Characterising northern estuaries using Digital Earth Australia

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Project A12 - Scoping a seascape approach to managing and recovering Northern Australian threatened and migratory marine species

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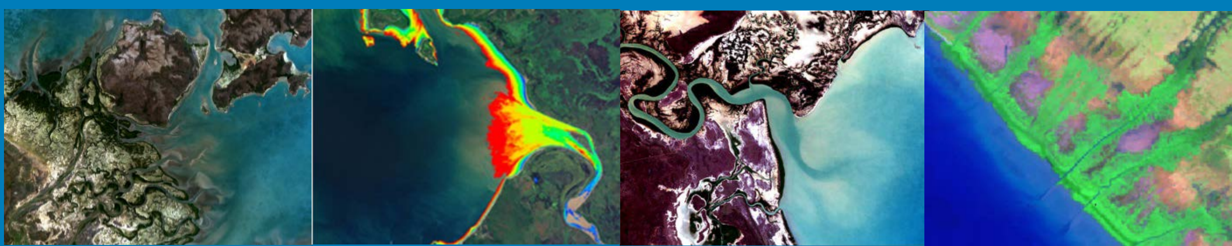
Milestone 15 – Research Plan v3 (2017)



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Important Disclaimer

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EXECUTIVE SUMMARY

This report provides a preliminary assessment of the utility of a satellite remote sensing approach for the identification and characterisation of coastal habitats that are critical for threatened and migratory species in northern Australia. This work is part of the Habitats research theme in the A12 Northern Seascapes Scoping Project. The Australian Landsat archive in the Digital Earth Australia (DEA) analysis platform for satellite imagery was utilised to demonstrate its potential for mapping intertidal areas and mangrove extent, and changes over time in the extent of coastal landforms and habitats.

Seven estuaries were examined, Darwin Harbour and the Keep, Daly, Roper, Macarthur, Flinders and Gilbert River estuaries. The estuaries were selected by the A12 Project team because they are known to provide important areas for the species of interest. Features of importance to shorebird populations were a focus. The focus of this scoping work was to utilise the DEA Landsat archive to build understanding of the effects of tidal dynamics on intertidal habitats across this region of large and complex tides, examine approaches to mapping the extent of key coastal habitats, and test the potential of the archive to detect coastal habitat change, in particular mangrove.

In northern Australia, cloud interference can make it difficult to obtain clear satellite imagery. To avoid this issue, the geometric median of surface reflectance values was used with tide-tagged imagery, subset by tide height and date, to produce crisp, cloud-free composite images that depict the maximum and minimum observed tidal extent in the seven estuaries.

Tide-tagging of satellite imagery was also successfully employed to allow any tide induced change to be removed from change-detection analyses and clearly depict the intertidal extent. Application of the Intertidal Extent Model in the DEA enabled the extent and morphology of estuarine intertidal environments to be mapped. The DEA also enabled habitat change detection using the fully processed, high density, three decade long Landsat time series. The results clearly depict the dynamic nature of some areas, including large-scale rapid island growth and mangrove expansion (e.g. Keep River and Gilbert River estuaries), gradual long-term expansion of mangrove (Flinders River and McArthur River estuaries), and estuaries with areas of rapid recent die back of mangrove (Roper River and Flinders estuaries). This information is important for the management of key species as well decisions around coastal developments. With Landsat and new satellite data streams (e.g. Sentinel 2) continually being added to the DEA, this time-series analysis approach could be developed into an effective habitat extent and condition monitoring tool for northern Australia.

The image products and analysis tools employed in this study demonstrate the potential utility of DEA for mapping the extent and dynamics of key coastal and estuarine habitats utilised by threatened and migratory species. To better inform the management of these species, a key next step in this approach is to utilise ground-validation data to enable these habitats to be robustly classified and quantified using the Landsat archive. This analysis should provide important baseline information and enable the extent and condition of key habitats to be monitored.

1. INTRODUCTION

This report provides a preliminary assessment of the utility of a satellite remote sensing approach for the identification and characterisation of coastal habitats that are critical for many threatened and migratory species in northern Australia. This work is part of the Habitats research theme in the A12 Northern Seascapes scoping project.

This project utilised the Australian Landsat archive in the Digital Earth Australia (DEA) analysis platform for satellite imagery and other Earth observations. The DEA incorporates advanced approaches to organising, analysing, and storing vast quantities of satellite data, enabling rapid, robust analysis across broad spatial and temporal dimensions (Lewis et al., 2016, 2017). The DEA Landsat archive comprises imagery for the entire continent with approximately fortnightly frequency of observation at 25 m resolution, continuously from 1987 to the present.

We test the potential of the DEA for mapping intertidal areas and mangrove extent, and changes over time in extent, in seven estuaries: Darwin Harbour and the Keep, Daly, Roper, Macarthur, Flinders and Gilbert River estuaries. The estuaries were selected by the A12 Project team because they provide important habitat areas for key species of interest.

The focus of this scoping work, across the seven study sites, is to:

- build understanding of the effects of tidal dynamics on the distribution of intertidal areas across this region of large and complex tides;
- use tidal modelling and Landsat imagery to map the extent of intertidal habitat and detect coastal change; and
- use the Landsat archive and a normalised difference vegetation index to identify change over time in mangrove communities.

Features of importance to shorebird populations are a focus, and include the intertidal mud flats which are pertinent for feeding, and high-tide areas which do not inundate with water for roosting. Such areas are variable over the lunar cycle but usually include sand spits, headlands and beaches as well as salt flats that are inundated on spring high tides.

2. HABITAT MAPPING METHODS & PRODUCTS

Here we test new approaches to remotely mapping the extent of intertidal areas and important coastal habitats. Intertidal areas were identified using the DEA archive based on modelled tide height (Egbert and Erofeeva, 2010, 2002) that occurred at the time of image acquisition (Sagar et al., 2017). This analysis utilises an advanced image classification scheme that enables viewing of coastal regions at selected tide stages. In this approach, composite images of coastal regions over varying stages of the tide and varying time periods are generated as a way of showing coastal change. Furthermore, this tidally attributed archive of coastal imagery enables mapping of intertidal extents, which effectively characterises the topography of intertidal zones.

Changes in vegetation cover can also be effectively mapped using the DEA. This project looked specifically at the effectiveness of mapping changes in mangrove extent over the past 30 years in the nominated priority estuaries.

These image-based characterisations of the study sites aim to reveal both the topography and cover types of the intertidal zone, in addition to detecting both event based and more gradual change in landscapes and habitats. An important aim is to develop products that provide a baseline understanding of the extent and dynamics of critical habitats on the northern coast, and that can be used to better understand how both the habitats and key inhabiting species respond to change.

2.1 Tidal composite imagery

For the purposes of tidal modelling, the Australian coastline was divided into 306 tidally self-similar polygons, from which ‘regional’ tide dates and heights were modelled and extracted. For a given date of Landsat image acquisition within a given polygon, the corresponding modelled tide height was attributed to the image (Figure 1). This allows the image archive to be sorted by tide height. Clear composite images of the northern coastline can then be generated based on tide stage/height and date range. Such an approach is invaluable for characterising coastal habitats, particularly in Northern Australia. This is because seasonal effects contaminate many of the individually captured satellite images with cloud cover. Our synthetic compositing approach creates an average reflectance value from the nominated dataset for every cloud-free pixel. The images produced in this work are composited from these average pixel values. As a result, the image composites assume coastal stability during the nominated time-range even though this will not always be the case.

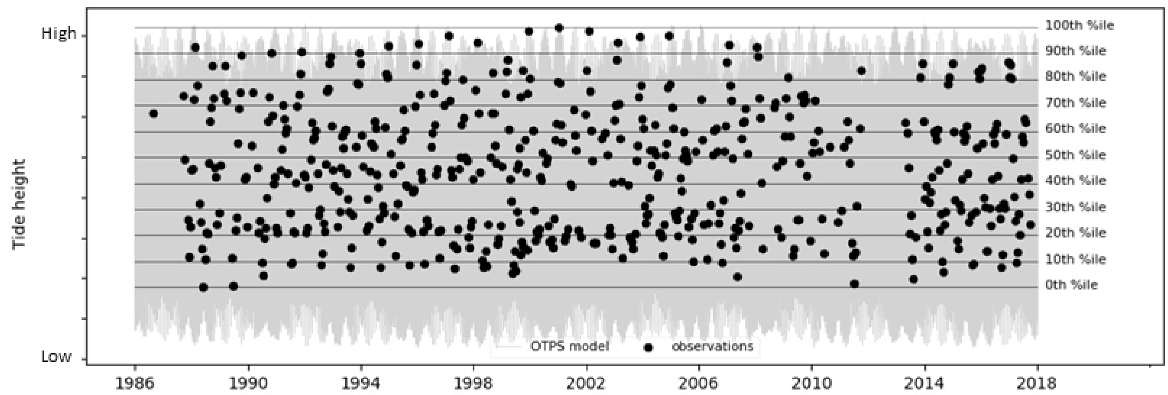

Figure 1 For any given coastal or marine region, tidal modelling (gray line – OTPS model) can be generated. All Landsat image acquisitions within that region (overlaid symbols – Observations) are attributed to the corresponding modelled tide height (meters above sea level). The dataset can then be sliced by tide range (represented as percentiles of the observed tidal range on the secondary y-axis) and/or date to generate a synthetic geomedian (Roberts et al., 2017) composite image of the nominated region.

2.1.1 High and Low tide composites

Composite images of high (HOT) and low (LOT) tide, in this work, represents the top and bottom 20% of tidal observations (from tide-tagged satellite imagery) respectively. Typically, the images are composited from Landsat observations acquired between 2000 and 2017. The only exceptions to this date range are for the low tide composites from the Daly and Keep Rivers where the data quality and resolution were sufficient to reduce the timeline to observations made between 2005 and 2017.

All high and low tide composites are shown as true colour images. That is, the red, blue and green spectral bands, measured via Landsat, are combined to produce an image that is representative of how the human eye naturally observes light.

2.1.2 Coastal change composites

The dynamic nature of intertidal zones makes them difficult to image or map consistently in any assessment of coastal change. In this work, the mid-tidal range (40th to 60th percentiles) of the tide-tagged subset of observations was used, being the most data rich part of the observed tidal range and representative of the region for the greatest part of the tidal cycle.

To assess how change affects the appearance of coastal regions, image composites were generated for short time periods of the total DEA archive. In this work, 6 year composites were produced, spanning 5 discrete epochs between 1988 and the present.

The coastal change composites are presented as false colour images. These images are generated using Landsat's short- and near-wave infrared and green bands. This band combination is very effective at distinguishing vegetation (which appears as bright green) from sediment laden water and saturated soil (both appear as bright blue). The appearance or absence of either water or vegetation is often the dominant feature of the change composite images and so false colour has been used here to highlight these changes. In the case of the Keep River, the data quality of the false colour composites was inferior to the true colour composites which were used instead.

2.2 Intertidal extents model

The Intertidal Extents Model (ITEM) is a national dataset of the exposed intertidal zone; the land between the observed highest and lowest tide (Sagar et al., 2017). ITEM provides the extent and topography of the intertidal zone of Australia's coastline (excluding off-shore Territories) and was generated using the same tidal modelling methodology that underpins the composite generation detailed above. ITEM uses a water identification algorithm to identify the tidal water extent in coastal imagery for every coastal image in the DEA archive. For every 10% increase in tide height, the average water extent is incorporated into the model. The result is an intertidal topographic model with 10 stepwise increments representing average tide height (or equivalently, average land exposure) at every 10% increase in the tidal range.

ITEM also has an associated confidence layer. This layer represents the average overall standard deviation (std) from each layer in ITEM. Regions of low confidence (high std) can represent areas where the original tidal modelling or ITEM methodology may not perform optimally. Low confidence may represent issues with the generation of a single layer of ITEM, which is propagating into the average std calculation for example. However, some areas show low confidence where the modelling and methodology is known to work well. In these places, coastal change is often reflected and is usually seen around river deltas and sandbars for example. The high std, generated from imagery collected since 1986, can be a useful indicator for areas of coastal change.

2.3 Normalised difference vegetation index (NDVI) of mangroves

2.3.1 Normalised Difference Vegetation Index

The Normalised Difference Vegetation Index (NDVI) is an algorithm that exploits the absorbance and reflectance characteristics of various parts of the light spectrum, as detected by Landsat. The returned values range between -1 and +1 and offer an interpretation of the analysed scene. Negative values usually correspond to non-vegetative targets such as water, values close to zero (-0.1 to 0.1) generally correspond to barren areas of rock, sand, or snow, while low, positive values usually represent shrub and grassland (approximately 0.2 to 0.4), and high values are indicative of healthy crops or dense vegetation such as temperate and tropical rainforests (values approaching 1).

NDVI is calculated as:

$$(NIR - RED) / (NIR + RED)$$

where RED and NIR stand for the spectral reflectance measurements acquired in the red and near-infrared regions, respectively.

2.3.2 Hovmoller plots

Hovmoller plots are used in this report to exploit the full depth of the DEA archive. These plots show landscape and land cover change over time. For a given spatial transect (x-axis), every DEA observation of the pixels along that transect is shown (y-axis). In this report, the

NDVI of each pixel is shown, depicting the interpreted location of water, sand and vegetation over time.

2.3.3 Mangrove dieback event detection

The 2015/2016 mangrove dieback event in northern Australia is highlighted in this work as a demonstration of the DEA's event detection capabilities.

The Global Mangrove Watch (Thomas et al., 2015) is a global mangrove baseline extent map, based on mangrove extents in 2010, as observed using radar and optical satellite data. For the current work, a prototype DEA mangrove extent product calculated NDVI within the Global Mangrove Watch extent mask for each of the case study sites. A well-documented mangrove dieback event occurred over 2015/2016 in Australia (Duke et al., 2017) so for this work, NDVI was generated within the mangrove mask for each of 2014 and 2016. The results present the NDVI difference ($NDVI_{2016}$ – $NDVI_{2014}$) within the masked mangrove area and highlights areas of dieback or increased growth within the mangrove canopy area, as detected by Landsat.

3. ESTUARY CHARACTERISATION

The seven case study estuaries are well distributed across the north marine bioregion (North MBR) and have one or more of the following features:

- Known occurrence of threatened and migratory elsmobranch, shorebird or inshore dolphin species;
- Potential or realised development pressures;
- Indigenous Sea Ranger group capacity;
- Links to other NESP Hubs working in northern Australia (Threatened Species Recovery Hub, Tropical Water Quality Hub and Northern Australia Environmental Resources Hub)

Northern Australia experiences some of the largest tidal ranges in Australia and this is reflected in the morphology and functioning of the estuaries examined in this study. The Keep, Daly and Roper Rivers are all tidally dominated estuaries. Similarly, Darwin Harbour is classed as a tide dominated system. This is contrasted by estuaries on the eastern side of the Gulf of Carpentaria where the tidal range is much lower. The McArthur, Gilbert and Flinders Rivers are all river dominated systems with tide dominated deltas. All six river systems are considered to be in near-pristine condition while Darwin Harbour is considered to be largely unmodified (Heap et al., 2001; Murray et al., 2006).

Australia's north coast has a tropical monsoonal climate with marked wet and dry seasons. The discharge of coastal rivers is limited to the wet season, during which tropical cyclones regularly occur. The combination of strong tidal currents and episodic river discharge is largely responsible for the distinctive estuarine morphologies of northern Australia, modified by local waves and cyclone-induced erosion. Australia's northern estuaries and low-gradient coast are also characterised by extensive mangrove communities that line the coast and the margin of channels, typically sitting landward of extensive mud flats and seaward of a supratidal zone (e.g. salt flats; low vegetation). Mangroves are also susceptible to damage by the passage of intense cyclones, and may take several years to recover (e.g. Brooke et al., 2017).

A number of these sites have been identified as being critical waterbird and shorebird habitat (Olsen and Weston, 2004). The McArthur, Roper and Daly river wetlands have been identified as qualifying for listing under the Ramsar Convention (designating them wetlands of international significance) and/or as sites under the East Asian-Australasian Shorebird Site Network (Olsen and Weston, 2004). Darwin Harbour, as well as the McArthur, Roper and Daly Rivers have also been identified as wetlands of national importance (Environment Australia, 2001). The Daly River contains a number of habitats that are unique to the Northern Territory, including habitat for most of the Territories freshwater turtle species as well as two species of threatened elasmobranchs, the freshwater whipray and the freshwater sawfish (Murray et al., 2006 and references therein).

The following sections provide an overview of the potential utility of the Landsat archive and analysis tools in the DEA for mapping and monitoring key habitat and important areas for threatened and migratory marine species. For each of the case-study estuaries the Landsat archive is employed to describe:

- The extent and stability of the intertidal zone;
- The dynamics of coastal landforms – the rate and extent of geomorphic change; and,
- The distribution and dynamics of mangrove extent, including evidence of recent die-back events.

3.1 Regional context

Composite imagery of the high and low tides at the mouth of each estuary show persistent coastal features that are visible above the water line at each extreme of the tidal range. Low tide composites reveal the intertidal zone, enabling differentiation between substrate types and show the location of persistent islands and sandbars in the channel and offshore. High tide composites show the typical extent of the high tide water mark and the habitats that interact with the high tide.

Tidal modelling and satellite imagery are combined (ITEM) to show the tidal extents for these same estuary mouths, indicating the dynamism of the tide at each location. This effectively provides a bathymetric map of the intertidal zone. The confidence maps associated with ITEM can be useful for identifying locations of coastal change. Thirty years of input imagery is used in the tidal modelling and coastal change that is represented in the confidence layer will have occurred at some time during that same period.

3.1.1 Gilbert River

The low (Figure 2) and high (Figure 3) tide image composites for the southern end of the Gilbert estuary show that the coastal topography at this site is considerably different between the two tide stages due to the extensive beached areas and sandbar. Figure 2 indicates the vegetated areas (green).

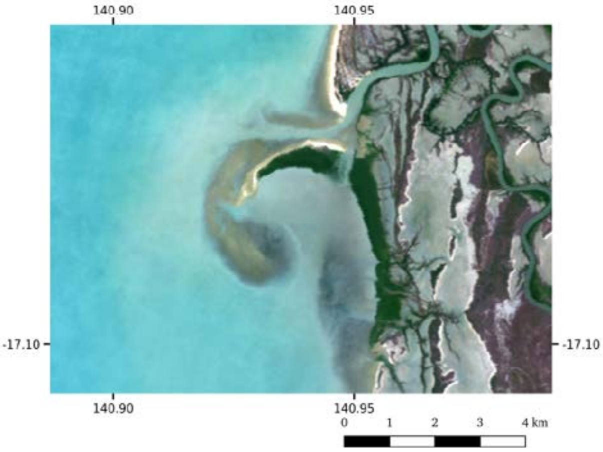

Figure 2 Lowest observed tides (LOT) composite image for the southern end of the Gilbert estuary

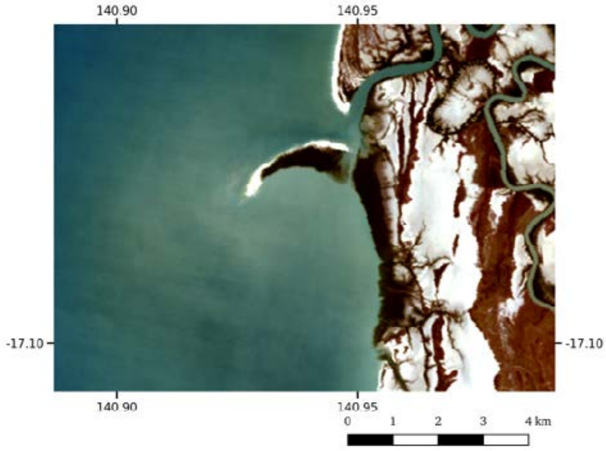

Figure 3 Highest observed tides (HOT) composite image for the southern end of the Gilbert estuary

Intertidal extent modelling shows the broad intertidal zone that exists around the sandbar at the southern end of the Gilbert River estuary (Figure 4). The confidence layer associated with the tidal extent modelling shows that uncertainty is high around the sandbar, possibly indicating a region of change (Figure 5).

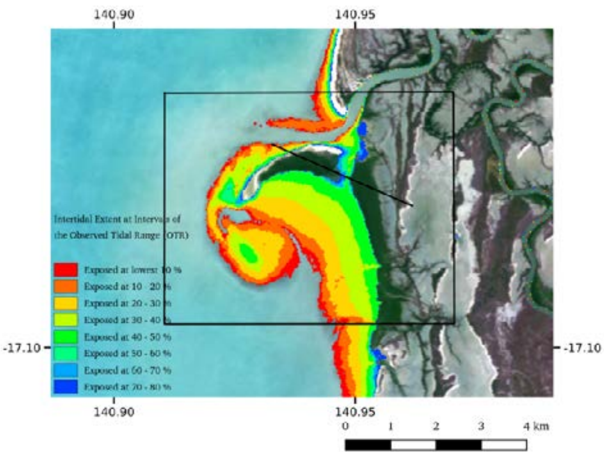

Figure 4 Tidal extent, southern mouth of the Gilbert River estuary. The colour coding represents exposed land at varying percentage ranges of the regional tidal scheme: red - exposed at the lowest 10% of tides, dark blue - exposed when tides are at 70 to 80 % of their maximum range.

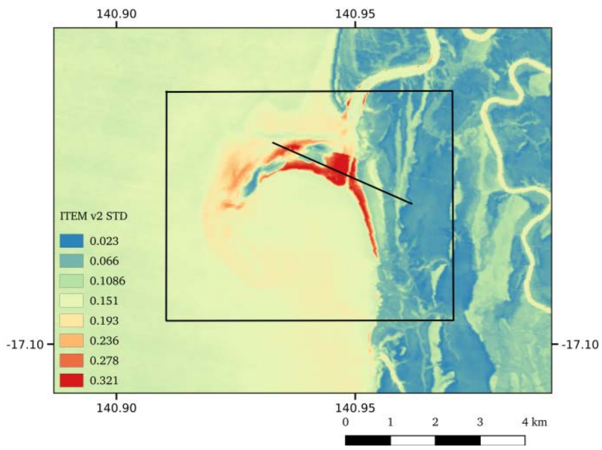

Figure 5 ITEM confidence layer at the mouth of the Gilbert River estuary. The transect represented in Figure 35 is shown in black as well as the coastal change detection (Figure 30) bounding box.

3.1.2 Flinders River (Norman River)

The low (Figure 6) and high (Figure 7) tide image composites for the Flinders River estuary show that bottom currents have eroded channels into the extensive low-tide flats.

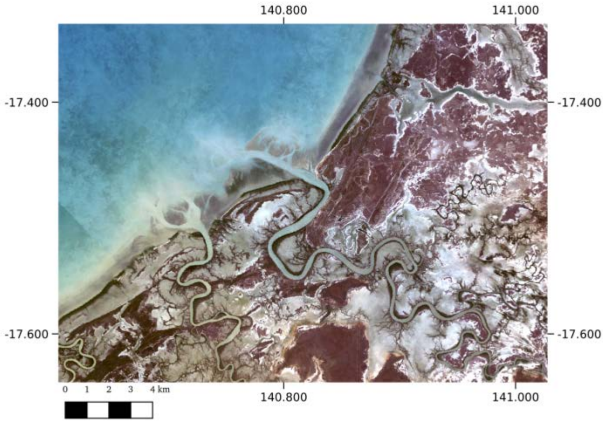

Figure 6 LOT composite image of the Flinders River estuary

Figure 7 HOT composite image of the Flinders River estuary

Intertidal extent modelling shows that the tidal influence is fairly uniform across the Flinders River estuary coastline (Figure 8). The confidence layer associated with the tidal extent modelling shows that minimal long-term change is evident in this region (Figure 9).

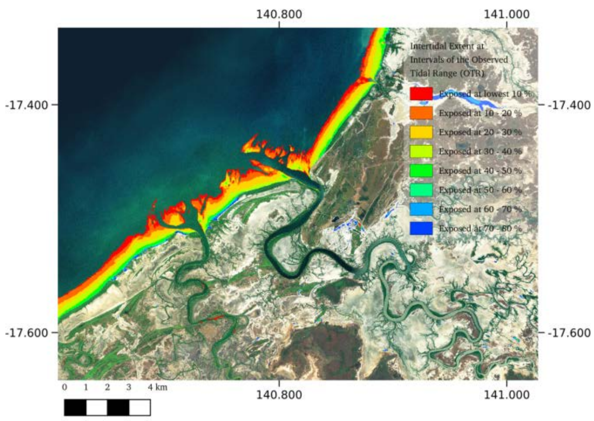

Figure 8 Tidal extent at the mouth of the Flinders River. The colour coding represents exposed land at varying percentage ranges of the regional tidal scheme: red being land exposed at the lowest 10% of tide heights, dark blue being land exposed when tide heights are at 70 to 80 % of their maximum range.

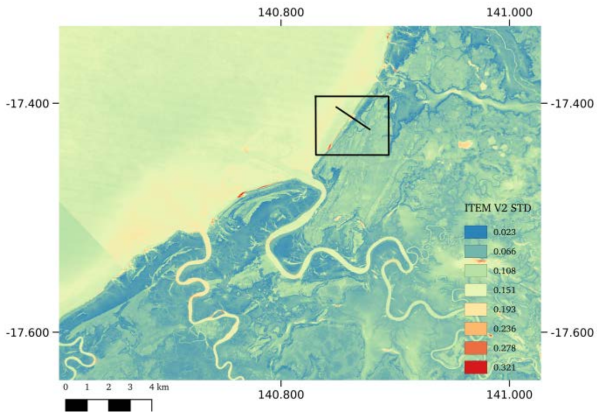

Figure 9 ITEM confidence layer for the Flinders River estuary. The transect represented in 36 is shown in black. The bounding box highlights a region of significant coastal mangrove habitat dieback over the 2015/2016 Austral summer.

3.1.3 Roper River

The low (Figure 10) and high (Figure 11) tide image composites for the Roper River estuary show extensive tidal flats in and around the delta.

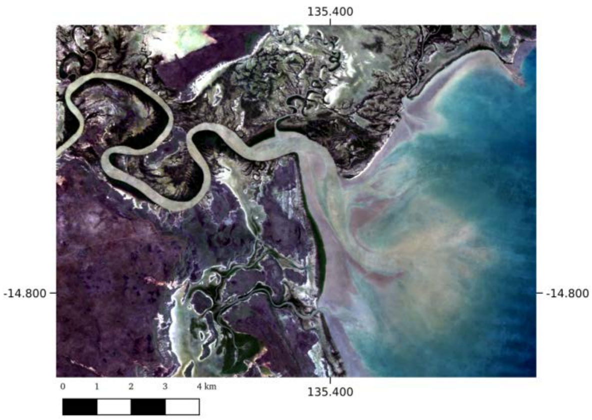

Figure 10 LOT composite image of the Roper River estuary

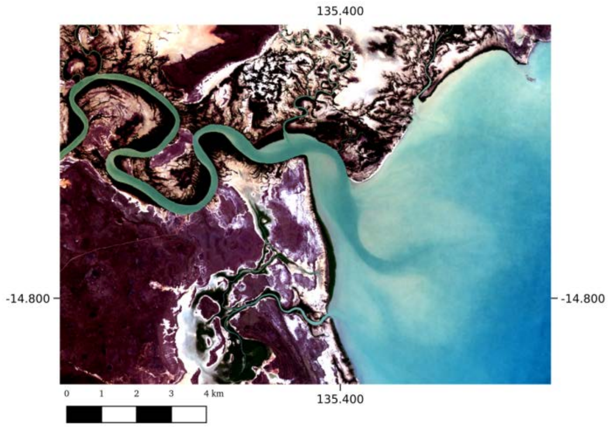

Figure 11 HOT composite image of the Roper River estuary

Intertidal extent modelling shows the broad tidal zone at the mouth of the Roper River (Figure 12). Notably, the large sand bank in the mouth of the river (Figure 10) only appears in the model when tides are at their lowest 0 to 20% in height. The confidence layer (Figure 13) shows this to be a region with higher uncertainty around the river mouth and adjacent coastlines, likely a reflection of the dynamic character of the mouth of this large river.

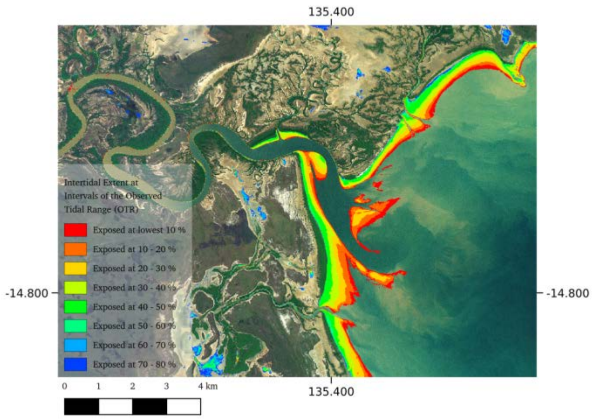

Figure 12 Tidal extent at the mouth of the Roper River. The colour coding represents exposed land at varying percentage ranges of the regional tidal scheme: red being land exposed at the lowest 10% of tide heights, dark blue being land exposed when tide heights are at 70 to 80 % of their maximum range.

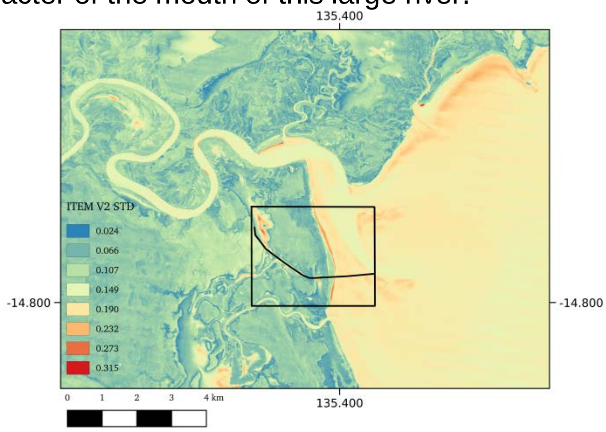

Figure 13 ITEM confidence layer for the Roper River estuary. The change detection highlighted in Figure 31 is represented by the black box. The transect represented in Figure 39 is shown in black.

3.1.4 McArthur River

The low (Figure 14) and high (Figure 15) tide image composites for the McArthur River estuary show that at low tide, there are extensive areas of exposed sand and mud banks whose topography is heavily influenced by the river channel flow.

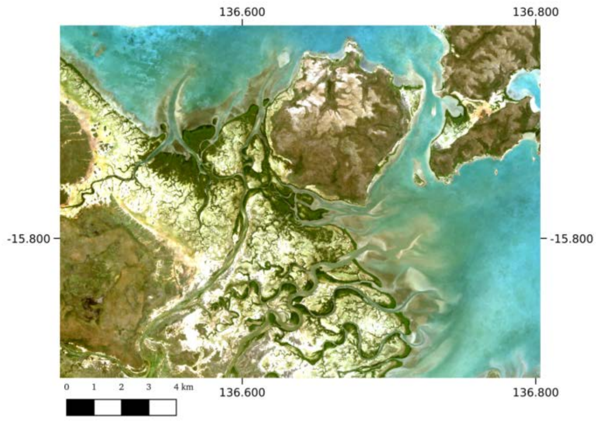

Figure 14 LOT composite image of the McArthur River estuary

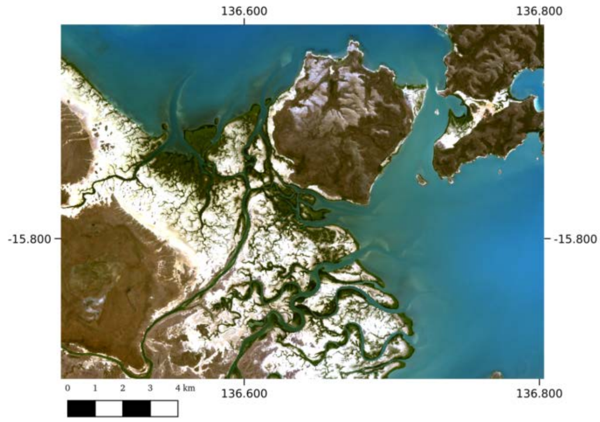

Figure 15 HOT composite image of the McArthur River estuary

Intertidal extent modelling (Figure 16) shows that the McArthur River estuary is a dynamic region with sand bank morphology that is highly influenced by the estuary. Despite this, the ITEM confidence layer indicates this to be an area with generally long-term stability (Figure 17). The area within the bounding box shows some of the highest variability in the region.

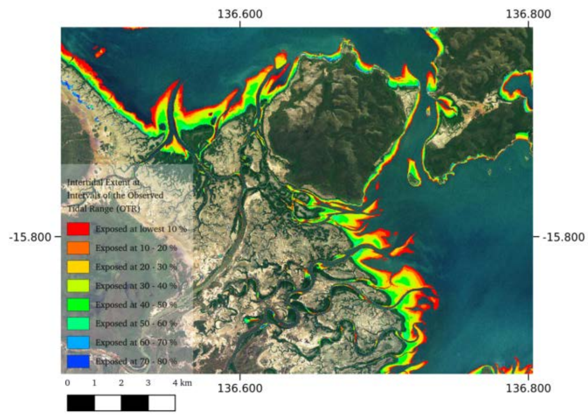

Figure 16 Tidal extent at the mouth of the McArthur River. The colour coding represents exposed land at varying percentage ranges of the regional tidal scheme: red being land exposed at the lowest 10% of tide heights, dark blue being land exposed when tide heights are at 70 to 80 % of their maximum range.

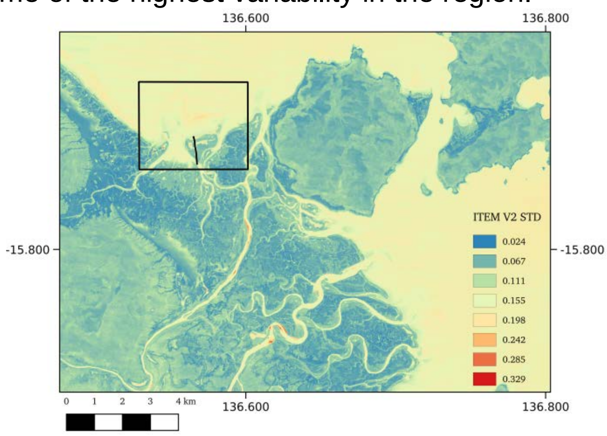

Figure 17 ITEM confidence layer for the McArthur River. The change detection highlighted in Figure 32 is represented by the black box. The transect represented in Figure 41 is shown in black.

3.1.5 Darwin Harbour

The low (Figure 18) and high (Figure 19) tide image composites of Darwin Harbour show wide areas of sandbank and beach that are exposed at low tide

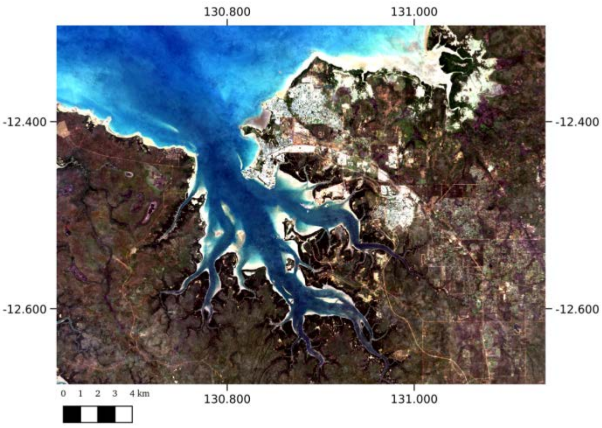

Figure 18 LOT composite image of Darwin Harbour

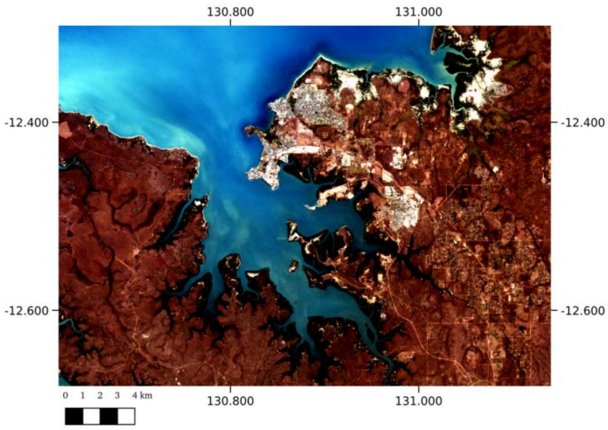

Figure 19 HOT composite image of Darwin Harbour

Intertidal extent modelling (Figure 20) closely mirrors the exposed areas of sandbank and beach in the Darwin Harbour LOT (Figure 18). The confidence layer (Figure 21) shows localised areas of variability, including changes related to the port development in the eastern harbour, but general long term stability in the region.

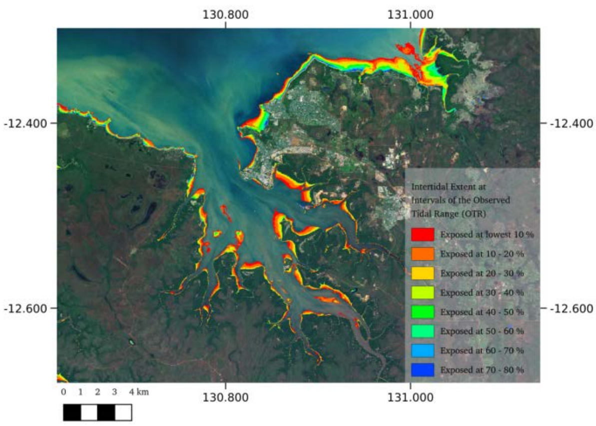

Figure 20 Tidal extent in and around Darwin Harbour. The colour coding represents exposed land at varying percentage ranges of the regional tidal scheme: red being land exposed at the lowest 10% of tide heights, dark blue being land exposed when tide heights are at 70 to 80 % of their maximum range.

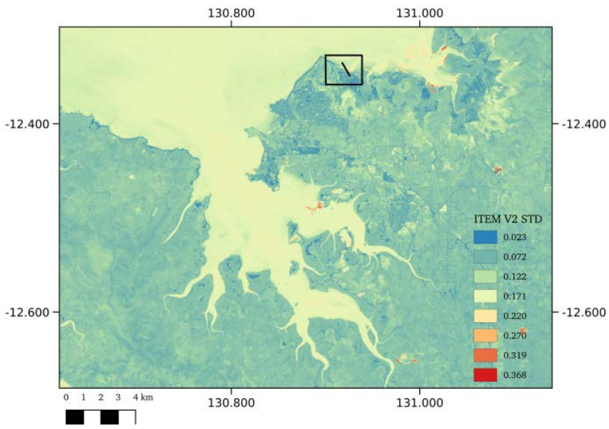

Figure 21 ITEM confidence layer for Darwin Harbour. Analyses for the regions in black are not shown.

3.1.6 Daly River

The low (Figure 22) and high (Figure 23) tide image composites for the Roper River estuary indicate that large areas of sandbank and beach are exposed at low tide. However, the reflectance of highly turbid waters may be interfering with the sand/mud signal at this site. Consequently, the low tide composite may be an average of both low tide areas and highly turbid water.

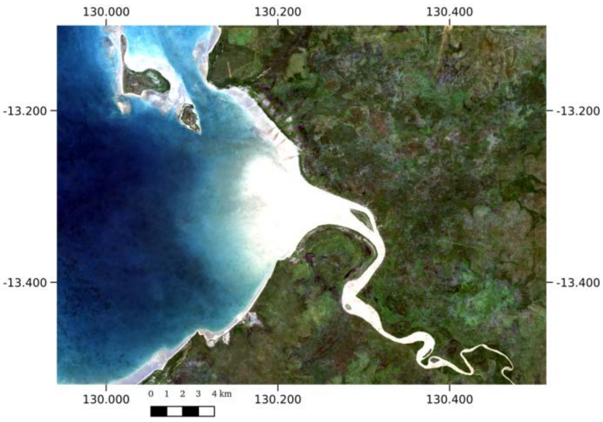

Figure 22 LOT composite image of the Daly River estuary

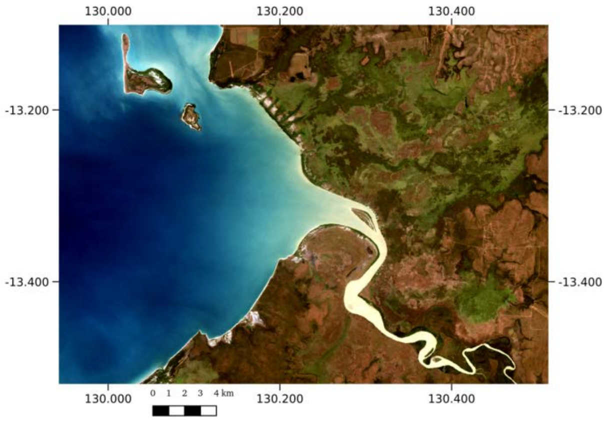

Figure 23 HOT composite image of the Daly River estuary

Intertidal extent modelling (Figure 24) shows that the intertidal areas either side of the Daly River mouth are fairly uniformly distributed. Like the composites, ITEM at this site is possibly biased by high levels of water turbidity mobilised in the river mouth. The confidence layer (Figure 25) likewise indicates lower confidence in the depiction of the intertidal area in the river mouth.

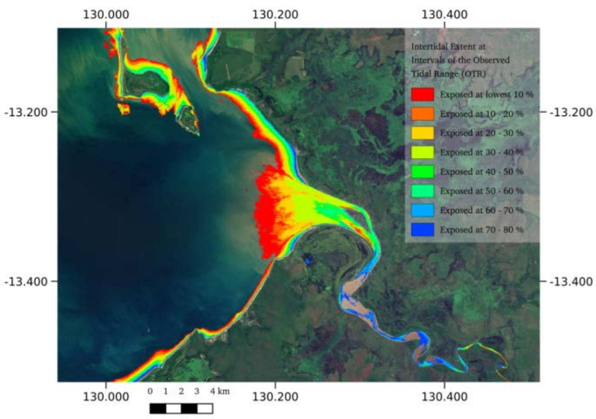

Figure 24 Tidal extent at the mouth of the Daly River. The colour coding represents exposed land at varying percentage ranges of the regional tidal scheme: red being land exposed at the lowest 10% of tide heights, dark blue being land exposed when tide heights are at 70 to 80 % of their maximum range.

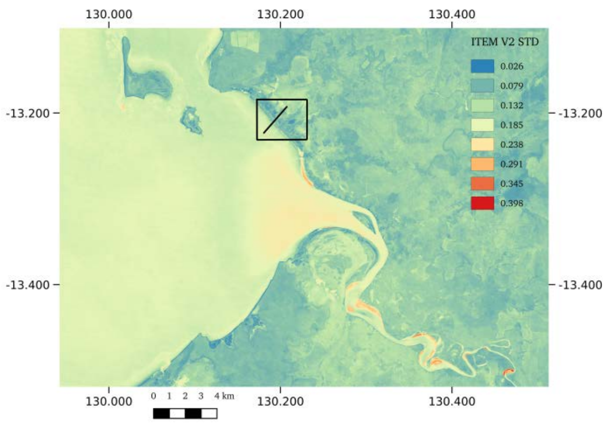

Figure 25 ITEM confidence layer for the Daly River estuary. Analyses for the region in black are not shown.

3.1.7 Keep River

The low (Figure 26) and high (Figure 27) tide image composites for the Keep River estuary show that large areas of sand/mud bank are exposed inside the estuarine channel at low tide.

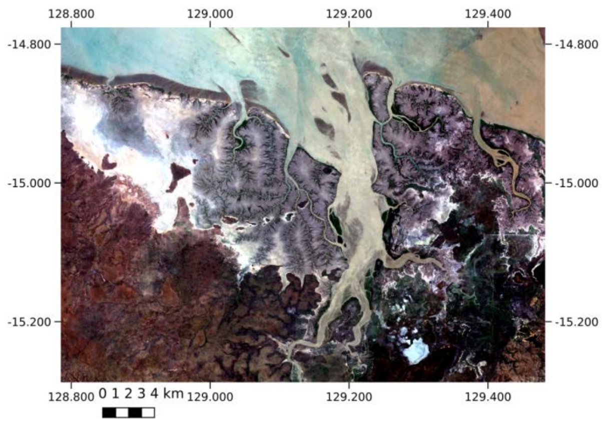

Figure 26 LOT composite image of the Keep River estuary

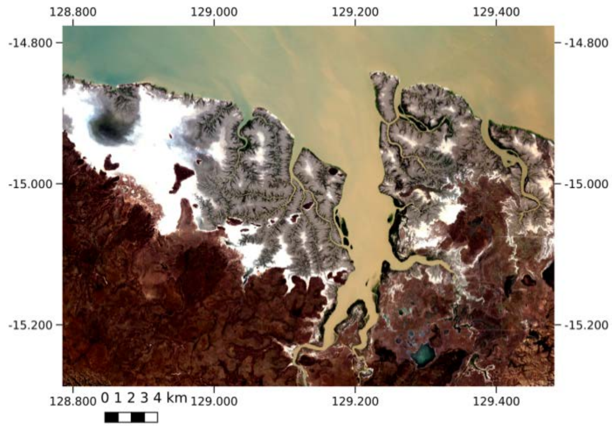

Figure 27 HOT composite image of the Keep River estuary

Intertidal extent modelling (Figure 28) shows extensive tidal areas in the Keep River mouth and along the open coastline. Within the outer estuary, the modelling is somewhat 'patchy' and ITEM at this site may be biased by high levels of turbidity (Figure 29). Down-river are regions where high uncertainty is possibly related to long-term geomorphic variability (Figure 29).

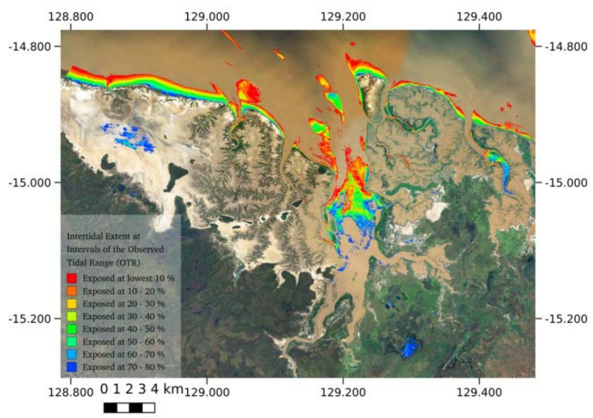

Figure 28 Tidal extent at the mouth of the Keep River. The colour coding represents exposed land at varying percentage ranges of the regional tidal scheme: red being land exposed at the lowest 10% of tide heights, dark blue being land exposed when tide heights are at 70 to 80 % of their maximum range.

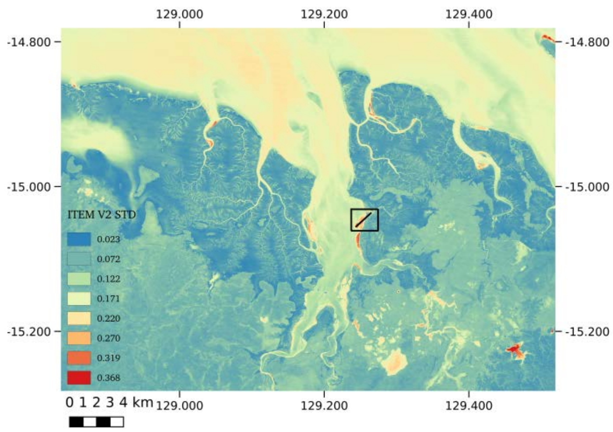

Figure 29 ITEM confidence layer for the Keep River estuary. The change detection highlighted in Figure 33 is represented by the black box. The transect represented in Figure 43 is shown in black.

3.2 Geomorphological change

The same method used to generate the high and low tide image composites can be used to profile coastal change by altering the tidal and date ranges to the composite input datasets. In these dynamic, tidal environments, real change is visible by creating a time series of composite images where the effects of tide height are removed.

The ITEM confidence layers in section 3.1 clearly showed regions of coastal change were evident in the Gilbert, Roper and Keep Rivers. The McArthur River also showed areas with slightly elevated standard deviation values. Geomorphological change has been investigated at these sites by creating 6 year composites using data from the mid-tide range (40^{th} to 60^{th} percentiles of observed tide heights). Unless noted otherwise, false colour images are displayed which highlight vegetated area (green), sand/mud sediment (beige) and water/saturated sediment (blue).

3.2.1 Gilbert River

To test whether the modelled tidal uncertainty seen in Figure 5 was due to geomorphological change, composite images of the mid-tide range were compiled for every 6 years from 1988 to the present. The Gilbert River sandspit was an area of dynamic change during this time (Figure 30). The overall shape of the sandspit elongated and migrated towards the coastline, progressively closing the channel that existed between the sand bar and coastline. Simultaneously, the vegetated area on the sandspit expanded towards the coastline, consistent with the trend seen in Figure 35.

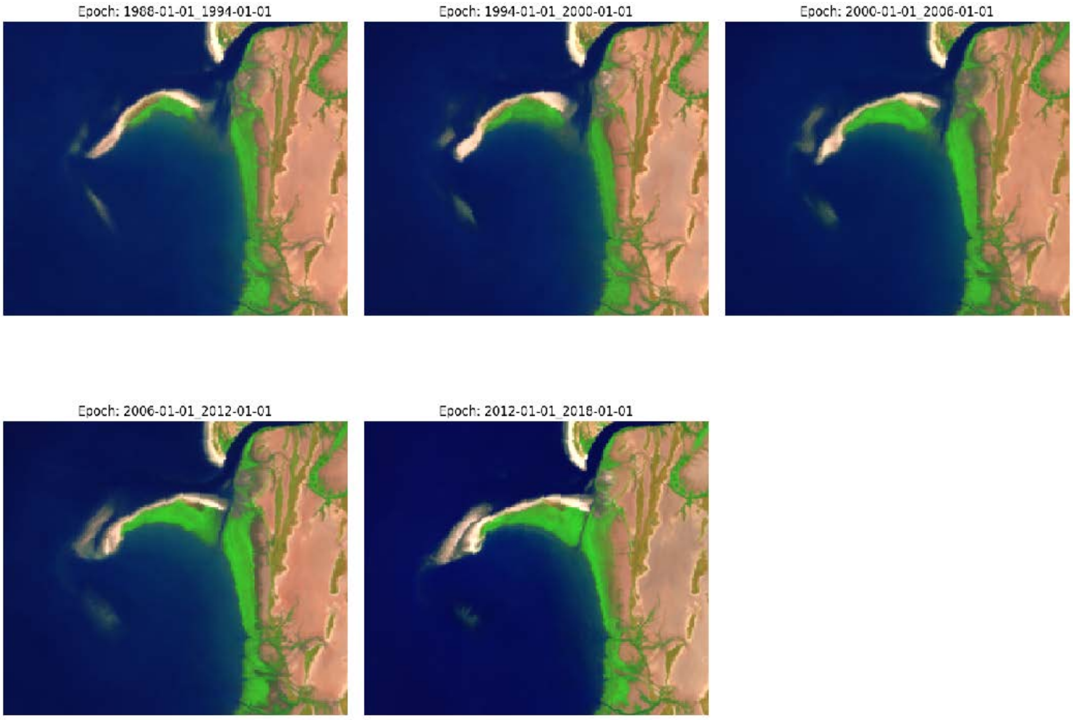

Figure 30 Geomorphic change at the Gilbert River estuary. Composite images of the mid-tide range for the area identified by the bounding box in Figure 5. The figure in the top left represents data composited between Jan 1988 and Jan 1994, increasing in 6 year increments from left to right, top to bottom. The bottom right figure represents data between Jan 2012 and the present.

3.2.2 Roper River

The six yearly composite images in Figure 31 show significant expansion of the vegetated communities in both directions along the coastline between 1988 and the present. The inland area in the north west corner of these composite images changes from water dominated between 1988 and 2000 to mixed water and vegetation dominated between 2000 and the present.

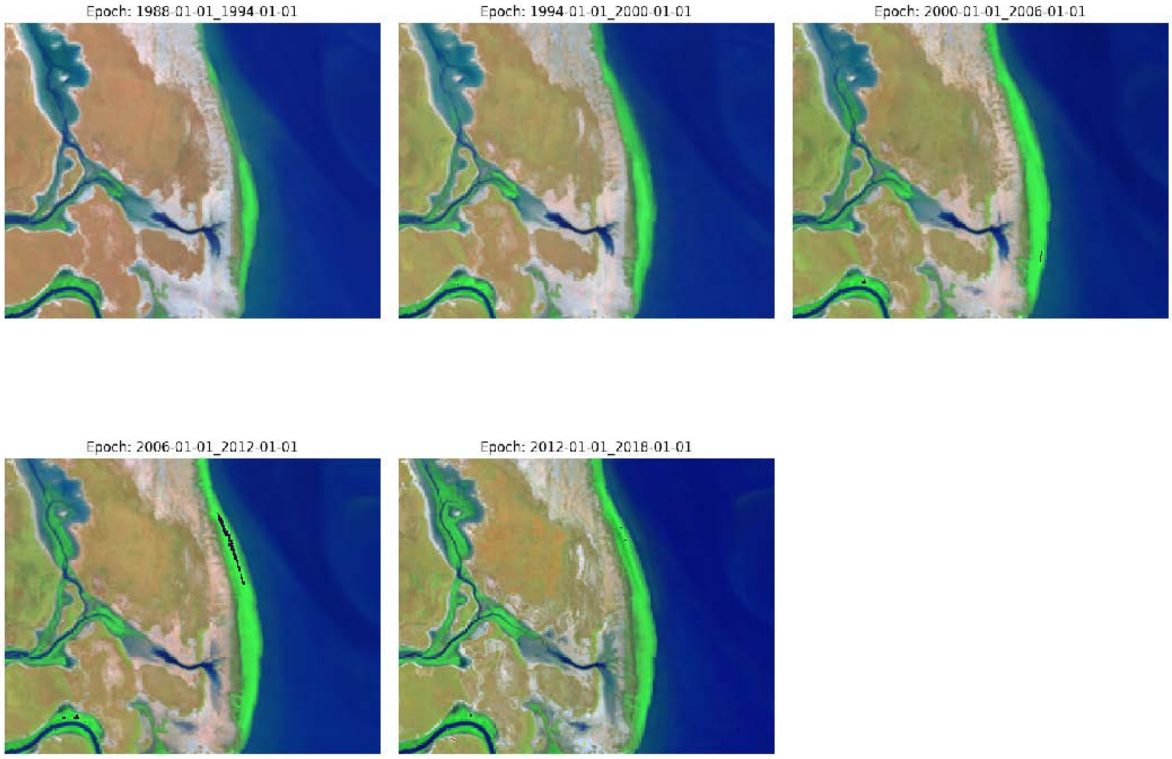

Figure 31 Composite images of the mid-tide range for the area identified by the bounding box in Figure 13. The figure in the top left represents data composited between Jan 1988 and Jan 1994, increasing in 6 year increments from left to right, top to bottom, to the bottom right figure representing data between Jan 2012 and the present.

3.2.3 McArthur River

The six yearly composite images for this part of the McArthur River shows that vegetation infills the central island in these composites over time. Of note is the significant colonisation over time by vegetation on the two small islands that sit just offshore. This suite of change over time composite images suggest that this has been an area of extensive vegetation extension over the last 30 years or that perhaps it is an environment recovering from a significantly damaging event or events such as the successive severe cyclones that made landfall in this area over 1984 (TC Kathy) and 1985 (TC Sandy).

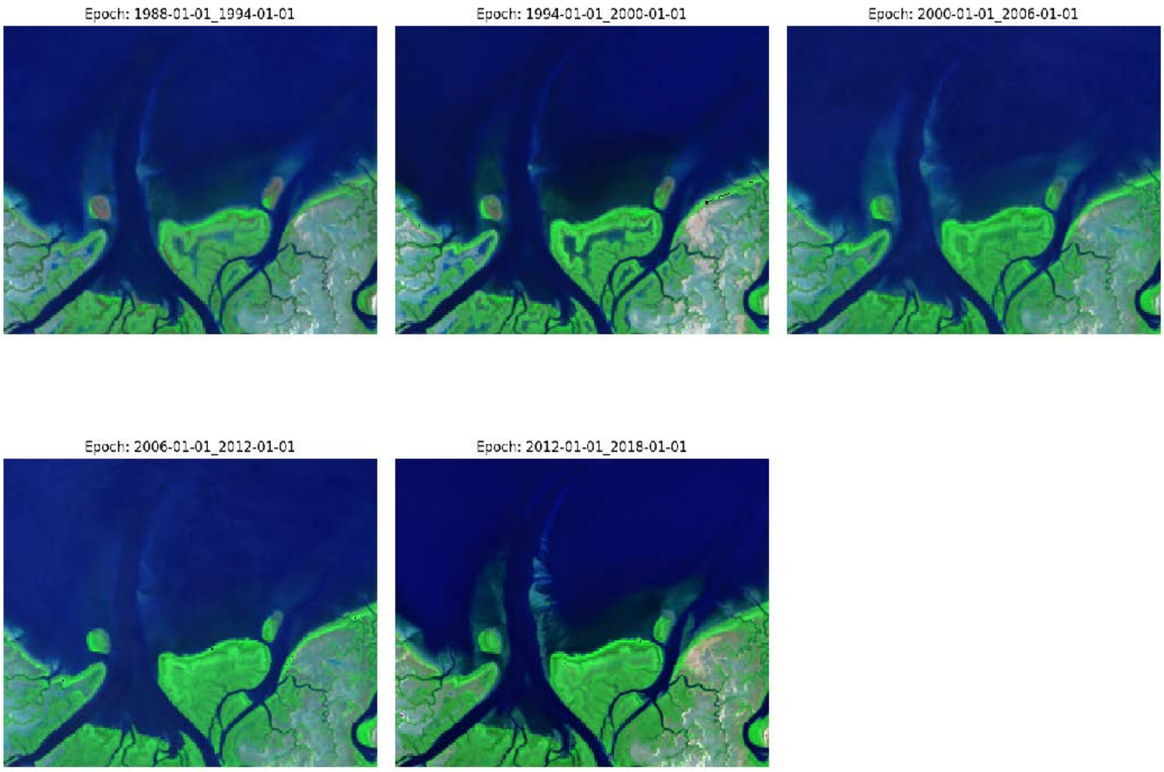

Figure 32 Composite images of the mid-tide range for the area identified by the bounding box in Figure 17. The figure in the top left represents data composited between Jan 1988 and Jan 1994, increasing in 6 year increments from left to right, top to bottom, to the bottom right figure representing data between Jan 2012 and the present.

3.2.4 Keep River

The true colour six year composites (Figure 33) for this part of the Keep River estuary show significant geomorphological and vegetation extent change over time. While the coastline appears unchanged over time, the island undergoes significant change in both shape and the extent of vegetation cover. From the first composite image between 1988 and 1994, the vegetation cover on the island appears to decrease while sediments build up, expanding the island between 1994 and 2006. From this time onwards, vegetation expands considerably on the island, which continues to grow. In the final composite (2012 to the present), further sedimentation is evident in the northwest corner of the image, which in turn may be colonised by vegetation in the future.

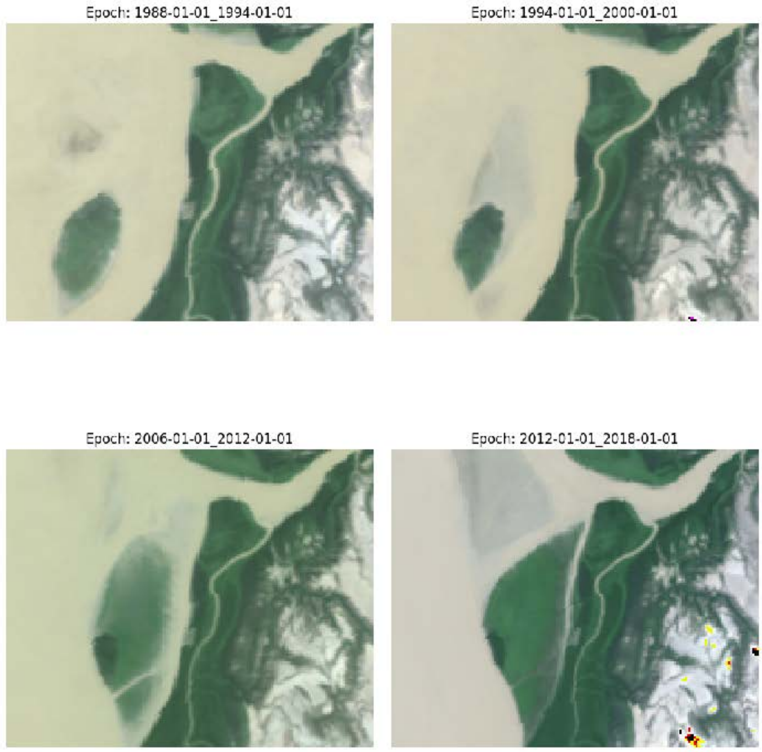

Figure 33 True colour composite images of the mid-tide range for the area identified by the bounding box in Figure 29. The figure in the top left represents data composited between Jan 1988 and Jan 1994, increasing in 6 year increments from left to right, top to bottom, to the bottom right figure representing data between Jan 2012 and the present.

3.3 Mangrove habitat change

Across a given geographical transect, a Hovmoller plot is a useful way to represent how a landscape has changed over time. In this work, the calculated NDVI for every imaged pixel over a given transect is plotted for the 30 year length of the DEA archive. Essentially, the NDVI index represents pixels that are calculated to show water (blue), sand/mud (beige) or vegetation (green). NDVI Hovmoller plots have been used in this work to characterise sediment and vegetation change over time. In these tropical, estuarine environments, the vegetation in the selected transects usually represents mangrove unless identified otherwise by the Global Mangrove Watch (GMV) mask (Thomas et al., 2015)

Event based mangrove habitat change is also reported for a major mangrove dieback event that occurred in Australia’s north over the Austral summer of 2015/2016 (Duke et al., 2017). The average annual NDVI over modelled mangrove areas (Thomas et al., 2015) is compared before and after the dieback event with areas of major change highlighted as either dieback or mangrove extension.

Some of the worst affected areas in this dieback event occurred in the Gulf of Carpentaria. For this reason, we have investigated mangrove habitat change in the Gilbert, Flinders, Roper and McArthur Rivers. Based on the significant geomorphological change observed in the Keep River, this site has also been investigated for mangrove habitat change.

3.3.1 Gilbert River

Mangrove dieback at the southern end of the Gilbert River estuary during the 2014-2016 dieback event is highlighted by the difference in vegetation greenness over mangrove areas between those years, with the deficit shown in red (Figure 34).

The transect shown in Figure 34 is represented on the x-axis in Figure 35, which is a Hovmoller plot showing how water, sand/mud and vegetation has changed across the transect between 1988 and the present (y-axis). The 2015/16 dieback highlighted in Figure 34 can be seen in the lower-most part of the Figure 35 with vegetated area changing to sand (as represented by NDVI). Notable is the expansion of the mangrove area across this transect during the previous 30 years, and mangrove dieback on the landward side of the transect for about 6 years from 1995 onwards.

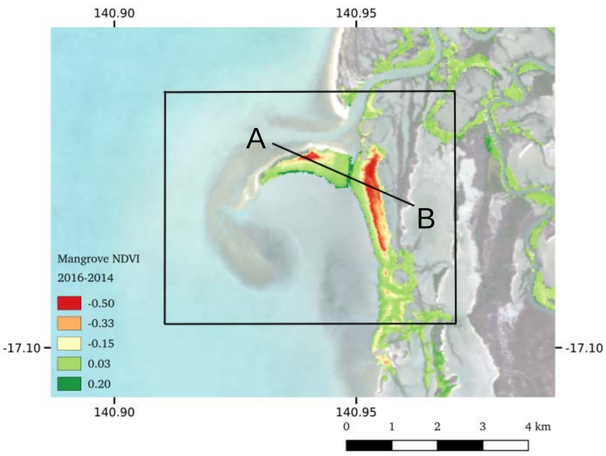

Figure 34 Mangrove dieback at the southern end of the Gilbert River estuary. Relative change in the calculated NDVI of mangrove areas between 2016 and 2014 is shown overlaid on a semi-transparent view of LOT. The transect represented in Figure 35 is shown in black between 'A' and 'B'.

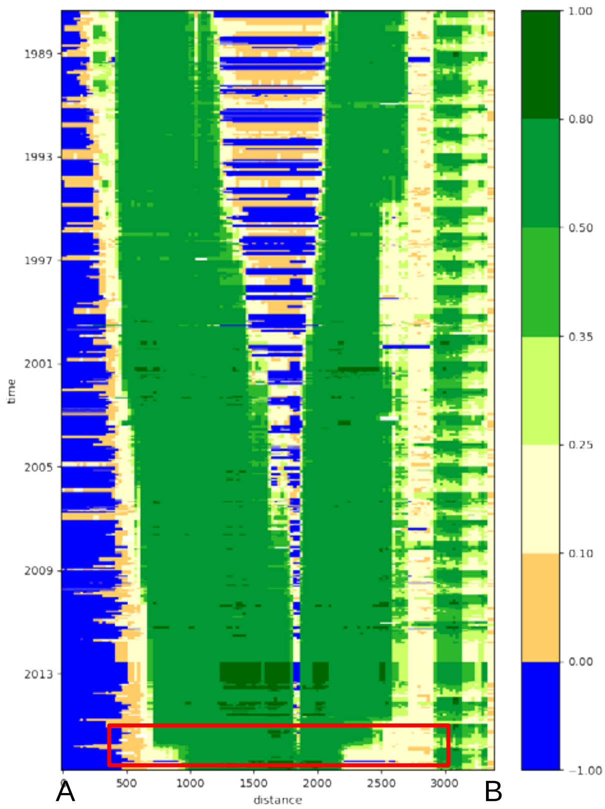

Figure 35 The transect in Figure 34 is represented on the x-axis of this Hovmoller plot, y-axis is time, colour is NDVI. The 2015-16 dieback event is highlighted in the red box.

3.3.2 Flinders River (Norman River)

Mangroves in the Flinders River region were severely impacted in the 2015/16 dieback event. The transect in Figure 36 is shown on the x-axis of Figure 37, clearly illustrating the dieback from this event. Furthermore Figure 37 show that mangroves have not been a permanent feature of this transect over the last 30 years. The early years of the Hovmoller plot show little to no vegetation is detected on the coastal fringe of the transect. This may be an artefact of the transect position (possibly consisting of a portion of the time-series), or may be reflective of the greater vegetation pattern of this coastline.

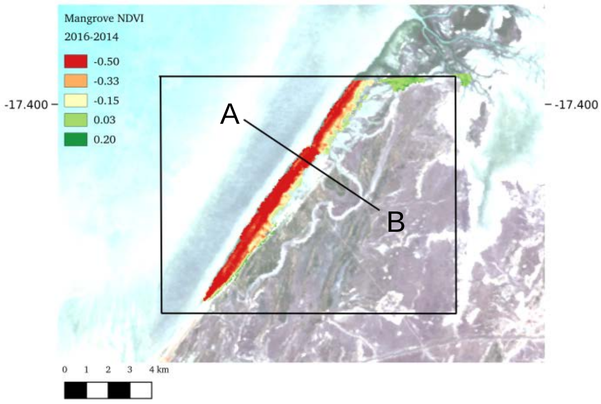

Figure 36 Mangrove dieback in the Flinders River estuary. The detailed Hovmoller transect line (Figure 37) is overlaid upon the transparent LOT image of the site with the relative 2016-2014 change in calculated NDVI in mangrove areas.

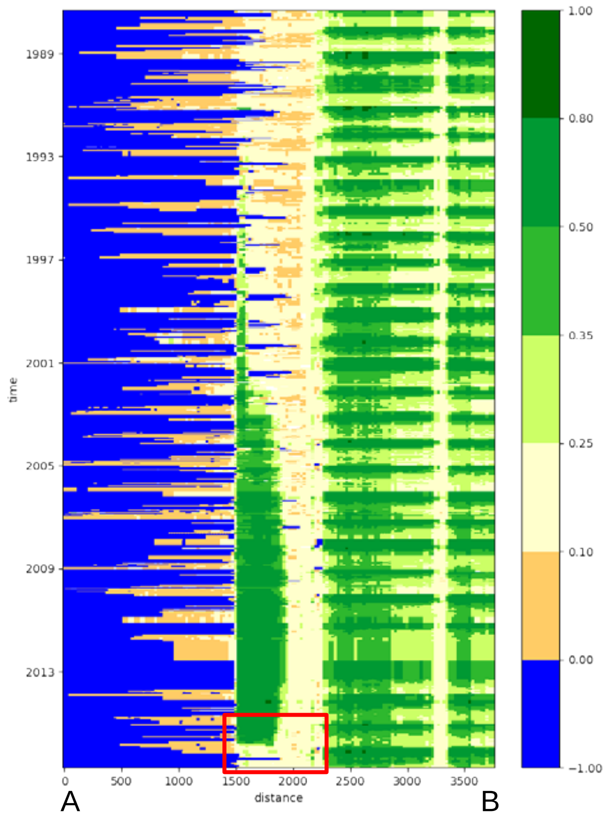

Figure 37 The Flinders River estuary transect detailed in Figure 36 is represented on the x-axis of this NDVI Hovmoller plot. The 2015-16 dieback event is highlighted in the red box.

3.3.3 Roper River

Mangrove dieback at the Roper River estuary is highlighted by the difference in vegetation greenness over mangrove areas around 2014-16, with the deficit shown in red (Figure 38). The Roper River coastline is a known region of extensive dieback and this is strongly reflected in the relative change in vegetation greenness at the southern side of the estuary mouth.

The Hovmoller plot (Figure 39) of the transect shown in Figure 38 demonstrates the dieback on the open coast observed at this location between 2014 and 2016. In the 30 year history shown in this plot (Figure 39), the 2014/2016 coastal dieback event is the most extensive. The upstream areas of mangrove have expanded over the last three decades.

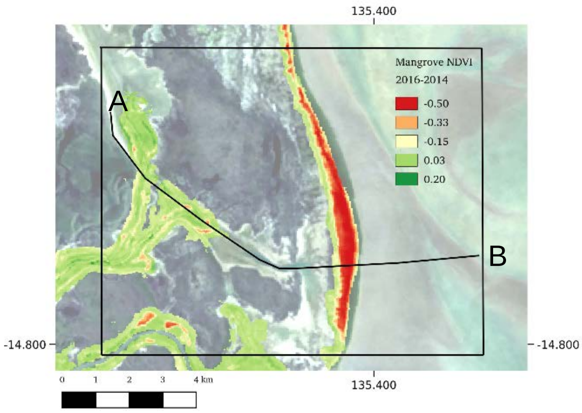

Figure 38 Mangrove dieback in the Roper River estuary. The detailed Hovmoller transect line (Figure 39) is overlaid upon the transparent LOT image of the site with the relative 2016-2014 change in calculated NDVI in mangrove areas.

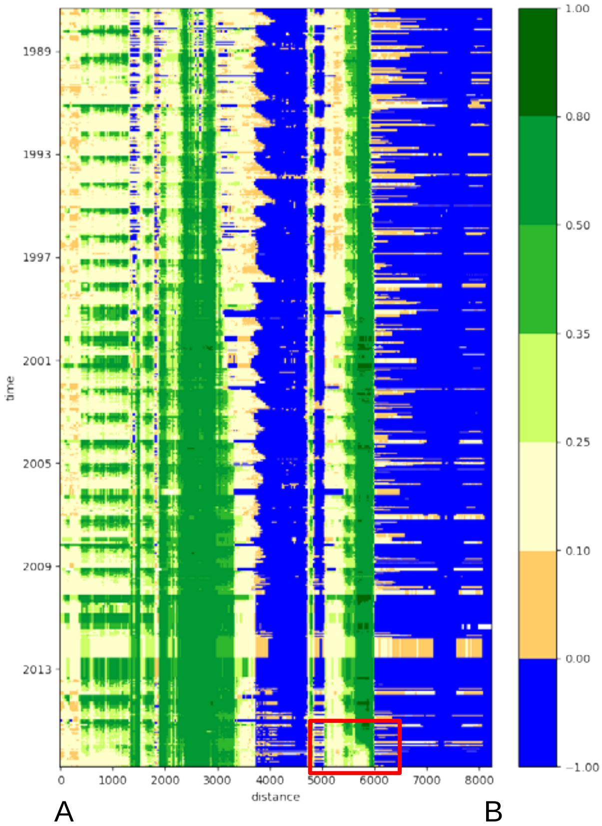

Figure 39 The Roper River estuary transect detailed in Figure 38 is represented on the x-axis of this NDVI Hovmoller plot. The 2014-16 dieback event is highlighted in the red box.

3.3.4 McArthur River

Mangrove dieback at the McArthur River estuary during the 2014-2016 dieback event appears to affect certain zones to a greater degree than others (Figure 40). The seaward fringing mangrove population appears unaffected by the event, while the population located inward of the seaward fringe shows evidence of dieback.

The Hovmoller plot of the transect shown in Figure 40 shows this site to have a history of both low vegetation and mangrove extension over the 30 year history shown (Figure 41). Two severe tropical cyclones made landfall in close proximity to this site in 1984 (TC Kathy) and 1985 (TC Sandy) and the denuded areas in the transect may have suffered from these events. Mangroves on the fringes of this transect appear stable over the length of this record. Interestingly, the same region of the transect that suffered dieback over 2014-16 also denuded and re-vegetated periodically up to around 2001 suggesting this might be an area vulnerable to change.

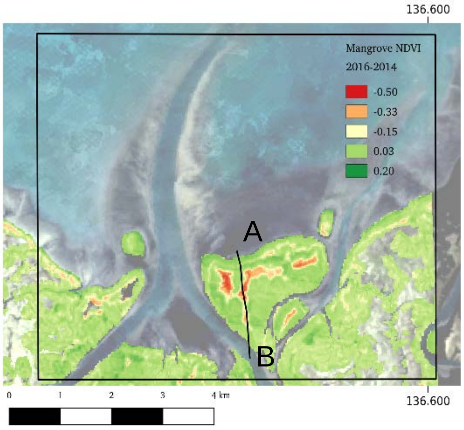

Figure 40 Mangrove dieback in the McArthur River estuary. The detailed Hovmoller transect line is overlaid upon the transparent LOT image of the site with the relative 2016-2014 change in calculated NDVI in mangrove areas.

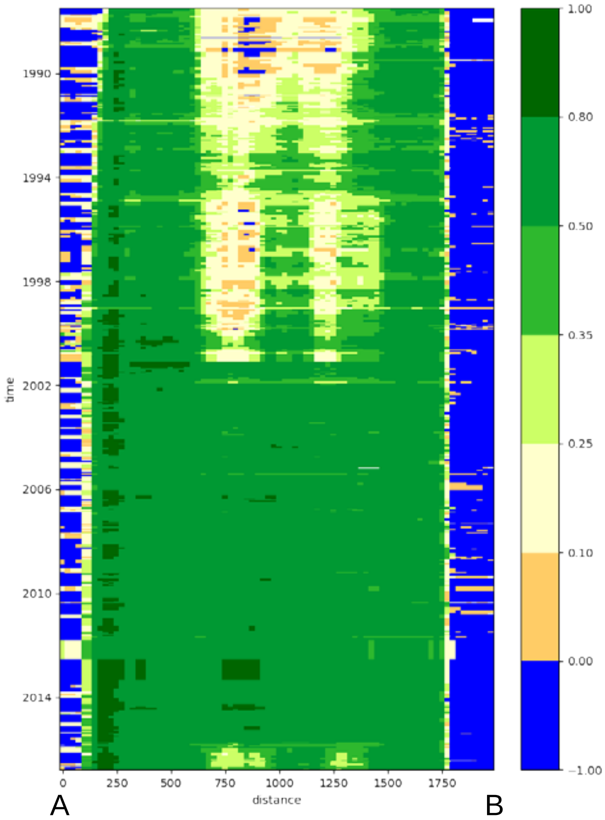

Figure 41 The McArthur River estuary transect detailed in Figure 40 is represented on the x-axis of this NDVI Hovmoller plot.

3.3.5 Keep River

Mangrove dieback at the Keep River estuary is limited to the fringing population only, as illustrated in Figure 42. However, the Hovmoller plot of the transect shown in Figure 42 shows that the mangroves on the island near the central western margin of the estuary have undergone significant movement over the last 30 years (Figure 43). The Hovmoller plot indicates the channel between the mainland coast and the island has been gradually filled in and been colonised by mangrove. Presumably, there has been a significant movement of sediment mass associated with the mangrove change.

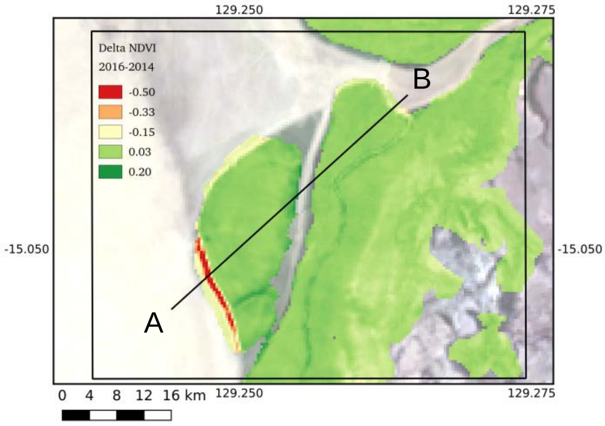

Figure 42 Mangrove change in the Keep River estuary. The detailed Hovmoller transect line is overlaid upon the transparent LOT image of the site with the relative 2016-2014 change in calculated NDVI in mangrove areas.

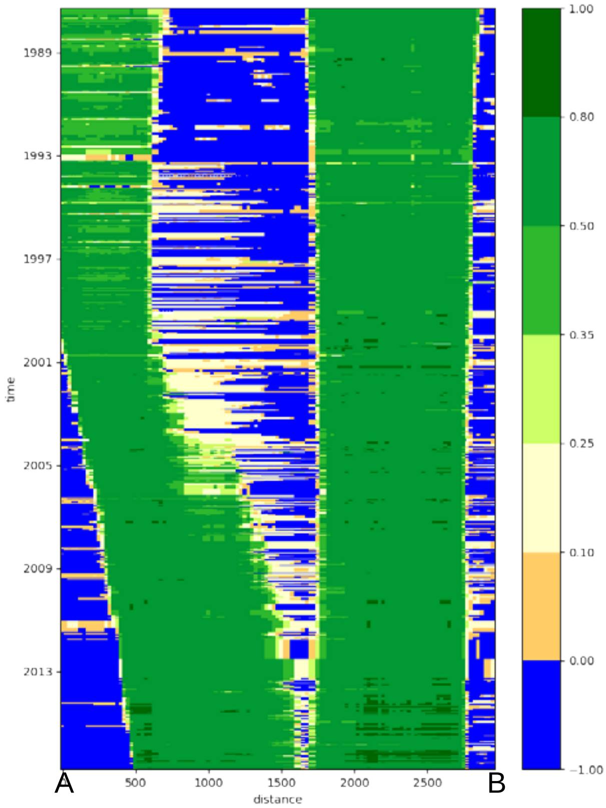

Figure 43 The Keep River estuary transect detailed in Figure 42 is represented on the x-axis of this NDVI Hovmoller plot.

4. DISCUSSION

The case study estuaries examined in this project are known areas of biological importance for threatened and migratory species of northern Australia. The image products and analysis tools employed in this study demonstrate the potential utility of Digital Earth Australia for mapping the extent and dynamics of key coastal and estuarine habitats utilised by these species. To better inform the management of these species, a key next step in this approach is to utilise ground-validation data to enable these habitats to be robustly classified and quantified, providing important baseline information and enabling their extent and condition to be monitored.

In northern Australia cloud interference can make it difficult to obtain clear satellite imagery. In this study we have demonstrated that this issue can be overcome using the geometric median of surface reflectance values from imagery subsets to produce composite imagery of the coast. In the case studies of estuarine and coastal environments, the geomedian approach, combined with imagery sorting based on tide height, produces clear and crisp image composites of high and low tide for the first time. These images depict the maximum observed tidal extent and provide an excellent basis upon which to undertake coastal and estuarine habitat mapping and classification.

Tide-tagging of satellite imagery allows any tide induced change to be removed from change-detection analyses. For example, image composites of coastline change, such as those observed in Figure 33, clearly depict the intertidal extent because the DEA compositing approach provides robust measures of average reflectance values for each set of co-located pixels across the tidal range. In contrast, using a traditional approach would produce considerably blurred coastal features due to high variability between observations. Application of ITEM further improves our understanding of the extent and morphology of the intertidal environment as well as the distribution of tidal currents and circulation, based on these physical characteristics of the intertidal area.

Another important advantage of utilising the DEA is the ability to undertaken change detection using a fully processed (atmospherically and geometrically calibrated), high density (several hundreds of observations per pixel), three decade long time series. The 30 years of data contained in the DEA Landsat archive enables investigation of event based changes on the landscape (floods, fires, cyclones and die-back), as well as more gradual changes that can be difficult to detect, such as changes in coastal morphology due to sediment erosion and deposition, and the revegetation of areas stripped by cyclonic wind (e.g. Figure 35 and Figure 30). The results of the analysis of the Landsat time series in the case study estuaries clearly depict the dynamic nature of some areas, including large-scale rapid island growth and mangrove expansion (e.g. Keep River and Gilbert River estuaries), gradual long-term expansion of mangrove (Flinders River and McArthur River estuaries), relatively stable mangrove (Darwin Harbour and Daly River estuaries), and estuaries with areas of rapid recent die back of mangrove (Roper River and Flinders estuaries). This information is important for the management of key species as well decisions around coastal developments. With Landsat and new satellite images (e.g. Sentinel 2) continually being added to the DEA, this time-series analysis approach could be developed into an effective habitat extent and condition monitoring tool.

Moving forward, the strength of these approaches will lie in their combination with field data. As threatened species ‘hotspots’ are further identified, tailored investigations can characterise the environment and assess how habitat change may have affected the species distribution over time. Field data that validates the interpretations from satellite data will be crucial to characterise the back-catalogue of imagery over the same region, establish accurate baselines, characterise and classify the landform dynamics of key coastal areas, and enable an ongoing habitat monitoring capability to be developed. Where appropriate, such a set of field measurements could be used to extrapolate across satellite observations over the greater region. Using this approach, predictions could be generated of potential areas of critical habitat for threatened and migratory species that are currently not documented.

5. ACKNOWLEDGEMENTS

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