Mud Crab Indicators for the Gladstone Harbour Report Card: Project ISP015-2021

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The authors would like to take this opportunity to respectfully acknowledge the Traditional Owners of the land on which we live, work and learn, and pay our respects to the Elders, past, present and future for they hold the memories, the traditions, the culture and hopes of Indigenous Australia. In particular, we pay our respects to the peoples on whose Country this research was carried out.

Version history

Version Number	Purpose/Changes	Authors	Date
1.1	Initial draft of interim report – to GHHP	Flint, De Valck, Anastasi	17/08/2021
1.2	Addressing ISP comments	Flint	13/09/2021

Executive summary

Giant mud crabs (*Scylla serrata*) are a recreationally and commercially important species in Gladstone Harbour, an iconic seafood item, and have cultural value to Indigenous Australians. The Gladstone Harbour Report Card mud crab indicator provides scores and grades for three metrics: abundance (catch per unit effort), prevalence of rust lesions, and sex ratio. The mud crab indicator has been monitored in seven Gladstone Harbour zones since 2017, and this report presents the results of the fifth year of sampling, 2021.

Two field sampling events were conducted during 2021, one in February and one in June. Scores and grades were calculated using both 2021 data sets for the three metrics within each of the seven recommended long-term monitoring zones in Gladstone Harbour. The scores for each of the three measures were averaged across all zones first to give a harbour average for each measure, and then the average of the three harbour averages was calculated as a harbour-wide score and grade for the mud crab indicator.

The following scores and grades have been calculated for 2021:

Zone	Abundance (CPUE)	Prevalence of rust lesions	Sex ratio	Zone score 2021
1. The Narrows	1.00	0.92	0.00	0.64
2. Graham Creek	0.27	0.89	0.00	0.39
4. Boat Creek	0.83	0.94	0.03	0.60
5. Inner Harbour	0.63	0.47	0.07	0.39
6. Calliope Estuary	0.26	1.00	0.14	0.47
7. Auckland Inlet	0.00	NC	NC	NC
13. Rodds Bay	0.16	0.96	0.57	0.56
Harbour Average	0.45	0.86	0.14	0.48

- NC – not calculable, n < 5

The scores and grades for the mud crab indicator reflect the variety of pressures on mud crabs in Gladstone Harbour, including commercial fishing, recreational fishing, and environmental/habitat condition. Over short time periods, they are also potentially influenced by biological variability. The highest zone score in 2021 was for the Narrows (0.64, C) followed by Boat Creek (0.60, C).

As has been the case since 2018, the zone score and grade for Auckland Inlet has not been calculated, as only two mud crabs were caught here in 2021. The small sample size (n < 5) means it is not appropriate to calculate grades for this zone, except for the abundance measure. Abundance scores have improved in most zones since 2020, and as in previous years the Narrows and Boat Creek had the highest zone scores. As well as human impacts, there are a range of factors that can influence the catchability of mud crabs such as the moult state of crabs, reproductive cycles, lunar and diel cycles, temperature, water motion and habitat quality. In light of this potential for natural variability, the decision was taken in 2018 to allow abundance to be scored based on a moving average technique, using the average of the 75th percentile of scores for current and previous sampling years, up to 10 years. This long-term adjustment to the benchmark allows for annual harbour-wide changes in catchability and abundance, which are more likely to reflect natural variations.

The prevalence of rust lesions scored highly (graded A) in all zones except Inner Harbour (D). As previously identified for Gladstone Harbour, sex ratios of mud crabs over the legal-size limit (for males) tended towards very high proportions of female mud crabs, a possible reflection of high participation in the sex-based fishery operating in Queensland.

Overall, the harbour scored higher for the mud crab indicator in 2021 (0.48) than in 2020 (0.39), but the same grade was assigned (D).

The mud crab indicator has been successfully monitored in Gladstone Harbour since 2017, with some revisions to the scoring and grading methods made over time as more information became available. On 8 March 2021, the GHHP ISP organised a workshop on the mud crab indicator, inviting mud crab experts from around Australia. On the basis of five years of monitoring and the discussions at the workshop, the following recommendations are provided for 2022 onwards:

- Continue to monitor the mud crab indicator, using the established monitoring methods, twice a year at the seven long-term monitoring sites. Invited experts at the GHHP mud crab indicator workshop agreed seasonal sampling should continue at a minimum.
- With five years of data now available from Gladstone Harbour, additional statistical analyses could be undertaken, investigating not only patterns in the indicator measures as described above, but in other variables that are monitored (e.g., the sex ratio of smaller mud crabs and variability in catch in relation to weather variables).
- GHHP may wish to consider increasing the number of zones sampled to include other estuaries in Gladstone Harbour (e.g., South Trees Inlet and Boyne Estuary). This would expand the dataset and increase the relevance of the indicator to additional portside industries.
- It would be beneficial to sample again at Eurimbula Creek, to test whether inter-annual catch trends at this reference site are similar to those in Gladstone Harbour.
- Bioaccumulation of relevant metal(loid)s in Gladstone Harbour could be considered as a possible additional measure for future monitoring.
- Research to determine the root cause of rust lesions is recommended.

Contents

Introduction

Giant mud crabs (*Scylla serrata*) are an important seafood product across Australasia and support an iconic Queensland fishery. Mud crabs are recreationally and commercially important in Gladstone Harbour and hold cultural value to Indigenous Australian peoples (Brewster, 2015). In 2014, the Gladstone Healthy Harbour Partnership (GHHP) Independent Science Panel (ISP) identified mud crabs as an important indicator species to assess the health of Gladstone Harbour (McIntosh *et al.*, 2014). In 2017, GHHP commissioned CQUniversity to develop mud crab indicators for the Gladstone Harbour Report Card (Project ISP015-2017).

An important aspect of monitoring programs is that the outputs are reported in a way that is understandable and meaningful to stakeholders, managers, and the community. Biological indicators such as mud crabs can help to fulfil this requirement in report cards (Flint *et al.*, 2021). The OECD defines environmental indicators, as "[…] a parameter, or a value derived from parameters, that points to, provides information about and/or describes the state of the environment, and has a significance extending beyond that directly associated with any given parametric value. The term may encompass indicators of environmental pressures, conditions and responses." Using this definition, environmental indicators do not necessarily reflect only a single, individual environmental pressure. This is often particularly true for biological indicators, as animals are exposed to the cumulative effects of a range of pressures and conditions in their environment, which can result in a range of biological responses.

Local pressures on mud crabs in Gladstone Harbour potentially include recreational and commercial fishing, coastal development affecting mangrove and estuarine habitat quality, water quality and local weather changes associated with global climate change. Prevalence of locally relevant disease is also an important consideration. The GHHP mud crab indicator is composed of three measures, which were selected in 2017 through a rigorous scoring process against predefined selection criteria (Flint *et al.*, 2017). A literature review was first undertaken to assemble a list of potential measures suitable for a mud crab monitoring program. These included biomarkers of contamination, bioaccumulation of toxicants, sex ratio of adult crabs, abundance (catch per unit effort of adult and sub-adult crabs), nursery value (catch per unit effort of juvenile crabs in nursery habitats), prevalence of rust lesions, prevalence of other diseases and parasites, the relationship between carapace width and body weight of adult crabs, and morphometrics (such as claw size ratio). These potential measures were reviewed, compared, and scored against a set of ten predefined selection criteria. The three measures selected for inclusion in the mud crab indicator include: abundance (catch per unit effort – CPUE), the prevalence of rust lesions, and sex ratio. The indicator was incorporated into the Gladstone Harbour Report Card and has been scored and graded each year since 2017.

The metric of abundance of mud crabs that are caught during the monitoring program provides a comparison of catch rates, using a standardised and fishery-independent methodology. To control potential monitoring variations that could arise due to capture technique and due to design constraints regarding sampling areas and sampling times, consistent methodologies are employed during each catch period. Catch rates can reflect a wide variety of natural and anthropogenic impacts on a population (Alberts-Hubatsch *et al.*, 2016). Factors influencing abundance of mud crabs may include localised and regional fishing pressure, habitat availability and habitat condition, the availability of food and proximity to suitable nursery grounds for the settlement of mud crab megalopae and metamorphosis to immature crabs. Climate has also been shown to impact the abundance of mud crabs (Meynecke *et al.*, 2012) so there is also potential for this indicator to be used to monitor climate effects on mud crabs in the longer term.

The prevalence of rust lesions measure reports the proportion of captured crabs that have 'rust spot' shell lesions. The lesions were first recorded by commercial fishers in Gladstone Harbour in

1994 (Andersen and Norton, 2001). The disease is not infectious and it is thought it could be related to inhibition of calcium uptake following sublethal copper exposure, although this has not yet been experimentally confirmed (Andersen and Norton, 2001). Since rust spots are not continuously observed in Gladstone Harbour, their prevalence at any given time provides an indication of environmental state. Rust spot lesions impact the seafood 'grade' of mud crabs, so are a concern for local fishers. Recording the presence of rust spot is a relatively straightforward and non-destructive monitoring tool.

The third measure used in the mud crab indicator is sex ratio. The major drivers of changes in sex ratio are recreational and commercial fishing pressure on male mud crabs over 150 mm carapace width (measured across the ninth posteriolateral spines, referred to as 'spine width' in this report). In Queensland, female mud crabs, and male mud crabs under 150 mm, may not be retained. Changes in the ratio of males to females in sex-based fisheries can indicate a change in fishing pressure (Heasman, 1980; Pillans *et al.*, 2005; Alberts-Hubatsch *et al.*, 2016). The impacts of shifts in sex ratio are not well understood but may have implications for population dynamics of mud crabs and reproductive success and may also influence ecosystem processes due to the different burrowing behaviours and movements exhibited by male and female crabs.

Objectives

The overall objectives of this project were to:

1. Conduct mud crab surveys of the 7 GHHP reporting zones consistent with the survey methods used in previous years and consisting of a summer (warm, wet season) survey and a winter (cool, dry season) survey.
2. Provide mud crab scores and grades for the 2021 Gladstone Harbour Report Card. Calculate scores and grades using the methods developed in the 2017 mud crab monitoring project with the revised thresholds for sex-ratio and abundance used for the calculation of the 2018, 2019 and 2020 mud crab scores. *[Note: A revision in 2020, requested by the GHHP ISP, resulted in a different averaging method for determining the overall harbour score]*

Methods

Field methods

The following permits and approvals are in place for this research:

- General Fisheries Permit (Queensland Department of Agriculture and Fisheries; Permit Number 207715)
- Animal Ethics Approval (CQUniversity Animal Ethics Committee; Approval Number 20633)
- Authorisation for research in the Great Barrier Reef Marine Park (Approval Number G17/05-027)
- Field Work Risk Assessment (CQUniversity Occupational Health and Safety Unit)

Two mud crab surveys were undertaken in 2021 (Table 1), representing a summer (warm, wet season) and winter (cool, dry season) sample. The seven monitoring sites (Figure 1) were previously chosen through a quantitative selection process (Flint *et al.*, 2017) related to the availability of suitable habitat types and the occurrence of previous sampling sites, and have been surveyed twice annually since 2017.

Sampling dates and times were determined by tidal cycles. Pots were set at least three hours before the low tide, and collected at least two hours after the low tide, resulting in soak times of at least five hours per pot. To comply with the conditions of Animal Ethics Approval, pots were placed so that they would still be submerged at low tide (preventing exposure mortality of any fish caught in the pots). Pots were placed as close as possible to mangrove habitats within this limit.

Table 1: Gladstone zones/sites sampled during February and June 2021.

Zone/site	Survey 1	Survey 2
Zone 1: Narrows	9 February 2021	4 June 2021
Zone 2: Graham Creek	9 February 2021	4 June 2021
Zone 4: Boat Creek	8 February 2021	5 June 2021
Zone 5: Inner Harbour	6 February 2021	3 June 2021
Zone 6: Calliope Estuary	8 February 2021	5 June 2021
Zone 7: Auckland Inlet	6 February 2021	3 June 2021
Zone 13: Rodds Bay	7 February 2021	6 June 2021

At each site and sampling event, 20 heavy duty 4-entry round collapsible crab pots were set a minimum of 100 m apart. The exception to this was Boat Creek in June 2021. Fewer pots can be accommodated in this smaller system. Collapsible crab pots were purchased from a local tackle store in 2017, as they are easy to transport, assemble on the vessel and replace (Fisheries Queensland, 2009). Some pots that have been lost or damaged have since been replaced with identical pots. Each pot was baited with one large sea mullet (*Mugil cephalus*) head, and all floats were attached with 10 m ropes and marked with researcher contact details and the Fisheries Queensland research permit number. Every float had a unique identifying number to allow any missing pots to be identified quickly during retrieval. The opening of each pot was secured with a cable tie, so that if crabs were removed by others this could be detected and recorded on retrieval.

At each sampling site, the following information was recorded:

- Zone and site name;
- GPS location;
- Date;
- Set time and retrieval time for each uniquely identified pot;
- The total number of animals of each species caught in every pot, and the sex of all mud crabs caught; and
- Water quality parameters (temperature, dissolved oxygen, conductivity, pH, turbidity, total dissolved solids, oxidation reduction potential and salinity) measured using a YSI ProDSS Multiparameter Sampling Instrument, recorded once before setting the first pot and once after retrieving the final pot (not reported but provided to GHHP).

For every mud crab captured at each site, the following information was recorded:

- Species;
- Sex;
- Carapace width (notch width) (mm); and
- Abnormalities: type, body location, dimensions of rust spot lesions, grade of rust spot lesions (source Andersen, 2003).

All bycatch species (including blue swimmer crabs, fish, and other crabs) were also recorded. Blue swimmer crabs were opportunistically weighed, measured, and checked for abnormalities before release. All catch was released alive at the site of capture. Used baits were kept on board the vessel for later disposal on land, and not discarded at the sampling site, to reduce interference with commercial and recreational mud crabbers in the area.

Eurimbula Creek (Figure 1) was surveyed in 2018/19 as a reference site and to refine benchmarks. Details are provided by Flint *et al.* (2019).

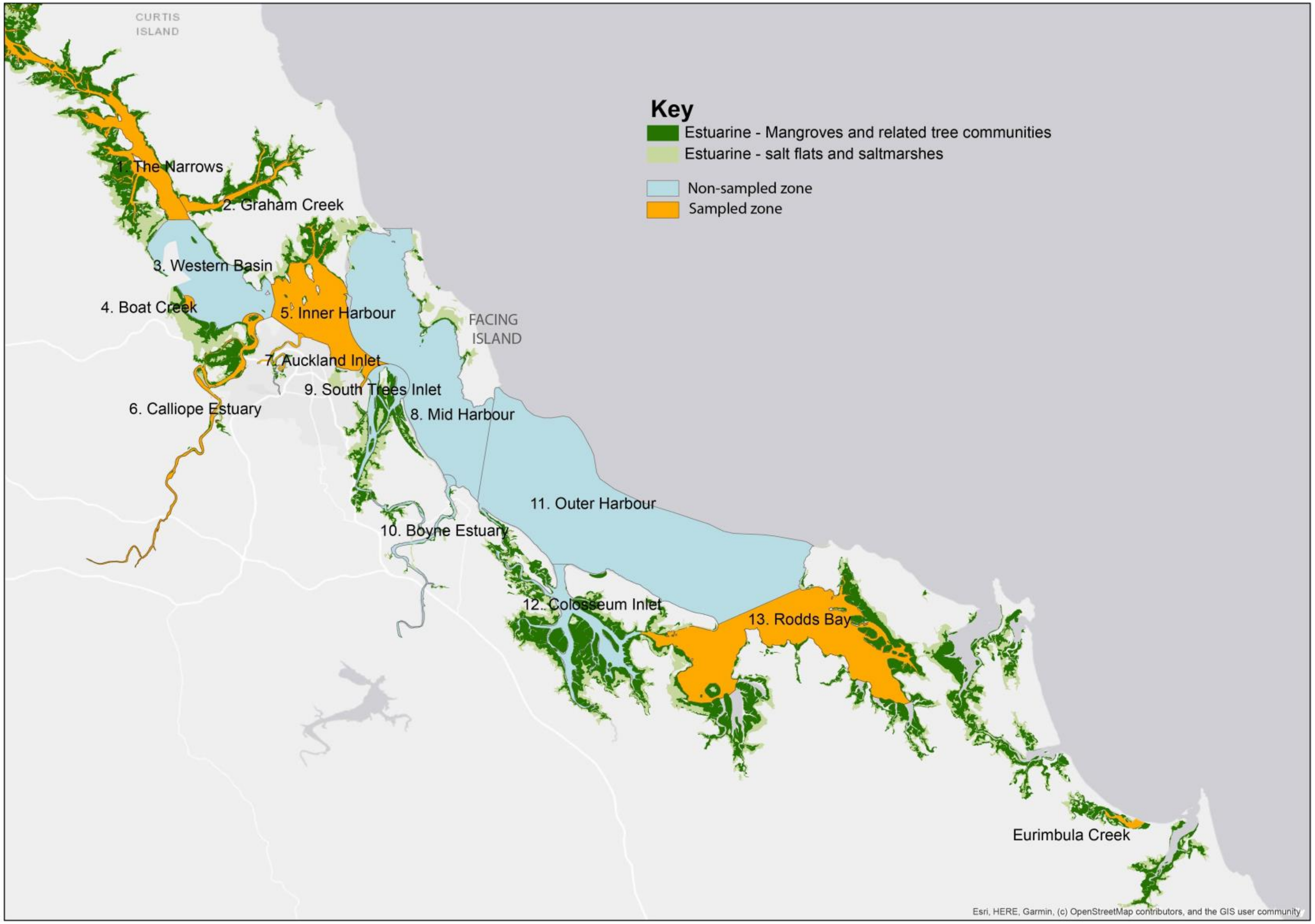

Figure 1: Map of the Gladstone Harbour zones showing long-term monitoring sites surveyed in 2017, 2018, 2019, 2020 and 2021. The map also shows the location of Eurimbula Creek, which was sampled in 2018 and 2019 as a reference site for measures including sex ratios.

Data analysis

Data from the two field surveys (February and June 2021) were analysed separately and then together. Exploratory analyses included descriptive statistics, for example distribution plots (kernel density), and box plots for visual comparisons of differences and variance around the mean. All analyses were conducted in R version 4.0.2 (https://www.r-project.org/).

Scoring, grading and aggregation

The mud crab measures were calculated for each Zone, as follows:

- **Abundance** (CPUE)

$$= \frac{\text{(total number of mud crabs caught)}}{\text{(number of pots set)}}$$

- **Prevalence of rust lesions**

$$= \frac{\text{(number of crabs with rust lesions)}}{\text{(number of crabs assessed for rust lesions)}}$$

- **Sex ratio** based on oversize mud crabs

$$= \frac{\text{(number of male mud crabs > 150 mm)}}{\text{(number of female mud crabs > 150 mm)}}$$

The formulae provided in Table 2 were used to score the mud crab measures, comparing each index value against a pilot benchmark and a worst case scenario (WCS) value. Using this method, index values worse than the WCS score a 0, while index values better than the benchmark score a 1 and all other index values range between these bounds. The method for determining benchmark and WCS values for each measure is described by Flint *et al.* (2017, 2018, 2019, 2020). The Gladstone Harbour Report Card grading system is provided in Table 3.

Sex ratio of legal-sized crabs (> 150 mm carapace spine width, which is equivalent to a crab with 143 mm notch width) is calculated against a 'minimally disturbed' benchmark from the international literature. In 2017, a conservative ratio of 3:1 (*sec.* Alberts-Hubatsch *et al*., 2016) was used as the benchmark for sex ratio (Flint *et al.*, 2017). In 2018, an unpublished thesis describing sex ratios in unfished Australian estuaries was made available (Butcher, 2004). The sex ratio in the thesis, 2 males:1 female, was equivalent to results in a separate study from an uncrabbed area in Moreton Bay (Pillans *et al*., 2005). As a result of this information, the benchmark for sex ratio was updated to 2:1 for 2018. In 2019, the full set of data became available for an unfished region in Central Queensland (Eurimbula Creek, which is located approximately 20 km south of Rodds Bay) and confirmed the benchmark of 2:1.

The benchmark for the abundance measure is updated annually. In 2017, the 75th percentile of the 2017 scores was used as the benchmark. In 2018, a moving average of the 75th percentile of this year (2018) and previous years (2017) scores was applied. Each year, a similar approach is used, taking the moving average of the 75th percentiles for all years (now 2017 to 2021). It is recommended that this approach continues in 2021 and beyond, using the 10-year moving average methodology. Notably, the CPUE in 2017 (3.5) was much higher than in every subsequent year.

Table 2: Benchmarks and scoring method for each of the three recommended measures. NC = not calculable. LTMP – long term monitoring program.

Measure	Benchmark	Worst case scenario	Method of calculation
Abundance (CPUE)	2017: 3.5 (75th %ile of 2017 scores) 2018: 2.5 (moving average of 75th %ile of 2017 and 2018 scores) 2019: 2.12 (moving average of 75th %ile of 2017, 2018 and 2019 scores) 2020: 1.95 (moving average of 75th %ile of 2017, 2018, 2019, 2020) **2021: 1.8** (moving average of 75th %ile of 2017, 2018, 2019, 2020) 2022+: Moving average of 75th %ile of scores for current and previous years, up to 10 years	**0.25**	The function used to calculate scores for abundance is: 1-((x-B)/(WCS-B)) Where: x = recorded CPUE B = benchmark (1.8) WCS = worst case scenario (0.25)
Prevalence of rust lesions	**0.04**	**0.35**	The function used to calculate scores for prevalence is: 1-((x-B)/(WCS-B)) Where: x = recorded prevalence B = benchmark (0.04) WCS = worst case scenario (0.35)
Sex ratio	2017: 3 **2018+: 2**	**0.25**	The function used to calculate scores for sex ratio is: 1-((x-B)/(WCS-B)) Where: x = recorded sex ratio B = benchmark (2) WCS = worst case scenario (0.25)

Table 3: Gladstone Harbour Report Card grading scale (Source: GHHP, 2015).

Score	Grade
>=0.85	A
>=0.65, <0.85	B
>=0.5, <0.65	C
>=0.25, <0.5	D
0, <0.25	E

Results

Abundance and size

A total of 139 mud crabs were caught in the seven Gladstone Harbour zones in February 2021. Of these, 41 were males and 98 were females. A total of 193 mud crabs were caught across all Gladstone Harbour zones sampled in June 2021 including 76 males and 117 females. Low catches of mud crabs were recorded in February 2021 at Calliope Estuary (n = 5), Auckland Inlet (n = 2) and Rodds Bay (n = 2). No mud crabs were caught at Auckland Inlet in June 2021 (n = 0).

The average size of mud crabs caught in February 2021 was 145.9 mm carapace notch width (Table 4) and in June 2020 was 152.1 mm (Table 5). A series of two-sample t-tests was conducted to compare this year's size data with corresponding data from the previous year (2020) and from the baseline (established from historical data for the 2001-09 period; Flint *et al.* 2017). The hypothesis being tested each time was whether this year's sample distribution (mean and variance) was equal to the distribution from the previous year and from the baseline. The full February 2021 sample including both males and females was on average not significantly different from that in 2020 ($p = 0.7232$) or from the baseline ($p = 0.8277$). However, males were significantly larger than in 2020 ($p = 0.0246$). Females were significantly smaller than in 2020 ($p < 0.005$), but they were not significantly smaller than the baseline ($p = 0.2188$) (Table 4). Mud crabs caught in June 2021 were significantly larger than last year ($p < 0.001$) and the baseline ($p = 0.0117$) (Table 5). Individuals from both sexes in June 2021 were significantly larger than last year (2020) and from the baseline ($p < 0.001$ in all cases).

Similar to previous years, the results of the two-sample t-tests found that females caught in February 2021 were significantly larger than males ($t = -3.53$, $df = 72.50$, $p < 0.001$; Figure 2). Females caught in June 2021 were also significantly larger than males ($t = -8.62$, $df = 149.27$, $p < 0.001$; Figure 3).

The largest average mud crab size in February 2021 was recorded from Rodds Bay (mean notch width of 160.5 mm) and the smallest from Calliope Estuary (138.2 mm notch width) (Figure 4), while the largest average mud crab size in June 2021 sampling was recorded from Rodds Bay (mean notch width of 161.7 mm) and the smallest at Inner Harbour (144.5 mm) (Figure 5).

Table 4: Notch width (in mm) of mud crabs caught in February 2021, in comparison to March 2020 and historical data collected between 2001-2009 by Fisheries Queensland (significance level p < 0.05)

	FULL SAMPLE			MALES			FEMALES		
	February 2021	March 2020	Historical data (2001-2009)	February 2021	March 2020	Historical data (2001-2009)	February 2021	March 2020	Historical data (2001-2009)
Mean	145.94	146.44	145.45	138.49	132.54	135.12	149.06	153.61	151.67
Standard deviation	16.53	17.13	20.74	16.30	14.98	18.65	15.68	13.38	19.43
2021-20 t-test	2021 > 2020?	2020 > 2019?	2021 > baseline?	2021 > 2020?	2020 < 2019?	2021 > baseline?	2021 < 2020?	2020 > 2019?	2021 < baseline?
t value	-0.3549	-0.0612	0.2178	2.3364	-2.7419	1.6041	-2.8737	0.47848	1.2324
p value	0.7232	0.9513	0.8277	0.02457	0.008615	0.1098	0.004984	0.6334	0.2188
Signif?	NO	NO	NO	YES	YES	NO	YES	NO	NO

Table 5: Notch width (in mm) of mud crabs caught in June 2021, in comparison to June 2020 and historical data collected between 2001-2009 by Fisheries Queensland (significance level p < 0.05)

	FULL SAMPLE			MALES			FEMALES		
	June 2021	June 2020	Historical data (2001-2009)	June 2021	June 2020	Historical data (2001-2009)	June 2021	June 2020	Historical data (2001-2009)
Mean	152.05	141.57	145.45	142.50	136.88	135.12	158.26	153.08	151.67
Standard deviation	14.38	16.48	20.74	12.86	12.04	18.65	11.69	20.06	19.43
2021-20 t-test	2021 > 2020	2020 < 2019	2021 > baseline	2021 > 2020	2020 < 2019	2021 > baseline	2021 > 2020	2020 < 2019	2021 > baseline
t value	10.125	-8.0332	2.53	3.81	-2.4424	4.526	4.7949	-1.8754	4.037
p value	2.2e-16	0.0000	0.0117	0.0003	0.0164	0.0000	4.874e-06	0.06824	0.0001
Signif?	YES	YES	YES	YES	YES	YES	YES	YES	YES

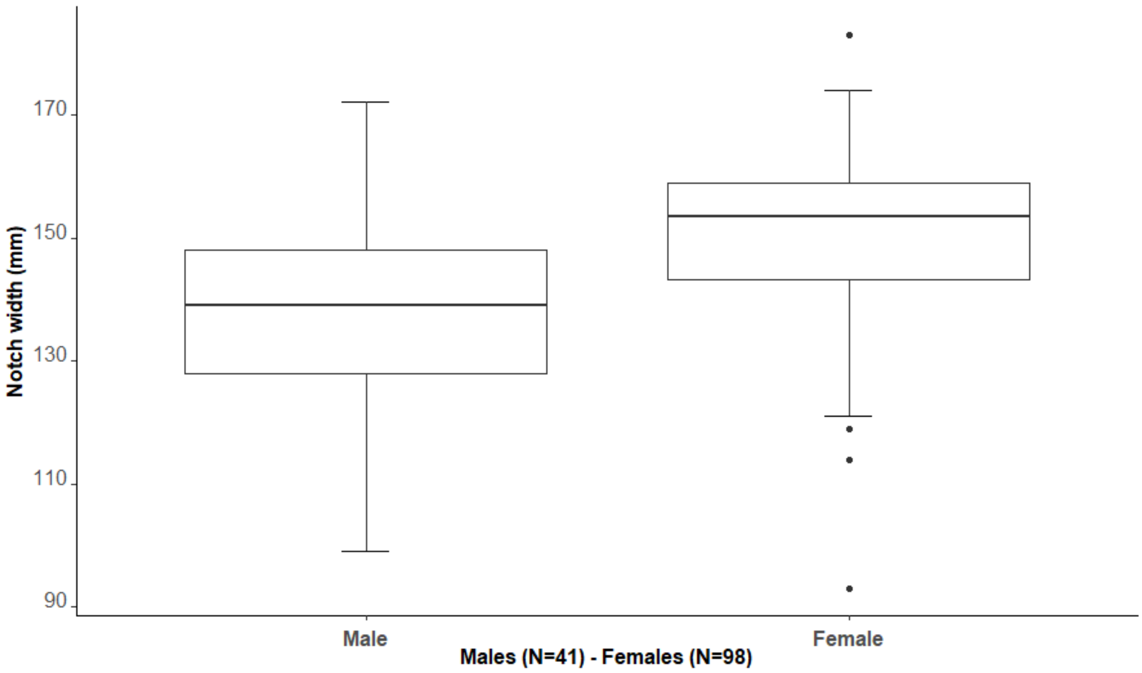

Figure 2: Notch width (mm) distribution of male and female mud crabs caught in February 2021. The box represents the middle 50% of ordered observations. Centre line is the median, the lower and upper edges correspond to the 25th and 75th percentiles. Whiskers extend from the box to the smallest and largest values no greater than 1.5 times the inter-quartile range. Data beyond the end of the whiskers are flagged as outliers and plotted individually as circles.

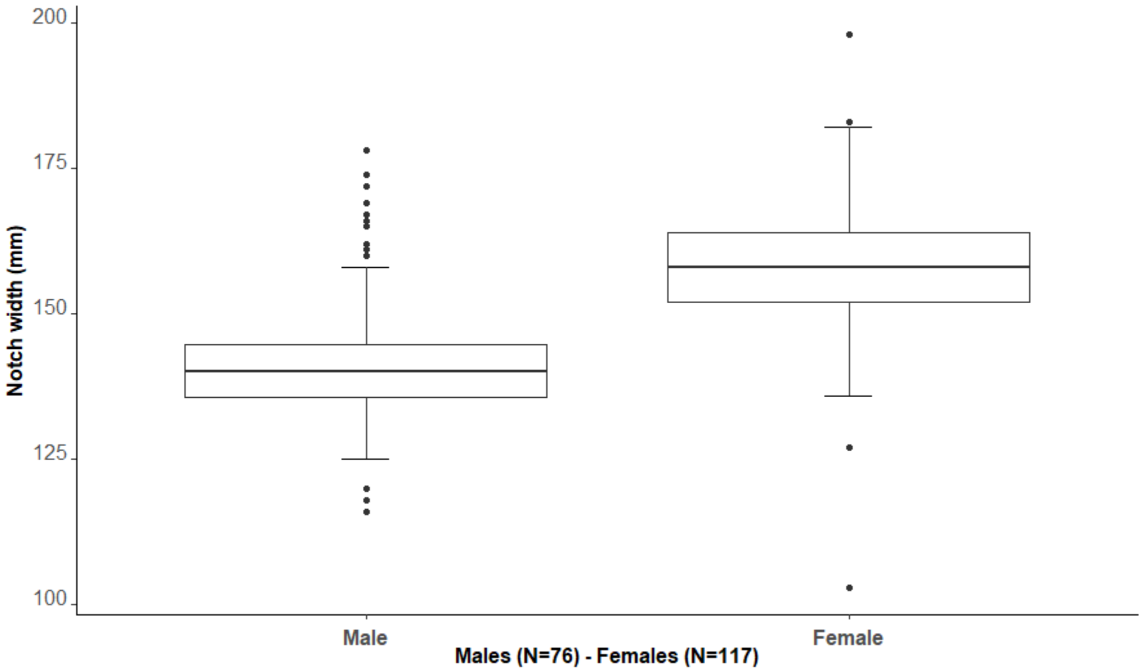

Figure 3: Notch width (mm) distribution of male and female mud crabs caught in June 2021.

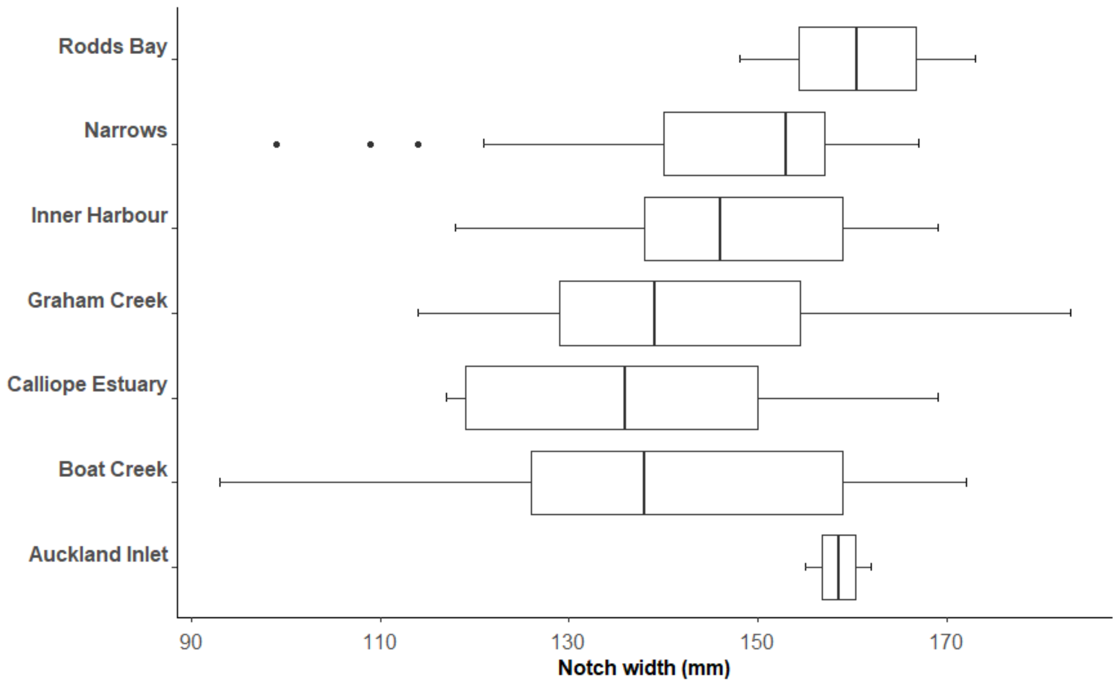

Figure 4: Notch width (mm) of mud crabs caught in February 2021, by zone.

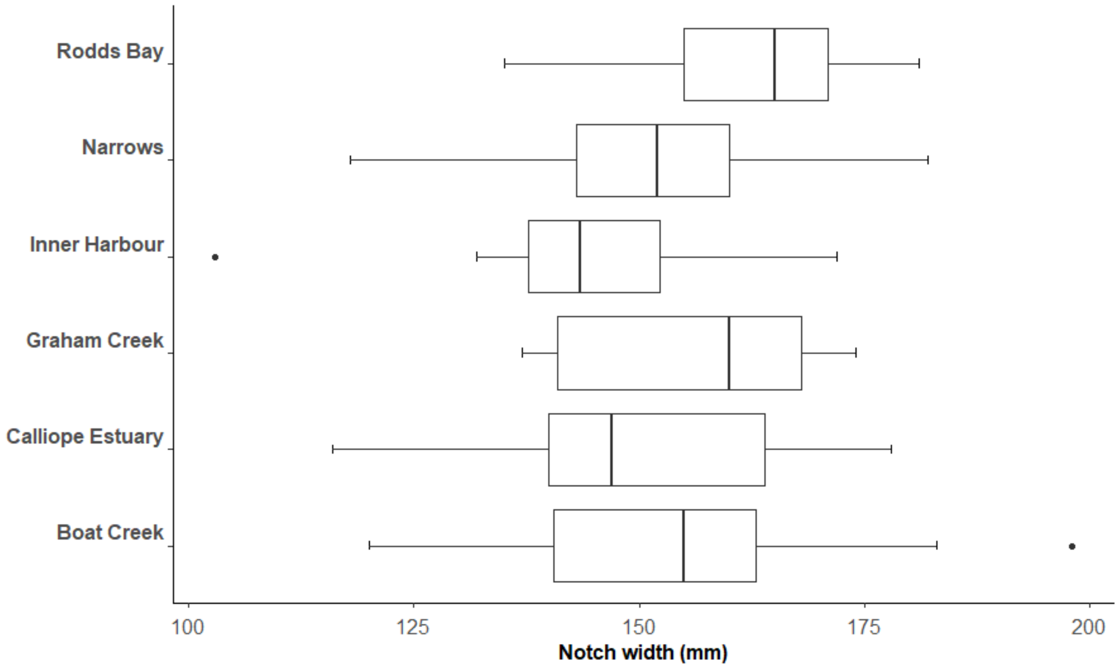

Figure 5: Notch width (mm) of mud crabs caught in June 2021, by zone. No crabs were caught at Auckland Inlet in June 2021 (n = 0).

In February 2021, for the fifth consecutive year, total CPUE was again highest at the Narrows (3.70) and lowest at Auckland Inlet (0.1) and Rodds Bay (0.01) (Table 6, Figure 6). In June 2021, CPUE was also highest at the Narrows (4.15), followed by Boat Creek (2.44) and, as in previous sampling years, again lowest at Auckland Inlet, where no mud crabs were caught (0) (Table 7, Figure 7).

Table 6: Catch per unit effort in February 2021, by zone.

ZONE	ZONE NAME	# POTS	# MUD CRABS CAUGHT	CPUE
1	Narrows	20	74	3.70
2	Graham Creek	20	18	0.90
4	Boat Creek	20	13	0.65
5	Inner Harbour	20	25	1.25
6	Calliope Estuary	20	5	0.25
7	Auckland Inlet	20	2	0.10
13	Rodds Bay	20	2	0.10

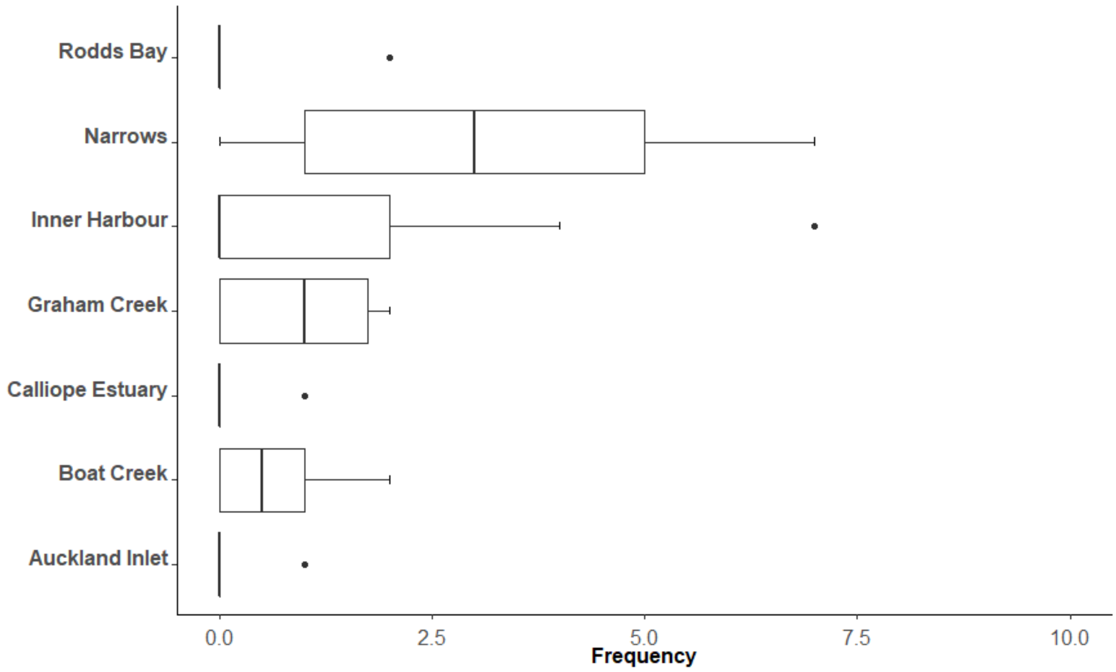

Figure 6: Number of mud crabs in each pot set in February 2021, by zone.

Table 7: Catch per unit effort in June 2021, by zone.

ZONE	ZONE NAME	# POTS	# MUD CRABS CAUGHT	CPUE
1	Narrows	20	83	4.1500
2	Graham Creek	20	9	0.4500
4	Boat Creek	16	39	2.4375
5	Inner Harbour	20	24	1.2000
6	Calliope Estuary	20	21	1.0500
7	Auckland Inlet	20	0	0.0000
13	Rodds Bay	19*	17	0.8947

* One pot went missing from Rodds Bay, so only 19 were retrieved.

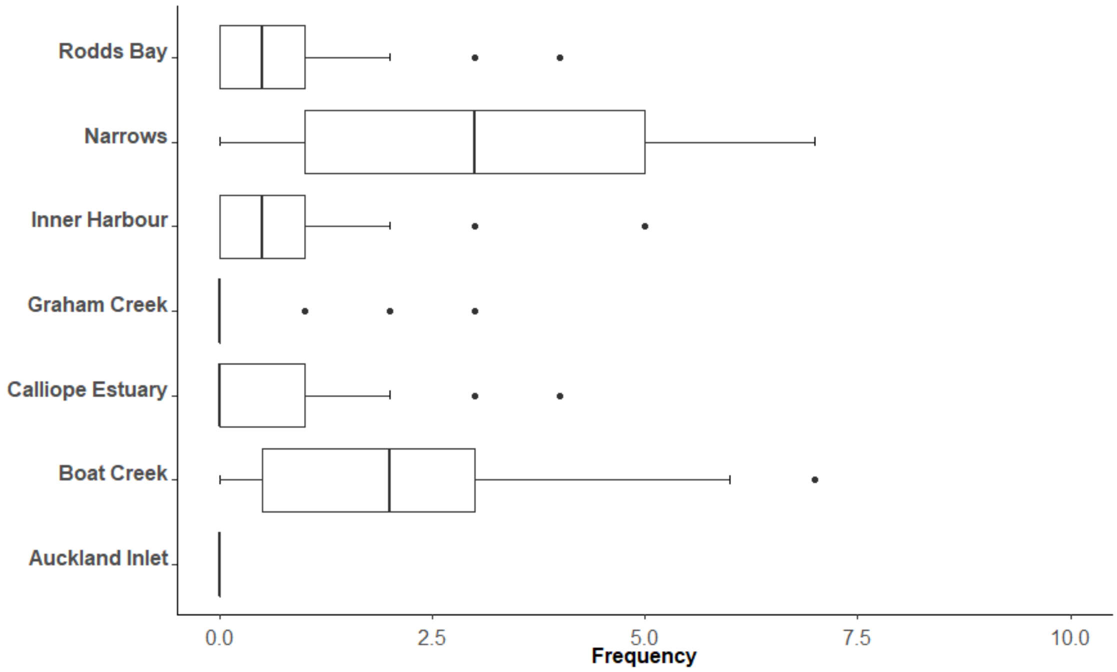

Figure 7: Number of mud crabs in each pot set in June 2021, by zone. No mud crabs were caught at Auckland Inlet in this sampling event.

Sex ratio

In February and June 2021, more oversized female crabs were caught than oversized male crabs in Gladstone Harbour. Sex ratios were therefore low across the harbour in both February and June (Table 8). A total of 229 mud crabs over the legal size limit of 150 mm carapace width (equivalent to 143 mm notch width) were caught in 2021, of which 43 were male.

Table 8: Sex ratios of mud crabs with notch width > 143 mm, in February and June 2021, by zone.

ZONE	ZONE NAME	FEBRUARY 2021 DATA			JUNE 2021 DATA		
		Males	Females	Sex ratio	Males	Females	Sex ratio
1	Narrows	5	48	**0.1042**	4	59	**0.0678**
2	Grahams Creek	2	7	**0.2857**	0	6	**0.0000**
4	Boat Creek	4	2	**2.0000**	4	24	**0.1667**
5	Inner Harbour	2	13	**0.1538**	6	8	**0.7500**
6	Calliope Estuary	0	2	**0.0000**	5	8	**0.6250**
7	Auckland Inlet	1	1	**1.0000**	/	/	**/**
13	Rodds Bay	1	1	**1.0000**	9	7	**1.2857**

Rust lesions

Of the 139 mud crabs captured in February 2021, 19 (13.7%) had rust lesions. During this sampling event, crabs with lesions were caught at all zones except Calliope Estuary (Table 9). In June 2021, fewer crabs with rust lesions were encountered (8 out of 193 mud crabs caught, i.e. 4.1%). Rust lesions were again encountered at all zones except Calliope Estuary (Table 9).

Table 9: Number and percentage of mud crabs with rust spot lesions caught in February and June 2021, by zone. / = no data as no mud crabs were caught.

ZONE	ZONE NAME	FEBRUARY 2021 DATA		JUNE 2021 DATA	
		# with lesions	% with lesions	# with lesions	% with lesions
1	Narrows	9	12.16	1	1.20
2	Graham Creek	1	5.56	1	11.1
4	Boat Creek	1	7.69	2	5.13
5	Inner Harbour	7	28.00	3	12.50
6	Calliope Estuary	0	0.00	0	0.00
7	Auckland Inlet	1	50.00	/	/
13	Rodds Bay	0	0.00	1	5.88

Mud crab measure results by zone

The mud crab data set used to score each selected zone for the 2021 Gladstone Harbour Report Card included combined data from February and June 2021. Results for each measure are provided by zone in Table 10.

Table 10: Calculated index values for 2021, for each of the three measures in each of the seven long-term monitoring sites. NC = not calculable (Auckland Inlet, n < 5 crabs caught in 2021).

Zone	Zone name	Abundance (CPUE)	Prevalence of rust lesions	Sex ratio
1	Narrows	3.93	0.06	0.08
2	Graham Creek	0.68	0.07	0.15
4	Boat Creek	1.54	0.06	0.31
5	Inner Harbour	1.23	0.20	0.38
6	Calliope Estuary	0.65	0.00	0.50
7	Auckland Inlet	0.05	NC	NC
13	Rodds Bay	0.50	0.05	1.25

Indicator scores and grades

Scores and grades for the mud crab measures for the 2021 Report Card are provided in Table 11. Scores > 1 and < 0 were bounded by 0 and 1 in line with GHHP standard methods (GHHP, 2015). An overall score for the Mud Crab Indicator of 0.48 (D) has been calculated as the average of the three "Harbour Average" measure scores (following advice from the GHHP ISP in 2020), and an overall grade is provided for each zone. Only two mud crabs were caught in Zone 7 – Auckland Inlet. Given the very small sample size (n < 5 mud crabs from 40 pots), there was insufficient data to calculate scores and grades for the prevalence of rust lesions or sex ratio measures in this zone.

Table 11: Scores and grades for mud crab measures and the mud crab indicator by Zone. NC = Not calculable, n < 5.

Zone	**Abundance (CPUE)**	**Prevalence of rust lesions**	**Sex ratio**	**Zone score 2021**
1. The Narrows	1.00	0.92	0.00	0.64
2. Graham Creek	0.27	0.89	0.00	0.39
4. Boat Creek	0.83	0.94	0.03	0.60
5. Inner Harbour	0.63	0.47	0.07	0.39
6. Calliope Estuary	0.26	1.00	0.14	0.47
7. Auckland Inlet	0.00	NC	NC	NC
13. Rodds Bay	0.16	0.96	0.57	0.56
Harbour Average	0.45	0.86	0.14	0.48

Discussion

The Harbour Average was graded a D. The Harbour Average score is higher than in 2020, but the grade remains the same.

The overall grades for the Mud Crab Indicator for each zone are as follows:

- A: No zones.
- B: No zones.
- C: Zone 1 – Narrows, Zone 4 – Boat Creek, Zone 13 – Rodds Bay.
- D: Zone 2 – Graham Creek, Zone 5 – Inner Harbour, Zone 6 – Calliope Estuary.
- E: No zones.
- Not Calculable (n < 5 mud crabs caught): Zone 7 – Auckland Inlet.

For comparison, the full set of scores and grades from 2017, 2018, 2019, 2020 and 2021 are provided in Appendix 1. Data collection and scoring methods used in 2021 are identical to those used in 2020. In 2020, the GHHP ISP recommended changing the way the Harbour Average score and grade is determined, by averaging the scores for each measure across all zones first, then calculating the Harbour score as the average of those three average measure scores. Previously, the overall indicator score for each zone was calculated first and the Harbour score was taken as the average of the zone scores. This change was made as an alternative mechanism to allow for the inclusion of relevant and sufficient data on abundance in Auckland Inlet, in the overall Harbour score/grade. Hence, the harbour average scores and grades from 2020 and 2021 are directly comparable, and those from 2019 and earlier were calculated using a different averaging order.

Scores and grades have improved slightly in 2021, in comparison to 2020 and 2019. Zone 1 – the Narrows, again scored a C in 2021 (similar to 2020 and 2019), but the score (0.64) was higher than

2020. The grade for Zone 2 – Graham Creek is the same as in 2020, 2019 and 2018 (D) but again there was an improvement in score since 2020. The grade for Zone 4 – Boat Creek decreased to a C in 2021, compared to a B in 2020. The score and grade (D) for Zone 5 – Inner Harbour, was identical in 2020 and 2021. The grade for Zone 6 – Calliope Estuary has increased from an E in 2020 to a D in 2021. Zone 13 – Rodds Bay has increased to a C, following four consecutive years at D.

As in 2018, 2019 and 2020, an overall score for Zone 7 – Auckland Inlet was again incalculable in 2021 due to very low catches (n = 2). In situations where less than five mud crabs are caught in a zone, abundance can be scored but the sample size is insufficient to give a reliable indication of the prevalence of rust lesions or sex ratio.

In 2021, mud crab catches increased overall, and in most zones, in comparison to 2020 but remain low in comparison to 2017. The catch of mud crabs in baited pots can vary in response to a range of natural and anthropogenic factors, including weather variations such as rainfall and temperature. The use of a 10-year moving average benchmark will eventually help to allow for any natural variations in catch, but still allow any long-term declining trends (e.g., linked to extraction rates or recruitment limitation) to be identified. Mud crab populations rely on the presence of suitable habitat and on sufficient recruitment from adult populations. As recruitment of juvenile mud crabs in Gladstone Harbour is not monitored, the relationship between recruitment and adult abundance is not yet well understood. It is also possible that the times of year that adult crabs are active is gradually changing. Notably, the reference, unfished and good habitat quality site at Eurimbula Creek was graded A for abundance in 2018/19 and that the Narrows, which is classified as high ecological value, is consistently graded A for mud crab abundance.

The potential for weather and climate factors to influence mud crab catches in Gladstone Harbour is the topic of a new CQUniversity internship which will be undertaken by a current PhD student. The project will model catches in relation to a range of potentially influential variables, using data from GHHP monitoring, Fisheries Queensland's previous long term monitoring program (LTMP, 2000-2009) and possibly commercial catch data.

The prevalence of rust lesions measure also scored better in 2021 than in 2020, returning to an A grade in most zones, except Inner Harbour which was graded D. This measure is based on a moderately-high confidence benchmark and WCS developed using research data published by Andersen and Norton (2001) and Dennis *et al.* (2016), and data collected in June 2017. The cause of rust shell lesions is likely to be related to inhibition of calcium update following exposure to some metals in the environment, possibly copper and zinc, although this has not been experimentally confirmed (Andersen *et al.*, 2000; Andersen and Norton, 2001). However, the exact reasons for changes in prevalence of rust shell lesions in Gladstone (and elsewhere) has never been definitively explained. This represents a knowledge gap that should ideally be addressed.

As also noted by invited experts during a GHHP workshop to discuss the mud crab indicator (8 March 2021), it is important to continue to monitor rust shell lesions in Gladstone, given the high prevalence that has been reported from the region at various times. Monitoring during non-event periods provides valuable baseline data and provides assurance to the report card's audience (managers and the community) that rust shell lesions are usually at low prevalence in the harbour. In the future, as more data are collected, the measure could potentially be revised to incorporate lesion severity based on lesion size and whether the shell has been perforated (sensu Andersen and Norton, 2001).

In areas such as Queensland, where a sex-based fishery is enforced, differences between the sex ratio (the ratio of legal-sized males to females of the same size) that cannot be explained by biological factors, are most likely to be related to fishing pressure. The sex ratio measure scored an E in every zone except Rodds Bay (D) in 2021 a similar result to 2020 (E in all but Boat Creek), 2019 (E in all zones) and 2018 (E in all but Boat Creek). As noted in previous years, the pattern also suggests that fishers are observing regulations regarding the release of female mud crabs. Shifts in sex ratio caused by high fishing pressure have implications for population dynamics and may also influence ecosystem processes through sex-biased behaviours such as burrow digging. Research is underway by a PhD student at CQUniversity to determine whether smaller males are as successful at mating as larger males.

A second PhD scholarship has also been advertised, to investigate habitat use and movements of male and female mud crabs. The Fisheries Research and Development Corporation (FRDC) has funded Fisheries Queensland, CQUniversity and NSW Fisheries to gather new biological data on Queensland mud crabs, to support the new management arrangements for the fishery. One of the targeted regions is Gladstone Harbour, and results will potentially be relevant to GHHP.

As new management changes are coming into effect in the Queensland Mud Crab Fishery (for up-to-date information, refer to Queensland Government websites, including https://www.daf.qld.gov.au/business-priorities/fisheries/commercial/commercial-fishing-rules), commercial fisheries data may be more detailed, providing a potential source of additional data. The issue with this data source is that it is biased towards retained catch (i.e., large males) so it does not provide information on the whole mud crab population. Nevertheless, as the GHHP ISP pointed out in the workshop, commercial fishers set far more pots each year than is achievable for an independent monitoring program, and these data could provide a valuable addition or cross reference. CQUniversity is currently discussing the potential use of commercial catch data with GHHP.

An important criterion when selecting measures to include in the GHHP mud crab indicator when it was developed in 2017, was the monitoring cost and complexity. Technically-complex indicators, indicators that are very costly to monitor, or those requiring substantial additional research to allow them to be incorporated into the report card, were not considered practical. The GHHP mud crab indicator developed in 2017 is relatively simple to monitor in comparison to some other potential biological indicators that require laboratory analysis, and importantly, it also has minimal impacts on the target species, local ecosystem or stakeholders, as sampling is non-lethal and uses a low-impact fishing method. As described in the CQUniversity reports to GHHP since 2017 (Flint *et al.*, 2017, 2018, 2019, 2020), there are some ongoing considerations relating to the continuous improvement of the GHHP mud crab indicator as new information becomes available.

In addition to abundance, rust lesions and sex ratio, two other potential indicators were identified by Flint *et al.* (2017) as potentially useful. Both would require additional research and/or monitoring costs. These two indicators were bioaccumulation of metal(loid)s and recruitment to nursery grounds of juvenile crabs. Of these, bioaccumulation is likely to be of higher interest and could be incorporated into the existing adult mud crab monitoring program. It potentially requires lethal sampling of mud crabs to measure toxicant concentrations in tissues (depending on which tissues are analysed), with additional costs for dissection and analysis. Bioaccumulation of toxicants can be a particularly relevant indicator for urban and industrialised areas such as ports and is measured using established methods.

Several historical studies have used mud crabs as bioindicators of contaminants including persistent organic pollutants (POPs) and metals (Mortimer, 2000), and pesticides (Negri *et al.*, 2009). In Gladstone, elevated metal (As, Cr, Cu, Fe, Hg, Mn, Ni, U, Zn) concentrations have previously been reported from the hepatopancreas mud crabs collected at two sites at Spillway Creek, in comparison to two additional sites in the same creek, and to sites in Wild Cattle Creek (Gladstone Harbour), Baffle Creek (south of Rodds Bay) and Ayr (North Queensland) (Andersen *et al.*, 2001). A subsequent study identified measurable concentrations of Fe and Se only, from ten metals tested in hepatopancreas tissues (Andersen *et al.*, 2003), with both recorded at concentrations below food safety guidelines.

Recommendations

The mud crab indicator has been successfully monitored in Gladstone Harbour since 2017, with some revisions to the scoring and grading methods made over time as more information became available. On 8 March 2021, the GHHP ISP organised a workshop on the mud crab indicator, inviting mud crab experts from around Australia.

On the basis of five years of monitoring and the discussions at the workshop, the following recommendations are provided for 2022 onwards:

- Continue to monitor the mud crab indicator, using the established monitoring methods, twice a year at the seven long term monitoring sites. Invited experts at the GHHP mud crab indicator workshop agreed seasonal sampling should continue at a minimum.
- With five years of data now available from Gladstone Harbour, additional statistical analyses could be undertaken, investigating not only patterns in the indicator measures as described above, but in other variables that are monitored (e.g., the sex ratio of smaller mud crabs and variability in catch in relation to weather variables).
- GHHP may wish to consider increasing the number of zones sampled to include other estuaries in Gladstone Harbour (e.g., South Trees Inlet and Boyne Estuary). This would expand the dataset and increase the relevance of the indicator to additional portside industries.
- It would be beneficial to sample again at Eurimbula Creek, to test whether similar declining catch trends are identified at this reference site.
- Bioaccumulation of relevant metal(loid)s in Gladstone Harbour could be considered as a possible additional measure for future monitoring.
- Research to determine the root-cause of rust lesions is recommended.

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Appendix 1 Scores and grades from 2017 – 2021

Scores and grades for mud crab measures and the mud crab indicator by GHHP Zone for 2017.

Zone	Abundance (CPUE)	Prevalence of rust lesions	Sex ratio*	Zone score (grade) 2017
1. The Narrows	1.00 (A)	1.00 (A)	0.00 (E)	0.67 (B)
2. Graham Creek	0.52 (C)	0.95 (A)	0.36 (D)	0.61 (C)
4. Boat Creek	1.00 (A)	1.00 (A)	0.11 (E)	0.70 (B)
5. Inner Harbour	1.00 (A)	0.89 (A)	0.71 (B)	0.87 (A)
6. Calliope Estuary	0.14 (E)	0.90 (A)	0.36 (D)	0.47 (D)
7. Auckland Inlet	0.12 (E)	0.63 (C)	0.00 (E)	0.25 (D)
13. Rodds Bay	0.03 (E)	0.67 (B)	0.39 (D)	0.36 (D)
Harbour Average				0.56 (C)

Scores and grades for mud crab measures and the mud crab indicator by Zone for 2018.

Zone	Abundance (CPUE)	Prevalence of rust lesions	Sex ratio*	Zone score (grade) 2018
1. The Narrows	1 (A)	1 (A)	0 (E)	0.67 (B)
2. Graham Creek	0.3 (D)	1 (A)	0.03 (E)	0.44 (D)
4. Boat Creek	0.25 (D)	1 (A)	0.29 (D)	0.51 (C)
5. Inner Harbour	0.52 (C)	1 (A)	0.02 (E)	0.52 (C)
6. Calliope Estuary	0.47 (D)	1 (A)	0.11 (E)	0.52 (C)
7. Auckland Inlet	0 (E)	NC	NC	NC
13. Rodds Bay	0.2 (E)	0.90 (A)	0.06 (E)	0.39 (D)
Harbour Average				0.51 (C)

Scores and grades for mud crab measures and the mud crab indicator by GHHP Zone for 2019.

Zone	Abundance (CPUE)	Prevalence of rust lesions	Sex ratio*	Zone score (grade) 2019
1. The Narrows	1 (A)	0.90 (A)	0 (E)	0.63 (C)
2. Graham Creek	0.12 (E)	1 (A)	0.24 (E)	0.45 (D)
4. Boat Creek	0.46 (D)	0.94 (A)	0.05 (E)	0.49 (D)
5. Inner Harbour	0.67 (B)	0.70 (B)	0.08 (E)	0.48 (D)
6. Calliope Estuary	0.29 (D)	1 (A)	0 (E)	0.43 (D)
7. Auckland Inlet	0 (E)	NC	NC	NC
13. Rodds Bay	0.27 (D)	0.70 (B)	0.12 (E)	0.36 (D)
Harbour Average				0.47 (D)

Scores and grades for mud crab measures and the mud crab indicator by Zone for 2020.

Zone	Abundance (CPUE)	Prevalence of rust lesions	Sex ratio	Zone score 2020
1. The Narrows	1 (A)	0.80 (B)	0 (E)	0.60 (C)
2. Graham Creek	0.18 (E)	0.84 (B)	0(E)	0.34 (D)
4. Boat Creek	1 (A)	0.84 (B)	0.29 (D)	0.71 (B)
5. Inner Harbour	0.19 (E)	0.99 (A)	0(E)	0.39 (D)
6. Calliope Estuary	0.13(E)	0.45 (D)	0(E)	0.19 (E)
7. Auckland Inlet	0(E)	NC	NC	NC
13. Rodds Bay	0.13(E)	0.45 (D)	0.06(E)	0.22 (D)
Harbour Average	0.38 (D)	0.73 (B)	0.06(E)	0.39 (D)

Scores and grades for mud crab measures and the mud crab indicator by Zone for 2021.

Zone	Abundance (CPUE)	Prevalence of rust lesions	Sex ratio	Zone score 2021
1. The Narrows	1	0.92	0	0.64
2. Graham Creek	0.27	0.89	0	0.39
4. Boat Creek	0.83	0.94	0.03	0.60
5. Inner Harbour	0.63	0.47	0.07	0.39
6. Calliope Estuary	0.26	1.0	0.14	0.47
7. Auckland Inlet	0	NC	NC	NC
13. Rodds Bay	0.16	0.96	0.57	0.56
Harbour Average	0.45	0.86	0.14	0.48