Gladstone Healthy Harbour Partnership

Project ISP018

Development of Mangrove indicators for the Gladstone Harbour Report Card

Norman C Duke and Jock Mackenzie

Report No. 18/38

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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) 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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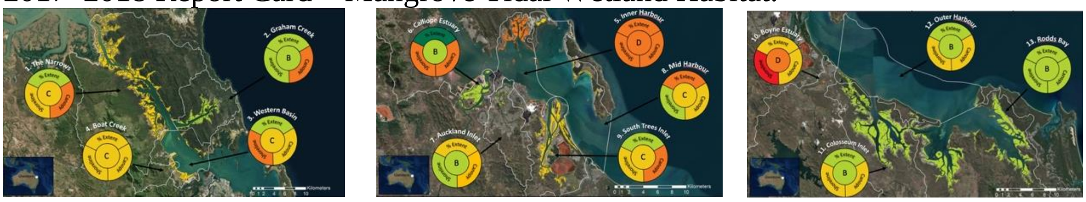
EXECUTIVE SUMMARY

1) The MangroveWatch Hub with TropWATER Centre at James Cook University have investigated and developed a primary suite of four key condition indicators for the regular monitoring of the overall 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). This monitoring scheme extends from this report for the 2017–2018 report card.

2) 2017–2018 Report Card – Mangrove Tidal Wetland Habitat.



The proposed 2017–2018 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 2017–2018 condition of mangrove habitat was satisfactory to good, with Boyne Estuary having the poorest condition.

3) The current project findings represent a significant reference point for the likely longer term application and monitoring of tidal wetland ecosystems throughout the Port Curtis study area. As such, this reporting framework, and specifically the indicators identified, provide a valuable baseline benchmark of structure and condition for comparative assessments both into the future, as well as back in time.

4) Decisions regarding the choice of indicators were based on expert opinion underpinned by robust scientific data, research publications, field observations and practical experience of these highly-specialised natural ecosystems. The authors have also relied on their specialised and in-depth knowledge of the study area including a number of recent projects funded by the Gladstone Ports Corporation Environmental Research and Management Program and the National Environmental Science Programs’ Tropical Water Quality Hub.

5) Before the indicators could be developed, it was necessary to re-evaluate and map the 13 environmental reporting zones used by the GHHP. This enabled the same zones to have relevance to both tidal wetlands as well as their prior focus on marine habitats. Upland boundaries were created for individual land catchments and drainage areas relating to each of the 13 zones. This resulted in an increase in assessment areas, described as sub-zones. For example, the division of The Narrows (Zone 1) into mainland side and Curtis Island shoreline sub-zones (sub-zones 1a & 1b). The total number of tidal wetland sub-zones needed to represent the 13 GHHP reporting zones was limited to 22. These new sub-zones provide the basis for comparative assessments of tidal wetlands and associated marine habitats throughout the Port Curtis study area.

6) The three condition indicators selected in consultation with the GHHP Independent Science Panel (ISP) include: ‘Extent’; ‘Canopy’; and ‘Shoreline’. Each indicator was developed from distinct datasets collected from independent sources, including specific field surveys.

7) ***‘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 first report, the period of evaluation was based on imagery acquired in 2016. 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 2016 and 2018, mangrove extent contracted more in northern areas

8) ***‘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. These assumptions can be verified across a broad selection of field sites where measures were made of the number of leaves counted in living leafy shoots of shoreline fringing canopies of *Rhizophora stylosa* mangroves.

9) ***‘Shoreline’ - the shoreline condition indicator*** was based on the assessment of oblique aerial imagery at 50m 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 then compared and validated against field summary scores made for each sub-zone during the aerial survey.

10) Overall, the scores were consistent with a number of changes taking place within mangroves and tidal wetlands observed across the region. Scores reflected 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 on-going port activities (like pollution, direct damage and boat traffic.

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A 2018 MANGROVE REPORT CARD SCORES

This section provides a summary of findings of Project ISP018: ‘Development of mangrove indicators for the Gladstone Harbour Report Card’. With this project, research specialists with the MangroveWatch Hub at James Cook University (JCU) TropWATER Centre, describe the first substantive indicators of ecological condition of tidal wetlands (including mangrove and saltmarsh habitat) for the Port Curtis region. 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 is presented in Section B.

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 1997. 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). More 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 (NESP) 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.

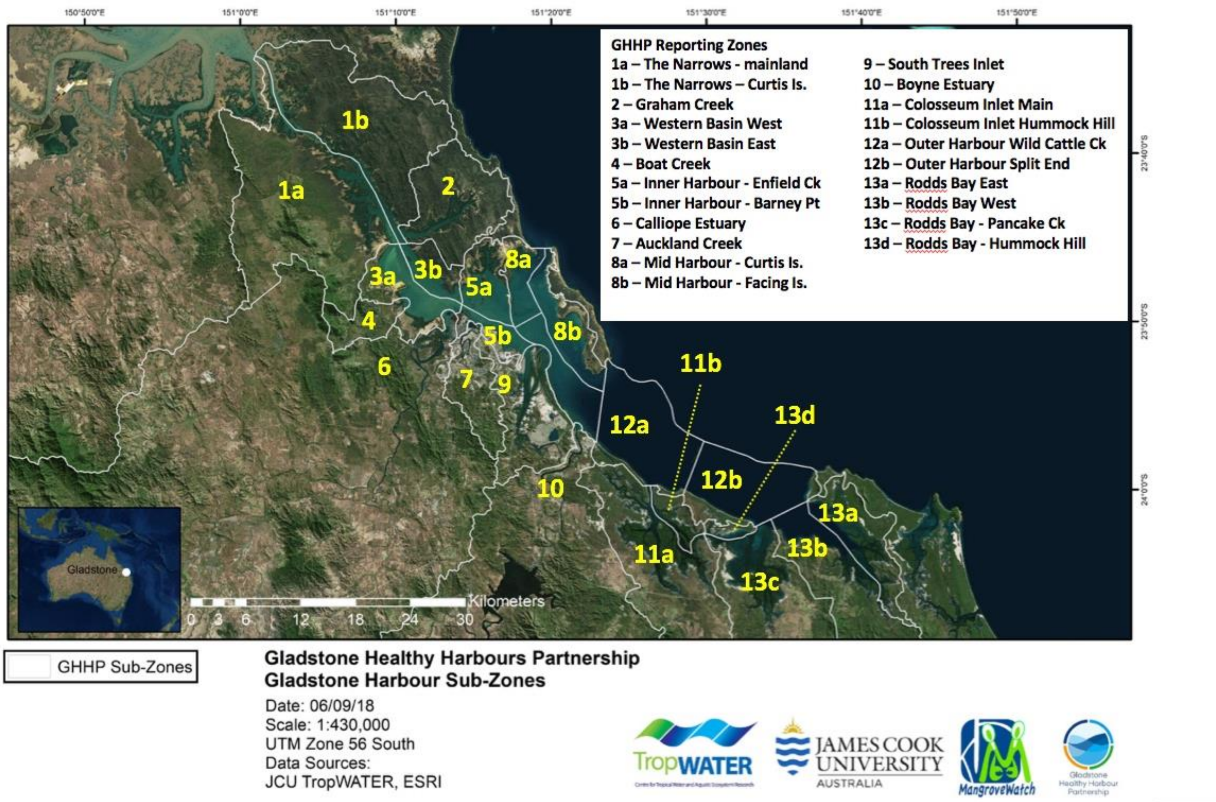

Figure 1. Map showing the 13 GHHP zones and the 22 sub-zones needed for mapping of tidal wetland vegetation and the factors affecting them.

The first task of the project team was to map the areas of tidal wetlands along with the upland catchments for each of the 13 zones designated by the GHHP. Many of these zones had different catchment influences. For assessment purposes, these were divided into 22 sub-zones reflecting sub-catchment boundaries as shown in Figure 1. Scores for each indicator were prepared for each sub-zone and were later combined as single scores for each of the 13 GHHP Report Card zones (Figures 2-4). Results for 2017-2018 have been based on three indicators including: 'Extent', 'Canopy' and 'Shoreline' (Table 1).

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

GHHP Zone		Mangrove Extent	Mangrove Canopy Condition	Shoreline Condition	Overall Score
The Narrows	**1**	0.67	0.40	0.61	**0.56**
Grahams Creek	**2**	0.82	0.47	0.71	**0.66**
Western Basin	**3**	0.74	0.60	0.38	**0.58**
Boat Creek	**4**	0.64	0.63	0.63	**0.63**
Inner Harbour	**5**	0.44	0.37	0.47	**0.43**
Calliope Estuary	**6**	0.85	0.59	0.56	**0.67**
Auckland Inlet	**7**	0.66	0.63	0.74	**0.68**
Mid Harbour	**8**	0.40	0.55	0.70	**0.55**
South Trees Inlet	**9**	0.77	0.49	0.58	**0.61**
Boyne Estuary	**10**	0.60	0.50	0.14	**0.41**
Colosseum Inlet	**11**	0.84	0.59	0.63	**0.69**
Outer Harbour	**12**	0.79	0.60	0.58	**0.65**
Rodds Bay	**13**	0.76	0.68	0.68	**0.71**

Mangrove and tidal saltmarsh vegetation 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. While these changes are now well-established, the condition of remaining habitat is now the chief focus of the 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 far less modified 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 June 2018 field survey—and on other occasions. 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. Such indicators can be developed using the same shoreline imagery acquired currently for this project. And, the concept has been demonstrated using the rapid assessment scores made during the aerial survey (see Section B of this report).

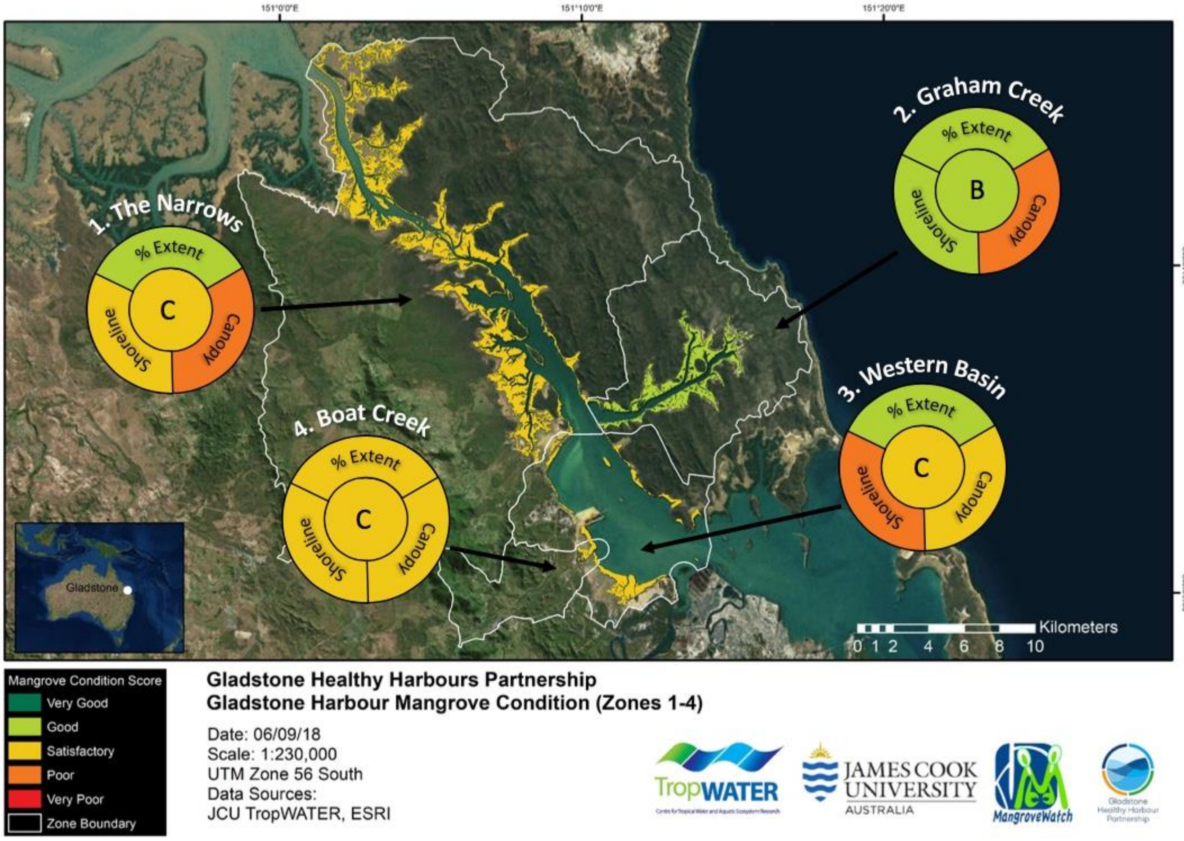

Figure 2. 2017–2018 Mangrove Report Card zones 1–4.

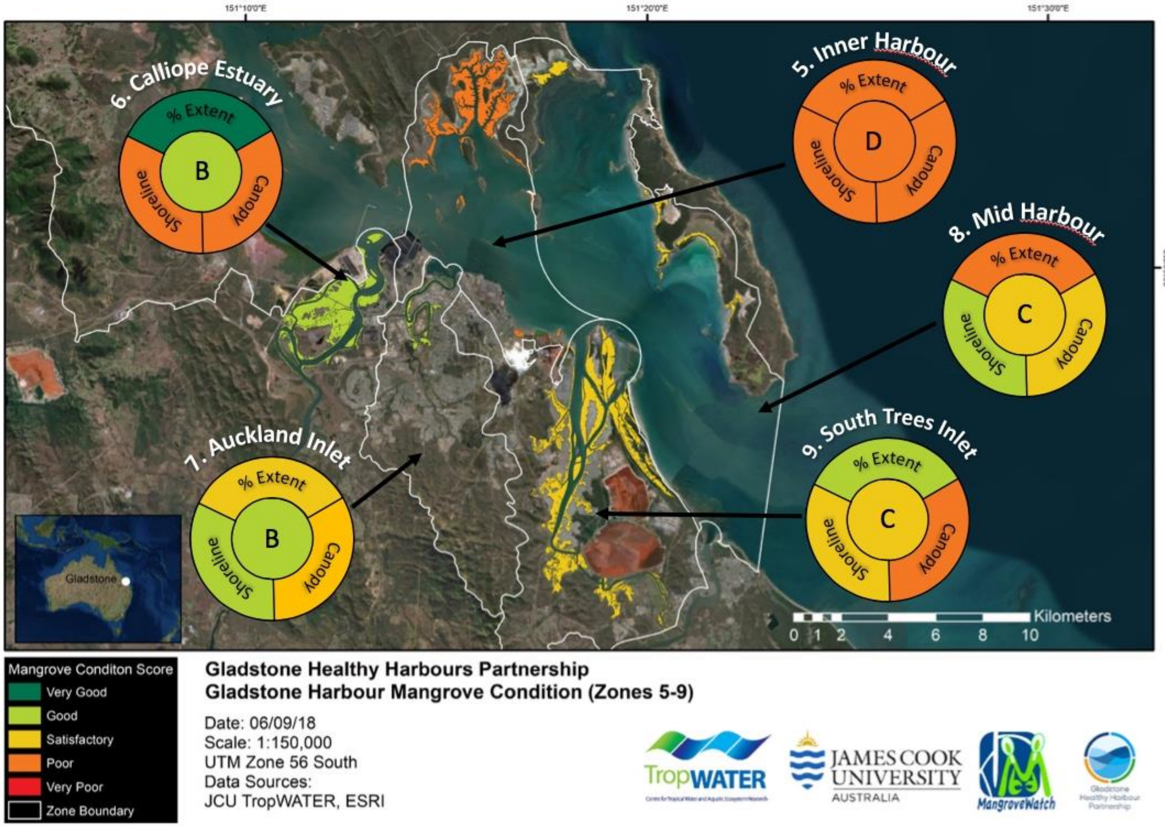

Figure 3. 2017–2018 Mangrove Report Card zones 5–9.

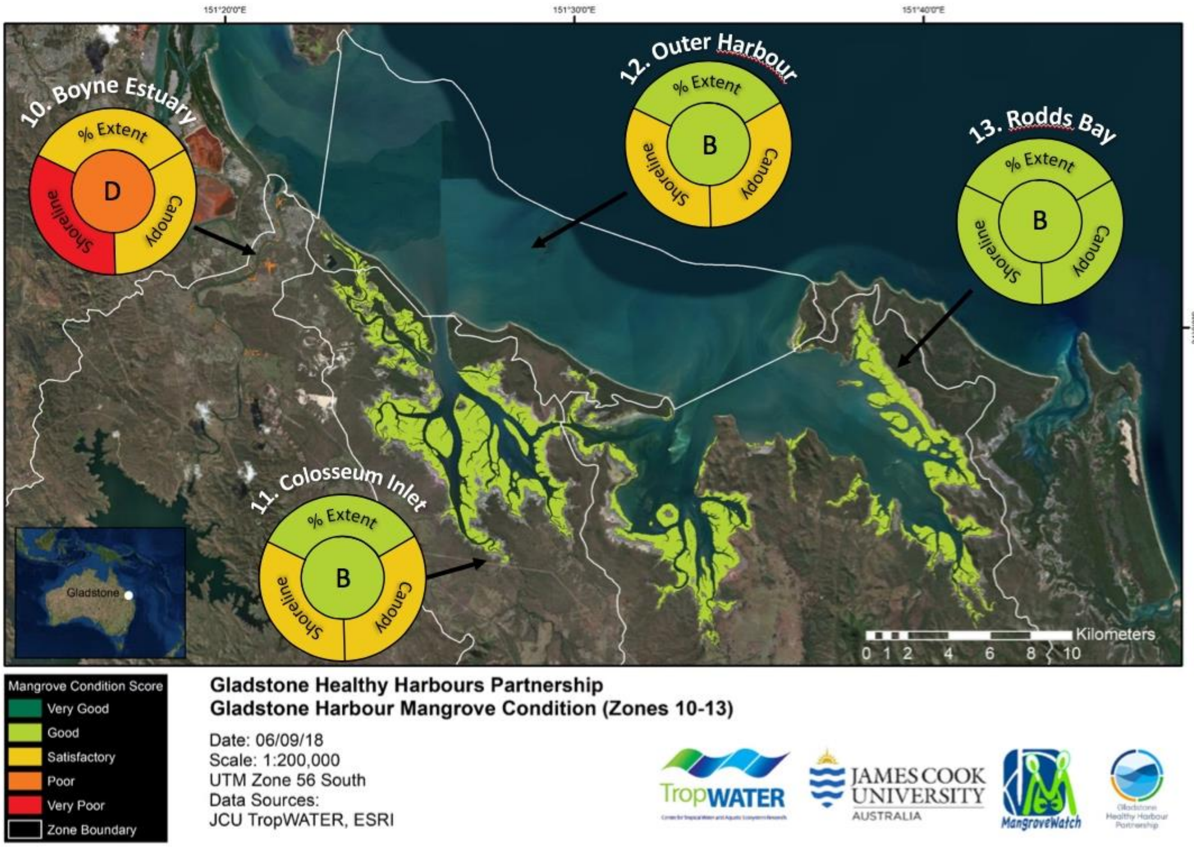

Figure 4. 2017–2018 Mangrove Report Card zones 10–13.

B REPORT ON MANGROVE INDICATOR DEVELOPMENT

1 INTRODUCTION

Development of mangrove indicators for the Gladstone Harbour Report Card was led by research specialists from James Cook University (JCU) TropWATER Centre. The work program involved an evaluation of the extent, change, overall condition, health and status of tidal wetlands including mangroves, as outlined in the Scope of Works for this project.

The metrics listed in the scope of works as potential indicators of mangrove health included: changes to extent of mangrove coverage; changes in distribution; and changes in species composition. While it was acknowledged that these features had value as longer-term indicators of habitat status, the project team instead reasoned that changes to shorter-term condition would be better indicators of condition and health, rather than the more 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 Table 2). This report documents the reasoning behind this response with our re-evaluation and this initial development of three indicators of mangrove and tidal wetland habitat condition. As this approach is largely new, it has been an essential undertaking of the project team to prepare the findings for formal publication.

The TropWATER MangroveWatch hub members have been collecting substantial environmental and physical data from which a number of specific indicators of mangrove condition have now been developed as report card indicators (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 have been collected as part of the GPC ERMP PCPCA CHAMP program (Duke & Mackenzie 2016, 2017). Based on these data combined with additional data collected in June 2018, it has been possible to develop and derive condition report card scores for mangrove tidal wetlands in the GHHP study area zones for 2017-2018.

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, it was useful to consider that the indicators listed in the Scope of Works were all measures of mangrove structure and diversity. They did not represent immediate and current mangrove habitat condition.

Table 2: Mangrove indicators considered for the Gladstone Harbour 2017-2018 Report Card.

Indicator - Method	Available Reference Data	Required Data Collection	Calculation of grades and scores method
Extent - Wetland Cover Index	2014-6 Data.	2006-2018 satellite imagery. Basic resolution imagery to be acquired by TropWater	WCI as changes from mean and the year before.
Canopy - NDVI	2014-6 Data	2006-2018 satellite imagery. Basic resolution imagery to be acquired by TropWater	Variations from mean and the year before
Shoreline - condition scores	Prior filming in 2016	June 2018 Helicopter filming	Percent live/dead trees
Canopy - leafy shoot counts	2016 Data for ~2 zone	June 2018 site surveys	Variations from mean and the year before

The methods proposed were derived and developed using our established and published research experience working on various environmental assessments of tidal wetland ecosystems around the world, and in the Port Curtis region. We therefore relied on our broad experience in not only mangrove habitat ecology, biogeography, genetics and productivity of mangrove wetlands, but also 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) (Duke and Mackenzie 2016, 2017).

2 METHODS

2.1 Study area sub-zones – a re-evaluation for tidal wetland application

The GHHP 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 Figure 1). The 13 GHHP zones do not 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 new sub-zones were based on the original GHHP marine zones but specifically adapted to relate to land catchment areas (white lines) for respective portions of tidal wetlands (including mangroves) describing 22 sub-zones linked to the 13 GHHP environmental monitoring zones.

The sub-zones occur as separate sections of GHHP zones—for example, consider The Narrows with its two distinct mangrove areas on either side of the channel on Curtis Island and on the mainland. There were a number of other similarly split zones. Sub-zones boundaries follow sub-catchment areas derived from the Queensland Government drainage sub-basin areas (Dept. Natural Resources, Mines & Energy, 2009), environmental protection water quality policy sub-catchments (Dept. Environment & Science, 2017) and topographical maps.

For each of the sub-zones, estimates for each indicator have been developed for the 2018 Gladstone Harbour Report Card. These indicators are listed in Table 3. The indicators have been derived from satellite image mapping, plus aerial shoreline survey data, and other field measures. The indicators are essentially independent and robust measures of vegetation extent, canopy density and shoreline condition.

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 2014). 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 Wetland Cover Index) can provide a useful indicator of habitat and environmental condition.

So, in addition to using tidal wetland and mangrove extent as primary indicators of mangrove structural condition, we also use the Wetland Cover Index (WCI). WCI values have been estimated for each of the sub-zones for each of the 13 GHHP environmental reporting zones using maps drawn from satellite imagery. 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).

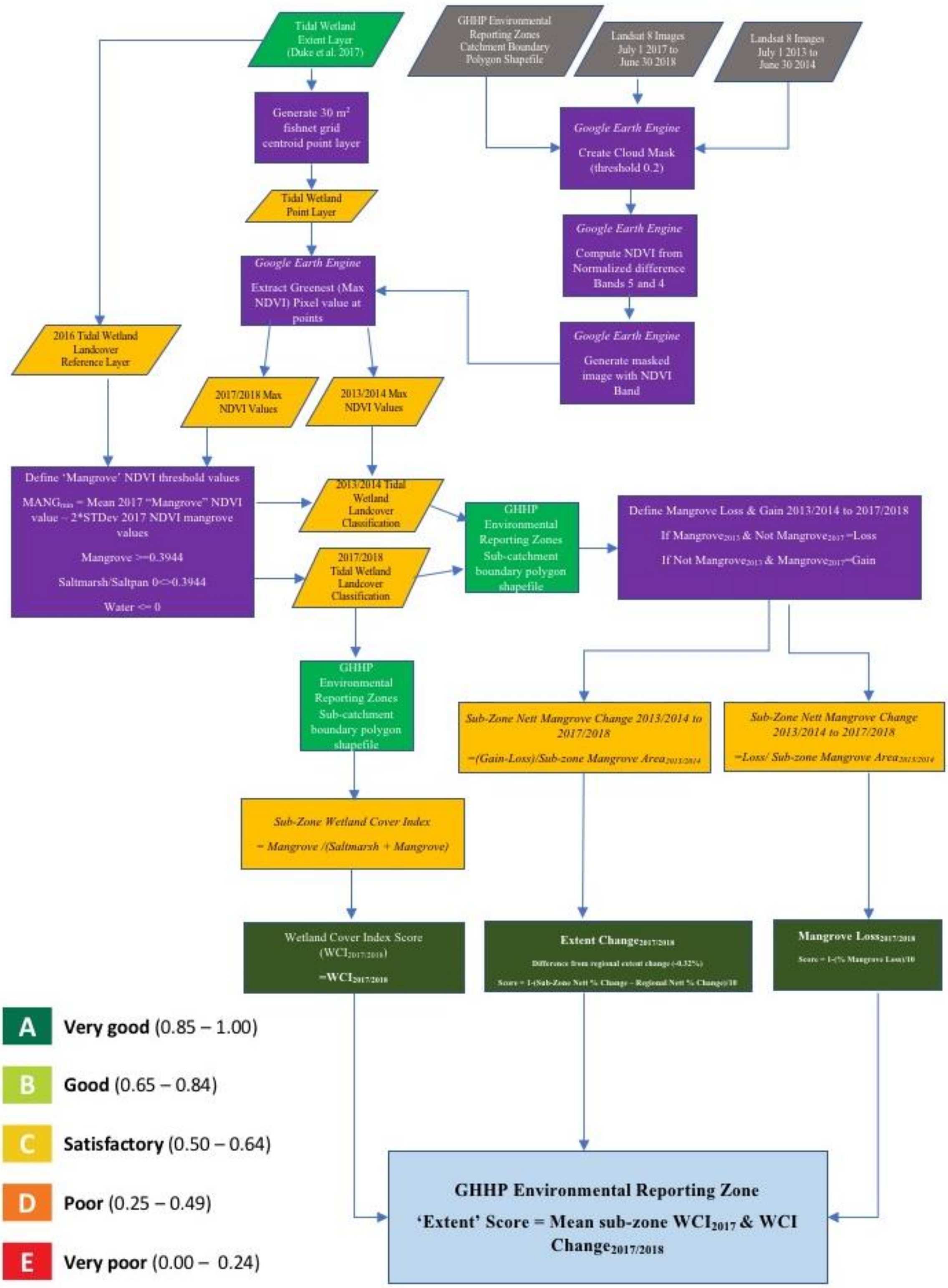

Figure 5. Flow diagram of the logical derivation of the 'Extent' indicator score.

Structural Indicators used

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

Table 3. Scoring system for the Extent indicator of mangrove condition, based on cover area and the ratio of relative mangrove extent (=Wetland Cover Index).

	Very Good 0.85 – 1.00	Good 0.65 – 0.84	Satisfactory 0.50 – 0.64	Poor 0.25-0.49	Very Poor 0-0.24
Wetland Cover Index (WCI) 2017/2018	WCI 0.85 – 1.00	WCI 0.65 - 0.84	WCI 0.50 - 0.64	WCI 0.25 - 0.49	WCI 0 - 0.24
Mangrove Loss 2013/2014 to 2017/2018	0 to 1.5% Loss	1.6 to 3.5% Loss	3.6 to 5.0% Loss	5.1 to 7.5% Loss	>7.5% Loss
WCI Nett Mangrove Extent Change (Gain & Loss) 2013/2014 to 2017/2018	0 to 1.5% deviation	1.6 to 3.5% deviation	3.6 to 5.0% deviation	5.1 to 7.5% deviation	>7.5% deviation

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. However, changes to such area 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.

While these episodic changes are important aspects of change, there is arguably also a greater need to track subtle and on-going changes as is likely to occur along habitat ecotones, both internally and externally. This needs a different approach

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 2017 mapping (see Figure 5 & Table 3).

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 2017/2018 NDVI classification was compared to 2013/2014 NDVI maximum values for all points.

Mangrove loss and gain was classified as follows;
Mangrove Loss: $NDVI_{13/14} >= Mang_{MIN}$ & 2017 Classification = Saltmarsh/Saltpan or Water
Mangrove Gain: $NDVI_{13/14} < Mang_{MIN}$ & 2017 Classification = Mangrove

Percent change represents the proportion relative nett change in mangrove area between 2013/14 and 2017/18. $WCI_{13/14}$ Values were adjusted to reflect tidal area lost due to erosion (Mangrove to Water) between 2013 and 2017. Dieback of upland trees at the terrestrial-upper tidal ecotone – indicative of rising sea levels.

Mangrove and saltmarsh extent within a tidal wetland area fluctuate with changing rainfall and climate conditions influencing surface sediment salinity and water availability. Natural fluctuations in mangrove and saltmarsh extent relative to climate may be altered by anthropogenic influences such as elevated nutrient loads and altered hydrology influencing overland freshwater flows and groundwater. As such, larger than expected increases or decreases in mangrove area may reflect these altered states. To reflect the influence of potential anthropogenic influences on WCI, the percentage change in mangrove extent in each sub-zone was compared to the expected regional change for all zones, with scores assigned based on the deviation (either positive or negative) from the regional percent change. Between 2013-2014 and 2017-2018 there was a regional -0.31% nett change in mangrove extent.

The WCI mangrove change score was calculated as follows:
WCI change score = 1 - abs(sub-zone % change - regional % change) / 10

Mangrove Loss Score. A separate score was derived to reflect loss of mangrove habitat between 2013-2014 and 2017-2018. This score reflects loss of remnant habitat and does not consider any potential loss offsets from mangrove habitat gain which may have occurred as a result of landward or shoreline mangrove colonisation. As such, this score reflects loss of established mangrove habitat within the assessment timeframe.

The mangrove loss score was calculated as follows:
Mangrove Loss: $NDVI_{13/14} >= Mang_{MIN}$ & 2017 Classification = Saltmarsh/Saltpan or Water

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 stress events leads to loss of plant 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.

NDVI = (NIR-Red)/(NIR + Red)

To determine the health of mangrove forests in the GHHP assessment area we used NDVI as a relative measure of mangrove forest health.

A 2016 mangrove extent layer for the GHHP region was generated using multiple available sources (see Figure 6 & Table 4). These data sources were used to create a probabilistic model of mangrove forest presence. This approach was used to reflect the high degree of variability in existing mapped mangrove extent layers in the region. The mangrove extent layer was divided into $30m^2$ square sections using a fishnet approach in ArcGIS 10.5.1 to reflect the $30m^2$ pixel size of Landsat 8 satellite imagery. A point-layer was generated from the centroids of the $30m^2$ squares. Using Google Earth Engine, a NDVI ‘greenest pixel’ value was derived from all available cloud-free Landsat 8 imagery for each of the $30m^2$ satellite image pixels that were within a defined ‘mangrove’ extent layer across a 12-month period between 1 July and 30 June over the five-year period between 2013 and 2018. The annual time period was chosen to capture peak mangrove seasonal productivity which occurs in the Gladstone region between March and April (Duke 2002; Duke & Burns 2003; Duke et al. 2000) with the ‘greenest pixel’ value capturing the maximum NDVI value at each point across the sampling period. A total of 5 ‘greenest pixel’ values were derived for each point in each sampling year (2013/2014 to 2017/2018). A mangrove extent layer (Duke et al 2017) which had high classification accuracy but high degrees of omission error was used to derive a threshold of mangrove NDVI values. Mangrove $NDVI_{2017/2018}$ values ranged from 0.30 to 0.81.

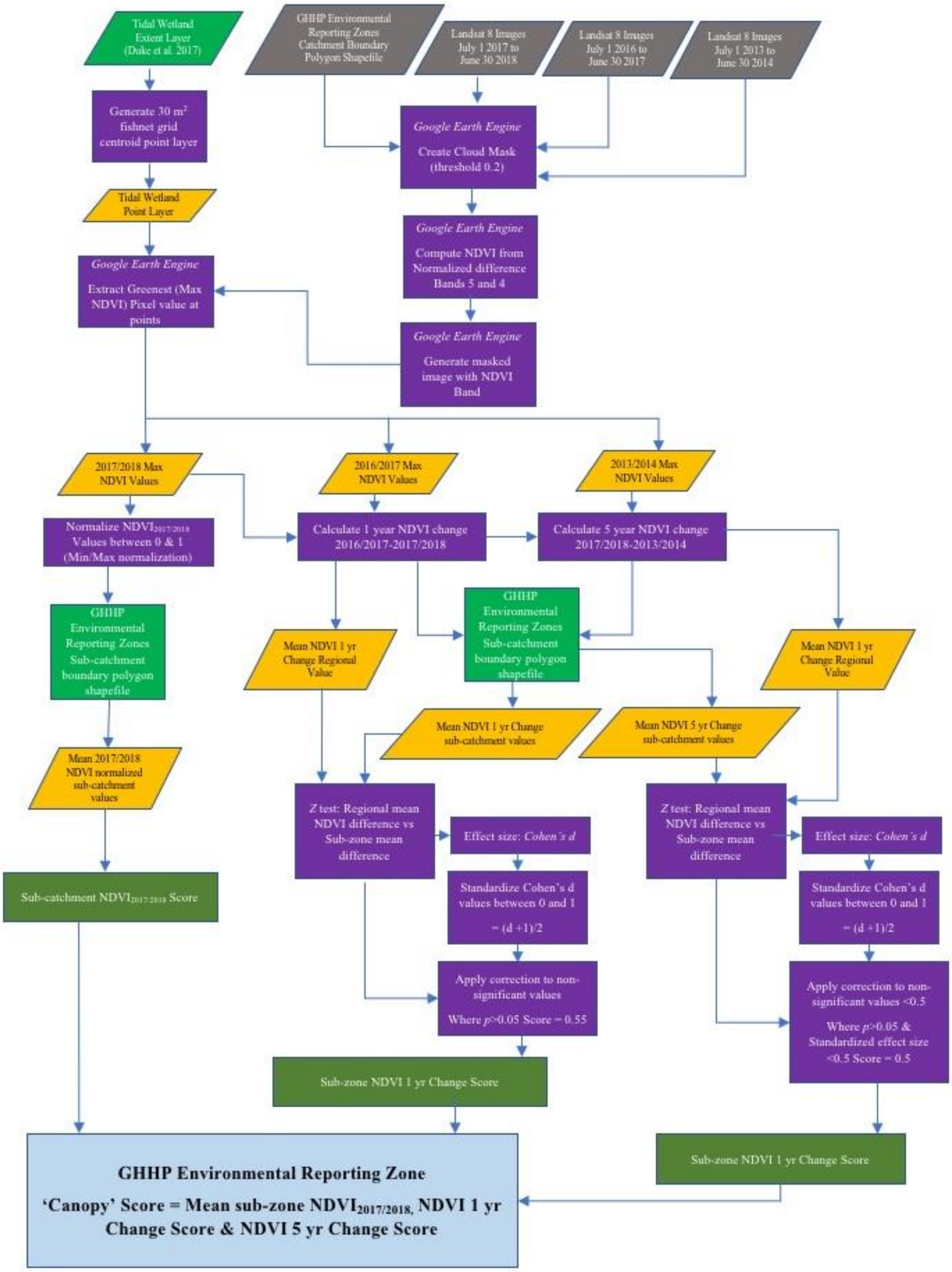

Figure 6. Flow diagram of the logical derivation of the 'Canopy' indicator score.

Table 4. Derivation of NDVI estimates for GHHP sub-zones for trends over the last 5 years.

<table>
<tr><th></th><th>Very Good
0.85 – 1.00</th><th>Good
0.65 – 0.84</th><th>Satisfactory
0.50 – 0.64</th><th>Poor
0.25-0.49</th><th>Very Poor
0-0.24</th></tr>
<tr><td>Mean NDVI 2017/2018</td><td>Mean NDVI value 0.81-0.73</td><td>Mean NDVI value 0.0.72 - 0.63</td><td>Mean NDVI value 0.62-0.55</td><td>Mean NDVI value 0.54-0.43</td><td>Mean NDVI value 0.42-0.30</td></tr>
<tr><td>Mean NDVI Change 2016/2017 to 2017/2018</td><td rowspan="2">Mean inter-annual NDVI difference significantly (p<0.05) greater than regional mean and effect size (Cohen's d) > 0.70</td><td rowspan="2">Mean inter-annual NDVI difference significantly (p<0.05) greater than regional mean and effect size (Cohen's d) 0.69 to 0.30</td><td rowspan="2">Mean inter-annual NDVI difference not significantly (p>0.05) different from regional mean.
OR
Mean inter-annual NDVI difference significantly (p<0.05) greater than regional mean and effect size (Cohen's d) 0.29 to 0</td><td rowspan="2">Mean inter-annual NDVI difference significantly (p<0.05) less than regional mean and effect size (Cohen's d) -0.01 to -0.50</td><td rowspan="2">Mean inter-annual NDVI difference significantly (p<0.05) less than regional mean and effect size (Cohen's d) -0.51 to -1.0</td></tr>
<tr><td>Mean 5 year NDVI change 2013/2014 to 2017/2018</td></tr>
</table>

Three NDVI measures were used to determine the overall mangrove condition score for sub-zones (Figure 6) of the GHHP environmental reporting zones. A standardized mean mangrove point 2017/2018 NDVI value was used to compare spatial differences in mangrove condition between zones. A mean annual change in mangrove point NDVI value between 2016/2017 and 2017/2018 and the mean 5-year mangrove point NDVI change between 2013/2014 and 2017/2018 were used to compare temporal changes in NDVI values as a measure of mangrove forest condition and resilience.
Table 4 details the derivation of scores for each of the NDVI measures. Scores for the 2017/2018 NDVI comparison were derived by dividing the range of mangrove NDVI values (0.30-0.75) by 5. Scores for the inter-annual NDVI comparisons were determined using a z-test to compare sub-zone values with a regional mean. Where sub-zone mean inter-annual NDVI difference values were significantly greater or less than the regional expected mean value, Cohen's d was used as a measure of relative effect size to determine the extent to which values deviated from the mean. Where there was no significant difference between the sub-zone mean and the regional mean and the standardized score was less than 0.5, a score of 0.5 was assigned. The regional mean value was used to reflect that climatic conditions are likely to affect all mangroves across all zones between years causing overall declines or improvements in mangrove NDVI.

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, sub-lethal Indicators – proxies of canopy condition as NDVI and leafy shoot counts

Where annual measures are required, tidal wetland extent and the WCI indicators are likely be less responsive over short time scales. These rely on rapid, widespread tree death or seedling colonisation of large areas to be noticeable. As such, the percent extent (=WCI) indicator is not considered a measure of sub-lethal impact—accordingly the results are less beneficial in annual re-evaluations of habitat condition. Other indicators are needed to address this requirement. We proposed two additional indicators; canopy condition and shoreline condition.

Vegetation indices like NDVI derived from satellite imagery are routinely used to quantify mangrove canopy condition states. The project team are currently developing these measures for the study area as part of the PCPA CHAMP. High resolution image resources have been sourced. Using these imagery, appropriate indices are applied to estimate proxy measures of mangrove canopy health. The basic criteria of what the preferred index must demonstrably show is whether mangrove forest canopies are actually stressed beyond overall mean seasonal fluctuation. This requires field validation with an overall regional assessment. The GHHP project data will enable the further development and refinement of these condition indicators.

To ensure cost-effective data acquisition, we will investigate the efficacy of using recently freely-available high-resolution via Sentinel platforms, the Geosciences Australia Data Cube and Google Earth Engine.

Mangrove leafy shoot counts – comparative proxy for canopy cover. The annual production of leaves on mangroves of the *Rhizophoraceae* family provides a direct measure of mangrove productivity. A useful proxy for this process is the rapid field measure of leaf counts for leafy shoots. Averaged counts from specific locations provide a representative proxy of mangrove productivity. This requires further validation with a dedicated study of canopy litterfall measurements—proposed as extended works in 2019–2020.

As meaningful mangrove litterfall measurements require at least 18 months of sampling, it is proposed that shoot leaf counts be undertaken as part of the initial indicator suite, with ongoing field validation of canopy litterfall to further validate the results at a later stage.

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 and 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, Duke et al. 2016) as a practical means to monitor shoreline condition.

These measures are 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 *unpub data*). 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 50m intervals along target shorelines using oblique aerial shoreline image analysis following an adapted shoreline video assessment method approach (Mackenzie et al 2016).

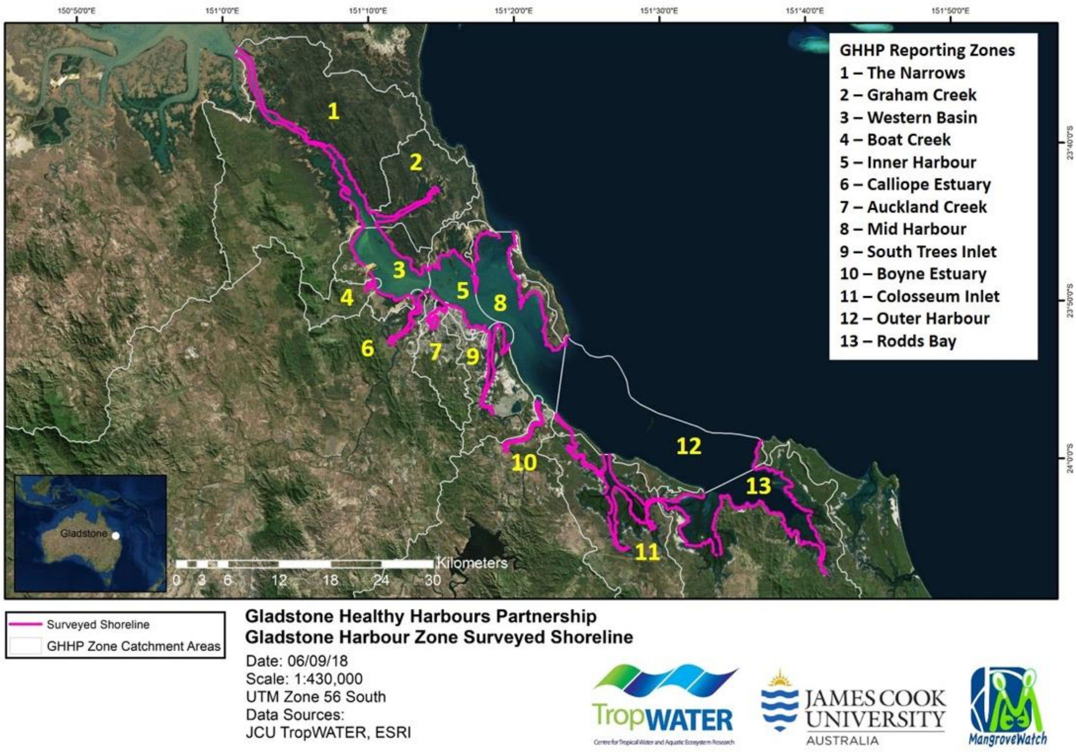

Figure 7. Map showing 13 GHHP zones and the track of the shorelines assessed in June 2018.

Image Acquisition. An aerial shoreline survey of shorelines bordering GHHP water quality zones was undertaken in May 2018 (see Figure 7). Overlapping oblique high-resolution photographs of the shoreline were taken from an open R44 helicopter travelling perpendicular to the shoreline. Flying height was approximately 150m 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 or Nikon D850 camera with a 50mm lens.

Image Assessment. A random stratified sampling design was used to assess the presence of dead mangroves within shoreline fringe mangrove forest along GHHP water quality zone shorelines (see Figure 8 & Table 6). Shoreline sampling points were created at 50m intervals along a shoreline line feature derived from a 0m contour line approximating mean sea level generated using a 5m Digital Elevation Model raster (Geosciences Australia, 2018) and snapped to an existing mangrove polygon feature with a tolerance of 50m (Duke et al – ERMP report). 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 'dead mangrove' score was assigned based on the proportion of shoreline mangrove points with dead mangroves visible.

To account for seasonal climate effects on observed shoreline mangrove death, a seasonally adjusted score was derived comparing sub-zone shoreline dead mangrove frequency relative to the regional observed frequency. 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). Where the observed frequency of fringing mangroves with dead mangrove individuals present in the target zone (O) was significantly higher or lower than the expected overall frequency (E), Cramér's V (SQRT(X^2/n) was calculated as a measure of effect size. The effect size based on the value of Cramér's V was classified following Cohen (Cohen 1988) where scores less than 0.5 represent low to moderate effect size and scores greater than or equal to 0.5 represent a large effect size. The Cramér's V Scores were assigned negative or positive values relative to whether sub-zone dead mangrove frequency was less than or greater than the regional mean. The adjusted Cramér's V were then standardized to a range of 0 to 1. Scores were assigned based on the results of the chi-square analysis and a standardized Cramér's V following Table 6. Where sub-zone dead mangrove frequencies were not significantly ($p>0.05$) greater than the expected regional dead mangrove frequency, but Cramér's V was less than 0, a score of 0.5 was assigned.

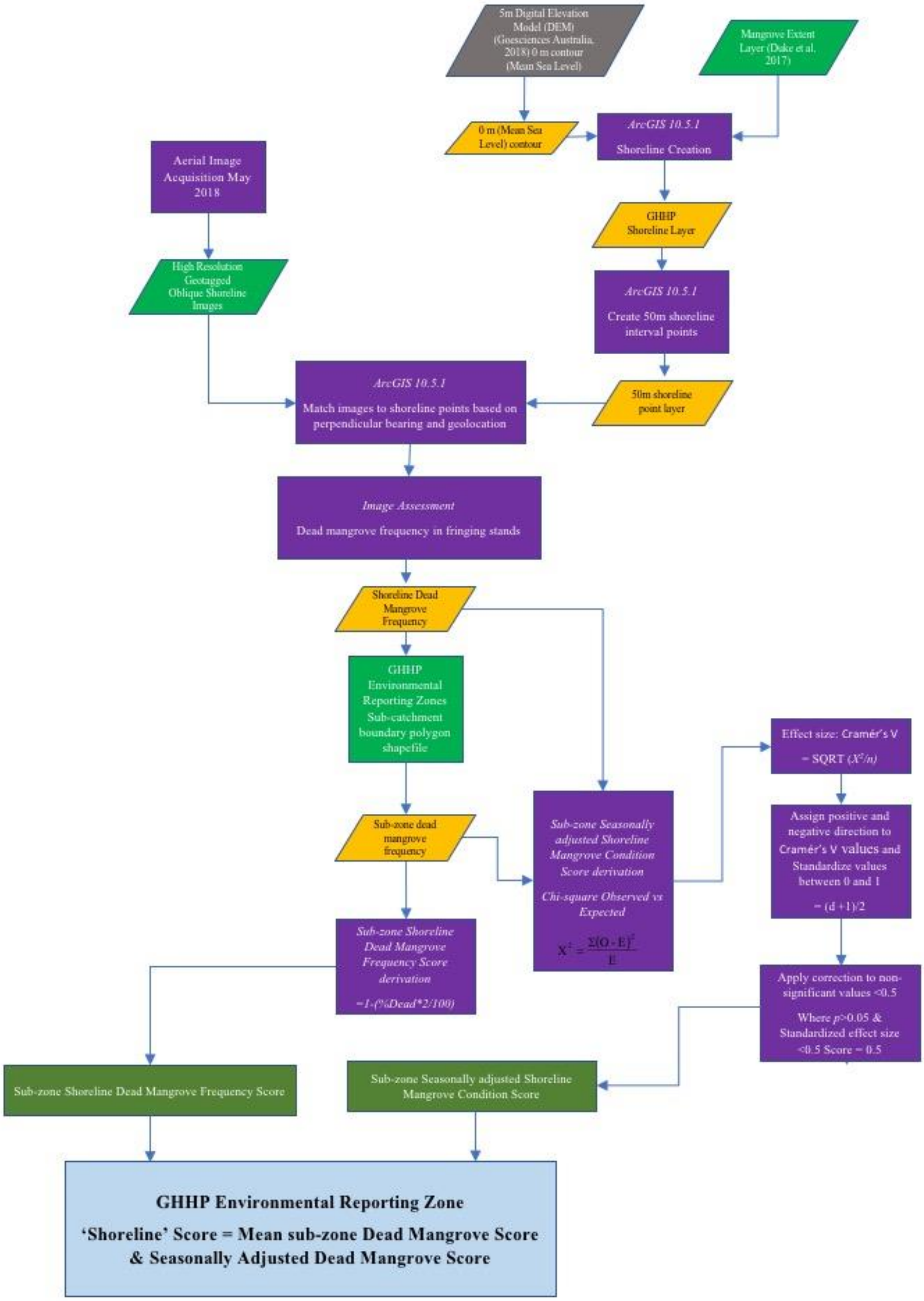

Figure 8. Flow diagram of the logical derivation of the 'Shoreline' indicator score.

Table 6. Classification of shoreline dead mangrove scores.

	Very Good **0.85 – 1.00**	Good **0.65 – 0.84**	Satisfactory **0.50 – 0.64**	Poor **0.25 – 0.49**	Very Poor **0 – 0.24**
Shoreline Condition Score (Dead mangrove frequency)	Observed dead mangrove frequency 0 to 7.5%	Observed dead mangrove frequency 7.6 to 17.5%	Observed dead mangrove frequency 17.6 to 25%	Observed dead mangrove frequency 25.1 to 37.5%	Observed dead mangrove frequency >37.5%
Seasonally adjusted Shoreline Condition Score (Relative Dead mangrove frequency)	Observed dead mangrove frequency significantly greater than expected regional value ($p<0.05$), Cramér's V 1.0 to 0.7	Observed dead mangrove frequency significantly greater than expected regional value ($p<0.05$), Cramér's V 0.69 to 0.30	Observed dead mangrove frequency not significantly different from expected regional value ($p>0.05$), OR Observed dead mangrove frequency significantly greater than expected regional value ($p<0.05$), Cramér's V 0.29 to 0	Observed dead mangrove frequency significantly less than expected regional value ($p<0.05$), Cramér's V <0.30 to 0.69	Observed dead mangrove frequency significantly less than expected regional value ($p<0.05$), Cramér's V 0.7 to 1.0

3 RESULTS

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

This indicator was derived from estimates of change to mangrove forest canopy area (Figure 9) as the primary structural indicator for tidal wetlands. Spatial cover is the total area for each of the major vegetation types of mangroves, tidal saltmarsh. Dieback of upland trees at the terrestrial-upper tidal ecotone – indicative of rising sea levels.

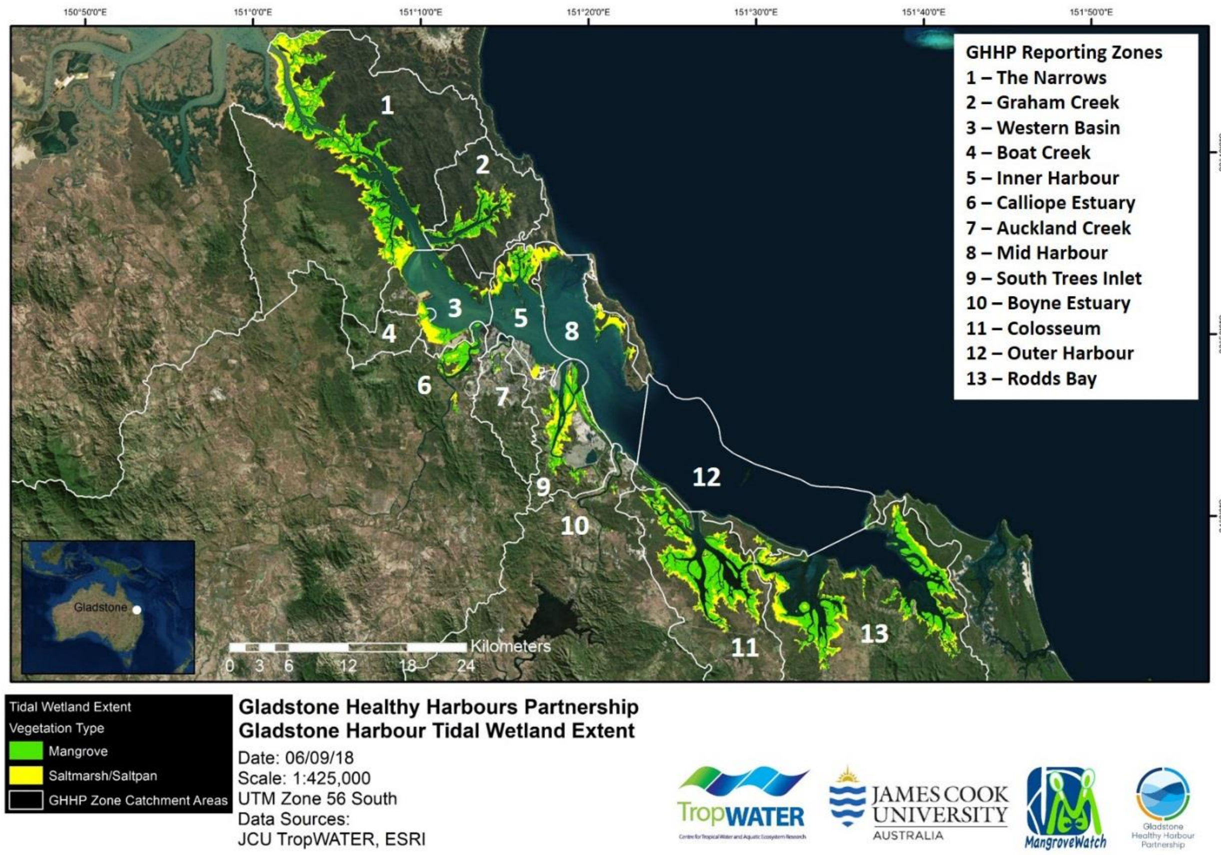

Figure 9. Map showing the extent of dominant tidal wetland vegetation types, mangroves and tidal saltmarsh plus saltpans.

Results are tabulated in Table 7. This includes derivation results and scores for each of the sub-zones combined then for the 13 Zones.

Table 7. Estimates of Wetlands Cover Index (WCI) for GHHP sub-zones plus recent 2016-2017 changes, and change trends over the last 5 years.

GHHP Zone		GHHP Sub Zone	WCI 2017/18	Raw WCI Score	Mangrove Gain 2013/14 to 2017/18 (%)	Mangrove Loss 2013/14 to 2017/18 (%)	*Nett Mangrove Change 2013/14 to 2017/18 (%)*	WCI Change score	Mangrove Loss Score	Combined score	Zone Mangrove Extent Score
The Narrows	1a	*Narrows West (mainland)*	0.61	0.61	0.8	1.4	-0.6	0.93	0.78	0.77	**0.67**
	1b	*Narrows East (Curtis Island)*	0.61	0.61	0.6	2.6	-2	0.61	0.50	0.57	
Grahams Creek	2	*Grahams Ck*	0.75	0.75	0.8	1.6	-0.8	0.91	0.79	0.82	**0.82**
Western Basin	3a	*Western Basin West (mainland)*	0.44	0.44	2.4	1	1.4	0.76	0.86	0.69	**0.74**
	3b	*Western Basin East (Curtis Island)*	0.66	0.66	1.7	1	0.7	0.88	0.86	0.80	
Boat Creek	4	*Boat Creek*	0.37	0.37	2.5	1.2	1.3	0.68	0.86	0.64	**0.64**
Inner Harbour	5a	*Enfield Creek*	0.54	0.54	1	1.3	-0.2	0.93	0.77	0.75	**0.44**
	5b	*Barney Point*	0.17	0.17	8.5	27.4	-18.9	0.22	0.00	0.13	
Calliope Estuary	6	*Calliope Estuary*	0.83	0.83	1.5	2.1	-0.6	0.97	0.76	0.85	**0.85**
Auckland Inlet	7	*Auckland Creek*	0.72	0.72	6.4	1.2	5.2	0.47	0.80	0.66	**0.66**
Mid Harbour	8a	*Mid Harbour Curtis Island*	0.24	0.24	4.5	12.1	-7.6	0.58	0.00	0.27	**0.40**
	8b	*Mid Harbour Facing Island*	0.23	0.23	4.8	7.7	-2.8	0.94	0.40	0.52	
South Trees Inlet	9	*South Trees*	0.6	0.6	2.1	1.3	0.8	0.91	0.80	0.77	**0.77**
Boyne Estuary	10	*Boyne*	0.76	0.76	5.6	7.2	-1.6	0.85	0.18	0.60	**0.60**
Outer Harbour	11a	*Outer Harbour - Wild Cattle Creek*	0.96	0.96	0.7	0.6	0.1	0.98	0.91	0.95	**0.79**
	1bb	*Outer Harbour - Split End*	0.47	0.47	3.7	2.7	1.1	0.63	0.77	0.62	
Colosseum Inlet	12a	*Colosseum Creek*	0.72	0.72	0.8	0.4	0.4	0.91	0.92	0.85	**0.84**
	12b	*Colosseum Inlet Hummock Hill*	0.72	0.72	1.4	0.3	1	0.80	0.96	0.83	
Rodds Bay	13a	*Rodds Bay East*	0.75	0.75	0.6	0.4	0.2	0.90	0.95	0.87	**0.76**
	13b	*Rodds Bay West*	0.68	0.68	1.7	1.1	0.5	0.83	0.87	0.79	
	13c	*Rodds Bay Pancake Creek*	0.63	0.63	1.4	1.2	0.2	0.93	0.85	0.80	
	13d	*Rodds Bay Hummock Hill*	0.35	0.35	4.3	6.6	-2.3	0.89	0.48	0.57	

3.2 'Canopy' indicator – canopy density and condition

This indicator was derived from estimates of NDVI of mangrove forest canopies (Figure 10) as a primary condition indicator of tidal wetlands. Estimates particularly relate to the canopy condition of mangroves and tidal saltmarsh.

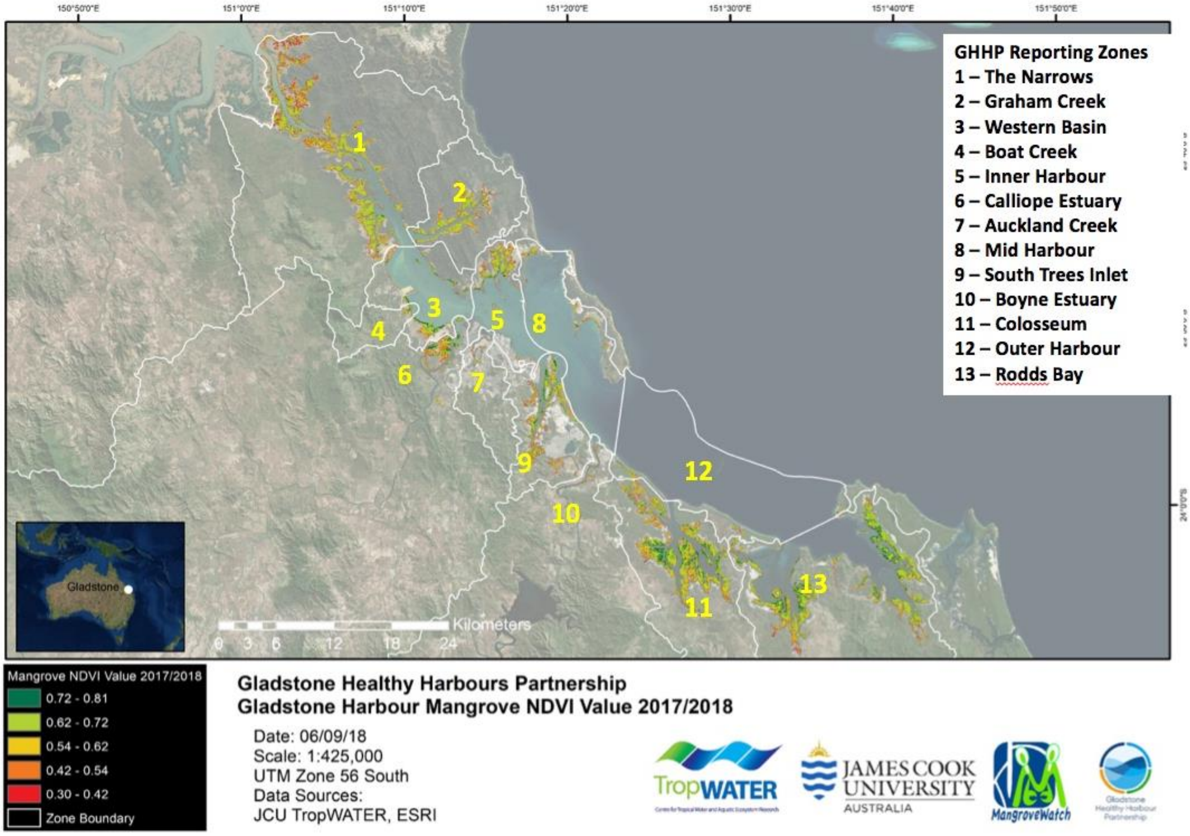

Figure 10. Map showing 13 GHHP zones and the canopy condition as NDVI measures of tidal wetland vegetation across the Port Curtis study area.

Results are tabulated in Table 8. This includes derivation of results and scores for each of the sub-zones and the 13 environmental reporting zones.

Table 8. Summarised estimates of NDVI for GHHP sub-zones showing change trends over the last year and 5 years.

GHHP Zone		GHHP Sub Zone	Mean NDVI Score 2017/2018	Mean 1-year Change 2016/2017 to 2017/2018	*p*	Score	Mean 5-year change 2013/2014 to 2017/2018	*p*	Score	Sub-zone Comb. score	Zone Comb. Score
The Narrows	1a	*Narrows West (mainland)*	0.60	-0.019	***	0.38	0.000	***	0.40	0.46	**0.40**
	1b	*Narrows East (Curtis Island)*	0.53	-0.020	***	0.34	-0.013	***	0.14	0.34	
Grahams Creek	2	*Grahams Ck*	0.60	-0.017	***	0.45	-0.003	***	0.35	0.47	**0.47**
Western Basin	3a	*Western Basin West (mainland)*	0.65	-0.015	ns	0.51	0.015	***	0.70	0.62	**0.60**
	3b	*Western Basin East (Curtis Island)*	0.67	-0.019	***	0.39	0.012	***	0.65	0.57	
Boat Creek	4	*Boat Creek*	0.63	-0.016	ns	0.50	0.015	***	0.71	0.61	**0.61**
Inner Harbour	5a	*Enfield Creek*	0.60	-0.021	***	0.33	-0.003	***	0.34	0.42	**0.37**
	5b	*Barney Point*	0.42	-0.031	***	0.00	0.008	ns	0.56	0.32	
Calliope Estuary	6	*Calliope Estuary*	0.61	-0.013	***	0.57	0.009	***	0.59	0.59	**0.59**
Auckland Inlet	7	*Auckland Creek*	0.48	-0.013	*	0.55	0.023	***	0.87	0.63	**0.63**
Mid Harbour	8a	*Mid Harbour Curtis Island*	0.58	-0.019	***	0.37	0.023	***	0.86	0.61	**0.55**
	8b	*Mid Harbour Facing Island*	0.53	-0.022	***	0.29	0.012	***	0.65	0.49	
South Trees Inlet	9	*South Trees*	0.60	-0.018	***	0.42	0.002	***	0.44	0.49	**0.49**
Boyne River Estuary	10	*Boyne*	0.52	-0.017	**	0.44	0.004	ns	0.50	0.49	**0.49**
Outer Harbour	11a	*Outer Harbour - Wild Cattle Creek*	0.63	-0.011	***	0.64	-0.012	***	0.16	0.48	**0.60**
	11b	*Outer Harbour - Split End*	0.57	-0.011	***	0.62	0.027	***	0.96	0.72	
Colosseum Inlet	12a	*Colosseum Creek*	0.65	-0.013	***	0.55	0.006	***	0.53	0.58	**0.59**
	12b	*Colosseum Inlet Hummock Hill*	0.67	-0.016	**	0.48	0.012	***	0.64	0.59	
Rodds Bay	13a	*Rodds Bay East*	0.72		***	0.73	0.015	***	0.72	0.72	**0.68**
	13b	*Rodds Bay West*	0.63	-0.006	***	0.78	0.019	***	0.80	0.73	
	13c	*Rodds Bay Pancake Creek*	0.66	-0.012	***	0.59	0.014	***	0.68	0.64	
	13d	*Rodds Bay Hummock Hill*	0.56	-0.015	ns	0.50	0.019	***	0.80	0.62	

3.3 **'Shoreline' indicator – condition as dead mangrove frequency**

A total of 7,229 shoreline points were assessed across all 13 GHHP environmental reporting zones (Figure 11). Of these points 5,288 (87%) represented shoreline mangroves. The overall proportion of shoreline mangroves with dead mangroves present was 15.8%. The proportion of shoreline mangroves with dead mangroves present in individual zones ranged from 6.8% (Auckland Inlet – Zone 7) to 42.5% (Boyne River Estuary – Zone 10). The Boyne River Estuary (Zone 10) and Western Basin (Zone 3) had significantly higher frequency of dead mangrove observations compared to the overall region. Graham Creek (Zone 2), Auckland Inlet (Zone 7), Mid Harbour (Zone 8) and Rodds Bay (Zone 13) all had significantly fewer observations of dead mangroves compare to the overall region. All other zones were not significantly different from regional observations.

Sub-zone regions with the highest frequency of dead mangroves observed in shoreline mangroves were the Boyne River estuary (42.5%), Western Basin mainland (31.1%), Inner Harbour Barney Point shoreline (28.9%) and Western Basin Curtis Island (25.6%).

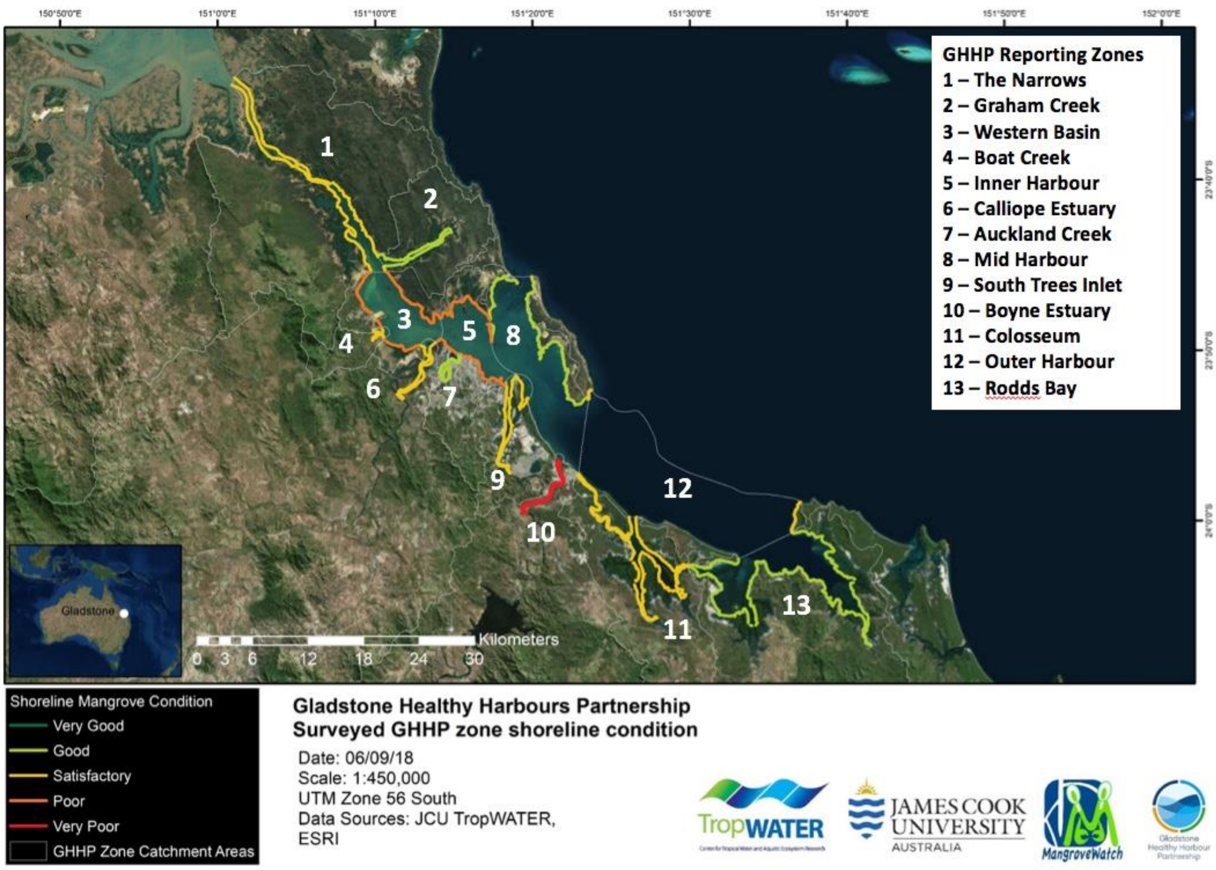

Figure 11. Map showing the shoreline condition rankings for each of the 13 GHHP zones. These are colour coded for each of the 50 m interval data points along the coastal shorelines.

Results are tabulated in Table 9. This includes derivation results and scores for each of the sub-zones combined for the 13 Zones.

Table 9. Estimates of Shoreline condition for GHHP sub-zones showing recent changes 2016-2017, and change trends in recent 5 years.

GHHP Zone		GHHP Sub Zone	Shoreline Points Assessed	% Mangrove	Dead Mangrove Frequency	% Shoreline mangrove with dead trees	*p*	Sub-zone Shoreline Dead Mangrove Frequency Score	Sub-zone Seasonally Adjusted Shoreline Mangrove Condition Score	Sub-zone Shoreline Mangrove Condition Score	Zone Shoreline Mangrove Condition Score
The Narrows	1a	*Narrows West - mainland*	547	99	125	23	***	0.54	0.40	0.47	**0.61**
	1b	*Narrows East - Curtis Is.*	535	99	31	6	***	0.88	0.64	0.76	
Grahams Creek	2	*Grahams Ck*	365	98	31	9	***	0.83	0.60	0.71	**0.71**
	3a	*Western Basin West*	212	99	65	31	***	0.38	0.29	0.33	**0.38**
	3b	*Western Basin East - Curtis Is.*	204	86	45	26	***	0.49	0.37	0.43	
Boat Creek	4	*Boat Creek*	141	95	18	13	ns	0.73	0.53	0.63	**0.63**
Inner Harbour	5a	*Enfield Creek*	225	97	39	18	ns	0.64	0.50	0.57	**0.47**
	5b	*Barney Point*	135	28	11	29	ns	0.42	0.32	0.37	
Calliope Estuary	6	*Calliope Estuary*	315	89	52	19	ns	0.63	0.50	0.56	**0.56**
Auckland Inlet	7	*Auckland Creek*	257	86	15	7	***	0.86	0.62	0.74	**0.74**
Mid Harbour	8a	*Mid Harbour Curtis Island*	145	92	8	6	**	0.88	0.63	0.76	**0.70**
	8b	*Mid Harbour Facing Island*	474	58	36	13	ns	0.74	0.54	0.64	
South Trees Inlet	9	*South Trees*	524	96	86	17	ns	0.66	0.50	0.58	**0.58**
Boyne Estuary	10	*Boyne*	337	82	117	43	***	0.15	0.13	0.14	**0.14**
Colosseum Inlet	11a	*Colosseum Creek*	1040	92	148	15	ns	0.77	0.56	0.67	**0.63**
	11b	*Colosseum - Hummock Hill*	196	77	17	11	ns	0.69	0.50	0.60	
Outer Harbour	12a	*Outer Harbour - Wild Cattle*	116	83	16	17	ns	0.64	0.50	0.57	**0.58**
	12b	*Outer Harbour - Split End*	71	15	2	18	ns	0.67	0.50	0.58	
Rodds Bay	13a	*Rodds Bay East*	302	86	13	5	***	0.90	0.65	0.77	**0.68**
	13b	*Rodds Bay West*	447	81	56	15	ns	0.69	0.51	0.60	
	13c	*Rodds Bay - Pancake Creek*	457	96	51	12	*	0.77	0.56	0.66	
	13d	*Rodds Bay - Hummock Hill*	139	86	11	9	*	0.82	0.59	0.70	
Overall			**7184**	**87**	**993**	**16**					

3.4 **Comparison between 'Canopy' indicator and leafy shoot scores**

Leafy shoots were scored in the field and the results tabulated in Table 10. The aim was to make comparisons with NDVI data at the specific points where leaf scores were made. This objective can be met once this project has been completed. The advantage in making this comparison is that is can provide validation or otherwise for this apparent proxy of canopy density.

Table 10. Summarised estimates of leafy shoot counts and canopy condition.

GHHP ZONE	ZONE #	Sub-Zone Nos.	Shoot total	Shoot Count mean	Shoot Count 1x SE	Photo Count	LAI mean	%Cover Mean
The Narrows	1	2	60	6.68	0.15	8	1.77	68.2
Grahams Creek	2	2	61	6.67	0.57	6	2.37	80.8
Western Basin	3	2	60	6.55	0.32	6	2.34	79.4
Boat Creek	4	0	0			0		
Inner Harbour	5	3	90	6.17	0.42	9	2.15	77.2
Calliope Estuary	6	2	60	6.70	0.20	6	2.74	84.6
Auckland Inlet	7	4	113	8.12	0.49	11	2.60	82.9
Mid Harbour	8	2	60	6.77	0.30	6	2.33	79.6
South Trees Inlet	9	1	30	7.17		3	2.59	84.5
Boyne Estuary	10	2	61	5.30	0.23	6	1.79	68.7
Outer Harbour	11	2	60	6.93	0.43	6	2.50	82.3
Colosseum Inlet	12	2	60	6.57	0.37	6	2.52	81.9
Rodds Bay	13	2	60	6.75	0.72	6	2.64	83.3
		26	775	6.63	0.20	79	2.34	79.5

4 DISCUSSION

4.1 General observations

There were a number of areas with healthy mangrove stands marked by intact canopies and few dead trees (Figures 12 to 13). However, there were many other areas with notable impacts observed to be symptomatic of a variety influencing factors.

Figure 12. Healthy Mangroves, possibly enhanced effects by relatively high nutrient loads - Auckland Creek, Zone 7.

Figure 13. Healthy mangroves away from direct human influences – Rodds Bay East, Zone 13a.

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. Severe flood impacts were observed within major riverine estuaries, especially the Boyne River estuary (Figures. 14 to 17). Recovery was notably slow in these instances. The situation appeared somewhat exacerbated by access tracks, clearing and cutting of dead vegetation – preventing and inhibiting seedling recruitment and re-establishment.

Figure 14. Flooding impacts on the Boyne River showing recovery is slow – Boyne River estuary, Zone 10.

Figure 15. Flooding impacts on the Boyne River showing recovery is slow – Boyne River estuary, Zone 10.

Figure 16. Flood damaged shoreline vegetation - Boyne River estuary, Zone 10.

Figure 17. Further flood damaged shoreline vegetation – Boyne River estuary, Zone 10.

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 appeared indicative of rising sea levels generally across the entire study area (Figures. 18 to 19). 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.

It would be useful to have further indicators that monitor such progressive changes.

Figure 18A & B. Retreat and erosion of the terrestrial fringe is a serious growing threat to supra-tidal habitats throughout the study area—Colosseum Creek, Zone 11a.

Figure 19. Terrestrial dieback and retreat marked by lines of dead upland trees – Western Basin West (mainland), Zone 3a.

Dieback at the saltpan ecotone – indicative of a longer-term decrease in rainfall. (See Figures. 20)

Figure 20. Dieback marking retreat of the saltpan ecotone, corresponding with low NDVI and reduced canopy condition – The Narrow East (Curtis Island), Zone 1b.

Dieback and erosion loss of shoreline trees – indicative of sea level rise and/or storm impacts. (See Figures. 21 to 24).

Figure 21. Mangroves in poor condition with notable shoreline dieback – Inner Harbour West (Barney Point), Zone 5b.

Figure 22. Shoreline dieback of *Rhizophora stylosa* trees – The Narrows West (mainland), Zone 1a.

Figure 23. Scattered Dead Trees within Fringe zone - Colosseum Inlet Hummock Hill, Zone 11b.

Figure 24. Shoreline dieback of *Rhizophora stylosa* trees – Western Basin East (Curtis Island), Zone 3b.

Point source effluent discharges – potential risk from direct human pressures. (See Figures 25 to 26).

Figure 25. Dust impacted mangrove trees, browning of canopy foliage – South Trees estuary, Zone 9.

Figure 26. Black discolouration in Calliope River estuary associated with pump effluent from the coal loading facility site—Calliope estuary, Zone 6.

4.2 A further indicator for shoreline habitat risk

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 a more useful indicator of mangrove resilience to stochastic events such as cyclones (Feller et al. 2015) or oil spills (Duke 2016a), than the existing condition state. This has been demonstrated recently where mangroves exposed to eutrophication were less resilient to cyclones (Feller et al 2017) and drought (Lovelock et al 2011). 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 a measure of relative existing pressures on mangroves that may reduce ecosystem resilience. We propose using such indicators as an additional measure of mangrove vulnerability (Duke 2014).

There are two useful measures that can be used to rapidly identify threats to mangrove habitats and quantify their potential level 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 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 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 informing environmental managers for better targeting of management intervention works.

Vulnerability 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.

Table 11. Mangrove vulnerability index measured as a composite score of the following indicators.

Indicator	Indicator Descriptor	Assessment Scoring Criteria	Derived Metrics
1) Shoreline Human Modification	The presence of human-related shoreline physical modification (e.g. wharves, boat ramps, pontoons), and the resulting level of habitat modification.	Shoreline Modification 4 Natural – No obvious human modification 5 Modified – indirect human-related habitat modification but some habitat integrity maintained. 6 Highly modified – direct human related shoreline habitat modification resulting in complete alteration of habitat structure or loss of habitat integrity.	***Shoreline Naturalness*** – The proportion of shoreline classified as natural. ***Shoreline Modification*** – the proportion of shoreline modified and human impacted.
2a) Human Direct Impact Descriptors	The types of direct human impacts present	Direct Human Impacts present 1. Reclamation, landfill 2. Cattle grazing, tracks 3. Pigs present, wallows, diggings, tracks 4. Vehicles present, tracks 5. Cleared mangrove or saltmarsh 6. Cutting of vegetation, cut stumps 7. Trimming, canopy cutting 8. Mowing of verges	***Direct Human Impact Type*** - Identification of types of direct human impacts present. ***Direct Human Impact Extent*** – the proportion of shorelines influenced

		9. Agricultural Encroachment	by direct human impacts.
2b) Human Indirect Impact Descriptors	The types of indirect human impacts present	<u>Indirect Human Impacts present</u> 1. Altered hydrology – various pondings 2. Habitat Alterations – rockwalls, groins 3. Pollutants present, effects – like oil spills 4. Pollutant effects on vegetation – herbicides 5. Nutrients – effluent effects, algae, growth 6. Sediments – point source, mud banks 7. Introduced species – weeds, exotics 8. Lack of Buffer zone – proximity + damage 9. Lack of riparian vegetation – edge exposure	***Indirect Human Impact Type*** - Identification of indirect human impacts present. ***Indirect Human Impact Extent*** – the proportion of shorelines influenced by indirect human impacts.
2c) Climate-Natural Impact Descriptors	The types of relatively natural impacts present	<u>Climate/Natural Impacts present</u> 1. Waterfront/seaward erosion 2. Inner fringe collapse - dieback 3. Estuarine channel bank erosion 4. Tidal flat erosion, scouring, sheet erosion 5. Storm Damage – broken stems, canopy loss 6. Light gaps, lightning strikes 7. Root burial and dieback 8. Impoundment – natural altered hydrology 9. Depositional Gain – encroachment seaward 10. Flood Damage - dieback and debris 11. Ecotone Shift Negative – pan edge dieback 12. Ecotone Shift Positive – pan edge expansion 13. Terrestrial Retreat - erosion + dieback 14. Upstream shift – dieback + encroachment 15. Fruit Bat roost site – loss of canopy 16. Herbivory – loss of canopy, possible dieback 17. Fire damage – high tide verge dieback	***Climate-Natural Impact Type*** - Identification of natural impacts present. ***Climate-Natural Impact Extent*** – the proportion of shorelines influenced by direct human impacts. ***Shoreline Change*** – ratio of Erosion vs Deposition. ***Mangrove Movement*** – ratio of Retreat landward vs Encroachment seaward. ***Ecotone Shift*** – ratio of negative vs positive states.

An example of the type of source material for developing such a scoring system is shown in Table 12. 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 the classification system under development, it is possible to group changes into human related impacts (local management issues) and indirect human and climate impacts (regional management issues.

Table 12. Rapid field scores of shoreline drivers for the 13 GHHP environmental reporting zones showing five most observed processes for human and climate-natural influences in the Port Curtis region in June 2018.

GHHP Zones		HUMAN	1 Direct Loss	2 Altered Hydrol.	3 Structure	4 People Access	5 Stock Damage	CLIMATE	1 Shore Erosion	2 Terr'l Retreat	3 Pan Scour	4 Bank Erosion	5 Ecotone Shift	Human	Natural	Overall SCORE
1	The Narrows	1	0.50	0.00	0.50	0.50	0.20	1	1.60	1.20	0.90	0.00	0.80	1.70	4.50	0.4
2	Graham Creek	2	0.00	0.00	0.20	0.00	0.80	2	0.40	1.20	1.20	0.60	0.80	1.00	4.20	0.2
3	Western Basin	3	3.00	2.25	2.50	0.20	0.70	3	2.25	0.20	0.40	0.00	0.00	8.65	2.85	3.0
4	Boat Creek	4	2.00	1.20	0.20	1.60	0.40	4	1.60	0.40	0.80	3.20	0.80	5.40	6.80	0.8
5	Inner Harbour	5	1.00	1.07	1.00	0.27	0.13	5	1.00	0.40	0.27	0.00	0.00	3.47	1.67	2.1
6	Calliope Estuary	6	3.00	1.80	1.80	0.80	0.00	6	0.00	0.00	0.40	1.80	0.80	7.40	3.00	2.5
7	Auckland Inlet	7	4.00	3.20	2.70	0.60	0.00	7	0.00	0.00	0.00	0.60	0.40	10.50	1.00	10.5
8	Mid Harbour	8	0.00	0.55	0.53	0.45	0.10	8	0.15	0.65	0.30	0.15	0.00	1.63	1.25	1.3
9	South Trees Inlet	9	3.00	2.10	1.20	0.40	0.00	9	1.00	0.60	0.80	0.00	0.80	6.70	3.20	2.1
10	Boyne Estuary	10	1.00	2.70	1.20	1.20	0.80	10	0.00	0.40	0.40	1.80	0.00	6.90	2.60	2.7
11	Outer Harbour	11	0.00	0.00	0.10	0.00	0.00	11	1.15	1.20	0.50	0.00	0.80	0.10	3.65	0.0
12	Colloseum Inlet	12	0.20	0.13	0.27	0.67	0.60	12	0.60	1.70	1.33	0.53	0.00	1.87	4.17	0.4
13	Rodds Bay	13	0.35	0.25	0.30	0.45	0.55	13	1.13	1.20	0.80	0.15	0.10	1.90	3.38	0.6
MEAN			**1.39**	**1.17**	**0.96**	**0.55**	**0.33**		**0.84**	**0.70**	**0.62**	**0.68**	**0.41**	**4.40**	**3.25**	**2.04**

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