Gladstone Healthy Harbour Partnership

Project ISP018

Development of Mangrove indicators for the Gladstone Harbour Report Card

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Report No. 19/34

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"We acknowledge the traditional owners of this land wherever we walk.
We pay our respects to the elders both past and present and to the future generations yet to come."

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This report has been produced for the Gladstone Healthy Harbour Partnership (GHHP) as part of the harbour report card program by their Independent Science Panel (ISP). The study was undertaken through a Consultancy Agreement (ISP018-2019) between the GHHP and James Cook University (JCU) to monitor the condition and status of changes to tidal wetlands (including Mangroves/Saltmarsh/Saltpans) in the Port Curtis region.

This publication has been compiled by the Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), JCU.

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EXECUTIVE SUMMARY

1) The MangroveWatch Hub with TropWATER Centre at James Cook University have developed three overall condition indicators for the regular monitoring of the health of tidal wetlands including mangroves, saltpans and tidal saltmarsh habitats within the Port Curtis study area in partnership with the Gladstone Healthy Harbour Partnership (GHHP).

2) 2018–2019 Report Card – Mangrove Tidal Wetland Habitat.
The 2018–2019 mangrove project consists of three indicators measured in each of the 13 GHHP environmental reporting zones: '%Extent', 'Canopy' and 'Shoreline'. The three represent independent parameters of condition quantifying recent changes to relative mangrove extent, canopy density and shoreline presence of dead trees. The overall zone scores show that the 2018–2019 condition of mangrove habitat was satisfactory to good, with Boyne Estuary having the poorest condition.

3) ***'%Extent' - the Wetland Cover Index (WCI) indicator*** was based on the WCI metric for the proportion of the area of mangrove to the total area of tidal wetlands for each sub-zone at the time of image acquisition. Area measures were taken from high resolution satellite imagery for each of the key vegetation units of mangroves and for tidal saltmarsh and saltpans. For this report, the period of evaluation was based on imagery acquired in 2018 and 2019. The WCI indicator shows changes in vegetation cover that might be related to direct loss and damage from human activities and/or from natural losses and gains with periodic storms, flooding, longer term changes in rainfall and sea level rise. Between 2018 and 2019, mangrove extent contracted more in northern areas

4) ***'Canopy' - the mangrove canopy condition indicator*** was based on satellite measures of the Normalised Difference Vegetation Index (NDVI) taken from the same imagery used for the WCI indicator. In this case, canopy reflectance measured using the mapping algorithm of the NDVI was used as a proxy measure of foliage health and canopy density.

5) ***'Shoreline' - the shoreline condition indicator*** was based on the assessment of oblique aerial imagery at 50 m interval points along all of the mangrove-dominated shorelines of each sub-zone and zone. The Shoreline indicator in this case was scored for the presence/absence of dead trees within each interval. The results were compared and validated against field summary scores made for each sub-zone during the aerial survey.

6) Overall, the scores were consistent with a number of changes taking place within mangroves and tidal wetlands observed across the region. These were marked by notable and recent detrimental impacts resulting from changing climatic conditions, decreasing rainfall, severe flood events (notably more for riverine estuaries) and rising sea levels (notable as terrestrial retreat in particular) coupled with pressures from normal port activities (like minor pollution, habitat encroachment and boat traffic wake).

7) Changes from last year were slight. Grahams Creek had deteriorated in the mangrove canopy condition, possibly reflecting impacts from decreased rainfall levels. There were some areas of mangrove dieback in Calliope River and Auckland Creek, possibly reflecting delayed impacts from flooding and low rainfall conditions. And, in Rodds Bay, there was also a drop in canopy condition possibly reflecting low rainfall levels also.

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A 2019 MANGROVE REPORT CARD SCORES

This section provides a summary of findings of Project ISP018-2019: ‘Development of mangrove indicators for the 2019 Gladstone Harbour Report Card’. With this project, research specialists with the MangroveWatch Hub at James Cook University (JCU) TropWATER Centre, describe specific indicators of ecological condition of tidal wetlands (including mangrove and saltmarsh habitat) for the Port Curtis region (Fig. 1). The broad nature of these condition indicators was outlined in the scope of works by the GHHP ISP. Full information on how the indicators were developed and how the studies were conducted was presented by Duke & Mackenzie (2018).

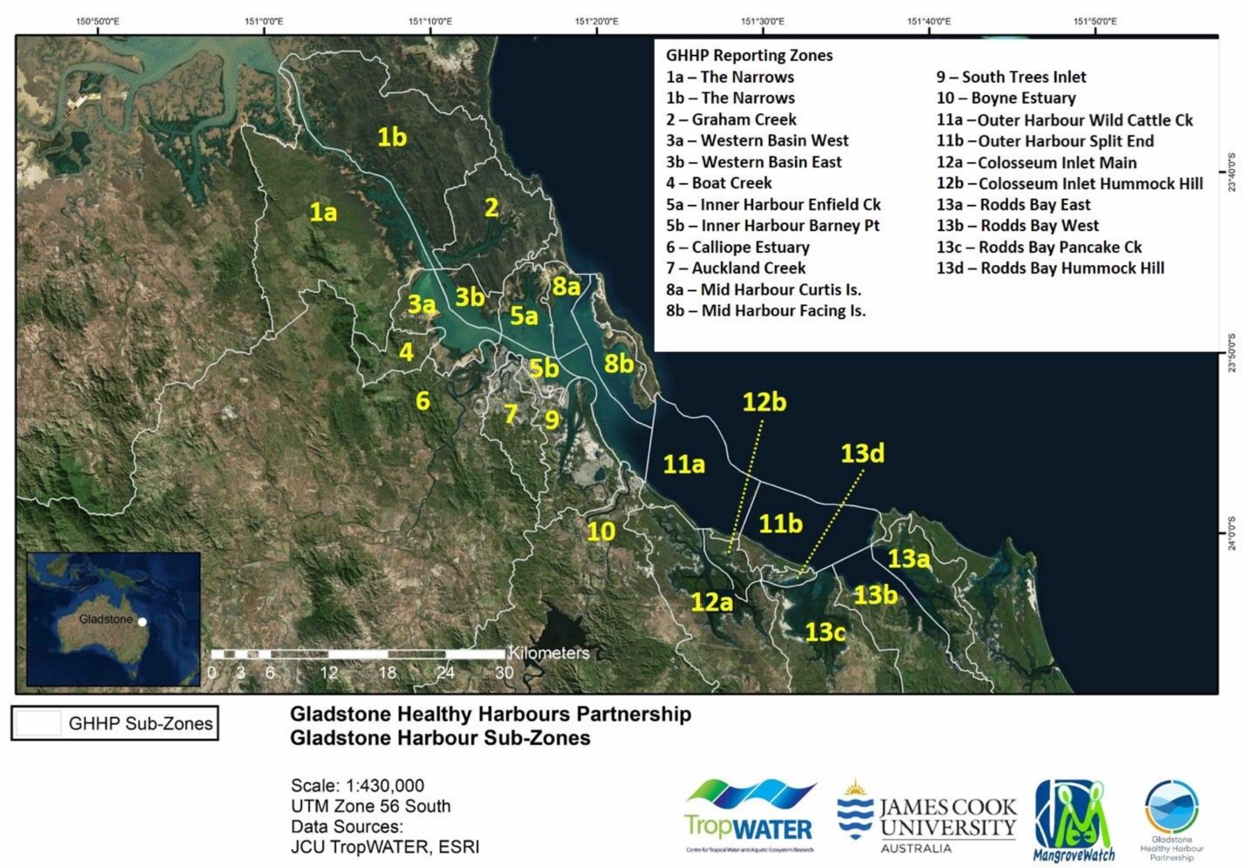

Figure 1. Map showing the 13 GHHP zones and the 23 sub-zones needed for mapping of tidal wetland vegetation and the factors affecting them.

In summary, the work program involved drawing on the considerable experience of the research team who have been monitoring the extent, biomass, biodiversity, productivity, change, overall condition and status of tidal wetlands including mangroves in the region, since 1975. MangroveWatch hub members have been collecting environmental and physical data from local mangrove habitat for various projects (Duke 2002, 2006, 2014, 2016a, 2016b; Duke and Burns 1999; Duke et al. 2000, 2003, 2016, 2017; Mackenzie and Duke 2017; Mackenzie et al. 2016). And recently, data continues to be collected as part of the Gladstone Ports Corporation Ecosystem Research and Monitoring Program Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (GPC ERMP PCPCA CHAMP) (Duke & Mackenzie 2016, 2017) and projects with the National Environmental Science Program Water Quality Hub. Based on these projects and others, the project team have developed considerable experience and expertise of these unique intertidal habitats, as well as how to evaluate their condition.

Table 1. Scores for three 2019 mangrove indicators as '%Extent', 'Canopy' and 'Shoreline' condition for the 13 GHHP reporting zones (see Section B for a full account).

Zone	Mangrove sub-zone	Zone Canopy Mangrove Condition Score	Zone Mangrove Extent Score	Zone Shoreline Mangrove Condition	2019 Overall Mangrove Score	*2018 Overall Mangrove Score*
1. The Narrows	1a. Mainland 1b. Curtis Island	0.54	0.79	0.50	0.64	*0.56*
2. Graham Creek	2. Graham Creek	0.36	0.83	0.75	0.64	*0.67*
3. Western Basin	3a. Mainland 3b. Curtis Island	0.39	0.76	0.37	0.51	*0.57*
4. Boat Creek	4. Boat Creek	0.38	0.54	0.46	0.46	*0.63*
5. Inner Harbour	5a. Enfield Creek 5b. Barney Point	0.51	0.61	0.52	0.55	*0.43*
6. Calliope Estuary	6. Calliope Estuary	0.48	0.80	0.47	0.58	*0.67*
7. Auckland Inlet	7. Auckland Inlet	0.57	0.76	0.62	0.65	*0.68*
8. Mid Harbour	8a. Curtis Island 8b. Facing Island	0.62	0.40	0.63	0.55	*0.55*
9. South Trees Inlet	9. South Trees Inlet	0.50	0.79	0.51	0.60	*0.61*
10. Boyne Estuary	10. Boyne Estuary	0.19	0.39	0.19	0.26	*0.41*
11. Outer Harbour	11a. Wild Cattle Creek 11b. Split End	0.64	0.76	0.58	0.66	*0.65*
12. Colosseum Inlet	12a Colosseum Creek 12b. Hummock Hill	0.67	0.85	0.54	0.72	*0.69*
13. Rodds Bay	13a. East 13b. West 13c. Pancake Creek 13d. Hummock Hill	0.57	0.68	0.67	0.64	*0.71*
Harbour score					**0.57**	***0.60***

Scores for each indicator were prepared for each sub-zone and these were later combined as single scores for each of the 13 GHHP Report Card zones. Results for 2018-2019 have been based on three indicators including: '%Extent', 'Canopy' and 'Shoreline' (Table 1).

Mangrove and tidal saltmarsh vegetation overall have changed considerably across the Port Curtis region since the 1940's, especially in areas around the central port area where there has been substantive urban, port and industrial development. But, while these changes are now well-established, the condition of new and remaining habitat is now the chief focus with the mangrove scores for of the 2019 GHHP Report Card. Scores presented in Table 1 reflect this aspect, noting in particular, areas like Auckland Inlet, where after having undergone severe modification and loss of habitat extent and hydrological conditions over previous decades, this area now shows scores equivalent to more isolated areas of Rodds Bay. The enhancement of habitat condition in these central zones is likely also to be related to higher levels of nutrients in these urban estuarine waters.

The strength of these shorter-term indicators is however demonstrated where they reflect ongoing recent changes like the notable and persistent damage caused by severe flooding events—especially in the Boyne River estuary.

However, it is recommended that additional indicators be added to subsequent report cards since there were unacknowledged changes observed during the 2018 and 2019 field surveys. These changes relate to shifts at specific ecotones including the terrestrial fringe at the highwater contour, and the seaward edge of mangroves at around mean sea level. Each of these ecotones are showing unidirectional change with the often-narrow loss of mangroves at the seaward edge, and retreat of terrestrial habitat (with less noticeable expansion of mangrove seedlings) at the highwater edge. These changes are consistent with rising sea levels. But these features were not adequately captured in the indicators shown in Table 1. We propose that a further 'habitat risk' indicator be developed to capture and quantify such increasingly notable changes to tidal wetland habitat – see Section B4.4 of this report. Such indicators can be developed using the same shoreline imagery acquired currently for this project. And, the concept has been demonstrated using rapid assessment scores made during the aerial survey.

B MANGROVE INDICATORS

1 INTRODUCTION

Use of mangrove indicators for the 2019 Gladstone Harbour Report Card involved an evaluation of the percent extent, change, overall condition, health and status of tidal wetlands including mangroves, developed for the 2018 Gladstone Harbour Report Card (Duke & Mackenzie 2018).

The metrics of mangrove health included: changes to extent of mangrove coverage; changes in distribution; and changes in species composition. While it was acknowledged these features had value as longer-term indicators of habitat status, the project team reasoned that changes to shorter-term condition would be better indicators of mangrove condition and health, rather than the relatively static structural features of mangrove forests, particularly tree biomass and species diversity. The latter features develop and change mostly over largely decadal periods while the ones chosen are more sensitive to year to year influences (see Duke & Mackenzie 2018). This report documents the reasoning behind this approach with our evaluation and development of three indicators of mangrove and tidal wetland habitat condition.

Mangrove condition, as noted, relates to the capacity of mangroves to provide ecosystem services supporting healthy marine environments in the Gladstone Harbour region (SKM 2013). Such indicators usefully represent existing mangrove structure, habitat productivity and ecosystem resilience. However, we have developed three informative indicators of mangrove condition that include observations of mangrove forest structural attributes, productivity measures and proxies and indicators of the risks and pressures that threaten resilience. In this context, we have focused on measures of mangrove structure and diversity because these represent immediate and current indicators of mangrove habitat condition.

The methods proposed were derived and developed using established and published research on various environmental assessments of tidal wetland ecosystems around the world, as well as in the Port Curtis study area. We therefore relied on this broad experience in not only mangrove habitat ecology, biogeography, genetics and productivity of mangrove wetlands, but specifically in the development of beneficial and practical indicators of their habitat condition and health. Our studies of immediate relevance to the current project includes the PCPA Coastal Habitat Archive and Monitoring Program (PCPA CHAMP) with the Gladstone Ports Corporation Environmental Research and Management Program (ERMP) (cs. Duke et al. 2019a).

2 METHODS

2.1 Study area sub-zones – for tidal wetlands

The Gladstone Harbour Report Card has 13 environmental reporting zones initially developed by The Queensland Department of Environment and Heritage Protection to define regionally specific water quality objectives for the Capricorn Coast (DEHP 2014). These zones extend from The Narrows to Rodds Bay (see Fig. 1). The 13 GHHP zones do not readily apply to tidal wetlands. So, to include this habitat in the Report Card the zones had to be re-defined and mapped for their relevance to tidal wetland habitats.

The sub-zones used were based on the original GHHP marine zones and adapted to relate to land catchment areas (white lines) for respective portions of tidal wetlands (including mangroves). This required the description of 23 sub-zones of component portions of the 13 GHHP environmental monitoring zones. Further details are presented by Duke & Mackenzie (2018).

2.2 '%Extent' indicator – the Wetland Cover Index (WCI)

Mangrove extent and biomass, structural indicators - specifically spatial extent and WCI

The proportional representation of mangrove area compared to other tidal wetland vegetation types offers a specific and useful measure of the status and functional state of tidal wetland habitats (Duke et al. 2019b). This includes the observation that mangroves exist as an alternate vegetative state to areas of saltmarsh and saltpan depending on levels of rainfall as a primary influencing factor. Together these habitat states often occupy soft sediment tidal slopes between mean sea level and highest tide levels. And, since their relative abundances depend on climate and sea level, the percent cover ratio (the WCI) can provide a useful indicator of habitat structure and environmental condition.

WCI values were estimated for each of the sub-zones and reduced further for each of the 13 GHHP environmental reporting zones. The PCPA CHAMP project had previously acquired spatial imagery and derived GIS resources from which to provide baseline measures of this primary habitat indicator (Duke and Mackenzie 2016, 2017).

Structural Indicators used

- Change in tidal wetland (mangrove, saltmarsh & saltpan) area relative to a baseline state.
- Change in tidal wetland WCI relative to observed overall regional change and expected change relative to annual rainfall variability.

A primary structural indicator for tidal wetlands is spatial extent as total areas of each of the major vegetation units of mangroves, tidal saltmarsh and saltpans (Duke et al., 2019). However, changes to such areas are either considered less sensitive or difficult to discriminate, especially where these occur along ecotones between notable vegetation units both internally and externally. In this way, changes would only be evident following extreme events like severe flooding and storms, large oil spills, or larger-scale reclamation works.

Scoring system - Raw WCI Score. Calculated as the relative proportion of mangrove within the tidal wetland area (Mangrove and Saltmarsh/Saltpan) in each sub-region determined from SPOT 2018 mapping (see Duke & Mackenzie 2018).

Mangrove Loss/Gain and WCI change score. Mean 'Mangrove' NDVI and standard deviation were calculated as per above for 2017/18. A minimum mangrove NDVI value threshold ($Mang_{MIN}$) was determined as less than 2 standard deviations from the mean 2017 'mangrove' NDVI value (0.39). A point layer representing $30m^2$ Landsat 8 pixel centroids was created for the 2017 tidal wetland areas. Points were classified as either mangrove, saltmarsh/saltpan or open water based on their location within mapped polygons. The 2018/2019 NDVI classification was compared to 2014/2015 NDVI maximum values for all points.

Mangrove loss and gain was classified as follows;
Mangrove Loss: $NDVI_{14/15} >= Mang_{MIN}$ & 2018 Classification = Saltmarsh/Saltpan or Water
Mangrove Gain: $NDVI_{14/15} < Mang_{MIN}$ & 2018 Classification = Mangrove

2.3 'Canopy' indicator – NDVI and canopy density

The location of mangroves in the inter-tidal zone exposes mangrove forests to a wide range of natural and anthropogenic stressors that vary temporally and spatially. Natural stressors range from long-term regional rainfall and sea level variability, localised stochastic weather events such as storms and localised herbivory. Anthropogenic stressors include altered hydrological regimes, increased sediment and nutrient loads related to catchment modification and localised pollution events such as oil spills. Natural and anthropogenic stressors alter the structure and function of mangroves leading to changes in ecosystem service delivery and potential loss of habitat. These stressors may be localised as is the case for pollution events or regional, as occurs during periods of lower rainfall.

Exposure of mangrove trees to stressed conditions leads to loss of productivity and reduced leaf production with eventual tree death once the plants available photosynthetic capacity fails to meet the high energetic requirements of living in the intertidal zone. In a resilient healthy forest when conditions improve and the stressor is no longer present, remnant living trees increase leaf production and gaps created by dead trees are occupied by mangrove seedlings. Plant productivity is expressed as canopy density at a forest scale and forest resilience can be measured by the rate and extent to which a forest recovers from a stress event. Remote sensing satellites can detect the reflectance and absorption of light wavelengths from mangrove forest canopies. Patterns of light reflectance detected by satellites are used to develop vegetation indices of forest condition. Healthy forests with dense canopy cover and high leaf chlorophyll content absorb high levels of red light and reflect near-infra red light. A commonly used vegetation index of forest canopy cover is the normalized difference vegetation index (NDVI) which is a measure of the relative absorption and reflectance of red and near-infra red (NIR) light and is therefore a measure of relative forest canopy condition. For further details see Duke & Mackenzie (2018).

The overall mean score across the three NDVI scores and each sub-zone was used to generate the final mangrove condition score for each GHHP zone.

Mangrove condition indicators

- Change in mean NDVI value relative to regional baseline.
- Area of extreme NDVI value declines (-2 standard deviations from regional mean) as a percentage of total mangrove area.

- Annual change in shoreline mangrove condition score.
- Comparison between leafy shoot counts and canopy condition.

2.4 'Shoreline' indicator – shoreline condition & dead mangroves

Shoreline edge mangrove stands are sites of maximal exposure to coastal environments. In these settings, exposure-hardened trees offer high ecosystem service value by protecting shorelines from episodic severe erosion events, like storms and flooding. Mangroves along the shoreline interface are often exposed to multiple stressors, including both natural and anthropogenic kinds. Shoreline mangroves can respond quickly to changes in tidal conditions, water quality and climate. As such, their status can be a useful indicator of shoreline condition. The project team have developed the Shoreline Video Assessment Method (Mackenzie et al. 2016) as a practical means to monitor shoreline condition.

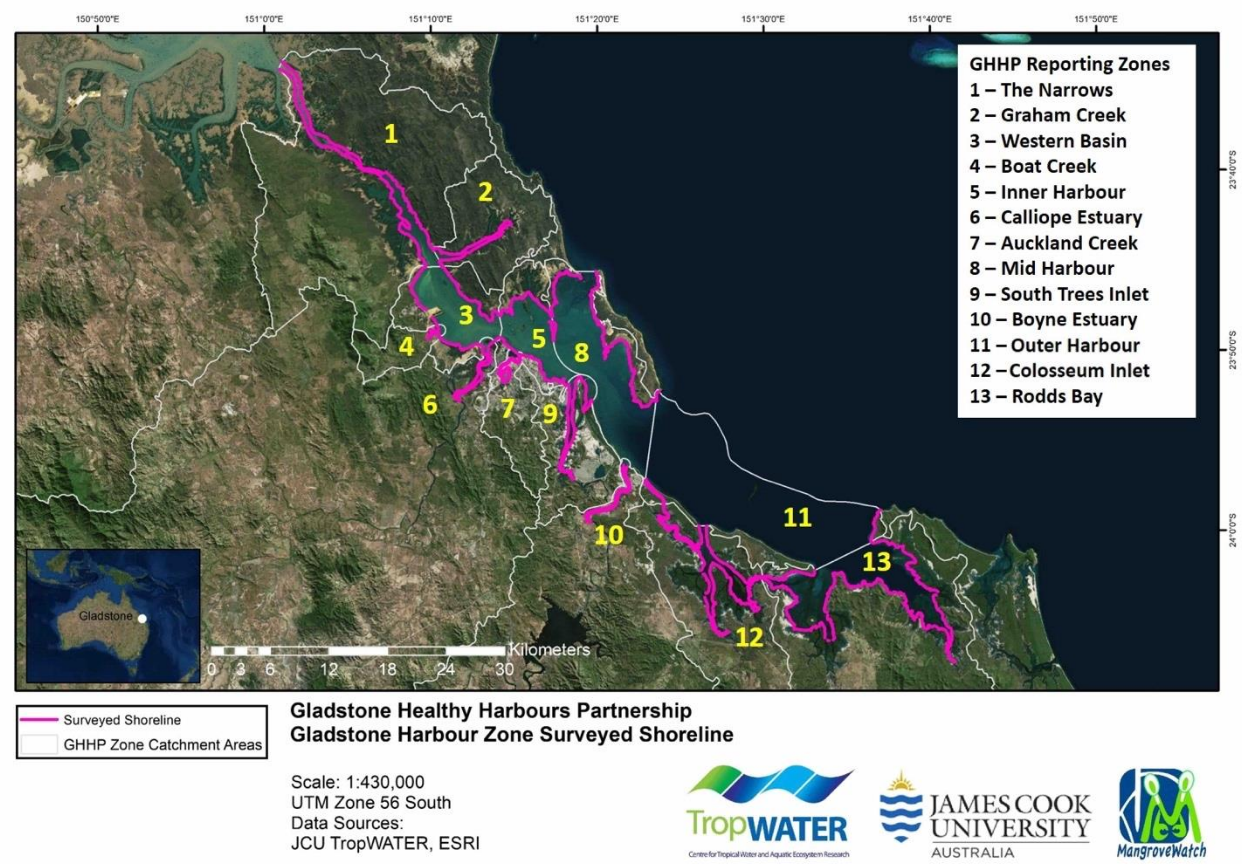

Figure 2. Map showing 13 GHHP zones and the track of the shorelines assessed in 2019 matching that made in 2018.

These measures were gathered from aerial and boat-based shoreline surveys as being used in many shoreline assessment projects, like the PCPA CHAMP (Duke et al. 2017; Mackenzie & Duke 2017; Duke et al. 2019). We have used shoreline mangrove condition as a further measure of mangrove shoreline condition. This measure compliments canopy and extent assessments enabling additional quantification of habitat condition.

The presence of dead mature canopy trees in shoreline fringe mangrove stands was recorded at 50 m intervals along target shorelines using oblique aerial shoreline image analysis following an adapted shoreline video assessment method approach (Mackenzie et al. 2016).

Image Acquisition. An aerial shoreline survey of shorelines bordering GHHP water quality zones was undertaken in April 2019 (Fig. 2). Overlapping oblique high-resolution photographs of the shoreline were taken from an open R44 helicopter travelling perpendicular to the shoreline. Flying height was approximately 150 m above sea level with the helicopter positioned such that photographs captured included the mangrove-shoreline interface and the extent of the fringe forest zone. Photographs were taken using either a Nikon D800E camera with a 50 mm lens.

Image Assessment. A stratified sampling design was used to assess the presence of dead mangroves within shoreline fringe mangrove forest along GHHP water quality zone shorelines. Shoreline sampling points were created at 50m intervals along a shoreline line feature derived from a 0 m contour line approximating mean sea level generated using a 5 m Digital Elevation Model raster (Geosciences Australia, 2018) and snapped to an existing mangrove polygon feature with a tolerance of 50 m (Duke et al. 2019a). An oblique image was matched to the shoreline sampling points based on the perpendicular bearing of a 1 second GPS track such that the centreline of the image approximated (within +/- 25m) features present at the matched shoreline sampling point. Shoreline creation and the image to shoreline point matching process was undertaken in ArcGIS 10.5.1 following Mackenzie et al. 2016. Images not matched to a shoreline sampling point, or where the shoreline interface was not clearly visible were discarded. Where the same image was matched to two or more sampling points due to shoreline angle and flight trajectory, the sampling point nearest to the perpendicular bearing shoreline intercept was used. The presence of individual dead mangroves either along the shoreline or within the shoreline fringe zone coincident with the centreline of the image was recorded to create a binary ‘dead mangrove’ variable. Dead mangroves were clearly visible in the oblique images either as standing dead trees or fallen trees along the shoreline. Only dead canopy trees were recorded. This assessment was undertaken for all shorelines that bordered the GHHP environmental reporting zones.

Score derivation. The oblique aerial image assessment provided a representation of the proportion of shoreline fringe mangrove forest with dead mangroves present within each of the GHHP water quality zones. A chi-square goodness of fit analysis with unequal proportions was conducted on ‘dead mangrove’ frequency using SPSS v.24 to test the hypothesis that the frequency of observations of shoreline mangrove with dead individuals in each GHHP zone was the same as the expected frequency for the overall study area (all GHHP zones). For further details see Duke & Mackenzie (2019).

3 RESULTS

3.1 '%Extent' indicator – application of the Wetland Cover Index

This indicator was derived from estimates of change to mangrove forest canopy cover (Fig. 3) as the primary structural indicator for tidal wetlands. Spatial cover is the total area for each of the major vegetation types of mangroves, and tidal saltmarsh plus saltpan. Dieback of upland trees at the terrestrial-upper tidal ecotone is indicative of rising sea levels.

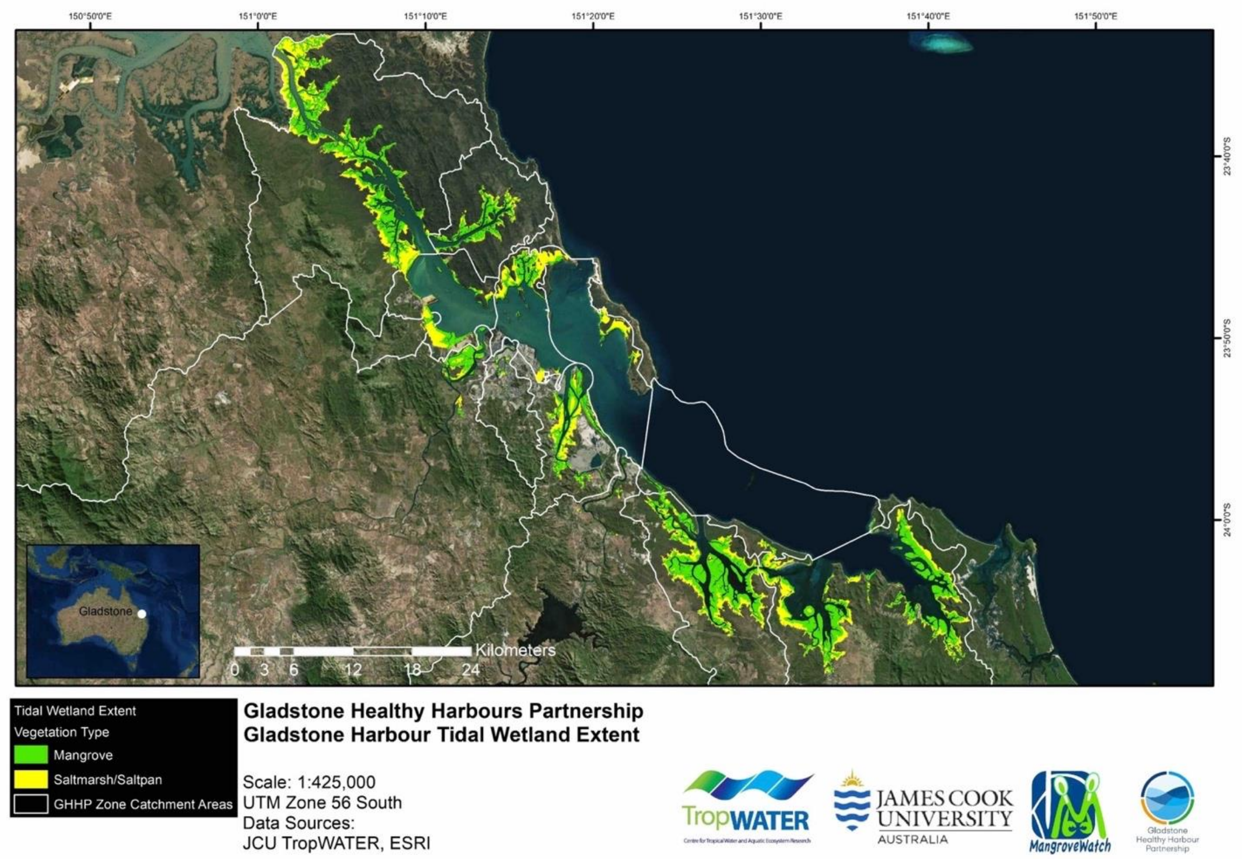

Figure 3. Map showing the overall extent of dominant tidal wetland vegetation types, mangroves and tidal saltmarsh plus saltpan for the entire GHHP study area.

Results for 2019 are tabulated in Table 2. This includes derivation results and scores for each of the sub-zones combined as the 13 GHHP zones.

Table 2. Estimates of Wetlands Cover Index (WCI) for GHHP sub-zones and zones plus recent 2018-2019 changes.

GHHP Zone	GHHP sub-zone	WCI 2018–19	WCI change score	Mangrove loss score	Sub-zone score	Zone extent score
1. The Narrows	1a. Mainland	0.60	0.96	0.86	0.81	0.79
	1b. Curtis Island	0.60	0.82	0.88	0.77	
2. Graham Creek	2. Graham Creek	0.75	0.83	0.90	0.83	0.83
3. Western Basin	3a. Mainland	0.44	0.95	0.76	0.72	0.76
	3b. Curtis Island	0.64	0.82	0.94	0.80	
4. Boat Creek	4. Boat Creek	0.40	0.68	0.55	0.54	0.54
5. Inner Harbour	5a. Enfield Creek	0.54	0.75	0.94	0.74	0.62
	5b. Barney Point	0.25	0.46	0.75	0.49	
6. Calliope Estuary	6. Calliope Estuary	0.82	0.86	0.71	0.80	0.80
7. Auckland Inlet	7. Auckland Inlet	0.63	0.94	0.70	0.76	0.76
8. Mid Harbour	8a. Curtis Island	0.30	0.63	0.88	0.60	0.39
	8b. Facing Island	0.27	0.30	0.00	0.18	
9. South Trees Inlet	9. South Trees Inlet	0.59	0.97	0.80	0.79	0.76
10. Boyne Estuary	10. Boyne Estuary	0.68	0.35	0.15	0.39	0.39
11. Outer Harbour	11a. Wild Cattle Creek	0.93	0.90	0.92	0.92	0.76
	11b. Split End	0.50	0.76	0.52	0.59	
12. Colosseum Inlet	12a Colosseum Creek	0.70	0.99	0.84	0.84	0.85
	12b. Hummock Hill	0.71	0.95	0.88	0.85	
13. Rodds Bay	13a. East	0.73	0.92	0.78	0.81	0.68
	13b. West	0.66	0.74	0.58	0.66	
	13c. Pancake Creek	0.61	0.84	0.66	0.70	
	13d. Hummock Hill	0.46	0.67	0.46	0.53	
Harbour score						**0.69**

3.2 'Canopy' indicator – canopy density and condition

This indicator was derived from estimates of NDVI of mangrove forest canopies (Fig. 4) as a primary condition indicator of tidal wetlands. Estimates particularly relate to the canopy condition of mangroves and tidal saltmarsh.

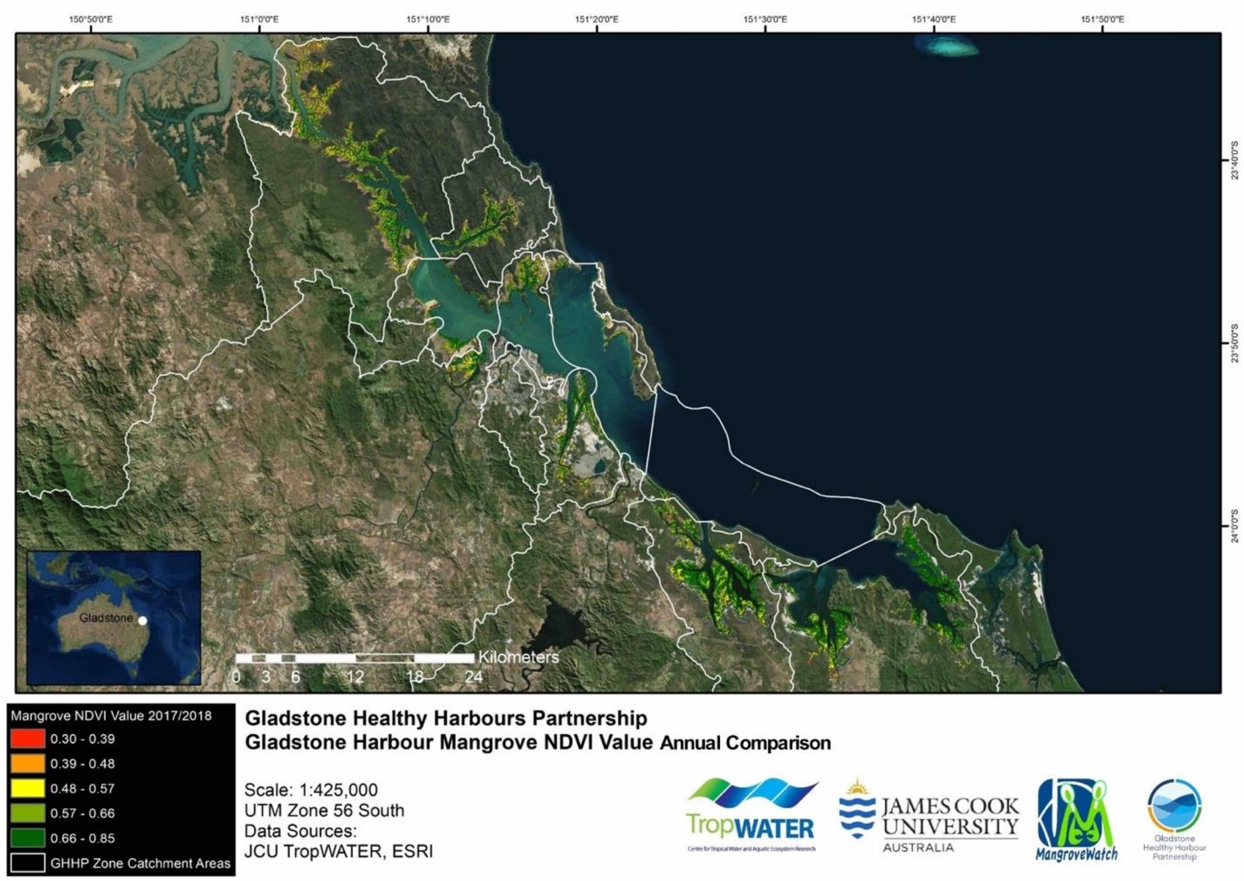

Figure 4. Map showing 13 GHHP zones and the 2019 canopy condition as NDVI measures of tidal wetland vegetation across the Port Curtis study area.

Results are tabulated in Table 3. This includes derivation of results and scores for each of the sub-zones and the 13 GHHP environmental reporting zones.

Table 3. Summarised estimates of NDVI for GHHP sub-zones and zones showing change trends over the last year and 5 years previous.

GHHP Zone	GHHP sub-zone	2019 NDVI score	1-year change	5-year change	Sub-zone score	Zone score
1. The Narrows	1a. Mainland	0.63	0.61	0.34	0.53	0.55
	1b. Curtis Island	0.60	0.77	0.31	0.56	
2. Graham Creek	2. Graham Creek	0.65	0.25	0.11	0.34	0.34
3. Western Basin	3a. Mainland	0.70	0.32	0.15	0.35	0.39
	3b. Curtis Island	0.72	0.41	0.26	0.43	
4. Boat Creek	4. Boat Creek	0.66	0.61	0.09	0.38	0.38
5. Inner Harbour	5a. Enfield Creek	0.70	0.21	0.70	0.67	0.51
	5b. Barney Point	0.53	0.34	0.33	0.35	
6. Calliope Estuary	6. Calliope Estuary	0.67	0.29	0.43	0.48	0.48
7. Auckland Inlet	7. Auckland Inlet	0.57	0.41	0.86	0.57	0.57
8. Mid Harbour	8a. Curtis Island	0.61	0.57	0.78	0.60	0.63
	8b. Facing Island	0.64	0.36	0.75	0.65	
9. South Trees Inlet	9. South Trees Inlet	0.66	0.00	0.47	0.50	0.50
10. Boyne Estuary	10. Boyne Estuary	0.56	0.55	0.00	0.19	0.19
11. Outer Harbour	11a. Wild Cattle Creek	0.60	0.48	0.58	0.55	0.64
	11b. Split End	0.63	0.62	0.91	0.73	
12. Colosseum Inlet	12a Colosseum Creek	0.68	0.55	0.70	0.65	0.67
	12b. Hummock Hill	0.71	0.66	0.70	0.69	
13. Rodds Bay	13a. East	0.74	0.46	0.59	0.59	0.57
	13b. West	0.67	0.26	0.56	0.50	
	13c. Pancake Creek	0.68	0.43	0.66	0.59	
	13d. Hummock Hill	0.63	0.43	0.71	0.59	
Harbour score						**0.49**

3.3 'Shoreline' indicator – condition as frequency of dead trees

A total of around 8,000 shoreline points were assessed across all 13 GHHP environmental reporting zones. Of these points, around 90% were represented with shoreline mangroves. The overall proportion of shoreline mangroves with dead mangroves present was about 15%. The proportion of shoreline mangroves with dead mangroves present in individual zones ranged from around up to 40% (Boyne River Estuary – Zone 10). The Boyne River Estuary (Zone 10) had a significantly higher frequency of dead mangroves compared to the overall region. All other zones were not significantly different from regional observations.

Results are tabulated in Table 4. This includes derivation results and scores for each of the sub-zones combined for the 13 Zones.

Table 4. Estimates of Shoreline condition for GHHP sub-zones showing recent changes 2018-2019.

GHHP Zone	GHHP sub-zone	Dead mangrove frequency score	Seasonally Adjusted dead mangrove frequency score	Sub-zone shoreline condition score	Zone shoreline condition score
1. The Narrows	1a. Mainland	0.57	0.45	0.51	0.60
	1b. Curtis Island	0.81	0.59	0.70	
2. Graham Creek	2. Graham Creek	0.88	0.64	0.76	0.76
3. Western Basin	3a. Mainland	0.36	0.32	0.34	0.37
	3b. Curtis Island	0.43	0.37	0.40	
4. Boat Creek	4. Boat Creek	0.50	0.41	0.46	0.46
5. Inner Harbour	5a. Enfield Creek	0.72	0.54	0.63	0.52
	5b. Barney Point	0.45	0.38	0.42	
6. Calliope Estuary	6. Calliope Estuary	0.52	0.43	0.47	0.47
7. Auckland Inlet	7. Auckland Inlet	0.70	0.53	0.62	0.62
8. Mid Harbour	8a. Curtis Island	0.85	0.62	0.73	0.63
	8b. Facing Island	0.59	0.46	0.52	
9. South Trees Inlet	9. South Trees Inlet	0.57	0.45	0.51	0.51
10. Boyne Estuary	10. Boyne Estuary	0.16	0.21	0.19	0.19
11. Outer Harbour	11a. Wild Cattle Creek	0.60	0.56	0.54	0.58
	11b. Split End	0.71	0.47	0.63	
12. Colosseum Inlet	12a Colosseum Creek	0.72	0.54	0.63	0.64
	12b. Hummock Hill	0.76	0.56	0.66	
13. Rodds Bay	13a. East	0.74	0.56	0.65	0.67
	13b. West	0.78	0.58	0.68	
	13c. Pancake Creek	0.74	0.55	0.65	
	13d. Hummock Hill	0.80	0.59	0.70	
Harbour score					**0.54**

4 DISCUSSION

4.1 General observations – dot point summary

A number of issues were observed across the study area. Many of these effects were notably observed also in 2018. This is as expected with either slow recovery to severe impacts from flooding and severe storms, or slow progressive trends consistent with sea level rise and climate change.

Decreases in canopy condition – indicative of possible seasonal and overall levels of rainfall. This was observed in changes since 2018 in canopy condition in sites including: Grahams Creek, Western Basin, Boat Creek, Auckland Creek, Boyne River Estuary and Rodds Bay.

Dieback and damage to mangrove trees along the estuarine margins – indicative of flood and erosion damage. Impacted mangrove areas were observed in several tidal wetlands of the study area during 2017-2018 and 2018-2019. Severe flood impacts were observed within major riverine estuaries, especially for the Boyne River estuary. Recovery was notably slow in these instances – and, conditions in some ways have worsened. The 2019 situation appeared exacerbated by access tracks, further declines in vegetation condition – reducing and inhibiting seedling recruitment, recovery and re-establishment.

Dieback of upland trees at the terrestrial-upper tidal ecotone – indicative of rising sea levels. A second notable feature was terrestrial retreat marked by bank erosion, dead terrestrial edge trees, mangrove seedling establishment and upper saltpan scouring. This feature is consistent with the responses expected with rising sea levels throughout the study area. The process was further recognisable in change detection imagery where changes were seen to be unidirectional and acting at three intertidal ecotone fronts simultaneously as: loss of both frontal edge mangrove trees; saltpan scouring; and coupled with terrestrial retreat with saline intrusion.

Dieback at the saltpan ecotone – indicative of a longer-term decrease in rainfall. This feature largely involves the retreat of mangrove vegetation and expansion of the saltpan and saltmarsh areas. These features need to more fully quantified with targeted monitoring.

Dieback and erosion loss of shoreline trees – indicative of sea level rise and/or storm impacts. This effect appears possibly exacerbated by storm impacts causing a disproportionate amount of shoreline erosion. This feature is being monitored with the Shoreline condition indicator. This feature has notably increased in Auckland Creek and Mid Harbour.

4.2 Shoreline change

Overall with this project, the condition of mangroves and tidal wetlands are being assessed across the GHHP study area using several complimentary lines of inquiry. To re-iterate briefly, the study components under consideration include: the accurate quantification of extent, biomass and canopy condition of tidal wetlands from detailed mapping; quantification of overall condition of tidal wetlands as well as the observed drivers of change observed during aerial shoreline surveys using the Shoreline Video Assessment Method (S-VAM); quantification of overall condition of tidal wetlands as well as the observed drivers of change as observed from vessel-based shoreline surveys also using S-VAM; and these resources will all be archived in the online database facility called PCPA CHAMP projects' ShoreView facility (http://mangrove.hpc.jcu.edu.au/home/) to display imagery and data collected during these and associated studies.

There are some observations of immediate interest. These current observations may be tested more fully as additional annual reports are completed. In each year, our findings will be compared.

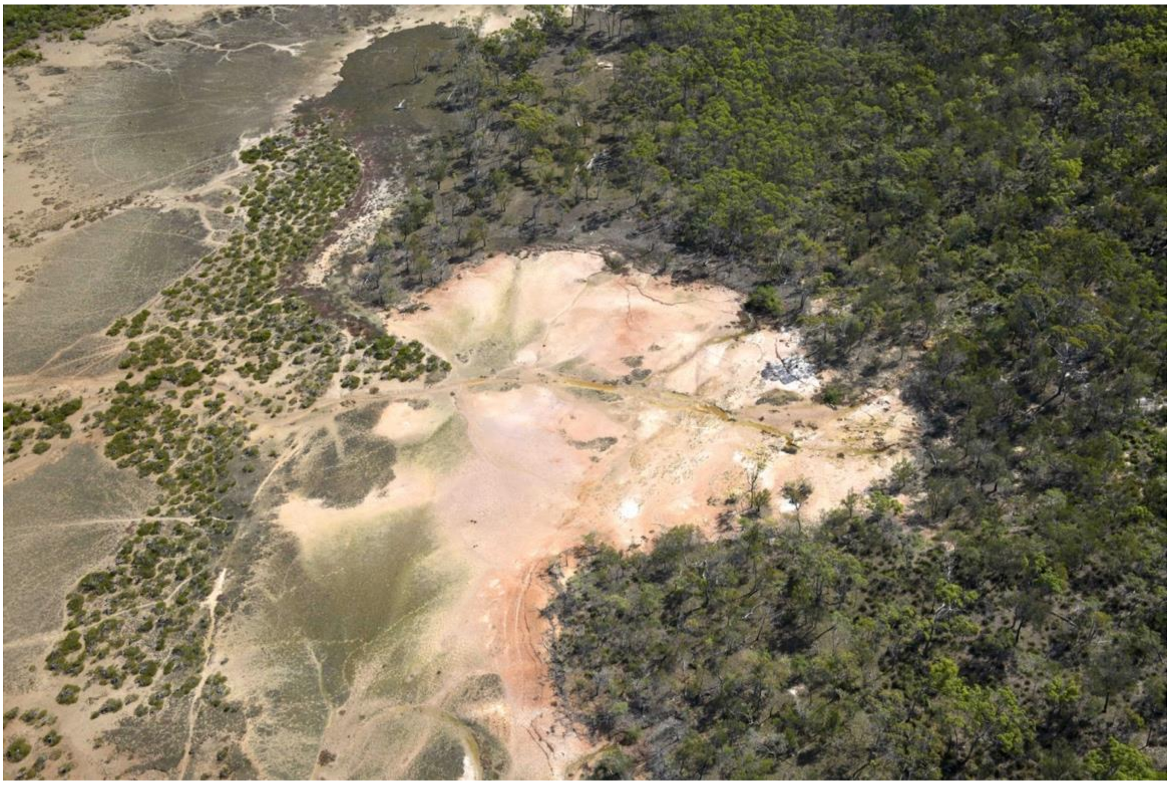

Figure 5. Observed in late April 2019, indicators of terrestrial retreat and scouring were evident throughout the GHHP study area. This example of scoring and erosion of upland marginal vegetation, accompanied by saline intrusion, was seen in the northern mainland sector of the Narrows.

Observations of shoreline retreat are consistent with sea level rise

As noted in 2018 and supported further in this report, mangrove and terrestrial shorelines throughout the GHHP study area show notable and multiple indications of active retreat. These changes are consistent with shoreline habitat responses expected as sea levels rise (Duke and Mackenzie 2018). Our observations of these changes were made for two distinct ecological ecotones that largely depend on sea level.

One ecotone is the mangrove-terrestrial margin (see Fig. 5) – more or less at the highest astronomical tide level. Our observations of damage occurring along this zone edge will be investigated further in both mapping and the field monitoring campaign with the concurrent PCPA CHAMP (Duke et al. 2019). Additional monitoring surveys however are needed to quantify rates of change accompanied by on-ground field assessments of shoreline retreat and saline intrusion within the GHHP study area.

The second retreating ecotone is the mangrove seaward margin (see Fig. 6) – closely matching mean sea level. And, where the proportion of shorelines affected in this way exceeds 50%, it implies there is a common agent acting throughout the wider area. Observations made during the recent aerial surveys provide observational data from which comparisons will be made. These and subsequent data will be assessed further over the years.

Figure 6. Observed in late April 2019, indicators of mangrove shoreline erosion were evident throughout the GHHP study area. This example of eroded front edge trees was seen in the northern channel of the Narrows.

Damage to mangrove shorelines can be exacerbated by localised events including anthropogenic factors as well as natural factors like damaging storm events and sea level rise (see Figs. 7 & 8). In the study area, pressures from rising sea levels appear to be threatening shoreline stability leading to the accelerated deterioration of exposed vegetation (Fig. 6) releasing soft sediments into surrounding shoreline environments.

Figure 7. Observed in early May 2019, this mangrove shoreline at the mouth of South Trees Inlet appears to have been hit by a severe storm and now the bank is seriously eroding before seedings can take hold. In this instance, it is clear that once trees have been killed then there is little to prevent shoreline erosion of dead trees and breakup of the underlying ancient peat layers.

Figure 8. Observed in early May 2019, nearby the previous image (Fig. 19), this damaged mangrove shoreline at the mouth of South Trees Inlet is seriously eroding. In this instance, it is clear that there is some recruitment but one key question is, how much will be lost before the shoreline bank is re-established.

5 REFERENCES

DEHP. 2014. Environmental Protection (Water) Policy 2009: Environmental values and waste quality objectives Curtis Island, Calliope River and Boyne River basins. Environmental Policy and Planning Division, Department of Environment and Heritage Protection, Queensland.

Duke, N.C. 2002. Sustained high levels of foliar herbivory of the mangrove *Rhizophora stylosa* by a moth larva *Doratifera stenosa* (Limacodidae) in north-eastern Australia. **Wetlands Ecology and Management** 10: 403-419.

Duke, N.C. 2006. **Australia's Mangroves.** The authoritative guide to Australia's mangrove plants. University of Queensland and Norman C Duke, Brisbane, 200 pages.

Duke, N.C. 2014. Mangrove Coast. Encyclopedia of Marine Geosciences, edited by Jan Harff, Martin Meschede, Sven Petersen and Jörn Thiede. **Springer** Netherlands. pp 412-422. ISBN 978-94-007-6237-4. http://link.springer.com/referenceworkentry/10.1007%2F978-94-007-6644-0_186-1

Duke, N.C. 2016a. Oil spill impacts on mangroves: recommendations for operational procedures and planning based on a global review. Marine Pollution Bulletin 109(2): 700-715.

Duke, N.C. 2016b. Mangrove Click! Australia: expert ID for Australia's mangrove plants. Currumbin, MangroveWatch Publication. ISBN: 978-0-9923659-2-9. https://itunes.apple.com/us/app/mangrove-au/id1157235522?mt=8

Duke, N.C., and K.A. Burns. 1999. Fate and effects of oil and dispersed oil on mangrove ecosystems in Australia. Main Report, 212 pages; Executive Summary, 23 pages. Report to the Australian Petroleum Production Exploration Association. Australian Institute of Marine Science and CRC Reef Research Centre, James Cook University.

Duke, N.C. and K.A. Burns 2003. Fate and effects of oil and dispersed oil on mangrove ecosystems in Australia, pp. 232-363. In Environmental implications of offshore oil and gas development in Australia: further research. A compilation of three scientific marine studies. Australian Petroleum Production and Exploration Association (APPEA), Canberra, 521 pages

Duke, N.C. and H. Kudo. 2018. *Bruguiera × dungarra*, a new hybrid between mangrove species *B. exaristata* and *B. gymnorhiza* (Rhizophoraceae) recently discovered in north-east Australia. Blumea 63: 279-285. DOI: 10.3767/blumea.2018.63.03.03

Duke N.C. and Mackenzie J. 2016. '2015 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 15/37, James Cook University, Townsville.

Mackenzie, J, Duke N.C. 2017. Mooloolah River Baseline Mangrove and Saltmarsh Condition Assessment. A data report prepared for Bunya Bunya Country Aboriginal Corporation as part of the Mangrove and Saltmarsh Dreaming Project. MangroveWatch Science Hub, Centre for Tropical Water & Aquatic Ecosystem Research. Publication, James Cook University, Townsville. 20pp.

Duke N.C., and Mackenzie J. 2018. Project ISP018: Development of mangrove indicators for the Gladstone Harbour Report Card. Report to Gladstone Healthy Harbour Partnership by TropWATER Centre. Report 18/38, James Cook University, Townsville, 42 pp.

Duke, N.C., K.A. Burns, R.P.J. Swannell, O. Dalhaus and R.J. Rupp 2000. Dispersant use and a bioremediation strategy as alternate means of reducing the impact of large oil spills on mangrove biota in Australia: the Gladstone field trials. **Marine Pollution Bulletin**, 41: 403-412.

Duke, N.C., P. Lawn, C.M. Roelfsema, S. Phinn, K.N. Zahmel, D. Pedersen, C. Harris, N. Steggles and C. Tack 2003. Assessing historical change in coastal environments. Port Curtis, Fitzroy River Estuary and Moreton Bay regions. Final Report to the **CRC for Coastal Zone Estuary & Waterway Management**. Historical Coastlines Project, Marine Botany Group, Centre for Marine Studies, The University of Queensland, Brisbane. 258 pages plus appendices.

Duke N.C., Mackenzie J., Kovacs, J., Hill, D., Eilert, F., Atkinson, I., and van der Valk, S. 2016. '2015–2016 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 16/52, James Cook University, Townsville.

Duke N.C., Mackenzie J., Kovacs, J., Hill, D., Carder, D., Eilert, F., Atkinson, I., Wyatt, M. and van der Valk, S. 2017. '2016-2017 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 17/56, James Cook University, Townsville.

Duke N.C., Mackenzie J., Kovacs, J., Cormier, R., Eilert, F., Atkinson, I. and van der Valk, S. 2018. '2017-2018 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Report 18/52, James Cook University, Townsville, 34 pp.

Duke N.C., Mackenzie J., Kovacs, J., Cormier, R., Eilert, F., Atkinson, I. and van der Valk, S. 2019a. '2018-2019 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Report 19/28, James Cook University, Townsville, 66 pp.

Duke, N.C., C. Field, J.R. Mackenzie, J.-O. Meynecke and A.L. Wood. 2019b. Rainfall and its possible hysteresis effect on the proportional cover of tropical tidal wetland mangroves and saltmarsh-saltpans. Marine and Freshwater Research, published online. DOI: 10.1071/MF18321.

Duke, N.C., Mackenzie, J., Fennessy, R., Cormier, R., Kovacs, J. 2019b. 'Final Report: Southern GBR Coastal Habitat Archive and Monitoring Program (S-GBR CHAMP)'. Final Report for the National Science Environmental Programme Tropical Water Quality Hub. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER). Two Volumes: Report #19/11. James Cook University, Townsville, 74 & 162pp.

Feller, I. C., Dangremond, E. M., Devlin, D. J., Lovelock, C. E., Proffitt, C. E., & Rodriguez, W. 2015. Nutrient enrichment intensifies hurricane impact in scrub mangrove ecosystems in the Indian River Lagoon, Florida, USA. *Ecology*, *96*(11), 2960-2972.

Kotze, DC, WN Ellery, DM MacFarlane, GPW Jewitt. 2012. A rapid assessment method for coupling anthropogenic stressors and wetland ecological condition. Ecological Indicators 13: 284-293.

Mackenzie, J. R., Duke, N. C., & Wood, A. L. 2016. The Shoreline Video Assessment Method (S-VAM): Using dynamic hyperlapse image acquisition to evaluate shoreline mangrove forest structure, values, degradation and threats. Marine pollution bulletin, 109(2), 751-763.

SKM 2013. Mangrove & Saltmarsh Monitoring: Literature Review, Report prepared for Gladstone Ports Corporation by SKM, South Brisbane.

Schultz, M., U. Pinto, J. Windle, J.D. Valck, N. Flint, M. Star, M. Logan, A. Anastasi, E. M. Chua, A. K. Rose, E.L. Jackson, C.V. Bryant, A. Carter, K.M. Chartrand, J. Wells, M.A. Rasheed, P. Costello, A.A. Thompson, J. Davidson, N.C. Duke, J.R. Mackenzie, B. Sawynok, B. Venables, S. Chisholm, B. George, N. Taylor, G. Chisholm and M. Watts 2019. Gladstone Harbour Report Card 2018 - Technical Report. Gladstone Healthy Harbour Program (GHHP). Rockhampton, Fitzroy Basin Association.

Appendix 1: Observations of trash along shorelines of the GHHP study area

During the aerial surveys in late April 2019, the project team observed and noted marine debris scattered around the GHHP study area and extending north and west around Port Alma and the mouth of the Fitzroy River (Duke et al., 2019). A preliminary map of these sightings is shown in Fig. 9. The trash consisted of a variety of items including: nets, small boats, parts of boats, floats, plastic drums and abandoned crab pots (Fig. 10). Much of this debris is plastic. The items have entrapped wildlife, like mud crabs and fish.

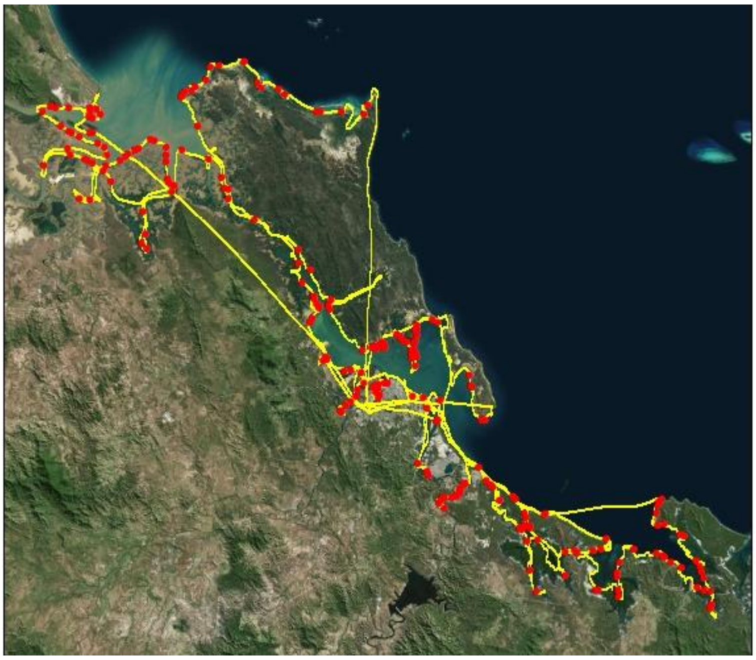

Figure 9 Location of trash and debris (red dots) throughout the GHHP study area (surveys covered the larger area as an extension of that for the GHHP study. Based on observations recorded during the aerial survey in late April 2019.

Figure 10. A large number of abandoned crab pots (being those pots without attached floats or other markers) were observed along low tide shorelines throughout the PCPA study area during aerial surveys in late April 2019.

The location of these trash items have been provided to the ‘Taking out the Trash’ community initiative – organised by local community members. This group of dedicated people and organisations have set out to remove as much trash from local tidal wetlands as possible.

Key organisational support for cleaning up Port Curtis mangroves came from:
Conservation Volunteers Australia
Boyne Island Environmental Education Centre
Tangaroa Blue
Gladstone Healthy Harbours Partnership
Gidarjil Development Corporation
MangroveWatch

Appendix 2: Reporting on risks of shoreline change using a Vulnerability Score

The resilience of mangroves to natural perturbations is influenced by the presence of existing stressors, particularly anthropogenic factors. The presence of such influences are likely to provide useful indicators of mangrove resilience to stochastic events such as cyclones (Feller et al. 2015) or oil spills (Duke 2016a), than the existing condition state. Using rapid aerial assessments and quantification of the presence of anthropogenic and natural drivers of change from shoreline aerial surveys, it is possible to derive measures of relative existing pressures on mangroves that may reduce ecosystem resilience and condition.

There are two useful measures that can be used to rapidly identify and quantify threats to mangrove habitats and quantify potential levels of impact. The first, a threat index score, is a qualitative score of threats for a defined area based on the extent and intensity of impacts determined during aerial surveys and from subsequent GIS assessment. Such indexes have previously been used for freshwater wetlands (Kotze et al. 2012). The second is a quantitative measure of the proportion of shoreline mangroves modified by anthropogenic disturbance and impacted by natural, direct and indirect anthropogenic pressures. Using these two measures and indicators of mangrove vulnerability not only provides improved knowledge of the changes taking place but also the quantification of each in terms of the extent of shorelines affected. This could also be readily and usefully applied to each of the 13 GHHP environmental reporting zones. The immense benefit in developing these measures is that human related impacts can be separated from climate-natural impacts. There are notable benefits in this approach to better inform environmental managers for more effective targeting of management intervention works.

Vulnerability Score Indicators Proposed

- Annual threat index score relative to acceptable level.
- Change in shoreline mangrove vulnerability index. A composite score derived from the presence of shoreline modification, linear habitat fragmentation, influence of natural climate, indirect and direct human impact.

A range of indicators for developing such a scoring system are shown in Table 5.

Table 5. Classification of environmental processes/responses observed during aerial shoreline surveys.

Driver Type	Driver Process	Driver CODE	Field Indicator	Tidal Wetland Habitat
Human related	Structures	Struct's	rockwalls, wharf, ramps, roads	all zones
	Direct Loss	DirectL	clearing, dead trees, landfill	all zones
	Altered Hydrol.	Altered	bunds, drains, impounded areas	mostly upper zones
	No Buffer	NoBuffr	ag/urban encroachment, cut-off tributaries	upper edge zones
	People Access	Access	vehicles, tracks, foot pathways	mostly saltpans - Salt pans + high tide edge
	Stock Damage	Stock	cattle, horses, goats, tracks	mostly saltpan-upper. Salt pans + high tide edge
	Feral Animals	Ferals	pigs, tracks, wallows, diggings	mostly saltpan-upper. inner mangrove + freshwater wetlands
	Pollutants	Pollut's	oil spill, scum, dump site, dieback & oil	all zones
	Nutrients	Nutri's	enhanced growth, expansion	all zones
	Fire	Fire	fire damage, blackened dieback	upper edge zone. Terrestrial margin - fringing mangroves
	Weeds	Weeds	smothering, weeds, dieback	mostly edge zone. Beach ridge veg. - to mangrove upper edges
Climate/ Natural	Storm Damage	StormD	broken trees, forest damage	mangrove zones. Mangrove closed canopies
	Shore Erosion	ErosionS	fallen trees, steep bank, dieback	seaward zone. seaward + main channel edge stands of mangroves
	Root Burial	RootB	fallen trees, steep bank, dieback	mostly seaward zone. shoreline and sea edge mangroves
	Fringe Collapse	FringeC	irregular dieback, canopy gaps	sea-edge mangroves
	Bank Erosion	ErosionB	fallen trees, steep channel bank	channel edges. lower estuary banks
	Pan Scouring	PanScour	sheet erosion, missing saltmarsh	saltpan zone. upper saltpans
	Ecotone -- Shift	Ecoton-	dead trees, fringe loss, retreating	saltpan-mangrove. AM + Ceriops closed canopies
	Ecotone +Shift	Ecoton+	young trees, fringe/ecotone gain, encroaching	saltpan-mangrove
	Deposit'l Gain	DepGain	young trees, bank & edge expansion	water edge. waters edge margins
	Terr'l Retreat	TerrRetr	back edge dieback, scouring erosion	upper zone. Terrestrial fringe
	Light Gaps	LGaps	circular canopy holes/dieback	mangrove zones. mangrove closed canopies
	Upland migration	Upland	young mangroves amongst dead terrestrial trees	along terrestrial margin of saltpans
	Altered hydrology	NAlterd	naturally impounded, ponded water, dead trees	shoreline and sea edge mangroves
	Bat Damage	Bats	presence of bat colony, canopy loss & damage	mangrove forest canopy
	Flood Damage	FloodD	wash damaged trees; debris; unidirectional fallen stems	riverine estuary; narrow fringing stands

These deductions were derived using the rapid assessment database, but similar scores could easily be taken also from the 'Shoreline' indicator image database. These data link observed responses of tidal wetlands with specific drivers of change. And, with this classification system, it is possible to broadly group changes observed into human related impacts (equals local management issues) and indirect human and climate impacts (equals regional and national management issues).

Vulnerability Scores for the 2019 aerial shoreline surveys

Aerial shoreline surveys were conducted for the GHHP project during late April 2019 (Fig. 11). The data were processed in part, and the results presented in Table 5. The shoreline survey track is shown in Fig. 2 covering most of the 23 sub-zone shorelines of the GHHP study area.

Figure 11. Aerial surveys were made of shorelines throughout the GHHP study area – from The Narrows to Port Curtis and Rodds Bay in late April 2019.

A tentative scoring of mangrove and saltmarsh condition indicators was developed and refined for this and other shoreline survey projects. The classification of observed processes affecting tidal wetland habitat are listed and described in Table 5. Scores of observed extent and severity were made during the aerial surveys. These scores were made for each of the sub-zones across the GHHP study area – see Figure 1 and Table 1.

Tidal wetland habitat categories used in this study included: the mangrove shoreline fringe; mangrove forests; the mangrove back fringe; all mangroves; samphire areas; salt couch areas; all saltmarsh areas; salt pans and the major ecotone interfaces with both marine and estuarine waters, as well as the supratidal upland terrestrial and freshwater areas.

Scores for these tidal wetland habitat components were based on two factors:

'Extent' was scored as the estimated proportion of the tidal wetland affected. This was scored from five categories as follows: 0-10%; 10-30 (~25)%; 30-60 (~50)%; 60-90 (~75)%; and greater than 90%.

'Severity' was scored as the severity of impact affecting natural recovery time, and overall prospect of recovery of ecosystem structure and function. This was scored from five categories as follows: None – maybe present - no observable effect; Minor – recovery within 6 months – no substantive ecological effect; Moderate – recovery between 6 months and two years – some ecological effect; Major – recovery from two to ten years – significant ecological effect; and, Severe – recovery unlikely – permanently damaged and reduced ecosystem services.

Table 6. Aerial shoreline surveys through the GHHP study area during April 2019. Factors related to Human (pink shaded) and Natural (green shaded) drivers are displayed for the three top ranking indicators, based on extent and severity scored from field observations made for each zone. Refer to Table 5 for a brief description of the indicator codes used; and to Table 1 for GHHP zone codes.

GHHP Sub-zone #	GHHP Zone#	Condition Score Nat:**Hum**	**Human**	**Human**	**Human**	Natural	Natural	Natural
			1	**2**	**3**	**1**	**2**	**3**
	1a	0.2	DirectL	Nutri's	Access	ErosionS	TerrRetr	FringeC
2	1b	0.2	Ferals	Altered	Polluts	Ecoton-	TerrRetr	StormD
3	2	0.3	Access	Ferals	Struct's	TerrRetr	Ecoton-	StormD
4	3a	0.7	DirectL	Struct's	Altered	ErosionS	StormD	Ecoton+
5	3b	1.6	Struct's	Altered	DirectL	Ecoton+	StormD	ErosionS
6	4	0.3	Altered	Access		ErosionB	PanScour	StormD
7	5a	0.2	Access	Struct's	NoBuffer	PanScour	TerrRetr	StormD
8	5b	1.4	DirectL	Altered	Struct's	ErosionS	StormD	Bats
9	6	1.0	DirectL	Struct's	Altered	ErosionB	DepGain	NAlterd
10	7	2.4	DirectL	NoBuffr	Struct's	ErosionB	Ecoton-	DepGain
11	8a	0.4	Struct's	Altered	Access	DepGain	PanScour	TerrRetr
12	8b	0.3	Altered	Struct's	Access	TerrRetr	PanScour	Ecoton+
13	9	0.8	DirectL	Struct's	Altered	ErosionB	FringeC	TerrRetr
14	10	1.4	Struct's	Stock	Access	FloodD	ErosionB	DepGain
15	11a	0.4	Access	Stock	DirectL	TerrRetr	Ecoton+	PanScour
16	11b	0.2	Struct's	Altered		TerrRetr	FringeC	PanScour
17	11c	0.2	DirectL	Access	NoBuffer	Ecoton+	TerrRetr	ErosionB
18	12a	0.0	Struct's	Polluts		DepGain	Ecoton+	TerrRetr
19	12b	0.0				UplandM	TerrRetr	NAlterd
20	13a	0.1	Nutri's	Ferals		PanScour	TerrRetr	FringeC
21	13b	0.4	Access	Stock	Altered	TerrRetr	PanScour	DepGain
22	13c	0.4	DirectL	Access	Struct's	TerrRetr	PanScour	Ecoton+
23	13d	0.2	Struct's	Altered	Access	TerrRetr	DepGain	PanScour
			1	**2**	**3**	**1**	**2**	**3**
	ALL		**Altered**	**Struct's**	**DirectL**	TerrRetr	PanScour	ErosionS

Based on prior experience, these extent and severity scores for each indicator and site were combined for this assessment using the following equation:
Condition Score = Extent X (Severity/5)

Vulnerability Scores for the 2019 shoreline aerial survey

The findings shown in Table 6 outline the 2019 assessment for the GHHP study area. The overall findings show that natural factors outweigh human factors as human : natural being 4:11, or ~0.4 overall; this shows natural factors are ~2.5 times greater overall.

There are five areas in the region however where human factors outweigh natural factors including sub-zones: 3b, 5b, 6, 7 and 10. As expected, these areas are those around the Port Curtis industrial and port areas as well as areas of heavy urbanisation and stock grazing.

The top three indicators observed throughout the area included: human related factors of altered hydrology, structures and direct damage losses; and, natural factors of terrestrial retreat, pan scouring and shoreline erosion. These top three scores for human and natural factors were the same for these same surveys in 2018.

The human factors are self-evident, but the natural factors are the combination of habitat responses that are indicative of the impacts of rising sea levels. These deductions are consistent with scores made with 2018 GHHP aerial surveys.

Appendix 3: Unusual fauna sightings and discovery made during recent surveys

Reef of Mangrove Leaf Oysters. During the field survey in May 2019, a rare Mangrove Leaf Oyster Reef was discovered by the project team at the southern end of the PCPA study area (Fig. 12). The species name is *Isognomon ephippium*. These reefs are extremely rare since they were extensively harvested for the shell in years gone by. The site of this reef is in Rodds Bay – and it is surrounded by mangrove forests and tidal estuaries. For approximate location, see Fig. 16.

Figure 12 a & b. A rare occurrence in Rodds Bay of a reef of Mangrove Leaf Oysters.

Australian Snubfin Dolphins in the Narrows. A pod of at least three Australian snubfin dolphins (*Orcaella heinsohni*) was observed during the aerial surveys in late April 2019. These were swimming in the main channel of the Narrows at the northern end (Fig. 13). These animals are considered Vulnerable and ranked as a critical priority by the Queensland Department of Environment and Science. For approximate location, see Fig. 16.

Figure 13a, b & c. Images of Australian snubfin dolphins taken at the northern end of the Narrows in late April 2019.

A large Queensland Groper in the central part of the PCPA study area. A large Queensland Groper (*Epinephalus lanceolatus*) was observed in shallow waters off Barney Point during field surveys in early May 2019 (Fig. 14). This protected species appeared at ease in the shallow waters near the busy port area of Gladstone. For approximate location, see Fig. 16.

Figure 14a & b. A large Queensland Groper was observed off Barney Point during late April 2019.

A school of eagle rays in the southern part of the PCPA study area. Eagle rays (*Aetomylaeus* spp.) were observed schooling in large numbers in Rodds Bay during field surveys in early May 2019 (Fig. 15). These animals gather at times, possibly for mating. For approximate location, see Fig. 16.

Figure 15. A rather large gathering of eagle rays observed in Rodds Bay during early May 2019.

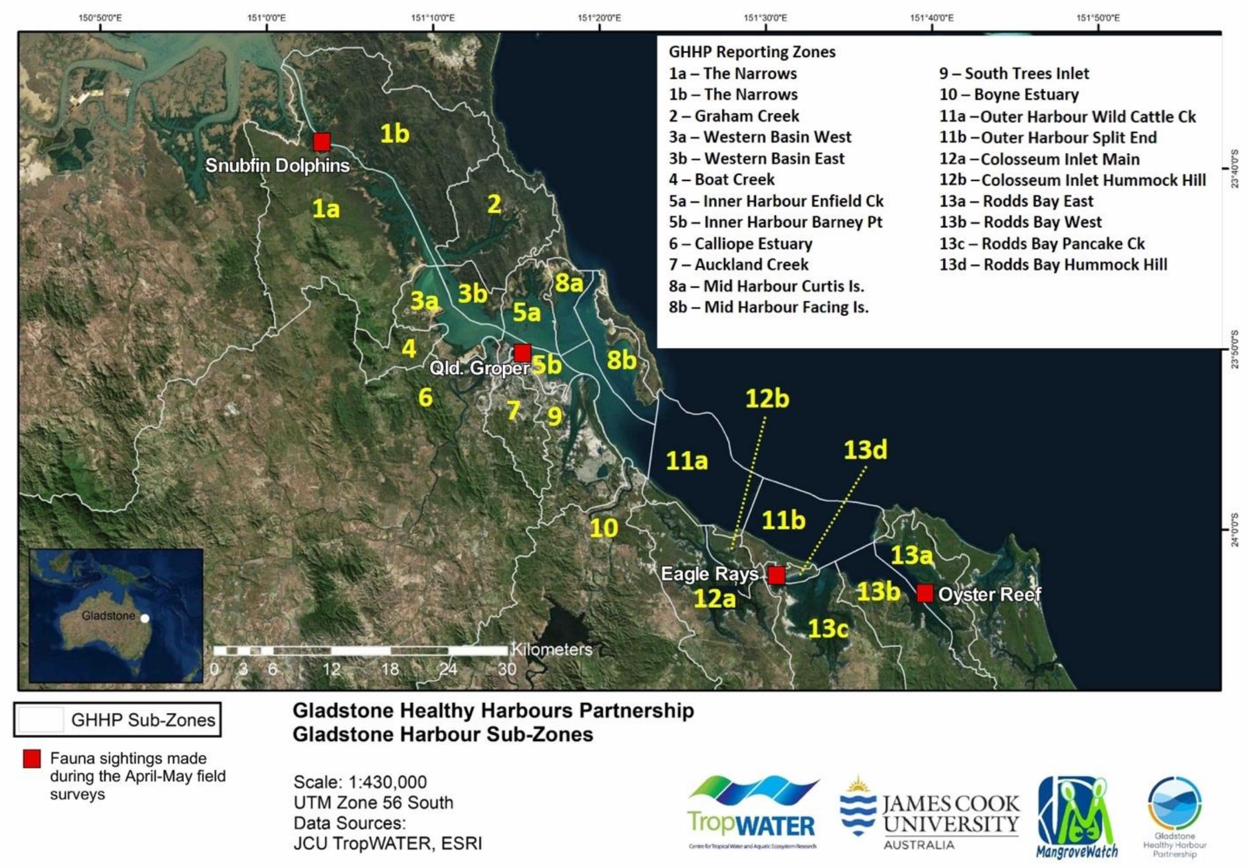

Figure 16. Map locations of the five noted fauna observations made during April-May 2019.

Appendix 4: Recent publications with relevance to GHHP mangrove indicators

The influences of rainfall on tidal wetlands. A key recent publication was published in the Journal of Marine and Freshwater Research (Duke et al. 2019b). In this article, we explore the relationship between mangrove forest cover and the longer-term influences of rainfall. This relationship is really significant as it can be used to quantify the influences of a primary climate factor, rainfall. This article explains in particular, the relationship used with the WCI as used in the effective mangrove condition indicator developed during this project, and in conjunction also with the ERMP project with GPC.

Duke, N.C., C. Field, J.R. Mackenzie, J.-O. Meynecke and A.L. Wood. 2019a. Rainfall and its possible hysteresis effect on the proportional cover of tropical tidal wetland mangroves and saltmarsh-saltpans. Marine and Freshwater Research, published **online**. DOI: 10.1071/MF18321.

Abstract. Mangroves and tidal wetlands are highly dynamic ecosystems, responding and adapting to climate and physical conditions that vary at all spatial and temporal scales. In these times of rapidly changing climatic conditions, identification of previously unrecognised large-scale ecosystem processes influenced by climate variables are highly relevant. This applies in particular, to a more enlightened understanding of the corresponding influences on respective beneficial ecosystem services. In deference to the many factors thought to influence tidal wetland ecosystems, we confirm that average annual rainfall (AAR) (250-5000 mm, 20-30 year average) has had a dominant influence on the vegetative cover and relative abundances as well as the composition and biomass of tidal wetlands. And, that the different condition states were predictable. Based on 205 unmodified, tropical and subtropical estuaries of predominately northern Australia, a sigmoidal relationship was derived between rainfall and the relative amounts of high-biomass mangroves and low-biomass saltmarsh-saltpan vegetation. The presence and probability of the observed combinations of these plant types were usefully quantified using the Wetland Cover Index (WCI), being the ratio of total mangrove area compared to the mangrove area plus the area of upper intertidal saltmarsh and saltpans.
For tidal wetland sites well-within the latitudinal range of mangroves, 1368 mm average annual rainfall marked a centroid inflection point in the probability of the transition between the alternate dominance of respective vegetation types of high and low biomass states. In the range of 1066 mm AAR and 1651 AAR the rate of change of the probability of mangrove dominance per 100 mm AAR was greater than 5%. These findings were consistent with rainfall having a significant effect on relative abundances of key vegetation types within tidal wetlands. Furthermore, periodic fluctuations are likely manifest as either encroachment or dieback of mangroves occurring along the ecotone separating mangroves from upper tidal saltmarsh-saltpans. To explore this concept further, a new conceptual framework and model was developed to display these ecosystem-scale processes taking place in tropical and subtropical tidal wetlands.

A new species of mangrove for the study area. Another recent publication was published in the journal Blumea: Biogeography of World Plants (Duke & Kudo 2018). This describes a new hybrid species likely to occur in the PCPA study area. There are no recorded sightings to date, but the species was noted in Shoalwater Bay, and both of parent species occur in the mangroves of Port Curtis area.

Duke, N.C. and H. Kudo. 2018. *Bruguiera* × *dungarra*, a new hybrid between mangrove species *B. exaristata* and *B. gymnorhiza* (Rhizophoraceae) recently discovered in north-east Australia. Blumea 63: 279-285. DOI: 10.3767/blumea.2018.63.03.03

Abstract. *Bruguiera* × *dungarra* (Rhizophoraceae), a previously undescribed hybrid species between *B. exaristata* and *B. gymnorhiza* is recorded from north-east Australia. Eight taxa are currently recognised in this Indo West Pacific genus, including three putative hybrids. The newly described hybrid is widely occurring, and it is described here with notes provided on typification, phenology, distribution and habitat. A revised identification key to all *Bruguiera* taxa is presented, along with a table of comparative diagnostic characters.

An assessment of estuaries and mangrove management plans for some estuaries also in the PCPA study area. A report publication of two volumes was recently completed with the NESP Water Quality Hub for the major riverine estuaries of the southern Great Barrier Reef catchment region (Duke et al. 2019b). This study was undertaken by the same key partners of the PCPA CHAMP project, and three of the estuaries (the Calliope, South Trees and Boyne) were in common between these projects. There have been a number of synergies between projects which has enhanced the outcomes of each program. A key strength has been the development and enhancement of the partnership and collaboration between aboriginal rangers of the GDC and the researchers from JCU.

Duke, N.C., Mackenzie, J., Fennessy, R., Cormier, R., Kovacs, J. 2019b. 'Final Report: Southern GBR Coastal Habitat Archive and Monitoring Program (S-GBR CHAMP)'. Final Report for the National Science Environmental Programme Tropical Water Quality Hub. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER). Two Volumes: Report 19/11. James Cook University, Townsville, 74 & 162pp.

Executive Summary

1) This is the Final Report where Traditional Owner rangers and local citizens of the Port Curtis Coral Coast (PCCC) TUMRA area were engaged in developing a Mangrove Management Plan (MMP) to provide a strategic basis for ongoing estuarine monitoring and repair activity for the maximization of water quality outcomes in southern Great Barrier Reef waters. Development of this MMP has built essential capacity amongst the Gidarjil Development Corporation (GDC) rangers and the local community to conduct scientifically-rigorous, ecological monitoring and assessment of key local estuarine resources. The management and rehabilitation strategies are needed for the protection of sea country assets using the partnerships forged between community, scientists and local Natural Resource Management (NRM) agencies. The MMP has enabled rangers and citizen scientists to undertake scientifically valid surveys for estuarine habitat monitoring, management and rehabilitation within the PCCC TUMRA area.

2) The project was lead by Dr Norm Duke with Jock Mackenzie from James Cook University (JCU) TropWATER Centre, plus project partners: Prof John Kovacs of Nipissing University (NU) in Canada, Ric Fennessy with Rangers of the GDC, Kirsten Wortel and Sue Sargent with Burnett Mary Regional Group (BMRG), and, Rebecca French, Holly Lambert and Shannon van Nunen with Fitzroy Basin Association (FBA).

3) The primary undertaking of this program was to build the capacity of Gidarjil Indigenous Rangers for monitoring, managing and rehabilitating estuarine wetland sea country within the PCCC TUMRA, southern GBR. The PCCC is the 5th largest TUMRA of its kind. Estuarine wetlands are an integral component of this sea country, comprising sites of immense cultural heritage significance, including middens, fish traps, and traditional fishery resources. Estuarine wetlands also provide essential ecosystem services that protect the GBR, including water quality improvement. But, shoreline habitats within estuaries of the southern GBR have been badly damaged by repeated, recent extreme flood events. Existing anthropogenic stressors reduce the recovery potential of these impacted estuarine wetlands, reducing ecosystem resilience to future damaging events. Estuarine wetland repair is a priority for improving GBR water quality. However, there are no existing national strategies for prioritizing sites of estuarine wetland rehabilitation, to minimize anthropogenic stressors that maximize water quality improvement and other ecosystem services. A whole-of-system assessment is necessary, incorporating socio-cultural, ecological, and economic considerations, to inform cost-effective, successful investment in shoreline habitat rehabilitation.

4) Local stakeholders and endusers were specifically sought out and engaged in a series of two dedicated workshops in early 2016 and 2017. The workshops were hosted by the BMRG and the FBA respectively. Both workshops were highly successful with broad and representative gatherings of endusers attending. All participants actively contributed to the listing of issues raised and the general exchange of ideas. Attendees included members of all local governments (Rockhampton, Gladstone, Livingstone, Bundaberg), a number of State agency officers (Fisheries DAF, Herbarium, EHP), industry representatives like Gladstone Ports Corporation (GPCL) and Bundaberg Sugar, members of the general public, as well as the local NRM groups (FBA and BMRG) and the Gidarjil rangers (Fig. 1.1).

5) Training sessions for rangers were undertaken in conjunction with each of the two stakeholder workshop meetings. Additional training sessions were included as needed, in an on-going effort to accommodate the scheduled field program, changes in ranger staff, and the development of new projects. Training followed the standard estuarine field survey methods used by the MangroveWatch community partnership organisation (www.mangrovewatch.org.au), using mostly the Shoreline Video Assessment Method (S-VAM). Training involved discussions, equipment demonstrations, practice sessions and field surveys in small boats. Dedicated field equipment of cameras, gps and other items were purchased beforehand, specifically for the training program and the field surveys.

6) In collaboration with project partner, Prof Kovacs, evaluation and mapping of mangroves and saltmarsh tidal wetlands was done for all eight estuarine systems with on-going development of methods to be used in the overall data management plan. These plans included the evaluation of values and threats to saltmarsh habitats in the southern GBR region.

7) Field surveys of specific estuarine river systems were undertaken by Gidarjil rangers initially with JCU researchers until the rangers achieved confidence in conducting this task independently. The estuarine systems surveyed for this project included: Calliope River, South Trees Inlet, Boyne River, Baffle Creek, Kolan River, Burnett River, Elliott River and Burrum River. One amendment to the selection of rivers had been made to ensure all estuarine systems were within the appropriate PCCC sector of the TUMRA. Assessments were done for each of the 8 estuarine systems making observations and capturing imagery of the condition, management issues and the notable drivers of change.

8) Regional impacts related to climate change and sea level rise were apparent in all eight estuarine systems surveyed. Specific indicators included: unusually high proportions of shoreline and bank erosion, saltmarsh-saltpan scouring, upland migration, and terrestrial retreat. These factors were exacerbated further by recent severe weather events with intense periods of either drought, cyclonic winds, torrential rains or severe flooding. These influences were notably combined with local environmental issues associated with a range of direct human activities. The resulting overall condition differed for each estuary.

9) Calliope River estuary, a modified system of ~794 ha of tidal wetlands, was successfully surveyed by 12 Gidarjil rangers and 3 community members on three occasions in 2015, 2017 and 2018, filming 51 km of shorelines. Overall condition was scored at 74 with ~53% directly human related impacts. The main local management issues identified were driven by development expansion, shoreline habitat modification, and the loss of tidal wetland areas.

10) South Trees Inlet estuary, a modified system of ~1,802 ha of tidal wetlands, was successfully surveyed by 8 Gidarjil rangers and 3 community members on two occasions in 2014 and 2018, filming 32 km of shorelines. Overall condition was scored at 73 with ~50% directly human related impacts. The main local management issues identified were driven by development expansion, altered hydrology, and the loss of tidal wetland areas.

11) Boyne River estuary, a modified system of ~105 ha of tidal wetlands, was successfully surveyed by 10 Gidarjil rangers and 5 community members on four occasions in 2014, 2015, 2016 and 2018 filming 21.5 km of shorelines. Overall condition was scored at 73.5 with ~48% directly human related impacts. The main local management issues identified were driven by development expansion, agricultural intensification, and the flood damage of tidal wetland areas.

12) Baffle Creek estuary, a near pristine system of ~1,209 ha of tidal wetlands, was successfully surveyed by 12 Gidarjil rangers and 2 community members on two occasions in 2017 and 2018 filming 89.7 km of shorelines. Overall condition was scored at 79 with ~59% directly human related impacts. The main local management issues identified were driven by cattle grazing, vehicle damage of tidal wetland areas, and extreme weather events.

13) Kolan River estuary, a modified system of ~969 ha of tidal wetlands, was successfully surveyed by 16 Gidarjil rangers and 3 community members on three occasions in 2013, 2016 and 2018 filming 51.6 km of shorelines. Overall condition was scored at 84 with ~69% directly human related impacts. The main local management issues identified were driven by altered hydrology, agricultural intensification, bank erosion damage of tidal wetland areas, and extreme weather events.

14) Burnett River estuary, an extensively modified system of ~540 ha of tidal wetlands, was successfully surveyed by 13 Gidarjil rangers and 2 community members on three occasions in 2013, 2016 and 2018 filming 52 km of shorelines. Overall condition was scored at 89 with ~69% directly human related impacts. The main local management issues identified were driven by development expansion, agricultural intensification, altered hydrology, extreme weather events, and the loss of tidal wetland areas.

15) Elliott River estuary, a largely unmodified system of ~589 ha of tidal wetlands, was successfully surveyed by 8 Gidarjil rangers and 2 community members on three occasions in 2013, 2016 and 2017 filming 19.4 km of shorelines. Overall condition was scored as 79 with ~48% directly human related impacts. The main local management issues identified were driven by development expansion, ground water extraction, and the vehicle damage of tidal wetland areas.

16) Burrum River estuary, a largely unmodified system of ~644 ha of tidal wetlands, was successfully surveyed by 12 Gidarjil rangers and 3 community members on three occasions in 2013, 2016 and 2018 filming 58.4 km of shorelines. Overall condition was scored as 65 with ~60% directly human related impacts. The main local management issues identified were driven by development expansion, agricultural intensification, altered hydrology, and the loss of tidal wetland areas.

17) Key project recommendations include: continue supporting Gidarjil rangers in the monitoring of estuarine shorelines in their region; support on-going shoreline video assessment analyses along with the development of a regional report card on southern Great Barrier Reef estuarine waters.