps of calculated bed shear stress that indicate significant changes across wide areas of the intertidal zone (e.g., Figure 178 & Figure 179), even though the maps of bed shear stress are for the previous scenario 6.2.0. The models have not demonstrated effective simulation of measured currents in McKay Creek and/or elsewhere in the creek systems. This means that the results presented here from individual locations (Figure 176) cannot be taken to demonstrate that the ponds have no effect on the current, because they might indicate that the tidal inundation model might not be particularly sensitive to the changes on the intertidal areas.

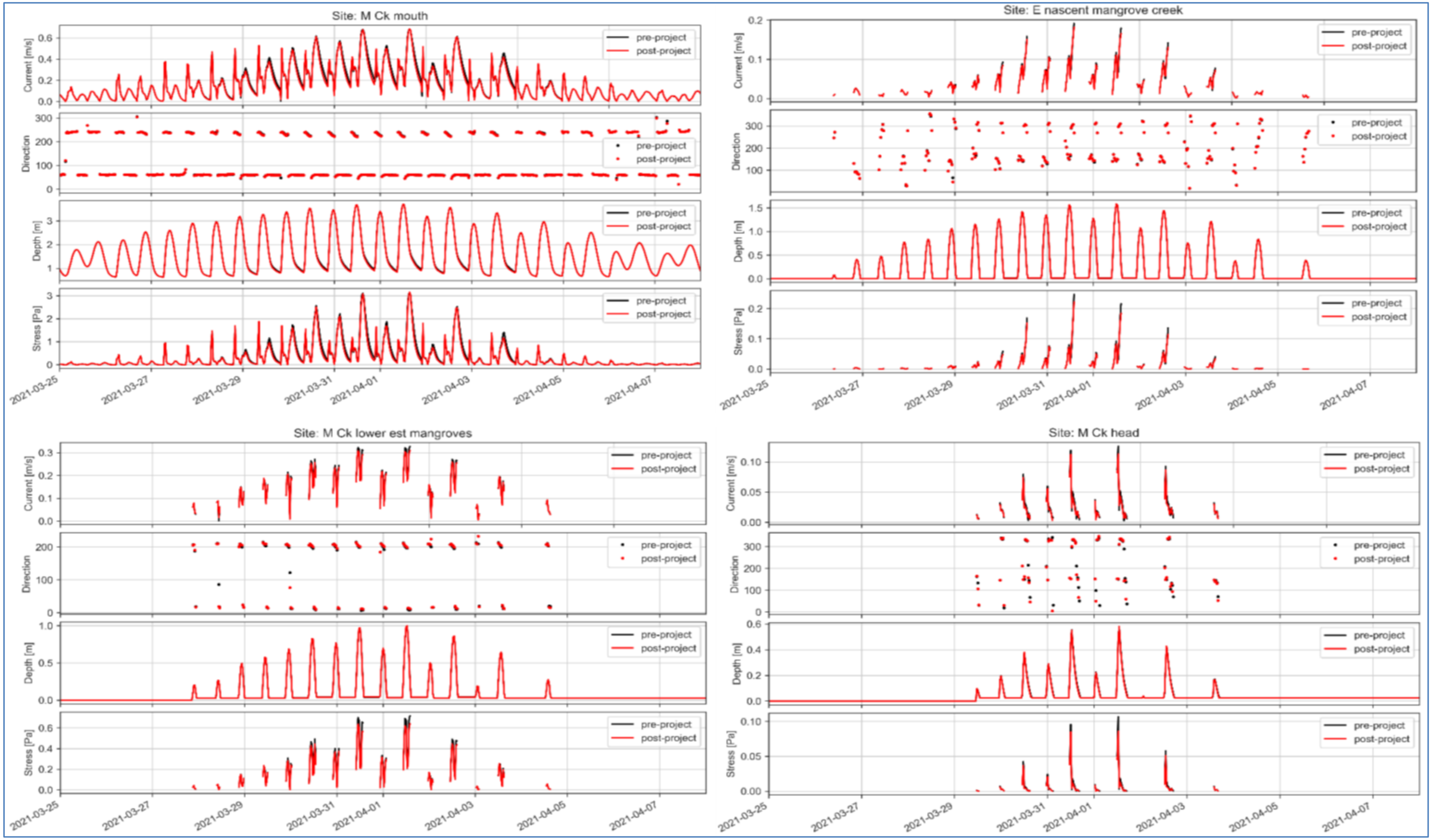


Figure 176. Modelled depth-averaged current speed and direction, water depth and bed shear stress for McKay Creek mouth, its lower estuary within mangroves, and McKay Creek head, and results for the easternmost creek mouth of the nascent mangroves. Black = baseline conditions, Red = with ponds of scenario 7.2.1.

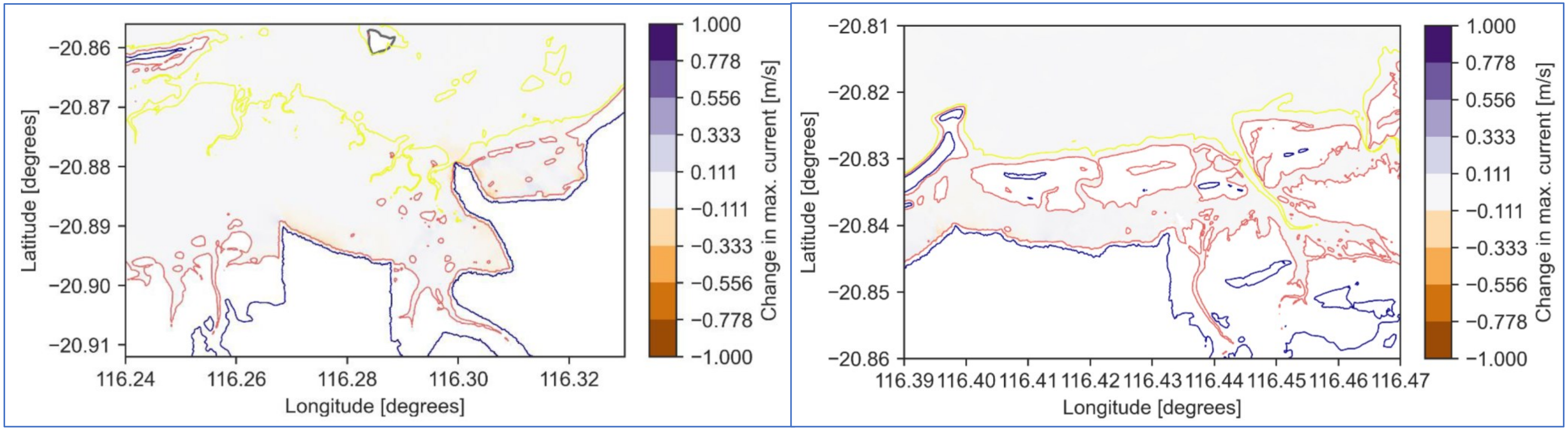


Figure 177. Changes in maximum depth-averaged tidal current speed in the western (left) and eastern (right) ESSP area with ponds of scenario 7.2.1.

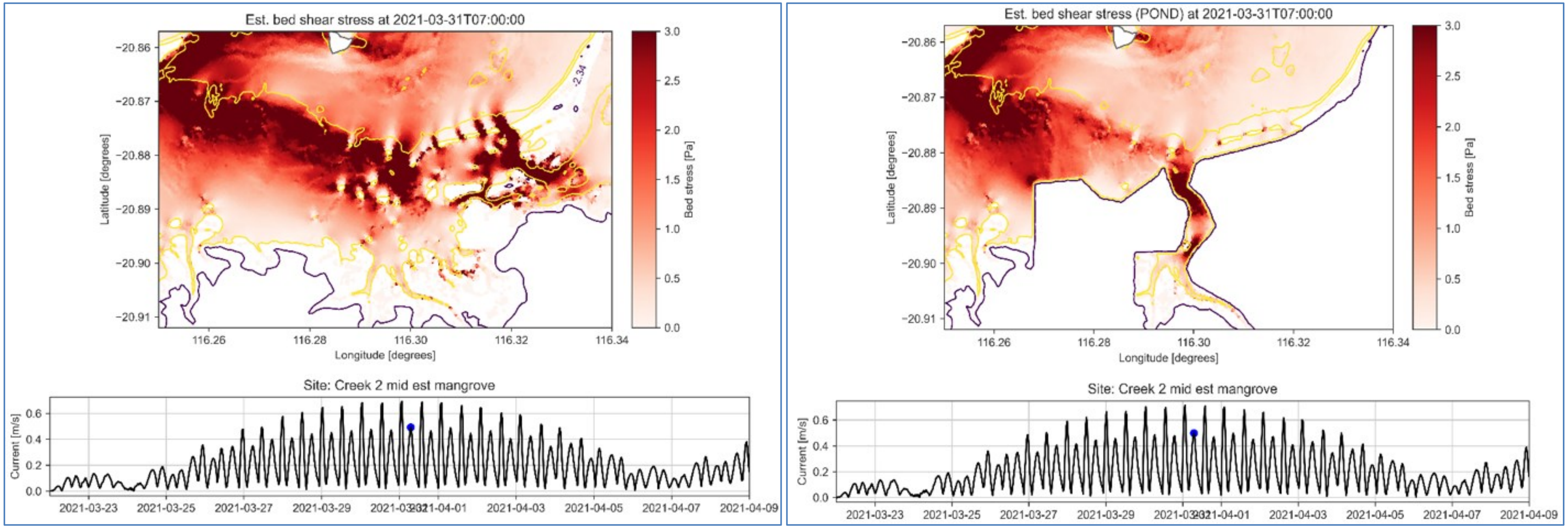


*Figure 178. Distribution of calculated bed shear stress (map) across the estuary and inundated southern shoreline environments during peak ebb tide (time-series) at Creek 2 within the mid-estuarine mangroves. LEFT = present conditions. RIGHT = **With ponds, but NB – SUPERSEDED SCENARIO 6.2.0**. Elevation contours (yellow) are at LAT, MSL and +3.5 m AHD.*

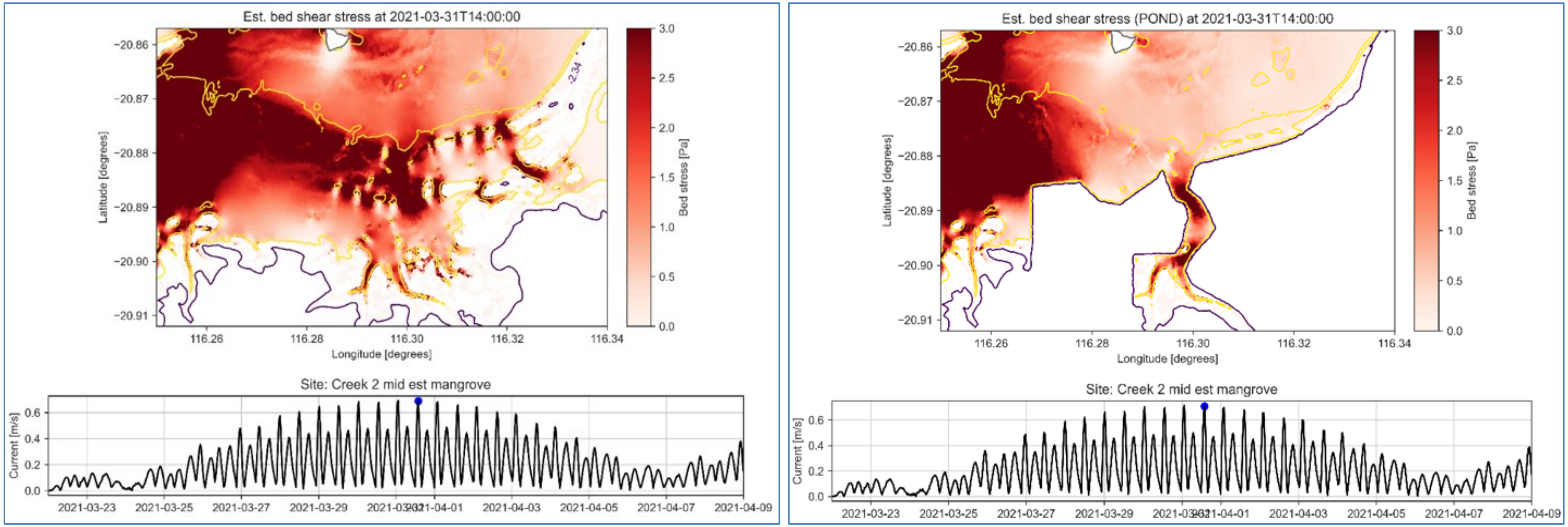


Figure 179. As above, but for the following peak flood tide. LEFT = present conditions. RIGHT = ***With ponds, but NB - SUPERSEDED SCENARIO 6.2****.*

19.2. The western ESSP area's high tidal flats

Model outputs indicate that tidal flow on the high tidal flats landward of creeks 3, 2 and 1 (location on Figure 40) peak at around 0.2 m/s, and may be relatively unaffected by the ponds' presence.

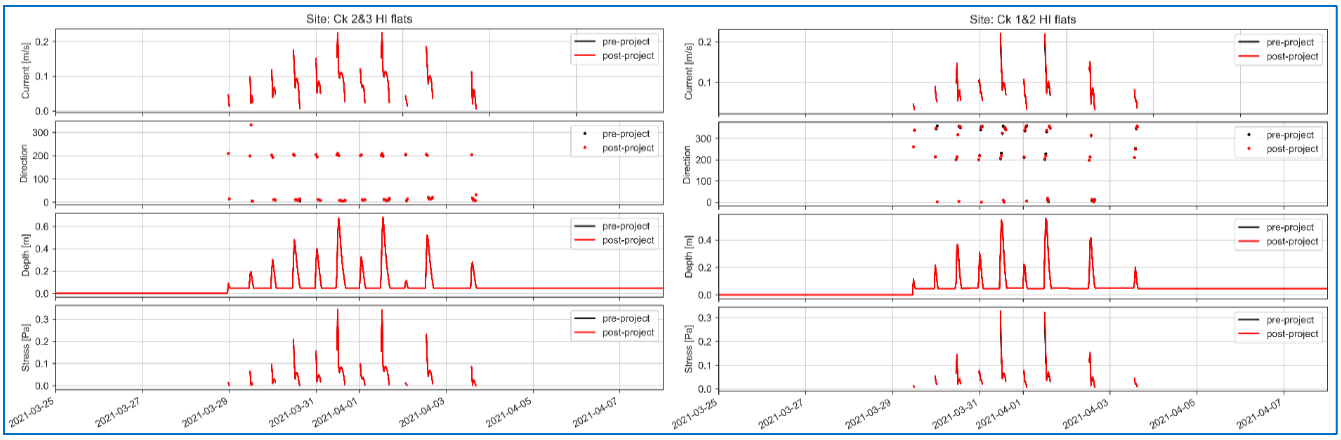


Figure 180. Changes in depth-averaged tidal current speed, direction, depth and bed shear stress on the high tidal flats landward of Creeks 2 and 3 (left) and of Creeks 2 and 1 (right) with ponds of scenario 7.2.1. Data gaps indicate periods of drying.

19.3. The ESSP area under surge conditions

Work produced for scenario 6.2 included data for the peak of the surge (Figure 181) and illustrates the capacity of waves to penetrate far to the south. Here the model adjusts bed stress to account for the time-averaged influence of wave-induced stress on the mean flow. This is less than the peak stress under the wave that would be material to mobilising bed sediment.

Simulations 5 upwards investigated the effects of scenario 7.2.1 ponds using a large storm surge and strong, persistent wind forcing from different wind directions. These winds were chosen for their different potential effects on the coastline. For each simulation, maps of total water depth, bed shear stress, depth-averaged currents and significant wave heights were generated (Figure 31 through to Figure 35). Observations of note are:

- With the surge, wind forcing from the NW (O2 Metocean 2023a) generated the largest current speeds, significant wave heights and bed shear stresses across the whole ESSP area compared to the other modelled wind directions (Figure 182, Figure 183) illustrates the results for W winds.at mid tide).
- With the surge, strong and persistent easterly winds generate large current speeds, shear stresses and significant wave heights along the western ESSP area, including in areas that are normally sheltered, such as the western estuary.

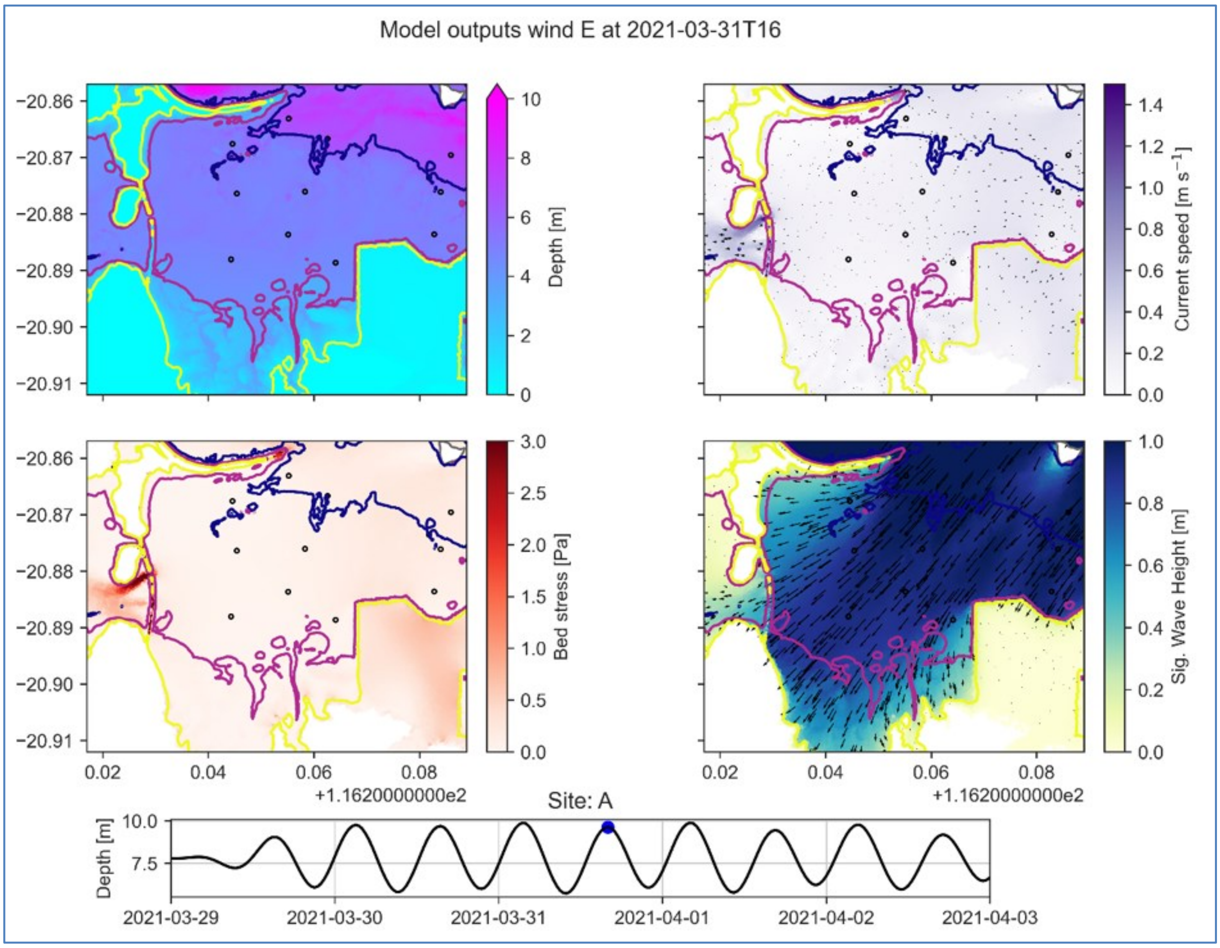


Figure 181. Model outputs for high tide plus 2 m surge for the western estuary. Waves from the NE penetrate the entire estuary and cross the shoreline and the mangroves to reach at and beyond the high tidal areas. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

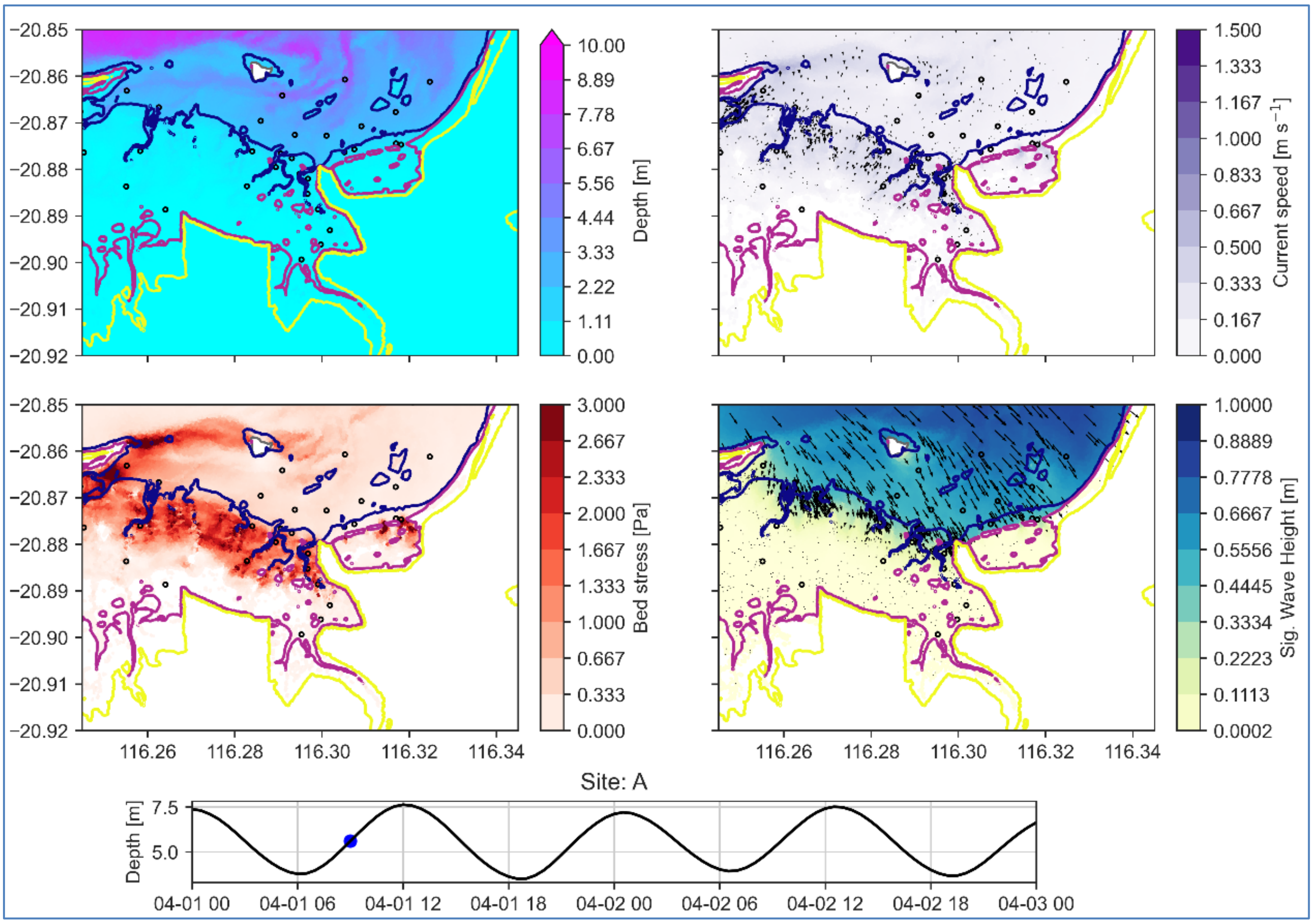


Figure 182. Simulation 9 (northwesterly wind forcing): Total water depth, current speed, bed shear stress and significant wave height, for the western ESSP area. Elevation contours are at MSL (blue), HAT (purple) and 6 m AHD (yellow). Scenario 7.2.0.

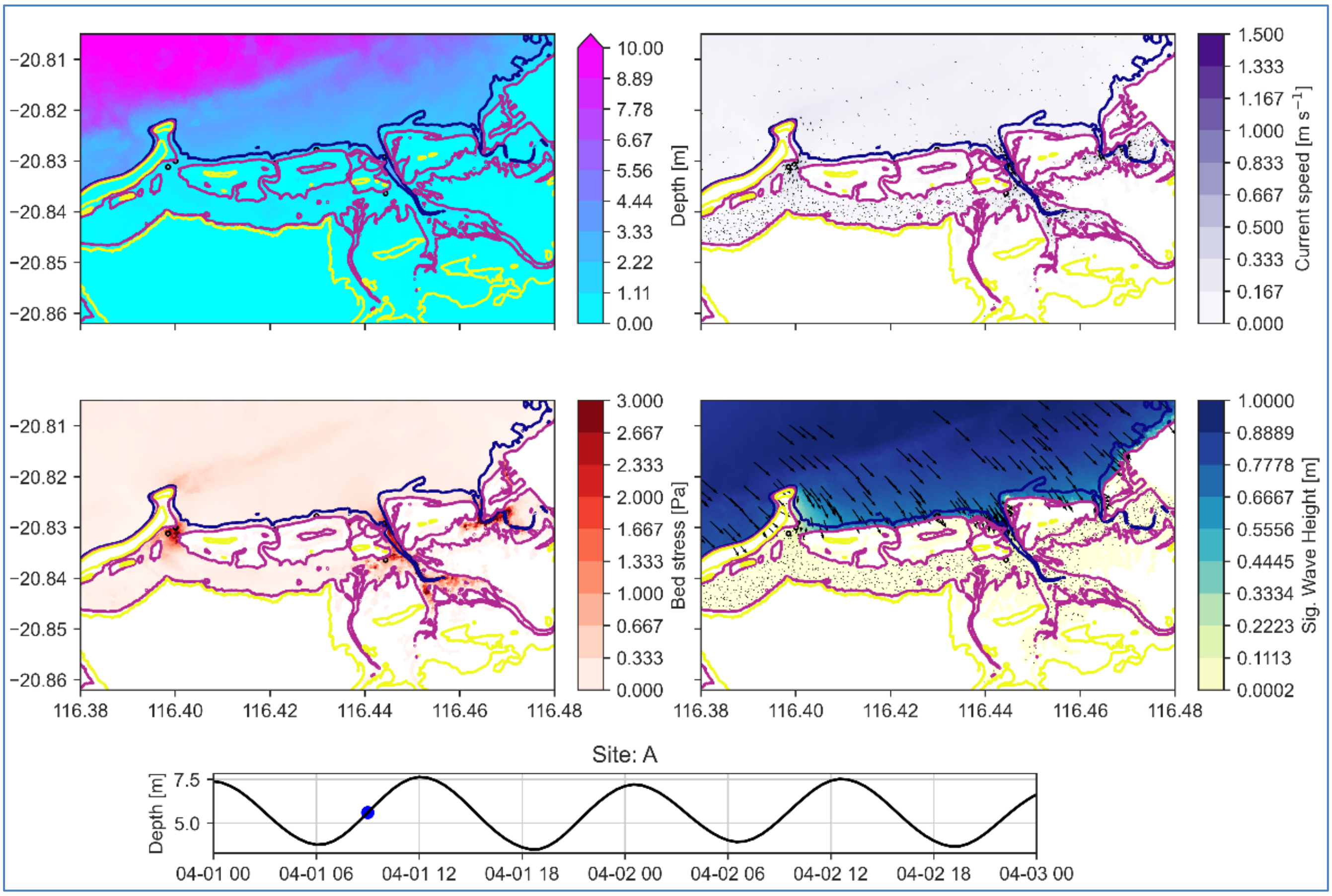


Figure 183. Simulation 9 (northwesterly wind forcing): Total water depth, current speed, bed shear stress and significant wave height, for the eastern ESSP area. Elevation contours are at MSL (blue), HAT (purple) and 6 m AHD (yellow). Scenario 7.2.0.

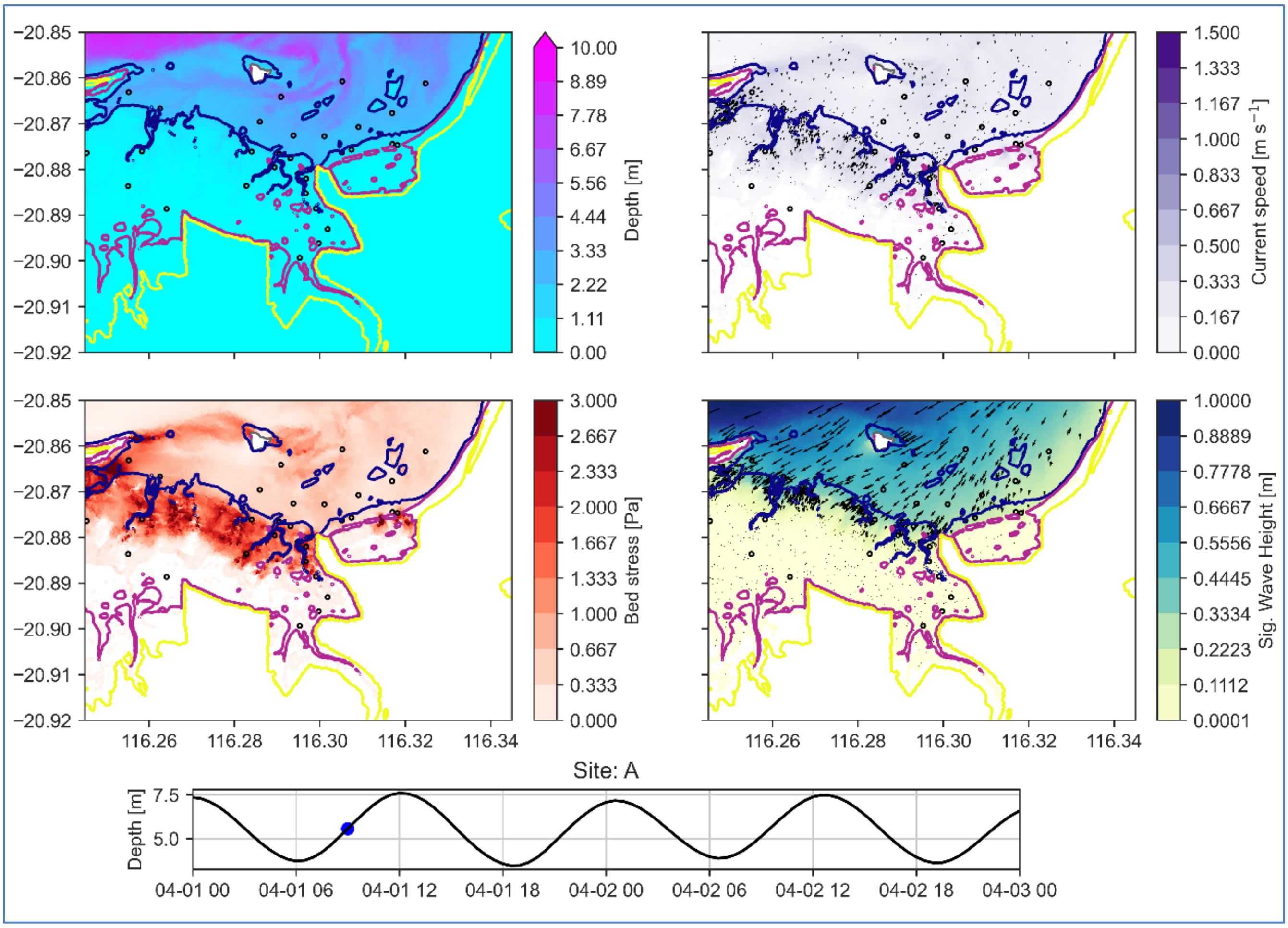


Figure 184. Simulation 7 (easterly wind forcing): Total water depth, current speed, bed shear stress and significant wave height, for the western ESSP area. Elevation contours are at MSL (blue), HAT (purple) and 6 m AHD (yellow). Scenario 7.2.0.

19.4. Summary

In the western ESSP area, for periods of large spring tides, the presence of the ponds appears to induce large changes in tidal current speeds, directions and bed shear stresses. Generally along the estuary's southern shoreline and especially in front of the nascent mangrove fringe, the ponds tend to significantly reduce bed shear stress induced by the fastest tidal currents (Figure 178) Overall, there is an alongshore gradient, whereby:

- The effects are greatest for the nascent mangrove creeks in front of the pond walls, i.e., where the pond walls are closest to the shoreline and have removed the largest area of the associated intertidal flats. There is much less water required to fill the smaller tidal catchment to high tide levels, but over the same ~6-hour period, so flow speeds are reduced.
- Effects are likely to be major for McKay Creek. Decreased flow speeds at the mouth may combine with the supply of eroded sediment from its resulting intertidal catchment, increasing the chances of the creek mouth receiving more sediment that it can export.
- A similar risk probably applies to Baldy/Straight Creek but to a lesser extent, and the same for the next creek to the west (Creek 1).
- Still further to the west, flows in the mouth of the two most westward creeks (Creeks 2 and 5) will be largely unaffected.

In broad terms, this is likely to be the case for pond scenario 7.2.1.

There, there appears to be increased potential for sediment accumulation on the central estuary southern shoreline, resulting in coastal progradation there, and perhaps especially in front of the nascent mangroves. Further landward, the modelling indicates increased flow speeds in the gaps between the ponds, that will likely cause major changes in bed elevations, including potential supply of eroded sediment to the mouth of McKay Creek. The general locations of changed flows are broadly consistent with those indicated by modelled intense rainfall events (Section 17).

Regarding winds, the results emphasise the importance of those tropical cyclones that pass to the NW of the area, driving winds with an easterly to northerly component, and then turning to northwesterlies. Any associated surge would likely be greatest under the trailing westerlies in the wake of the passage of the storm. These results tend to support an interpretation that cyclones are likely to play a role of regional coastal retreat (e.g., Section 11.6).

Further inferences on specific locations cannot be drawn from the modelling at this stage.

20. Possible areas of future erosion and accretion

This work has addressed a wide range of physical and timescales. The uncertainties in the outcomes are relatively large, for example, because in the same local area there can be changed factors that can act to drive coastal change in opposite directions, and there is a complex mix of periodic and episodic processes. It was originally envisaged to prepare predictions for a small number of time periods, ranging from immediate impacts of a few weeks after construction through to a century ahead. The view was that this approach would assist in developing the BCH impact assessment and its external presentation to the EPA. However, one clear result of this work is that there is great uncertainty about the relative impacts of day-to-day tidal processes versus waves, and periodic processes versus episodic events. The coastline's various gradients mean that predictions on short timescales carry enormous uncertainty, and the uncertainties in forming a century-long view are probably no more significant than forming a view on the next decade. Therefore, with the currently available evidence, it is possible to calculate predictions in quantitative fashion for the above range of timescales and in the presence of the proposed development. (That said, an attempt had been made using expert judgement, in Section 22).

Regarding SLR, and its relative importance in this instance of a solar salt development, the 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 nature of the human intervention - a largely unsurprising finding because the basic physics tends to dictate this result. Guo's conclusions are in line with:

- Work done through the 1980s, 1990s and since then on the physical dynamics of such systems (e.g., Friedrichs *et al.*, 1990; Wolanski & Ridd, 1990; Larcombe & Ridd, 1996);
- Previous foundational work, including Pethick 1984, on temperate saltmarshes;
- Work done on UK systems and the southern states of the USA, amongst others; and
- Conclusions drawn on a range of systems around Northern Australia.

This warrants a little explanation. In assessing the ESSP coastline and its future, key factors include that:

- In this system of spring tidal range around 5 m, the few largest overbank tides each year form the primary control on sediment fluxes across the coastline, (i.e., up and down within the creeks and across the mangrove swamps at the highest tides).
- Sand supply within some of the creeks may be limited[29] (Figure 55).
- The evidence in Regnard Bay is that near-bed turbidity is low even at high speeds (Section 7.2.1), indicating a limited supply of fine sediment, broadly consistent with the few bed samples and regional expectations.
- The effect of SLR, taken here as around a rise of 0.9 m in mean sea level by 2110, i.e., an average of 0.1 m/decade, will be to increase the number of 'overbank' tides each year, presuming the estuarine catchment as a whole cannot accumulate sediment at a rate matching the rate of proposed SLR. This presumption is almost certainly correct because…
- … the total area of the catchments between the western and eastern end of the project area, calculated at around HAT (~2.5 m AHD), is around 260 x 10^6 m^3, so that to naturally accumulate sediment across

---

[29] Although note the caveats about there being relatively few measurements in the ESSP area, and of turbidity as a poor indicator of sand transport (Bunt *et al.*,1999).

this entire area at 1 cm/year without the ponds in place would require the accumulation of 2.6 x 10^6 m^3 of sediment per year (i.e., ~6.8 x 10^6 t/year). This is unlikely because…

- … the riverine sediment load to the coastal zone is generally considered relatively low across the Pilbara region, and Margvelashvili *et al.* (2006) estimated that the entire ~300 km of coastline between North West Cape and Dampier receives only ~0.3 x 10^6 t/year of terrigenous sediment on average, with the Ashburton River contributing about half this amount. Even though Margvelashvili *et al.*'s (2006) estimates are not based on field data, for the estuarine region at Eramurra to consistently accumulate sediment at a rate ~20 times that received by the entire southern Pilbara shelf is not geologically feasible, if we are only considering 'new' sediments delivered to the shelf down rivers. If rivers were the only possible source of sediment, then it would be geologically inevitable that the shoreline would not be able to keep up with SLR and would begin to drown.
- However, the natural shoreline may be able to migrate through 'roll-over', whereby sediment at the coastline is eroded and carried landward to be deposited into the intertidal zone as it migrates landwards. Too little is known about the stratigraphy (including age) of the post-glacial sediments at the coast and in the marine environment, i.e., the volume of sediment available for such reworking, for this to be determined at present.

Therefore, regarding future changes to the coastal system that are projected to arise from the ESSP development being emplaced, there can only be formed some general **qualitative** scenarios. Below are presented:

- Brief comments on several time periods, encompassing:
    - Impacts of immediate (few weeks) after construction
    - The subsequent 6 months (seasonal waves & the first period of equinoctial tides)
    - The next major surge and strong alongshore winds
    - The first decade (0-10 years)
    - To 3 decades ahead (10-30 years)
    - The remainder of the century ahead (30-100 years).
- Summary maps of interpreted changes in bed sediment transport directions, driven by tides and by waves, with resulting tendencies for possible sediment accumulation or erosion (Figure 185 to Figure 188). Note that this draws heavily on expert judgement because supporting field data are few. The relative transport rates of waves versus tidal currents have not been explored over any timescales, from daily to a century.
- A summary table of possible morphological changes and implications for BCH (Table 31) taking a century-long viewpoint.

20.1. Impacts of immediate changes (few weeks) after construction

Whilst this has not been specifically analysed, the sediment dynamics of the tides are strong, and changes may be rapid in some places even without any surge events, tropical cyclones or periods of intense rainfall. The McKay Creek channel system between the ponds and at its mouth, the nascent fringing mangroves and the creeks in the eastern project area are all possible areas where physical impacts may become apparent first, particularly regarding areas of erosion[30]. Remobilised sediment is likely to be removed into the estuary and distributed, so there may be few identifiable examples of the consequences of sediment accumulation.

---

[30] Changes DURING construction have not yet been considered.

20.2. The subsequent 6 months (seasonal waves & the first period of equinoctial tides)

Over such a time, it should be that the basic tidal effects begin to become apparent, in terms of areas of coastal erosion and those of progradation. There may be some early indications of new areas of BCH.

20.3. The next major surge and strong winds from the NE sector

This may be the first instance where the understanding of the potential multi-decadal changes might begin to become a little clearer. Areas where tides and seasonal processes have caused erosion might be more susceptible to retreat, and beaches to erosion and/or landward migration. In contrast, those areas where the coastline has prograded might show lesser effects from the surge and waves.

20.4. The first decade (0-10 years)

Should no ‘events’ occur then many minor morphological changes might have been completed, and more major ones would be taking place at a relatively steady pace, becoming increasingly clear in nature. Some major new areas of BCH may be becoming well established. Some minor state changes, such as a creek mouth becoming temporarily blocked, might occur.

20.5. To 3 decades ahead (10-30 years)

It is likely that over such a period, several ‘events’ might have occurred, and their individual effects on the long-term evolution of the coastline and its BCHs should be becoming clearer. At this time, if SLR has taken place at an average rate of 10 mm/year, there would be a suite of clear and measurable signals in the coastal dynamics and the coastline itself. Some state changes might have occurred and may have persisted.

20.6. The remainder of the century ahead (30-100 years).

Quantification of the changes and understanding of the coastline should be mature enough to greatly reduce uncertainties about the future paths of change and the range of possible changes along the way.

21. Summary maps of interpreted changes

This section presents a series of summary maps of interpreted possible coastal changes. It is emphasised that these are illustrations of general possibilities, to help visualise some possible outcomes. The diagrams reflect work done with pond scenario 6.2.0. The new proposed pond scenario 7.2.1. will modify some aspects of these diagrams, and they should be viewed in conjunction with the detailed work performed on the current scenario 7.2.1., which is described in Section 22 and presented in Table 31, Table 33, Table 35 and Table 37.

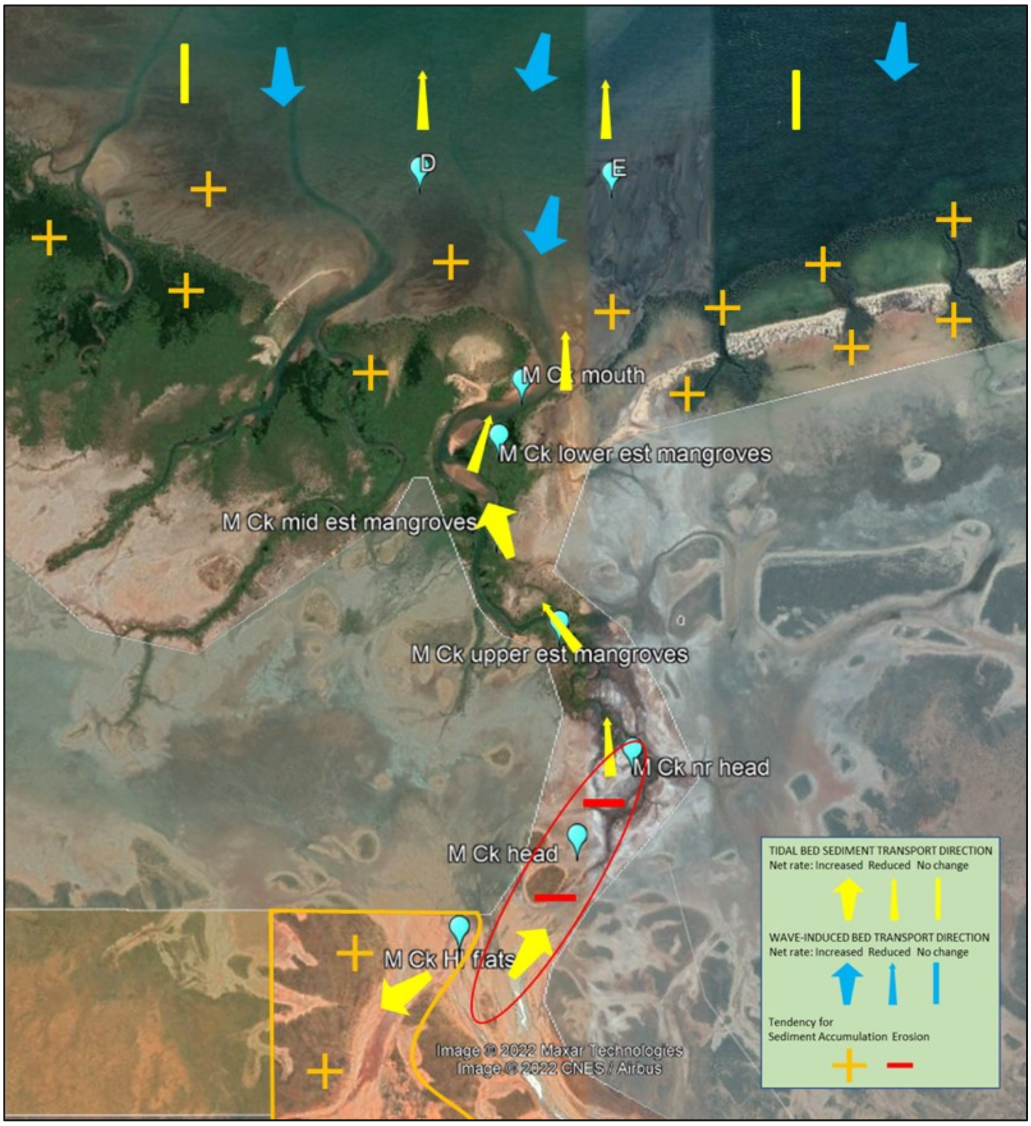


Figure 185. Summary of potential tidal and wave-related tendencies of changed sediment transport at McKay Creek. Red areas = Erosion. Orange areas = Accumulation.

Figure 186. Summary of potential tidal and wave-related tendencies of changed sediment transport at the eastern end of the project area.

Figure 187. Summary of potential tidal and wave-related tendencies of changed sediment transport in the estuary.

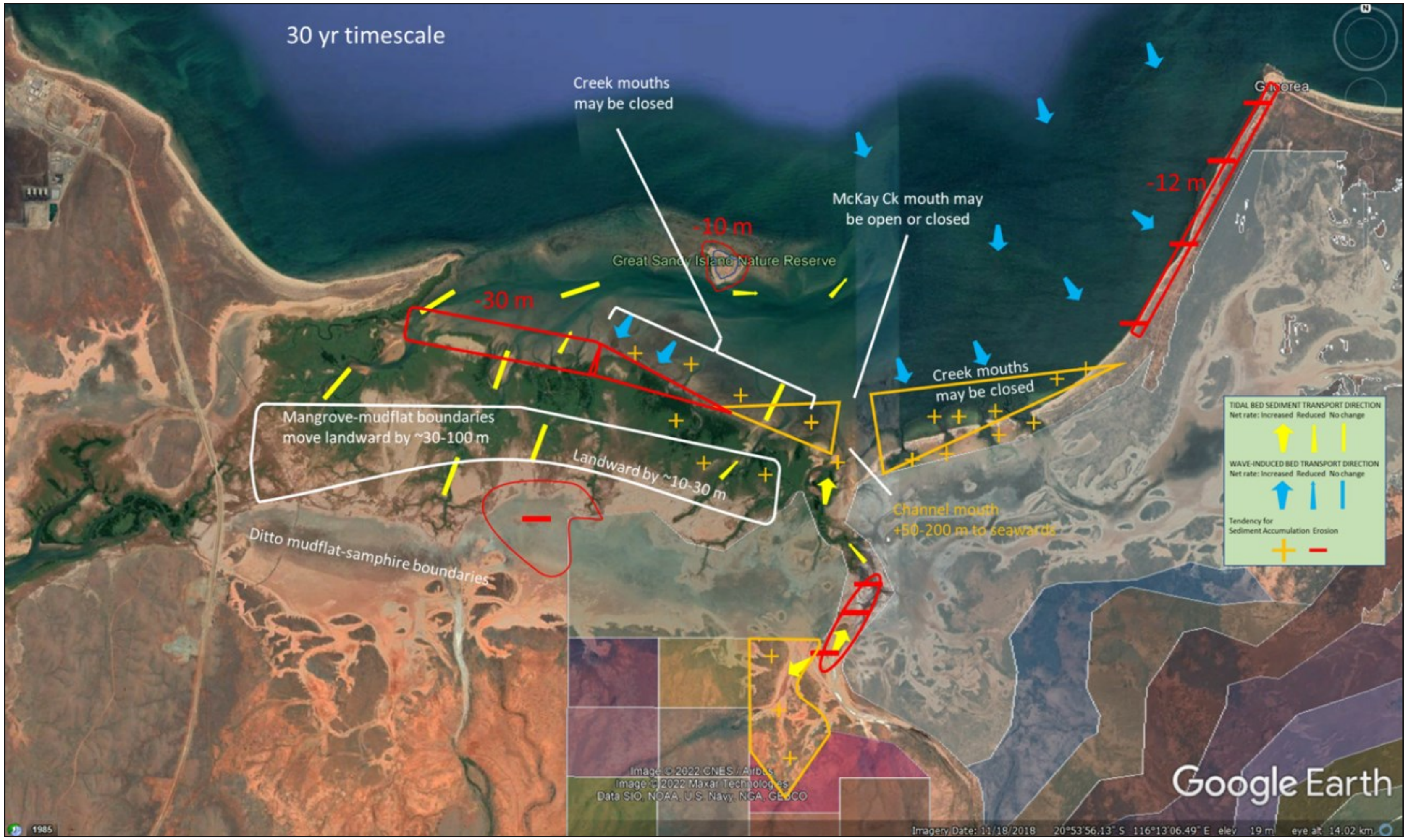


Figure 188. Indicative possible changes over a 30-year timescale in the estuary. Red areas = Erosion with general indicators of magnitude (NB – not drawn to scale). Orange areas = Accumulation.

Table 31. Summary of possible morphological changes (non-exhaustive), potential causes, potential changed vulnerability to events (e.g., surges, tropical cyclones & rainfall events), and implications for BCH, using a multidecadal to 100-year timescale. This table refers to those areas considered clearly at risk of such changes, and in general does not apply to those areas where no tidal changes are likely, nor to those areas close to the pond walls.

Environment or BCH name	Potential change from pond emplacement	Potential cause	Comment on consequence	'Vulnerability' to natural events	Scope for 'recovery' back to natural state	Level of confidence in the interpretation	Implications for BCH	Will SLR of 0.9 m over 100 years exacerbate or ameliorate the issue?[31]
Subtidal coral on rocky substrate	None	-	-	-		Very high	None	n/a
Subtidal seagrass beds	Reduced sand supply from shoreline creeks	Decreased tidal influence at N end of main estuarine subtidal channel	Potential slight local erosion and/or local accumulation of sand at the channel end	Unchanged	Unchanged	Very high	None	-
Intertidal seagrass beds	Reduced sand supply from shoreline creeks	As above plus changed tidal dynamics	Possible local small changes, but well within normal variation	Unchanged	Unchanged	Very high	None	Ameliorate
Intertidal flats (seawards of the coast)	Reduced sand supply from some creeks	Changed tidal dynamics	Possible change of slope or bed elevation close to the coast, so waves reach further in.	Increased	High, because of ample sandy sediment in the system	Medium	Possibly slightly increased risk to beaches to their landward	Exacerbate
"	Increased landward transport of sand	Reduced tidal currents, increased relative flood strength	Widespread accumulation of sand	Reduced	Low	Medium	Increased subtidal accretion, so perhaps potential new sites for seagrass, and increased progradation of	Ameliorate

---

[31] SLR will generally be a minor factor compared to the human intervention, so amelioration might be minor.

Environment or BCH name	Potential change from pond emplacement	Potential cause	Comment on consequence	'Vulnerability' to natural events	Scope for 'recovery' back to natural state	Level of confidence in the interpretation	Implications for BCH	Will SLR of 0.9 m over 100 years exacerbate or ameliorate the issue?[31]
							fringing mangroves	
"	Reduced persistence of ebb channels across intertidal zone seaward of the coast	Changed tidal dynamics, so increased relative influence of waves	Risk of tidal creek mouths closing	Reduced	Highly variable	Medium	Greater temporal variation in intertidal BCHs, potential of new growth of flora in and around closed tidal creeks, reduced fauna near head of creek.	Both possible. SLR faster than vertical accumulation of intertidal sediment may allow access to slightly larger waves but will also increase overbank volumes and act to strengthen ebb tidal flows.
Nascent fringing mangroves	Chance of slight increase in bed stresses where pond walls are closest to the coast	Reflection off pond walls at extreme tides plus surge	Erosion	Increased - but low possibility	Very high	Medium	Greater areas of fringing mangrove, decreased areas of estuarine mangrove	Exacerbate
"	Increased accumulation within the small creeks	Changed tidal dynamics at the shoreline and to seawards	Shallowing, infilling and seawards progradation of the system	Increased - the smaller system size will be less resilient to those events that cause morphological change	High, the system will infill and there may be a wider and more continuous mangrove fringe than at present	High	Greater areas of fringing mangrove, decreased areas of estuarine mangrove	Ameliorate
Estuarine mangroves	Increased accumulation of sediment	Changed tidal dynamics	Seawards progradation of the sandy system mouth, plus	Decreased except at the margins	Low	High	Enhanced in the lower and middle parts of the catchments but	Ameliorate

Environment or BCH name	Potential change from pond emplacement	Potential cause	Comment on consequence	'Vulnerability' to natural events	Scope for 'recovery' back to natural state	Level of confidence in the interpretation	Implications for BCH	Will SLR of 0.9 m over 100 years exacerbate or ameliorate the issue?[31]
			possible downcutting at the creek heads				probably reduced in upper parts. Probably a smaller overall area of estuarine mangroves.	
"	Creek migration is reduced	Changed tidal dynamics	Slow rates in sediment recycling	Increased	Very low	Very high	Estuarine mangrove stands are likely to last longer on average	Ameliorate
Tidal creeks	Accumulation of sediment	Changed tidal dynamics	Creeks channels will shallow and narrow, especially McKay Creek, and to a lesser extent to Baldy/Straight Creek and the creek to its west.	Decreased	Very low	Very high	New areas of estuarine mangroves on creek banks as they accumulate sediment	Ameliorate
The gap between the ponds at McKay Creek	Faster freshwater flows down this creek	Altered runoff patterns with intense rainfall events	Local erosion in McKay Creek gap between ponds	Higher to intense rainfall	Low	Medium	May cause enhanced scour of any BCHs present e.g., algal mats, samphire, estuarine mangroves. Greater temporal variability in BCHs.	~Neutral
"	Increased local supply of sediment and reduced tidal currents to remove it	Erosion in the gap, tidal and/or freshwater	Increased accumulation at McKay Creek mouth, increasing	Decreased risk of coastal erosion	Low - medium	Low - medium	Increased accumulation of estuarine and fringing	Ameliorate

Environment or BCH name	Potential change from pond emplacement	Potential cause	Comment on consequence	'Vulnerability' to natural events	Scope for 'recovery' back to natural state	Level of confidence in the interpretation	Implications for BCH	Will SLR of 0.9 m over 100 years exacerbate or ameliorate the issue?[31]
			risk of blockage				mangroves in the infilling creek channel, near the mouth and along the adjacent shoreline	
Beaches	Reduced bed levels to seawards, beaches more active.	Changed tidal dynamics	Possible change of slope or bed elevation close to the coast, so waves reach further in.	Slightly increased - beaches may migrate landwards faster	High	High	Few	Exacerbate
"	Increased accumulation, e.g., of sand near creek mouths or of fringing mangroves, so beaches less active	Changed tidal dynamics	Elevated bed levels seawards of the beaches, so waves attenuated more	Decreased - the beach itself system will be less resilient to those events that cause morphological change	Medium, the beach may become stabilised by vegetation	Medium	BCHs (e.g., estuarine mangroves) landward of the beach will have greater protection	Ameliorate
Algal mats	Reduced tidal inundation	Changed tidal dynamics	Variable, but will include seawards migration of the area	No change	No change	High	High	Ameliorate
Samphire	Reduced tidal inundation	Changed tidal dynamics	Variable, but will include seawards migration of the area	No change	No change	High	High	Ameliorate
Pond walls to NW	Erosion near NW point	Change tidal dynamics	Might be fairly widespread as influence much of Creek 1's upper catchment	Increased to intense rainfall	Low	Medium-high	High, for edges of estuarine mangroves, for algal mats and local samphire	Ameliorate

PART FIVE - FUTURE CHANGE FOR KEY SITES

22. Worked examples of future change for key sites

22.1. Introduction

To revisit the overall purpose, this report is intended to:

- Use an analysis of physical factors to inform 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 the next 100 years
    - SLR over 100 years including the ESSP development.

These three items are necessarily dealt with in order, because the effects of the ESSP development can only be seen in the light of its potential differences to natural changes.

Regarding the analysis, it necessarily involves considering any gradual background trends. The consequences of episodic disturbance events (e.g., surges, extreme freshwater runoff, etc.) are also noted regarding their significance to sediment transport, geomorphology and BCHs. The significance of a specific event might vary depending at what stage in the future geomorphic evolution it occurs, and on its precise nature. Finally, the potential effects of the ESSP development are assessed against potential natural changes.

There are thus many possible aspects to consider, and over a century's timescale, there are a very large number of possible combinations of geomorphology and events. Work necessarily draws on meteorology, oceanography and data interpretation (e.g. O2 Metocean 2022a) and on 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 implicitly using the key questions and potential sediment transport pathways of Section 12, and some of those in Section 27. In places, we refer to a **Level of Confidence** in a statement, result or conclusion. This scale is described in Section 24.1.

Below are presented several 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 (Section 7.2.2.2 and Section 16), 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 4) 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 22.7).

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.

22.2. 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 what 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. The 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.

22.2.1. 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 189).

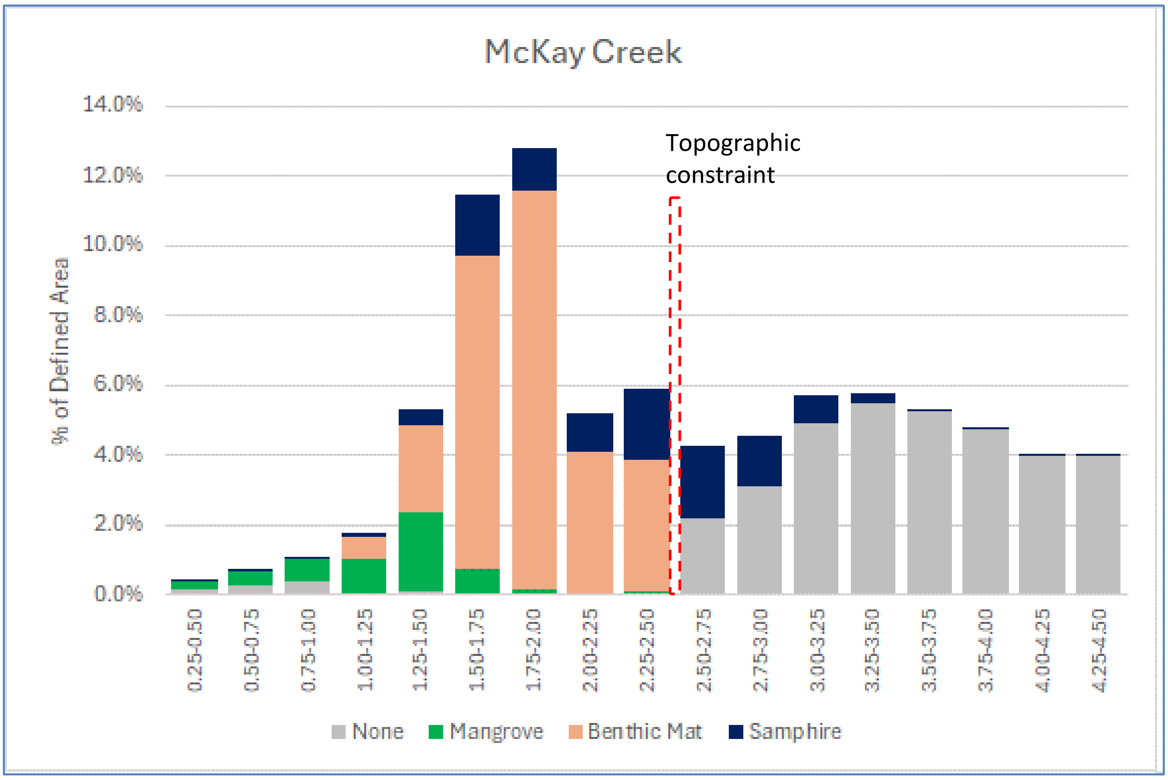


Figure 189. Vertical distribution (m AHD) of each BCH in McKay Creek, plus the vertical distribution of no BCH's, relative to the whole catchment area. Data are calculated for each 0.25 m elevation range. For example, the elevation range 1.75 to 2 m occupies 13% of the whole catchment. All this specific 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 190).

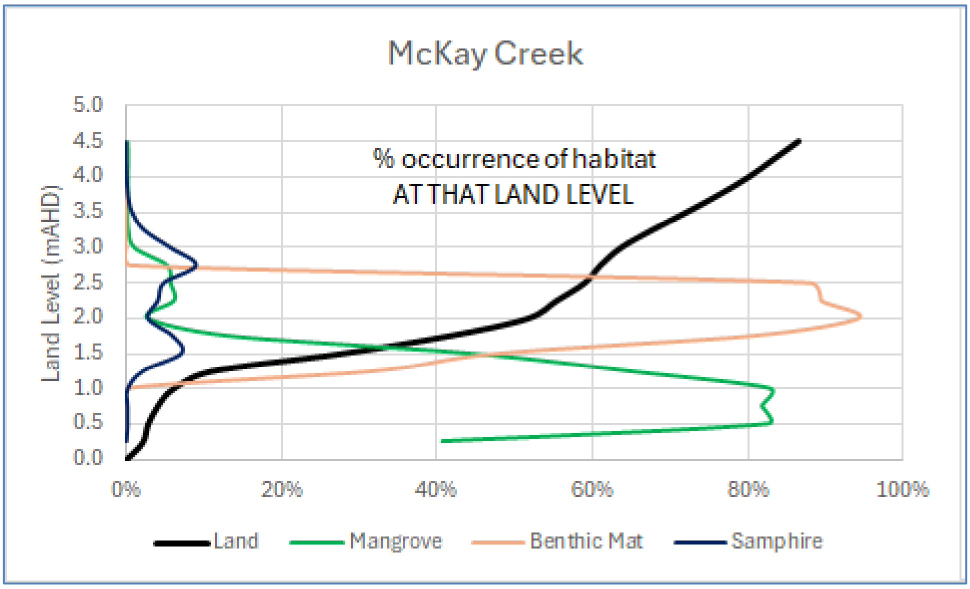


Figure 190. Vertical distribution of BCHs, expressed as a % of land occupied by each BCH at that specific elevation, to allow comparison with the catchment-averaged hypsometry (bed elevation). The bed elevation curve (black) indicates that there is a wide shallow-gradient area at 1.25 to 2 m AHD, above 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 190 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 191). 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.

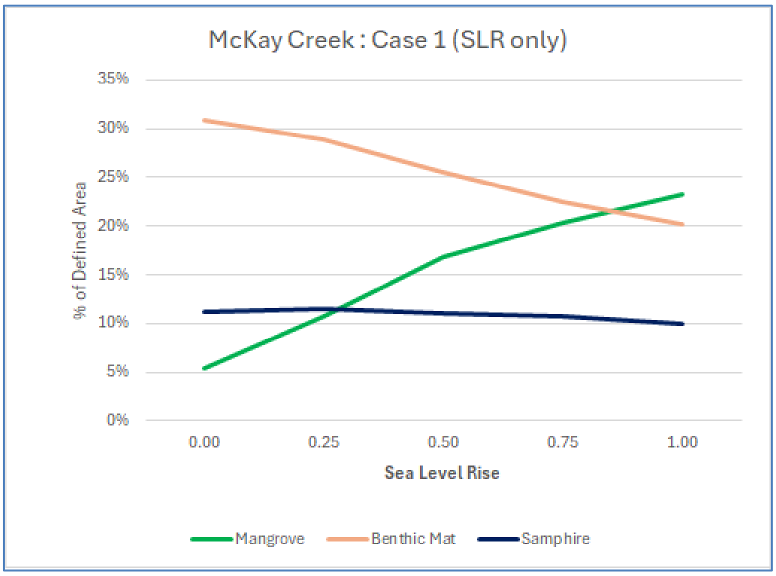


*Figure 191. The **‘SLR only’** case . Hypothetical proportion of each BCH in the tidal McKay Creek catchment at various stages of SLR (using 0.25 m increments) assuming no bed elevation change. So, taking all mangroves together, they occupy 5% of the catchment at present sea level, but will increase to 23% with a 1 m SLR. These numbers are upper bounds and over-estimate the proportions.*

22.2.2. 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 32) were then applied to that vertical increment for that BCH. **The result represents Case 2 – the ‘SLR plus sedimentary response’ case.**

Table 32. 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[32]	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 Section 37 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 192, 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 it 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.

---

[32] 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).

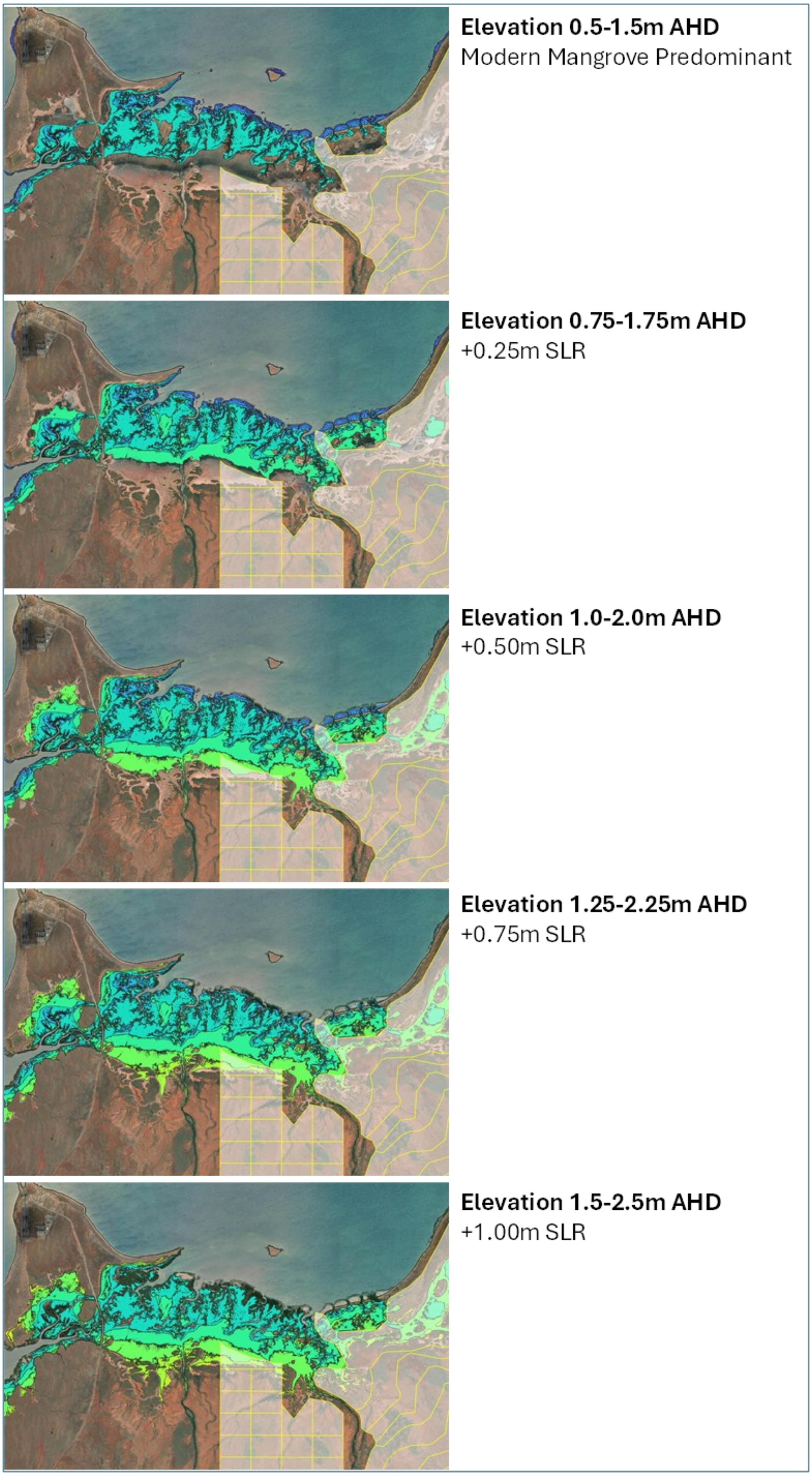


Figure 192. Elevation Zone of Present-Day Mangroves (Central), i.e., with no ponds. (The proposed ponds are shown only to help visual assessment with other figures).

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 189, Figure 190) and are constrained at the upper limit by steeper topography and cemented rocks – they favour low undulating ground and shallow basins. Therefore, SLR will inevitably decrease the available area for benthic mats (Figure 191). 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 193). Similar sediment release might also occur in locations further landward, but probably to a lesser extent because of the harder material.

22.2.3. 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 175] 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 194), 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.

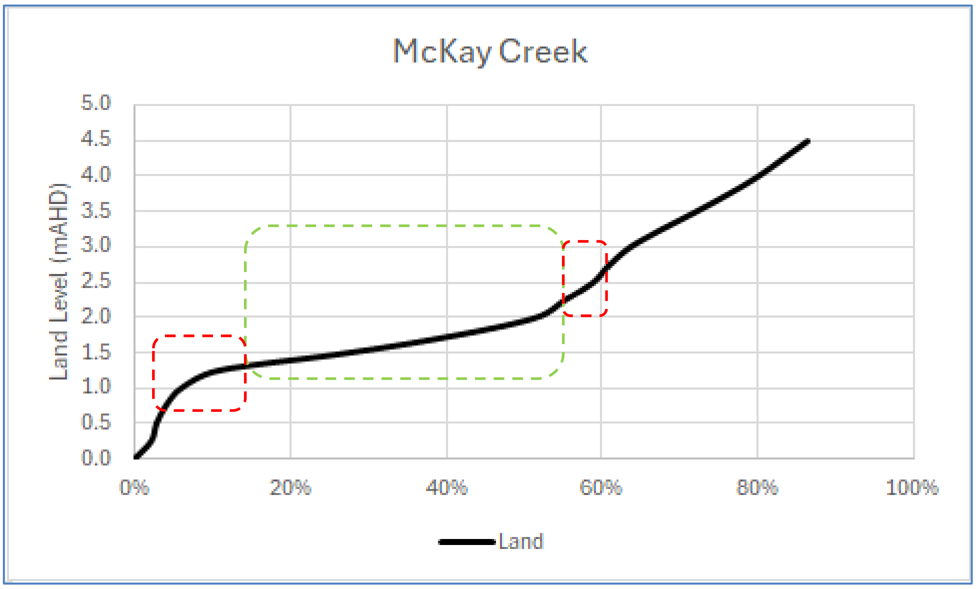


Figure 193. Hypsometric curve for McKay Creek, showing hypothetical areas of possible changed bed elevation (red = erosion, green = accumulation) for the 'SLR plus sedimentary response' case.

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 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 9.3.3), 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 113) 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.

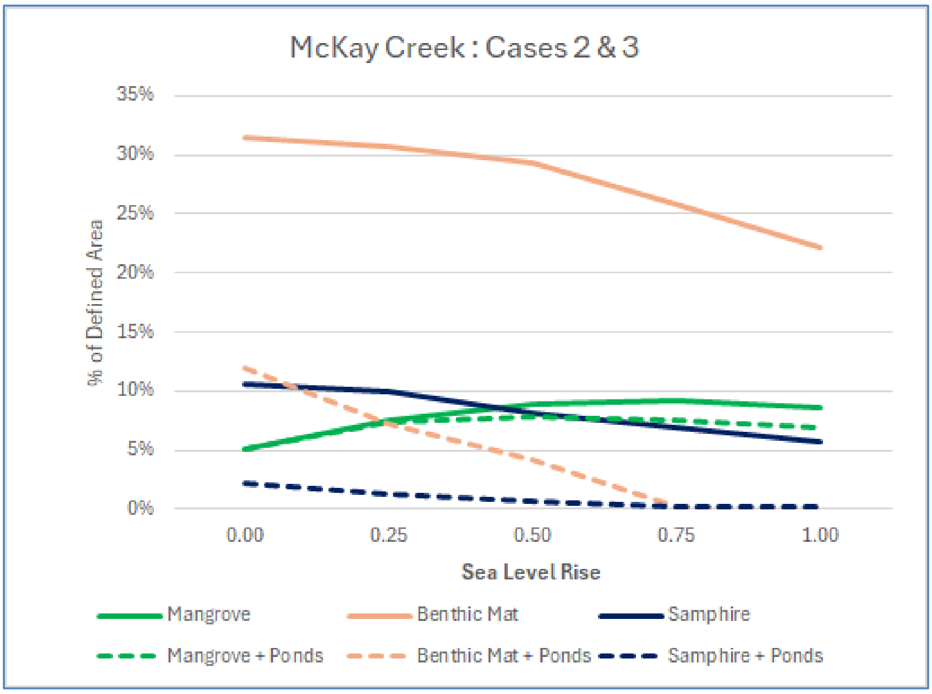


*Figure 194. Case 2 - **'SLR plus sedimentary response'** case (solid lines) and Case 3 - the '**SLR plus sedimentary response plus ponds'** case (dashed lines) for the McKay Creek catchment. The difference between solid and dashed lines indicates the changing effect of the ponds through time.*

A level of confidence is presented for each key result, with the terms used defined in Section 24.1.

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.

22.3. 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 195). 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 (Table 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 196, Figure 197). The intertidal flats appear to include surface exposures of fossil mangrove stumps (Figure 198), indicating a phase of coastal erosion since their formation. Given their sharp gradient with the base of the active beach (upper image of Figure 198), 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.

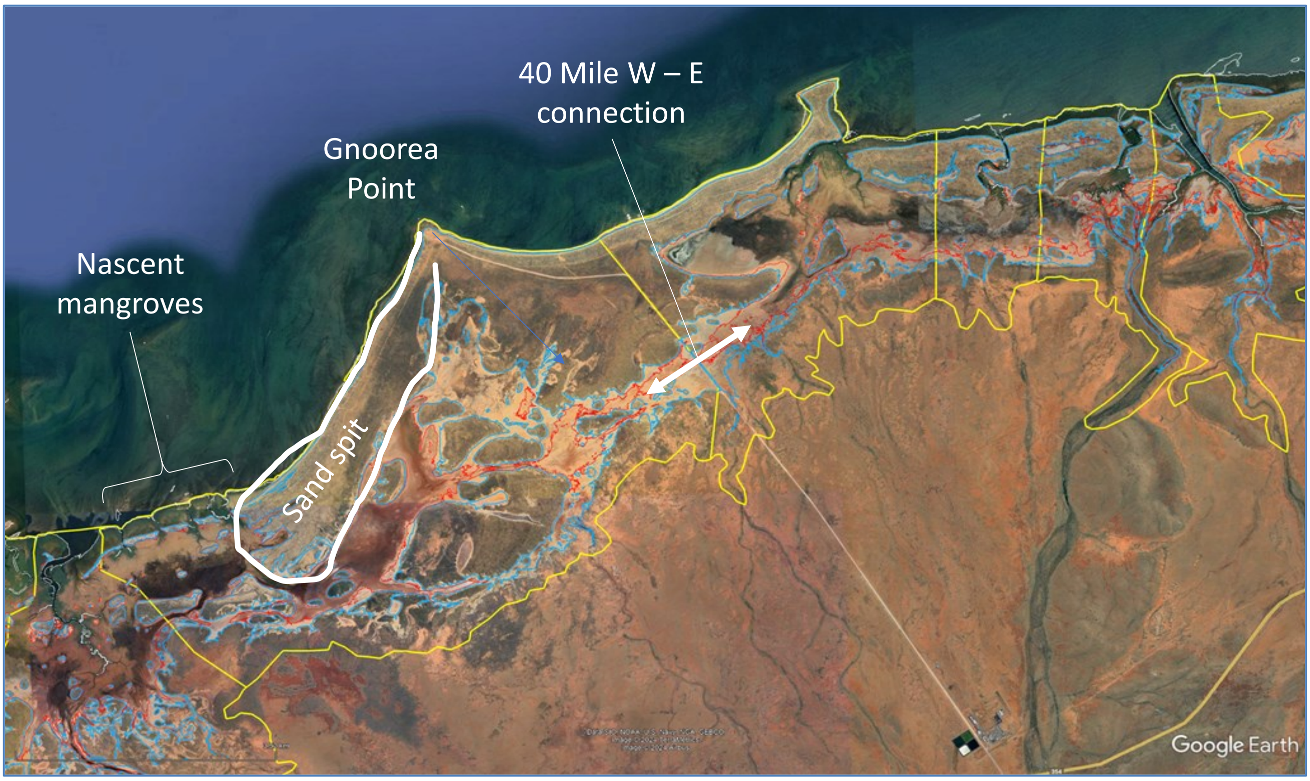


Figure 195. The sand spit complex SW of Gnoorea Point that fronts the western part of the 40 Mile Road W catchment, and the connection (before road construction) between the 40 Mile Road W and 40 Mile Road E catchments.

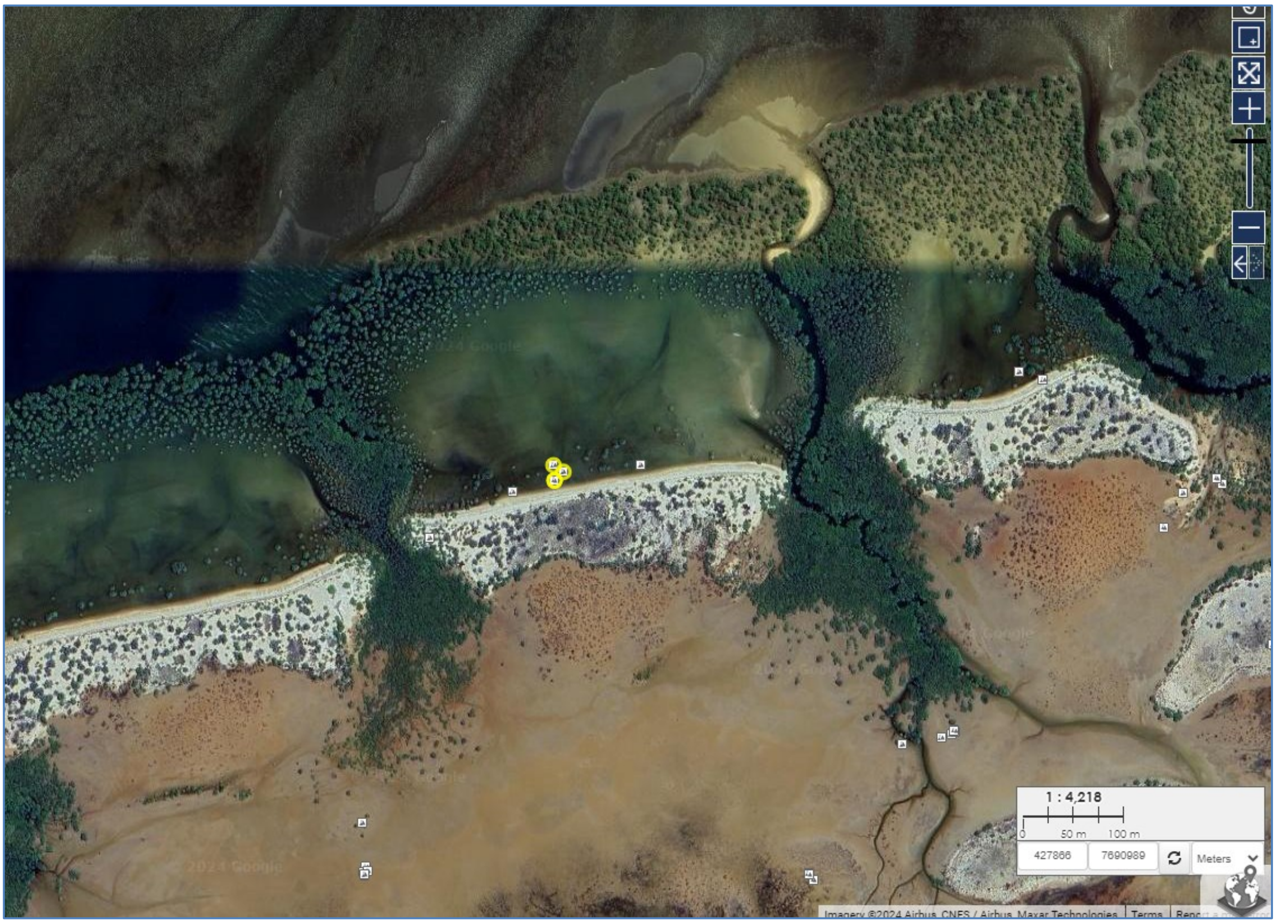


Figure 196. Aerial image of nascent mangrove coastline. Note the sparse fringing mangroves at the seaward fringe, and the denser mangroves along creek margins and at their landward end. The creeks occur in gaps between remnants of the most recent sandy barrier. Yellow dots indicate location of photos in Figure 198.

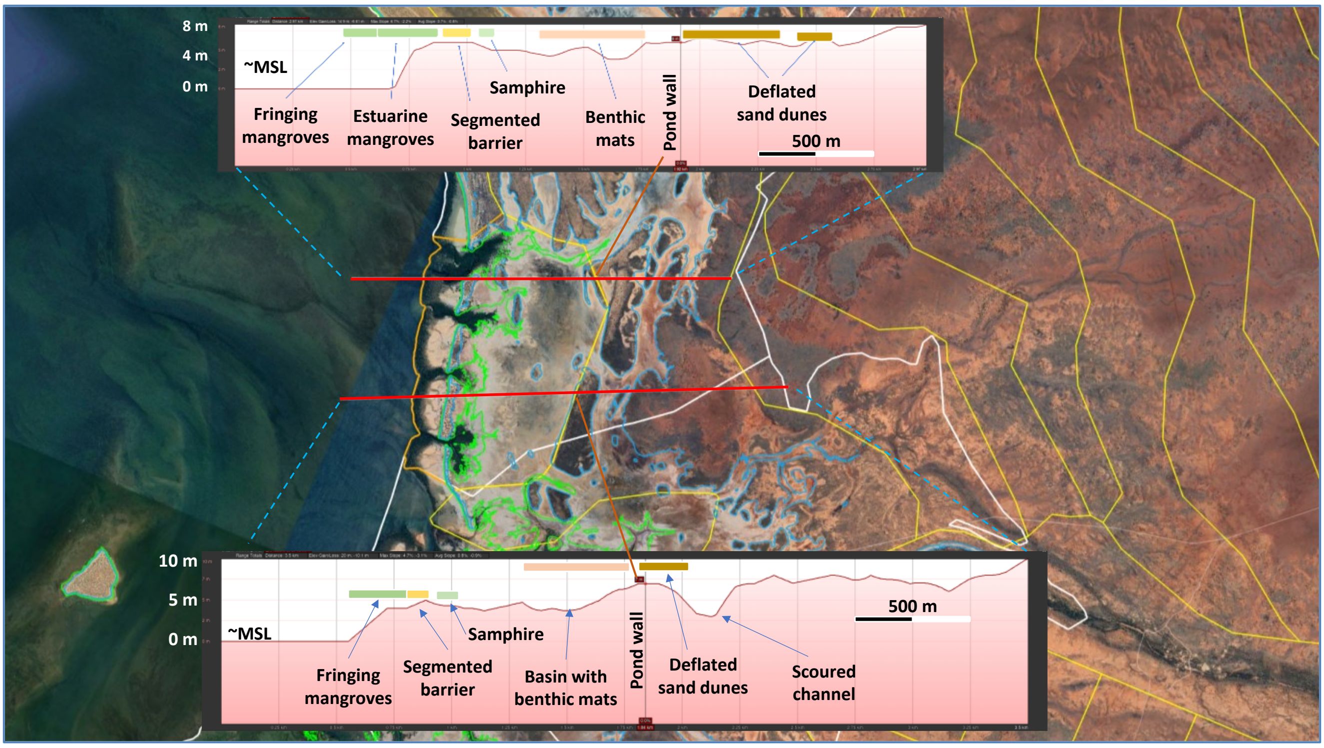


Figure 197. Contoured map of the nascent mangroves (using Google Earth profile tool – even with its inaccuracies it is a useful indication). Contours are in 1 m intervals from -0.5 to +5 m AHD derived from LIDAR survey. Elevation profile across the W (lower) and E (upper) of the area (red lines) marked 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 198. 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 196) form higher ground with a relatively flat top, at 2.5 to 3.5 m AHD (Figure 197), 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 195). 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, Section 16) and their location behind a rock-anchored spit, tend to indicate that these catchments are not yet adjusted to changes in sea level in the last few thousand years (Figure 15) and possibly also to past periods of intense rainfall in the catchments (Rouillard *et al.* 2016). The ‘mouth’ of 40 Mile Road W catchment occurs 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 199, Figure 200).

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 sand splays extending into the tidal flat area, and there appear a 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 201) 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 199. Aerial photo (view towards the E) of the nascent mangroves east of McKay Creek mouth.

Figure 200. 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.

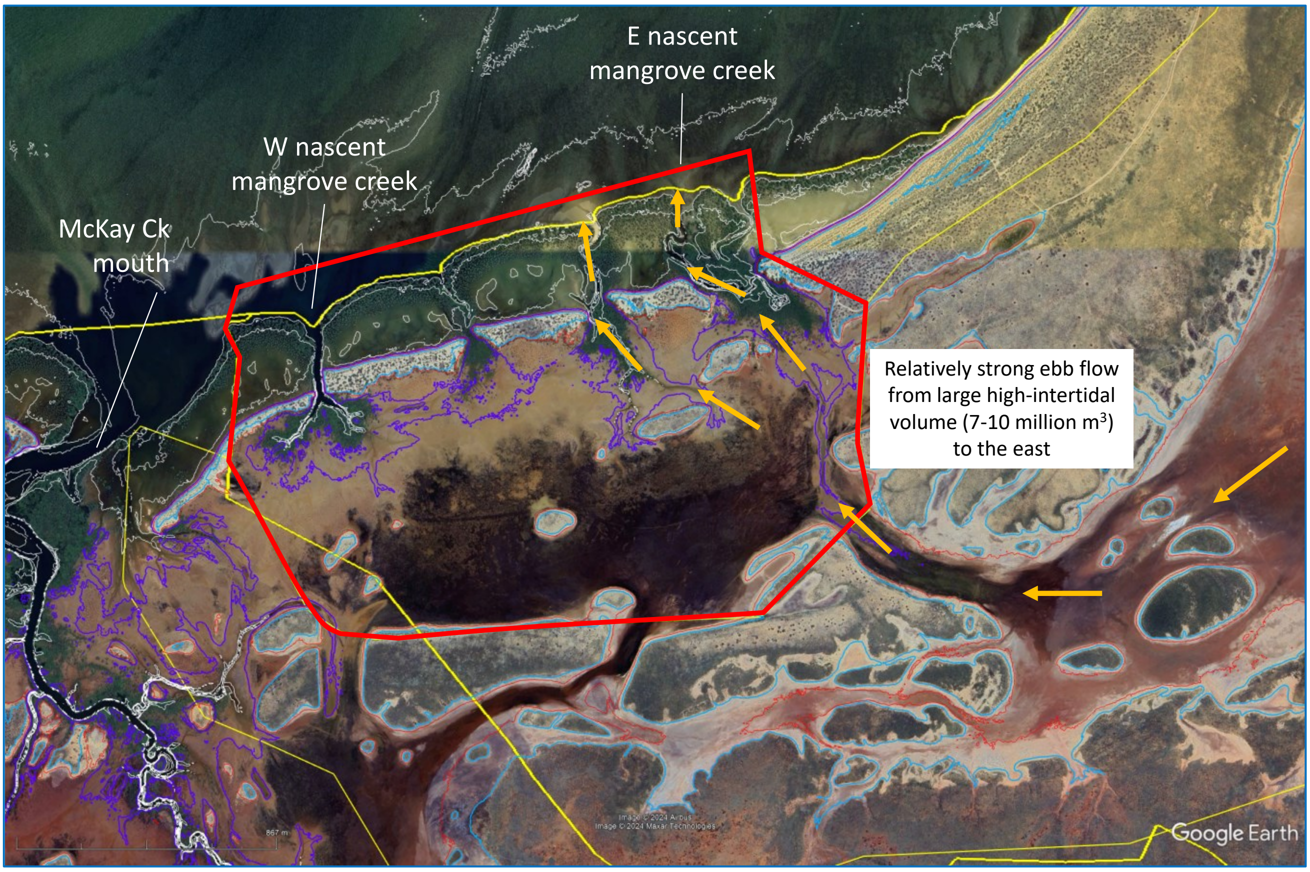


Figure 201. The possible flowlines (orange arrows) of strong ebb flows and/or runoff from the catchment to the east of the present nascent mangrove creeks east of McKay Creek. Elevation contours are at 0.5 m intervals from -1.0 m upwards, including +1.5 m (purple), +2 m (red) and to +2.5 m AHD (light 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 202) 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.

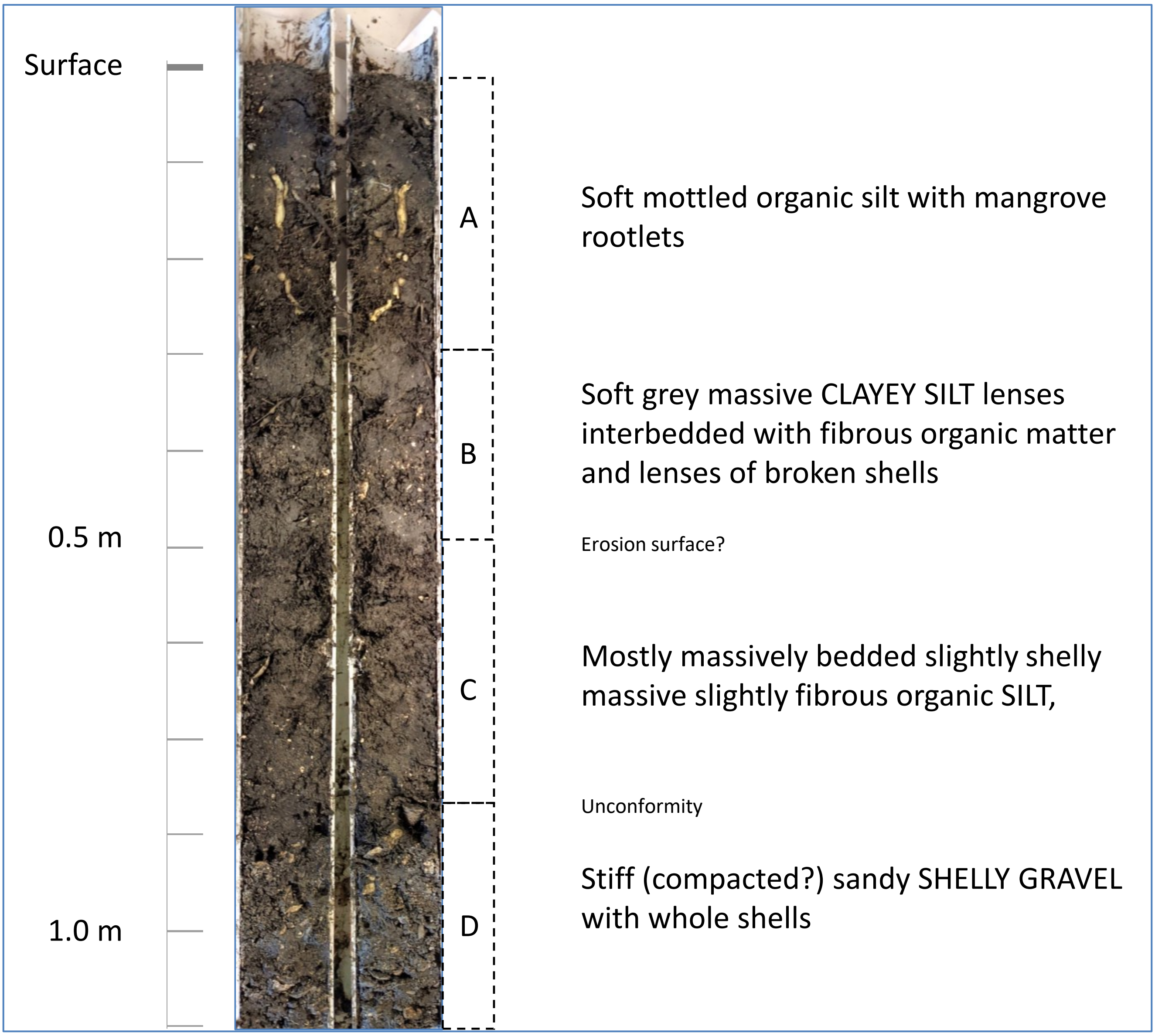


Figure 202. An unpublished 1 m-long core in the sediments in the easternmost nascent mangrove area showing 6 or 7 sedimentary units (ECU, pers comm.) with bioturbation (sediment mixing by biological organisms) throughout. Modern roots extend down to a depth of 0.25 m and organic matter occurs throughout the upper 0.45 m. Overall, there are layers rich in whole and broken shells interbedded with uniform grey, silty units.

22.3.1. 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 in front of the pond walls (contains benthic mats on Figure 197) 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.

22.3.2. 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 175). 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).

22.3.3. Assessment – qualitative

The above assessment leads to a suite of possible qualitative outcomes for this area (Table 33). This table notes that there is the possibility of some drowning of the area over the next century, without or without the ponds.

Table 33. 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 7.3.4). 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.

22.3.4. 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 203.

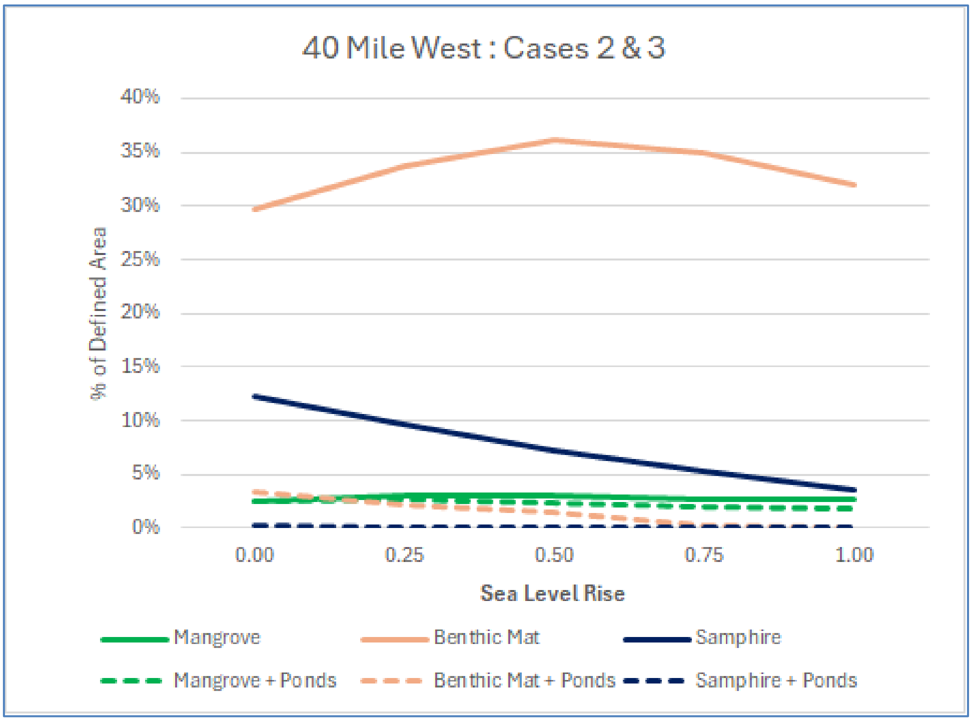


*Figure 203. Case 2 - **'SLR plus sedimentary response'** case (solid lines) and Case 3 - the '**SLR plus sedimentary response plus ponds'** case (dashed lines) for the 40 Mile Road W catchment. The difference between solid and dashed lines indicates the changing effect of the ponds through time.*

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

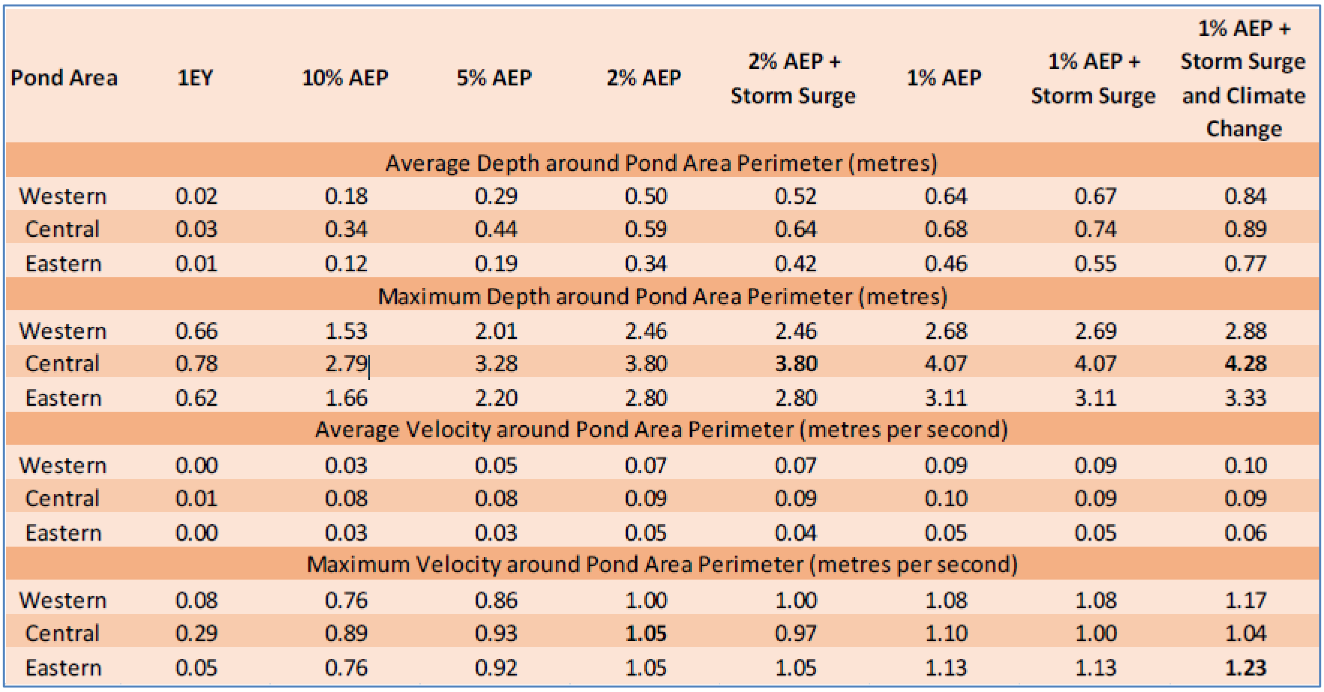
experience decline. The remnant proportion of benthic mats is projected to reduce from 3% to 0% with sea level rise, replaced by mangroves. These numerical changes are well within the bounds of uncertainty, but the general theme is little significant change. **Moderate confidence**.

22.4. 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 204, Figure 205). 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 34). 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 34. 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 206) is advantageous to assessing potential transport and thus potential morphological change at and near the pond walls.

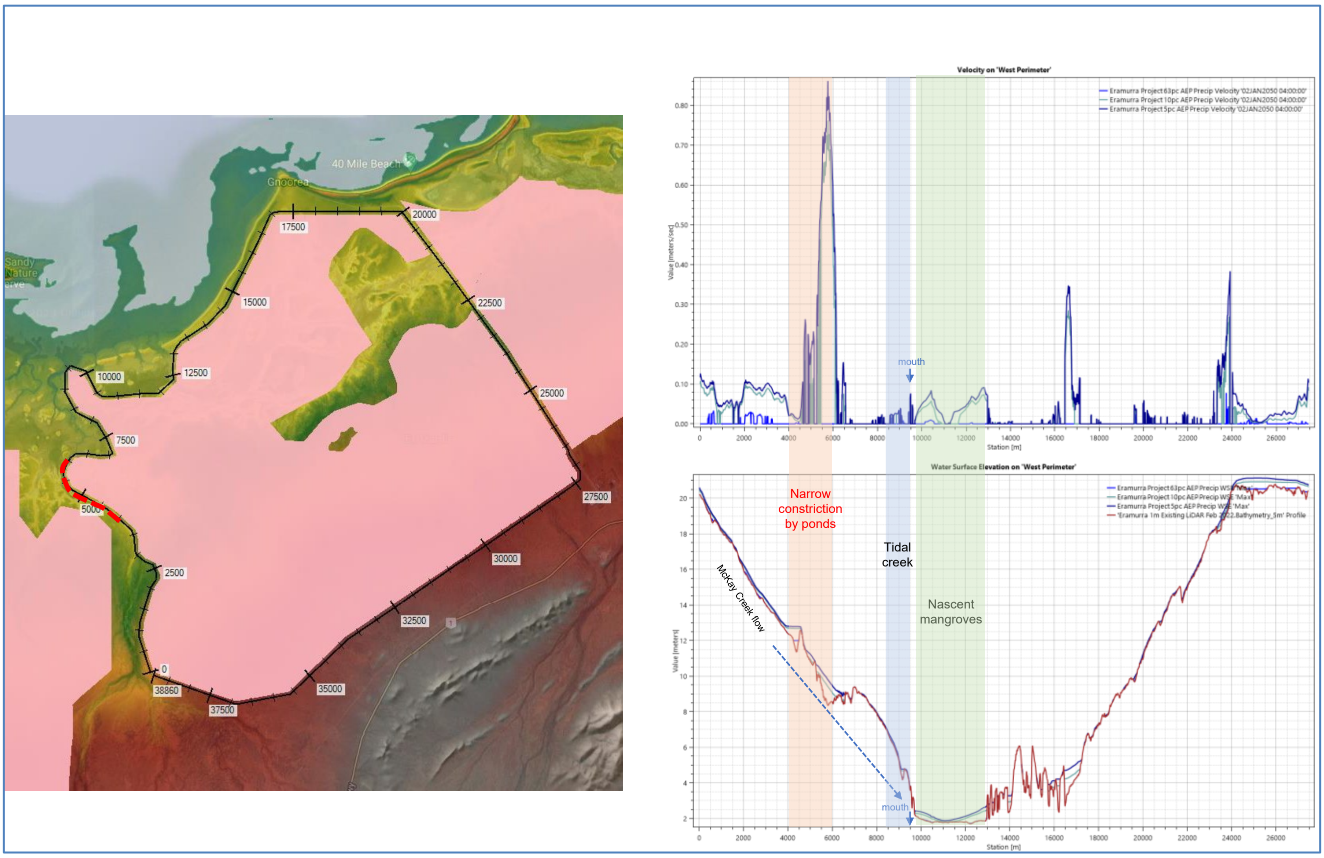


Figure 204. Modelled current speeds and elevation along the perimeter of the western ponds (modified from Land and Water Consulting 2023a) for 1EY, 10% AEP, and 5% AEP events.

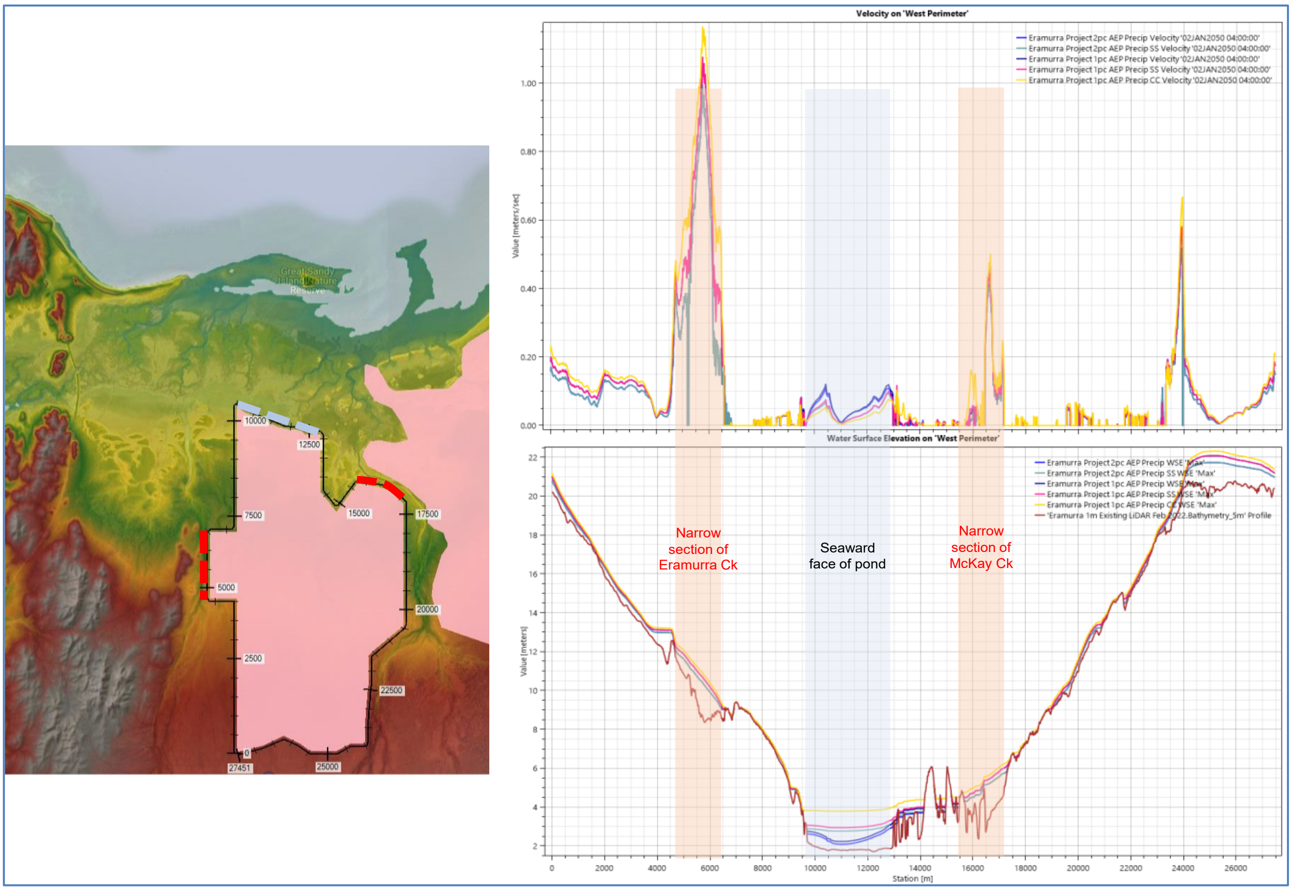
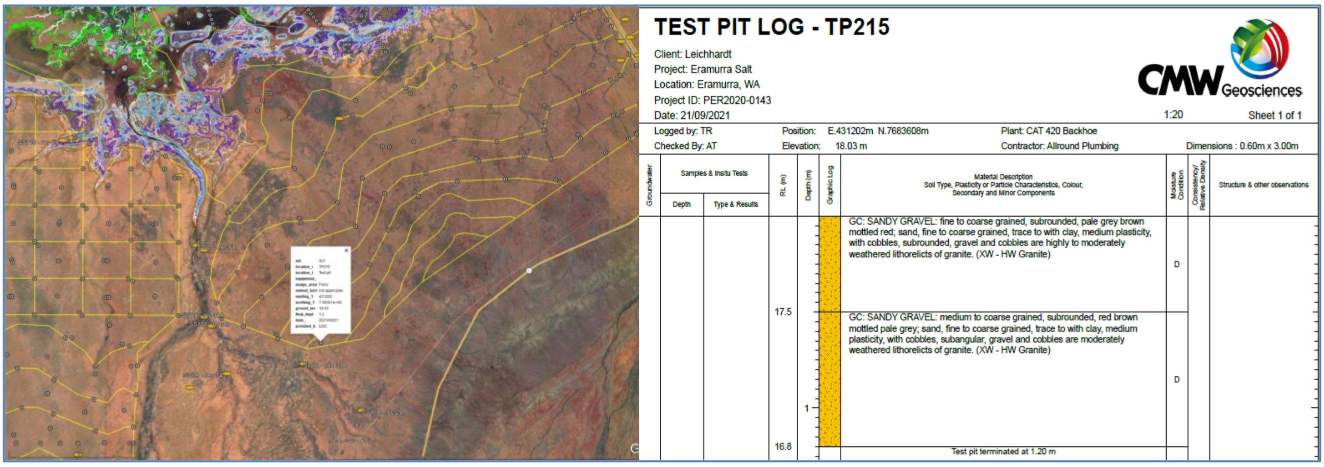


Figure 205. Modelled current speeds and elevation along the perimeter of the western ponds (modified from Land and Water Consulting 2023a).

A key issue is the lack of time-series data on individual events, as noted in Section 17.1. Some examples for each of the three major creeks and/or the entire area would help to assess the potential for sediment limitation to occur, either through exhaustion of the available sediment or by sediment armouring.



TEST PIT LOG - TP215

Client: Leichhardt
Project: Eramurra Salt
Location: Eramurra, WA
Project ID: PER2020-0143
Date: 21/09/2021

1:20
Sheet 1 of 1

Logged by: TR
Checked By: AT
Position: E.431202m N.7683608m
Elevation: 18.03 m
Plant: CAT 420 Backhoe
Contractor: Allround Plumbing
Dimensions : 0.60m x 3.00m

Groundwater	Samples & Insitu Tests		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
	Depth	Type & Results							
						GC: SANDY GRAVEL: fine to coarse grained, subrounded, pale grey brown mottled red; sand, fine to coarse grained, trace to with clay, medium plasticity, with cobbles, subrounded, gravel and cobbles are highly to moderately weathered lithorelicts of granite. (XW - HW Granite)	D		
			17.5			GC: SANDY GRAVEL: medium to coarse grained, subrounded, red brown mottled pale grey; sand, fine to coarse grained, trace to with clay, medium plasticity, with cobbles, subangular, gravel and cobbles are moderately weathered lithorelicts of granite. (XW - HW Granite)	D		
				1					
			16.8			Test pit terminated at 1.20 m			

Figure 206. 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).

22.5. McKay Creek system

The McKay Creek system encompasses a river catchment of 291 km^2 (Figure 52) 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 207).

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 (Table 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 8.6. including Table 12, and Section 9.3.4 including Table 19). 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 overbank 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 mud on the intertidal flats and mangrove areas, with more presumed sandy sediments in the intertidal areas seawards of the present coastline.

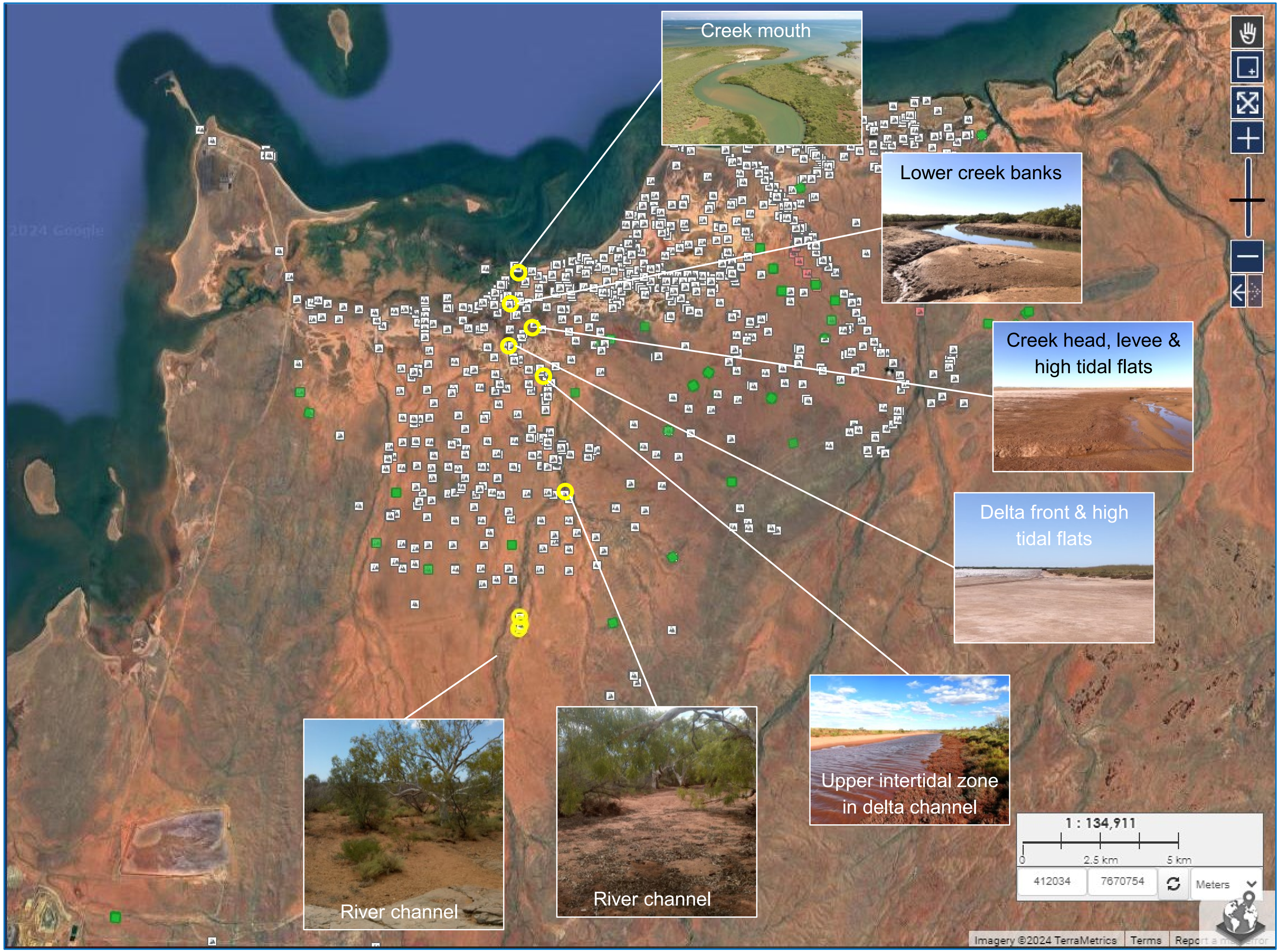


Figure 207. Selected sedimentary environments of the McKay Creek catchment and associated tidal creek system (photos from CMW Geosciences, 2022).

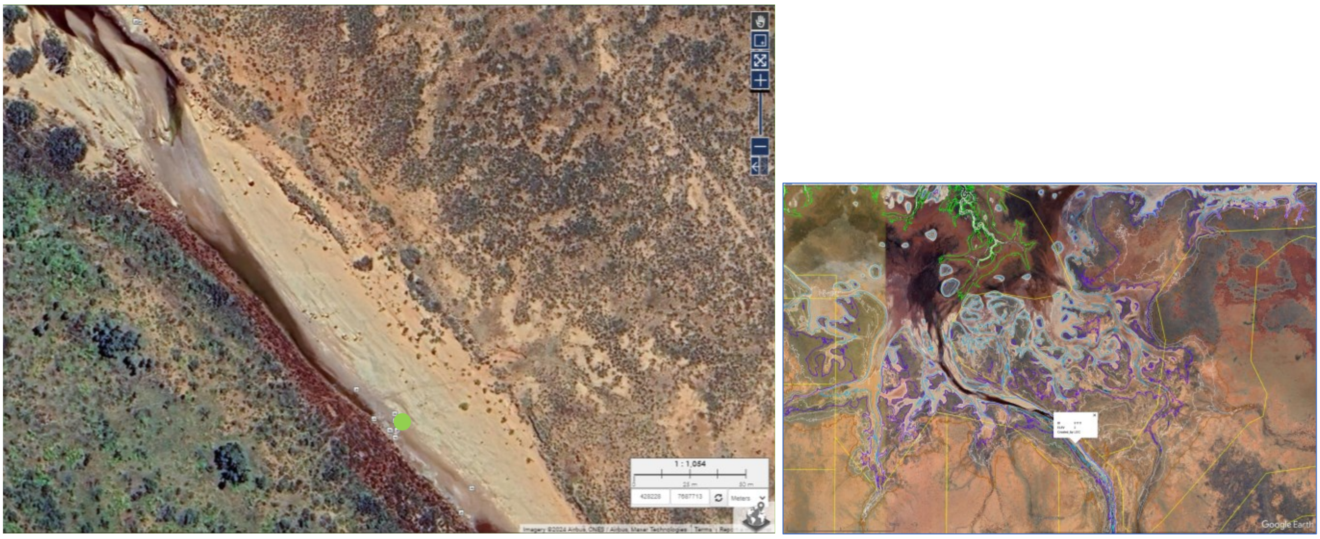


Figure 208. LEFT – Aerial photo of the channel of McKay Creek at 2 to 2.5 m AHD with multiple sediment tails developed seawards of vegetation. Green dot is location of image in Figure 209. RIGHT – Aerial photos of the lower McKay fluvial system and delta front. White label is location of detailed image to left. (Photos from CMW Geosciences, 2022).

Figure 209. 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).

22.5.1. 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 overbank's 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. Further, river flood events may result in enhanced erosion in the narrowed channel between the western and central ponds, sediment accretion immediately seawards of the narrows and in the lower tidal creek (Section 17.1, Figure 174).
- 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 overbank 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, because the tidal system would remain ebb-dominated in the incised channel, driven by overbank tides. Transport of mud landward across overbank muddy areas is likely to increase, and landward extension of creek heads and levees will also increase. The western ponds may reduce freshwater and sediment input to the main McKay Creek delta front (Figure 53, Figure 75). 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.

22.5.2. 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 175). This may be a factor in influencing BCHs in this area, especially the viability of mangroves (Section 22.3.2).

22.5.3. Assessment – qualitative

The above assessment leads to a suite of possible outcomes for this area (Table 35). 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 only flooded by the highest tides, and landwards of the delta front, the main fluvial creek is tidal for ~3.5 km landward. This section of the McKay Creek contains a series of fluvial pool-and-riffle features, housing extensive benthic mats and several large areas of samphire. 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.

22.5.4. 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 210. 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 36) 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 36) 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 35. 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

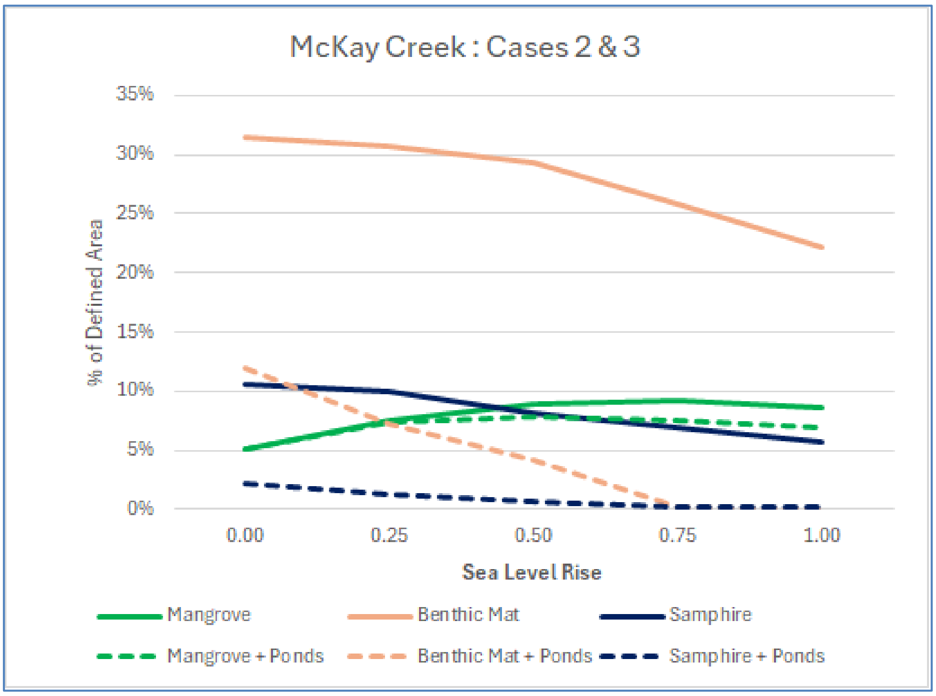


*Figure 210. Case 2 - **'SLR plus sedimentary response'** case (solid lines) and Case 3 - the '**SLR plus sedimentary response plus ponds'** case (dashed lines) for the McKay Creek catchment. The difference between solid and dashed lines indicates the changing effect of the ponds through time.*

Table 36. Data plotted for the mangroves in Figure 210.

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 %

22.6. 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 would 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 (Table 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 10.5.1).

These systems occur behind a wide (500 to 800 m) vegetated sand barrier up to 5 m high (Figure 211, Figure 212). 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 213) 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 214).

Figure 211. 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.

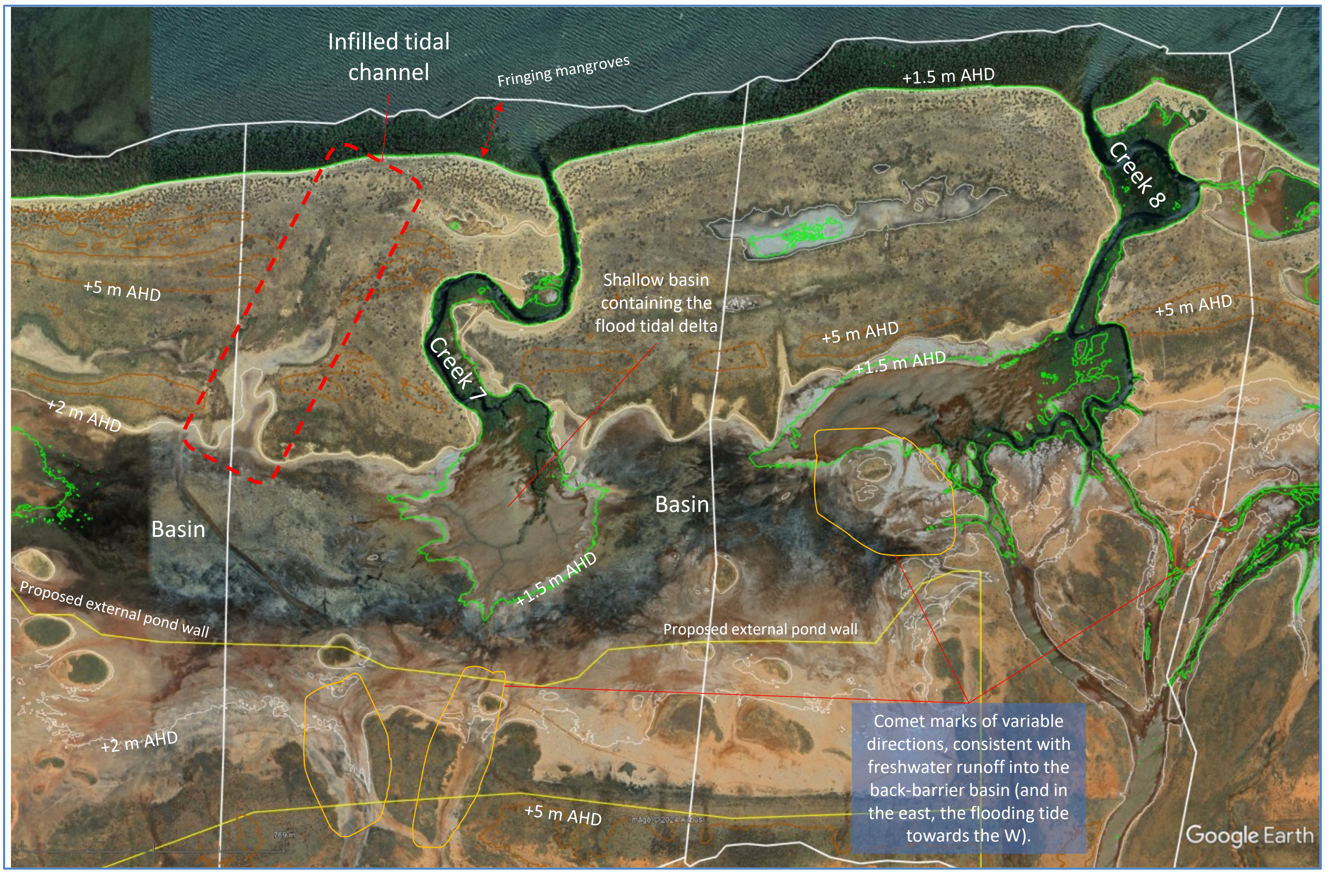
Creeks 7 & 8 are very similar in their hypsometric shape (Figure 38), with the lines on the log plots strongly parallel – these systems are likely to operate in a similar way regarding tidal flows. Creek 7 has a larger ebb tidal delta (at least as inferred from its wider mangrove fringe) and its flood delta sits in a shallow basin, indicating formation that might have involved some head-cutting around the delta perimeter (Figure 214). 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 214, Figure 215), 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 215), 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 175) that may affect BCH response to SLR.

Figure 212. A narrow band of active eolian dunes on the barrier fronting the basin of the 40 Mile Road E catchment.

Figure 213. Main channel of creek 7, inset within coastal plain and cut through past coastal deposits.



Comet marks of variable directions, consistent with freshwater runoff into the back-barrier basin (and in the east, the flooding tide towards the W).

Figure 214. Details of the Creek 7 barrier, estuarine channel and back-barrier basin.

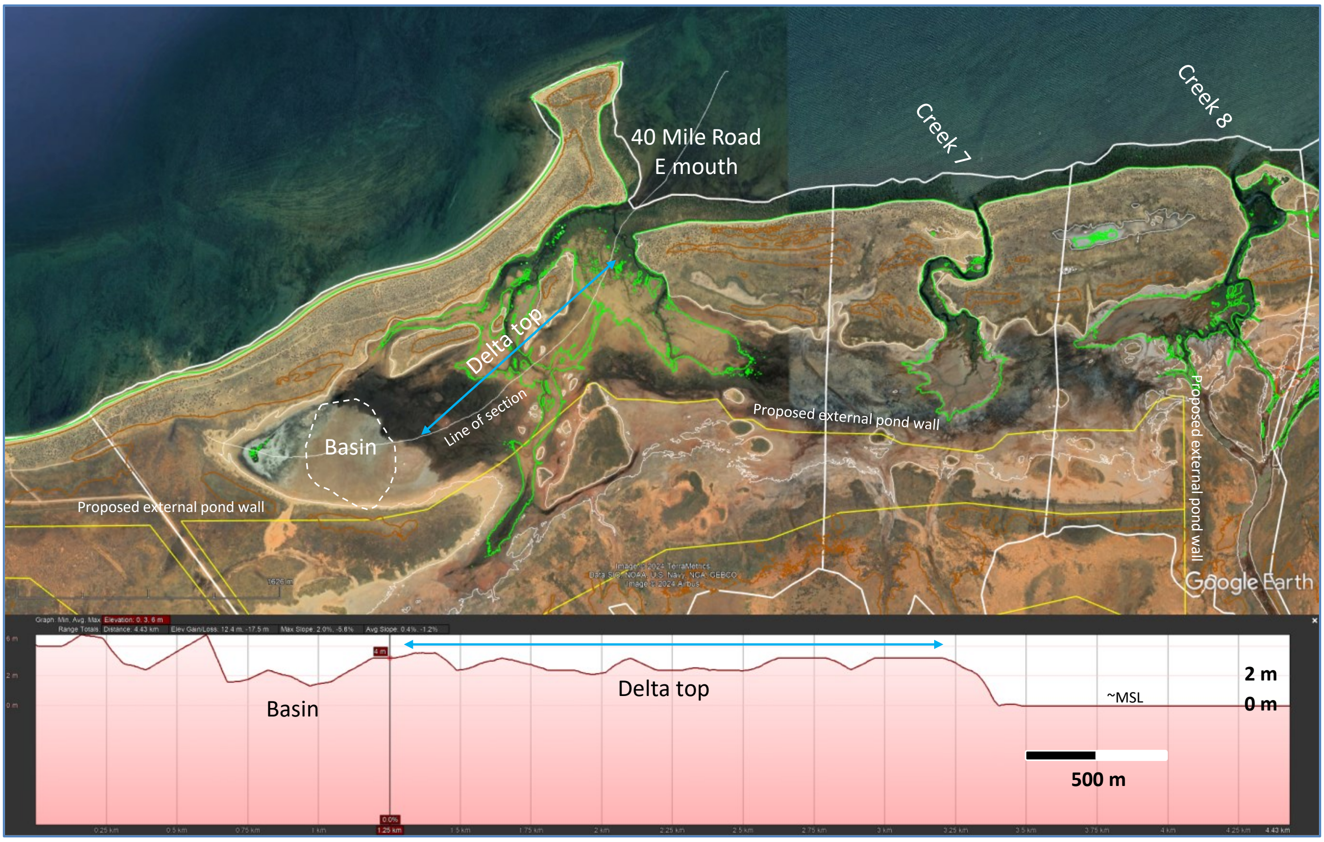


Figure 215. Detail of the barrier and back-barrier features of the combined area of 40 Mile Road E, Creek 7 & 8.

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.

22.6.1. 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.

22.6.2. 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 175). This may be a factor in influencing BCHs in this area.

22.6.3. Assessment – qualitative

The above assessment leads to a suite of possible outcomes for this area (Table 37). 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.

22.6.4. 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 216, 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 mats 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 37. 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 mat – 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

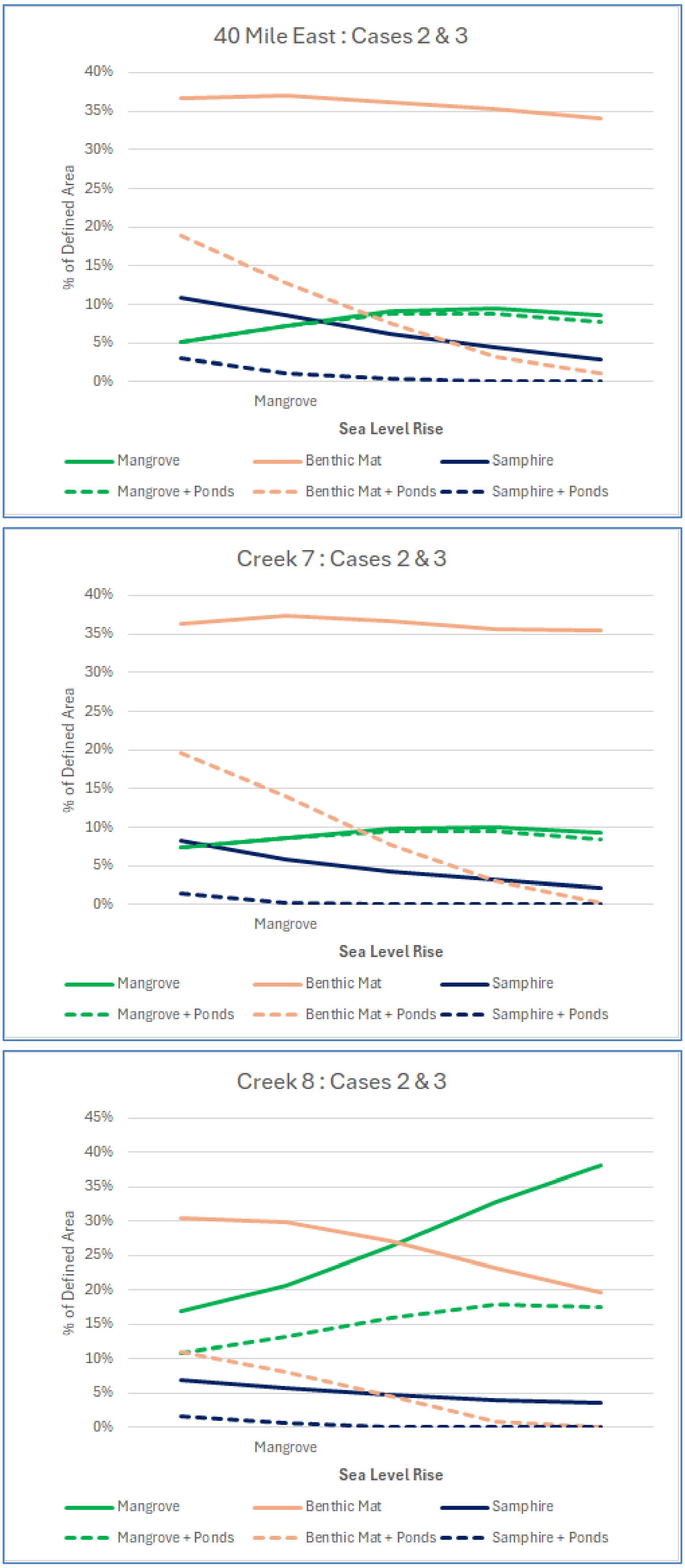


*Figure 216. Case 2 - **'SLR plus sedimentary response'** case (solid lines) and Case 3 - the '**SLR plus sedimentary response plus ponds'** case (dashed lines) for the systems of 40 Mile Road E, and Creeks 7 & 8. The difference between solid and dashed lines is indicates the changing effect of the ponds through time.*

22.7. Faunal habitats

22.7.1. Turtles

22.7.1.1. Controlling features and dynamics

The proposed solar salt pond arrangement has ponds constructed landward of the existing shoreline. In the immediate future, this provides limited direct influence on alongshore and cross-shore sediment dynamics, specifically those developed through wave action. However, the ponds enclose significant existing intertidal and supratidal lagoons, whose tidal hydraulics provide localized redistribution of sediments, particularly cycles of fine sediment infilling or scour across the tidal flats.

In the longer term, under projected SLR, much of the area directly affected by tides and waves will migrate landward and overall, rise slowly in bed elevation, subject to the normal physical constraints of whether sediment is available and geology to landward allows (e.g., Cowell *et al.* 1995). This migration is commonly assumed to occur in a cross-shore direction, however alongshore differences in sediment, geology and hydrodynamics will result in a three-dimensional reconfiguration. For the ponds either side of McKay Creek, landward migration of the existing coastal geomorphology will be constrained to varying degrees by the proposed ponds. For the eastern ESSP area, the ponds are proposed to be placed landward of either a wide coastal spit, or a coastal barrier, which provide a substantial sediment mass to experience migration before interacting with the ponds (with the exception at creek mouths).

Projected SLR will increase potential for wave-driven alongshore sediment transport along the spit and adjacent beach, Forty Mile Beach West. The geological control at Gnoorea Point (Figure 64, Figure 195) is anticipated to limit sand availability, leading to beach rotation (described in Section 23.5.1) with scarping immediately southwest of Gnoorea Point, and increased sand accumulation towards the southern end of the beach. This may be exacerbated by changes at the fringing mangroves which presently act as an alongshore control point. Proposed construction of the most seawards point of the ponds landward of the existing mangroves at the eastern side of McKay Creek mouth (point in yellow line, centre left of Figure 201) provides potential for the ponds to act as a new coastal control point should the mangroves be substantially lost.

22.7.1.2. Nesting habitat

Regarding turtle nesting habitat at the estuary coast, the location of the ponds to landward of the shoreline effectively prevents significant change to alongshore sediment storage or cross-shore sediment cycles. Consequently, impacts such as the beach rotation observed at Barrow Island (BMT 2016) or the scarp development observed along the western side of Cape Preston (Astron Pty Ltd. 2020) are unlikely to be caused in the estuary coastline by the presence of the ESSP ponds.

- **Natural impacts (timeframe of 10-30 years)**. Projected SLR and associated changes to alongshore sediment transport are anticipated to cause landward beach migration, and the continuation of the anticlockwise beach rotation SW of Gnoorea Point, causing some scarping. This will reduce the potential length of beach optimal for turtle nesting, although it is noted that observations of turtle nesting activity along this coast are minimal (O2 Marine 2022b, Pendoley Environmental 2024). These anticipated changes are not attributable to the ESSP ponds.
- **Pond-related impacts to turtle habitat (timeframe of 30-100 years)**. Should there be physical degradation of mangroves at the south end of the Gnoorea spit that forms Forty Mile West beach, it may cause extension and further activation of the spit, accelerating spit migration, rotation and scarping. This would reduce the potential length of beach optimal for turtle nesting. This response would be attributable to effects of the ESSP ponds, but is effectively inseparable from the natural response to projected SLR (i.e., the proposed ponds may reduce the time it takes for these changes to occur).

22.7.1.3. Foraging habitat

It is anticipated that the ponds would induce local changes to turtle foraging areas. Pond emplacement will reduce the areas of back-barrier intertidal flats and basins and will reduce tidal and sediment exchange between the lagoons and the coast, including of any silty sediments and of disseminated organic material. Therefore, some of the more silty and organic environments at the mouths of the small creeks in the nascent mangroves (Figure 199, Figure 200 and the core shown in Figure 202) may be reduced in size and/or become more sandy. Such areas have been identified as potential foraging habitat (O2 Marine 2022b). Such a change may also limit the capacity for the finer-grained areas of the nascent mangroves (i.e., the muddy parts within the mangrove itself) to re-form following severe storm impacts and/or to adapt to rising MSL.

- **Pond-related impacts to turtle habitat (several decades)**. There may be a gradual change in mangrove type from present mix of small estuarine mangroves and blocks of fringing mangroves in the nascent mangrove area and immediately to its east, to a more continuous area of fringing mangrove, probably narrower and less physically resilient than the present areas. Should this occur, it may add to the natural changes of coastal rotation along Gnoorea spit (see Section 22.7.1.2 above).

22.7.1.4. Cape Preston East beach

The beach located east of Cape Preston faces NE and contains many rock outcrops on the beach itself or immediately to seawards (Short, 2005). Some sections are perched, and some steep and reflective to incident waves. The port plans have not yet been reviewed in the context of turtle nesting, so no comments are provided.

22.7.2. Green Sawfish

As noted above (9.3.5), the timing of key phases in the sawfish life cycle is relevant to the potential timing and duration of changes at the ESSP's tidal creeks and elsewhere.

22.7.2.1. Dredged channel at the Cape Preston Offloading Facility

As noted by studies of sawfish movement in the region (Lear *et al.* 2024) physical barriers to migration at the coast can include rock walls and areas of deepened water. Assessment has not yet taken place of the nature of the proposed channel at Cape Preston and how it might influence coastal processes.

22.7.2.2. Creek changes at the coast

One conclusion of the ESSP Sawfish Survey report (Morgan *et al.* 2025) was a need to prevent a reduction of water level within creeks during any part of the tidal cycle, because it may lead to "more restricted access to shallow habitats, which are already naturally constrained by the flow of tides". Whilst this view was related to water extraction, it is also relevant to geomorphic changes associated with pond emplacement. At present, the level of low water in the creek is limited by the presence of a mouth bar, which tends to isolate the creek from the sea when tides fall below about negative 0.12 m AHD (O2 Marine 2020, O2 Metocean 2022a). This bar is controlled by the local interaction of waves and tides and while there is little clear information on its past variations, it is highly unlikely to have been a permanent feature. The mouth bar's presence is neither predictable now nor into the future. Although bathymetric surveys have not been conducted on other creeks, aerial images indicate that a bar is not obviously present on the other tidal creeks along the estuary's southern bank. Therefore, it can be concluded that the use of McKay Creek by Green Sawfish and sympatric species is likely to have been variable through time for decades and longer into the past, and by extension to other similar creeks. It can also be postulated that the use of McKay Creek and other nearby creeks by such species might occur as long as future geomorphological conditions allow frequently enough access and protection.

With SLR only and, this general situation will not greatly change, with landward system migration likely and a little drowning of the system at the head near the delta front (Section 22.5.1 and Table 35). With SLR and the addition of the ESSP's ponds, the tidal system will remain ebb-dominated in the incised channel, and there appears no reason to expect any significant changes in the general availability of suitable habitats for the Green Sawfish and sympatric species.

PART SIX – CONCLUSIONS AND SUMMARY

23. Caveats and uncertainties (non-exhaustive)

Whilst most caveats have been mentioned in the main text, this part presents a series of clear statements of the work's caveats and uncertainties, then provides detail on some more significant aspects.

1. The area of interest includes a large mix of driving processes, some periodic and relatively predictable, and others episodic and unpredictable. In particular, some of the episodic processes (e.g., cyclones, intense rainfall, surges, tsunami) have the potential to cause rapid and major local changes in coastal geomorphology, meaning that there are a wide range of possible future timelines for different sections of the coast and their various sedimentary environments. Most of these events remain undocumented for the ESSP area.
2. The ESSP coastline houses several strong spatial gradients, including in tidal currents, waves, and the apparent effects of episodic events. Hence, the coast is strongly heterogenous in form, modern process and future development.
3. There are few measurements of currents in the key region of the estuary, except in McKay Creek itself. There are some measurements in Regnard Bay and to the west at Cape Preston that have been used where appropriate.
4. There are few available local measures of rainfall or freshwater flow[33]. Measurements of rainfall are thus only from distant sites and so there are uncertainties associated with the modelling and interpretations of the impacts of intense rainfall events.
5. There are no available local measurements of cyclonic conditions regarding weather, oceanography, or sediment transport[34]. The nearest available measurements are in the Dampier Archipelago taken by the Pilbara Ports Authority, 35-60 km away.
6. Tsunami have not been considered, although over a century timescale it might be expected that the area would experience a small number of them[35].
7. To date there are few samples of the seabed so that inferred sediment transport pathways have not yet been tested.
8. The coastal environments are predominantly sandy, but there are no direct measurements of sand transport. Turbidity has been measured in some places, but it cannot be used to quantify sand transport (Bunt *et al.*, 1999).
9. The stratigraphy of the terrestrial part of the ESSP area is well established, and the main sedimentary units and their spatial relationship is understood, and the likely general pattern of past sedimentation over multiple decades to centuries appears fairly clear, but their ages are not defined (see caveat 14 below and Section 23.2).
10. Parts of the coastal system, the river channels and the tidal creek channels, might be scoured down to resistant material in places, so that in some parts of the system even fast flows might mobilise relatively little sediment. This hinders the prediction of future change from changed flows.
11. The stratigraphy of the lower intertidal zone is not known, producing some uncertainties about sediment availability.
12. Some marine areas in Regnard Bay are known to have mobile sediment that is thin and/or patchy in places, producing some minor uncertainties.
13. There is insufficient geological knowledge to begin to assess whether coastal roll-over might be limited by local sediment availability at the modern shoreline.
14. Given the lack of age data, developing the existing information into a semi-quantitative form about present processes involves large uncertainties and expert judgements.

---

[33] Rainfall data are recorded by the Cape Preston Port Company at Cape Preston but are not available.

[34] There are measurements of cyclones at Cape Preston (for Cape Preston Port Company) but these data are not available to the ESSP.

[35] Anecdotally, these have had some effects, such as the 1994 tsunami that scoured out newly planted mangroves and damaged existing ones in No Name Bay in the Burrup Peninsula (Offshore Engineering, 1994).

15. Further, assessments of future potential rates of physical change and associated timescales are therefore estimates based on expert judgement, and the range of possible ages can produce two very different potential futures (Section 23.2).
16. There are no ages determined for the mangroves or other flora at the coast or elsewhere, so that such information cannot contribute towards quantifying past changes.
17. Some aspects of measured coastal migration since 1988 may reflect a signal related to long-term SLR, but uncertainties include that there is no knowledge of whether the system was in a state of near equilibrium with sea level in 1988, the starting year of quantitative annualised data.
18. Compared to adjacent areas, the open coastline at McKay Creek has been relatively stable in location since 1988, but at present it can only be hypothesised why.
19. In this report, emplacement of the pond wall has been assumed as instantaneous, whereas in fact there will be an extended phase of construction. Specific construction-related changes have not been considered here.
20. Potential changes associated with areas close to the pond walls (e.g., scouring at the walls themselves) are not dealt with in this report. Work has focused on the general physical sedimentary conditions in the areas around the edge of the pond structures, relevant to the implications for BCH communities.
21. The details of the ESSP development at Cape Preston have not been assessed for this work, including regarding the potential changes that might be relevant to along-coast migration of Green Sawfish, so no comments can be given on this issue.
22. The potential effects of active water abstraction at the coast have not been considered.
23. The magnitude of bed roughness applied in the tidal inundation modelling has not been validated, and no spatial variation in bed roughness has been applied.
24. Bed shear stress is derived from the model's hydrodynamic module and was calculated by averaging over periods much longer than the wave period, i.e., it does not represent peak wave stresses and thus cannot be used quantitatively regarding assessing the onset of bed sediment motion.
25. Some modelling results are not available for the pond scenario 7.2.1., so some data outputs represent the ponds of the almost identical scenario 7.2.0., and others the superseded scenario 6.2.0. Where used, they have been used with circumspection and with clear caveats stated.
26. Although unlikely, there may be some features of future coastal change, such as state change, or successive state changes, that may change the risk to BCH in unforeseen ways.
27. The level of uncertainty in predicting the possible range of sedimentary environments in the future is lower than any associated assessment of potential changes to areas of BCH, with or without the ESSP development.
28. Whilst reasonable changes and options have been considered here, the full range of possible outcomes over a century into the future is beyond prediction.

Below is provided detail on some of the more significant aspects contributing to uncertainty.

23.1. 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 several 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 22 (in Section 12.1). Such samples have been taken[36] so that it is anticipated that it will be possible to test the hypotheses and contribute to the analysis of potential consequences for the habitats.

23.2. 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 8.6). 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 are 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.

23.3. 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.

Figure 217. Sparse mangroves near the eastern branches of Creek 5 and Creek 3. The bedforms and morphology as seen on aerial images indicate that these may relate to past channels that received the outflow of Eramurra Creek.

---

[36] Laboratory analysis was underway in Feb. 2025.

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 217).

23.4. 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.

23.5. 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 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.

23.5.1. 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. The 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 218).

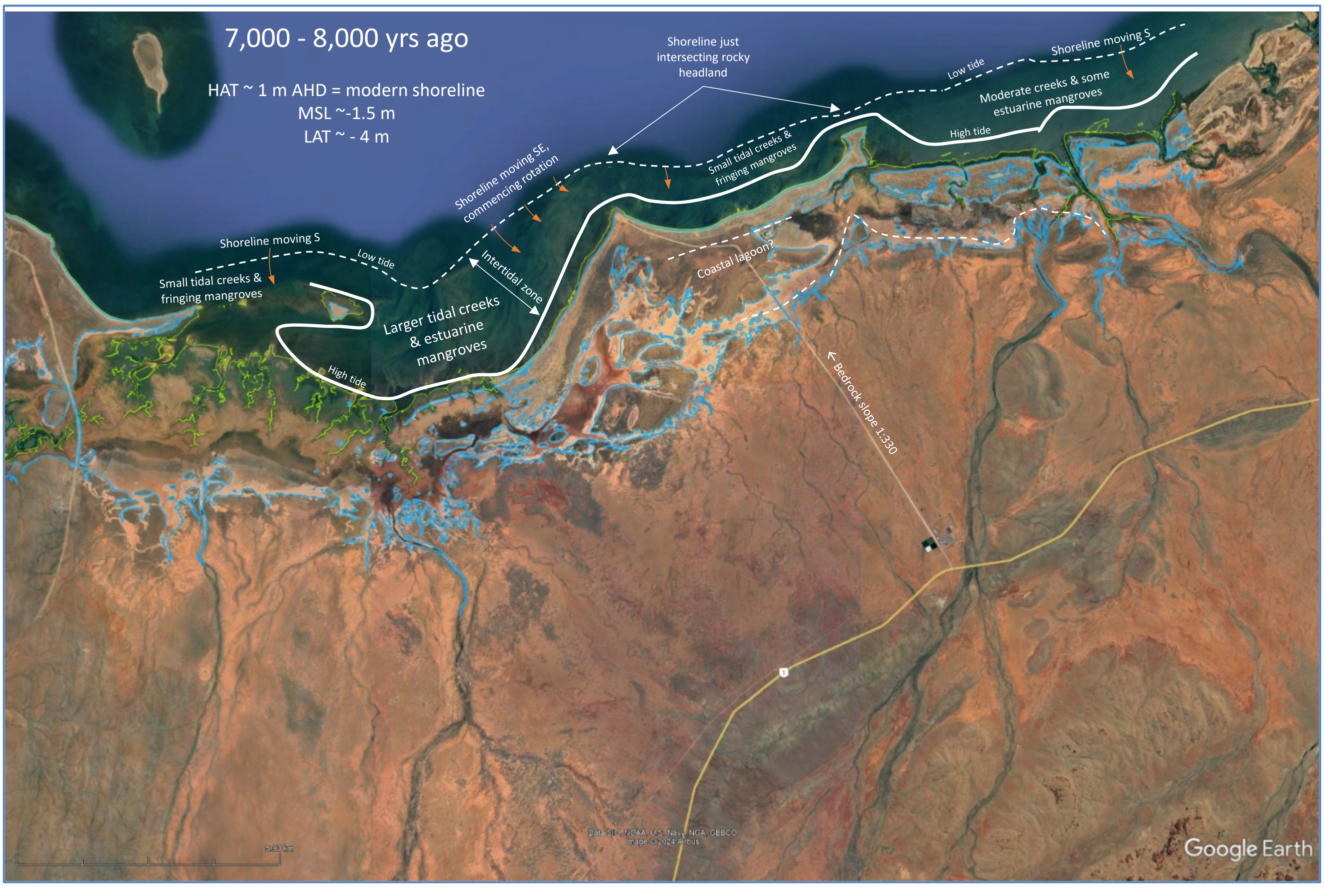


Figure 218. Generalised coastal position and possible features at 7,000 to 8,000 years ago for the ESSP area.

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 219), 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 likely ESSP coastline at 6,000 years ago is very similar to the features exhibited along the modern shoreline 70 km to the SW (inset of Figure 219 – located immediately W of the southern limit of the Mardie solar salt development zone). This section of the Mardie shoreline illustrates well a past stage in the development of the ESSP shoreline. However, since 6,000 years ago, significant changes in sedimentary processes and local coastal geological constraints mean that the ESSP coastline has evolved into a very different form.

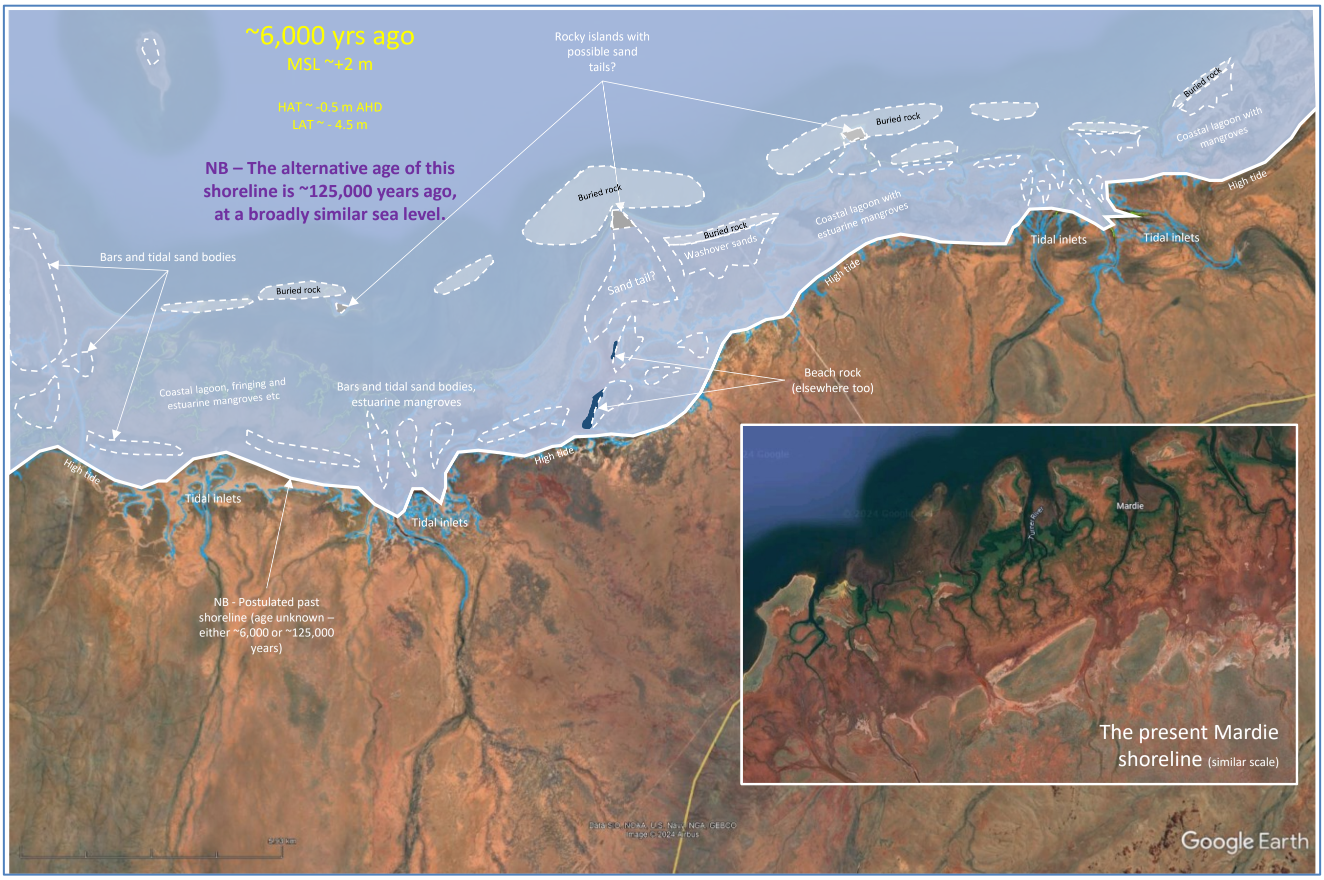


Figure 219. Generalised coastal position and possible features at 6,000 years ago (or 120,000 yrs ago) for the ESSP area. The solid white line indicates the approximate location of high tide. Inset – a section of the present Mardie shoreline that is a physical analogy for the ESSP coastline at 6,000 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 220).

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.

23.5.2. 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 22.2) to its east.

- If the barrier sands of the Gnoorea spit (Figure 195) and their presumed past extension across the nascent mangroves (Figure 199, Figure 200) 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.

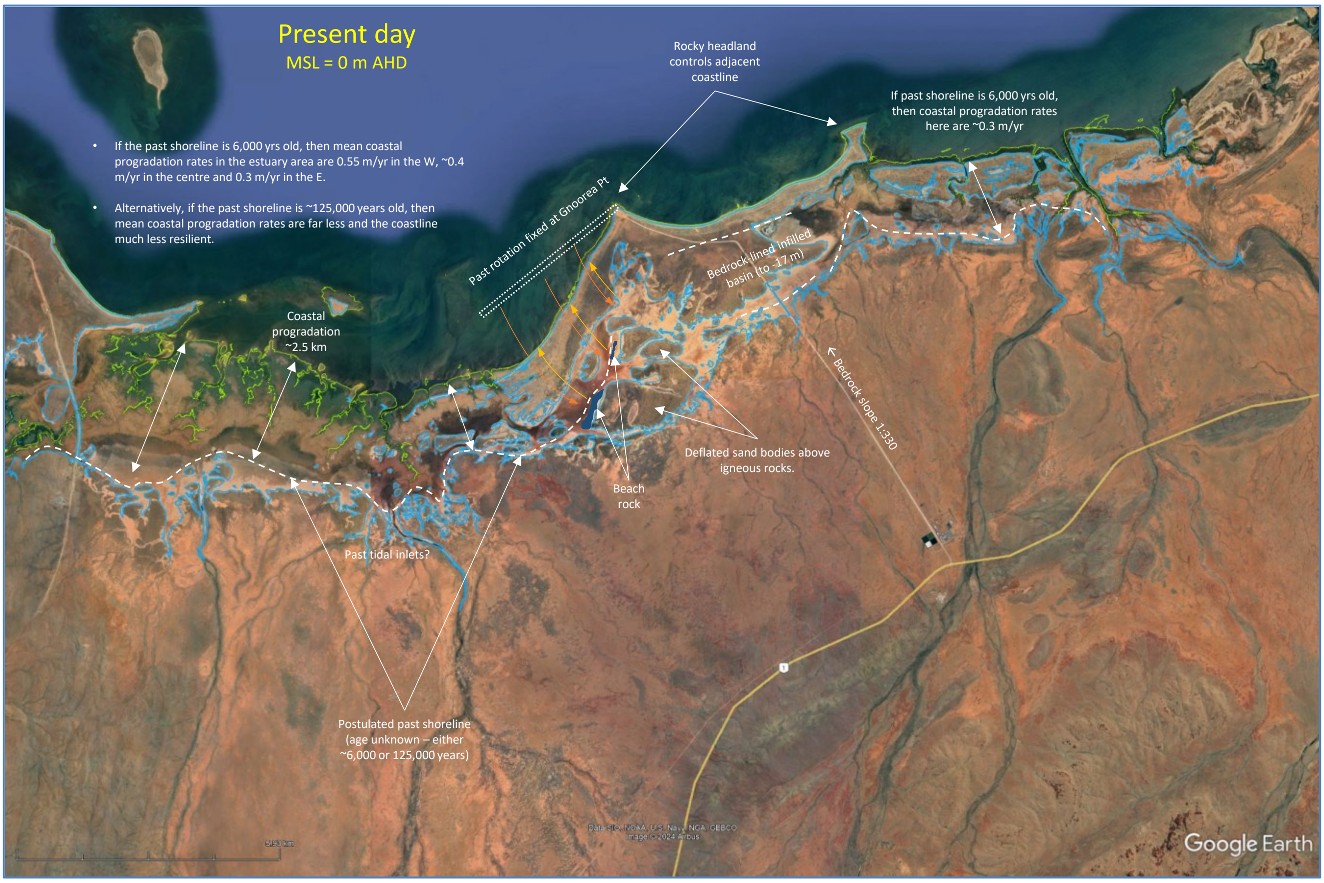


Figure 220. Modern coastline, the past interpreted coastline (white dash) and main interpreted possible features for the ESSP area. Contour lines shown for 0 m AHD (light green) and 2.5 m AHD (blue). The mid-Holocene highstand (~6,000 yrs ago) was 1.5 m to 3 m AHD.

23.6. Method of quantitative assessment

As noted elsewhere (Section 22.2), the 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 22.2, 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 areas 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.

24. Conclusions

Using defined levels of confidence, a series of conclusions are stated regarding the past and present natural system, natural future change, and potential change with the ESSP development in place.

24.1. Levels of confidence

Conclusion are provided with the stated level of confidence in each. We use the following definitions[37].

- 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.

24.2. The natural system

24.2.1. 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 23.5).

1. The key shoreline units that underpin the future shoreline change are Holocene in age (i.e., ~6,000 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.

This deep uncertainty leads to uncertainty in the nature of future natural changes in sedimentation, geomorphology and habitats - see conclusions 5 to 8 inclusive below.

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**.

---

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

4. In the last two decades, the head of some tidal creek systems in the ESSP area have had the capacity to migrate landward at mean rates of between 4 and 17.5 m/yr, and the associated mangrove forests at generally slower rates. However, different creek systems vary, with some showing negligible change.

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

5. 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.**

24.2.2. 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 sediment 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 the conclusions cannot be specific. The two end-member alternatives and the implications of each are noted below.

6. 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

7. 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.

8. Projected SLR and associated changes to alongshore sediment transport are likely to cause the continuation of the anticlockwise rotation of the beaches SW of Gnoorea Point. Over the next 10-30 years, this will involve increased beach scarping, reducing the potential length of beach optimal for turtle nesting. **High confidence.**
9. If the shoreline has built seaward 2 to 3 km over the past ~6,000 years, then it has captured a large quantity of sediment. Continuation of this capture may offset, or even exceed general coastal pressure associated with SLR. This provides a degree of resilience of the coastline to changes induced by the ESSP ponds.
10. There appears no reason to expect any significant natural changes in the general availability of suitable habitats for the Green Sawfish and sympatric species with SLR. **High confidence**.

24.3. Influences of the ESSP development

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

11. 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

12. 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 detailed in Section 22, including the relative effects of SLR alone compared to SLR plus ponds. In general, pond emplacement means that 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 so for 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 26), 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.

13. Major river floods and tropical cyclones will likely influence coastal erosion, transport and accumulation over the future century. These impacts are substantially unaffected by the ponds when viewed at the regional scale. **High confidence.**

14. 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.**

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

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

17. The likely incremental influence upon the habitats of the ponds is not greatly affected over the future century on the local scale. **Low to Moderate confidence.**

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

18. Over the future century, for the McKay Creek catchment system, the incremental 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**.

19. Over the future century, for the nascent mangrove system, which sits at the mouth of the 40 Mile Road W catchment, the incremental 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.**

20. Over the future century, for the combined systems of 40 Mile Road E, and Creeks 7 & 8, the incremental effect of the ponds is:
    - moderate on the mangroves. **Low to Moderate confidence**;
    - very large on the samphire. **Moderate to High confidence**;
    - very large on the benthic mats. **Moderate confidence**.

21. Over the future century, some potential turtle foraging habitat east of McKay Creek and in front of the nascent mangroves may be reduced in area as an incremental result of the ESSP ponds, and these areas may become less resilient to disruptive events. This refers specifically to those areas within the fringing mangroves where the present sediments are silty and organic. Such changes would speed up the natural trend resulting from adjustments to SLR. **Moderate confidence**.

22. There appears no reason to expect any significant natural changes in the general availability of suitable habitats for the Green Sawfish and sympatric species with SLR plus the ESSP's ponds. **High confidence**.

24.4. 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 begin to develop, describe and define a suite of requirements.

25. EPA guidelines on Coastal Processes

Whilst the purpose of this report specifically relates to potential changes to BCHs induced by sedimentary changes, it is appreciated that the work may also assist the EPA and others to consider the broader potential environmental consequences of the proposed ESSP development. Therefore, below is presented (Table 38) selected relevant EPA Guideline Topics and details of whether and how this study helps to address them.

Table 38. Summary of EPA guidelines and how this study addresses them.

EPA Guideline Topic	Section	Page	Description: Excerpt from EPA Guideline	Is the topic addressed in this study?	How is it addressed?	Section(s)	Comments and Caveats
Primary focus for EIA	What are coastal processes?	2	Environmental values most likely to be affected by the predicted changes in coastal processes	Y	Report considers system-wide changes, processes, and links	Appendix Section 31	and noted throughout report
EPA's Environmental Objective	The environmental objective for the Coastal Processes factor	2	To maintain the geophysical processes that shape coastal morphology so that the environment values of the coast are protected	Y	Physical processes underpin this entire report	All sections	Throughout
Considerations for EIA	Considerations for environmental impact assessment	2	Application of the mitigation hierarchy to avoid or minimise impacts on coastal processes, where possible.	-	Not addressed	-	Not the purpose of this report
			The predicted changes to the coastal processes based on modelling and analyses to a standard consistent with recognised published guidance	Y	Predictions are based on expert analysis and judgement	-	There is insufficient knowledge to support meaningful numerical modelling
			The significance of the likely change to coastal processes as well as the environmental values affected by those changes	Y	Throughout the report	All sections	-
			Impacts to coastal processes in the context of the latest climate change science and projections.	Y	Changes are based on expert analysis and judgement	All sections	Report uses EPA's projection of future SLR
			The technical and practical feasibility of proposed management measures and approaches	-	Not addressed	-	Not the purpose of this report
Coastal processes values of focus during EIA	Environmental values of coastal processes and their significance	3	Benthic communities and habitats such as coral reefs, mangroves, salt marshes, seagrass meadows and	Y		All sections	

			sponge gardens				
			Conservation of significant marine fauna and critical habitat such as nesting, breeding or foraging habitat	-	Conservation not specifically addressed		Not the purpose of this report
			Conservation of significant low lighting areas including tidal creeks, deltas and river mouths		Lighting not addressed		Not the purpose of this report
			Conservation of significant flora and vegetation and terrestrial fauna species		Conservation not specifically addressed		Not the purpose of this report
			Unique landforms		Not addressed		Not the purpose of this report
			Significant cultural and aesthetic values		Not addressed		Not the purpose of this report
			Active or passive recreation		Not addressed		Not the purpose of this report
Issues commonly encountered by the EPA	Coastal development pressures	3	The EPA is focused on ensuring that coastal processes and the ecological and social values of the coastal environment that they support can be maintained despite growing development pressures.	-	-	-	-
	Changing climate	4	The EPA 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 metre (m) in mean sea level by 2110 is currently considered the best prediction for decision making.	Y	Adopted	Section 4.3	A century-long view was adopted
			The EPA recognises that there is potential for significant habitat changes to coastal terrestrial ecosystems as well	Y	Consideration of spatial variations is fundamental throughout this	-	Variation of impacts to terrestrial systems mostly not considered

			as aquatic ecosystems from rising sea levels. However, the impacts to, and responses of, individual ecosystems will vary.		report		
			The consequences of other effects of a changing climate such as increasing storms and wave energy are likely to significantly affect coastal processes and associated environmental values in the coastal zone.	-	Not specifically addressed but implicitly judged throughout	-	Historical knowledge of changes from past tropical cyclones and lows is too poor to allow specific consideration
			The EPA is concerned with proposal-specific impacts that, when considered in combination with climate change, are likely to exacerbate changes to coastal processes and significant environmental values in the coastal zone.	Y	Fundamental throughout this report…	-	… considered as part of the overall development of understanding processes and possible future changes
			The EPA is also concerned with protecting ecosystems from the impacts that damaged infrastructure may cause because of sea level rise and to ensure that infrastructure does not prevent ecosystems from adapting to higher sea levels.	-	Damaged infrastructure not addressed	-	… considered as part of the overall development of understand processes and possible future changes
	State of science and/or knowledge	4	The EPA recognises that the current state of scientific knowledge for the coastal processes and the environmental values they support is highly variable.	Y	Expert judgement used	-	Knowledge is poor in this region
			Mathematical models for simulating the effects of coastal development proposals on hydrodynamic and most	Y	Expert judgement used	-	Underpinning knowledge is poor in this region, for all conditions, and especially for

			coastal processes are reasonably well developed for 'normal' or 'average' conditions. However, the ability to predict the impacts under extreme weather events such as cyclones is less well developed.				episodic events
			Information that may be used to inform modelling and predictions is variable across the state.	Y	Expert judgement used	-	Agreed, and see above
			Reliable bathymetric data is fundamental for predictive modelling of water currents and circulation patterns.	Y	Data suitable for most sedimentary purposes	-	Some minor bathymetric limitations exist but are far less significant than many other controlling factors. Some extra work about waves may be required
		5	The effects of modifying coastal processes on the existing environmental values are difficult to predict and not well documented. The collection of coastal process data before and after the development, and over time, will provide insight and provide calibration and validation data to tune model outputs and assess model performance and predictions in the future.	-	Not addressed	-	Recommendations on this are not a purpose of this report
			The EPA will consider the level of knowledge and confidence underpinning the predicted environmental impacts and risks.	Y	Caveats and uncertainties presented	Section 23	… and throughout
Impacts to coastal processes	Infrastructure that can alter wave energy and current patterns	5	Includes (but not necessarily limited to): • Marina or harbour water bodies	Y	Specifically addressed	Section 20	… and throughout

			• canal developments • groynes, boat launching facilities or marinas • alteration of river mouths or deltas The associated impacts may include: • changed water quality • accumulation of wrack • retention of nutrients and other contaminants saltwater intrusion or coastal inundation				
	Infrastructure that can interrupt tidal flows or cause a reduction in water exchange	5	Includes (but not necessarily limited to): • Marina or harbour water bodies • canal developments • groynes, boat launching facilities or marinas • alteration of river mouths or deltas The associated impacts may include: • changed water quality • accumulation of wrack • retention of nutrients and other contaminants • saltwater intrusion or coastal inundation	Y	Specifically addressed	-	Wrt changed tidal flows and some effects of waves in high intertidal areas
	Activities that directly alter the morphology of the coastal zone resulting in changes to sediment sources or sinks	5	Includes (but not necessarily limited to): • reclamation/excavation of the coastline • capital and maintenance dredging	Y	Specifically addressed	-	Wrt changed sediment transport pathways and changed patterns of erosion and accumulation

			• creation of shipping channels • disposal of dredge spoil • sand bypassing The associated impacts may include: • interruption of longshore sediment transport changes in erosion/deposition patterns				
	Activities that remove natural communities and habitats that protect the coastline and increase exposure to the action of coastal processes	6	Included (but not necessarily limited to): • removal of benthic communities, e.g., mangroves • habitats, e.g., reef structures • terrestrial vegetation, e.g., foreshore or dune vegetation. The associated impacts may include: Increased erosion	Y	Specifically addressed	-	Wrt changed exposure of the coastal environments to coastal processes
Requirements for EIA (the EPA may require)	Information required for EIA	6	Demonstrate how the proposal has been located and designed to avoid, minimise and mitigate impacts on coastal processes	-	Not addressed	-	Not a purpose of this report
			Characterise the coastal type and current coastal processes	Y	Specifically addressed	-	-
			Predict the changes to coastal processes as a result of the proposal, taking into account the appropriate spatial and temporal scales	Y	Based on expert judgement	Sections 20 and 22	Predictions out to a century ahead are not possible, but a range of possibilities are described
			Describe the impacts resulting from changes due to coastal processes	Y	Specifically addressed	-	-
			Consider cumulative impacts from and to other existing and	-	Not addressed	-	Not a purpose of this report

			approved developments				
			Determine coastal vulnerability and the potential impacts as a result of climate change	-	Not specifically addressed	-	Potential changes due to SLR are described
			Identify monitoring strategies and management and mitigation measures.	-	Not addressed	-	Not a purpose of this report
			Identify governance arrangements for the ongoing management of impacts	-	Not addressed	-	Not a purpose of this report
			Commission peer review of coastal process modelling and predicted impacts.	-	Not addressed	-	Can facilitate if desired

26. References

Actis Environmental Services 2023 Benthic Mat Study. Productivity Estimate of Proposed Eramurra Project, Eramurra Solar Salt Project. ESSP-EN-14-TRPT-0024. June 2023, 50 pp.

Alongi, D.M., 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuarine, coastal and shelf science, 76(1), pp.1-13.

Anthony, E. and Goichot, M., 2020. Sediment flow in the context of mangrove restoration and conservation. A BMZ, IUCN and WWF project. A rapid assessment guidance manual.

Ayoubi, S.; Milikian, A.; Mosaddeghi, M.R.; Zeraatpisheh, M.; Zhao, S. 2022 Impacts of Clay Content and Type on Shear Strength and Splash Erosion of Clay–Sand Mixtures. Minerals, 12, 1339. https://doi.org/10.3390/min12111339

Bao TQ. 2011. Effect of Mangrove Forest Structures on Wave Attenuation in Coastal Vietnam. Oceanologia 53, 807–818.

Belperio, A.P. 1979. Negative evidence for a mid-Holocene high sea-level along the coastal plain of the Great Barrier Reef province. Mar. Geol., 32: Ml-M9.

Belperio, A. P. 1983. Terrigenous sedimentation in the central Great Barrier Reef lagoon: A model from the Burdekin region. BMR Journal of Australian Geology and Geophysics, 8(3)179–190.

Berger U, Rivera-Monroy VH, Doyle TW, Dahdouh-Guebas F, Duke NC, Fontalvo-Herazo ML, Hildenbrandt H, Koedam N, Mehlig U, Piou C. & Twilley RR. 2008. Advances and limitations of individual-based models to analyze and predict dynamics of mangrove forests: A review. Aquatic Botany, 89 260-274.

Biota Environmental Sciences Pty Ltd. 2005. Yannarie Salt Project Mangrove and Coastal Ecosystem Study. Baseline Ecological Assessment. Prepared for Straits Salt Pty Ltd. https://www.epa.wa.gov.au/sites/default/files/PER_documentation/1295-ERMP-Appendix%204%20-%20Mangroves%20and%20Coast_Biota_CD.pdf

Bishop-Taylor R., Nanson R., Sagar S. & Lymburner L. 2021. Mapping Australia's dynamic coastline at mean sea level using three decades of Landsat imagery. Remote Sensing of Environment, 267, 112734. Available: https://doi.org/10.1016/j.rse.2021.112734

Bowen, Anthony John, and Douglas Lamar Inman. Budget of littoral sands in the vicinity of Point Arguello, California. No. 19. US Army Coastal Engineering Research Center, 1966.

Boyd, R., Dalrymple, R. and Zaitlin, B.A., 1992. Classification of clastic coastal depositional environments. Sedimentary Geology, 80(3-4), pp.139-150.

Brocx, M., & Semeniuk, V, 2015. The development of solar salt ponds along the Pilbara Coast, Western Australia–a coastline of global geoheritage significance used for industrial purposes. Geological Society, London, Special Publications, 419(1), 31-41.

Bureau of Meteorology: BoM. 2010. Tropical Cyclone Vance 18 – 24 March 1999. http://www.bom.gov.au/cyclone/history/pdf/vance.pdf

Bureau of Meteorology: BoM. 2012. Record-breaking La Nina events. An analysis of the La Nina life cycle and the impacts and significance of the 2010-11 and 2011-12 La Niña events in Australia.

Brinkman RM, Massel SR, Ridd PV & Furukawa K. 1997. Surface Wave Attenuation in Mangrove Forests. Proceedings of the Combined Australasian Coastal Engineering and Ports Conference, Christchurch, 1997, 941–946.

Bruun P. (1962) Sea-level rise as a cause of shore erosion. Journal Waterways and Harbours Division, American Society of Civil Engineers, 88: 117-130.

Bryce, S., Larcombe, P., & Ridd, P. V. 1998. The relative importance of landward-directed tidal sediment transport versus freshwater flood events in the Normanby River estuary, Cape York Peninsula, Australia. Marine Geology, 1491-4, 55-78.

Bryce, S, Larcombe, P & Ridd, PV 2003. 'Hydrodynamic and geomorphological controls on suspended sediment transport in mangrove creek systems, a case study: Cocoa creek, Townsville, Australia', Estuarine, Coastal and Shelf Science, vol. 56, pp. 415–431.

Bunt, JAC, Larcombe, P & Jago CF. 1999. "Quantifying the Response of Optical Backscatter Devices and Transmissometers to Variations in Suspended Particulate Matter." Continental Shelf Research 19 (9): 1199–1220. https://doi.org/10.1016/S0278-4343(99)00018-7.

Bunt, J.S., Williams, W.T. and Bunt, E.D. 1985. Mangrove species distribution in relation to tide at the seafront and up rivers. Aust. J. Mar. Freshwater Res., 36: 481-492.

Carter, R.M., Larcombe, P. Dye, J.E., Gagan, M.K. & Johnson, D.P. 2009. Longitudinal shelf sediment transport and storm-bed formation during and after Cyclone Winifred (February, 1986, Great Barrier Reef). Marine Geology, 267, 101-113.

Chen H-C, Cheng IJ & Hong E. 2007. The influence of the beach environment on digging success and nest site distribution of the Green Turtle, Chelonia mydas, on Wan-an Island, Penghu Archipelago, Taiwan. Journal of Coastal Research, 22(5), 1277-1286.

Chevron Australia. 2016. Gorgon Gas Development and Jansz Feed Gas Pipeline: Coastal Stability Management and Monitoring Plan Supplement: Management Triggers. Chevron Australia, Perth, Western Australia. Document G1-NTREPX0002461.

Church J, White N, Coleman R, Lambeck K & Mitrovica J. 2004. Estimates of the Regional Distribution of Sea-level Rise over the 1950 to 2000 Period. Journal of Climate. 17: 2619-2625.

Church, J.A., White, N.J. and Arblaster, J.M., 2005. Significant decadal-scale impact of volcanic eruptions on sea level and ocean heat content. Nature, 438(7064), pp.74-77.

CMW Geosciences 2022 Eramurra Salt Project, Cape Preston East, Western Australia, Geotechnical Investigation Report Report to Leichhardt Industrials, 1849 pp.

Cobb SM, Saynor MJ, Eliot M, Eliot I & Hall R. (2007) Saltwater intrusion and mangrove encroachment of coastal wetlands in the Alligator Rivers Region, Northern Territory, Australia. Supervising Scientist Report 191.

Commonwealth of Australia 2017. Recovery plan for marine turtles in Australia. https://www.environment.gov.au/marine/publications/recovery-plan-marine-turtles-australia-2017

Cowell PJ, Roy PS & Jones RA. 1995. Simulation of large-scale coastal change using a morphological behaviour model. Marine Geology, 126(1-4), 45-61.

Astron Pty Ltd. 2020. Coastal Stability Monitoring Cape Preston. Prepared for Citic Pacific Mining Management Pty Ltd. Ref 2075-20-GSSR-1Rev0_201009.

Crase B, Liedloff A, Vesk PA, Burgman MA & Wintle BA. 2013. Key factors influencing mangrove species distribution. Global Ecology and Biogeography, 22, 806-817. doi:10.1111/geb.12063

Dare RA & Davidson NE. 2004. Characteristics of Tropical Cyclones in the Australian Region. Monthly Weather Review, 132: 3049-3065.

Davidson-Arnott RGD. 2005. Conceptual Model of the Effects of Sea Level Rise on Sandy Coasts. Journal of Coastal Research, 21 (6): 1166-1172.

Davis, R.A. and Dalrymple, R.W. eds., 2012. Principles of tidal sedimentology (Vol. 625). New York: Springer.

Department of Agriculture, Water and the Environment (DAWE) 2020. Habitat critical to the survival of marine turtles in Australian waters. Online dataset: https://fed.dcceew.gov.au/datasets/erin::habitat-critical-to-the-survival-of-marine-turtles-in-australian-waters/explore?location=-20.515995%2C116.483452%2C7.75

Department of Environment and Conservation 2006. An Inspection of marine turtle nesting activity, Cape Preston, December 2006.

Department of Transport (2010) Sea Level Change in Western Australia. Application to Coastal Planning. Department of Transport, Coastal Infrastructure, Coastal Engineering Group. 24 pp.

Donnelly C, Kraus N & Larson M. 2006. State of Knowledge on Measurement and Modeling of Coastal Overwash. Journal of Coastal Research, 22 (4): 965-991.

Douglas B, Kearney M & Leatherman S. 2001. Sea Level Rise. History and Consequences. Academic Press, San Diego.

Dufois, F., Lowe, R. J., Branson, P., & Fearns, P. 2017. Tropical cyclone-driven sediment dynamics over the Australian North West Shelf. Journal of Geophysical Research: Oceans, 122, 225–244.

Duke NC 1985. Data on mangrove distributions in north-eastern Australia and other areas. CS-84-1. Australian Institute of Marine Science. 140 p.

Dyer, K.R., 1986. Coastal and Estuarine Sediment Dynamics. Wiley-Interscience, Chichester.

Eliot M. (2011) Influence of Inter-annual Tidal Modulation on Coastal Flooding Along the Western Australian Coast. Journal of Geophysical Research, 115, C11013, doi:10.1029/2010JC006306.

Eliot M & Eliot I. (2013) Interpreting estuarine change in northern Australia: physical responses to changing conditions. Hydrobiologia. SI: Climate Change and Australian Wetlands. DOI 10.1007/s10750-012-1097-x.

Eliot I., Gozzard B., Eliot M., Stul T. & McCormack G. 2013. Geology, Geomorphology & Vulnerability of the Pilbara Coast, In the Shires of Ashburton, East Pilbara and Roebourne, and the Town of Port Hedland, Western Australia. Damara WA Pty Ltd and Geological Survey of Western Australia, Innaloo, Western Australia.

Ellison, J.C. and Stoddart, D.R., 1991. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. Journal of Coastal Research, pp.151-165.

Ellison AM. 2002. Macroecology of mangroves: large-scale patterns and processes in tropical coastal forests. Trees, 16, pp.181-194.

Environmental Protection Agency 2020. Cape Preston East - Multi-Commodity Export Facility – inquiry under section 46 of the Environmental Protection Act 1986 to amend Ministerial Statement 949. Report and recommendations of the Environmental Protection Authority. Report 1680.EPA 2016 Technical Guidance Protection of Benthic Communities and Habitats. December 2016. 24 pp.

EPA 2016 Environmental Factor Guideline: Coastal Processes, EPA, Western Australia, 6 pp.

Ewel K, Twilley R & Ong JIN. 1998. Different kinds of mangrove forests provide different goods and services. Global Ecology & Biogeography Letters, 7, 83-94.

Fandry, C., and R. Steedman 1994., Modelling the dynamics of transient, barotropic response of continental shelf waters to tropical cyclones, Cont. Shelf Res., 14, 1723–1750, doi:10.1016/0278-4343(94)90045-0.

Fairbridge, R. W. 1961. Eustatic changes in sea level. Physics and Chemistry of the Earth, 4, 99-185.

Feng, M., Li, Y. and Meyers, G., 2004. Multidecadal variations of Fremantle sea level: Footprint of climate variability in the tropical Pacific. Geophysical Research Letters, 31(16).

Feng, M., Meyers, G., Pearce, A. and Wijffels, S., 2003. Annual and interannual variations of the Leeuwin Current at 32 S. Journal of Geophysical Research: Oceans, 108(C11).

Fossette S, Loewenthal G, Peel L, Vitenbergs A, Hamel M, Douglas C, Tucker A, Mayer F & Whiting S 2021 Using aerial photogrammetry to assess stock‐wide marine turtle nesting distribution, abundance and cumulative exposure to industrial activity. Remote Sensing 13(6), p. 1116. https://doi.org/10.3390/rs13061116.

Friedrichs, C. T., Aubrey, D. G., & Speer, P. E., 1990. Impacts of relative sea-level rise on evolution of shallow estuaries. In R. T. Cheng (Ed.), Residual currents and long-term transport, Coastal and estuarine studies (Vol. 38, pp. 105–120). Springer-Verlag.

Gagan, M., Johnson, D. P., & Carter, R. M. 1988. The cyclone Winifred storm bed, central Great Barrier Reef shelf, Australia. Journal of Sedimentary Petrology, 58, 845–856.

Gagan MK, Chivas AR, Herczeg AL. 1990. Shelf-wide erosion, deposition and suspended sediment transport during cyclone Winifred, central Great Barrier Reef, Australia. J Sediment Petrol 60: 456−470.

Gagan, M.K., Johnson, D.P. and Crowley, G.M. 1994. Sea-level control of stacked late Quaternary coastal sequences, central Great Barrier Reef. Sedimentology, 41: 329-351.

Gallop, S.L., Collins, M., Pattiaratchi, C.B., Eliot, M.J., Bosserelle, C., Ghisalberti, M., Collins, L.B., Eliot, I., Erftemeijer, P.L., Larcombe, P. and Marigómez, I., 2015. Challenges in transferring knowledge between scales in coastal sediment dynamics. Frontiers in Marine Science, 2, p.82.

Galloway W. (1975) Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In: Broussard M (ed.) Deltas: Models for Exploration. Houston Geologic Soc., Houston TX, 87-98.

Geoscience Australia 2023. DEA Coastlines website https://cmi.ga.gov.au/data-products/dea/581/dea-coastlines#details [last accessed 18/04/2024].

Gilman E, Ellison J & Coleman R. 2007. Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. Environmental Monitoring and Assessment, 124, 105-130.

Goff, J. and Chagué-Goff, C., 2014. The Australian tsunami database: a review. Progress in Physical Geography, 38(2), pp.218-240.

Gornitz, V., 1993. Mean sea-level changes in the recent past. Climate and sea-level change: observations, projections and implications, pp.25-44.

Gregson, P.J. and van Reeken, I.A., 1998. Tsunami observations in Western Australia. Maritime natural hazards in the Indian Ocean, Wollongong papers on maritime policy, (6).

Guo, L., Zhu, C., Xu, F., Xie, W., van der Wegen, M., Townend, I., *et al.*, 2022. Reclamation of tidal flats within tidal basins alters centennial morphodynamic adaptation to sea-level rise. Journal of Geophysical Research: Earth Surface, 127, e2021JF006556. https://doi.org/10.1029/2021JF006556

Haigh ID, Eliot M & Pattiaratchi CB. 2011a. Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. Journal of Geophysical Research: Oceans, 116(C6).

Haigh ID, Eliot M, Pattiaratchi C & Wahl T. 2011b. Regional changes in mean sea level around Western Australia between 1897 and 2008. Coast & Ports 2011. Proceedings: 20th Australasian Coastal & Ocean Engineering

Conference and the 13th Australasian Port and Harbour Conference, held 28-30 September 2011, Perth Convention Exhibition Centre.

Harris, P., Heap, A., Passlow, V., Sbaffi, L. Fellows, M., Porter-Smith, R., Buchanan, C., & Daniell, J. 2005. Geomorphic Features of the Continental Margin of Australia. Geoscience Australia, Record 2003/30, 142pp.

Harris, P.T. and Hughes, M.G., 2012. Predicted benthic disturbance regimes on the Australian continental shelf: a modelling approach. Marine Ecology Progress Series, 449, pp.13-25.

Hengesh, J., Dirstein, J.K. and Stanley, A.J., 2012. Seafloor geomorphology and submarine landslide hazards along the continental slope in the Carnarvon Basin, Exmouth Plateau, North West Shelf, Australia. The APPEA Journal, 52(1), pp.493-512.

Hewavisenthi S & Parmenter CJ. 2002. Incubation environment and nest success of the flatback turtle (Natator depressus) from a natural nesting beach. Copeia, pp 303-312

Horstman, E.M., Dohmen-Janssen, C.M., Narra, P.M.F., Van den Berg, N.J.F., Siemerink, M. and Hulscher, S.J., 2014. Wave attenuation in mangroves: A quantitative approach to field observations. Coastal engineering, 94, pp.47-62.

Motyka, JM, and Brampton, A (1993). Coastal Management: Mapping of littoral cells. HR Wallingford, Report SR 328. HR Wallingford, Wallingford.

HR Wallingford (1997) Coastal cells in Scotland. Scottish Natural Heritage Research Survey and Monitoring Report No.56. HR Wallingford, Wallingford.

Hubbard, D.K., 1992. Hurricane-induced sediment transport in open shelf tropical systems—an example from St. Croix,US Virgin Islands. Journal of Sedimentary Petrology 62,949–960.

IUCN (1995) A global strategy for the conservation of marine turtles.

James, N.P., Bone, Y., Kyser, T.K., Dix, G.R., Collins, L.B. 2004. The importance of changing oceanography in controlling late Quaternary carbonate sedimentation on a high energy, tropical oceanic ramp: north-western Australia. Sedimentology 51, 1179–1938.

Johannes RE & Rimmer D .1984. Some distinguishing characteristics of nesting beaches of the green turtle Chelonia mydas on North West Cape Peninsula, Western Australia, Marine Biology, 83, 149-154.

Jones, H. A. 1973. Marine geology of the Northwest Australian shelf. Canberra: Bureau of Mineral Resources.

Kamrowski RL, Limpus C, Pendoley K & Hamann M. 2014. Influence of industrial light pollution on the sea-finding behaviour of flatback turtle hatchlings. Wildlife Research 41 (5), 421-434.

Kendrick P. 2000. An inspection of Sea-turtle nesting activity, Cape Preston, December 2000. Department of Conservation and Land Management. File 22.04.1.

Kikukawa A, Kamezaki N & Ota H. 1999. Factors affecting nesting beach selection by loggerhead turtles (Caretta caretta): a multiple regression approach. Journal of the Zoological Society of London.

Land and Water Consulting 2022 Baseline Soil and Sediment Testing, Eramurra Salt Project, Leichhardt Salt Pty Ltd, November 2022, 451 pp.

Land and Water Consulting 2023a. Eramurra Salt Project, Hydrologic Assessment for Scenario 7.2, Leichhardt Salt, July 2023, 104 pp.

Land and Water Consulting 2023b. Eramurra Solar Salt Project – Groundwater Effects Assessment and Seepage Modelling 13 December 2023.

Larcombe, P. 2007. Continental shelf environments. In Perry, C. & Taylor, K. (Eds.) Environmental Sedimentology. Blackwell Publishing.

Larcombe, P. 2024. Review of the interpretations and conclusions made by the CP-BCH Report, updating them using the latest pond scenarios and corrected hypsometric data - Eramurra Solar Salt Project. Report PL2024-001 to Leichhardt Salt Pty Ltd, 44 pp, Rev.1.2. 6th March 2024. Leichhardt Document No. ESSP-EN-14-TRPT-0031

Larcombe, P. and Carter, R.M. 2004. Cyclone pumping, sediment partitioning and the development of the Great Barrier Reef shelf system: a review. Quaternary Science Reviews, 23, 107-135.

Larcombe, P., Carter, R.M., Dye, J., Gagan, M.K. and Johnson, D.P. 1995. New evidence for episodic post glacial sea-level rise, central Great Barrier Reef, Australia. Marine Geology, 127, 1-44.

Larcombe, P. and Morrison-Saunders, A. (2017) Managing marine environments and decision-making requires better application of the physical sedimentary sciences. Australasian Journal of Environmental Management, 24 (2): 200-221.

Larcombe, P., & Ridd, P. V., 1996. Dry season hydrodynamics and sediment transport in a mangrove creek. In C. Pattariatchi (Ed.), Mixing processes in estuaries and coastal seas, Coastal and estuarine studies 46 (pp. 388-404). Washington, DC: American Geophysical Union.

Larcombe, P., Ward, I. A. K., & Whitley, T. 2018. Physical sedimentary controls on subtropical coastal and shelf sedimentary systems: Initial application in conceptual models and computer visualizations to support archaeology. Geoarchaeology, 33, 661–679.

Larcombe, P., Wilson, M., Whitley, T., Ward, I., Pirrie, D., Li, T., Hill, J., Florec, V. and Bateman, M., 2022, May. Sedimentary evidence for a Quaternary mega-tsunami in NW Australia. In EGU General Assembly Conference Abstracts (pp. EGU22-3848).

Larcombe, P, Ross, PJ. and Fandry, C., 2025. Applying Geoarchaeological Principles to Marine Archaeology: A New Reappraisal of the ‘First Marine’ and ‘in-Situ’ Lithic Scatters, Murujuga (Dampier Archipelago), NW Australia. Geomorphology 468 (January):109494. https://doi.org/10.1016/j.geomorph.2024.109494

Larson M, Donnelly C, Jiménez JA & Hanson H. 2009. Analytical model of beach erosion and overwash during storms. In: Proceedings of the Institution of Civil Engineers. Maritime Engineering, 162 (3), 115-125.

Lear, Karissa O, Brendan C Ebner, Travis Fazeldean, Rebecca L Bateman, and David L Morgan. 2024. “Effects of Coastal Development on Sawfish Movements and the Need for Marine Animal Crossing Solutions.” Conservation Biology, e14263.

Lebrec, U., Paumard, V., O'Leary, M.J. and Lang, S.C., 2021. Towards a regional high-resolution bathymetry of the North West Shelf of Australia based on Sentinel-2 satellite images, 3D seismic surveys, and historical datasets. Earth System Science Data, 13(11), pp.5191-5212.

Leichhardt Salt, 2024. Environmental Review Document, Eramurra Solar Salt Project.

Lewis, S.E., Sloss, C.R., Murray-Wallace, C.V., Woodroffe, C.D., Smithers, S.G. 2013. Post-glacial sea-level changes around the Australian margin: a review. Quat. Sci. Rev. 74, 115–138.

Lovelock, C., A. Grinham, F. Adame and H. Penrose 2010. Elemental composition and productivity of cyanobacterial mats in an arid zone estuary in North Western Australia. Wetlands Ecology and Management 18: 37-47.

Lugo, A. E., & Snedaker, S. C. 1974. The ecology of mangroves. Annual review of ecology and systematics, 51, 39-64.

McBride J & Keenan T. 1981. Climatology of tropical cyclone genesis in the Australian region. Journal of Climatology, 2: 13-33.

Mariani A, Shand TD, Carley JT, Goodwin ID, Splinter K, Davey EK, Flocard F & Turner IL. 2012. Generic design coastal erosion volumes and setbacks for Australia. Antarctic Climate & Ecosystems Cooperative Research Centre, Hobart.

May, S.M., Brill, D., Engel, M., Scheffers, A., Pint, A., Opitz, S., Wennrich, V., Squire, P., Kelletat, D., Brückner, H., 2015. Traces of historical tropical cyclones and tsunamis in the Ashburton Delta (northwest Australia). Sedimentology 62, 1546–1572.

May, S.M., Falvard, S., Norpoth, M., Pint, A., Brill, D., Engel, M., Scheffers, A., Dierick, M., Paris, R., Squire, P. 2016. A mid-Holocene candidate tsunami deposit from the NW Cape (Western Australia). Sediment. Geol. 332, 40–50.

May, S.M., Gelhausen, H., Brill, D., Callow, J.N., Engel, M., Opitz, S., Scheffers, A., Joannes-Boyau, R., Leopold, M., Brückner, H. 2018. Chenier-type ridges in Giralia Bay (Exmouth Gulf, Western Australia)-processes, chronostratigraphy, and significance for recording past tropical cyclones. Mar. Geol. 396, 186–204.

Mearns, D.L., Hine, A.C., Riggs, S.R. 1988. Comparison of sonographs taken before and after Hurricane Diana, Onslow Bay, North Carolina. Geology 16,267–270.

Mills D & Kemps H. (2016) Generation and release of sediments by hydraulic dredging: a review. Report of Theme 2 - Project 2.1 prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia. 97 pp.

Milton D. 1980. The Contribution of Tropical Cyclones to the Rainfall of Tropical Western Australia. Singapore Journal of Tropical Geography, 1, 46-54.

Moir-Barnetson, L, Veneklaas, EJ and Colmer, T, 2014. Salinity tolerances of three succulent halophytes (Tecticornia spp.) differentially distributed along a salinity gradient. Functional Plant Biology 43(8) 739-750 https://doi.org/10.1071/FP16025

Morgan, D., Ebner, B. C., Allen, M. G., Gleiss, A. C., Beatty, S. J., & Whitty, J. M. (2017). Habitat use and site fidelity of neonate and juvenile green sawfish Pristis zijsron in a nursery area in Western Australia. Endangered Species Research, 34, 235–249. https://doi.org/10.1111/cobi.14263

Morgan, D, Fazeldean, T, Ingelbrecht, J. 2025. Eramurra Sawfish Survey August 2024 Final Report. Leichhardt Salt Pty Ltd – Eramurra Solar Salt Project. Centre for Sustainable Aquatic Ecosystems: Harry Butler Institute, Murdoch University.

Mortimer JA. 1982. Factors influencing beach selection by nesting sea turtles. In: Bjorndal, K.A. (ed.) Biology and Conservation of Sea Turtles, Smithsonian Institution Press, Washington DC, pp. 45-52.

Morton, R.A. 1988. Nearshore responses to great storms. In: Clifton, H.E. (Ed.), Sedimentologic Consequences of Convulsive Geologic Events, Geological Society of America Special paper 229, pp. 7–22. Boulder, CO.

Mazda Y, Magi M, Ikeda Y, Kurokawa T & Asano T. 2006. Wave Reduction in a Mangrove Forest Dominated by Sonneratia Sp. Wetlands Ecology and Management 14, 365–378.

Nott, J., 2006. Tropical cyclones and the evolution of the sedimentary coast of northern Australia. Journal of Coastal Research, 22(1), pp.49-62.

Offshore Engineering, 1994. Letter from Steve Waller, in Report 0948.

O2 Environment 2025a. Eramurra Solar Salt Project. Subtidal Benthic Communities and Habitat Report. R210228, Rev. 6. 7 Feb 2025.

O2 Environment 2025b. Eramurra Solar Salt Project. Intertidal Benthic Communities and Habitat Report. R200304, Rev. 7. 18 Feb. 2025.

O2 Marine 2020. Eramurra Solar Salt Project: Refined Clive's Corner and Other Creeks' Bathymetry, O2 Marine Report R200207, Perth, Western Australia. Rev 1. 30 September 2020.

O2 Marine, 2020. Mardie Project. Intertidal Benthic Communities & Habitat. Mardie Minerals Pty Ltd. Rev 2. R1800007. 2 April 2020.

O2 Marine 2022. Eramurra Solar Salt Project. Subtidal Benthic Communities and Habitat Assessment Report. Prepared for Leichhardt Salt Pty Ltd.

O2 Marine 2022b. Eramurra Solar Salt Project Turtle Nesting Study Report. Prepared by O2 Marine for Leichhardt Salt Pty Ltd, Perth, Western Australia

O2 Marine 2023. Eramurra Solar Salt Project. Intertidal Benthic Communities and Habitat Report. Leichhardt Salt Pty Ltd. Report no. R200304, Rev 6. 16 November 2023.

O2 Metocean 2022a. Coastal processes study to support BCH assessment. Final Report. Leichhardt Salt Pty Ltd. Rev. 2. 18 November 2022.

O2 Metocean 2022b. Metocean Data Appraisal Report. Eramurra Solar Salt Project. Leichhardt Industrials Pty Ltd. Rev 0. 18 October 2022.

O2 Metocean 2022c. Eramurra Solar Salt Project: Base Hydrodynamic Model, O2 Metocean Report R210323, Perth, WA.

O2 Metocean 2022d. Eramurra Solar Salt Project: Tidal Inundation Modelling, O2 Metocean Report R210327, Rev. 5. 4 July 2023.

O2 Metocean 2023a. Eramurra Solar Salt Project - Coastal and Intertidal Processes Assessment, ESSP Scenario 7.2. Leichhardt Salt Pty Ltd. Report no. R220181, Rev 0. 04 July 2023.

O2 Metocean 2023b. Dredge Plume Modelling, ESSP Scenario 7.2. Eramurra Solar Salt Project. Leichhardt Industrials Pty Ltd. Rev 5. 19 June 2023.

Orpin, A. R., Brunskill, G. J., Zagorskis, I., & Woolfe, K. J. 2004. Patterns of mixed siliciclastic ‐ carbonate sedimentation adjacent to a large dry-tropics river on the central Great Barrier Reef shelf, Australia. Australian Journal of Earth Sciences, 515, 665–683. https://doi.org/10.1111/j.1400-0952.2004.01083.x

Paerl, H.W., Joye, S. B., & Fitzpatrick, M. 1993. Evaluation of nutrient limitation of CO2 and N2 fixation in marine microbial mats. Marine Ecology Progress Series 101: 297-306.

Paling EI, McComb AJ & Pate JS. 1989. Nitrogen fixation (acetylene reduction) in non-heterocystous cyanobacterial mats from the Dampier Archipelago, Western Australia. Marine and Freshwater Research, 40, 147-153.

Passlow V, Rogis J, Hancock A, Hemer MA, Glenn K, Habib A. 2005. Final report − national marine sediments database and seafloor characteristics project. Geoscience Australia Record 2005/8, Canberra.

Pattiaratchi C & Buchan S. 1991. Implications of long-term climate change for the Leeuwin Current. Journal of the Royal Society of Western Australia, 74: 133-140.

Pattiaratchi C & Eliot M. 2008. Sea level variability in south-west Australia: from hours to decades. In: Proceedings of the 31st ASCE International Conference on Coastal Engineering, Hamburg, Germany 2008, pp. 1186–1198.

Pearce A, Buchan S, Chiffings T, d'Adamo N, Fandry C, Fearns P, Mills D, Phillips R & Simpson C. 2003. A review of the oceanography of the Dampier Archipelago, Western Australia. In: Wells F, Walker D & Jones D (Eds). The Marine Flora and Fauna of Dampier, Western Australia. Western Australian Museum, Perth, 13-50.

Pendoley K, Whittock P, Vitenbergs A & Bell C. 2016. Twenty years of turtle tracks: marine turtle nesting activity at remote locations in the Pilbara, Western Australia. Journal of Zoology 64(3), pp. 217-226.

Pendoley Environmental (2023) Eramurra Solar Salt Project: Marine Turtle Monitoring 2022/23, Pendoley Report J106002-1, Perth 6000, Western Australia. Report prepared for Leichhardt Salt Pty Ltd.

Pendoley Environmental 2024. “Eramurra Solar Salt Project: Marine Turtle Monitoring 2023/24.” J106003-2 / ESSP-EN-TRPT-0035. Leichhardt Salt Pty Ltd.

Perri, S., Detto, M., Porporato, A., & Molini, A. 2023. Salinity-induced limits to mangrove canopy height. Global Ecology and Biogeography, 32, 1561–1574. https://doi.org/10.1111/geb.13720

Pethick, J.S 1984. An introduction to coastal geomorphology. London: Edward Arnold.

Picard K., Nichol, S.L., Hashimoto, R., Carroll, A.G., Bernardel, G., Jones, L.E.A., Siwabessy, P.J.W., Radke, L.C., Nicholas, W.A., Carey, M.C., Stowar, M., Howard, F.J.F., Tran, M. & Potter, A., 2014. Seabed Environments and Shallow Geology of the Leveque Shelf, Browse Basin, Western Australia; GA0340/SOL5754 – Post-survey report. Record 2014/10. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2014.010

Porter-Smith R, Harris PT, Andersen OB, Coleman R, Greenslade D, Jenkins CJ. 2004. Classification of the Australian continental shelf based on predicted sediment threshold exceedance from tidal currents and swell waves. Mar Geol 211: 1−20.

Quartel S, Kroon A, Augustinus P, Van Santen P & Tri NH. 2007. Wave Attenuation in Coastal Mangroves in the Red River Delta, Vietnam. Journal of Asian Earth Sciences 29, 576–584.

Reef, Ruth E, Prudence V Perry, and Vanessa NL Wong. 2023. “A New Approach to Mapping Littoral Cells within a Tide-Dominated Embayment.” Marine Geology 461:107068.

RPS. 2021. Eramurra Solar Salt Project, Preliminary Metocean Study. 100-CN-REP-1960 Rev. A.

Rossington K, Whitehouse RJS & Spearman J. 2009. Morphological modelling of intertidal profiles in estuaries with strong tidal currents. Rivers, Coastal and Estuarine Morphodynamics, 941-946.

Rouillard, A., Skrzypek, G., Turney, C., Dogramaci, S., Hua, Q., Zawadzki, A., Reeves, J., Greenwood, P., O’Donnell, A.J. and Grierson, P.F., 2016. Evidence for extreme floods in arid subtropical northwest Australia during the Little Ice Age chronozone (CE 1400–1850). Quaternary Science Reviews, 144, pp.107-122.

Ryan DA, Heap AD, Radke L & Heggie DT. (2003) Conceptual Models of Australia’s Estuaries and Coastal Waterways. Applications for Coastal Resource Management. Geoscience Australia Record 2003/09.

Sallenger AH. 2000. Storm Impact Scale for Barrier Islands. Journal of Coastal Research, 16 (3), 890-895.

Scheffers, S. R., Scheffers, A., Kelletat, D., & Bryant, E. A., 2008. The Holocene paleo-tsunami history of West Australia. Earth and Planetary Science Letters, 270, 137–146.

Seashore Engineering (2018) Erosion Due to Tropical Cyclones. Appendix C in Seashore Engineering (2018) Design Storms for Western Australian Coastal Planning: Tropical Cyclones. Report SE015-01.

Seashore Engineering (2021) Ashburton Salt: Response to Sea Level Rise. Report SE099-01-Rev4.

Semeniuk, V., & Searle, D. J., 1987. Beach rock ridges/bands along a high-energy coast in Southwestern Australia: Their significance and use in coastal history. Journal of Coastal Research, 331-342.

Semeniuk, V., 1994. Predicting the effect of sea-level rise on mangroves in northwestern Australia. Journal of Coastal Research, pp.1050-1076.

Semeniuk, V., 1996. An early Holocene record of rising sea level along a bathymetrically complex coast in southwestern Australia. Marine Geology 131, 177-193.

Semeniuk V. 1996. Coastal forms and Quaternary processes along the arid Pilbara coast of northwestern Australia. Palaeogeography, Palaeoclimatology, Palaeoecology, 123: 49-84.

Semeniuk, V., 2000. Sedimentology and Holocene stratigraphy of Leschenault Inlet. Journal of the Royal Society of Western Australia 83, 255-273.

Semeniuk, V. (2008). Holocene sedimentation, stratigraphy, biostratigraphy, and history of the Canning Coast, north-western Australia. Journal of the Royal Society of Western Australia, 91, 53-148.

Semeniuk, V., Searle, D.J., 1986. Variability of Holocene sea-level history along the southwestern coast of Australia - Evidence for the effect of significant local tectonism. Marine Geology 72, 47-58.

Shamblott KM, Reneker JL & Kamel SJ. (2021) The thermal impacts of beach nourishment across a regionally important loggerhead sea turtle (Caretta caretta) rookery. Ecosphere, 12(3), e03396.

Short A D (2005) Beaches of the Western Australian Coast: Eucla to Roebuck Bay: A guide to their nature, characteristics, surf and safety. Sydney University Press.

SKM, 2013a. Marine Geotechnical Investigation Interpretive Report. Iron Ore Holdings - Buckland Project.

SKM, 2013b. Marine Geotechnical Investigation Factual Report. Iron Ore Holdings - Buckland Project. WV04717, Rev 0, 09 July 2013.

Sørensen, K., Canfield, D., Teske, A. and Oren, A., 2004. Salinity Responses of Benthic Microbial Communities in a Solar Saltern (Eilat, Israel). Applied and Environmental Microbiology 70(3): 1608-1616.

Sørensen, K., Canfield, D., Teske, A. & Oren, A. 2005. Community composition of a Hypersaline Edo-evaporitic Microbial Mat. Applied and Environmental Microbiology 71(11): 7352-7365.

Spenceley, A.P. 1982. Sedimentation pattern in a mangal on Magnetic Island near Townsville, North Queensland, Australia. Singapore J. Trop. Geogr., 8: 100-107.

Stern H, de Hoedt G & Ernst J. 2000. Objective classification of Australian climates, Australian Meteorological Magazine, 49: 87-96.

Susilo, A. 2004. Groundwater flow in arid tropical tidal wetlands and estuaries. PhD Thesis, James Cook University.

Taukulis F. 2018. Assessment of Mangal and Algal Communities for the Mardie Solar Salt Project. Prepared for BCI Minerals Ltd. Stantec Pty Ltd.

Twiggs, E. J., & Collins, L. B. 2010. Development and demise of a fringing coral reef during Holocene environmental change, eastern Ningaloo Reef, Western Australia. Marine Geology, 275, 20-36.

Twilley RR, Rivera-Monroy VH, Chen R & Botero L. 1999. Adapting an ecological mangrove model to simulate trajectories in restoration ecology. Marine Pollution Bulletin, 37, 404-419.

Vo-Luong P & Massel S. 2008. Energy Dissipation in Non-Uniform Mangrove Forests of Arbitrary Depth. Journal of Marine Systems 74, 603–622.

Ward, I. A. K., Bateman, M., Larcombe, P., Scott, P., Li, T., Murai, K., Khan, N. S., Veth, P., & Cullen, P., 2022. A pilot study into the geochronological and geomorphic context for the archaeology of Barrow Island, Western Australia. Quaternary International. https://doi.org/10.1016/j.quaint.2022.02.002

White NJ, Haigh ID, Church JA, Koen T, Watson CS, Pritchard TR, Watson PJ, Burgette RJ, McInnes KL, You Z-J, Zhang X & Tregoning P. 2014. Australian Sea Levels – Trends, Regional Variability and Influencing Factors, Earth Science Reviews, doi: 10.1016/j.earscirev.2014.05.011

Winterwerp JC, Erftemeijer PLA, Suryadiputra N, Van Eijk P & Zhang L. 2013. Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. Wetlands, 33, 515-526.

Wolanski, E & Ridd, PV, 1990. ‘Mixing and trapping in Australian coastal waters’, in RT Cheng (ed), Residual currents and long-term transport, Coastal and Estuarine Studies 38, Springer-Verlag, New York, pp. 165–183.

Wolanski, E., Jones, M. and Bunt, J.S. 1980. Hydrodynamics of a tidal creek mangrove swamp system. Aust. J. Mar. Freshwater Res., 31: 431-450.

Wolanski E, Mazda Y, Ridd PV. (1992). Mangrove hydrodynamics. In Tropical Mangrove Ecosystems, ed. AI Robertson, DM Alongi, pp. 43–62. Washington, DC: Am. Geophys. Union.

Woodroffe, C.D. 1988. Mangroves and sedimentation in reef environments: indicators of past sea-level changes, and present sea-level trends? Proc. 6th Int. Coral Reef Symp., Australia, 3: 535-539.

Woolfe, K. J., Larcombe, P., & Stewart, L. K. 2000. Shelf sediments adjacent to the Herbert River delta, Great Barrier Reef, Australia. Australian Journal of Earth Sciences, 47(2), 301-308.

World Bank. 2016. Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs. Editors: Beck MW & Lange G-M. Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES), World Bank, Washington, DC.

White NJ, Haigh ID, Church JA, Koen T, Watson CS, Pritchard TR, Watson PJ, Burgette RJ, McInnes KL, You Z-J, Zhang X & Tregoning P. 2014. Australian Sea Levels – Trends, Regional Variability and Influencing Factors, Earth Science Reviews (2014), doi: 10.1016/j.earscirev.2014.05.011

Whittock PA, Pendoley KL & Hamann M. 2014. Inter-nesting distribution of flatback turtles Natator depressus and industrial development in Western Australia. Endangered Species Research, 26, 25 – 38.

Wood D & Bjorndal K. 2000. Relation of temperature, moisture, salinity, and slope to nest site selection in loggerhead turtles. Copeia, 1, 119-128.

Wright LD & Thom BG. 1977. Coastal depositional landforms: A morphodynamic approach. Progress in Physical Geography,1: 412-459.

Yokoyama, Y., Lambeck, K., De Deckker, P., Johnston, P. and Fifield, L.K., 2000. Timing of the Last Glacial Maximum from observed sea-level minima. Nature, 406(6797), pp.713-716.

Yokoyama, Y., De Deckker, P., Lambeck, K., Johnson, P., Fifield, L.K. 2001. Sea-level at the last glacial maximum: evidence from northwestern Australia to constrain ice volumes for oxygen isotope stage 2. Palaeogeogr. Palaeoclimatol. Palaeoecol. 165, 281–297.

APPENDICES – Sections 27 to 38.

27. Coastal processes – some key questions

To help gain the requisite understanding of sedimentary processes at the coast itself, there are a set of questions to be answered, listed below. Consideration of these and associated questions helped design the work presented in this report.

The tidal controls on flow and sediment transport in the creeks

1. Can we see clear tidally controlled flow in McKay Creek, especially the different flows associated with overbank tides compared to within-creek tides.
2. What are the inferences regarding sand transport processes in the creek, and are there inferences for transport of finer sediment?
3. Is there any significant modulation of tidal elevation and flows by the weather, for example during periods of persistent strong winds?
4. Does the time series of measured turbidity in the creek fit with first principles based on the measured creek currents? Is there any evidence for limited sediment availability at any time?
5. Do the time-series data of temperature and other water quality parameters in the creeks fit expectations given the measured flows and turbidity? Are there any exceptions and how might they be explained?
6. Can we use the above data to identify defining tidal elevations for the transition to and from overbank tidal patterns of sediment transport? Resolving this to predicted local tides is a very important stage to support assessments of future change, because of the strong tidal control on sediment transport.

Influence of episodic events

7. How do freshwater rainfall events influence the turbidity data in the creek? Can we quantify this in a meaningful way?
8. How do waves influence the turbidity data in the creek? Can we quantify this in a meaningful way?

Inferring multi-decadal sediment transport patterns

9. What are the indicated long-term tidal sediment transport rates and total quantities? What are the assumptions made here and the resulting uncertainties?
10. Can we extrapolate to assess tidally controlled net sediment transport? Where are we in the 18-year cycle of periodic tidal elevation changes?
11. Can we then extrapolate the freshwater and wave data to assess their potential influence on creek dynamics in the long-term?
12. What does the above tell us about the processes that maintain the various physical environments where BCHs currently occur?
13. What are the inferred future changes in these environments caused by natural processes? What set of timescales and physical scales have been chosen and why?
    - Scientific reasons first – to get to a position to address the key questions
    - Regulatory reasons second – to ensure the work encompasses what regulators might require. Feedback from DWER was to look at a 100-year planning horizon, consistent with state coastal planning policies.

Coastal environments and those seawards of the creeks (e.g., mangrove fringe, intertidal and subtidal zones, including corals)

14. What is the control of waves on measured turbidity and how is it modulated by tidal elevation and tidal currents?
15. What can we infer are the key controls on transport of sand and of finer sediments in these environments?

Addition of Salt Ponds influencing BCH environments

16. From first principles, what does the above indicate are likely to be the main multi-decadal changes to BCH environments in:
    - those areas currently dominated by tidal controls?
    - those areas subjected to a mix of drivers?
    - those areas controlled by waves?

Modelling of physical processes

17. How can we most efficiently test these processes using hydrodynamic computer models?
18. Do all BCH’s have the same ‘value’. What’s the logic, if any? How does this help us target our work?

28. Tidal flow characteristics in different sedimentary environments

Understanding the physical transport of water and sediment between different parts of the sedimentary system is relevant because they help maintain various sedimentary environments that house benthic communities. Based on tidal processes alone, sediments (if available) are likely to be i) preferentially transported into the fringing and estuarine mangrove environments by the generally faster flood currents in those areas ii) and preferentially exported from the system down the incised creeks by the relatively powerful ebb tides. This leads to a hypothetical circulation of sediment in the coastal system. The variety of sediment sizes, tidal water levels and tidal currents would tend to result in:

- An overall movement of (limited) fine sediment into the coastal system, driven by currents, and consistent with its absence from the subtidal zones, and its presence in places in the mangroves and on the high tidal flats; and
- Export of sand from the coastal plain down into the low intertidal zone and shallow subtidal zone, because of the relatively strong ebb flows scouring the creeks.

To help illustrate this, data were extracted from the tidal inundation model outputs to produce a set of time series of current speed and direction for a series of locations (Figure 221, Figure 222).

Figure 221. Estuary locations where data was extracted from the tidal inundation model.

Figure 222. Locations at the eastern pond of the project area where data was extracted from the tidal inundation model.

Table 39. Flow ratio and Maximum velocity ratios for sites away from the shoreline (locations shown in Figure 221). Higher number is a relatively greater ebb.

Sites	Flow Ratio (Ebb/Flood)	Maximum Velocity Ratio (Ebb/Flood)
A	1.02	0.84
B	1.1	0.98
C	1.12	0.92
D	1.07	0.9
E	1.03	0.88
F	0.93	0.76
G	1.12	0.93
H	0.96	0.82
I	0.96	0.87

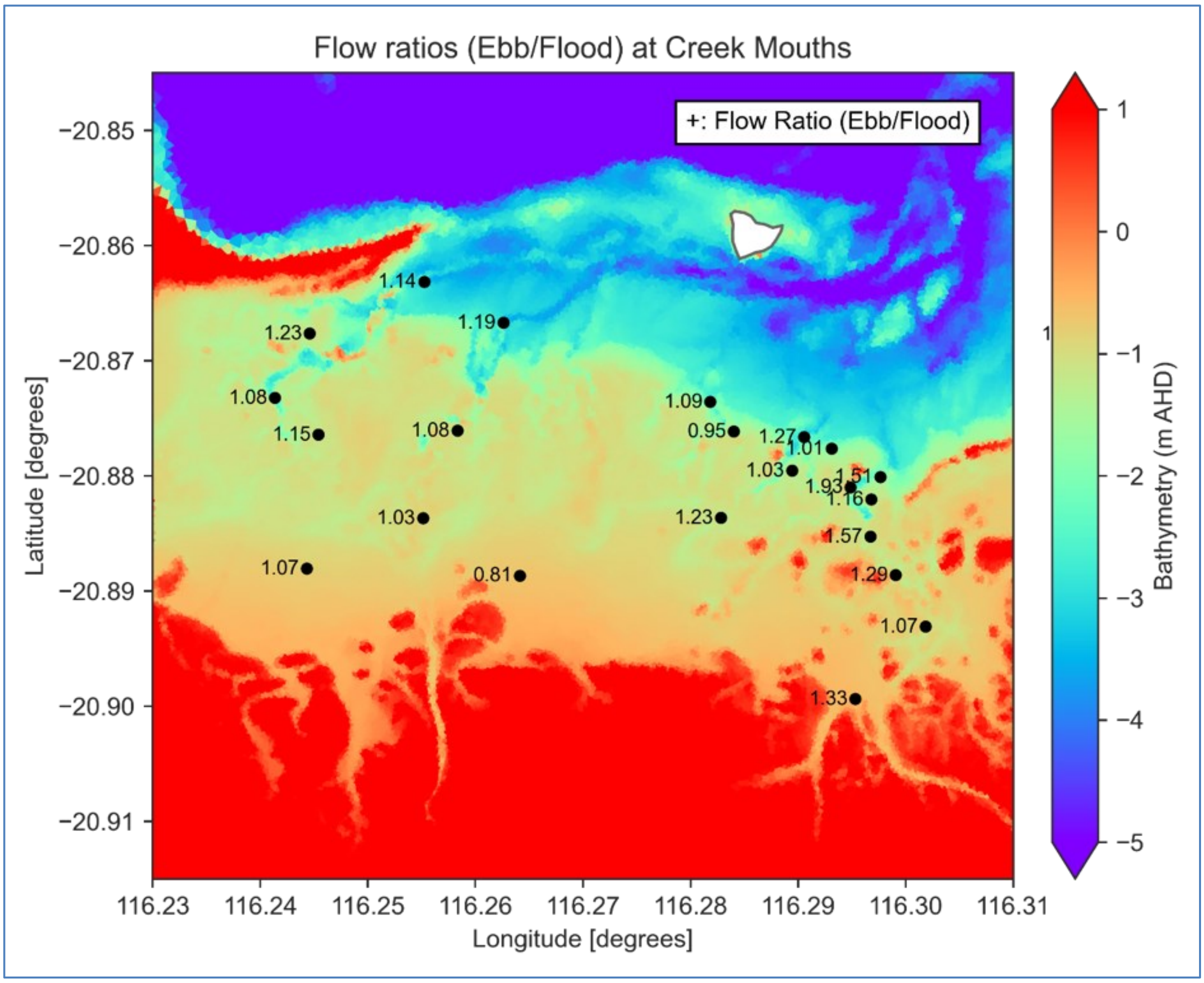


Figure 223. Flow ratios (Table 40) for the estuary shoreline and creek systems.

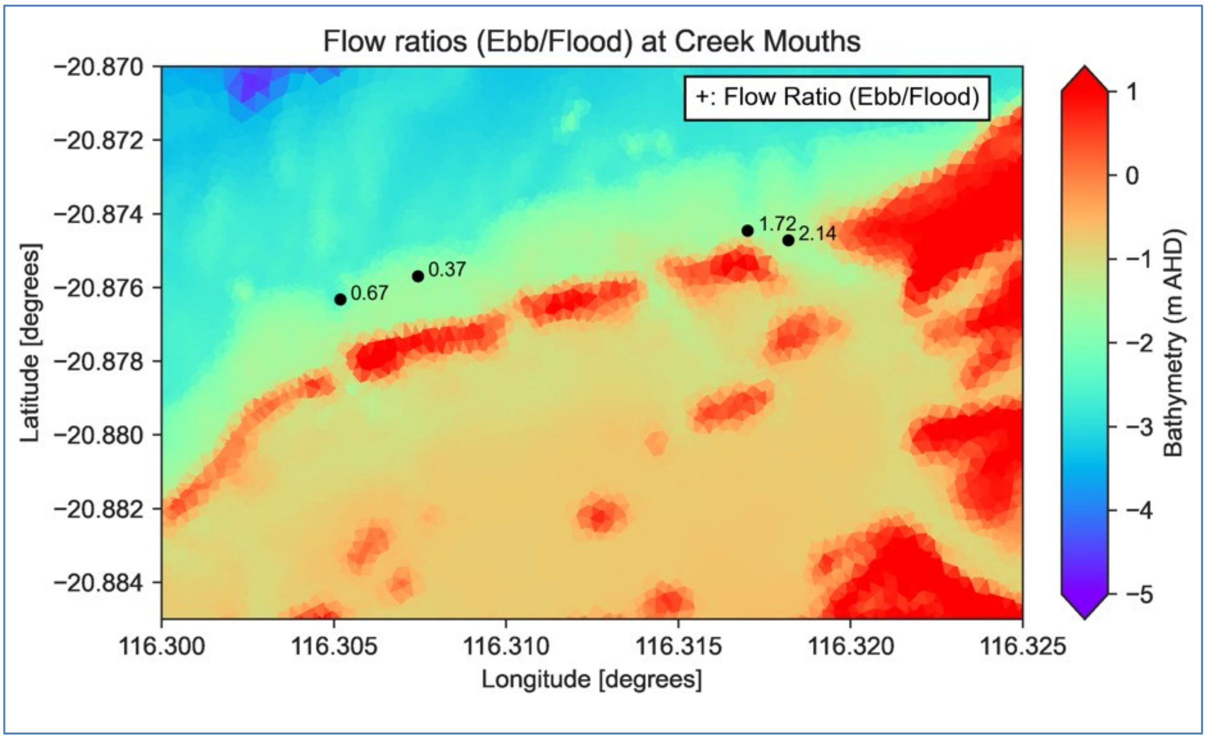


Figure 224. Flow ratios (Table 40) for the shoreline of nascent mangroves, east of McKay Creek.

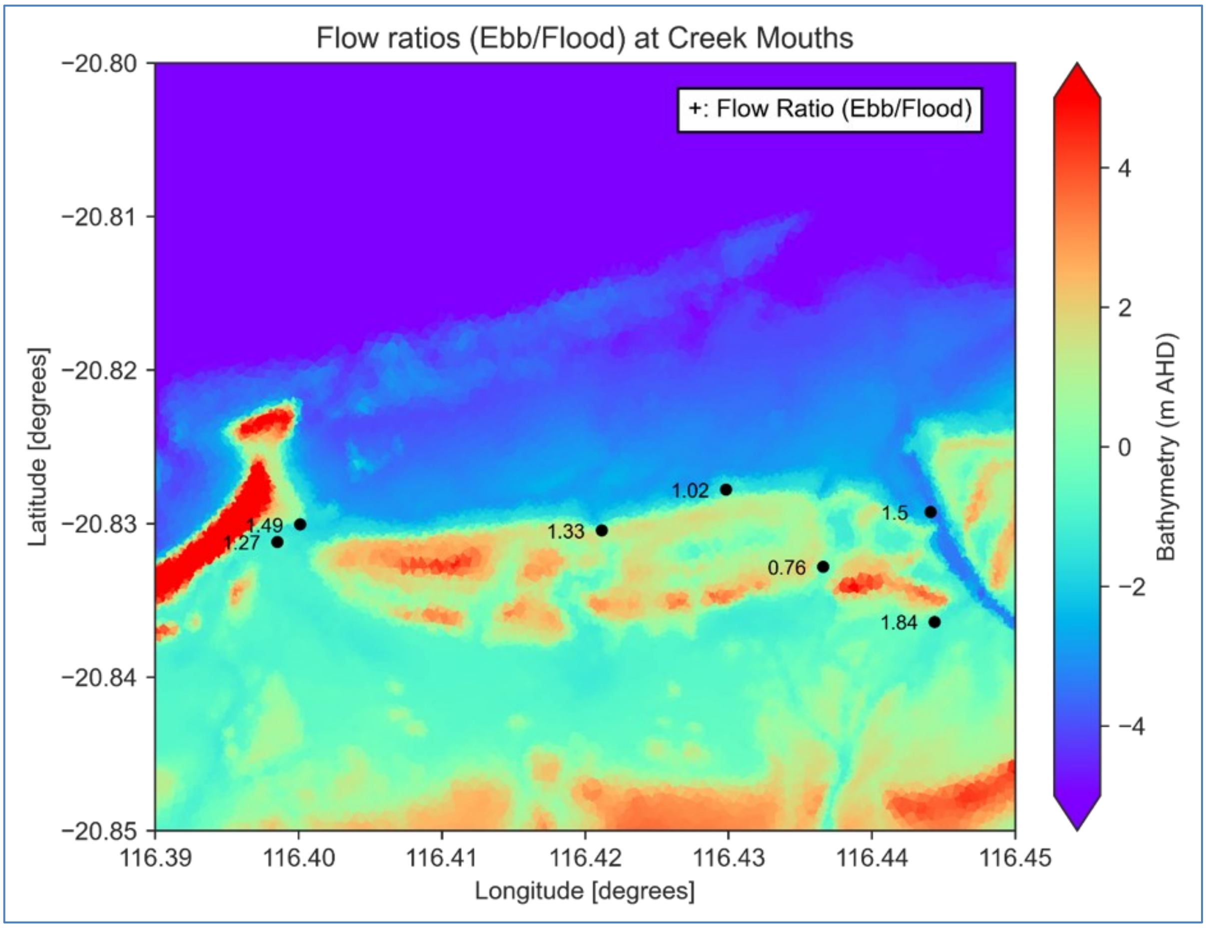


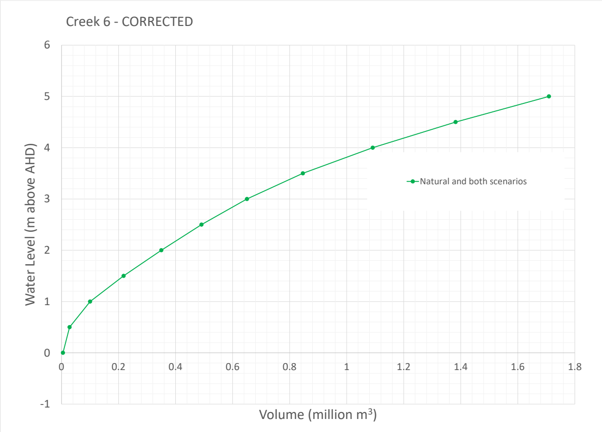
Figure 225. Flow ratios (Table 40) for the shoreline and creek systems at the eastern end of the project area.

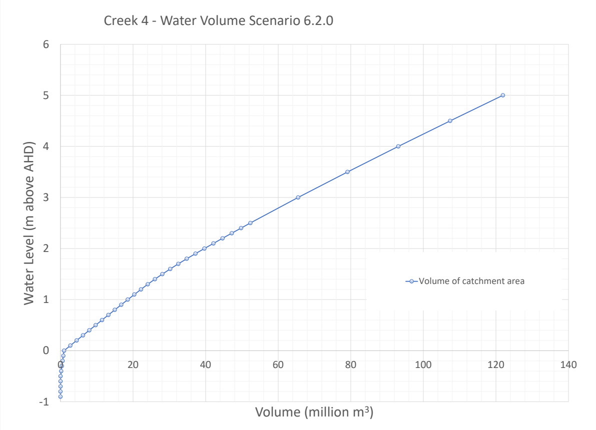
Table 40. Flow ratio and Maximum velocity ratios for coastal sites (locations shown in Figure 221 & Figure 222). Yellow highlight = creek mouth. Green highlight = estuarine mangrove. Higher number is a relatively greater ebb.

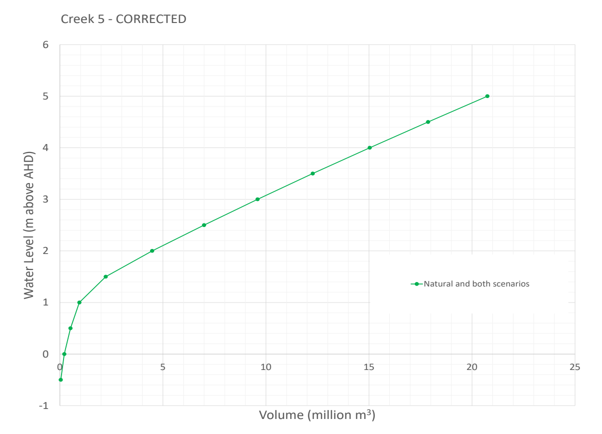
Sites	Flow Ratio (Ebb/Flood)	Maximum Velocity Ratio (Ebb/Flood)
Creek 3 mouth	1.14	0.81
Creek 3 mid est mangrove	1.23	0.68
Creek 3 mid	1.07	0.51
Creek 3 head est mangrove edge	1.13	0.54
Creek 2 mouth	1.19	0.91
Creek 2 mid est mangrove	1.08	0.68
Creek 1 mouth	1.09	0.97
B&S Ck mouth	1.27	1.13
B&S Ck head	1.23	0.84
SIC-02 or v near	1.93	1.17
M Ck mouth	1.51	1.59
M Ck mid est mangroves	1.57	1.07
M Ck upper est mangroves	1.29	0.57
M Ck HI flats	1.05	0.7
M Ck nr head	1.07	0.61
W nascent mangrove creek	0.67	0.83
E nascent mangrove creek	1.72	1.36
E nascent Fr mangroves	2.14	1.4
Barndar Ck	1.49	1.23
Barndar Ck Fr mangrove	1.27	0.68
Devil Ck mouth (Creek 8 of Section 7.5)	0.7	0.67
Cooglegong Ck mouth	1.5	1.92
Cooglegong est mangroves	1.84	1.44

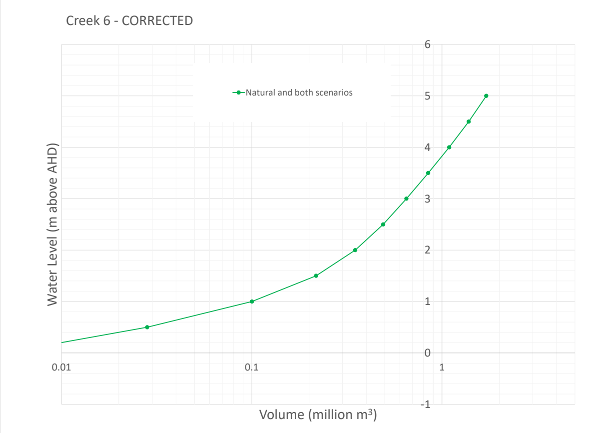
29. Hypsometric plots for catchments

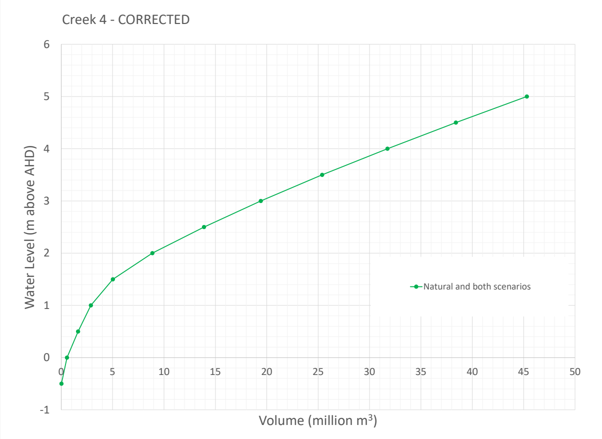
29.1. Plots ordered geographically - mostly from W to E

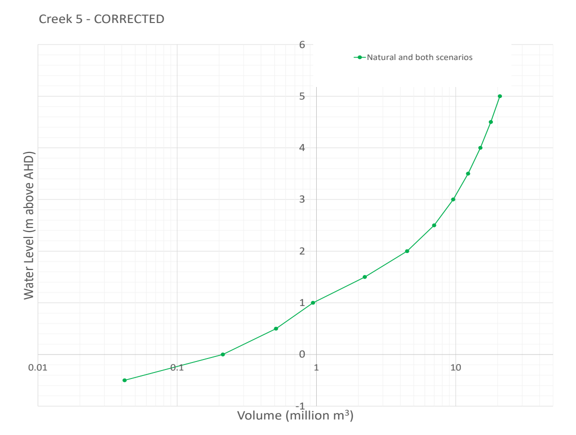

Creek 6 - CORRECTED

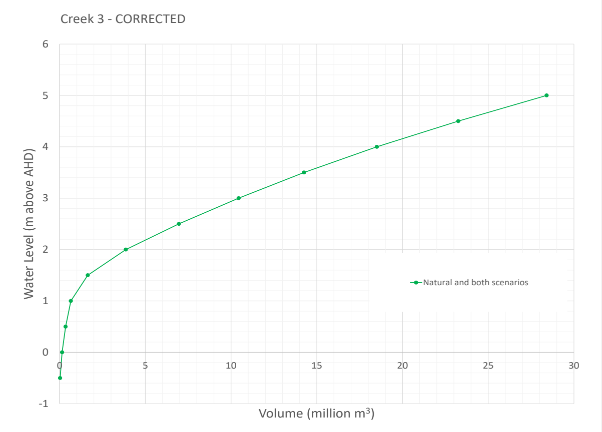

Creek 4 - Water Volume Scenario 6.2.0

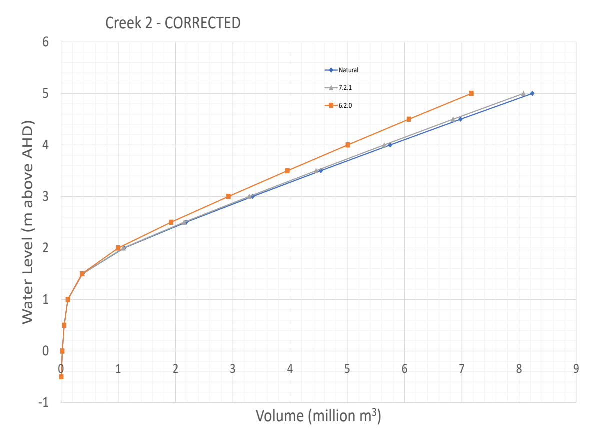

Creek 5 - CORRECTED

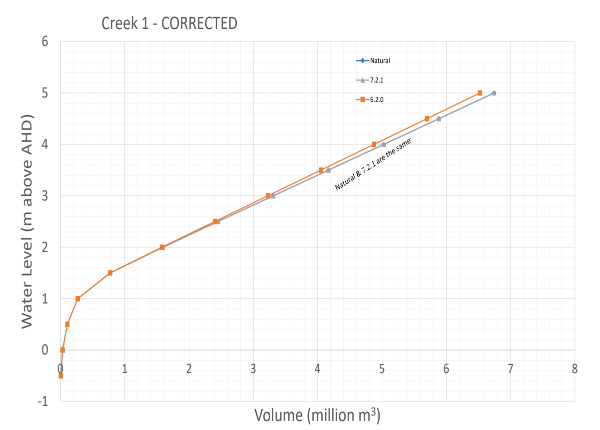

Creek 6 - CORRECTED

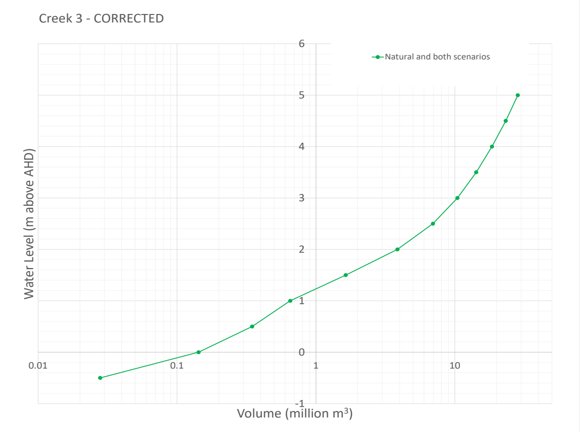

Creek 4 - CORRECTED

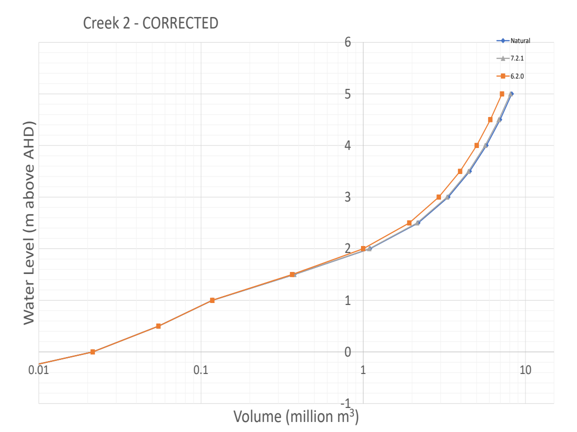

Creek 5 - CORRECTED

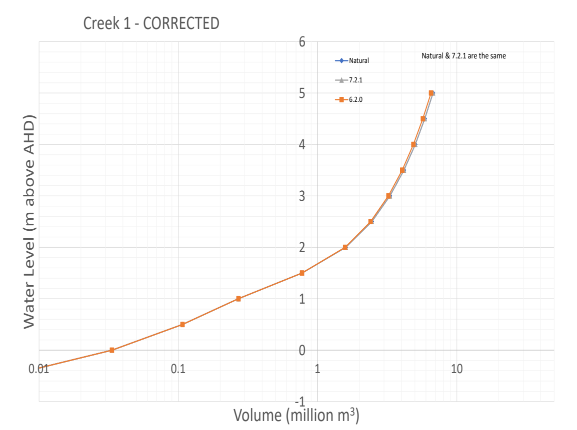

Creek 3 - CORRECTED
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
5
10
15
20
25
30
Volume (million m^3)
Natural and both scenarios

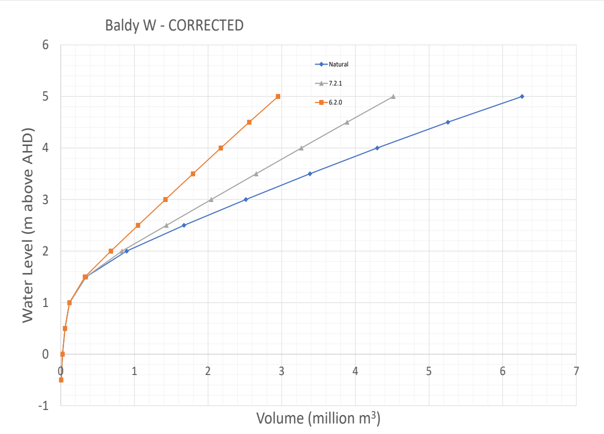

Creek 2 - CORRECTED
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7
8
9
Volume (million m^3)
Natural
7.2.1
6.2.0

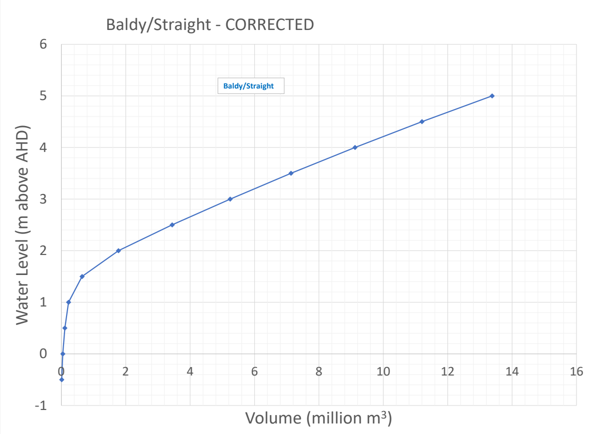

Creek 1 - CORRECTED
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7
8
Volume (million m^3)
Natural
7.2.1
6.2.0
Natural & 7.2.1 are the same

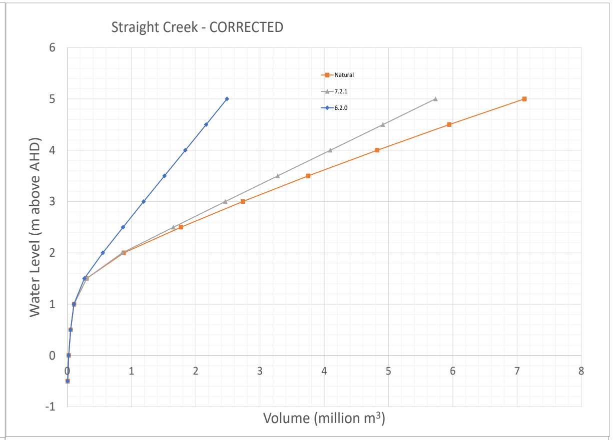

Creek 3 - CORRECTED
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
Volume (million m^3)
Natural and both scenarios

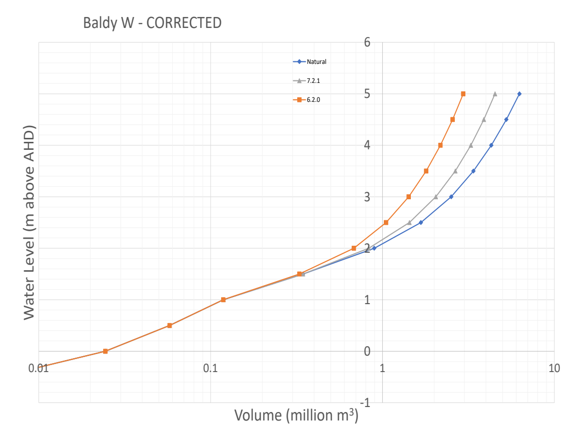

Creek 2 - CORRECTED
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
Volume (million m^3)
Natural
7.2.1
6.2.0

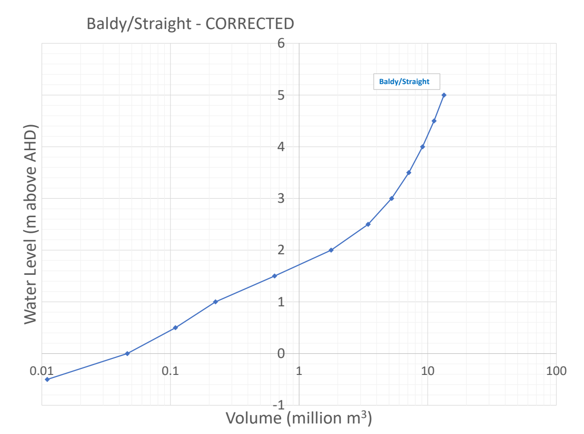

Creek 1 - CORRECTED
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
Volume (million m^3)
Natural
7.2.1
6.2.0
Natural & 7.2.1 are the same

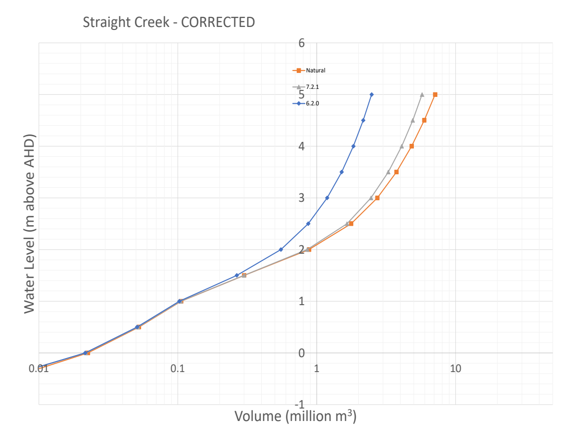

Baldy W - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
Volume (million m³)
6
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7

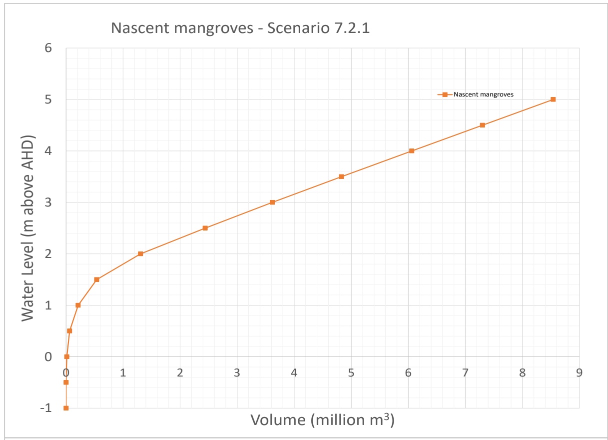

Baldy/Straight - CORRECTED
Baldy/Straight
Water Level (m above AHD)
Volume (million m³)
6
5
4
3
2
1
0
-1
0
2
4
6
8
10
12
14
16

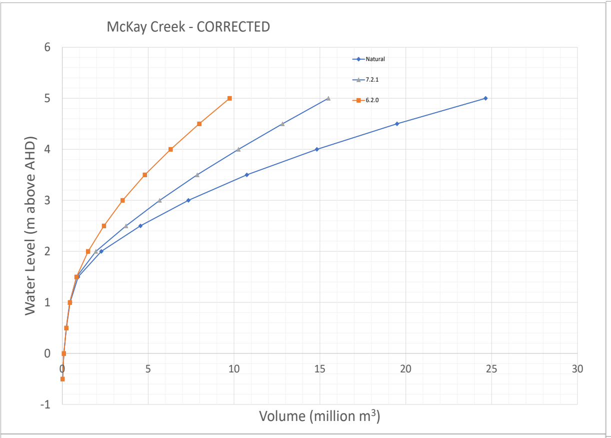

Straight Creek - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
Volume (million m³)
6
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7
8

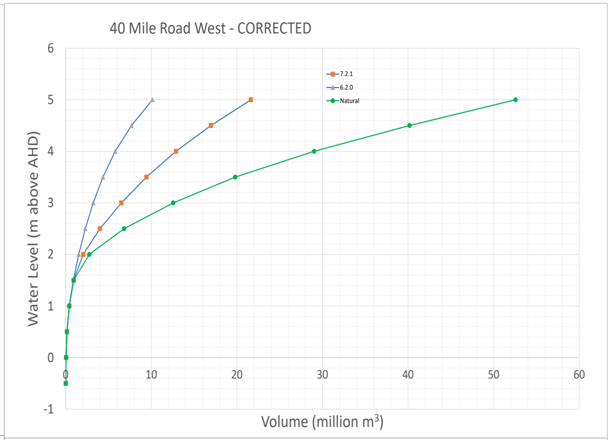

Baldy W - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
Volume (million m³)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10

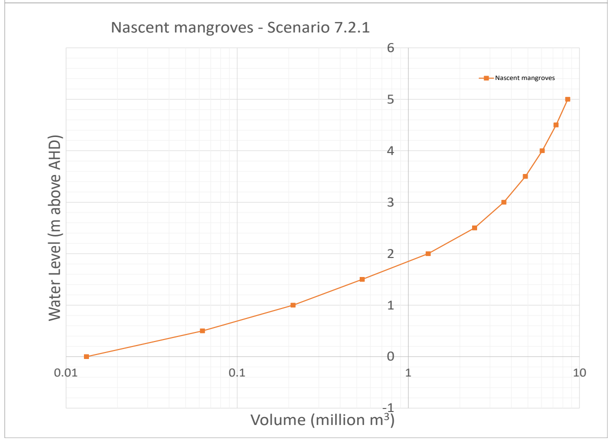

Baldy/Straight - CORRECTED
Baldy/Straight
Water Level (m above AHD)
Volume (million m³)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
100

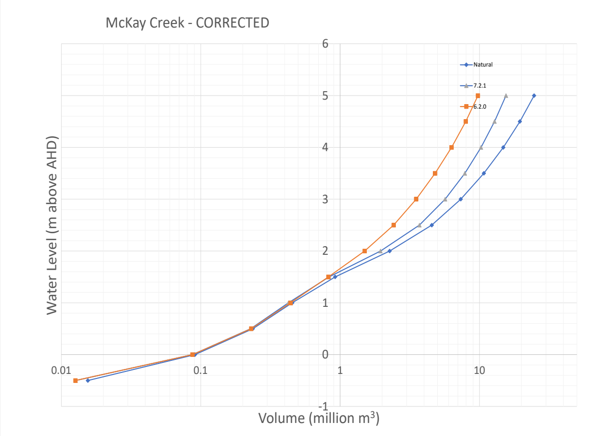

Straight Creek - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
Volume (million m³)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10

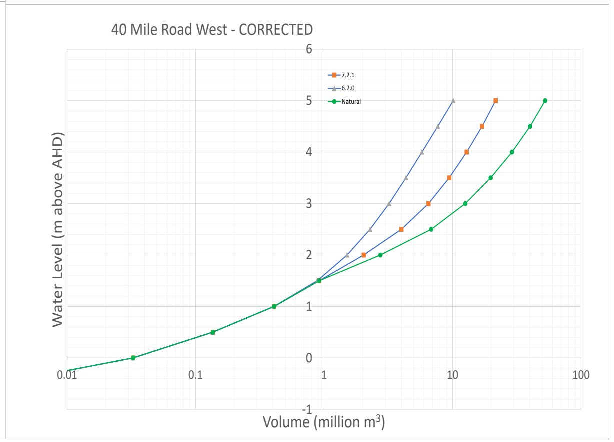

Nascent mangroves - Scenario 7.2.1
Nascent mangroves
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7
8
9
Volume (million m³)

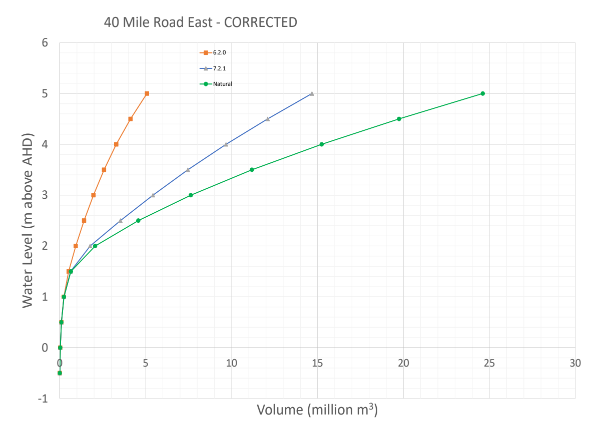

McKay Creek - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
5
10
15
20
25
30
Volume (million m³)

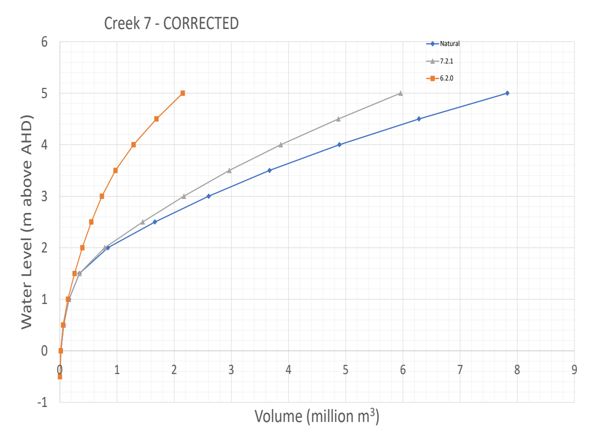

40 Mile Road West - CORRECTED
7.2.1
6.2.0
Natural
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
10
20
30
40
50
60
Volume (million m³)

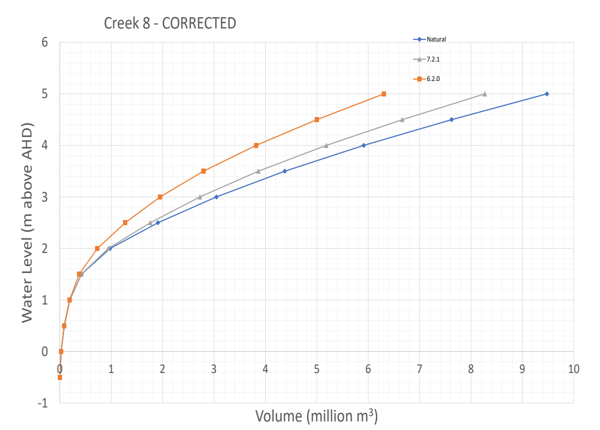

Nascent mangroves - Scenario 7.2.1
Nascent mangroves
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
Volume (million m³)

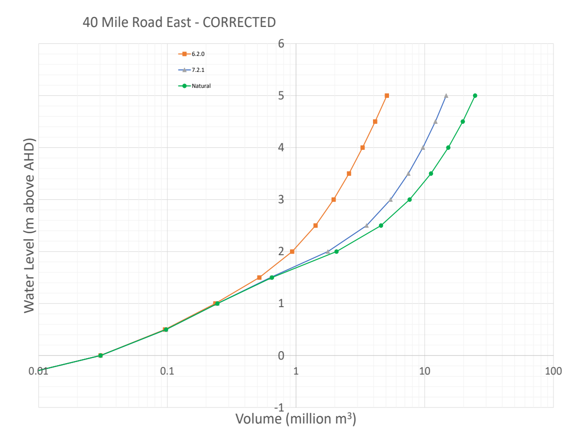

McKay Creek - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
Volume (million m³)

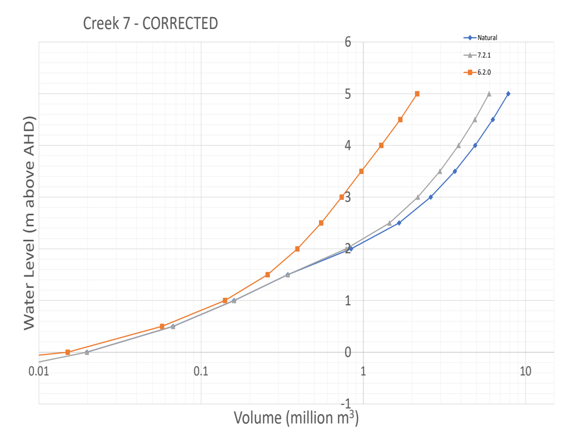

40 Mile Road West - CORRECTED
7.2.1
6.2.0
Natural
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
100
Volume (million m³)

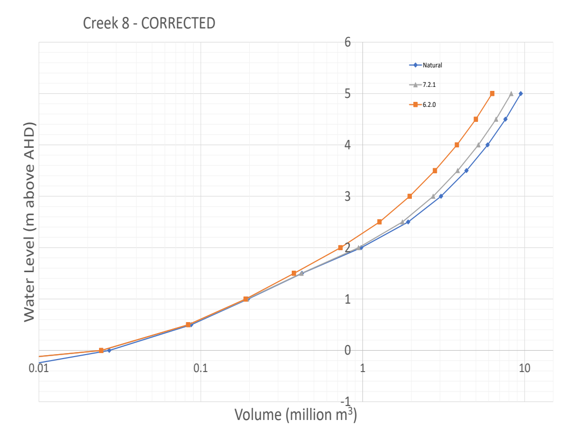

40 Mile Road East - CORRECTED
6.2.0
7.2.1
Natural
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
5
10
15
20
25
30
Volume (million m^3)

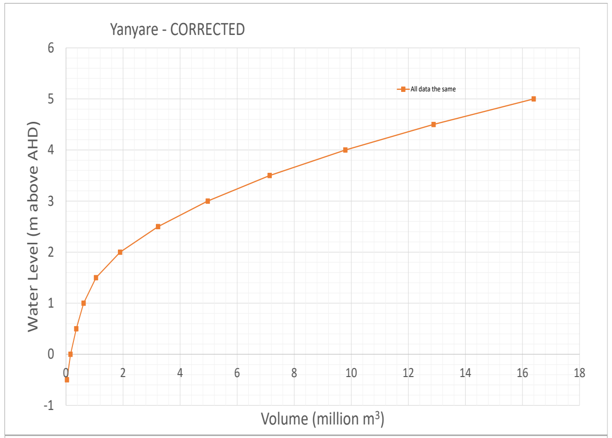

Creek 7 - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7
8
9
Volume (million m^3)

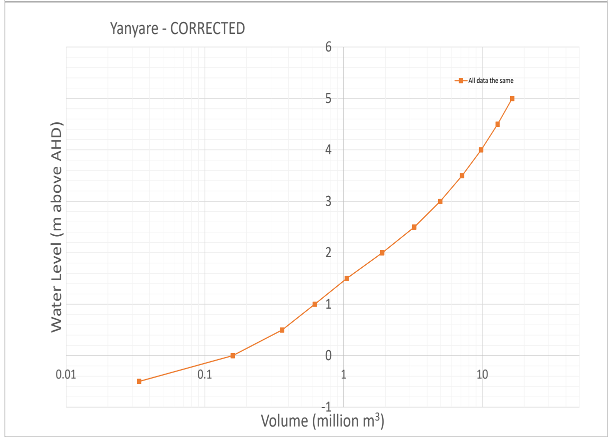

Creek 8 - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7
8
9
10
Volume (million m^3)


40 Mile Road East - CORRECTED
6.2.0
7.2.1
Natural
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
100
Volume (million m^3)

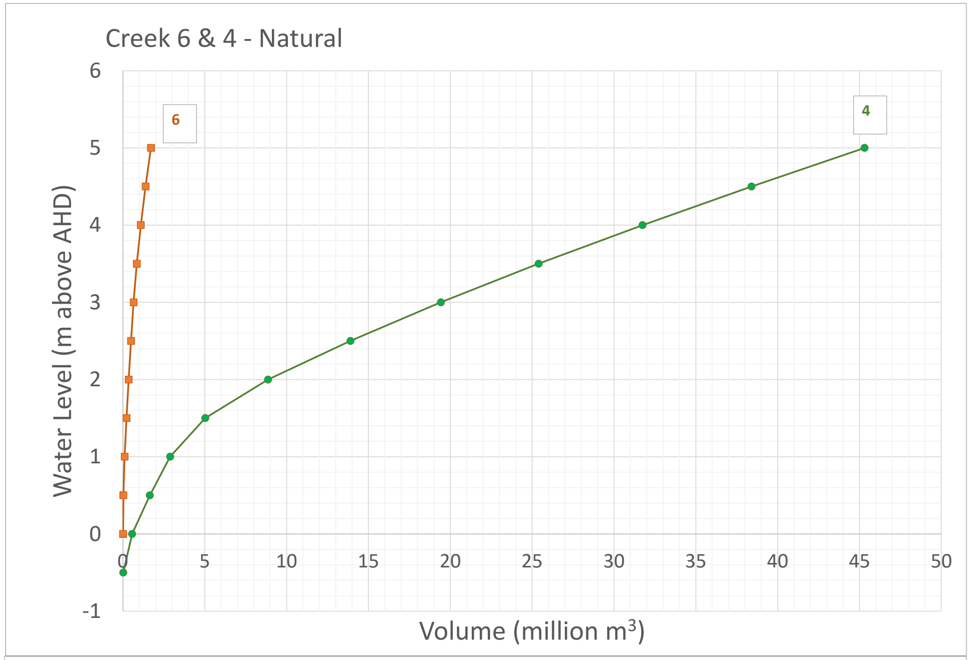

Creek 7 - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
Volume (million m^3)

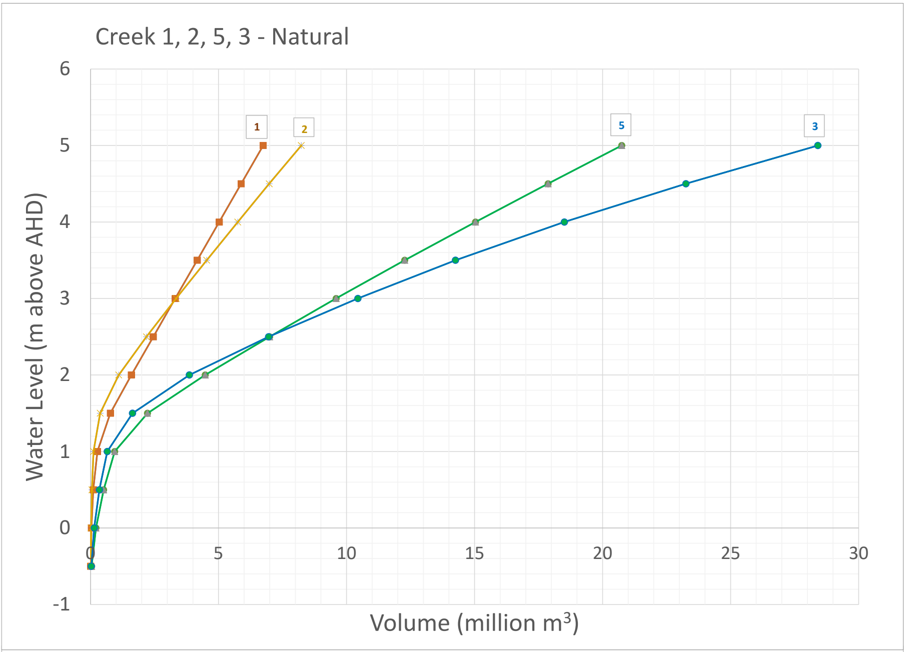

Creek 8 - CORRECTED
Natural
7.2.1
6.2.0
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
Volume (million m^3)

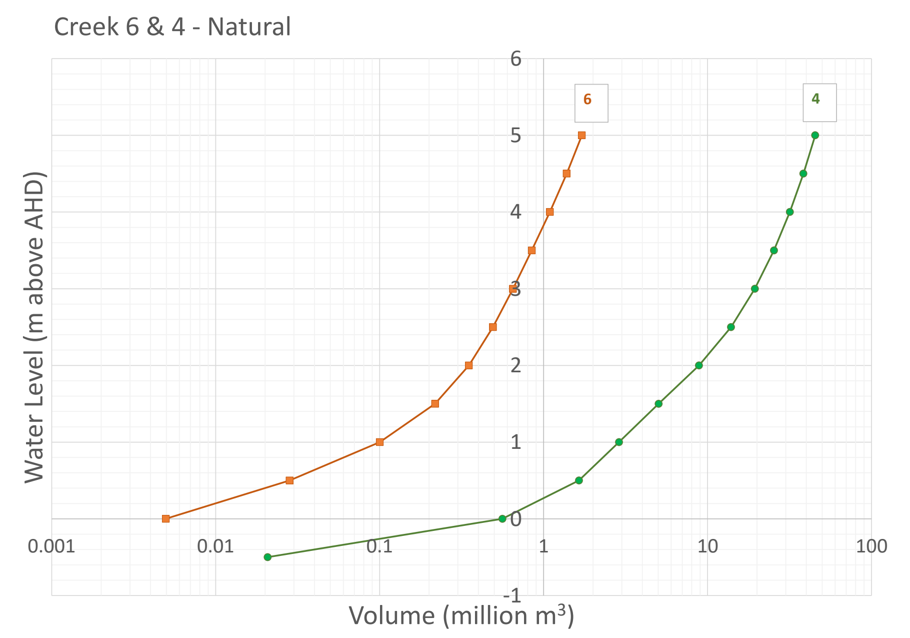

Yanyare - CORRECTED
All data the same
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
2
4
6
8
10
12
14
16
18
Volume (million m^3)

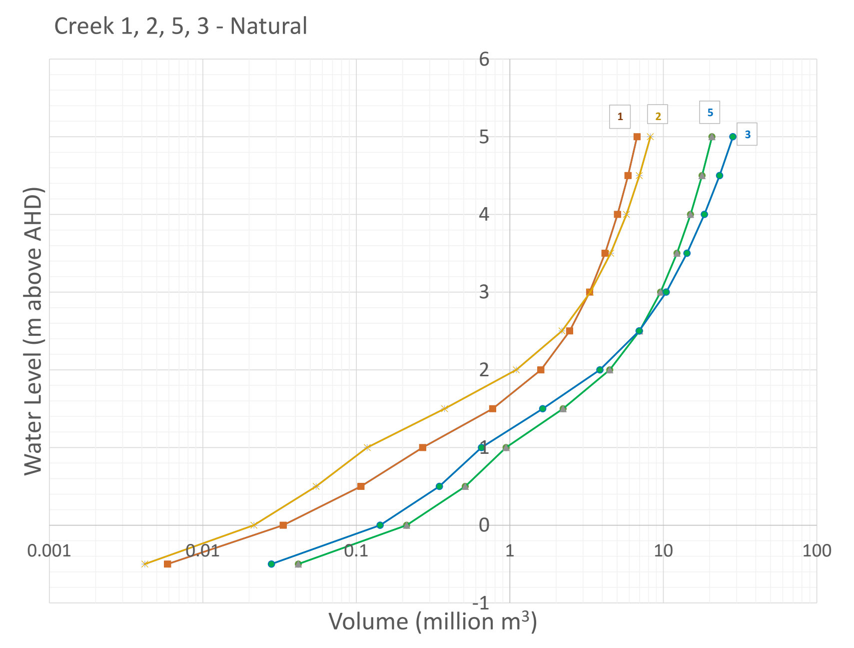

Yanyare - CORRECTED
All data the same
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
Volume (million m^3)

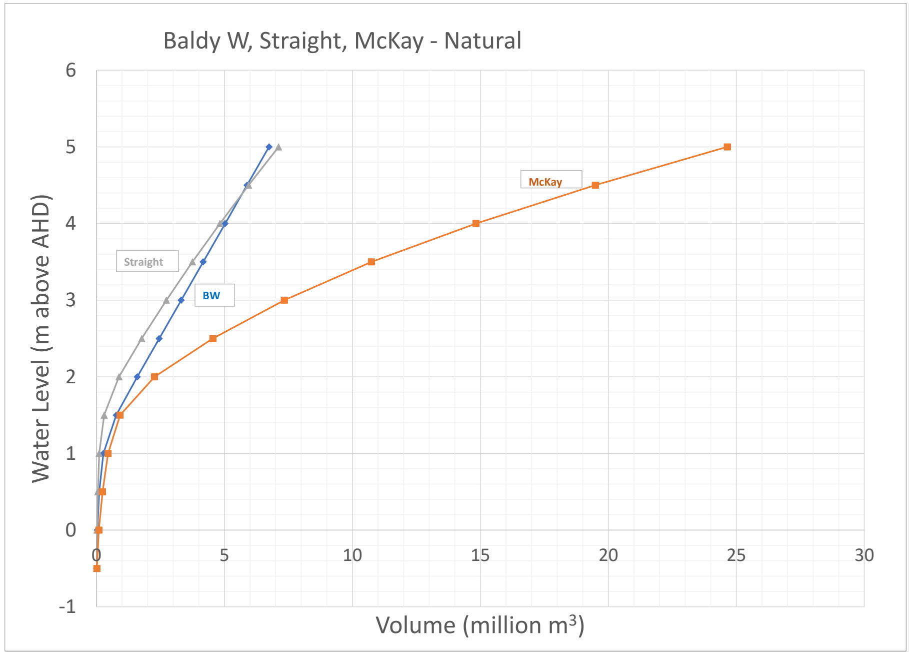
29.2. Selected curves overlain for direct comparison

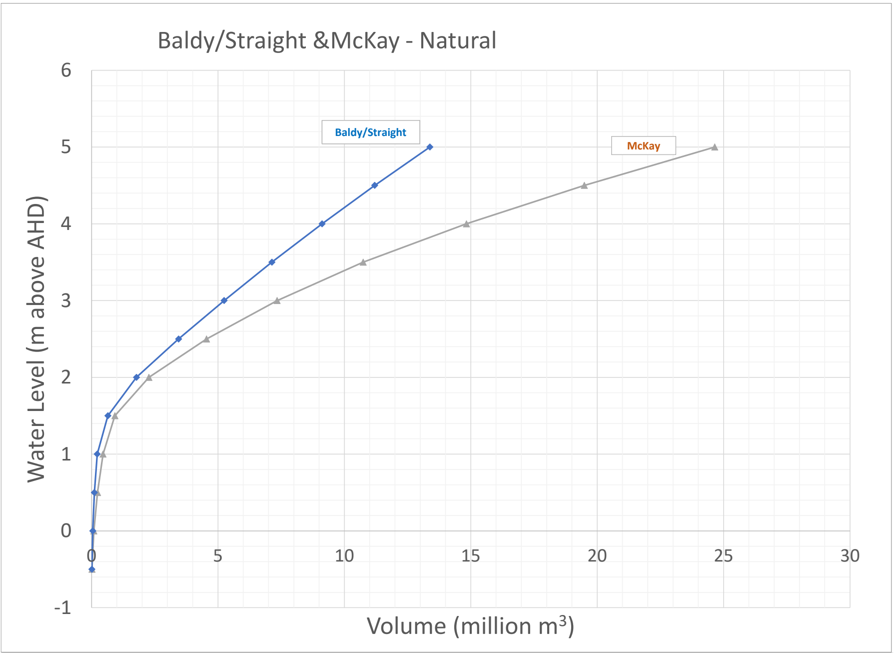

Creek 6 & 4 - Natural
Water Level (m above AHD)
Volume (million m^3)
6
5
4
3
2
1
0
-1
0
5
10
15
20
25
30
35
40
45
50
6
4

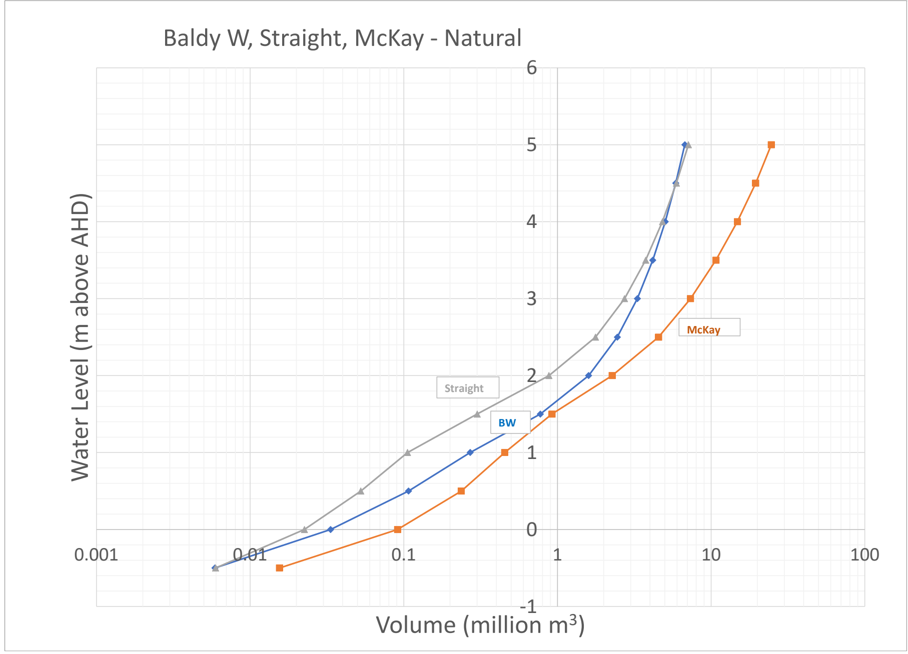

Creek 1, 2, 5, 3 - Natural
Water Level (m above AHD)
Volume (million m^3)
6
5
4
3
2
1
0
-1
0
5
10
15
20
25
30
1
2
5
3

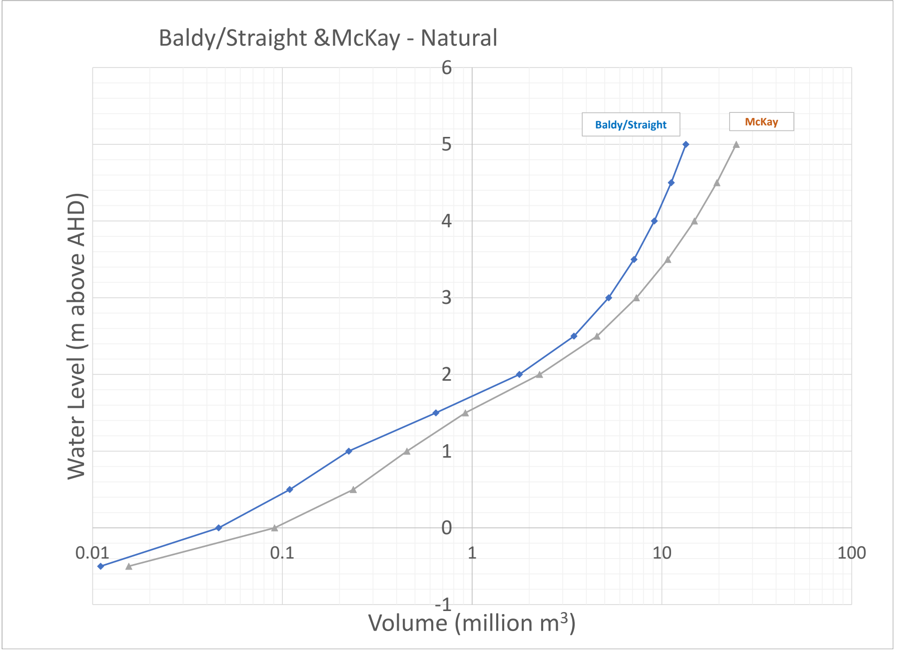

Creek 6 & 4 - Natural
Water Level (m above AHD)
Volume (million m^3)
6
5
4
3
2
1
0
-1
0.001
0.01
0.1
1
10
100
6
4

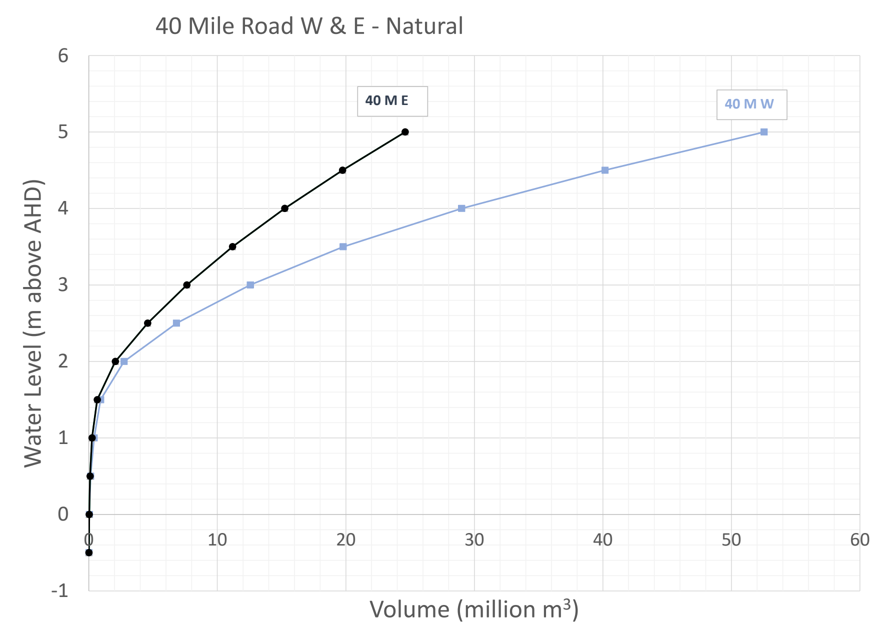

Creek 1, 2, 5, 3 - Natural
Water Level (m above AHD)
Volume (million m^3)
6
5
4
3
2
1
0
-1
0.001
0.01
0.1
1
10
100
1
2
5
3

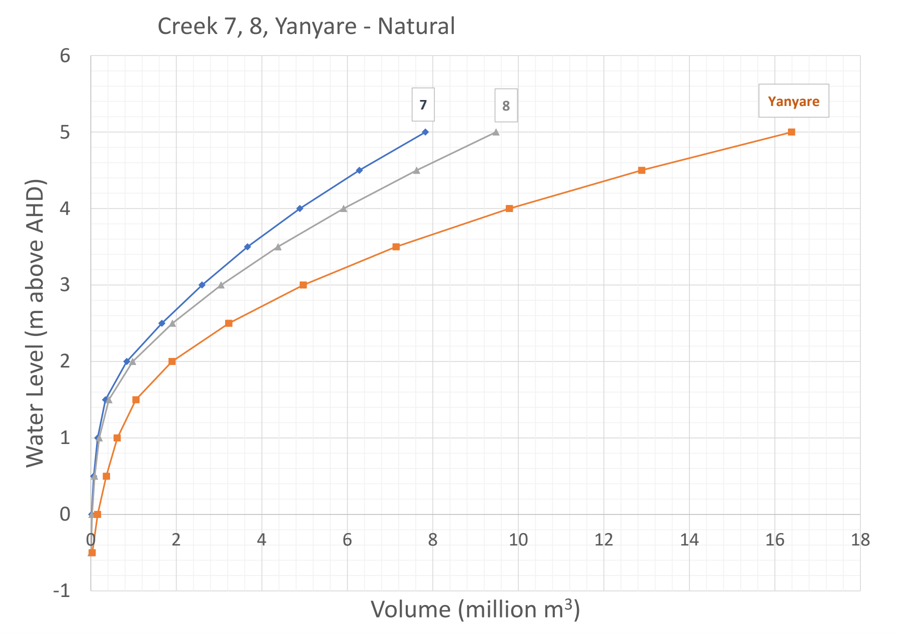

Baldy W, Straight, McKay - Natural
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
5
10
15
20
25
30
Volume (million m^3)
Straight
BW
McKay

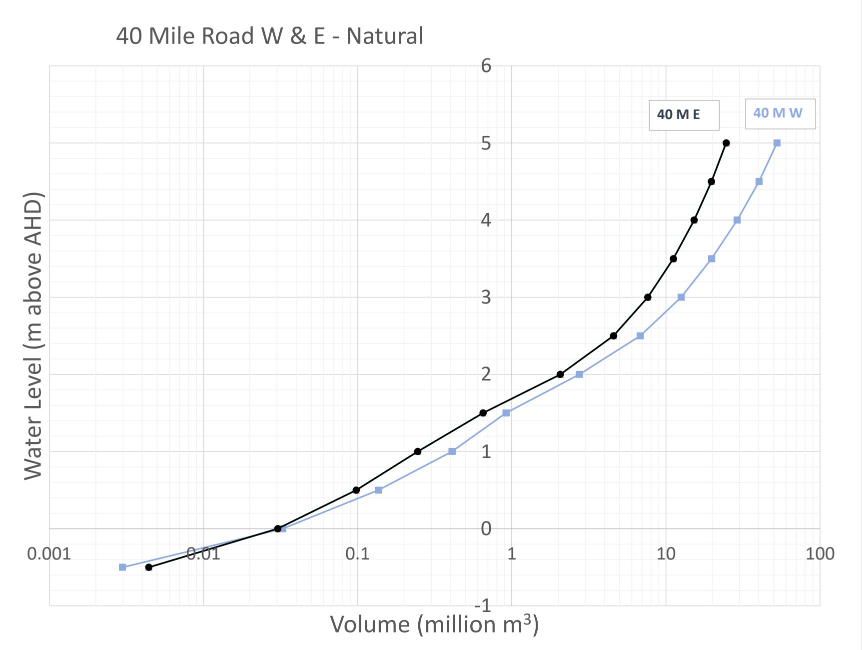

Baldy/Straight &McKay - Natural
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0
5
10
15
20
25
30
Volume (million m^3)
Baldy/Straight
McKay

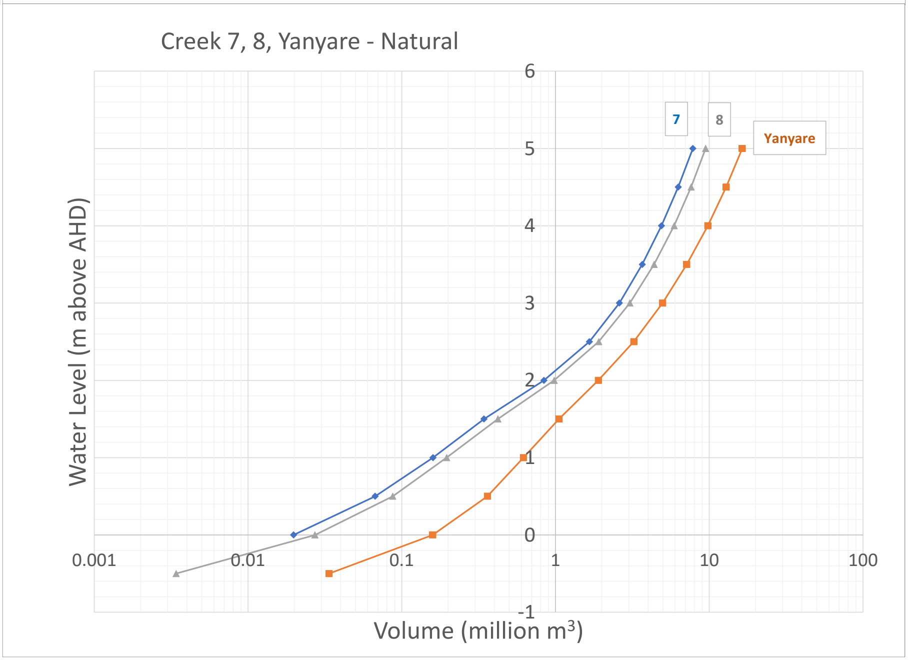

Baldy W, Straight, McKay - Natural
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.001
0.01
0.1
1
10
100
Volume (million m^3)
Straight
BW
McKay


Baldy/Straight &McKay - Natural
Water Level (m above AHD)
6
5
4
3
2
1
0
-1
0.01
0.1
1
10
100
Volume (million m^3)
Baldy/Straight
McKay


40 Mile Road W & E - Natural


Creek 7, 8, Yanyare - Natural


40 Mile Road W & E - Natural


Creek 7, 8, Yanyare - Natural

30. Numerical Modelling Simulations

30.1. Results – Simulations 1 and 2 – Impacts of ponds upon the tides

30.1.1. Changes seawards of the coast.

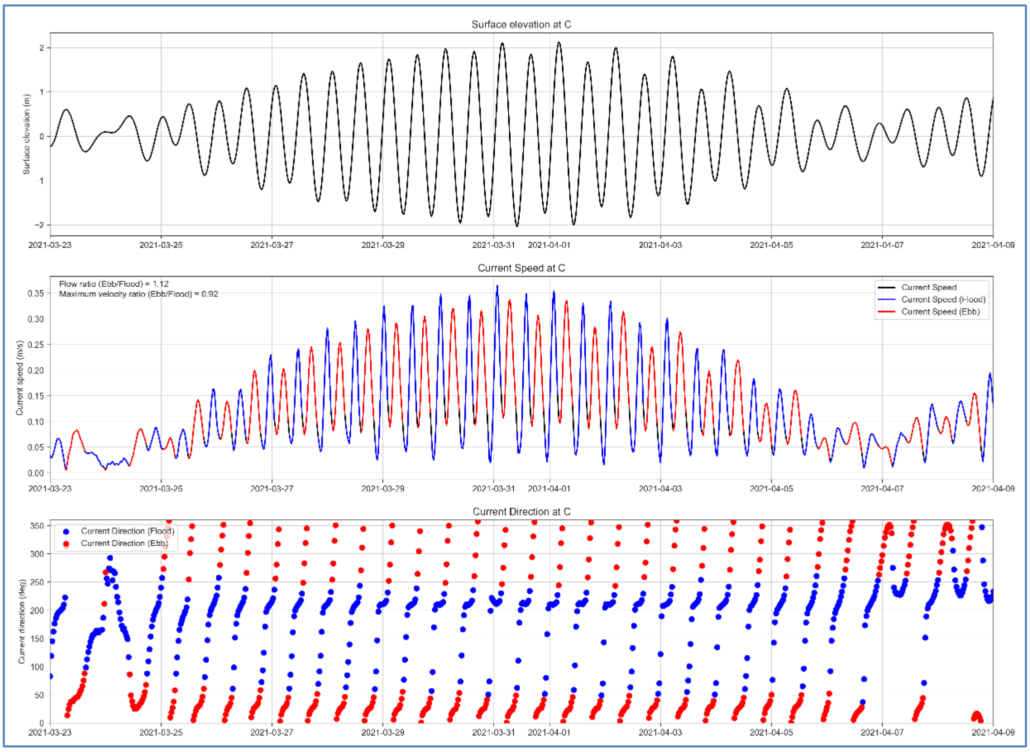


Figure 226. Modelled currents of existing tidal flows at location C, 850 m NW of the mouth of Baldy/Straight Creek and 500 m NE of Creek 1, for the period of large spring tides of March-April 2021. Flood tide in blue, ebb tide in red.

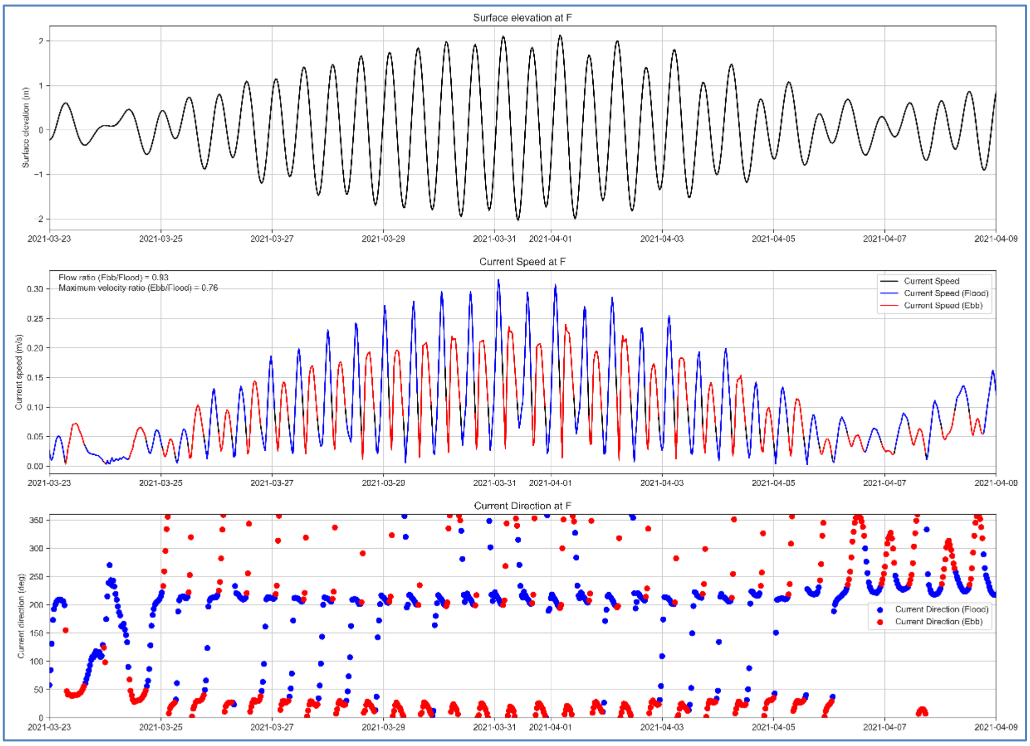


Figure 227. Modelled currents of existing tidal flows at location F, 350 m seawards of the nascent fringing mangroves, for the period of large spring tides of March-April 2021. Flood tide in blue, ebb tide in red

30.1.2. Changes at creek mouths – WESTERN CREEKS

c

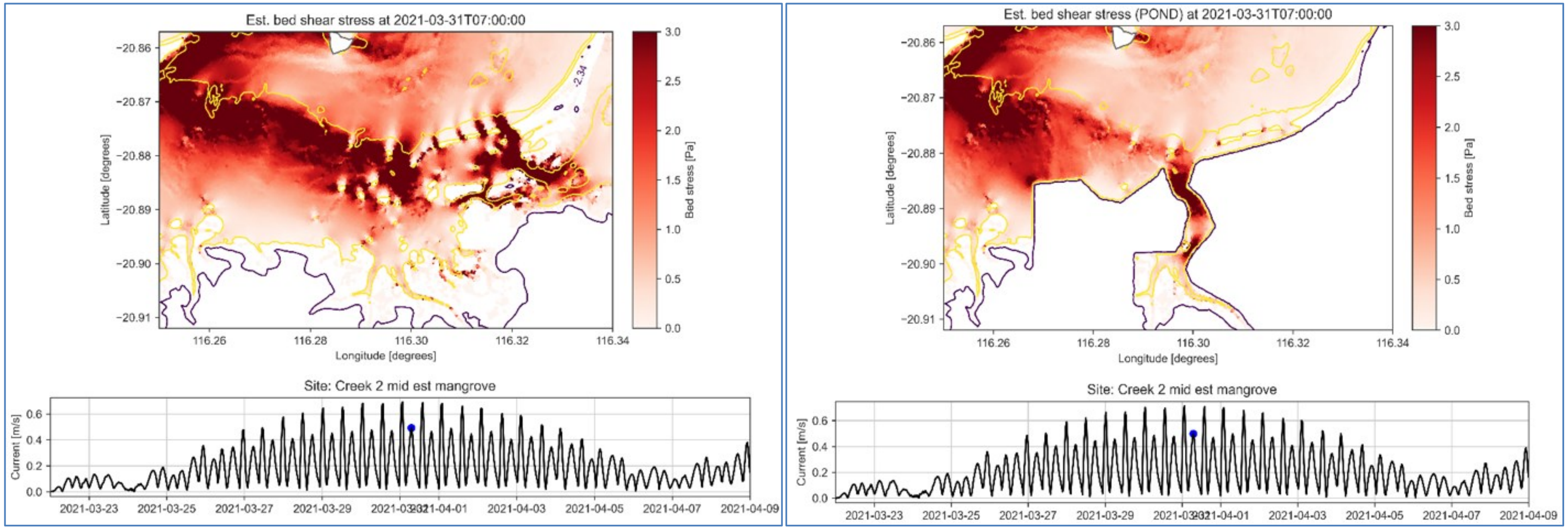


Figure 228. Distribution of calculated bed shear stress (map) across the estuary and inundated southern shoreline environments during peak ebb tide (time-series) at Creek 2 within the mid-estuarine mangroves (location on Figure 221). LEFT = present conditions. RIGHT = With ponds. NB - SCENARIO 6.2.0. Elevation contours are at LAT, MSL and 3.5 m AHD.

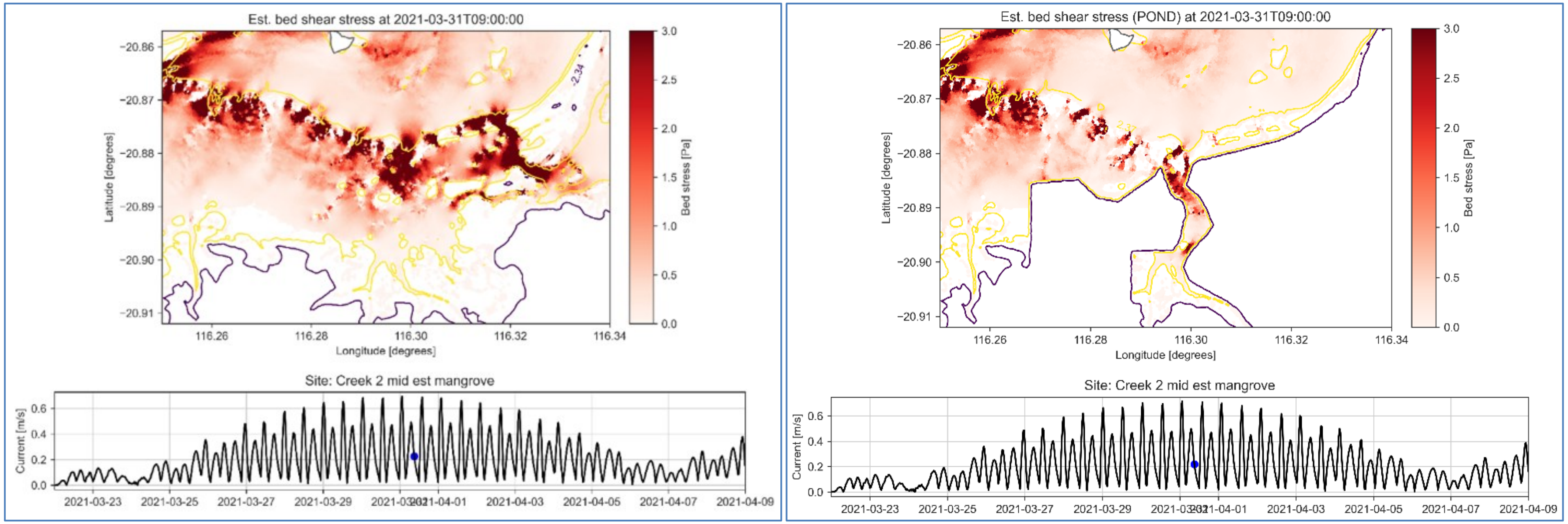


Figure 229. Waning ebb tide, 2 hours later than previous figure. NB - SCENARIO 6.2.0.

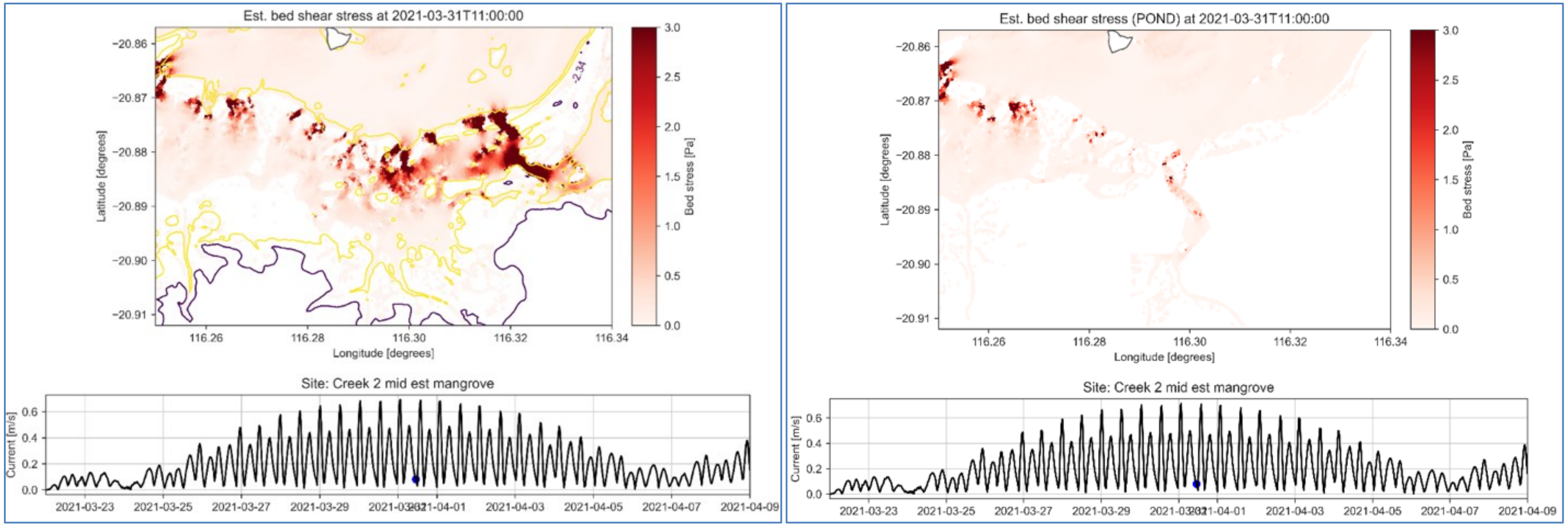


Figure 230. Near low tide, 2 hours later than previous figure. NB - SCENARIO 6.2.0.

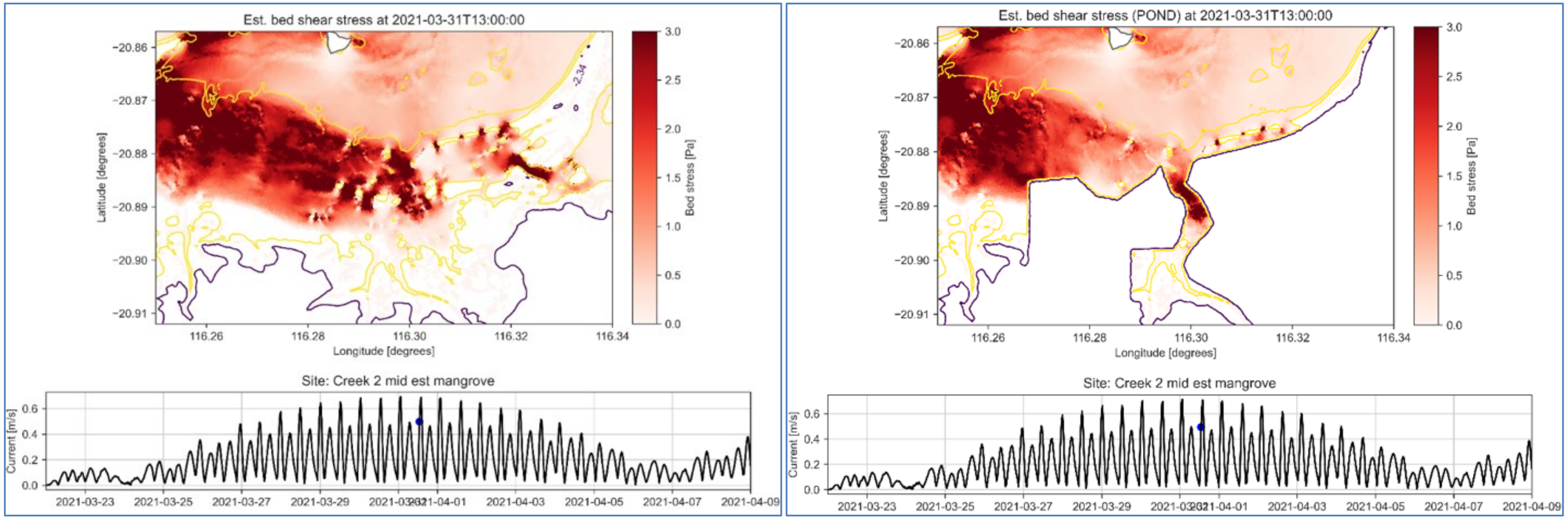


Figure 231. Early flood tide, 2 hours later than previous figure. NB - SCENARIO 6.2.0.

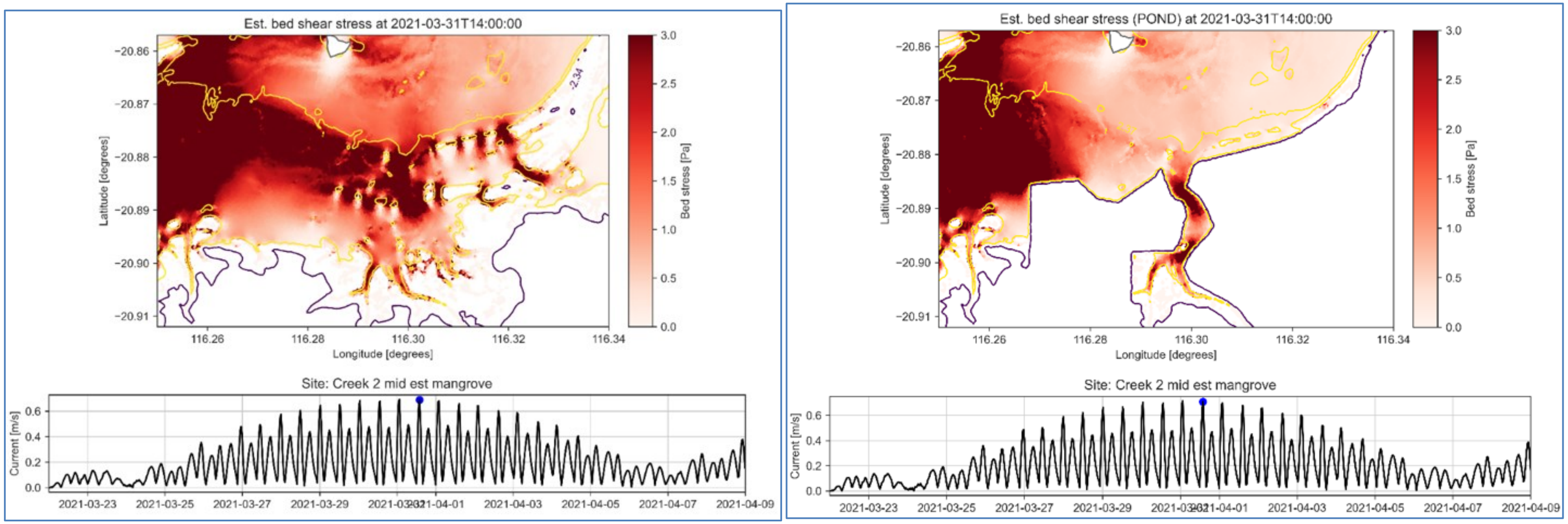


Figure 232. Peak flood tide, 1 hour later than previous figure. NB - SCENARIO 6.2.0.

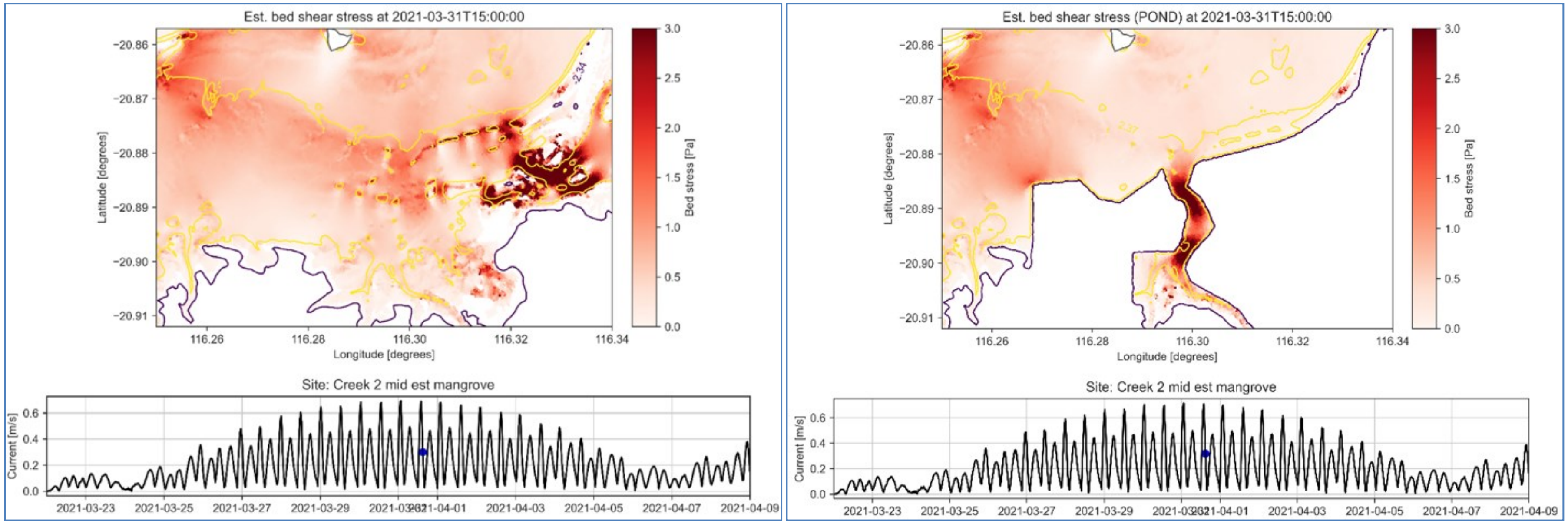


Figure 233. Waning flood tide, 1 hour later than previous figure. NB - SCENARIO 6.2.0.

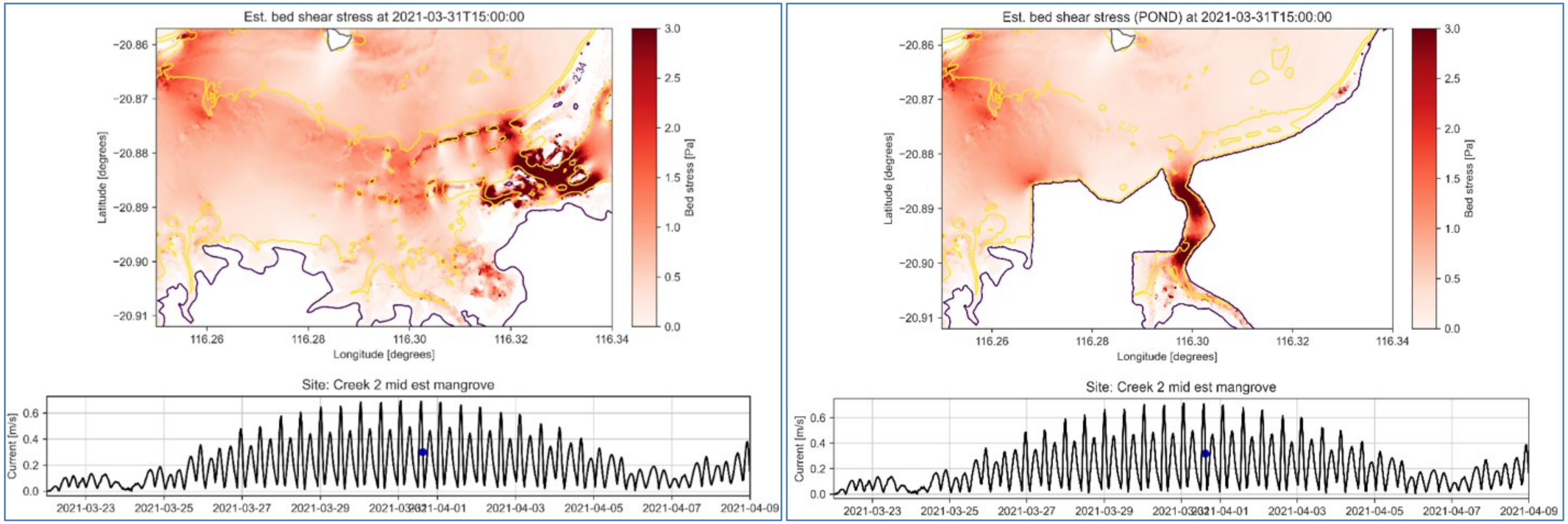


Figure 234. Waning flood tide, 1 hour later than previous figure. NB - SCENARIO 6.2.0.

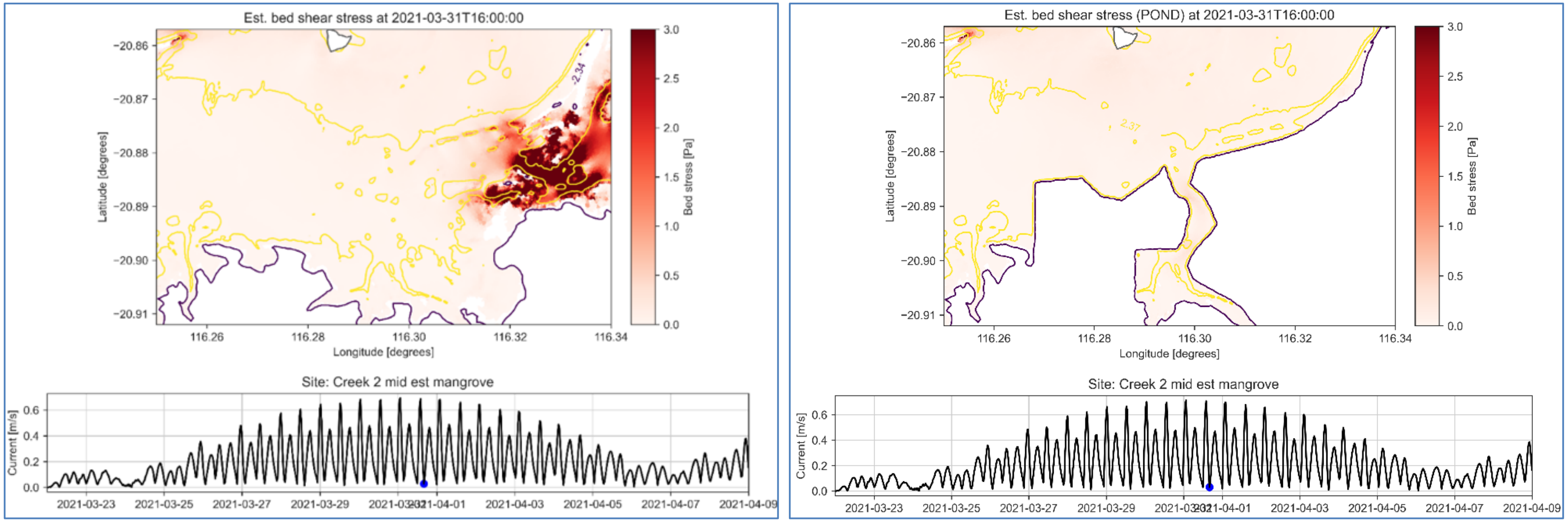


Figure 235. At high tide, 1 hour later than previous figure. NB - SCENARIO 6.2.0.

30.2. Relative effects of winds upon wind-waves

This set of Figures is based on pond scenario 7.2.0., and model outputs are expected to be identical to 7.2.1.

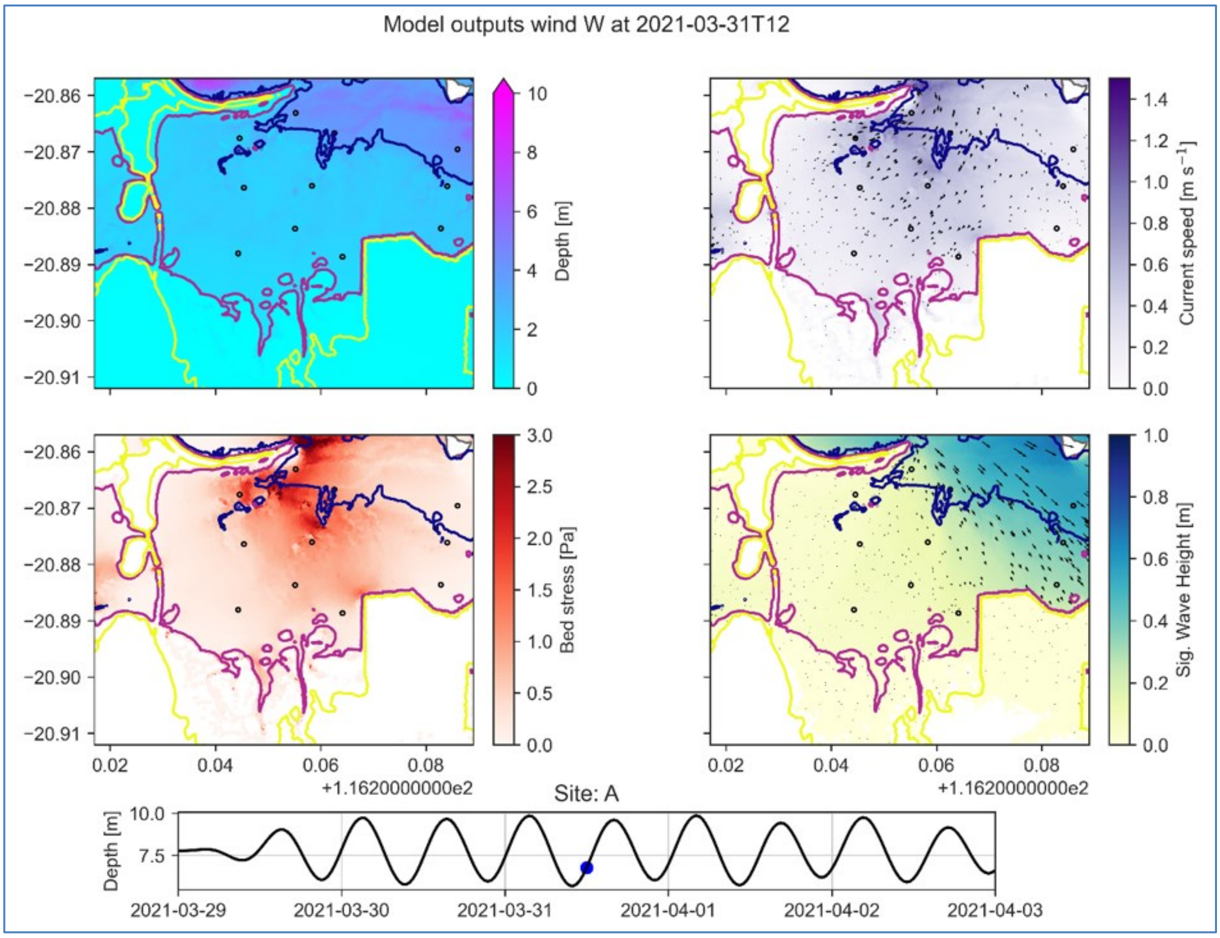


Figure 236. Model outputs for high tide plus 2 m surge for the western estuary. Waves from the NE penetrate the entire estuary and cross the shoreline and the mangroves to reach at and beyond the high tidal areas. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

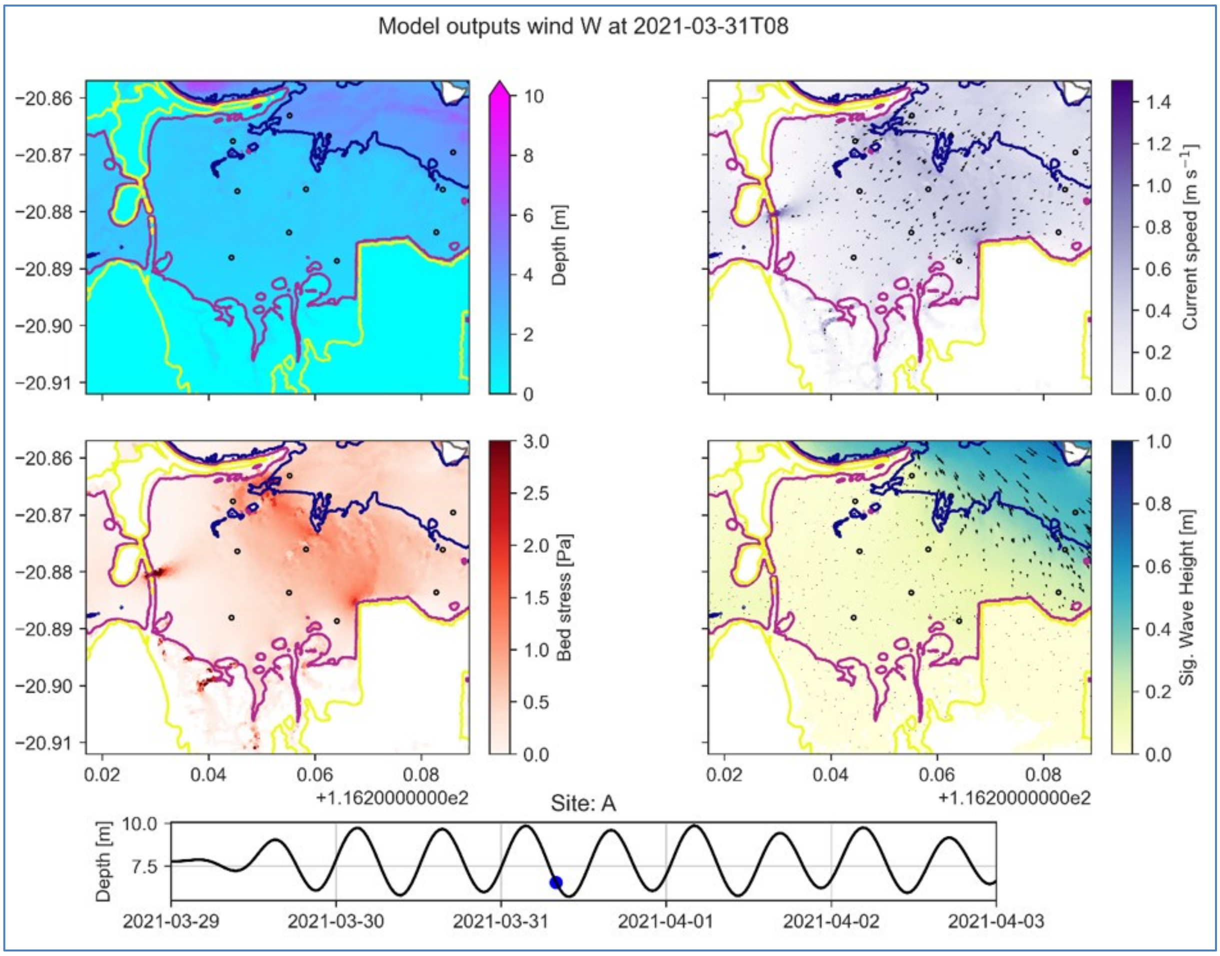


Figure 237. Model outputs for late in the ebb tide plus 2 m surge. Bed stresses are high across broad areas within the fringing and estuarine mangroves in the southern side of the extreme west of the estuary, and near the NW point of the pond walls. (Data plotted within the ponds should be disregarded). Elevation contours are at MSL (blue), HAT (purple) and 6 m AHD (green). Scenario 7.2.0.

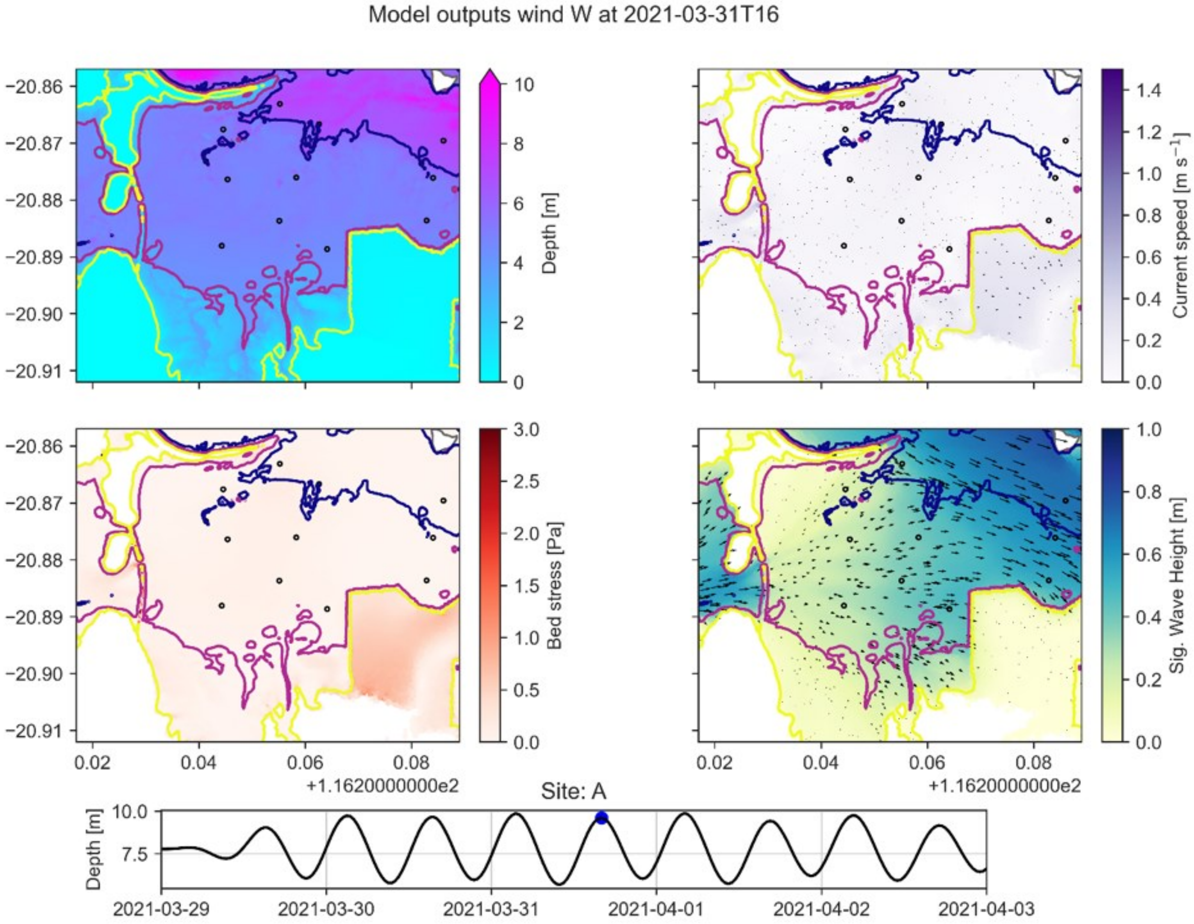


Figure 238. Model outputs for high tide plus 2 m surge. Waves moving towards the east in the estuary, and the same throughout the intertidal areas. (Data plotted within the ponds should be disregarded). Elevation contours are at MSL (blue), HAT (purple) and 6 m AHD (green). Scenario 7.2.0.

30.2.1. Easterly winds

Variations in bed stress for easterly winds at high tide (Figure 181) are more uniform, and the waves are large and orientated to drive sediment into and across the coast.

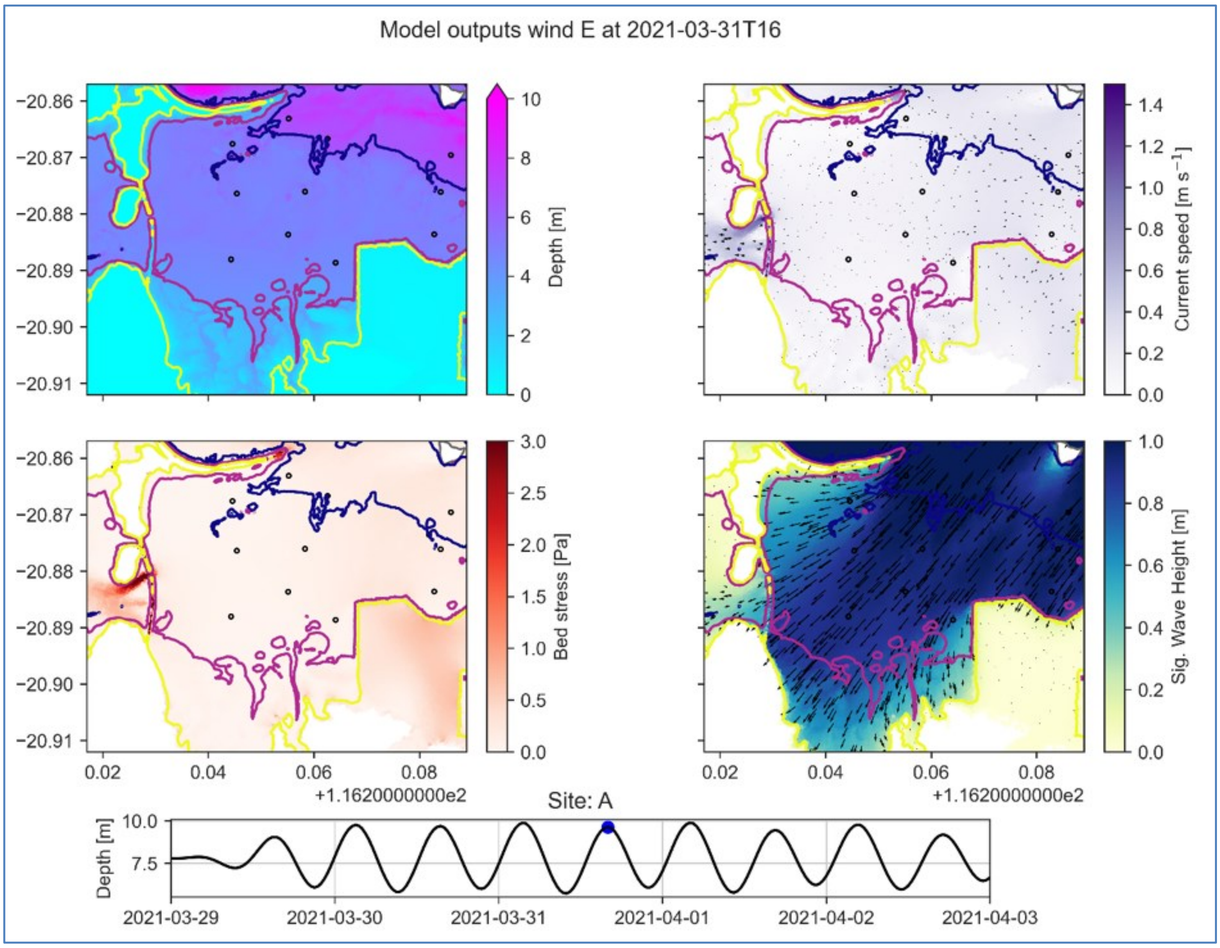


Figure 239. Model outputs for high tide plus 2 m surge. Waves from the NE penetrate the entire estuary and cross the shoreline into the mangrove and high tidal areas. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

30.2.2. Westerly winds

Waves become large and are directed to the eastern shore of the estuary (Figure 240) likely driving erosion there, especially at the coastline. Bed stresses are especially high in the McKay Creek area at mid-flood and mid-ebb tides (Figure 241, Figure 242) also likely driving erosion. NB – this set of Figures is based on pond scenario 6.2.0. but provides useful general information.

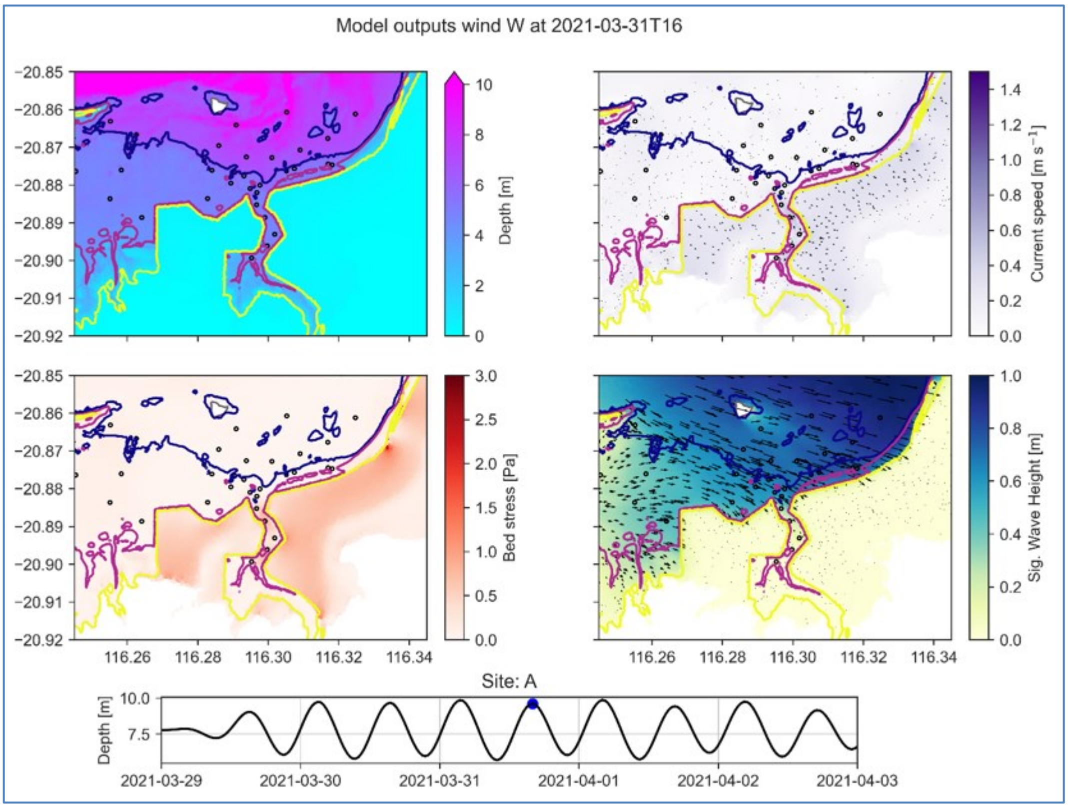


Figure 240. Model outputs for high tide plus 2 m surge. Waves from the W penetrate the entire estuary and cross the shoreline into the mangrove and high tidal areas. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

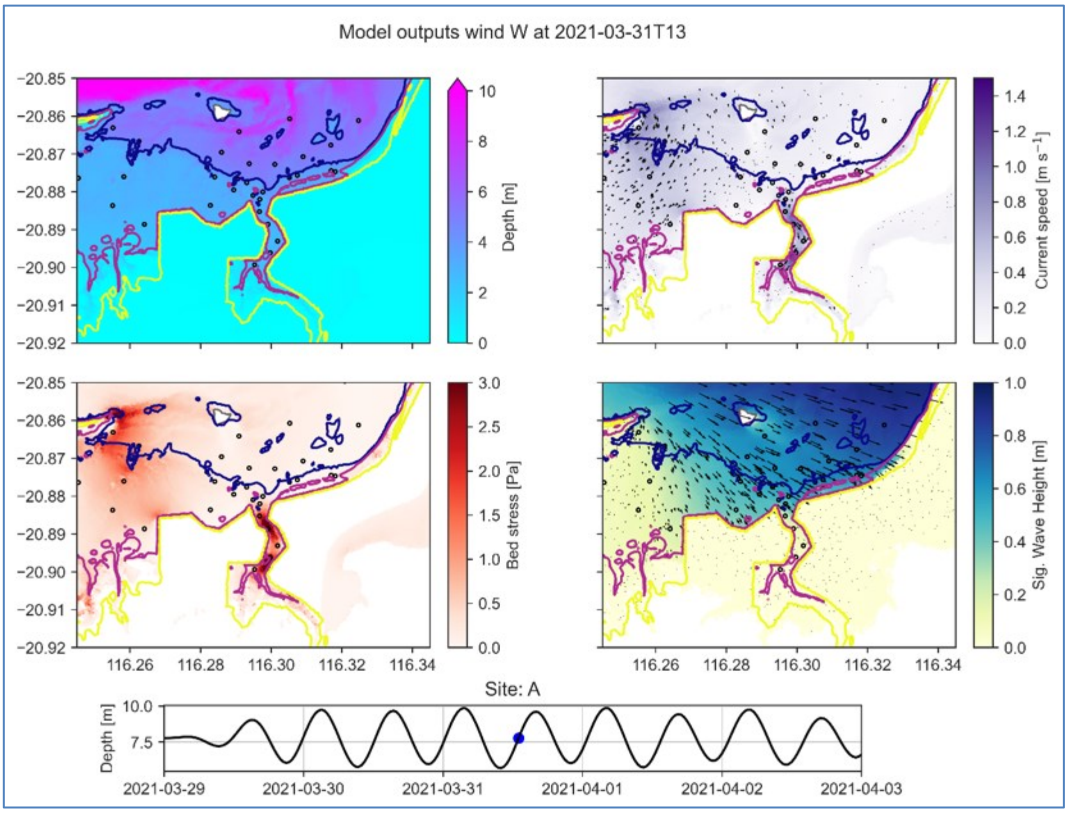


Figure 241. Model outputs for mid-flood tide. Bed stresses are especially high in the McKay Creek and large waves penetrate the eastern shoreline. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

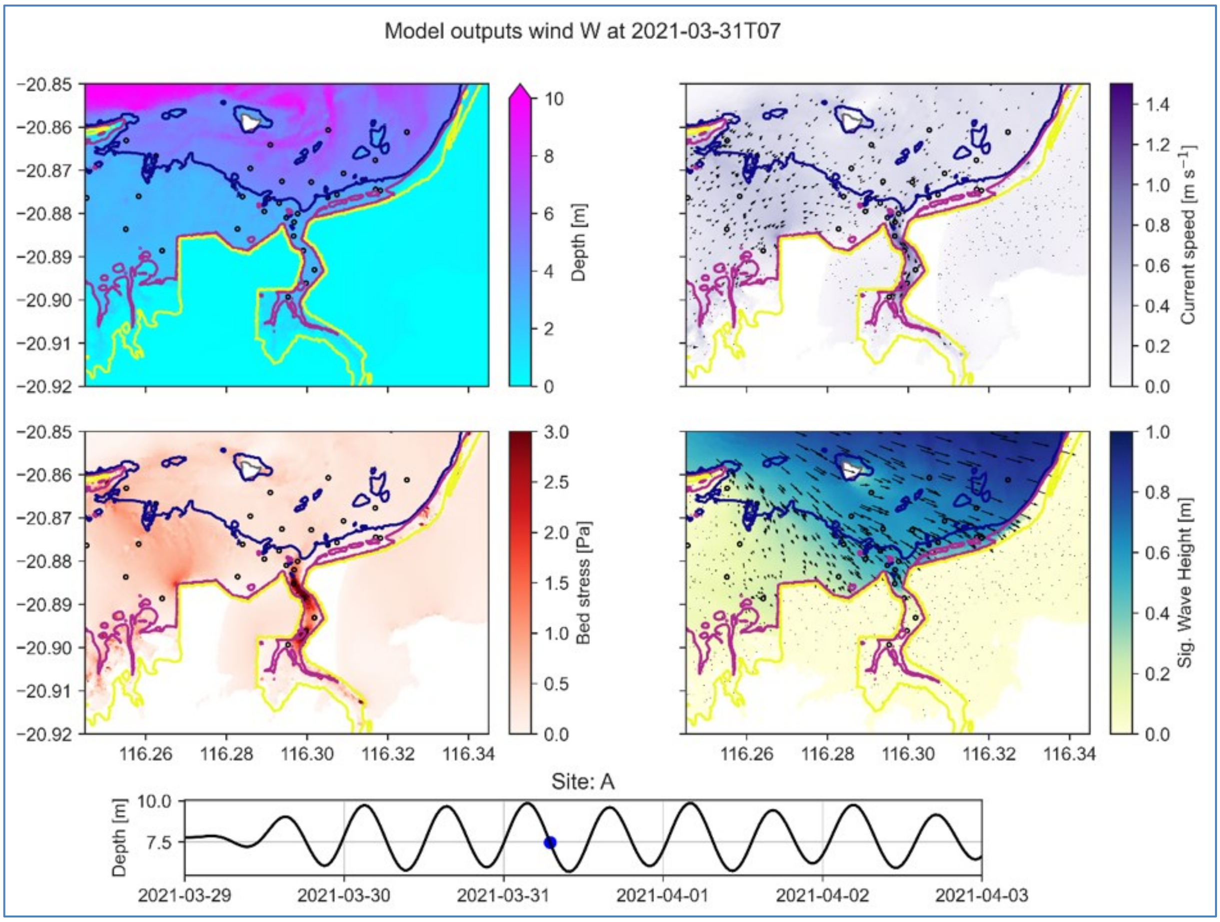


Figure 242. Model outputs for mid-ebb tide plus 2 m surge. Bed stresses are especially high in the McKay Creek and large waves penetrate the eastern shoreline. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

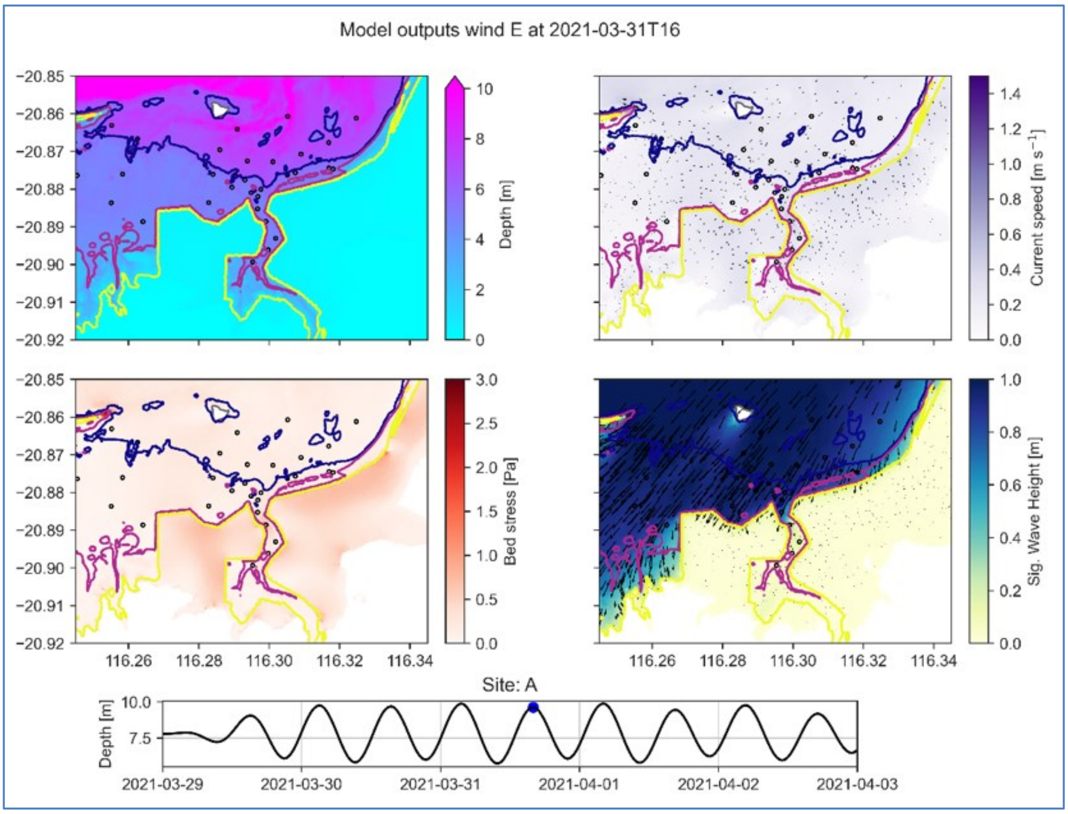


Figure 243. Model outputs for high tide plus 2 m surge. Large waves penetrate the shoreline. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

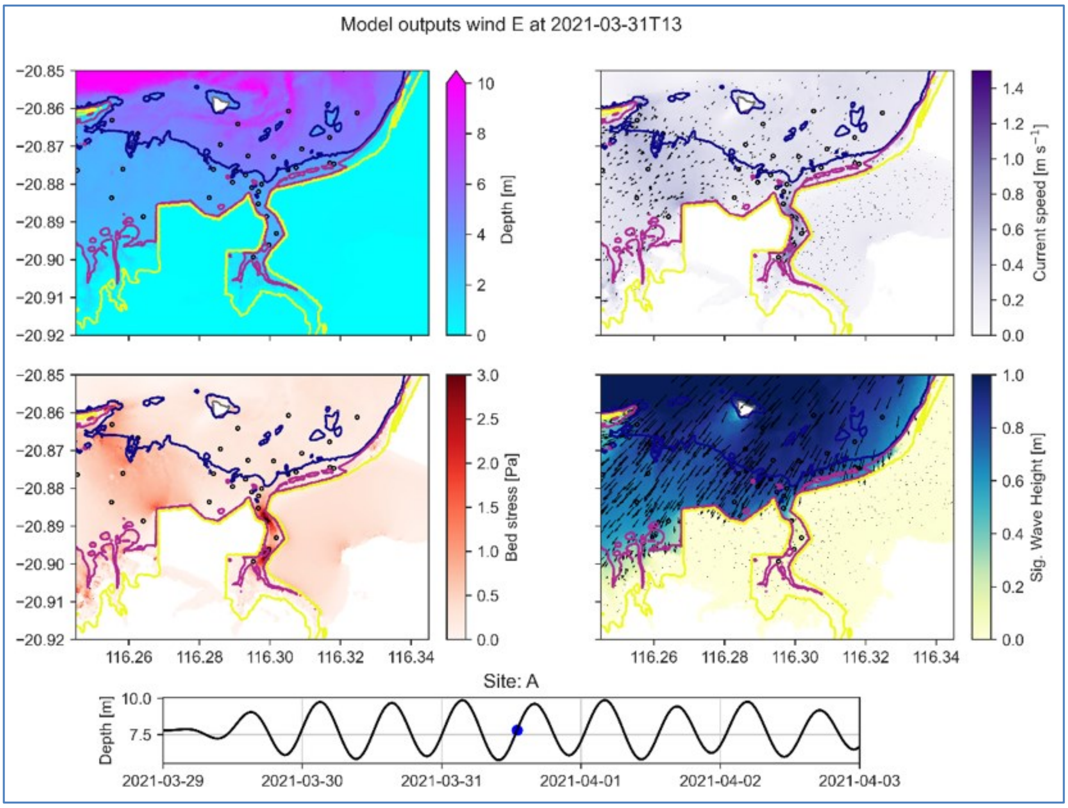


Figure 244. Model outputs for mid-flood tide plus 2 m surge. Bed stresses are especially high in the McKay Creek and large waves penetrate the shoreline. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

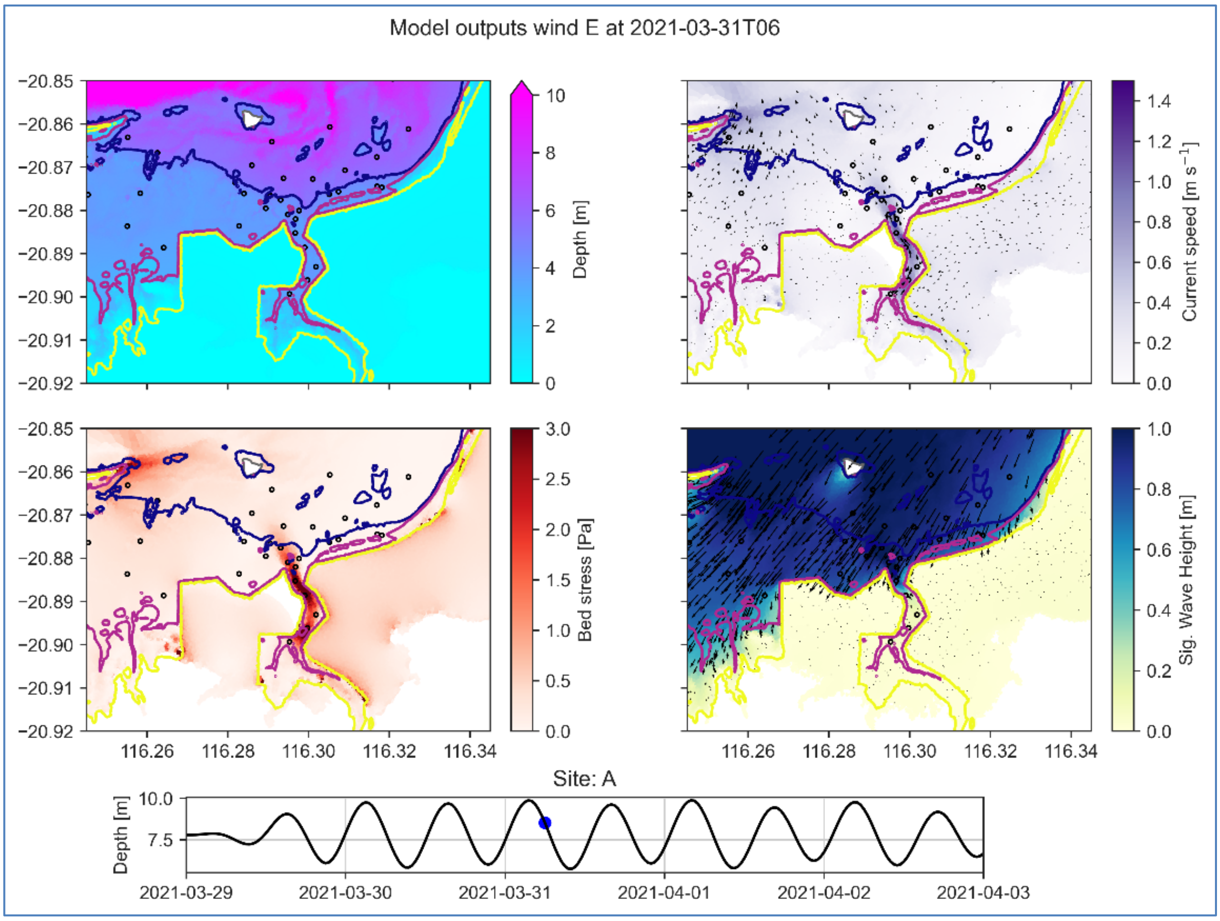


Figure 245. Results for mid-ebb tide plus 2 m surge. Bed stresses are especially high in the McKay Creek and large waves penetrate the eastern shoreline. (Data plotted within the ponds should be disregarded). Scenario 7.2.0.

31. Rating BCHs – an internal exercise

An exercise was designed and conducted to help ensure that the assessment of possible changes to habitats were appropriately focused. In June 2022, a list of benthic communities and habitats was extracted from intertidal and subtidal BCH reports in preparation for the project and was modified for this specific purpose. The resulting list of 20 BCHs includes intertidal and subtidal areas. Four marine habitat specialists from O2 Marine were asked to produce their own independent relative ranking of the habitats involved, in terms of their perceived value. The 'rules' of the exercise presented to them included:

- *"Number boxes, 1 to 20 as best you can.*
- *Assume that each named habitat is of equal area and equally represented in the physical area of interest.*
- *Assume that each habitat is at equal risk of being impacted by the development."*

The aim was to arrive with an idea of relative priority for the sedimentary study, so, for example, we might form a list of things that the sedimentary work:

- *"Must address as quantitatively as possible, making the greatest efforts to minimise and state the uncertainties*
- *Must address quantitatively, but with less effort spent on defining the uncertainties*
- *Will address in relatively qualitative terms i.e., things that will be assessed as part of considering the overall system dynamics and resilience, but don't necessarily need to quantify*
- *Probably doesn't need to address much in this study."*

These 'rules' were designed to maintain objectivity. There is always a risk that pre-existing thoughts about the area might unduly influence any returned views. So, the rules were an attempt to get the specialists to produce a generic ranking of importance that could then inform the sedimentary approach applied to the area in question.

31.1. Results

The results (Table 41) indicate a degree of agreement in the relative ratings of the 20 habitats. The main messages are:

1. It was considered necessary that any assessment should cover as best possible those areas of estuarine mangroves along tidal creeks, fringing mangroves at the coast, intertidal seagrass beds and subtidal seagrass beds. This emphasises the need to include tidal processes in the creek systems and throughout their vegetated margins, and to consider sediment transport processes driven by waves and wind-driven currents on the intertidal zones.
2. It was also considered necessary to cover any relevant areas of "Subtidal coral on rocky substrate" and "algal mats". This indicates the need to investigate physical processes on the high intertidal flats, including those associated with surges, to constrain as best possible the processes and potential future effects in the high intertidal areas around the salt ponds and landwards of them.
3. Many other areas have a lower relative ranking, but some needed addressing because
    - Of the critical importance of their processes (e.g., tidal flows in tidal creek environments)
    - They have relevance to protecting and maintaining higher-ranked areas (beaches, intertidal flats seawards of the coast, and many subtidal areas).

Table 41. Results of the internal BCH value-ranking exercise, using specialists A- D.

Habitat name	Specialists A - D				
	A	**B**	**C**	**D**	
	Ranking. 1 = high, 20 = low			**Ranking - 1 – 4**	**Comments**
Mudflat/Saltflats.	**10**	**9**	**20**	**4**	
Samphire/Samphire Mudflats;	**11**	**8**	**9**	**3**	
Algal Mats (high intertidal zone)	**2**	**3**	**8**	**2**	
Mangroves along tidal creeks	**1**	**2**	**4** **comment**	**1**	Creek mangroves typically older, more structurally complex hence more value than younger coastal mangroves.
Mangroves at the coast	**3**	**1**	**6**	**1**	
Foreshore Intertidal Mudflats	**14**	**7**	**12**	**4**	
Tidal creek banks	**12**	**14**	**14**	**4**	
Tidal creek bottoms	**13**	**15**	**15**	**4**	
Subtidal mudflats	**15**	**17**	**16**	**4**	
Intertidal seagrass beds	**6**	**5**	**5**	**1**	
Sandy beaches	**16**	**20**	**13** **comment**	**4**	Sandy beaches would be raised higher if being used for turtle nesting (possibly up to 2-3)
Pebbly beaches	**17**	**19**	**19**	**4**	
Subtidal seagrass beds	**5**	**4**	**3**	**1**	
Intertidal mobile sands	**18**	**13**	**18**	**4**	
Subtidal mobile sands	**19**	**16**	**17**	**4**	
Subtidal mobile gravels	**20**	**18**	**11**	**4**	
Subtidal coral on rocky substrate	**7**	**11**	**2**	**1**	
Subtidal coral on loose substrate	**9**	**10**	**7**	**2**	
Coral reef fringing a rocky island	**8**	**6**	**1**	**1**	
Mangroves on rocky limestone island	**4**	**12**	**10**	**1**	

KEY:

RED - High perceived value & most specialists agree.
GREEN - Middle range perceived value & most specialists agree.
GREY – Low perceived value & most specialists agree.
PURPLE - Variable views.

Additional general comments from Specialist C.

- Little difficult to compare values between intertidal and subtidal – the key 3 for EPA are usually coral, seagrass and mangrove habitats above all else.
- Eramurra mangroves are within a defined management area so may be considered higher value than ranked.

(https://www.epa.wa.gov.au/sites/default/files/Policies_and_Guidance/Protection%20of%20tropical%20arid%20zone_new%20FINAL.pdf).

As noted above, shallow water processes, waves, and wind-driven currents are directly relevant. It was also noted that:

- Some habitats unique in coastal geomorphology support higher densities or biodiversity of biota, support species protected under the EPBC Act (e.g., seagrass for dugong/turtles) or support important social considerations (e.g., macroalgae reefs for commercially fished, blue-lined emperor spawning), and thus might be considered very important. The importance of these habitats is therefore not just categorised on a broad scale but requires site-specific assessment.

- It is not possible to generate a truly comparative scale of relevance. For example, impacts to seagrass beds where dugongs are known to feed might generate the same view of having an "unacceptable" impact as the loss of mangroves.
- Further, within some of these habitats there will be variation in the perceived quality of the benthic community. For example, "mangroves on the coast" might comprise three to five different classified assemblages, within which impacts to the scattered mangrove assemblage might be deemed less significant than impacts to the taller and more dense fringing community that supports a far higher rate of productivity and biodiversity. Habitat that is generally broad and supports a low density or biodiversity of biota might generally be classified with less importance.

Finally, the EPA has published advice (EPA 2001) about protecting tropical arid-zone mangroves in the Pilbara region that was based upon ranking the importance of mangrove areas to prioritise conservation efforts. The ESSP occurs within the Cape Preston area which was designated as "regionally significant". In these areas, the EPA's operational objective is that:

> *"No development should take place that would significantly reduce the mangrove habitat or ecological function of the mangroves in these areas."*

31.2. Implications for designing the sedimentary work

Using all the above information, combined with the logical necessity to consider the sedimentary aspects, the resulting approach considered the whole sedimentary system, its processes, transport pathways, links, timescales (where possible) and its level(s) of internal resilience.

Therefore, to some extent, most habitats within the greater estuary were considered in some way, and the intertidal and associated peritidal zones required most focus. Outside the estuary, any minor changes to benthic seagrass beds would be smaller than those induced by natural processes and would re-establish, and coral reefs further offshore are at negligible risk of smothering impacts from any released sediment, partly because even if these areas receive fine sediment, which they will do naturally at times, the hydrodynamics are not conducive to it settling and accumulating, even for a few hours.

The sedimentary work necessarily assessed the links between some areas. As an example, those relatively barren and mobile intertidal flats (BCH name – 'intertidal mudflats', 'mudflats' or 'foreshore mudflats') seawards of the fringing mangroves might be low value in terms of BCH and thus not worthy of detailed sedimentary consideration. However, because these flats are wide and of shallow gradient, they absorb tidal and wave energy as it approaches the shoreline, helping protect fringing mangroves at the shoreline itself. Further, the flats provide a ready local store of sediment (terrigenous and in the form of shells) that can supply sediment to nearby areas such as the storm beaches, that themselves protect mangroves. Therefore, understanding the dynamics of the wide intertidal mudflats is critical to assess whether and how emplacement of the solar salt ponds might ultimately affect the BCH of fringing mangroves at the shoreline itself. Similarly, a sandy or gravelly beach may itself be of low value in terms of BCH, but such a feature has inherent value by forming a physical barrier in front of fringing mangroves, and may have higher value should it be a known turtle-nesting beach.

Therefore, the sedimentary work necessarily considered some environments, processes and links beyond and outside the BCHs of highest perceived value.

32. Subtidal Habitats

Subtidal BCH surveys (Figure 246) within Cape Preston East area identified six broad BCH classes, distinguished by varying levels of benthic cover and dominant taxa, examples of which are shown in Figure 247 and Figure 248. The latest BCH map is now complete (Figure 249)

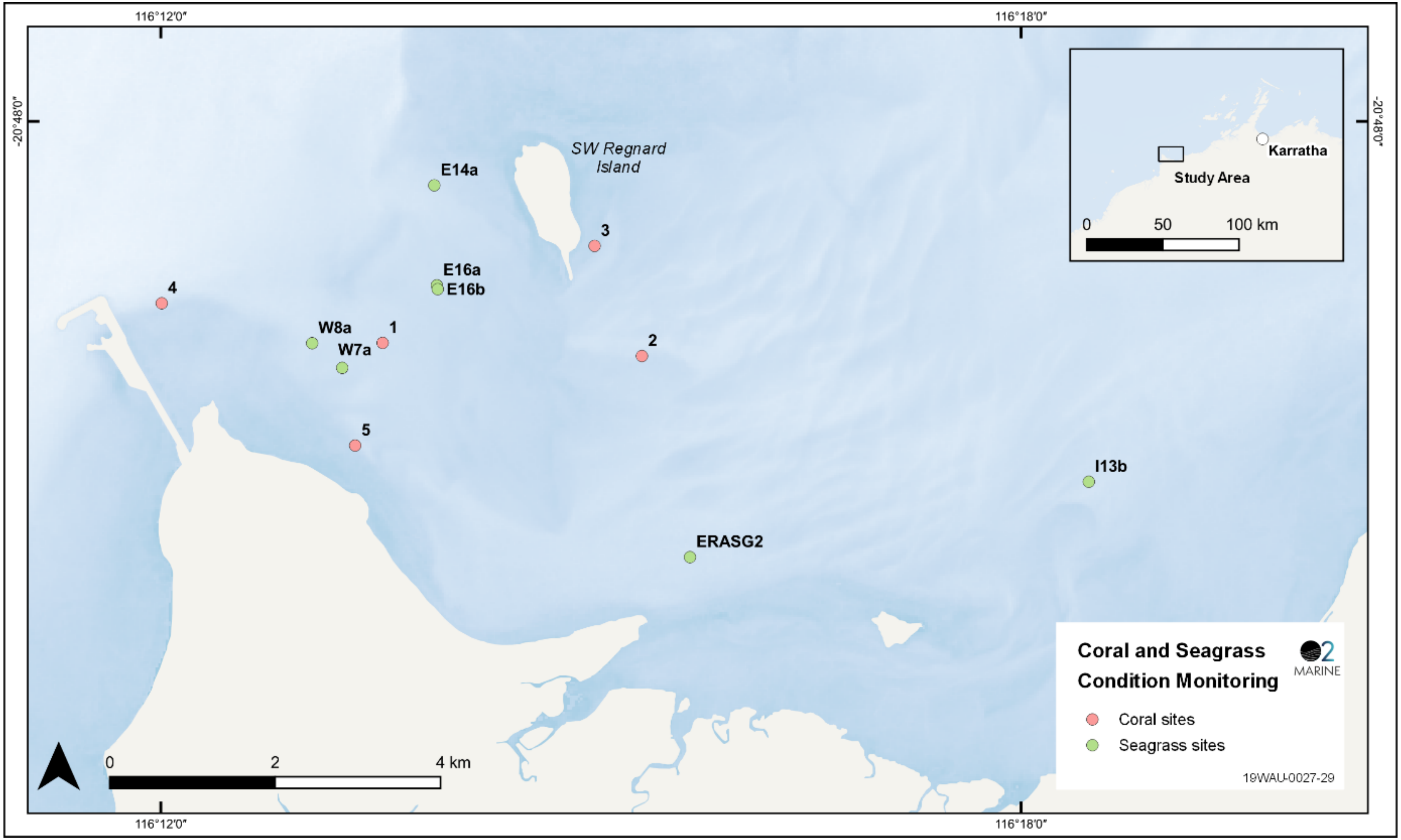
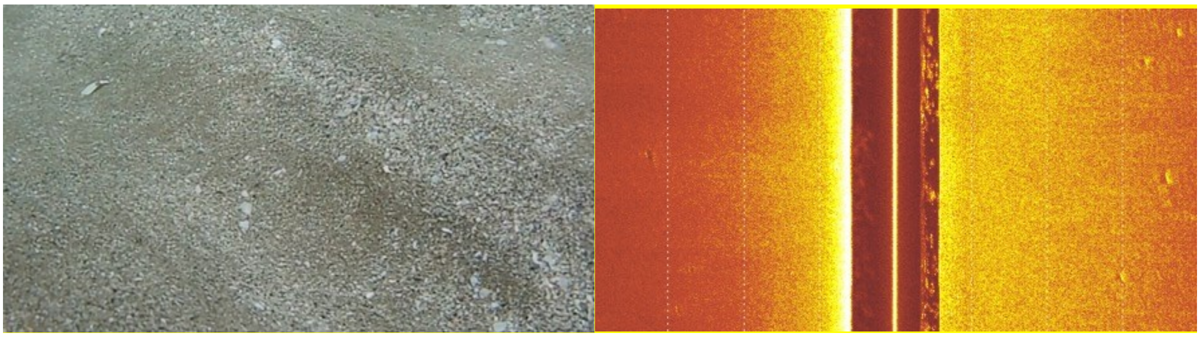
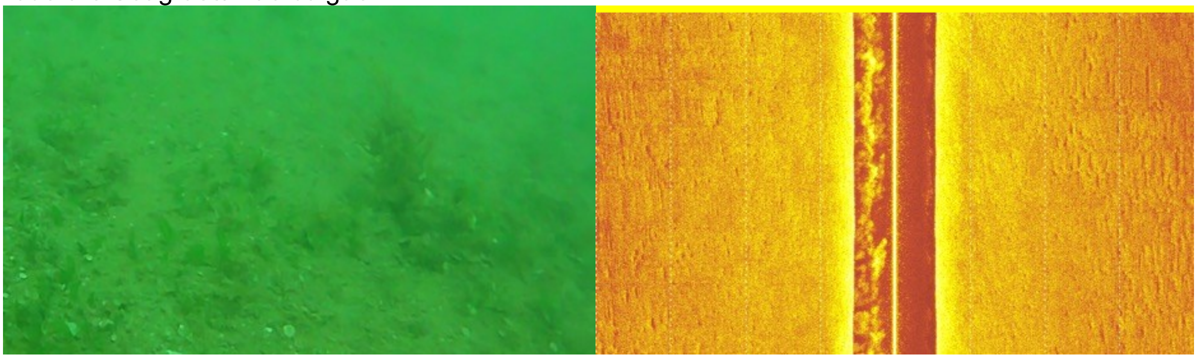


Figure 246. Subtidal BCH (coral and seagrass) monitoring locations (O2 Marine 2022).

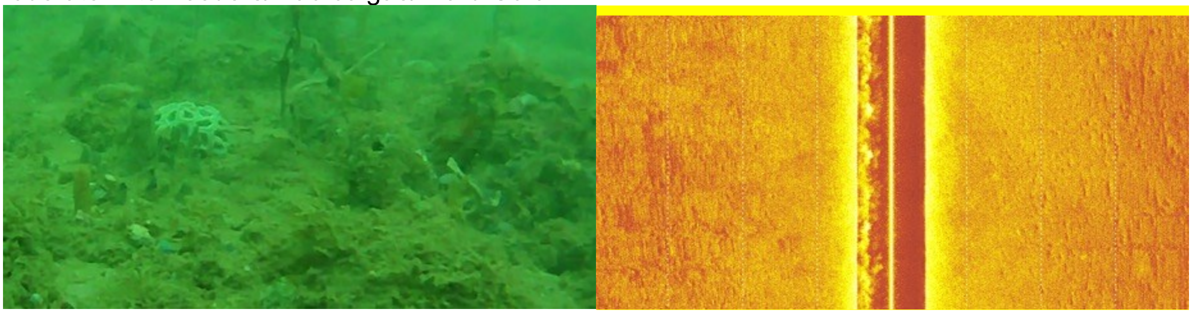
Bare sand



Low-Moderate Seagrass/Macroalgae



Low-Moderate Filter feeders/Macroalgae/ Hard Coral



Low-Moderate Hard Corals.

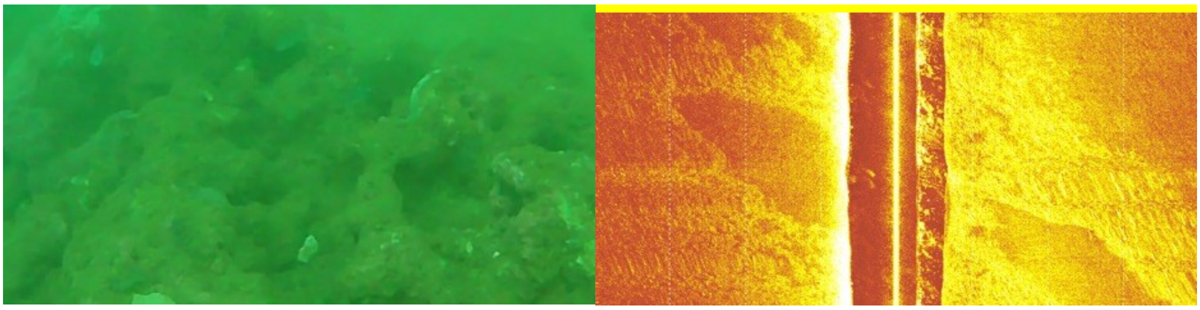
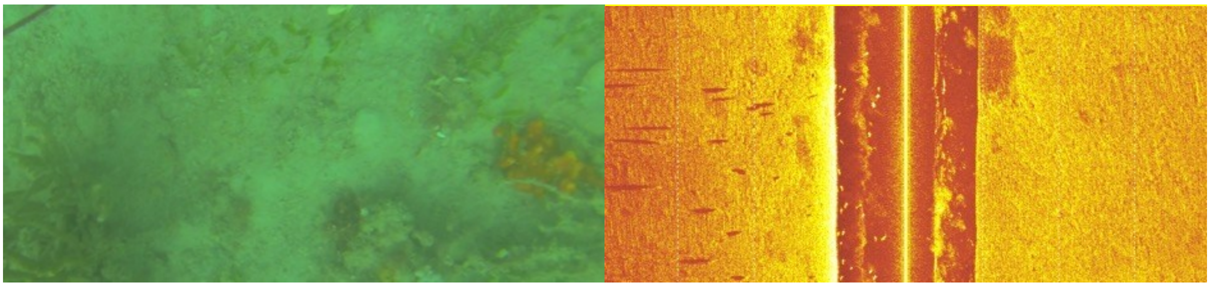
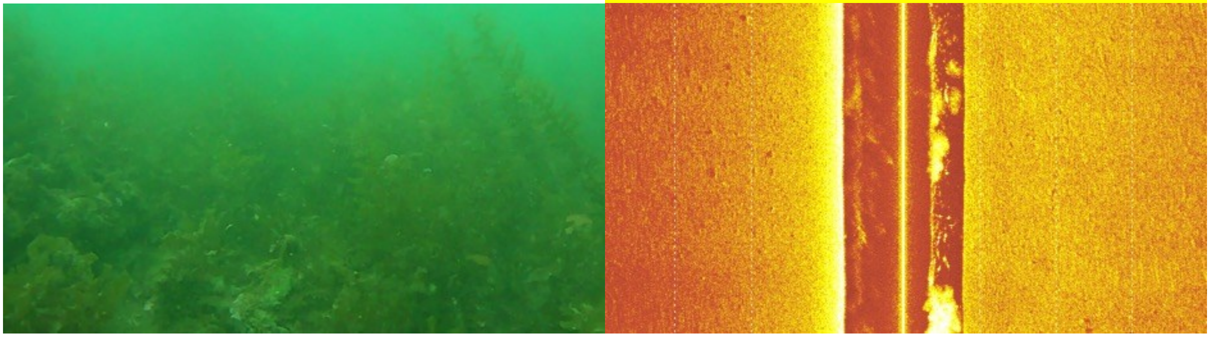


Figure 247. Example video snapshots (left) and side-scan sonar imagery for bare sand, Low-Moderate Seagrass/Macroalgae, Low-Moderate Filter feeders/Macroalgae/ Hard Coral, Low-Moderate Hard Corals.

High/Dense Hard Corals



High/Dense Macroalgae



High/Dense Filter feeders/Coral (Mixed Habitat).

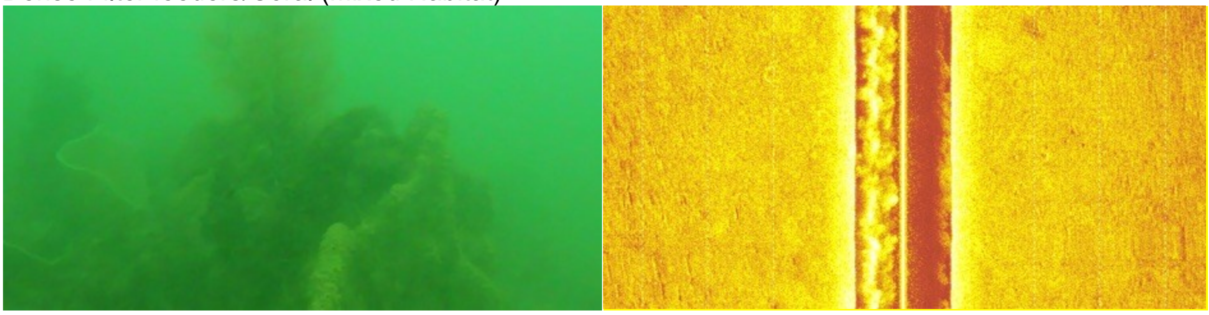


Figure 248. Example video snapshots (left) and side-scan sonar imagery for High/Dense Hard Corals, High/Dense Macroalgae, High/Dense Filter feeders/Coral (Mixed Habitat).

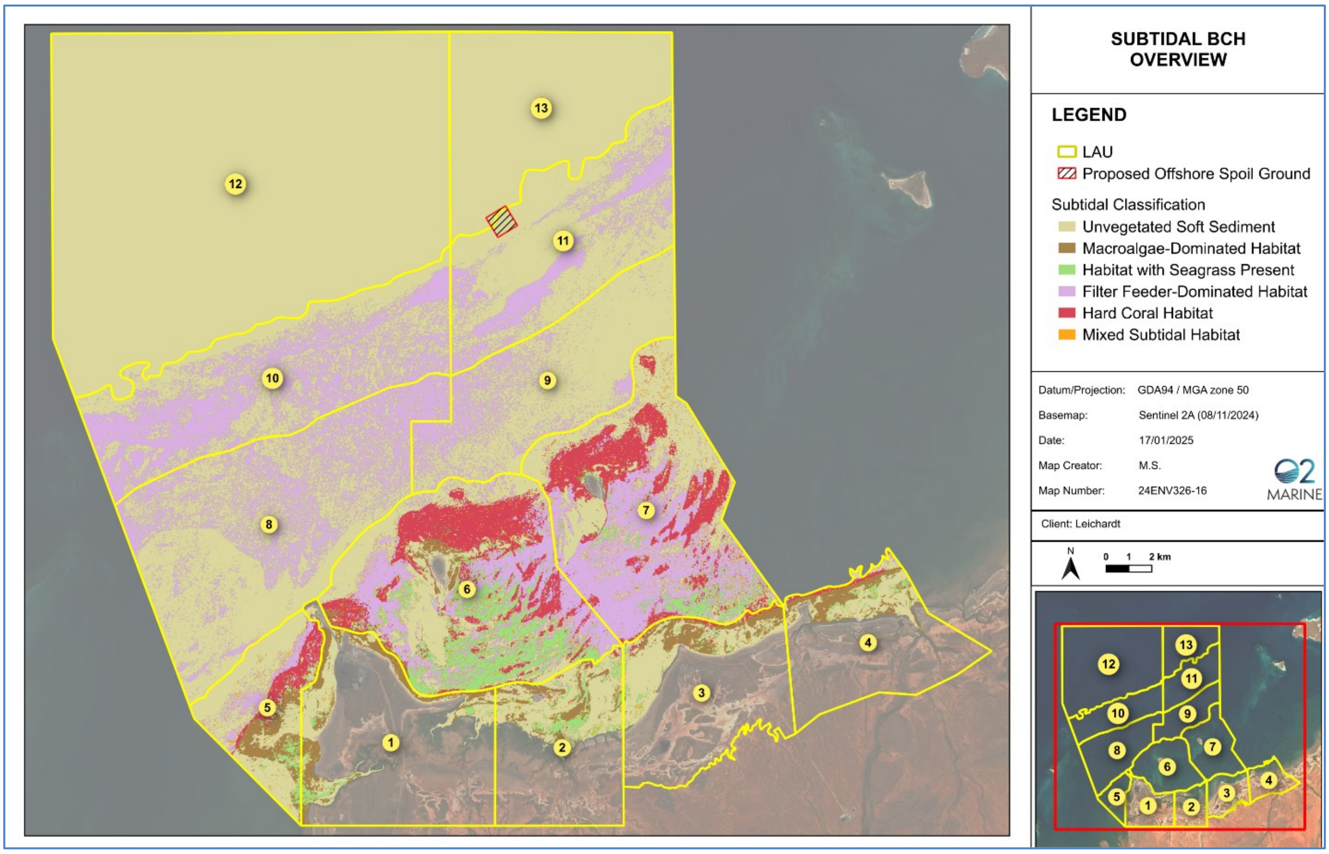


Figure 249. Compiled Subtidal BCH map for the study area within LAUs (O2 Environment 2025a).

33. Intertidal Habitats

33.1. Preliminary Mapping Methods

Analysis of 3-band satellite imagery (Landsat) was undertaken to produce a preliminary BCH map, and the GA - Mapping Foreshore Mudflats GIS layer was used to delineate the foreshore mudflats, although it was noted during field surveys that dataset accuracy varies due to sedimentary changes in the intertidal zone. The resulting Landsat image classification was also used to identify the location and extent of dominant mangrove species (i.e., *Avicennia marina* and *Rhizophora stylosa*). The boundaries of intertidal habitats and mangrove associations identified from ground-truthing and post-fieldwork imagery analysis were geographically registered in QGIS. Fine-scale 'habitat' polygons were then digitised on-screen in QGIS by using the rectified high spatial resolution digital imagery as background to inform the mapping and correct for any local spatial inaccuracies arising from the satellite imagery classification. The polygons were assigned the appropriate habitat classification, and the total areas for each habitat class were then calculated using QGIS.

The intertidal zone of the mapped area was classified into the following seven intertidal habitat classes and two associated terrestrial vegetation association classes that occur between BCH communities in the intertidal zone (i.e., Spinifex Sandplain islands surrounded by Samphire/Samphire Mudflats):

- Algal Mats;
- Foreshore Mudflat/ Tidal Creeks;
- Mangroves;
- Rocky Shores;
- Samphire/Samphire Mudflats;
- Sandy Beaches; and
- Mudflat/Saltflats.

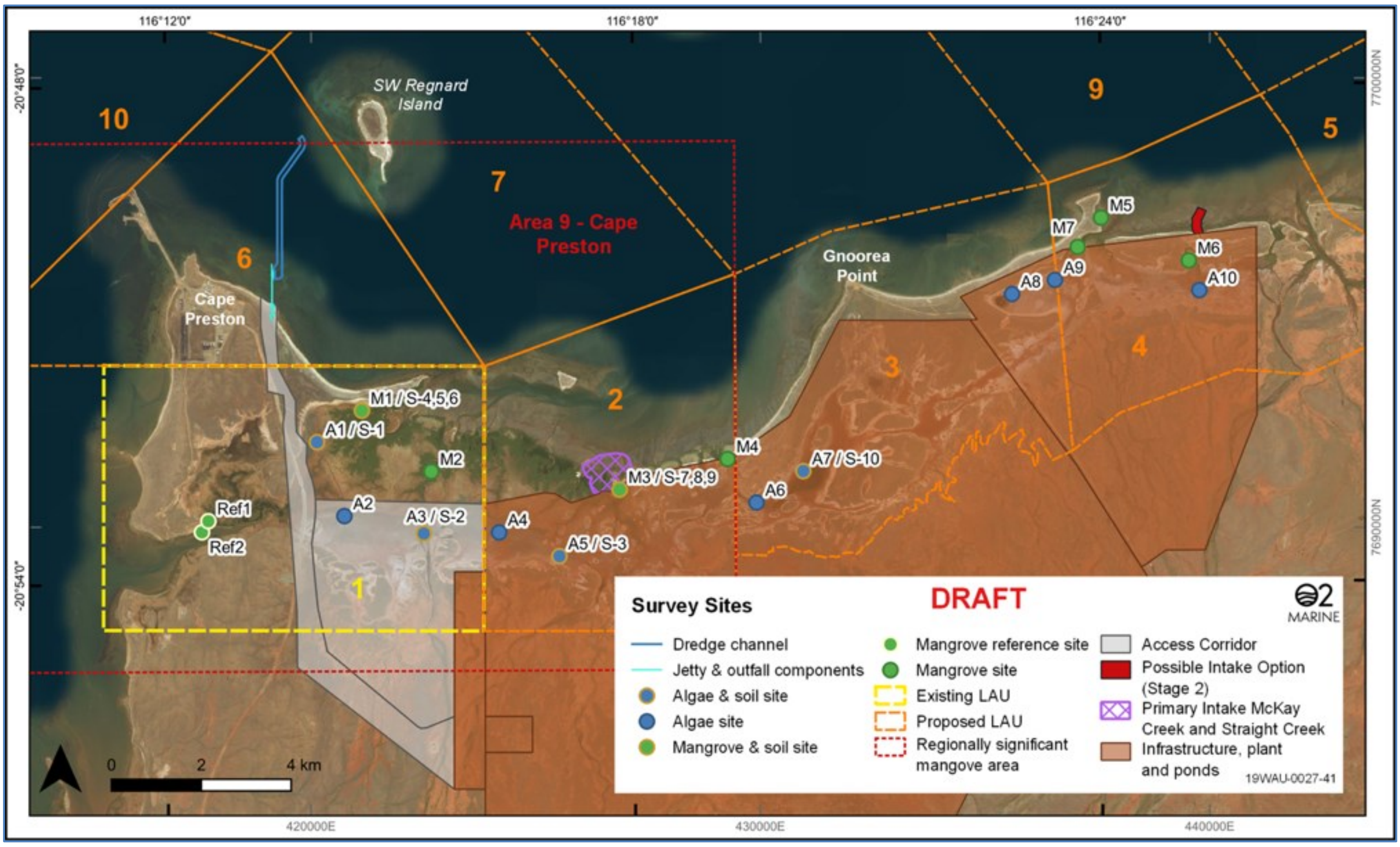


Figure 250. Mangrove, Algae and Sediment sampling locations for the Eramurra Solar Salt Project. From Eramurra Solar Salt Project (O2 Marine 2023)

33.2. Refinement & Validation - Field Survey

Georeferenced aerial videography and site walk observations were collected during May 2020 by flying helicopter transects across the length of the intertidal zone, with georeferenced images used to mark the boundaries of the various habitat types and mangrove association types. Field scientists also accessed the site by 4x4 vehicle and conducted site walks, recording GPS coordinates and associated observations. The information in the notes included habitat characteristics, vegetation type and fauna, and evidence of previous coastal shorelines and marine/estuarine habitats of either Holocene or Pleistocene origin. Draft Habitat classes and their habitat designation codes are illustrated below (Figure 251), followed by the various mangrove associations (Figure 252, Figure 253). Note that in this report, the “Foreshore” mangroves and mudflats referred to in these figures have generally been referred to as “Nascent mangroves”, because their sedimentary significance is their likely young age.

Note also that this report uses the term ‘intertidal mudflats’ to mean all those flats seawards of the current coast, as defined by the most seawards extent of mangroves. This line is important because either side of it the sediments and sedimentary processes are markedly different

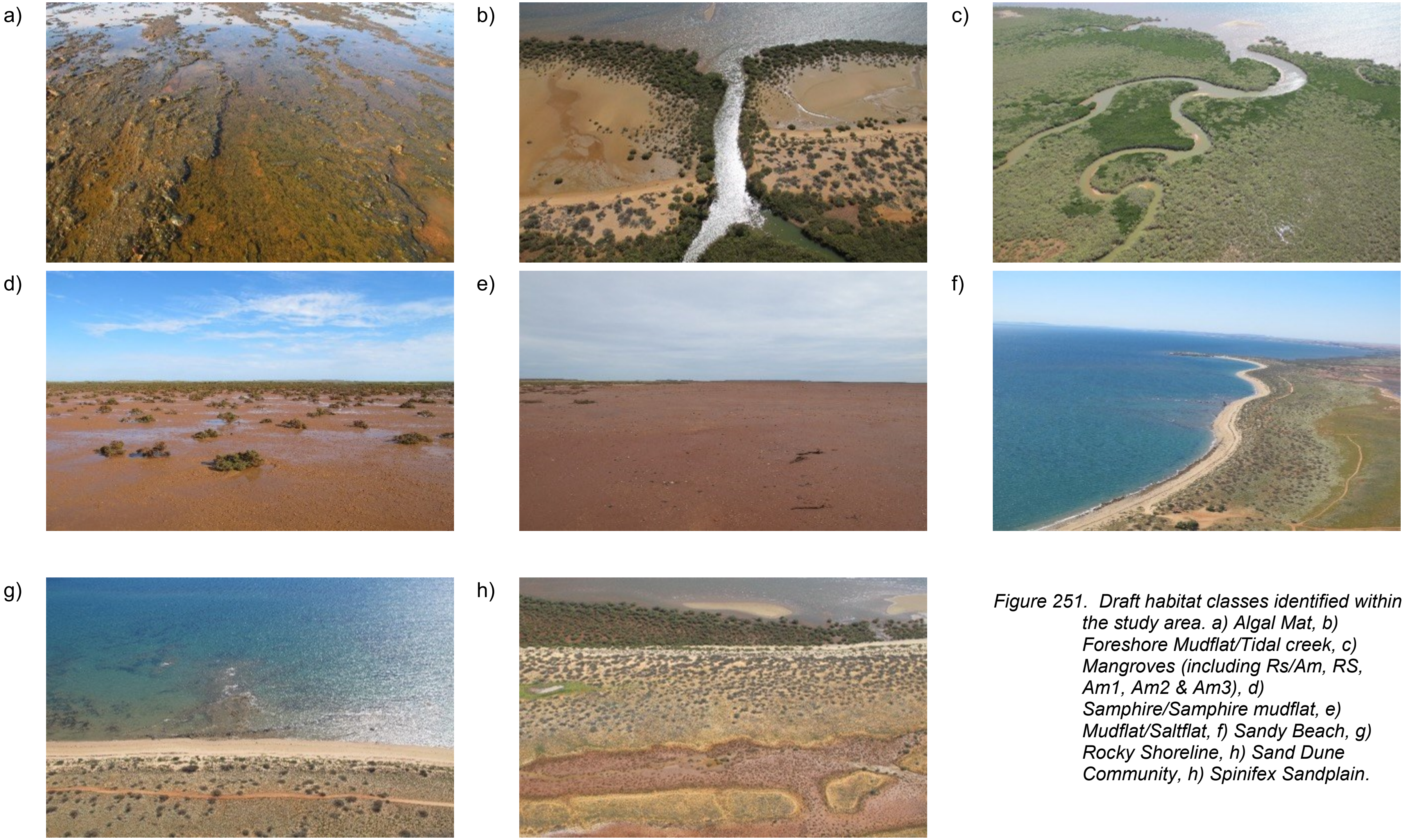


Figure 251. Draft habitat classes identified within the study area. a) Algal Mat, b) Foreshore Mudflat/Tidal creek, c) Mangroves (including Rs/Am, RS, Am1, Am2 & Am3), d) Samphire/Samphire mudflat, e) Mudflat/Saltflat, f) Sandy Beach, g) Rocky Shoreline, h) Sand Dune Community, h) Spinifex Sandplain.

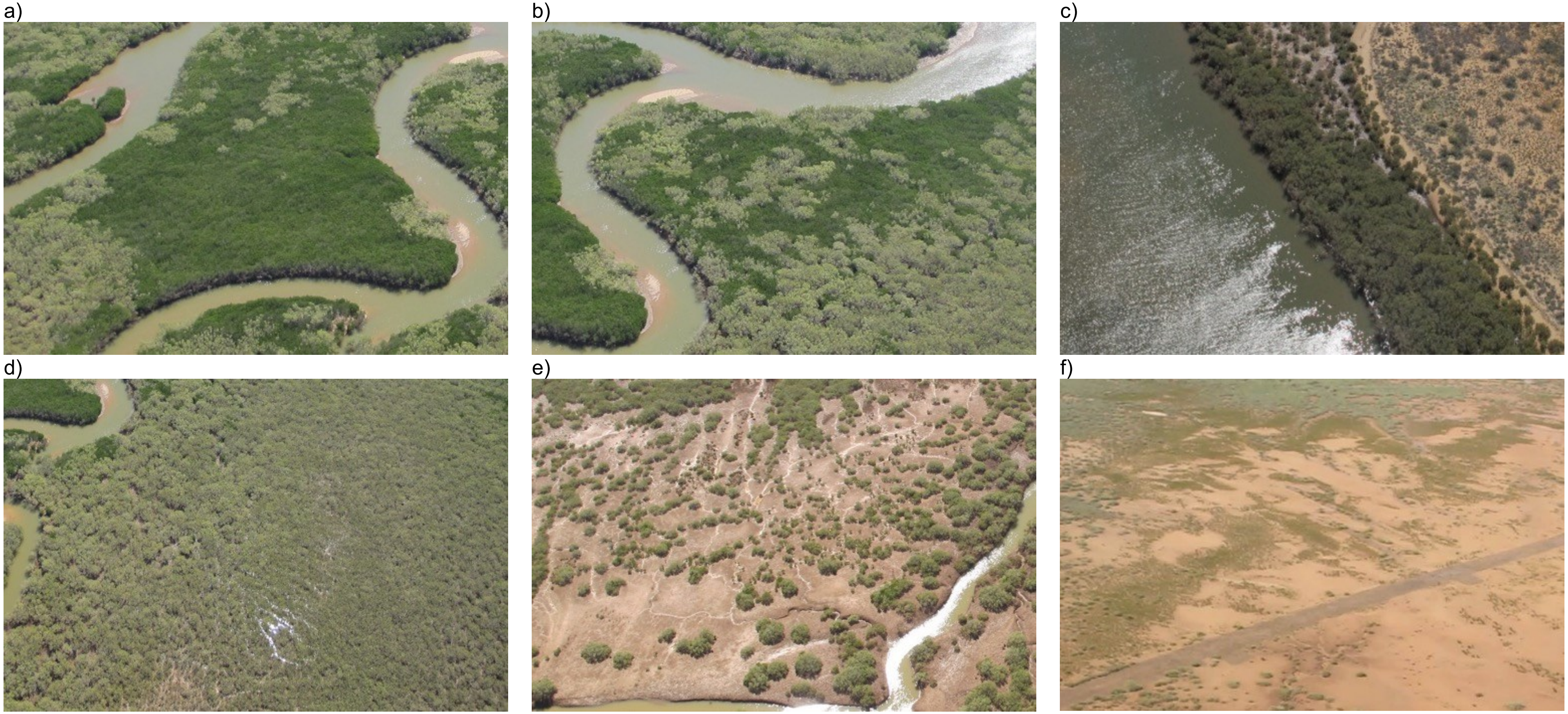


Figure 252. Photographs of the Mangrove Associations surveyed within the study area. a) Rs LAU2, b) Rs/Am LAU2, c) Am1 LAU4, d) Am2 LAU2, e) Am3 LAU1 and f) Ca LAU1.

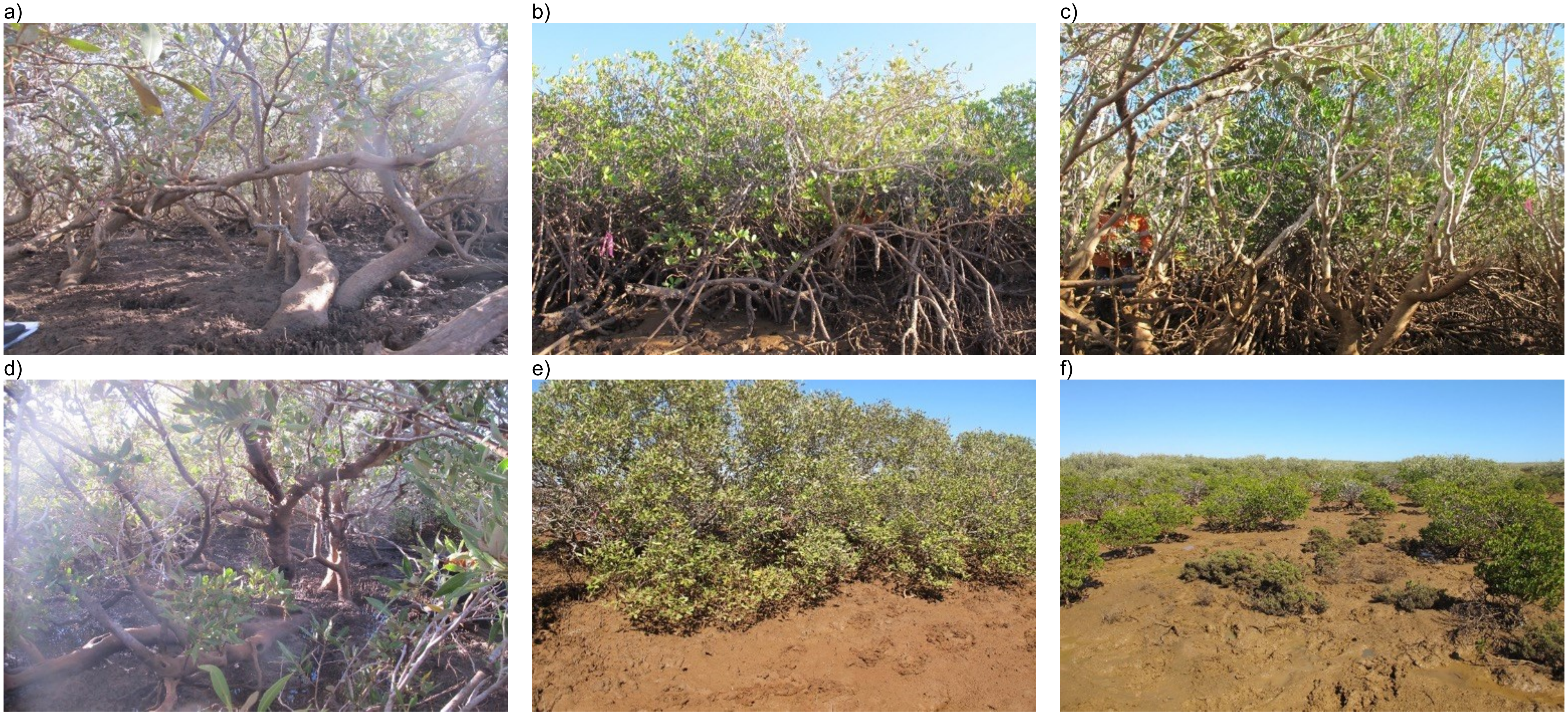


Figure 253. Photographs of the Mangrove Associations surveyed within the study area. a) Am1 Site M1 LAU1, b) Rs Site M2 LAU1, c) Rs/Am Site M2 LAU1, d) Am2 Site M3 LAU2, e) Am3 Site M3 LAU2, f) Ce Site M1 LAU1.

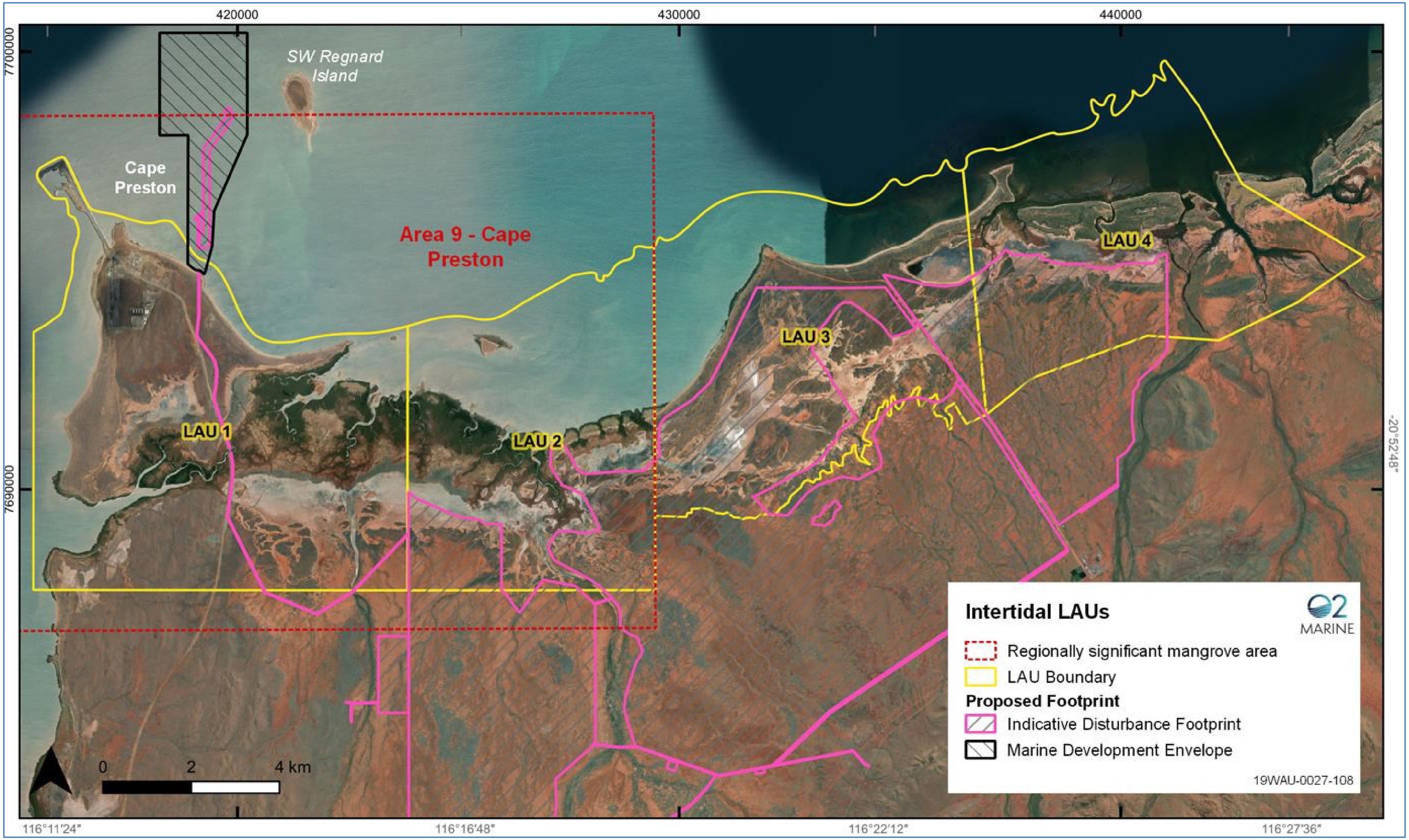


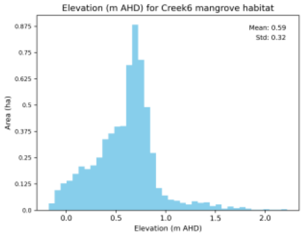
Figure 254. The ESSP development footprint, intertidal LAUs and Regionally Significant Mangrove Area #9 (O2 Marine 2023)

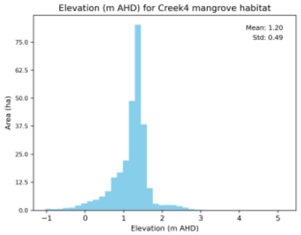
33.3. Mangroves

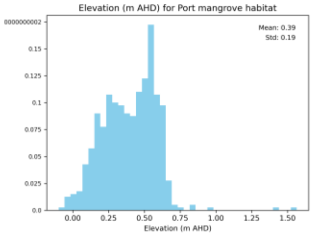
Although there are some geomorphological classifications of mangrove environments (Lugo & Snedaker, 1974; Woodroffe, 1992), they are largely descriptive and so are of limited use in dealing well with the sedimentary processes involved. Further, in this case of a sub-tropical environment subject to major episodic events, such classifications do not inform us about the range of change that might be expected in each sub-environment. For our purposes, and in this geographical area, physical systems that support mangroves can be divided based on the dominant range or mix of sedimentary process and their general location. Hence, we might distinguish three main groups, here defined as:

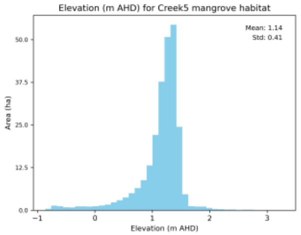
- Coastal fringing mangroves – These occur on the open coastline, such as those seawards of and between the creek mouth east of McKay Creek – these are likely to be ephemeral over timescales of a few decades. In some places these are clearly very young, probably representing ‘recovery’ of the shoreline after an erosive event - these have been referred to as nascent mangrove areas.
- Estuarine mangroves – These occur within tidal creek systems behind the open shoreline, these are likely to be relatively large and long-lived areas, although subject to change at their margins associated with channel migration and associated sedimentary changes.
- Island-fringe mangroves - These are often small and inhabit the rocky and often narrow margins of islands, such as around Great Sandy Island. These are likely to be relatively ephemeral in nature, vulnerable to erosion, for example with large waves from a particular direction.

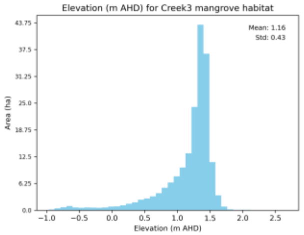
34. Distribution of BCHs with elevation for each catchment

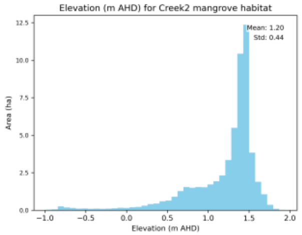

Elevation (m AHD) for Creek6 mangrove habitat

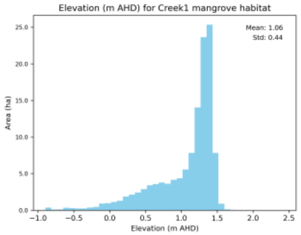

Elevation (m AHD) for Creek4 mangrove habitat

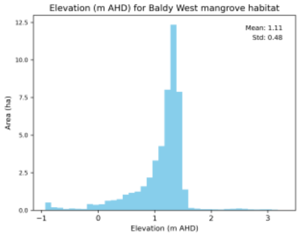

Elevation (m AHD) for Port mangrove habitat

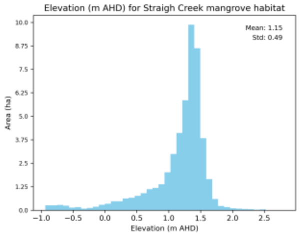

Elevation (m AHD) for Creek5 mangrove habitat

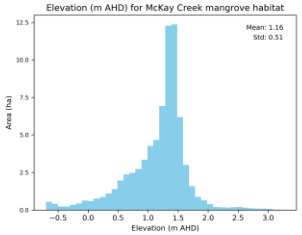

Elevation (m AHD) for Creek3 mangrove habitat

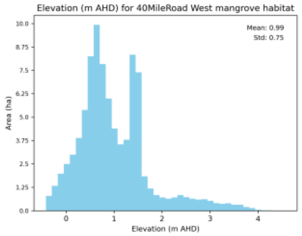

Elevation (m AHD) for Creek2 mangrove habitat

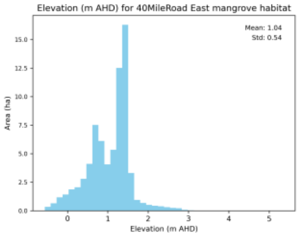

Elevation (m AHD) for Creek1 mangrove habitat

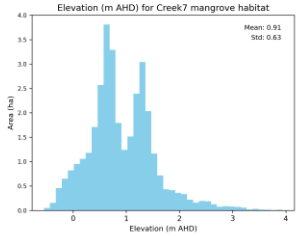

Elevation (m AHD) for Baldy West mangrove habitat

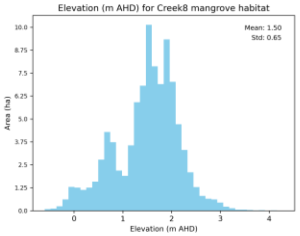

Elevation (m AHD) for Straigh Creek mangrove habitat

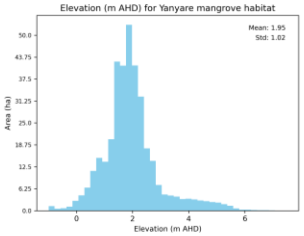

Elevation (m AHD) for McKay Creek mangrove habitat

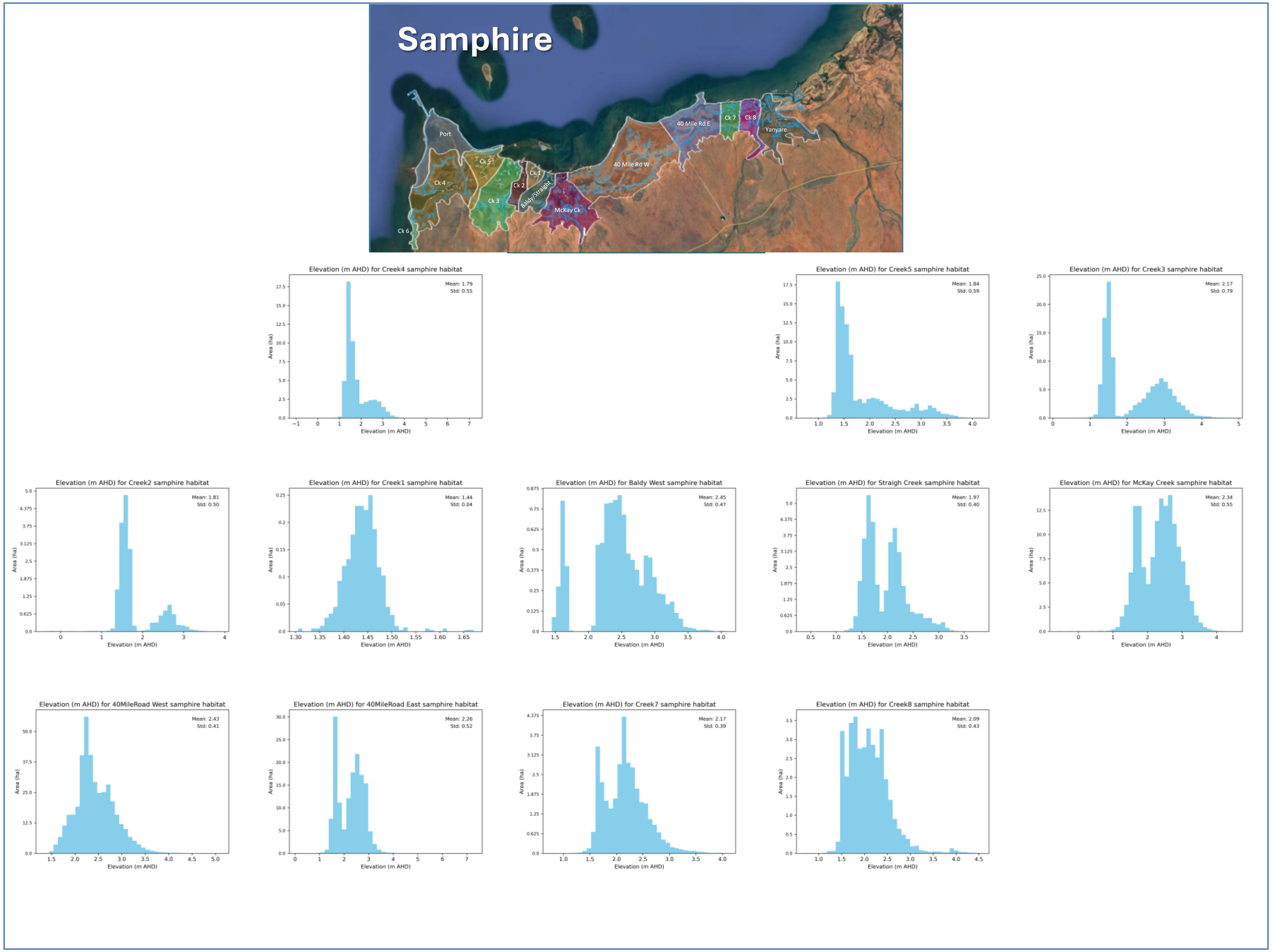

Elevation (m AHD) for 40MileRoad West mangrove habitat

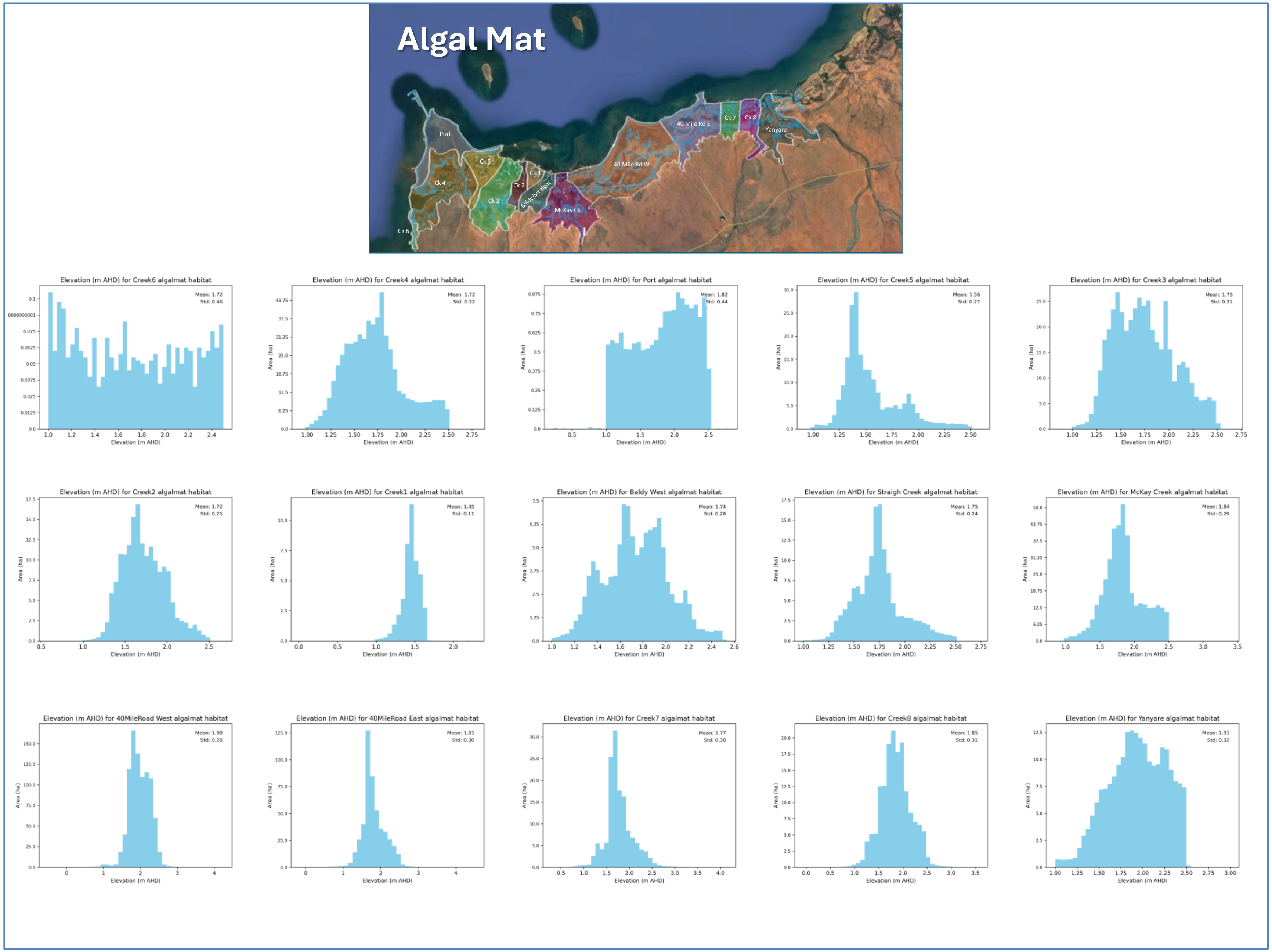

Elevation (m AHD) for 40MileRoad East mangrove habitat


Elevation (m AHD) for Creek7 mangrove habitat


Elevation (m AHD) for Creek8 mangrove habitat


Elevation (m AHD) for Yanyare mangrove habitat


Samphire
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
Elevation (m AHD) for Creek4 samphire habitat
Mean: 1.79
Std: 0.55
Area (ha)
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5
−1 0 1 2 3 4 5 6 7
Elevation (m AHD)
Elevation (m AHD) for Creek5 samphire habitat
Mean: 1.84
Std: 0.59
Area (ha)
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5
1.0 1.5 2.0 2.5 3.0 3.5 4.0
Elevation (m AHD)
Elevation (m AHD) for Creek3 samphire habitat
Mean: 2.17
Std: 0.79
Area (ha)
0.0 5.0 10.0 15.0 20.0 25.0
0 1 2 3 4 5
Elevation (m AHD)
Elevation (m AHD) for Creek2 samphire habitat
Mean: 1.81
Std: 0.50
Area (ha)
0.0 0.625 1.25 1.875 2.5 3.125 3.75 4.375 5.0
0 1 2 3 4
Elevation (m AHD)
Elevation (m AHD) for Creek1 samphire habitat
Mean: 1.44
Std: 0.04
Area (ha)
0.0 0.05 0.1 0.15 0.2 0.25
1.30 1.35 1.40 1.45 1.50 1.55 1.60 1.65
Elevation (m AHD)
Elevation (m AHD) for Baldy West samphire habitat
Mean: 2.45
Std: 0.47
Area (ha)
0.0 0.125 0.25 0.375 0.5 0.625 0.75 0.875
1.5 2.0 2.5 3.0 3.5 4.0
Elevation (m AHD)
Elevation (m AHD) for Straigh Creek samphire habitat
Mean: 1.97
Std: 0.40
Area (ha)
0.0 0.625 1.25 1.875 2.5 3.125 3.75 4.375 5.0
0.5 1.0 1.5 2.0 2.5 3.0 3.5
Elevation (m AHD)
Elevation (m AHD) for McKay Creek samphire habitat
Mean: 2.34
Std: 0.55
Area (ha)
0.0 2.5 5.0 7.5 10.0 12.5
0 1 2 3 4
Elevation (m AHD)
Elevation (m AHD) for 40MileRoad West samphire habitat
Mean: 2.43
Std: 0.41
Area (ha)
0.0 12.5 25.0 37.5 50.0
1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Elevation (m AHD)
Elevation (m AHD) for 40MileRoad East samphire habitat
Mean: 2.26
Std: 0.52
Area (ha)
0.0 5.0 10.0 15.0 20.0 25.0 30.0
0 1 2 3 4 5 6 7
Elevation (m AHD)
Elevation (m AHD) for Creek7 samphire habitat
Mean: 2.17
Std: 0.39
Area (ha)
0.0 0.625 1.25 1.875 2.5 3.125 3.75 4.375
1.0 1.5 2.0 2.5 3.0 3.5 4.0
Elevation (m AHD)
Elevation (m AHD) for Creek8 samphire habitat
Mean: 2.09
Std: 0.43
Area (ha)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
Elevation (m AHD)



Algal Mat

Elevation (m AHD) for Creek6 algalmat habitat

Elevation (m AHD) for Creek4 algalmat habitat

Elevation (m AHD) for Port algalmat habitat

Elevation (m AHD) for Creek5 algalmat habitat

Elevation (m AHD) for Creek3 algalmat habitat

Elevation (m AHD) for Creek2 algalmat habitat

Elevation (m AHD) for Creek1 algalmat habitat

Elevation (m AHD) for Baldy West algalmat habitat

Elevation (m AHD) for Straigh Creek algalmat habitat

Elevation (m AHD) for McKay Creek algalmat habitat

Elevation (m AHD) for 40MileRoad West algalmat habitat

Elevation (m AHD) for 40MileRoad East algalmat habitat

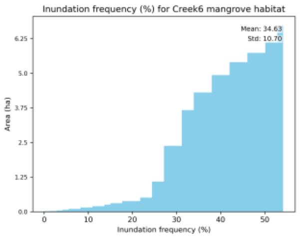
Elevation (m AHD) for Creek7 algalmat habitat

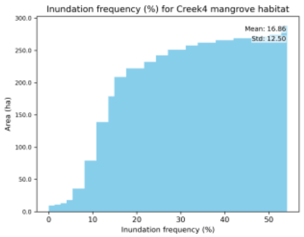
Elevation (m AHD) for Creek8 algalmat habitat

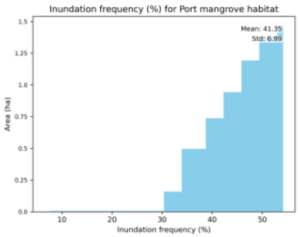
Elevation (m AHD) for Yanyare algalmat habitat

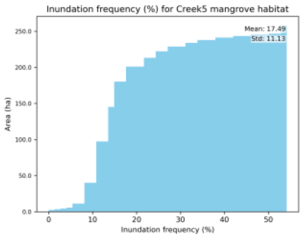
35. Frequency of inundation of BCH areas for each catchment

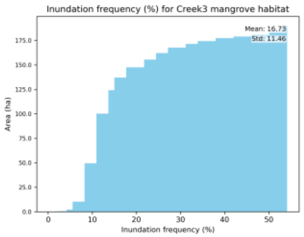

Mangrove
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

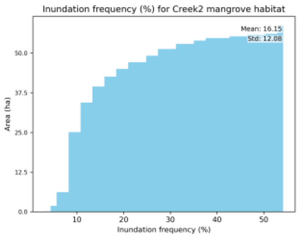

Inundation frequency (%) for Creek6 mangrove habitat
Mean: 34.63
Std: 10.70
Area (ha)
0.0
1.25
2.5
3.75
5.0
6.25
0
10
20
30
40
50
Inundation frequency (%)

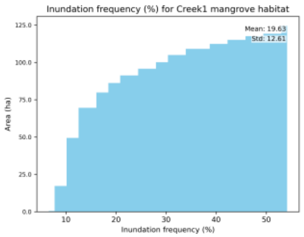

Inundation frequency (%) for Creek4 mangrove habitat
Mean: 16.86
Std: 12.50
Area (ha)
0.0
50.0
100.0
150.0
200.0
250.0
300.0
0
10
20
30
40
50
Inundation frequency (%)

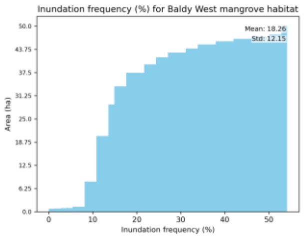

Inundation frequency (%) for Port mangrove habitat
Mean: 41.35
Std: 6.99
Area (ha)
0.0
0.25
0.5
0.75
1.0
1.25
1.5
10
20
30
40
50
Inundation frequency (%)

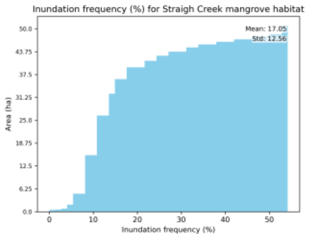

Inundation frequency (%) for Creek5 mangrove habitat
Mean: 17.49
Std: 11.13
Area (ha)
0.0
50.0
100.0
150.0
200.0
250.0
0
10
20
30
40
50
Inundation frequency (%)

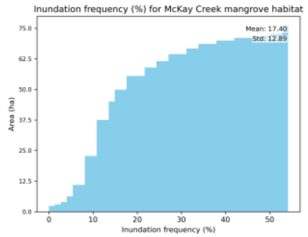

Inundation frequency (%) for Creek3 mangrove habitat
Mean: 16.73
Std: 11.46
Area (ha)
0.0
25.0
50.0
75.0
100.0
125.0
150.0
175.0
0
10
20
30
40
50
Inundation frequency (%)

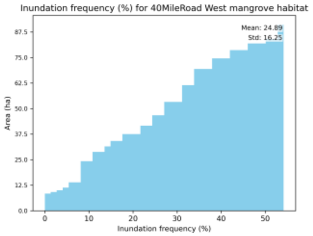

Inundation frequency (%) for Creek2 mangrove habitat
Mean: 16.15
Std: 12.08
Area (ha)
0.0
12.5
25.0
37.5
50.0
10
20
30
40
50
Inundation frequency (%)

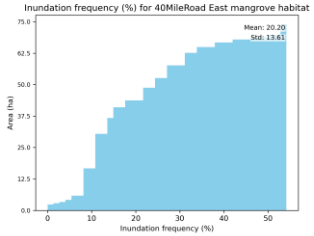

Inundation frequency (%) for Creek1 mangrove habitat
Mean: 19.63
Std: 12.61
Area (ha)
0.0
25.0
50.0
75.0
100.0
125.0
10
20
30
40
50
Inundation frequency (%)

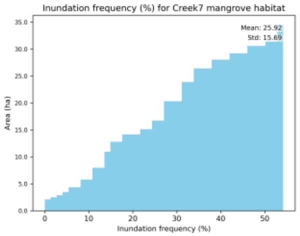

Inundation frequency (%) for Baldy West mangrove habitat
Mean: 18.26
Std: 12.15
Area (ha)
0.0
6.25
12.5
18.75
25.0
31.25
37.5
43.75
50.0
0
10
20
30
40
50
Inundation frequency (%)

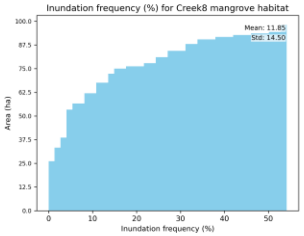

Inundation frequency (%) for Straigh Creek mangrove habitat
Mean: 17.05
Std: 12.56
Area (ha)
0.0
6.25
12.5
18.75
25.0
31.25
37.5
43.75
50.0
0
10
20
30
40
50
Inundation frequency (%)

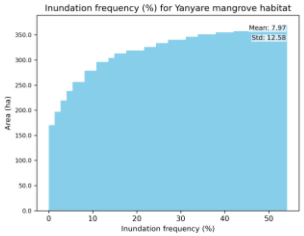

Inundation frequency (%) for McKay Creek mangrove habitat
Mean: 17.40
Std: 12.89
Area (ha)
0.0
12.5
25.0
37.5
50.0
62.5
75.0
0
10
20
30
40
50
Inundation frequency (%)

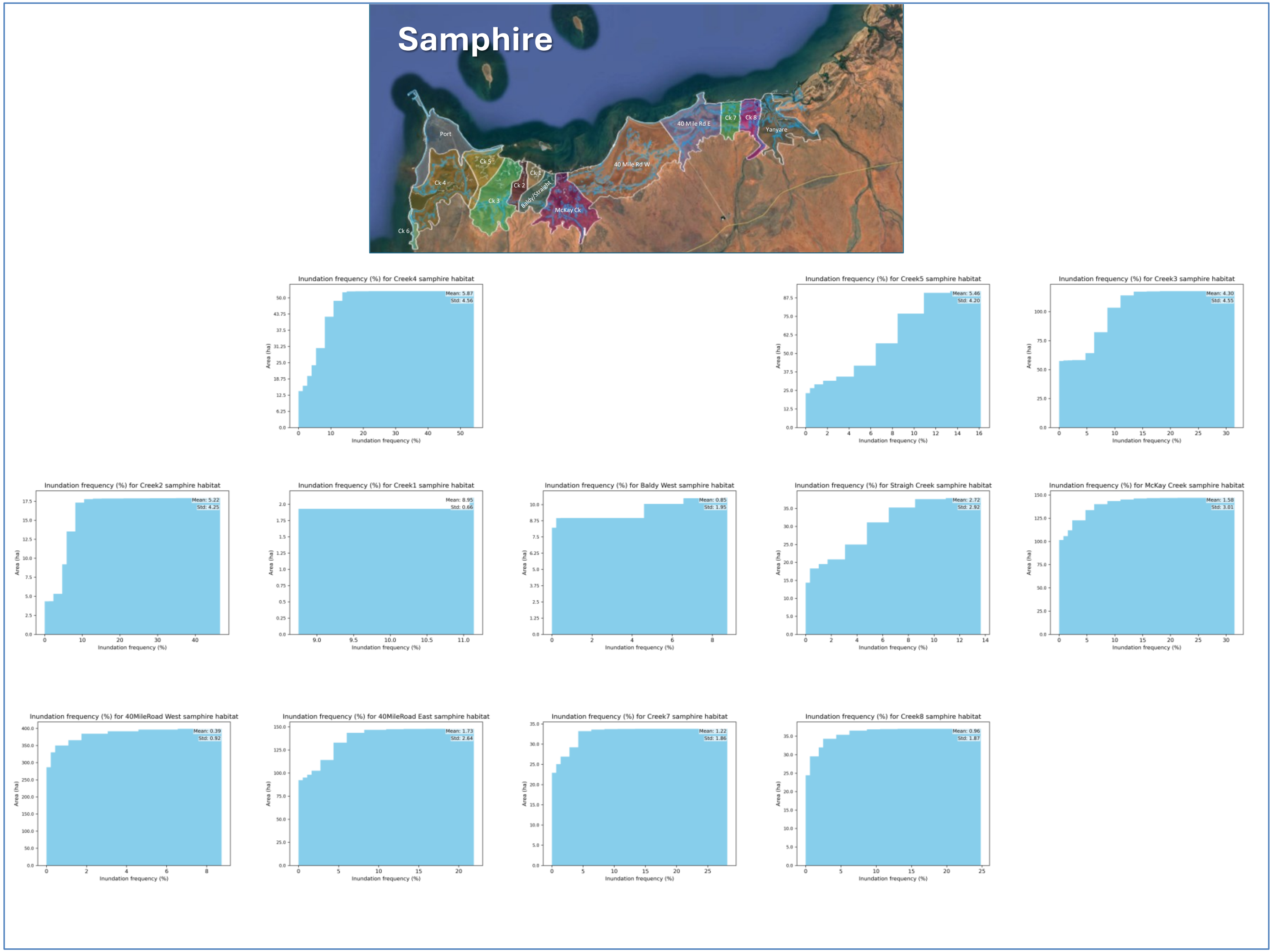

Inundation frequency (%) for 40MileRoad West mangrove habitat
Mean: 24.89
Std: 16.25
Area (ha)
0.0
12.5
25.0
37.5
50.0
62.5
75.0
87.5
0
10
20
30
40
50
Inundation frequency (%)

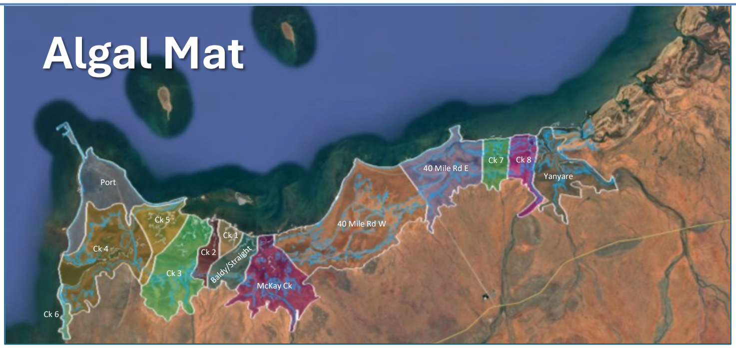

Inundation frequency (%) for 40MileRoad East mangrove habitat
Mean: 20.20
Std: 13.61
Area (ha)
0.0
12.5
25.0
37.5
50.0
62.5
75.0
0
10
20
30
40
50
Inundation frequency (%)

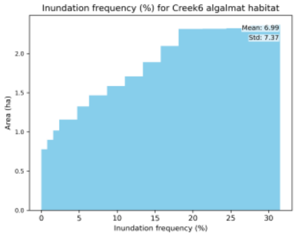

Inundation frequency (%) for Creek7 mangrove habitat
Mean: 25.92
Std: 15.69
Area (ha)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
0
10
20
30
40
50
Inundation frequency (%)

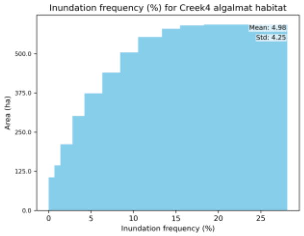

Inundation frequency (%) for Creek8 mangrove habitat
Mean: 11.85
Std: 14.50
Area (ha)
0.0
12.5
25.0
37.5
50.0
62.5
75.0
87.5
100.0
0
10
20
30
40
50
Inundation frequency (%)

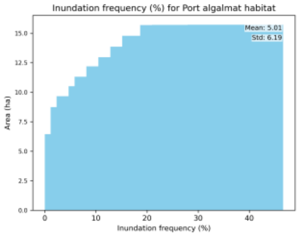

Inundation frequency (%) for Yanyare mangrove habitat
Mean: 7.97
Std: 12.58
Area (ha)
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
0
10
20
30
40
50
Inundation frequency (%)

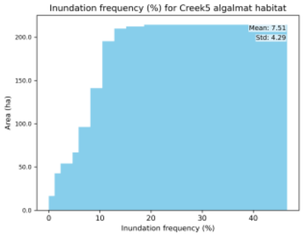

Samphire
Port
Ck 4
Ck 5
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6
Inundation frequency (%) for Creek4 samphire habitat
Mean: 5.87
Std: 4.56
Inundation frequency (%) for Creek5 samphire habitat
Mean: 5.46
Std: 4.20
Inundation frequency (%) for Creek3 samphire habitat
Mean: 4.30
Std: 4.55
Inundation frequency (%) for Creek2 samphire habitat
Mean: 5.22
Std: 4.25
Inundation frequency (%) for Creek1 samphire habitat
Mean: 8.95
Std: 0.66
Inundation frequency (%) for Baldy West samphire habitat
Mean: 0.85
Std: 1.95
Inundation frequency (%) for Straigh Creek samphire habitat
Mean: 2.72
Std: 2.92
Inundation frequency (%) for McKay Creek samphire habitat
Mean: 1.58
Std: 3.01
Inundation frequency (%) for 40MileRoad West samphire habitat
Mean: 0.39
Std: 0.92
Inundation frequency (%) for 40MileRoad East samphire habitat
Mean: 1.73
Std: 2.64
Inundation frequency (%) for Creek7 samphire habitat
Mean: 1.22
Std: 1.86
Inundation frequency (%) for Creek8 samphire habitat
Mean: 0.96
Std: 1.87
Area (ha)
Inundation frequency (%)

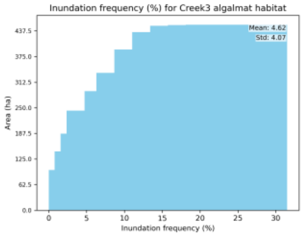

Algal Mat
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

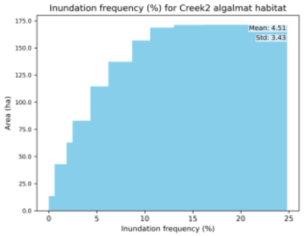

Inundation frequency (%) for Creek6 algalmat habitat
Mean: 6.99
Std: 7.37
Area (ha)
0.0
0.5
1.0
1.5
2.0
0
5
10
15
20
25
30
Inundation frequency (%)

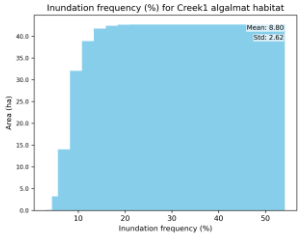

Inundation frequency (%) for Creek4 algalmat habitat
Mean: 4.98
Std: 4.25
Area (ha)
0.0
125.0
250.0
375.0
500.0
0
5
10
15
20
25
Inundation frequency (%)

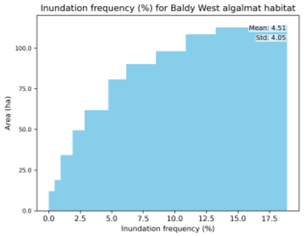

Inundation frequency (%) for Port algalmat habitat
Mean: 5.01
Std: 6.19
Area (ha)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
0
10
20
30
40
Inundation frequency (%)

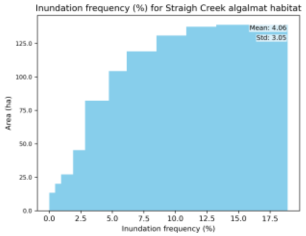

Inundation frequency (%) for Creek5 algalmat habitat
Mean: 7.51
Std: 4.29
Area (ha)
0.0
50.0
100.0
150.0
200.0
0
10
20
30
40
Inundation frequency (%)

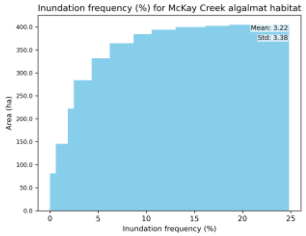

Inundation frequency (%) for Creek3 algalmat habitat
Mean: 4.62
Std: 4.07
Area (ha)
0.0
62.5
125.0
187.5
250.0
312.5
375.0
437.5
0
5
10
15
20
25
30
Inundation frequency (%)

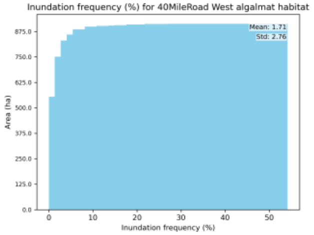

Inundation frequency (%) for Creek2 algalmat habitat
Mean: 4.51
Std: 3.43
Area (ha)
0.0
25.0
50.0
75.0
100.0
125.0
150.0
175.0
0
5
10
15
20
25
Inundation frequency (%)

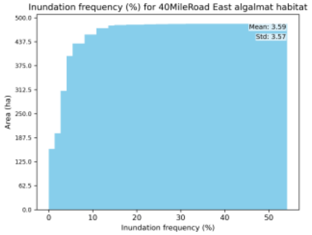

Inundation frequency (%) for Creek1 algalmat habitat
Mean: 8.80
Std: 2.62
Area (ha)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
10
20
30
40
50
Inundation frequency (%)

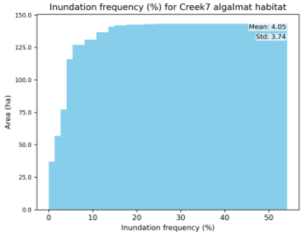

Inundation frequency (%) for Baldy West algalmat habitat
Mean: 4.51
Std: 4.05
Area (ha)
0.0
25.0
50.0
75.0
100.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
Inundation frequency (%)

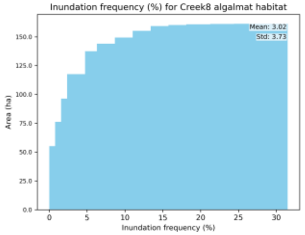

Inundation frequency (%) for Straigh Creek algalmat habitat
Mean: 4.06
Std: 3.05
Area (ha)
0.0
25.0
50.0
75.0
100.0
125.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
Inundation frequency (%)

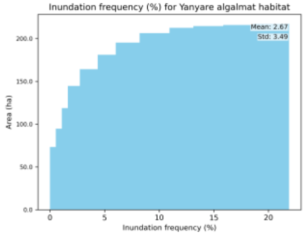

Inundation frequency (%) for McKay Creek algalmat habitat
Mean: 3.22
Std: 3.38
Area (ha)
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
0
5
10
15
20
25
Inundation frequency (%)


Inundation frequency (%) for 40MileRoad West algalmat habitat
Mean: 1.71
Std: 2.76
Area (ha)
0.0
125.0
250.0
375.0
500.0
625.0
750.0
875.0
0
10
20
30
40
50
Inundation frequency (%)

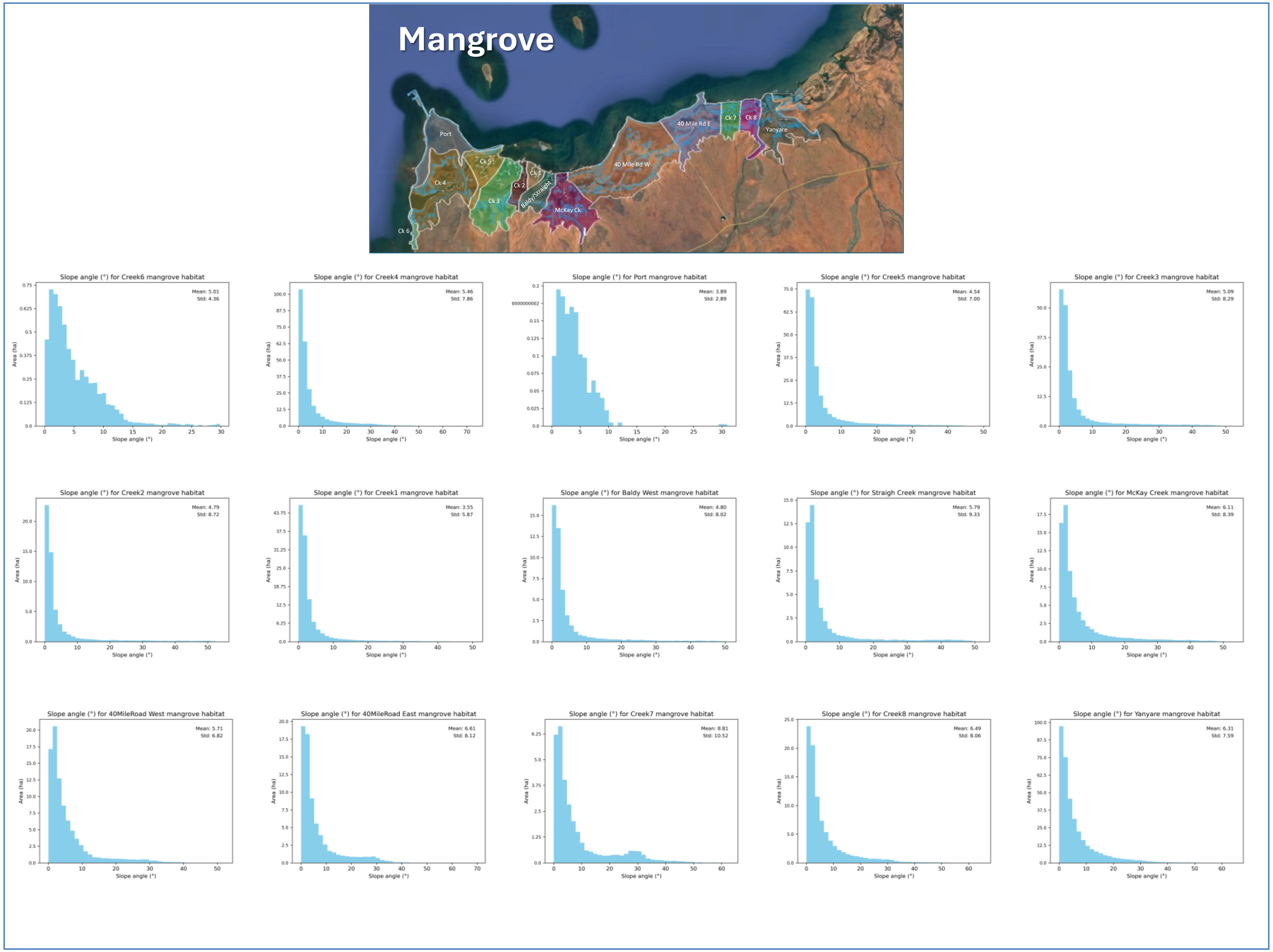

Inundation frequency (%) for 40MileRoad East algalmat habitat
Mean: 3.59
Std: 3.57
Area (ha)
0.0
62.5
125.0
187.5
250.0
312.5
375.0
437.5
500.0
0
10
20
30
40
50
Inundation frequency (%)

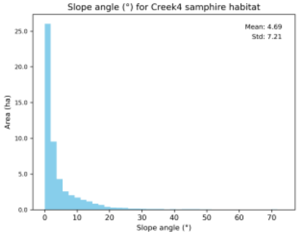

Inundation frequency (%) for Creek7 algalmat habitat
Mean: 4.05
Std: 3.74
Area (ha)
0.0
25.0
50.0
75.0
100.0
125.0
150.0
0
10
20
30
40
50
Inundation frequency (%)

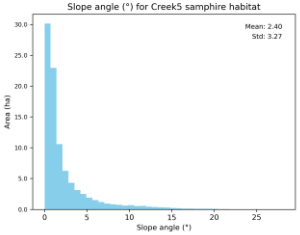

Inundation frequency (%) for Creek8 algalmat habitat
Mean: 3.02
Std: 3.73
Area (ha)
0.0
25.0
50.0
75.0
100.0
125.0
150.0
0
5
10
15
20
25
30
Inundation frequency (%)

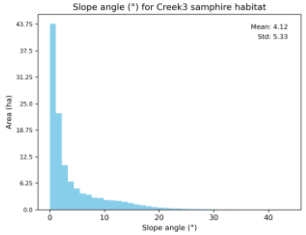

Inundation frequency (%) for Yanyare algalmat habitat
Mean: 2.67
Std: 3.49
Area (ha)
0.0
50.0
100.0
150.0
200.0
0
5
10
15
20
Inundation frequency (%)

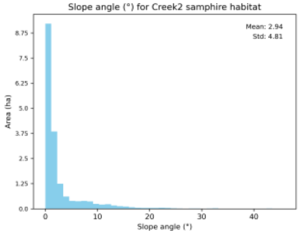
36. Bed slopes of BCH areas for each catchment

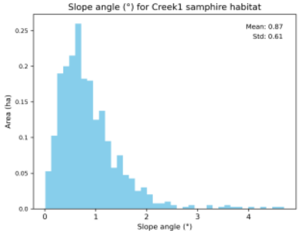

Mangrove
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6
Slope angle (°) for Creek6 mangrove habitat
Mean: 5.01
Std: 4.36
Slope angle (°) for Creek4 mangrove habitat
Mean: 5.46
Std: 7.86
Slope angle (°) for Port mangrove habitat
Mean: 3.89
Std: 2.89
Slope angle (°) for Creek5 mangrove habitat
Mean: 4.54
Std: 7.00
Slope angle (°) for Creek3 mangrove habitat
Mean: 5.09
Std: 8.29
Slope angle (°) for Creek2 mangrove habitat
Mean: 4.79
Std: 8.72
Slope angle (°) for Creek1 mangrove habitat
Mean: 3.55
Std: 5.87
Slope angle (°) for Baldy West mangrove habitat
Mean: 4.80
Std: 8.02
Slope angle (°) for Straigh Creek mangrove habitat
Mean: 5.79
Std: 9.33
Slope angle (°) for McKay Creek mangrove habitat
Mean: 6.11
Std: 8.39
Slope angle (°) for 40MileRoad West mangrove habitat
Mean: 5.71
Std: 6.82
Slope angle (°) for 40MileRoad East mangrove habitat
Mean: 6.61
Std: 8.12
Slope angle (°) for Creek7 mangrove habitat
Mean: 8.81
Std: 10.52
Slope angle (°) for Creek8 mangrove habitat
Mean: 6.49
Std: 8.06
Slope angle (°) for Yanyare mangrove habitat
Mean: 6.31
Std: 7.59
Area (ha)
Slope angle (°)

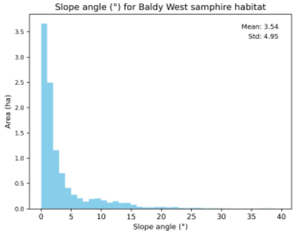

Slope angle (°) for Creek4 samphire habitat

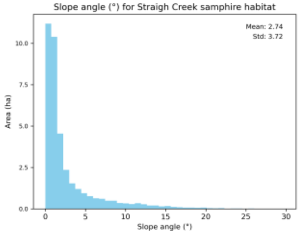

Slope angle (°) for Creek5 samphire habitat

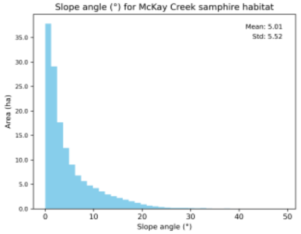

Slope angle (°) for Creek3 samphire habitat

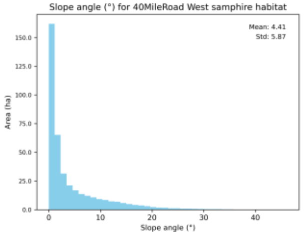

Slope angle (°) for Creek2 samphire habitat

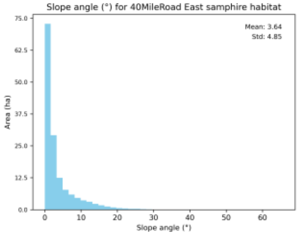

Slope angle (°) for Creek1 samphire habitat

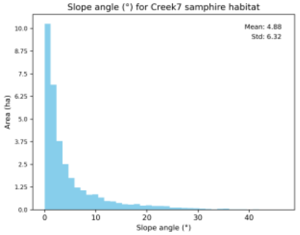

Slope angle (°) for Baldy West samphire habitat

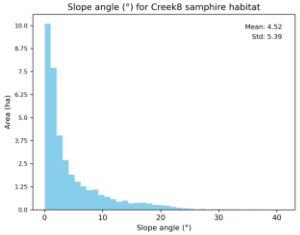

Slope angle (°) for Straigh Creek samphire habitat

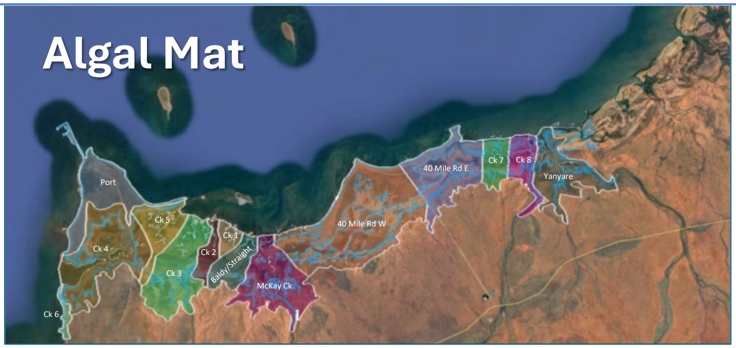

Slope angle (°) for McKay Creek samphire habitat

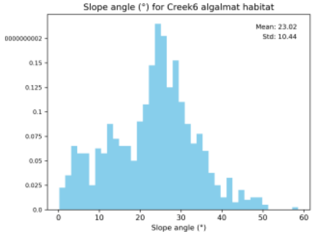

Slope angle (°) for 40MileRoad West samphire habitat

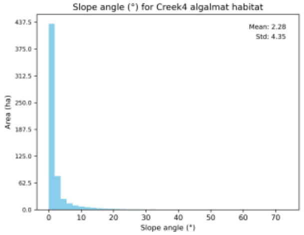

Slope angle (°) for 40MileRoad East samphire habitat

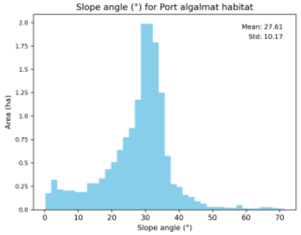

Slope angle (°) for Creek7 samphire habitat

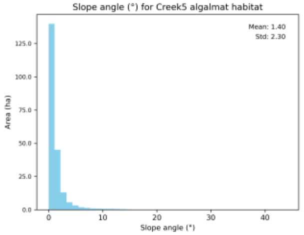

Slope angle (°) for Creek8 samphire habitat

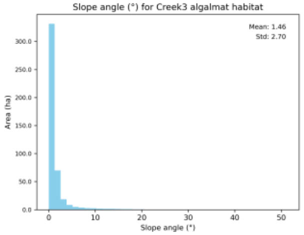

Algal Mat
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

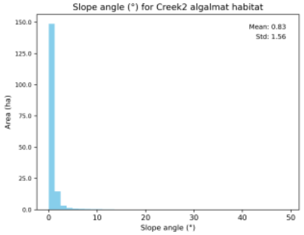

Slope angle (°) for Creek6 algalmat habitat
Mean: 23.02
Std: 10.44
0.0 0.025 0.05 0.075 0.1 0.125 0.15 0000000002
0 10 20 30 40 50 60
Slope angle (°)

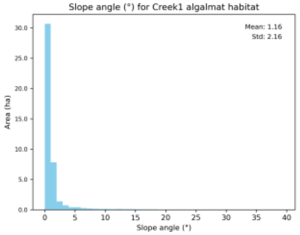

Slope angle (°) for Creek4 algalmat habitat
Mean: 2.28
Std: 4.35
Area (ha)
0.0 62.5 125.0 187.5 250.0 312.5 375.0 437.5
0 10 20 30 40 50 60 70
Slope angle (°)

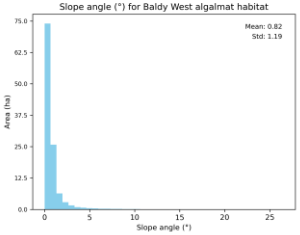

Slope angle (°) for Port algalmat habitat
Mean: 27.61
Std: 10.17
Area (ha)
0.0 0.25 0.5 0.75 1.0 1.25 1.5 1.75 2.0
0 10 20 30 40 50 60 70
Slope angle (°)

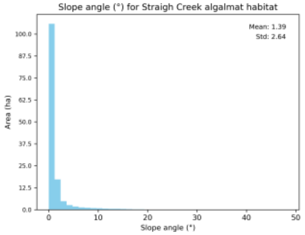

Slope angle (°) for Creek5 algalmat habitat
Mean: 1.40
Std: 2.30
Area (ha)
0.0 25.0 50.0 75.0 100.0 125.0
0 10 20 30 40
Slope angle (°)

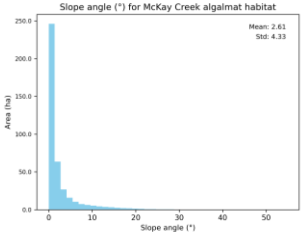

Slope angle (°) for Creek3 algalmat habitat
Mean: 1.46
Std: 2.70
Area (ha)
0.0 50.0 100.0 150.0 200.0 250.0 300.0
0 10 20 30 40 50
Slope angle (°)

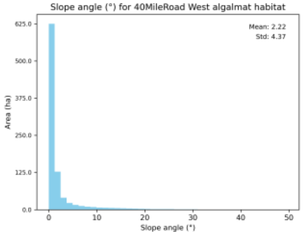

Slope angle (°) for Creek2 algalmat habitat
Mean: 0.83
Std: 1.56
Area (ha)
0.0 25.0 50.0 75.0 100.0 125.0 150.0
0 10 20 30 40 50
Slope angle (°)

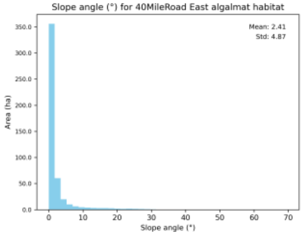

Slope angle (°) for Creek1 algalmat habitat
Mean: 1.16
Std: 2.16
Area (ha)
0.0 5.0 10.0 15.0 20.0 25.0 30.0
0 5 10 15 20 25 30 35 40
Slope angle (°)

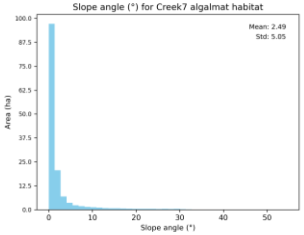

Slope angle (°) for Baldy West algalmat habitat
Mean: 0.82
Std: 1.19
Area (ha)
0.0 12.5 25.0 37.5 50.0 62.5 75.0
0 5 10 15 20 25
Slope angle (°)

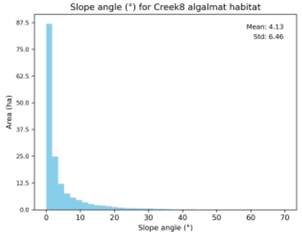

Slope angle (°) for Straigh Creek algalmat habitat
Mean: 1.39
Std: 2.64
Area (ha)
0.0 12.5 25.0 37.5 50.0 62.5 75.0 87.5 100.0
0 10 20 30 40 50
Slope angle (°)

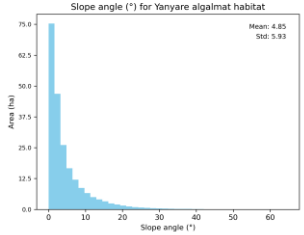

Slope angle (°) for McKay Creek algalmat habitat
Mean: 2.61
Std: 4.33
Area (ha)
0.0 50.0 100.0 150.0 200.0 250.0
0 10 20 30 40 50
Slope angle (°)


Slope angle (°) for 40MileRoad West algalmat habitat
Mean: 2.22
Std: 4.37
Area (ha)
0.0 125.0 250.0 375.0 500.0 625.0
0 10 20 30 40 50
Slope angle (°)


Slope angle (°) for 40MileRoad East algalmat habitat
Mean: 2.41
Std: 4.87
Area (ha)
0.0 50.0 100.0 150.0 200.0 250.0 300.0 350.0
0 10 20 30 40 50 60 70
Slope angle (°)


Slope angle (°) for Creek7 algalmat habitat
Mean: 2.49
Std: 5.05
Area (ha)
0.0 12.5 25.0 37.5 50.0 62.5 75.0 87.5 100.0
0 10 20 30 40 50
Slope angle (°)


Slope angle (°) for Creek8 algalmat habitat
Mean: 4.13
Std: 6.46
Area (ha)
0.0 12.5 25.0 37.5 50.0 62.5 75.0 87.5
0 10 20 30 40 50 60 70
Slope angle (°)


Slope angle (°) for Yanyare algalmat habitat
Mean: 4.85
Std: 5.93
Area (ha)
0.0 12.5 25.0 37.5 50.0 62.5 75.0
0 10 20 30 40 50 60
Slope angle (°)

37. 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.

37.1. 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.

37.2. Benthic Mats

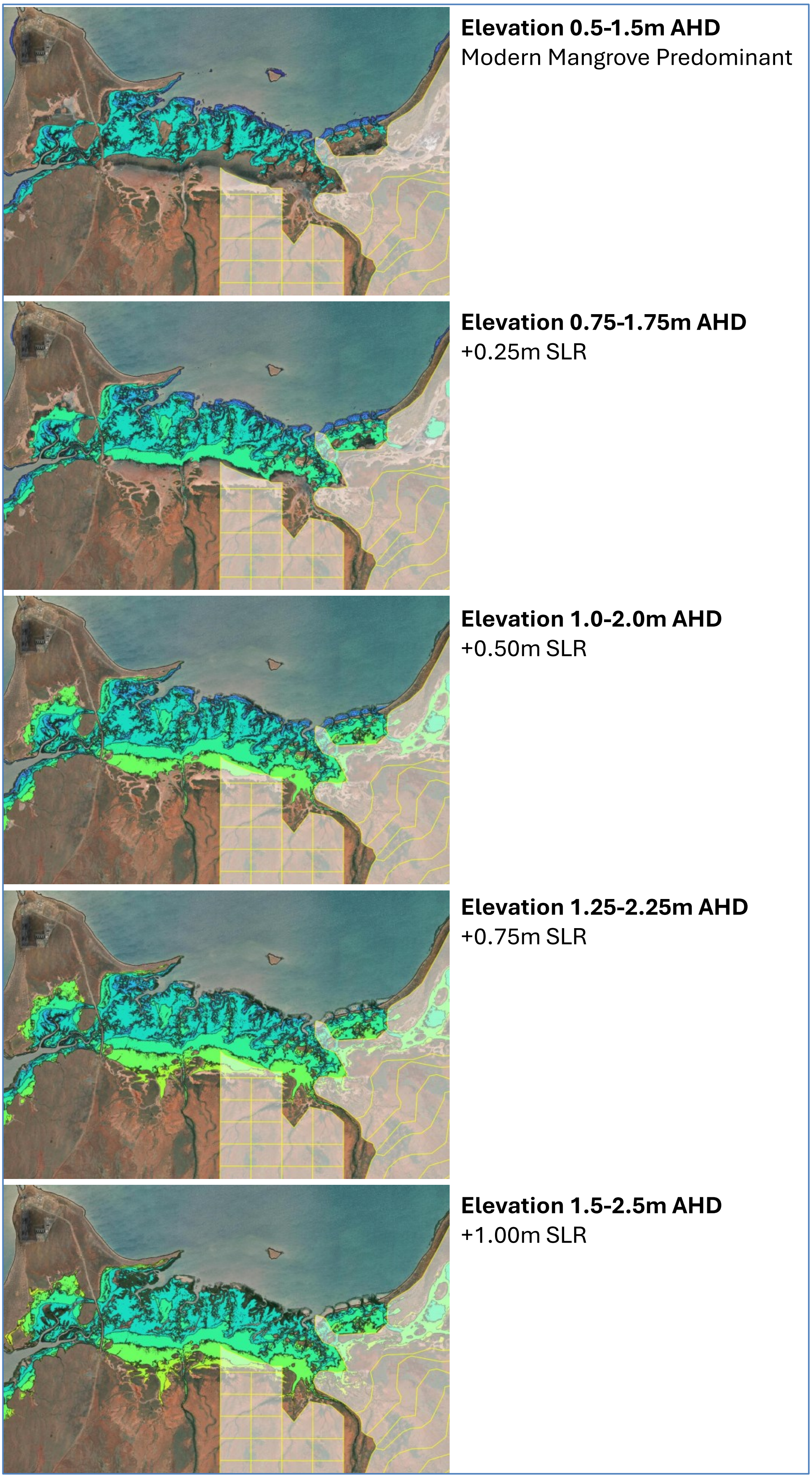
Translation of the present-day elevation zone for benthic mats indicates a progressive reduction of area with SLR, as these elevation zones are shifted from the wide salt flats on to the steeper hinterland. It is considered unlikely that migration of benthic mat habitats would correspond to this translation,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

37.3. 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

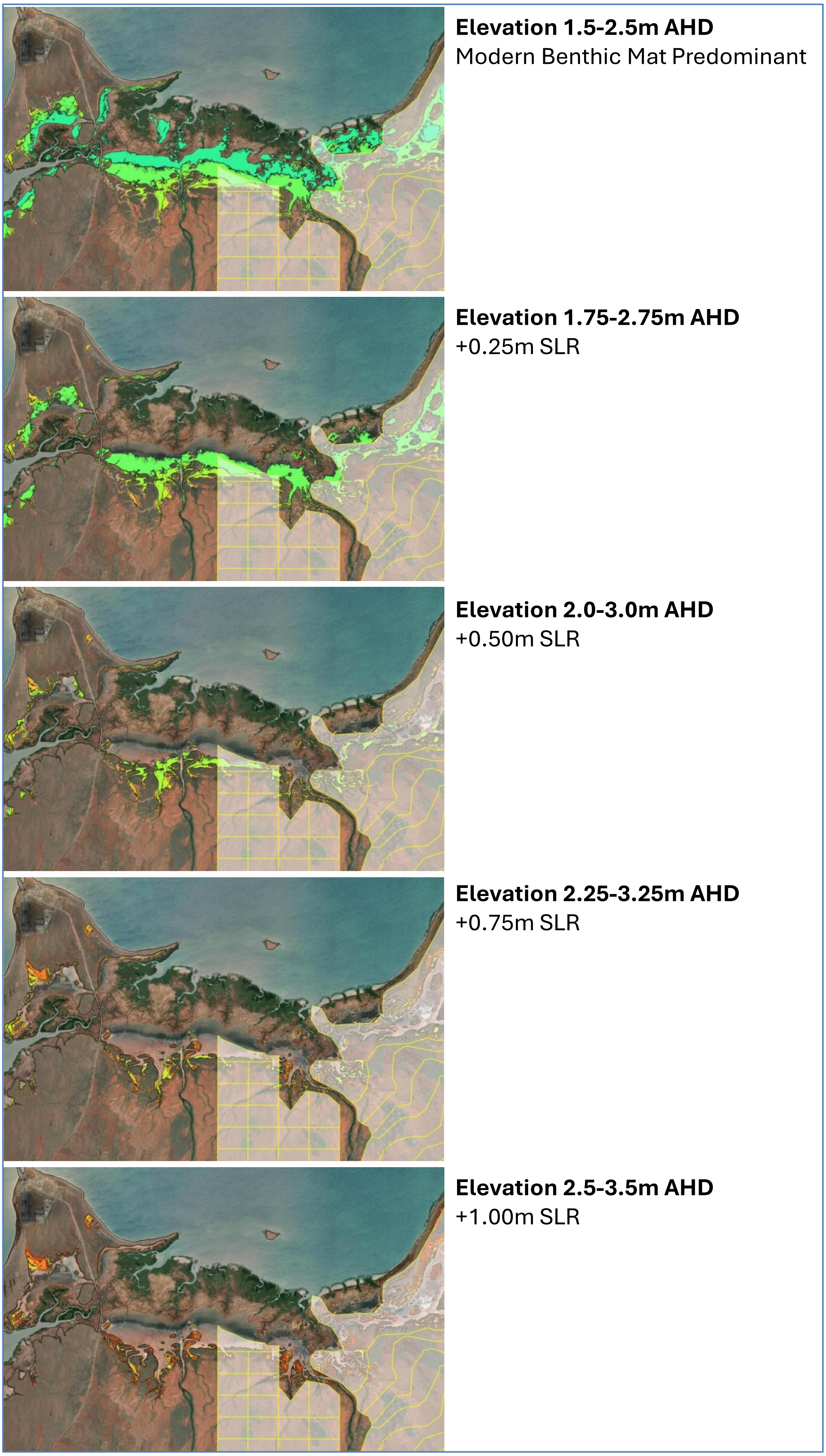
Elevation 0.75-1.75m AHD
+0.25m SLR

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 255. 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 256. Elevation Zone of Present-Day Benthic Mat (West).

Elevation 2.5-3.0m AHD
Modern Samphire Predominant

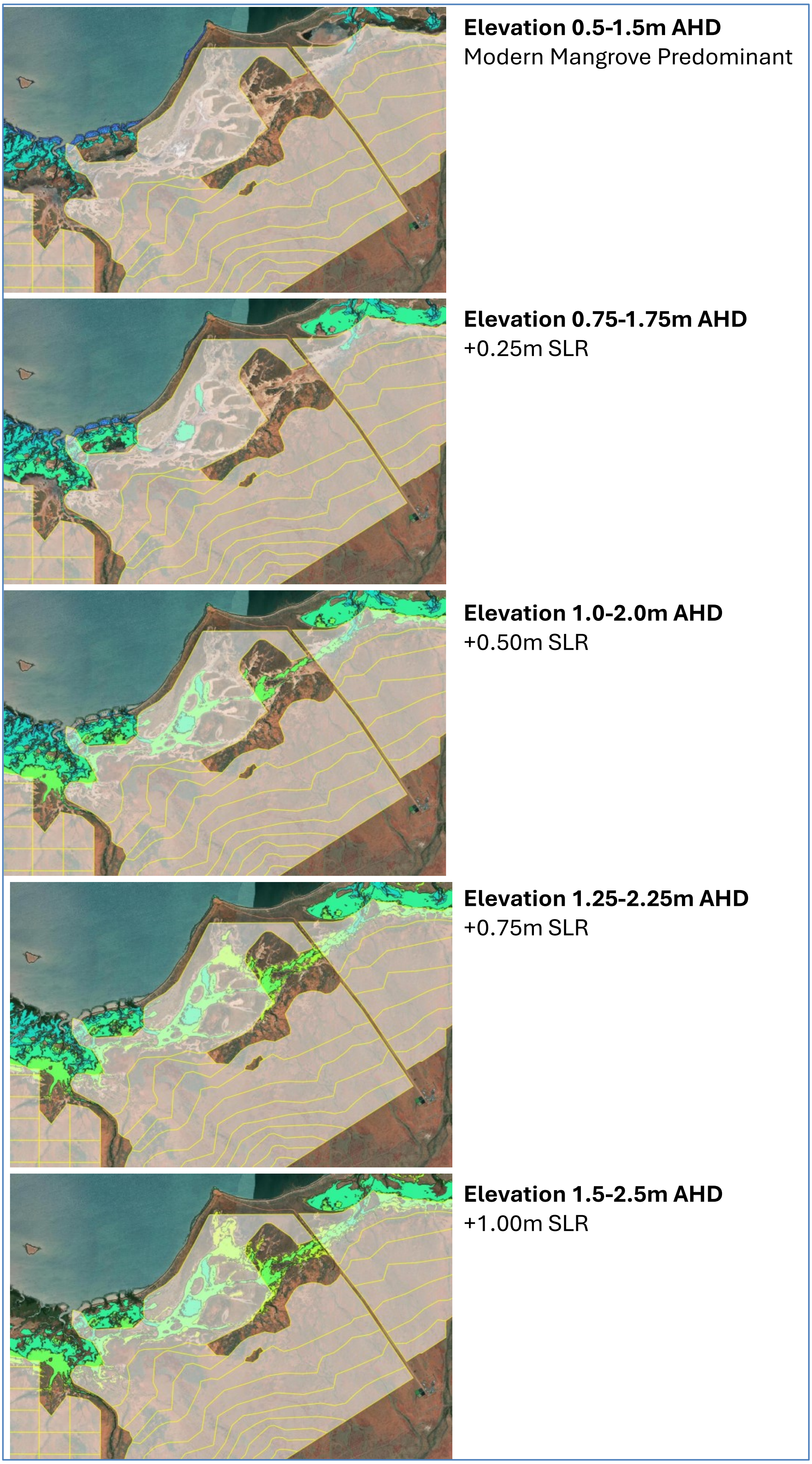
Elevation 2.75-3.25m AHD
+0.25m SLR

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 257. 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

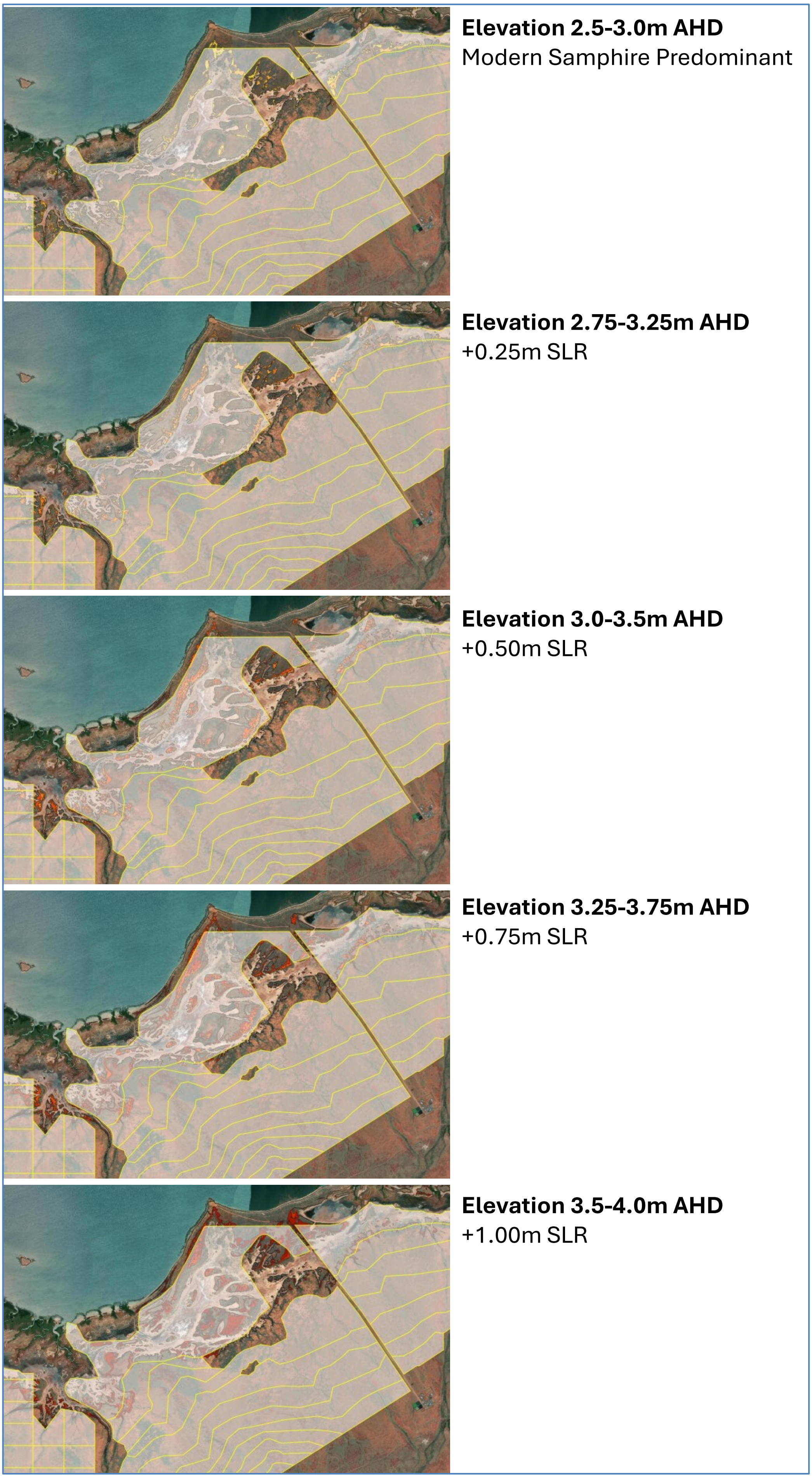
Elevation 1.0-2.0m AHD
+0.50m SLR

Elevation 1.25-2.25m AHD
+0.75m SLR

Elevation 1.5-2.5m AHD
+1.00m SLR

Figure 258. Elevation Zone of Present-Day Mangroves (Central).

Figure 259. 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 260. 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 261. 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

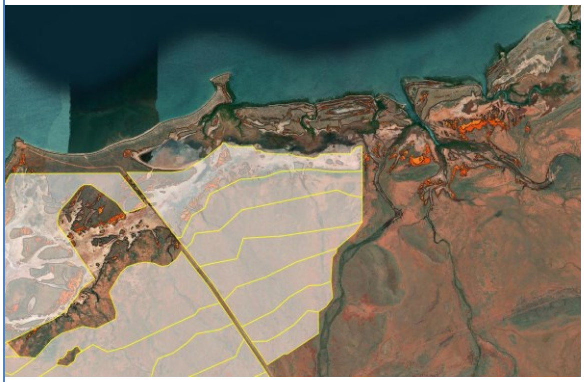
Figure 262. Elevation Zone of Present-Day Benthic Mat (East).

Elevation 2.5-3.0m AHD

Modern Samphire Predominant

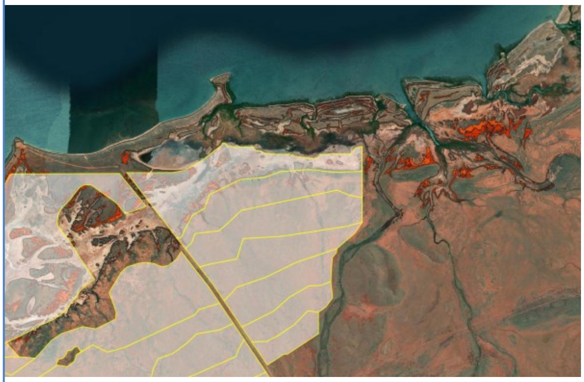
Elevation 2.75-3.25m AHD

+0.25m SLR



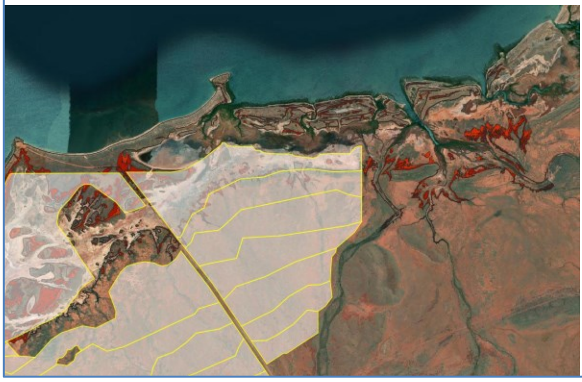
Elevation 3.0-3.5m AHD

+0.50m SLR



Elevation 3.25-3.75m AHD

+0.75m SLR

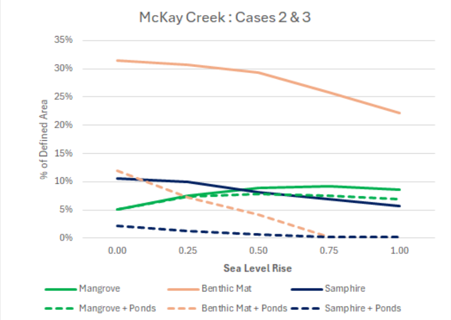


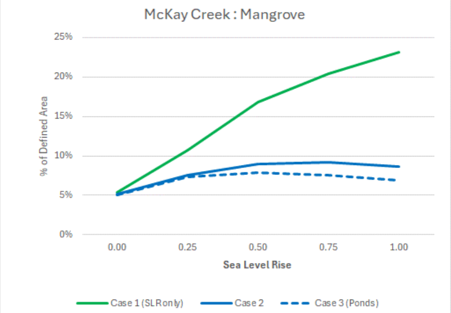
Elevation 3.5-4.0m AHD

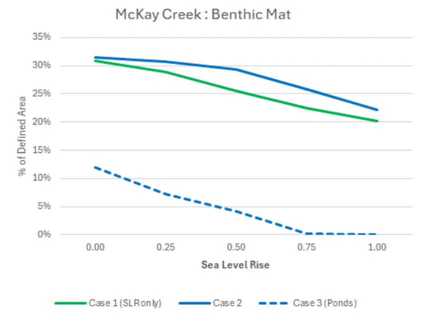
+1.00m SLR

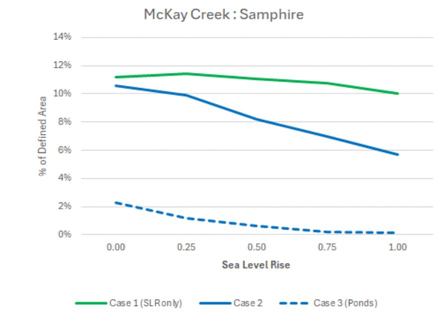
Figure 263. Elevation Zone of Present-Day Samphire (East).

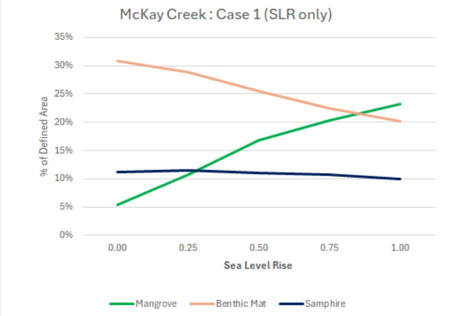
38. Plots of changes in BCHs

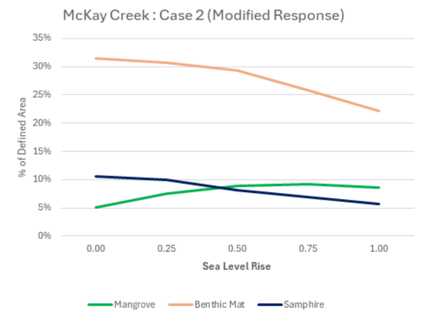

McKay Creek : Cases 2 & 3

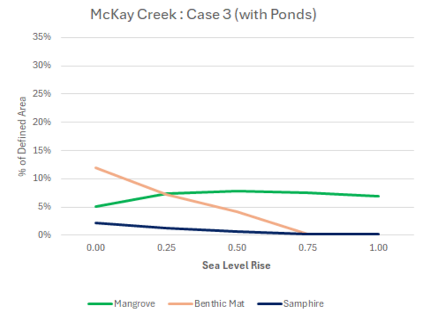

McKay Creek : Mangrove

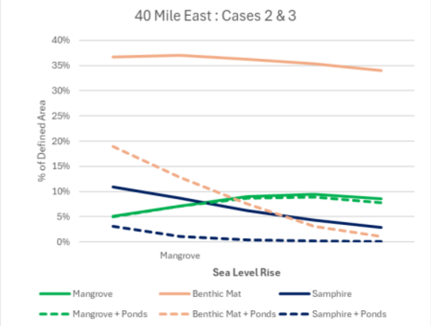

McKay Creek : Benthic Mat

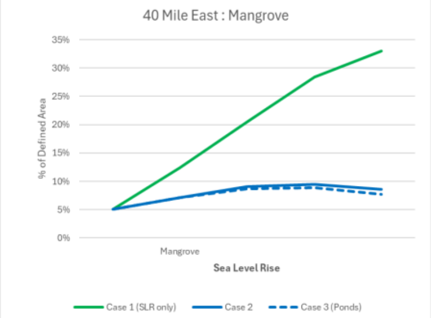

McKay Creek : Samphire

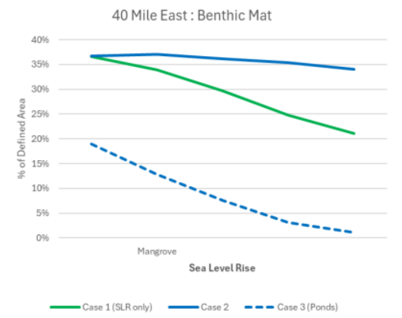

McKay Creek : Case 1 (SLR only)

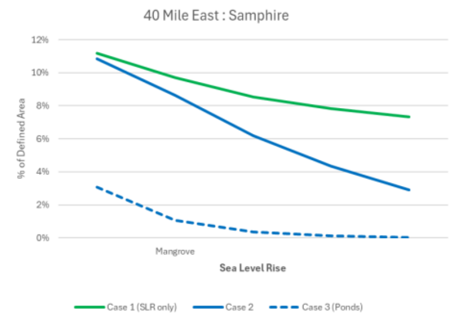

McKay Creek : Case 2 (Modified Response)

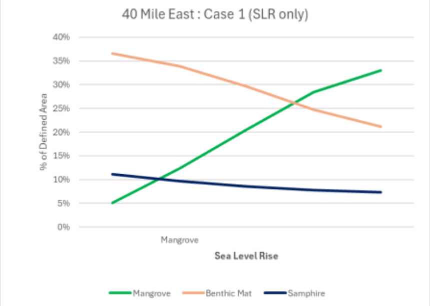

McKay Creek : Case 3 (with Ponds)

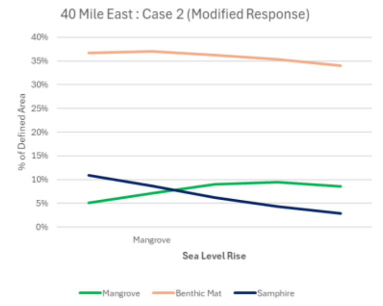

40 Mile East : Cases 2 & 3

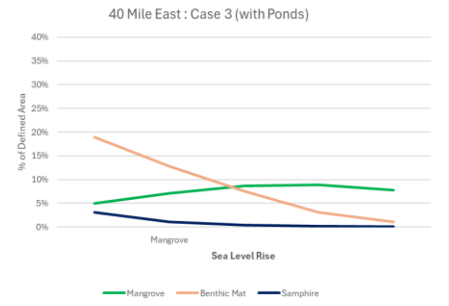

40 Mile East : Mangrove

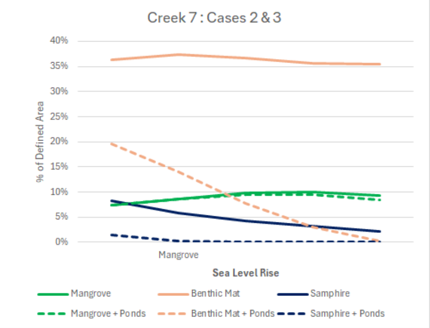

40 Mile East : Benthic Mat

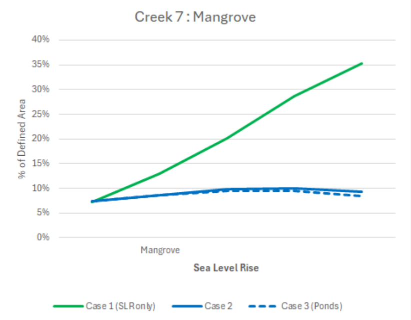

40 Mile East : Samphire

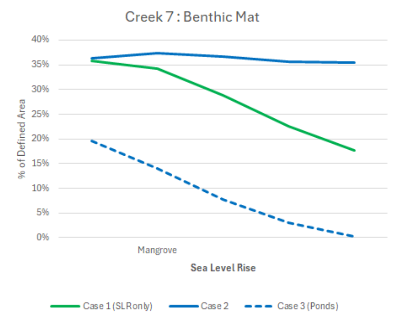

40 Mile East : Case 1 (SLR only)

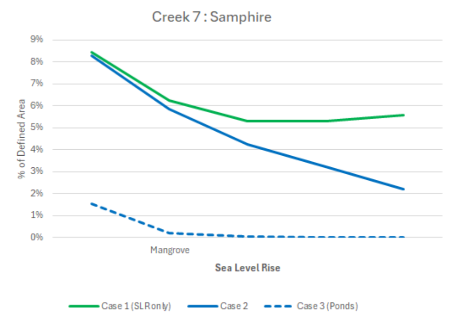

40 Mile East : Case 2 (Modified Response)

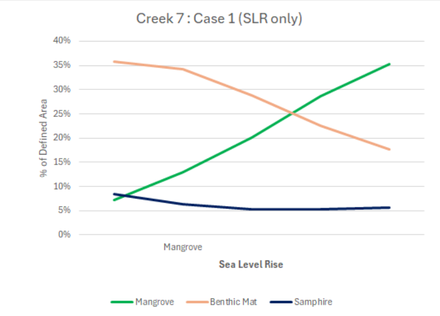

40 Mile East : Case 3 (with Ponds)

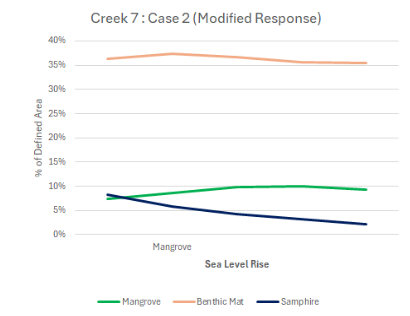

Creek 7 : Cases 2 & 3

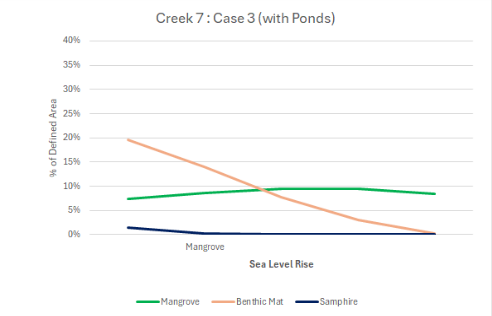

Creek 7 : Mangrove

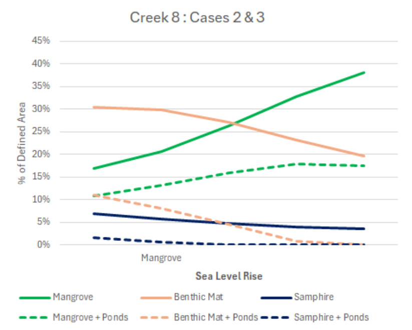

Creek 7 : Benthic Mat

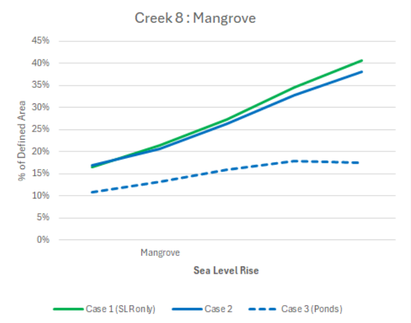

Creek 7 : Samphire

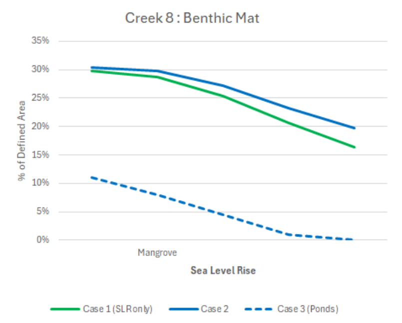

Creek 7 : Case 1 (SLR only)

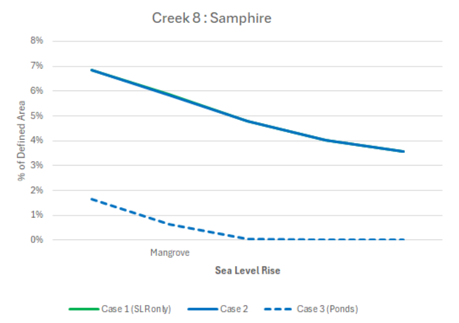

Creek 7 : Case 2 (Modified Response)

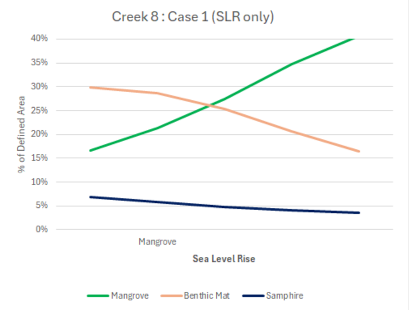

Creek 7 : Case 3 (with Ponds)

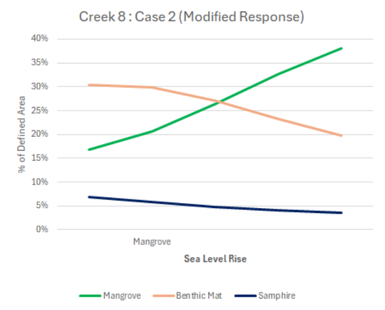

Creek 8 : Cases 2 & 3

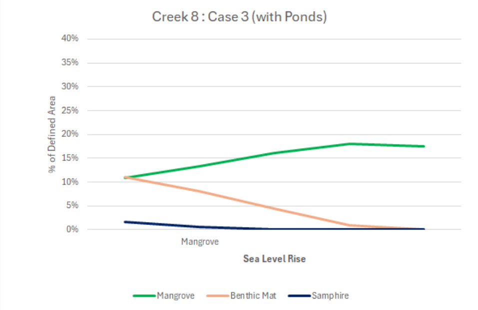

Creek 8 : Mangrove


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)