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Supplementary Report to the Final Report of the Coral Reef Expert Group:

S8. Monitoring Site Planner – choosing where to monitor coral reefs on the Great Barrier Reef

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Australian Institute of Marine Science

The Great Barrier Reef Marine Park Authority acknowledges the continuing sea country management and custodianship of the Great Barrier Reef by Aboriginal and Torres Strait Islander Traditional Owners whose rich cultures, heritage values, enduring connections and shared efforts protect the Reef for future generations.

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EXECUTIVE SUMMARY

Monitoring of ecosystems is essential for understanding the status of their health, the drivers of change, and measuring the effectiveness of various management actions. Monitoring of ecosystems, particularly marine ecosystems such as coral reefs, requires costly and time-consuming field work, placing a heavy constraint on the number of locations that can be monitored. The sampling density is often orders of magnitude less than is required to fully understand the dynamics of these complex environments.

In this project we develop a multi-criteria analysis and optimisation tool, called the Monitoring Site Planner, to assist in the evaluation of the existing and new proposed coral reef monitoring programs for the Great Barrier Reef (the Reef). This tool allows the performance of a given monitoring survey design (a set of reefs that will be monitored) to be evaluated against a set of performance criteria. This tool can be run as an interactive web application that is available for use from https://tools.eatlas.org.au/msp.

Predicting the future performance of a monitoring program is difficult because the drivers of change for the Reef are predominantly unpredictable acute disturbance events such as cyclones, bleaching and crown-of-thorns starfish outbreaks. The Monitoring Site Planner tool does not try to predict these future pressures, but instead focuses on ensuring the monitoring program captures the diversity of different conditions and places within the Reef.

The Monitoring Site Planner tool assesses a given survey design with the following criteria:

- **Environmental gradients:** These criteria assess whether the monitoring program captures the diversity of environmental conditions that influence coral communities including secchi depth, temperature and current.
- **Fairness tests:** These criteria assess whether the monitoring program has a fair number of monitoring sites in each NRM region and whether there is a fair number of pairs of reefs (one open to fishing / one closed to fishing) in each reef bioregion. These criteria help ensure an even spatial spread over each of the representative areas of the Reef.
- **Historic data:** This criterion determines what percentage of historic data is captured by the specified monitoring locations. This helps ensure that reefs with significant historical data are retained. If an existing monitoring site is moved to a new location then it should be from an existing site with little historic data.

Additional criteria can be added to the tool if necessary.

The currently implemented criteria were chosen to ensure that good survey designs should:

- Provide information about the status and trend of the Reef as a whole, as well as each region within the Reef.
- Include important historically monitored reefs to allow long trends to be tracked.
- Allow the continued evaluation of key management questions, in particular the effectiveness of the Marine Park zoning.

This tool helps choose which reefs should be monitored for any given monitoring program size, allowing the monitoring program to be adjusted to the program's available funds.

In this report we present the results of using this tool to compare the estimated performance of the existing coral reef monitoring on the Reef against a redesign based on expert opinion to improve its spatial coverage, verses a survey design optimised by the Monitoring Site Planner. We show that the expert redesign improved the performance of the monitoring program on all criteria except historic data. Existing historic monitored locations (corresponding to 14 per cent of all historic data) were traded for more spatial cover. The optimised survey design generated by the Monitoring Site Planner optimiser significantly outperformed the manual expert design on all criteria, improving the spatial coverage with far less loss of historic data (10 per cent of all historic data). This shows that the optimisation tools within the Monitoring Site Planner can be used to generate high quality monitoring programs of any size.

The Monitoring Site Planner can be used as a tool to assist key Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) stakeholders and the Coral Reef Expert Group to determine the best trade-offs between different criteria and monitoring program size. The Monitoring Site Planner can be extended to include additional criteria and 'must have' sites as needed. The advantage of using the interactive Monitoring Site Planner for future design refinement is that trade-offs between various criteria can be easily evaluated and visualised

1 BACKGROUND

As part of the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) there is renewed interest in assessing and improving the effectiveness of existing monitoring programs associated with the Great Barrier Reef (the Reef). Under RIMReP, multiple monitoring programs will be integrated and redesigned, with the goal of ensuring that there is sufficient monitoring to assess the effectiveness of the *Reef 20050 Long-Term Sustainability Plan* (Reef 2050 Plan) and to enable improved management of the Reef.

A number of issues have been raised with the existing coral reef monitoring of the Reef including its spatial coverage and temporal sampling. The existing monitoring has significant gaps in its coverage, in particularly in the Cape York region where there are no monitoring locations north of Lizard Island. The Australian Institute of Marine Science (AIMS) Long-Term Monitoring Program (LTMP) provides monitoring of mid-shelf and offshore reefs along the Reef. In 2006 the program was adjusted to monitor pairs of reefs to assess the effectiveness of rezoning. This doubled the number of fixed site reefs being monitored, and so with a relatively fixed budget the sampling was reduced from annual sampling to biennial where approximately half of the sites were monitored each year. This change introduced problems due to the infrequent sampling and low spatial coverage in any given year.

In this project we focus on developing a tool for assessing and improving the spatial coverage of the monitoring program, not analysing how temporal sampling affects the monitoring performance. At this stage we assume that the sampling is regular with all monitoring sites in a survey design being sampled in the same year.

Redesigning the existing coral reef monitoring of the Reef requires a careful trade-off between the costs of adding new monitoring locations against improvement in the spatial coverage. Improvements to the efficiency of the monitoring program (as measured by the amount of information we get verses the number of monitoring locations) can be achieved by moving existing monitoring locations from areas where there are redundant multiple sites in close proximity, to areas where there is little sampling. This, however, results in a trade-off between retaining locations with historical data for improved future monitoring efficiency. There is also a trade-off between pairing monitored reefs for evaluating the rezoning of the Great Barrier Reef Marine Park (the Marine Park), where the pairs should be similar close reefs, and spatial coverage where the monitored reefs should be spread apart from each other.

There is a complex interplay between these trade-offs and so a multiple-criteria tool was developed to make this process more objective, easy and transparent.

1.1 A multi-criteria analysis and optimisation tool for assessing coral reef monitoring of the Great Barrier Reef

In this project we develop a multi-criteria analysis and optimisation tool, called the Monitoring Site Planner, to assist in the evaluation of the existing and newly proposed coral reef monitoring programs for the Reef. This tool allows the performance of a proposed monitoring survey design (a set of reefs that will be monitored) to be evaluated against a range of criteria.

The Monitoring Site Planner tool can be run in two modes: as an interactive web application and on a headless cloud server (no user interface) for executing large optimisation runs.

As a web application it allows users to explore, evaluate and visualise changes to survey designs as well as run the optimisation features. The Monitoring Site Planner can be run from https://tools.eatlas.org.au/msp

When the tool is run as a server application it can be scripted to run batches of optimisations, without the overhead of running in a web browser. This allows optimisations to be run in parallel in the cloud, speeding up the time to produce optimised survey designs for a given set of criteria and weights. All the optimised survey results shown in this report were run on a cloud server.

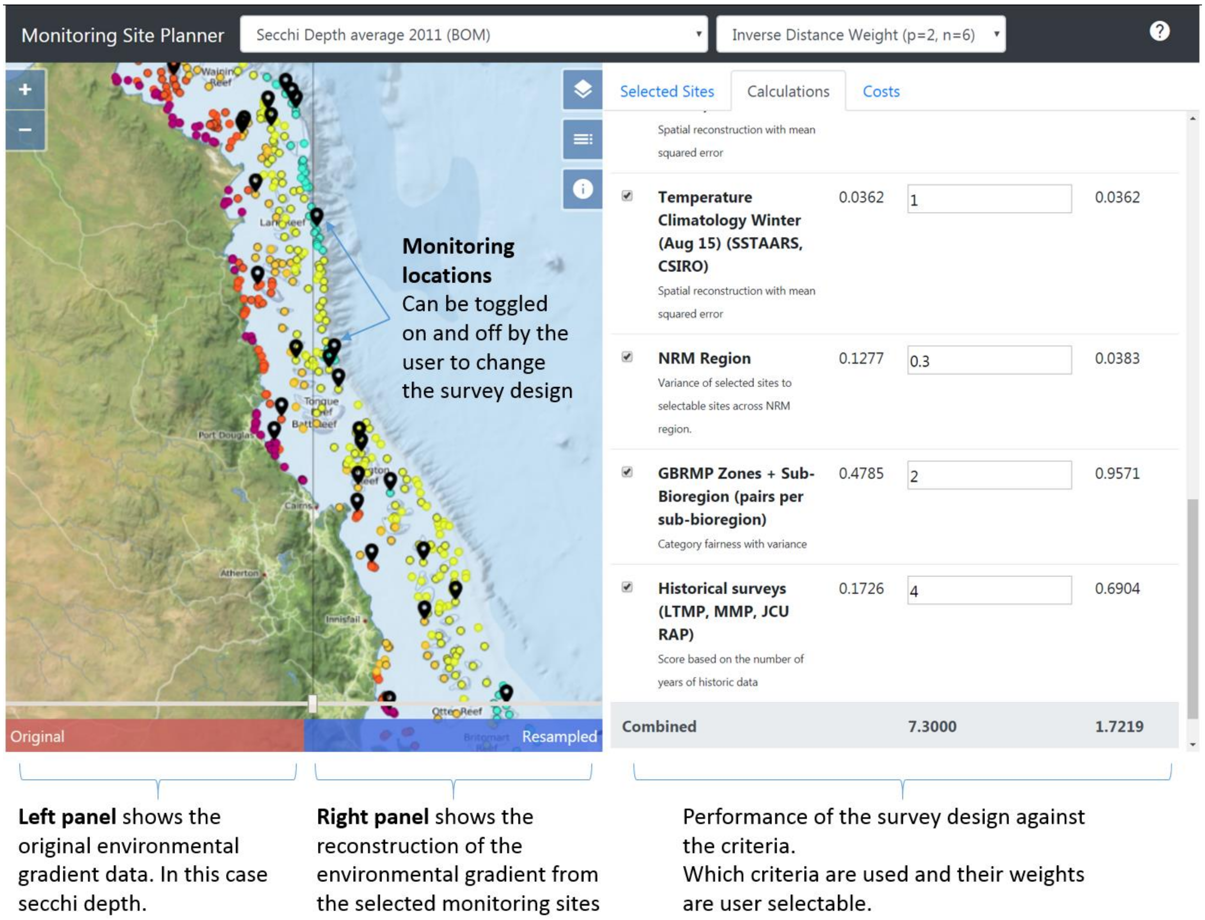


Figure 1. Screenshot of the Monitoring Site Planner tool. This shows the tool running as a web application that allows users to interactively change a survey design and see how these changes are reflected in the performance of each criteria.

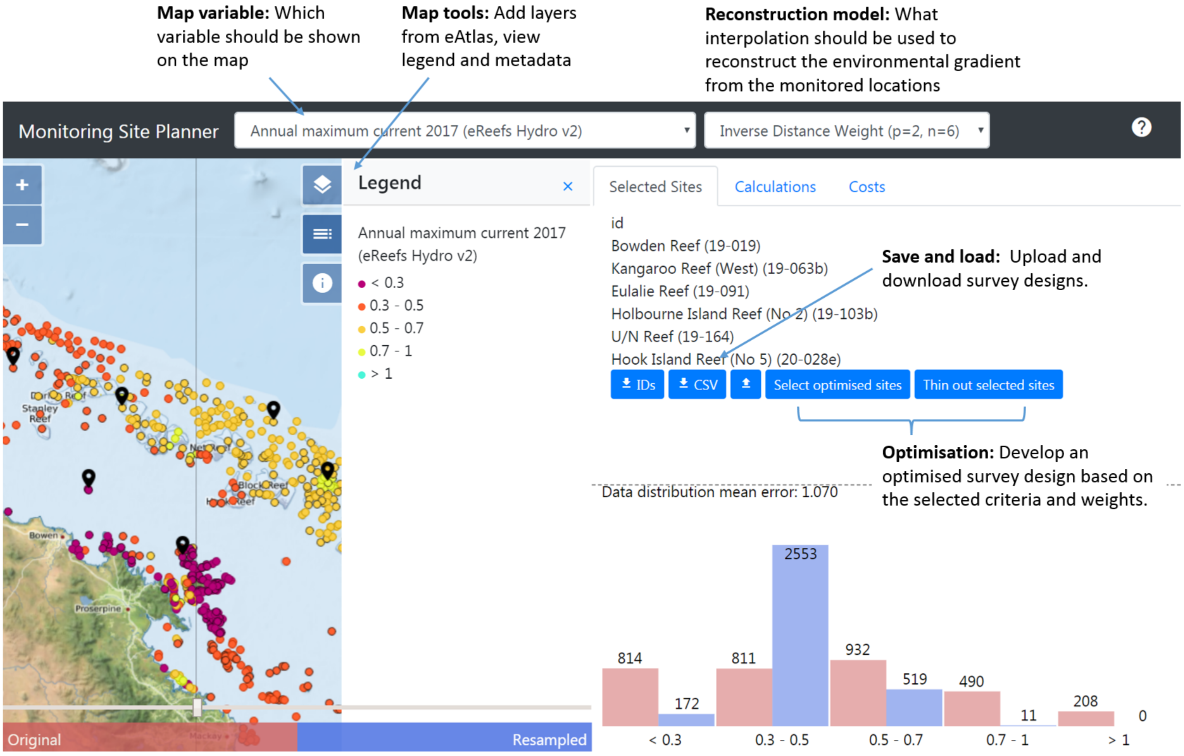


Figure 2. Second screenshot of the Monitoring Site Planner showing the mapping, save and load and optimisation features.

1.2 How do we predict the performance of a monitoring survey design?

Predicting the performance of a monitoring program is difficult as it requires us to estimate how well a given survey design will allow us to understand the future state of the Reef. This is challenging as the key drivers of change on the Reef are largely unpredictable acute disturbances such as cyclones, bleaching and crown-of-thorns starfish outbreaks, where historical events provide little guidance on the location of future events, particularly for cyclones and bleaching. In this work we assume that the relative spatial distribution of risk from disturbances is too poorly known to directly inform the coral reef survey design. We instead work from the basic assumption that the monitoring program should reflect the diversity of different conditions and places within the Reef. To achieve this we use two approaches: environmental gradients such as temperature, water quality and currents are used as proxies for the diversity of conditions that affect the composition of coral communities, and the Reef Bioregion mapping (developed as part of the Representative Areas Program) is used as part of the Marine Park Zoning + sub-bioregion criteria to ensure an even spread of reef pairs over each sub-bioregion.

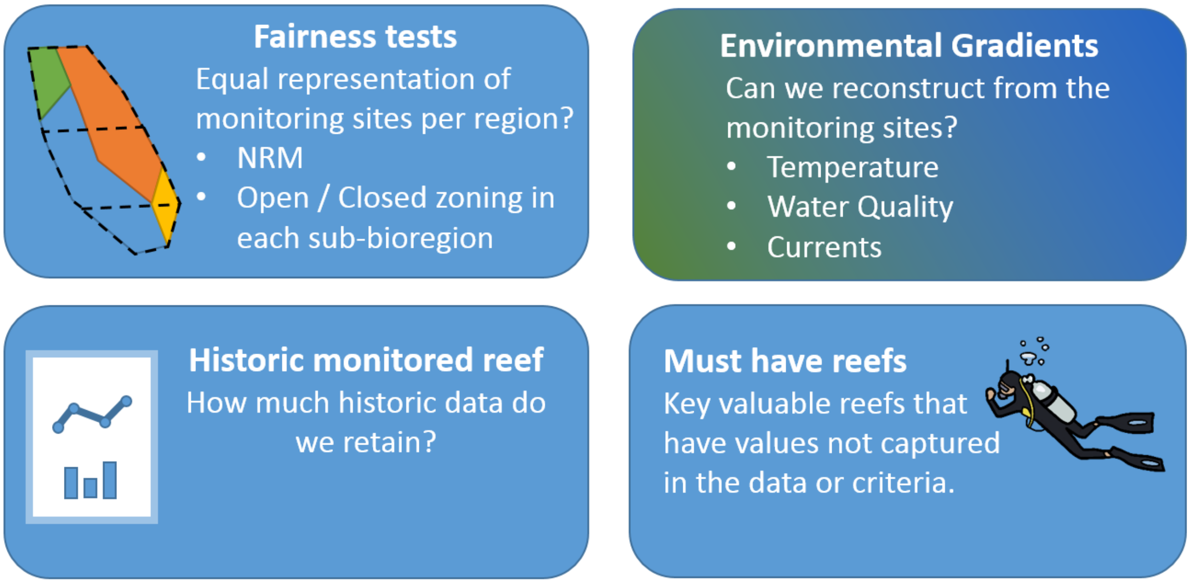


Figure 2. Overview of the types of criteria used in the Monitoring Site Planner. The fairness test criteria measures if the survey design contains an even spread of monitoring sites. The environmental gradients criteria assess if the survey design can be used to reconstruct a known gradient at all reefs. The historic monitored reefs criteria measures how much of the survey design contains sites with historic monitoring data. The tool also supports specifying "Must Have" reefs that should be included in any optimisation for reasons not captured in any of the other criteria.

The Monitoring Site Planner has criteria that assess whether a monitoring survey design:

- Has monitoring sites spread evenly over all representative areas.
- Captures the patterns of the environmental gradients.
- Links with historic data to ensure that long-term trends can be understood.
- Allows continued evaluation of the effectiveness of the Reef zoning.

These criteria are weighted and combined together to create a final score for a given survey design. The weights can be used to change the relative importance of each criteria to the final design of the monitoring program.

The criteria have been scaled so that a perfect score is 0 and a bad score is 1. This approach means that when multiple criteria are added together a perfect score still is 0. This approach was adopted as a natural extension of the *Environmental Gradient* criteria where the score is based on the reconstruction error. The best reconstruction has 0 error and thus the perfect score was 0. All other criteria were adapted to using this same approach.

The Monitoring Site Planner allows the user to interactively change the survey design to find the corresponding changes in the criteria performance. They can also use a range of automated optimisation tools that can iterate through thousands of survey designs to find the best designs for the chosen set of criteria and weights.

2 FAIRNESS TESTS

2.1 Natural Resource Management fairness test

The Natural Resource Management (NRM) fairness criteria ensures that each region gets a fair number of monitoring locations. This partly helps with the spatial spread of monitored pairs but was mainly added to ensure the monitoring-supported NRM groups understand their marine environment. For each NRM this criterion calculates the percentage number of monitored reefs in the region, ignoring the position within the region. It then looks at whether there is a fair number of monitored locations across all NRM regions by calculating the variance between the percentage counts. If all NRMs have the same percentage number of monitored reefs, then it receives a perfect score of zero. This criteria scales with the size of the monitoring program and so a small or large monitoring program can do well on this criterion.

2.2 Great Barrier Reef Marine Park Zones + Sub-Bioregion – Zoning pairs per sub-bioregion

This criterion serves two roles in assessing a given survey design. It assesses how useful the monitoring program will be for evaluating the effectiveness of the marine park zoning and whether the monitoring sites are evenly spread over each of the representative areas of the Reef.

This criterion assesses the suitability of the survey design for evaluating the performance of the zoning of the marine park. A good survey design must contain pairs of reefs, one open to fishing (blue zone) and one closed to fishing (green zone), that can be used to compare the relative performance of areas closed to fishing with those open to fishing. It is also important that this comparison is performed over different regions of the Reef and that the pairs of reefs are similar and close together (i.e. likely to get a similar amount of fishing pressure). As there is no dataset that captures the similarity in geomorphology between reefs we instead cluster reefs based on sub-bioregions developed as part of the Representative Areas Program (RAP) bioregions developed for the Marine Park rezoning (Great Barrier Reef Marine Park Authority, 2001). These reef sub-bioregions were developed by a panel of experts and based on more than 40 layers of data. The sub-bioregions is a clustering of the Great Barrier Reef reefs into 81 areas of similar reefs. Reefs are considered suitable for pairing if they are both in the same sub-bioregion.

Some reef sub-bioregions are much larger than others and thus there should be more pairs of reefs in these regions. To achieve this in the criteria, each sub-bioregion was allocated a quota of reef pairs based on the area of the sub-bioregion, with an average of two pairs over all sub-bioregions. The sub-bioregions for reefs were mapped as a polygon following the outer boundary of all the reefs contained in the sub-bioregions.

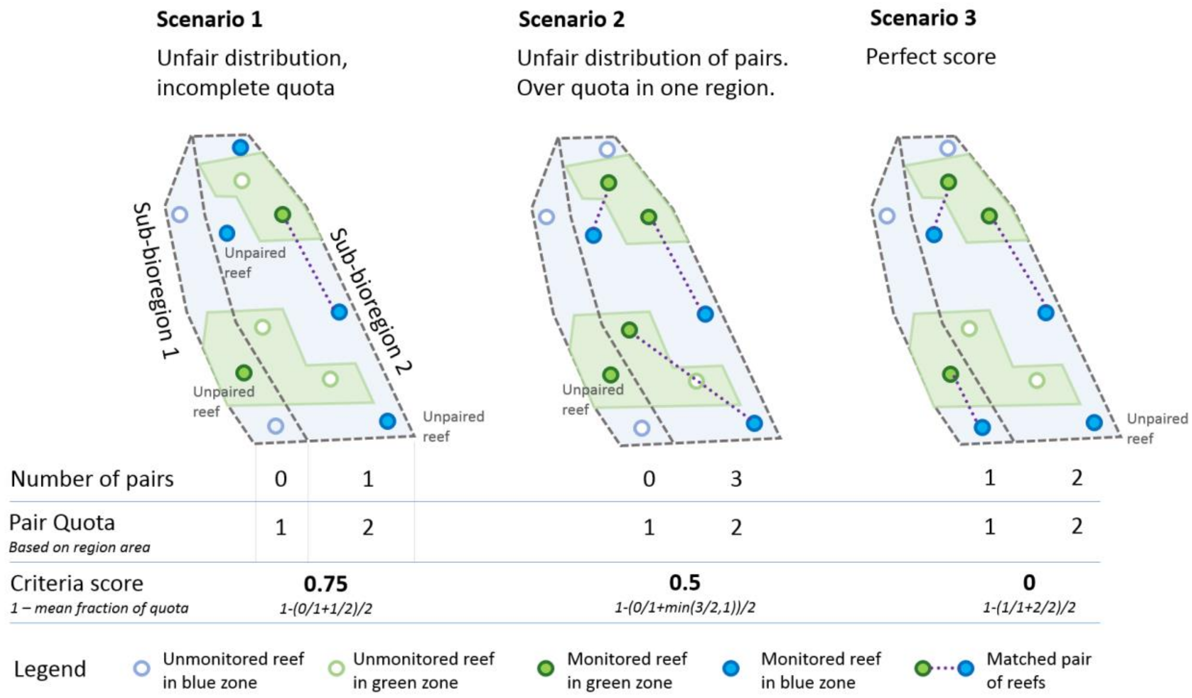


Figure 3. Calculation of the Marine Park Zones + sub-bioregion criteria. This shows the calculation of this criteria for three scenarios of a simplified example with only two sub-bioregions. Sub-bioregion 2 is twice as large as sub-bioregion 1 and so has twice the quota of paired reefs. Within each of the sub-bioregions, only pairs of green (closed to fishing) and blue (open to fishing) reefs are considered. Unpaired reefs are ignored by this criterion, allowing them to be moved around for optimising other criteria. In **scenario 1** most of the reefs are unpaired, resulting in neither sub-bioregion reaching their quota, leading to a poor criteria score, where 1 is the worst score and 0 is a perfect score. In **scenario 2**, sub-bioregion 1 still has no match pairs and so scores poorly. Sub-bioregion 2 has more than its allotted quota. Exceeding the allotted quota does not further improve the score. In **scenario 3** each sub-bioregion has reached its allotted quota and thus receives a perfect score. Additional unpaired reefs don’t contribute to this criterion.

2.3 Environmental Gradient criteria

Often for management purposes it is important to understand the state of the whole Reef, including areas that have not been monitored. We can estimate the state of unmonitored areas using models that interpolate from neighbouring monitored reefs. How well this works depends on the density of the monitoring and how well the monitored reefs represent the surrounding unmonitored reefs; in other words how well they are correlated. If the monitored locations are chosen at representative locations then the interpolation process will work better, resulting in a better reconstruction of the state of the whole Reef.

The original concept of this criteria was that if we somehow knew the historic state of all the reefs (via a massive hypothetical monitoring program) then we could test the performance of smaller survey designs by seeing how the measurements at the monitored sites could be used to reconstruct the state of all reefs. If the survey design captured most of the spatial patterns, then there would be little difference between our reconstruction and the known state at each reef.

Since we don't know the historical state for each reef we must therefore adapt the idea to use a source of information that we do have for all reefs. If we can reconstruct, from monitored sites, key environmental gradients (temperature, water quality and currents) that affect coral reef communities then we assume that we will have a monitoring program that captures much of the spatial diversity of the Reef.

This criterion requires that the environmental gradient data is known for all reef locations. This limits the data that can be used to drive this criterion. We therefore rely on environmental gradients estimated from remote sensing and eReefs models.

Table 1. Environmental gradients available in the Monitoring Site Planner.

Environmental Gradient	Notes	Data source
Temperature	Approximate summer peak temperature over the Reef. (15th February in daily climatology) Approximate winter coldest temperature over the Reef. (15th August in daily climatology)	SSTAARS (Wijffels, *et al.* 2018) Daily climatology derived from IMOS remote sensing.
Water quality	Primary (used for survey design optimisation): • Secchi depth annual average 2011 (wet year), 2015 (dry year) Secondary (used for comparison): • Chlorophyll annual average 2011 (wet year), 2015 (dry year) • Non-algal particulates (NAP) annual average 2011 (wet year), 2015 (dry year).	eReefs BOM Water Quality Dashboard (BOM, 2018, 5 30). Secchi (Weeks, et al. 2012) Yearly average based on MODIS remote sensing.
Current	Maximum annual current 2017. Also used as to detect reefs with currents that are too high to safely monitor.	eReefs Hydro v2 1km model. (Lawrey & Smith, 2017)

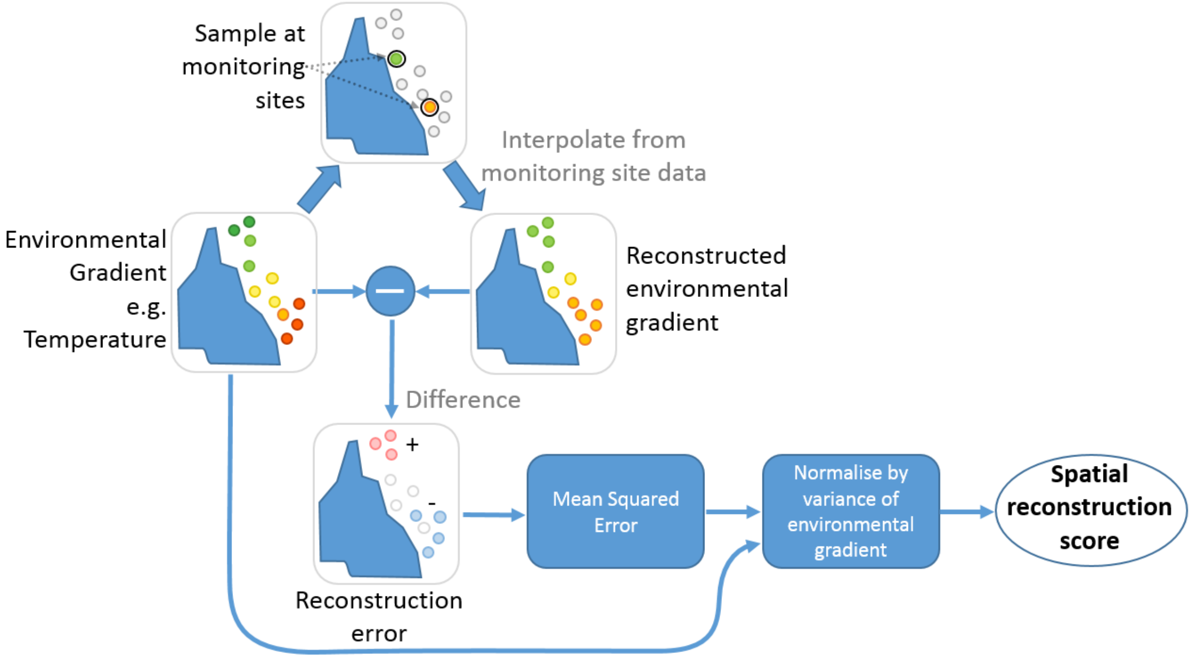


Figure 4. Overview of the calculation of the *Environmental Gradients* criteria. The *Environmental Gradients* criteria assesses how well the data measured at the monitoring sites can be used to reconstruct the original environmental gradient at all coral reefs. The environmental gradient is sampled based on the survey design. These measurements are then interpolated to produce an estimate for all reefs using an Inverse Distance Weighted (p=2, n=6) model. The reconstruction error is then estimated and normalised to a score from 0 (no error) to approximately 1, by dividing the mean squared error by the variance of the original environmental gradient. This normalisation helps ensure a similar scale to the criteria scores, irrespective of the units of the environmental gradient.

2.3.1 Choice of secchi as the primary water quality environmental gradient

While multiple water quality gradients (chlorophyll, Non-Algal Pariticulates (NAP) and secchi) were set up in the tool there was concern over the correlation and reliability of these data sources. An analysis was performed to look at the correlation between these measures and the affect each measure had on the resulting optimised monitoring program. It was found that chlorophyll, NAP and secchi depth were very strongly correlated, making the use of all three criteria redundant. Using each of these measures to optimise the monitoring program result in differences due to the different non-linear mapping between water quality and each measure. In poor water quality conditions, chlorophyll and NAP are high, whereas secchi is low. Chlorophyll and NAP have a linear change with water quality, whereas secchi has a log relationship. This difference results in each criterion emphasising monitoring sites either inshore (chlorophyll and NAP) or mid-shelf and offshore (secchi).

In recent years there have been concerns about the accuracy of remote sensing water quality products, particularly in inshore areas (Tracey, Waterhouse & da Silva, 2016). For this reason, we use secchi as our primary water quality criteria for all optimisation and survey design comparisons. The secchi criteria is less sensitive to these inshore areas where the error is likely to be largest. Secchi values decrease near the coast and since the reconstruction errors are approximately proportional to local mean value (due to the use of the Inverse Distance Weighted interpolation models used), any errors in the inshore areas will contribute less than errors in the offshore areas where the secchi is high. Chlorophyll and NAP both have high values in inshore areas resulting in an emphasis on the inshore areas where the original data is not likely to be robust.

2.3.2 Reconstruction interpolation

In the future, to create an accurate estimate of the status of the Reef, monitoring results would need to be fused with additional data about current environmental conditions and disturbance events using a complex model.

In the *Environmental Gradient* criteria we approximate this process by sampling the environmental gradient (which represents the average environmental conditions) at the monitored locations, then attempt to reconstruct the original environmental gradient at all reefs. How well the reconstruction works serves as the metric for how well the monitoring locations are positioned. If the survey design has few locations in a large area, then the reconstruction will be poor and the criteria will rate this design poorly. Even if there are lots of monitoring locations but they are not well spaced but clumped close together then the reconstruction will be poor and this survey design will receive a poor score.

For this analysis we use a simple robust interpolation model that can be applied independently to each environmental gradient. We use an Inverse Distance Weighted (n=6, p=2) interpolation for all analysis. This model uses the information from the 6 closest monitoring sites and their distances to produce an interpolated estimate for an unmonitored reef. Appendix 7.1 provides more details about additional interpolation models available in the Monitoring Site Planner.

2.4 Historic data criteria

The historic data index criterion assesses what percentage of all historic data is captured by the reefs in the survey design. The index is calculated by summating the number of years that the reef has been surveyed, with each survey type (benthic, manta tow, fish, etc.) being weighted by the type of the survey. Some of the survey types, such as the LTMP benthic surveys are highly detailed and provide a lot of information about the status and processes of the reef, where as other surveys such as the LTMP scuba survey only provides a quick assessment of the drivers of change and thus has been given a lower weight in the final historic data index.

Note: This historic data criterion focused on data from fixed site monitoring programs and data that was available to the authors.

Table 2. Relative weight applied to each type of historic data. The historic data index is the weighted sum of the number of years monitored at each reef. These weights were based on expert opinion. Example: A reef with 5 years of LTMP manta tows, 2 years of LTMP benthic and 2 years of LTMP Juvenile surveys would have an historic data index of 5 x 1 (manta) + 2 x 1 (benthic) + 2 x 0.5 (juvenile) = 5 + 2 +1 = 8. The historic data criteria is then a measure of the fraction of all historic data covered by monitoring locations.

Historic data measure	Index weighting
LTMP Benthic	1
LTMP Fish	1
LTMP Manta	1
LTMP Scuba	0.2
LTMP Juveniles	0.5
JCU Fish	1
JCU Benthic	0.5

2.5 “Must Have” reefs

Some reefs have high value characteristics not captured in the criteria analysis data. To ensure that these reefs are included in optimised survey designs, the Monitoring Site Planner supports tagging some reefs as “Must Have” reefs. These reefs are prevented from being removed or left out by the optimisation tools.

Appending 7.2 shows the list of “Must Have” reefs that were included in the analysis that is presented in this report.

3 REEF DATABASE – DATA TO DRIVE THE CRITERIA ANALYSIS

All the data needed to drive the Monitoring Site Planner was condensed into a single reef database. An overview of the data and workflow used to create this database is outlined in Figure 5. The Great Barrier Reef Database was initially based on the Complete Great Barrier Reef and Island Features dataset (Lawrey & Smith, 2017). This dataset includes reefs and island features from both the Marine Park and Torres Strait. Each reef was then augmented with additional attributes for the reef derived from various environmental gradients (current, temperature, and water quality), regional information (zoning, NRM regions), basic logistics information (reef top and maximum currents) and a record of the amount and type of historic data available at each reef. The reefs from just the Marine Park were then extracted for use in the Monitoring Site Planner. These reefs correspond largely to reef boundary features originally developed by the Great Barrier Reef Marine Park Authority (the Authority).

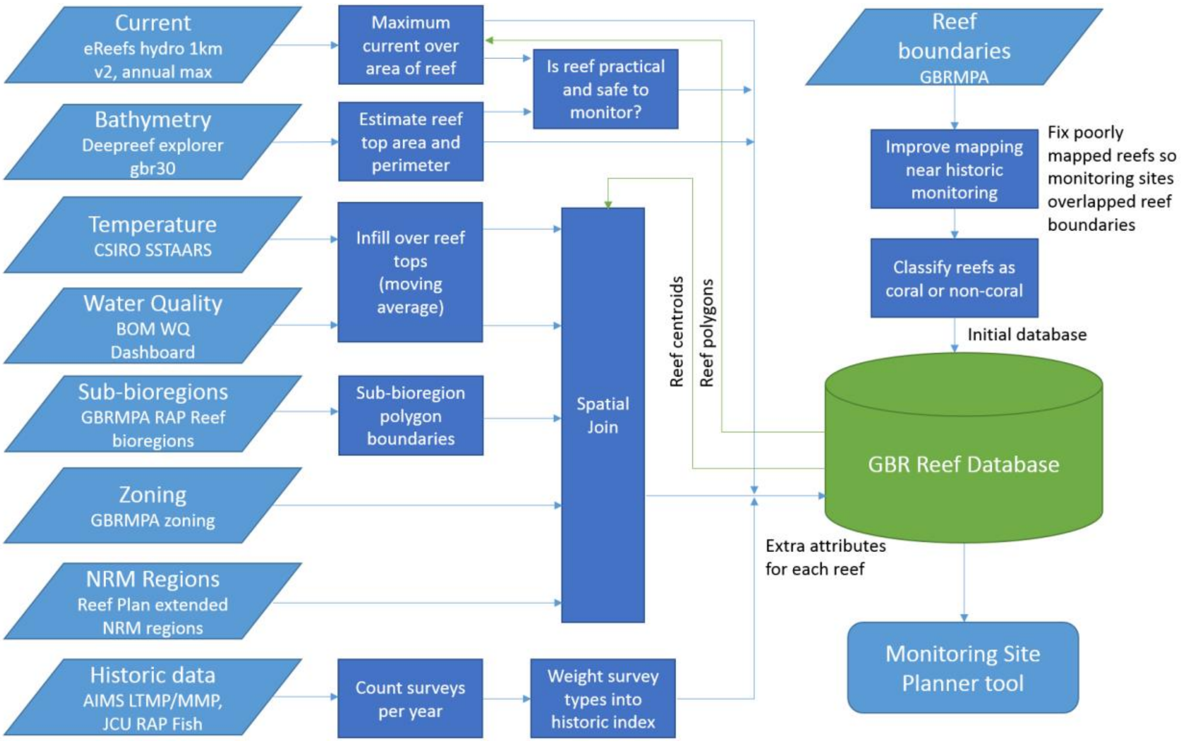


Figure 5. Overview of the source data and processing used to create the Great Barrier Reef Database. This database is used to drive the Monitoring Site Planner Tool.

3.1 Logistics – Which reefs can be monitored?

The Great Barrier Reef Database contains over 3000 reefs, however, many of these are unsuitable for monitoring using existing techniques. Current coral reef monitoring focuses on broad scale reef slope monitoring with manta tow surveys and detailed benthic and fish surveys also on shallow reef slopes of the northeast flank of reefs (Jonker et al. 2008). By focusing on one reef habitat, the results of all monitored reefs are comparable. If different reef habitats (such as the reef top, reef slope, back reef) were monitored on different reefs then they could not be combined to produce region-wide summaries. While it would be possible to survey multiple reef habitats on all reefs through a greatly expanded monitoring program, or via the introduction of a new technology, this was not considered as part of this project.

The Monitoring Site Planner was set up under the assumption that any new coral reef monitoring would continue to monitor shallow reef slope habitats. As a result, a reef can only be surveyed if it has a shallow reef top, with an associated reef slope. A reef can also only be surveyed if the currents around the reef are not too large. High tidal currents pose a safety hazard and make it impractical to survey. The following criteria were used to determine which reefs might be suitable for monitoring:

- The reef must have a reef top (area shallower than 5 m)
- The reef top perimeter is between 1.5 km and 30 km in length
- The maximum annual current is less than 1.4 m/s (as determined by the eReefs hydrodynamic model).

These threshold values were picked based on a discussion with the LTMP team and the range of values observed in the current monitoring program. While these thresholds included nearly all existing monitored reefs there were a number of exceptions. In some existing cases reefs with a perimeter larger than the threshold are being monitored. These reefs were manually added back as potential reefs for surveying.

This filtering removed 50 per cent of all the reefs on the Reef, limiting the reefs that could potentially be selected for monitoring in the Monitoring Site Planner. This filtering is particularly important for preventing the optimiser in the Monitoring Site Planner from designing a monitoring program with reefs that are unsuitable for monitoring.

3.1.1 Limitations in the logistic filtering

The approach used does however have some significant limitations and failings.

The eReefs 1 km hydrodynamic model fails to fully resolve many of the high currents experienced between close neighbouring reefs and so the filtering based on maximum current failed to remove quite a few reefs that are likely (based on their geomorphology) to have high reef slope currents. Most of these reefs were manually filtered out.

The approach does not consider the reef geomorphology and so there is no verification that there is a reef habitat (well-formed north east reef slope) suitable for monitoring.

Additionally, there is no consideration of safety issues from crocodiles. There was no reliable crocodile risk model available at the time of development and so without this filtering the Monitoring Site Planner often picks inshore areas (particularly in Cape York) that are likely to be unsuitable for safe monitoring with divers.

It is therefore important that recommendations generated by the tool are carefully reviewed for logistics not considered by the tool.

3.2 Optimisation – Automated monitoring program design

The Monitoring Site Planner allows users to interactively change a given survey design and see whether the changes they make improve the performance of the monitoring program (as measured by the criteria).

Using the interactive tool to optimise a monitoring program it quickly becomes apparent that there are a huge number of possible survey designs and discovering the best combination of locations using this process could take a very long time. For this reason, the Monitoring Site Planner contains two optimisation features that allow automated searching for good designs.

3.3 Genetic Algorithm optimisation – Automated survey designs from scratch

The first optimiser (*Select optimised sites* on the user interface) searches from scratch a survey design that performs well against the specified criteria and weights. This optimiser uses a genetic algorithm (see Figure 7) to progressively find new survey designs that perform better against the criteria. Due to the random nature of this optimiser it makes no assumptions about what a good solution should look like, but is directed solely by the specified criteria and weights. This makes it a useful tool for providing an independent opinion on what makes a good monitoring survey design. This optimiser is, however, slow due to the large number of survey designs that must be tested. The optimised survey designs presented in this report (in section 4 and 5) each required testing 100,000 potential monitoring designs (5000 generations, each with a population of 20), taking weeks of computation to produce.

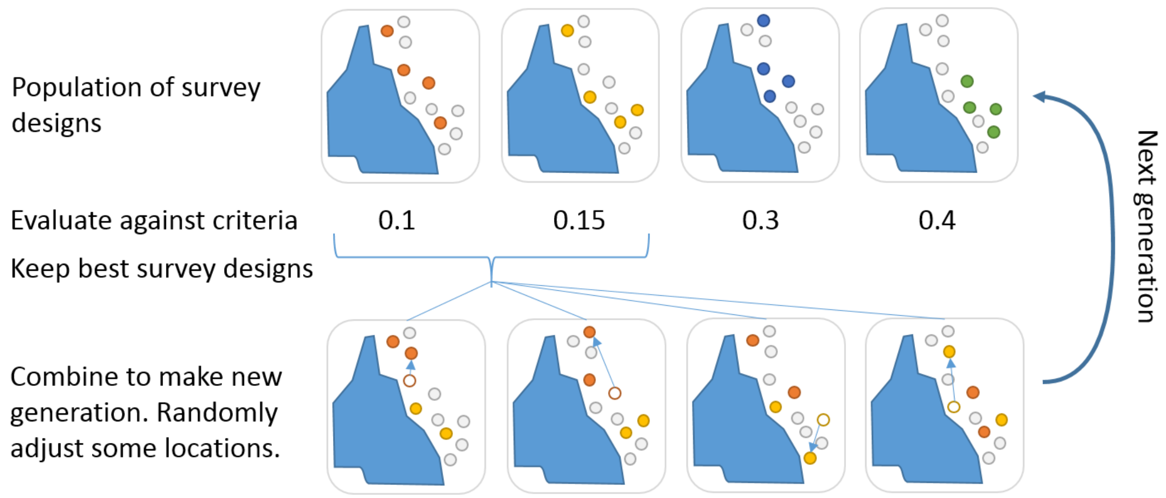


Figure 7. Overview of the Genetics Algorithms optimiser (*Select optimised sites* **on the user interface). This uses genetic algorithms to find good survey designs that match the specified criteria and weights. This process starts with a population of random survey designs (typically 20 – 40). These are then each evaluated against the performance criteria. The best ones are kept to make the next generation (typically 20 per cent of the original population). A new population is then created by mixing the designs from the previous generation (equivalent to sexual reproduction). Noise is then added by randomly moving some of the locations (mutation). The process is then repeated (typically for 1000 – 10000 generations). The amount of noise added is slowly reduced over the generations.**

3.4 Thinning out optimisation – Removing underperforming monitoring locations

The second optimisation feature (*Thin out selected sites* on the user interface) is designed to refine an existing survey design by progressively removing sites from a given survey design. It removes monitoring locations that least contribute to the performance of the survey design. This feature can typically remove 10 – 40 per cent of the monitoring program locations with only a small degradation in the performance (as determined by the criteria) of the survey design. How many locations can be removed depends on how optimised the survey design was to start with.

All the optimised results shown in this report used a combination of both optimisers.

4 RESULTS – OPTIMISED SURVEY DESIGNS – ONE CRITERION AT A TIME

What would the best monitoring program look like if we only cared about one criterion at a time? If all that mattered was our ability to monitor coral reefs across different water quality gradients what would be the best survey design? Studying the optimal survey design for each criterion helps us understand what each of the criterion are trying to achieve. Having an understanding of each individual criterion allows us to better understand the results as we mix and match multi-criteria with different weights.

The optimisation features in the Monitoring Site Planner tool were used to generate an optimised survey design with 50 monitoring locations for each of the key criterion setup in the tool. This number of locations was chosen because it is sufficiently high that the general patterns of the survey design can be seen, without too much detailed clutter. The number of locations is not a recommendation on the number of monitoring locations needed in a real monitoring program.

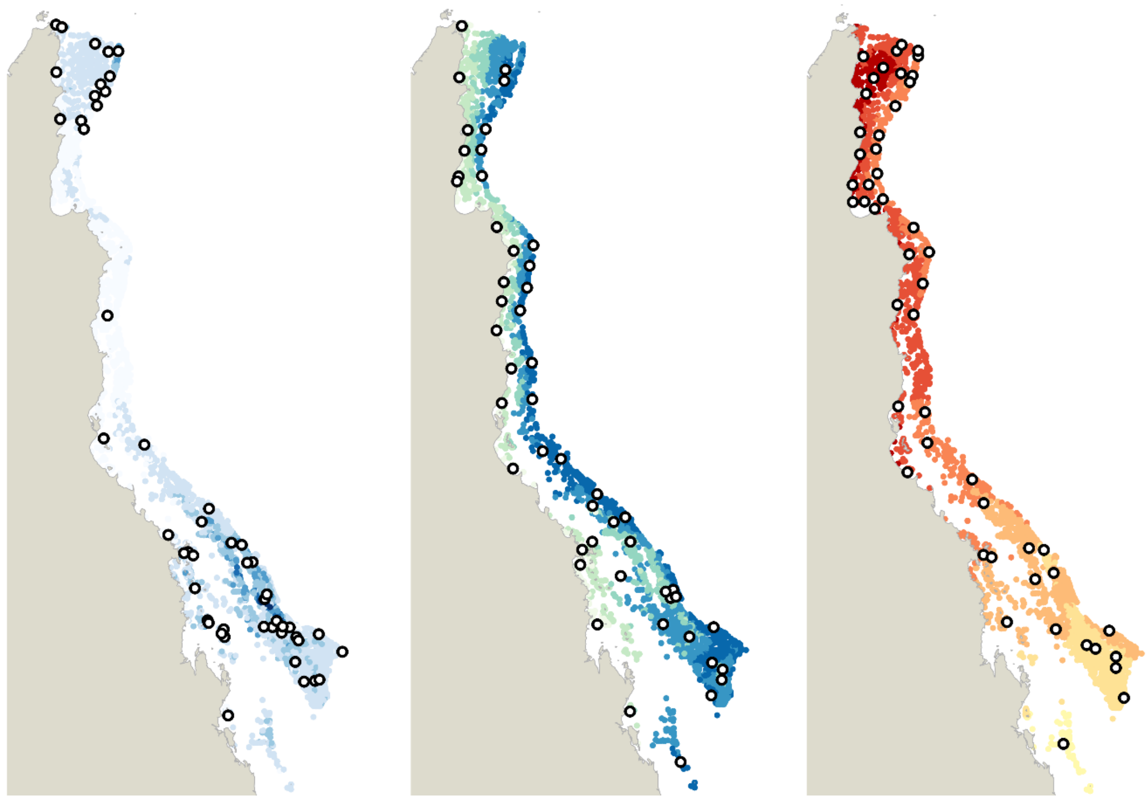
Figure 6 shows the results for each of the environmental gradients criteria.

For the maximum current environmental gradient (a) we can see a distinct lack of monitoring locations in the middle section of the Reef. The ocean currents in this region are quite low. In the southern and northern tip of the Reef there are quite strong tidal currents that pass through the reef matrix. As a result, these two regions have lots of detail that needs to be recreated by the monitoring.

For the secchi depth environmental gradient (b) there is a very even spread of monitoring location along the whole of the Reef. This is because there is a strong inshore to offshore gradient. The monitoring is made up of roughly evenly-spaced pairs of inshore and offshore locations that are at right angles to the secchi gradient.

For the temperature environmental gradient (c) the pattern of monitoring location spacing is mixed. There is a strong, but gentle north-south gradient and an inshore, offshore gradient in parts.

We can see from this analysis that the ideal monitoring survey design varies with each environmental gradient and that there are few particularly special reefs that are common to all gradients. In this analysis we only consider a few of the drivers of coral communities due to a lack of data and the approach and so we should be cautious about taking the optimised multi-criteria results at face value. Choosing a different set of environmental gradients or changing the weights of the gradients will result in a different optimised survey design.



a) maximum annual current

(2017 eReefs 1km hydro model v2)

b) Secchi depth

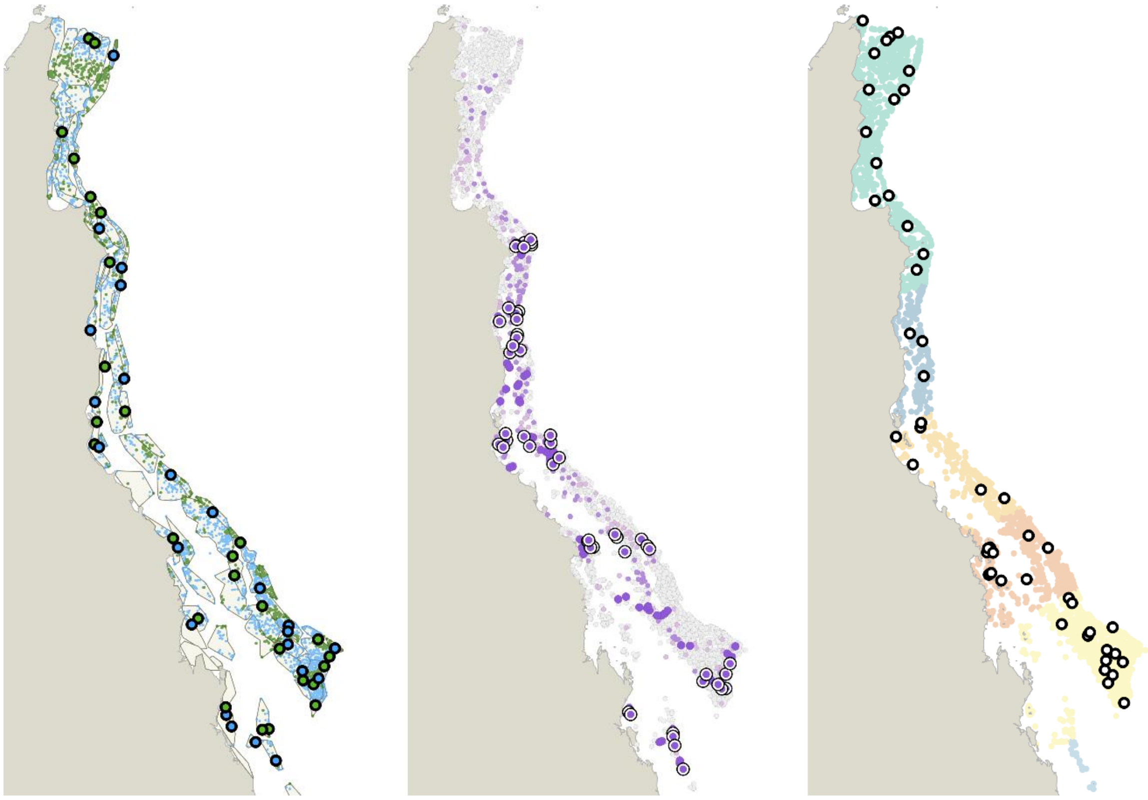
(2011 annual average secchi)

c) Summer maximum temperature

(From daily SSTAARS climatology)

Figure 6. Results of optimising the survey design with only 50 monitoring locations, against each of the environmental gradients. We can see that the monitoring locations tend to be positioned in areas of rapid gradient changes and are spaced at right angles to the main gradient.

Figure 7 shows optimised survey designs with 50 locations for each of the Marine Park Zones + sub-bioregion, historic data and the NRM fairness criterion. These are not as informative as the optimised designs for the environmental gradients. Figure 7a shows that with only 50 reefs and over 80 sub-bioregions there was little ability to produce an optimal pairing of reefs with so few monitoring locations. If we were designing a monitoring program this small it would be better to use large regions for pairing such as bioregions, rather than sub-bioregions. The optimal 50 location survey design for historic data simply corresponds to the 50 sites with the most historic data (see Figure 7b). The NRM fairness test is the least spatially explicit criteria (see Figure 7c). Its only concern is that the number of monitoring locations within each NRM region is in proportion to the number of reefs in that region. It does not care where they are within the region. Cape York has the most reefs and thus gets the most number of monitored locations.



a) Marine Park Zones + Sub-Bioregion

b) Historic data

c) NRM fairness

Figure 7**. Optimised survey designs, one criterion at a time for the Marine Park Zones + sub-bioregion, historic data and the NRM fairness criterion. This shows optimisation with just 50 reefs. a) The blue and green dots represent the zoning of each reef and the polygon boundaries show the sub-bioregions. b) Optimal survey design for historic data criteria. The size of the purple dots represents the amount of historic data at each reef. c) Each NRM region is shown as a different colour. The 50 reefs are spread fairly across the 6 NRM regions based on the number of reefs in each region.**

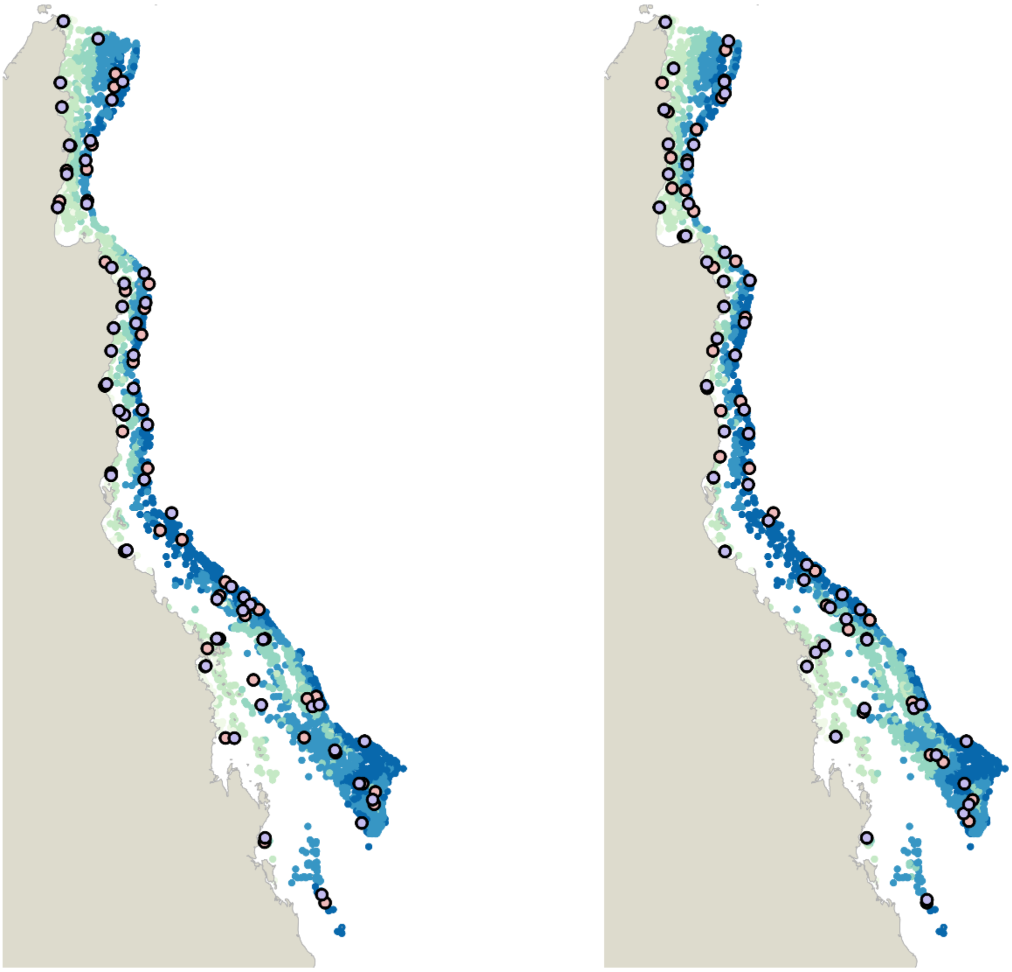
4.1 How much variability is there in the optimised survey designs?

The Monitoring Site Planner uses two optimisation techniques to produce the final optimised survey design based on the selected criteria and their weights. The primary optimiser uses genetic algorithms to evolve a solution that performs well. This process is stochastic as the optimisation process uses random modifications to find new and better solutions. As a result, each run of the optimiser will produce slightly different results.

We would assume that given enough searching the optimiser could find the ultimate best solution. This is, however, impractical due to the immense number of possible survey designs. Even with as few as 50 monitored reefs there are over 10^{90} possible survey designs. The optimisers do not search all possible designs, but instead focus on finding progressively better survey designs. There are many, many survey designs that are good and of similar level of performance.

Figure 8 shows multiple runs of the optimiser on a single environmental gradient, in this case secchi. The Genetic Algorithm optimiser was run for 5000 generations with a population of 20. The optimiser was also run over two versions of the environmental gradient (2011 and 2015) to see how slight changes in the gradient would change the survey design pattern. We can see that the reefs chosen are different in each run, but there are common large-scale patterns to the design.

We should keep the variability in the survey designs in mind when we consider the final multi-criteria survey design. The Monitoring Site Planner provides recommended patterns for the survey design, however there are many, many similar performing survey designs. If we need to change the monitoring survey design for practical reasons not considered by the tool but keep a similar pattern then it is likely that the overall performance will be similar.



a) Secchi – 2011 annual mean, 2 runs, 50 reefs

b) Secchi – 2015 annual mean, 2 runs 50 reefs.

Figure 8**. Multiple optimisation runs of the same core environmental gradient. Each panel shows 2 runs of the optimiser for exactly the same gradient data, while the two panels show the results when calculated for a wet year (2011) verses a dry year (2015). Since the optimiser is stochastic (driven by random evolution) the optimised solutions are different in each run. The large scale patterns of the survey design are however robust and repeatable. In the northern half of the Reef the best survey design contains roughly evenly spaced pairs of inshore and offshore monitored reefs, where the locations are perpendicular to the gradient. In the southern half of the Reef the gradients are more complex, but there is a consistent pattern between all four runs of the optimisation.**

5 RESULTS – PERFORMANCE OF EXISTING VERSES EXPERT REDESIGN VERSES OPTIMISED SURVEY DESIGNS

A three-way comparison was performed between the existing LTMP / MMP / JCU coral reef monitoring (Australian Institute of Marine Science 2014; Australian Institute of Marine Science 2015; Williamson et al. 2014), an expert adjustment to this existing survey design to improve its coverage in Cape York, and a survey design developed from scratch by the Monitoring Site Planner optimisers. Figure 9 shows the three survey designs under consideration and Figure 10 shows their corresponding performance as measured against each of the criteria.

5.1 Some criteria are harder than others

There are several things to note about these results. First we see that the performance of each criterion is significantly different, with current and zoning having the highest (and thus worst) criteria scores, regardless of the survey design. Some criteria are harder to score well on than others.

All survey designs received a low (good) score for the *temperature* gradient. This gradient is relatively smooth and thus is easy to recreate, even without many monitoring locations, or perfect placement of those locations.

The *current* criterion is more difficult to score well, as the currents are dominated by complex tidal flows through the reef matrix resulting in high variability between even close reefs. This low spatial correlation makes it difficult for any survey design to perform well on. Another reason why the current score is poor even for the optimised design is that reefs with high currents are excluded from the pool of potential monitoring locations.

The Marine Park Zoning + sub-bioregions criterion is difficult as the average quota was set to 2 reef pairs per sub-bioregion in this analysis. A perfect score could only be achieved with a survey design with over 320 monitored reefs (average of 2 pairs in each of the 81 sub-bioregions). In hind-sight this quota is probably set too high making it difficult for survey designs to score well. While the good score is hard to achieve, any pairing of reefs in the survey design will be rewarded by this criterion.

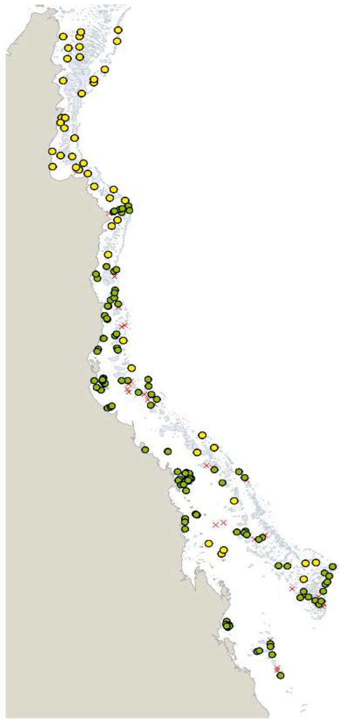
Due to differences in relative difficulty of the criteria it is more important to look for relative improvements in each criterion across survey designs rather than the absolute criteria scores. This is true for all the criteria except the historic data criteria, where the score tells us the percentage historic data retained by the survey design. This can be calculated with (1-historic data criteria score)*100 and so a historic data criteria score of 0.1 means the survey design contains locations that have 90 per cent of all historic data.

a) Existing survey design.

(159 reefs) *Existing-V5-159*

LTMP, MMP, JCU RAP

Note: all monitoring sites were mapped to Authority reef boundaries



b) Expert opinion adjustment.

(169 reefs) *Expert-V5-169*

Adjusted by Angus Thompson, Manuel Gonzalez Rivero to provide more coverage in Cape York. Allocation strategy:

1. Two Blue/Green pairs per bioregion (4 reefs). Preference for pink zones.

2. Big/long bioregions have more pairs.

3. Strong preference for existing sites.

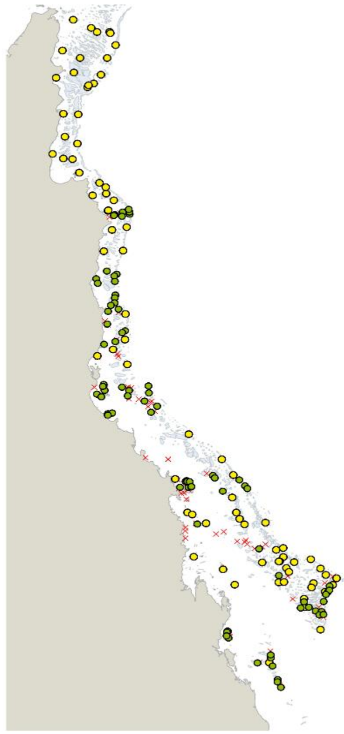
4. Bioregions with excessive existing pairs had reefs removed.

5. Bioregions without enough reefs had pairs added.

6. Reef structure, existing other surveys and logistics used to choose new reefs.

7. Inshore reefs retained based on water quality gradients, tourism sites, urban areas and reporting regions.

8. Includes all JCU RAP sites



c) Multi-criteria optimised.

(159 reefs).

All-v7-h4-200a-thin-159

Based on the following criteria and weights:

Criteria	**Weight**
Max Current	0.5
Secchi 2011	0.5
Secchi 2015	0.5
Temperature (summer)	0.8
Temperature (winter)	0.2
NRM	0.1
Zoning	2
Historic	4

200 reef monitoring program developed with the Genetic Algorithm optimizer, followed by the thinning out optimiser down to 159 reefs to match the size of the existing survey design.

(needs further review)

Figure 9 **Map of three survey designs under consideration. Green dots correspond to existing sites, yellow dots are new sites and crosses (x) are removed existing sites.**

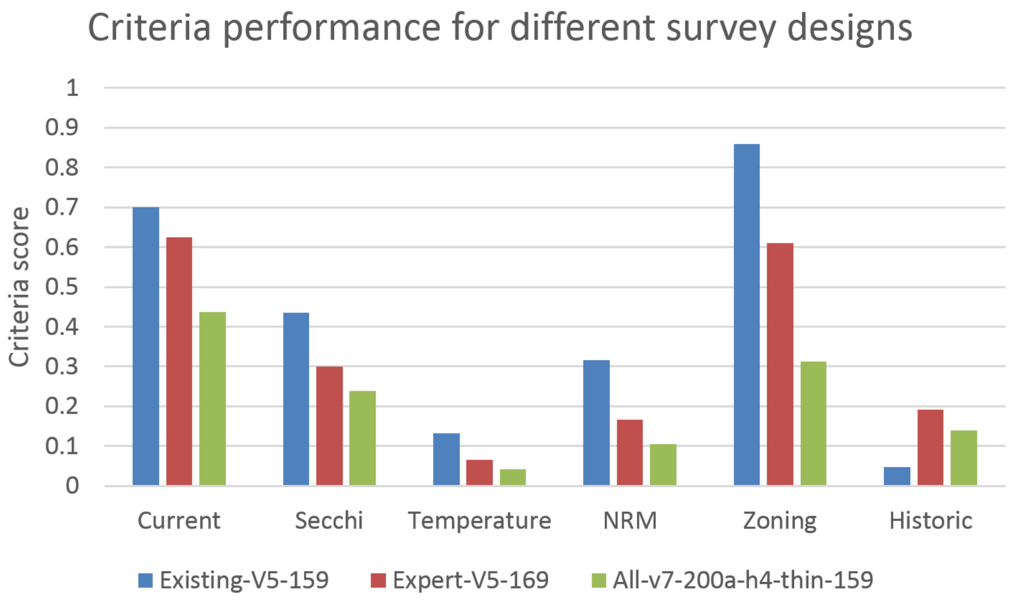


Figure 10**. Comparison between the criteria performance of the three survey designs. (Existing-V5-159, existing coral reef monitoring; Expert-V5-169, expert adjustment to improve coverage in Cape York, All-v7-200a-h4-thin-159, optimised by the Monitoring Site Planner tool). Note 1: Lower the score the better. Note 2: The existing coral reef monitoring does not capture all historic data because some historic manta tow surveys don't align with the current fixed monitoring sites.**

5.2 Choosing weights for optimisation

Understanding that some criteria are more difficult than others, combined with how important a criterion is, determines the appropriate weights that should be applied to optimising a survey design. In the case of the multi-criteria optimised design shown in Figure 9c) the weights were chosen to ensure that a high amount of historical data would be retained (weight of 4), it should try really hard to create reef pairs for zoning comparison (weight 2), it should consider a fair distribution of locations across NRMs, but not with high priority (weight 0.1), the secchi and temperature environmental gradients are nominally important (weight 1) and that of the current environmental gradients should be down weighted (weight of 0.5) because it is lower priority. Even with this down weighting the current will have a strong effect on the optimisation as this criterion has a high score and is difficult to meet.

The resulting optimised solution in Figure 9c) performs well under the criteria that it was tested against, however, a review of the survey design highlights some limitations. It has chosen 4 inshore sites in Cape York that are quite close to the mainland. These sites are probably unsuitable due to the potential risk from crocodiles. The optimiser has also chosen quite a few sites on the outer southern reefs as this area has reasonably high current flows allowing a better reconstruction of the current environmental gradient. In effect the optimiser found a set of reefs that were just below the maximum current allowed for safety reasons. It is therefore likely that on closer examination many of these sites will be impractical for surveying. These issues could be resolved with improved logistic modelling.

5.3 Monitoring survey design performance is a trade-off with historic data

From Figure 10 we can see that the expert adjustment for the monitoring program improved the performance for all criteria, but at the expense of losing some locations with historic data. The goal of this redesign was to improve coverage in Cape York, but without significantly increasing the number of monitored locations. Approximately 20 existing sites were moved, and an additional 10 sites were added, resulting in better spatial coverage of the overall program. This broader spatial coverage is what resulted in a better performance for the current, temperature, secchi, NRM and zoning, but resulted in almost a 14 per cent loss of historic data.

The survey design developed by the Monitoring Site Planner optimisers is also constrained by the trade-off between historic data and overall monitoring performance. It, however, managed to significantly outperform the manual redesign in all criteria, whilst using fewer monitoring locations at the expense of losing only 10 per cent of historic data. The optimiser moved more historic sites, but only those with the least historic data.

6 CONCLUSION

The Monitoring Site Planner tool was developed to capture the complex interplay between the various competing criteria for what makes for a good coral reef monitoring program for the Reef. We have developed a number of robust criteria and optimisation techniques that allow new monitoring survey designs of almost any size to be developed and evaluated. We demonstrated that the optimisation features allow the creation of survey designs that outperform manual designs against the criteria coded into the tool.

The Monitoring Site Planner does not model the full dynamics of the Reef and thus any recommendations from its multi-criteria analysis must be carefully considered by experts for logistical considerations and factors not modelled by the tool.

The final criteria, including any new criteria, and their weights, along with and “must have” reefs should be developed in close consultation with RIMReP stakeholders and the Coral Reef Expert Group. The Monitoring Site Planner was set up to evaluate and design new shallow coral reef monitoring programs, based largely on current monitoring techniques and technologies. In the future the criteria and reef database could be extended to assist in the design of monitoring other coral reef habitats such as deep reefs, or reef tops.

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7.1 Appendix – Interpolation models available for the Environmental Gradients criteria

The *Environmental Gradients* criteria takes samples of the environmental gradient at the monitoring locations then uses an interpolation model to estimate the value at all coral reefs in the Reef. The Monitoring Site Planner provides a range of simple and robust interpolation models for this purpose.

Inverse Distance Weight interpolation uses *n* nearest neighbour points to estimate the value at a location with an unknown value. The estimate is based on the weighted sum of the neighbouring locations with a known value. The value of the neighbours is weighted proportional to the inverse distance (p=1) or the inverse distance squared (p=2) from the neighbour to the interpolation location. The tool was setup with a range of simple interpolation models to allow the effect of changing the models on the resulting recommended survey design. After initial investigations it was determined that in most conditions the Inverse Distance Weight (n=6, p=2) performed best and thus was used for all survey design optimisation.

Table 2. Interpolation models available in the Monitoring Site Planner tool as part the Environmental Gradient criteria.

Interpolation Model	Notes
Nearest neighbour	Interpolated location gets the value of the closest known value. Added to the tool for comparison reason.
Inverse Distance Weight (n=4, p=1)	4 closest neighbours, weighted by inverse distance.
Inverse Distance Weight (n=4, p=2)	4 closest neighbours, weighted by inverse distance squared. This is the best model with few monitoring locations (< 50).
Inverse Distance Weight (n=6, p=1)	6 closest neighbours, weighted by inverse distance.
Inverse Distance Weight (n=6, p=2)	6 closest neighbours, weighted by inverse distance squared. This is the best model for > 50 monitoring locations.

7.2 Appendix – Must-have reefs

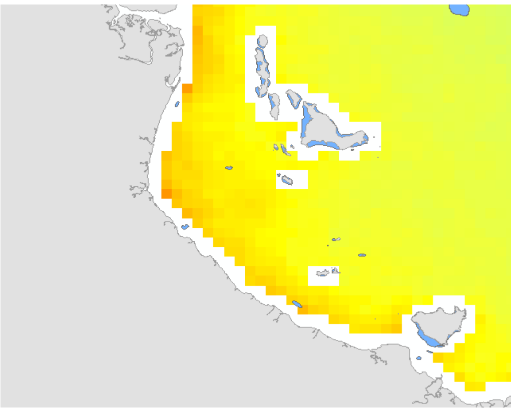
The following is the set of "Must Have" reefs that were included in the optimised multi-criteria survey design presented in section 5. When enabled, they are reinserted after each generation of the optimisation to ensure they are never removed from the survey design.

Table 3 **List of reefs that should be included in any reasonable monitoring program. These correspond to sites that are of high value, but this value is not captured in any of the existing criteria.**

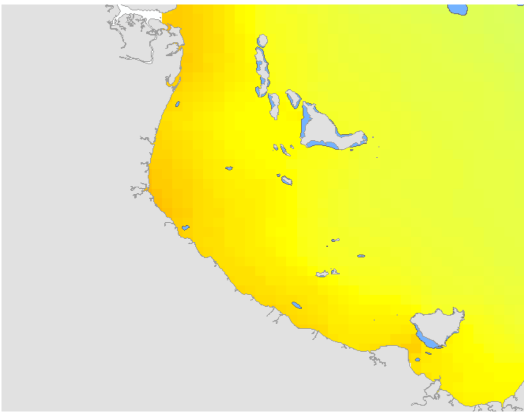
Location	Reason for inclusion	Expert
Agincourt Reefs (No 1) (15-099c)	Historic data close to AIMS weather station	Eric Lawrey, Kate Osborne
Low Islands Reef (16-028)	History, tourism	Kate Osborne
Orpheus (Goolboddi) Island Reef (No 5) (18-049e)	Research station, NE reef to best match LTMP photo transects	Hugh Sweatman, Kate Osborne
Pandora Reef (18-051)	Early AIMS science (historic cross shelf transect, TSV baseline)	Kate Osborne
Myrmidon Reef (18-034)	Early AIMS science (historic cross shelf transect, TSV baseline)	Kate Osborne
John Brewer Reef (18-075)	Location of museum of underwater art	Kate Osborne
Carter Reef (14-137)	Approximate oceanic reefs for global comparison	Kate Osborne
Green Island Reef (16-049)	Tourism	Eric Lawrey
Gannett Cay Reef (21-556)	Historic data	Kate Osborne
Heron Reef (23-052a)	Research station	Hugh Sweatman, Kate Osborne
North Keppel (Ko-no-mie) Island Rf (No 2) 23-004b	Close proximity to AIMS weather station	Eric Lawrey
One Tree Island Reef (23-055a)	Research station	Hugh Sweatman, Kate Osborne
Rib Reef (18-032)	Early responder reef (crown-of-thorns starfish); Early AIMS science (historic cross shelf transect, TSV baseline)	Hugh Sweatman, Kate Osborne
No Name Reef (14-139)	Approximates oceanic reefs for global comparison	Kate Osborne
Davies Reef (18-096)	AIMS weather station, easy logistics, close to TSV.	Kate Osborne
Lady Musgrave Reef (23-082a)	Tourism, AIMS weather station	Kate Osborne

7.3 Appendix – Infilling of raw environmental gradient data

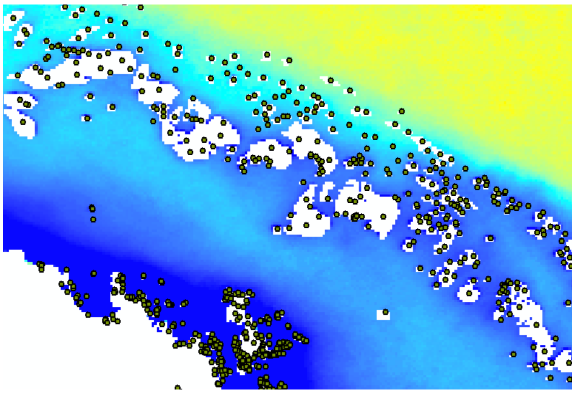
The *Environmental Gradients* criterion evaluates the performance of a given survey design by determining how well the environmental gradient (temperature, secchi, etc.) can be reconstructed at all reefs on the Reef from just the measurements taken at the monitoring locations. This criterion requires we have estimates at all reef locations in order for this to work. Many of the raw environmental gradient datasets contained holes around islands or reefs. These needed to be infilled before they could be used in the Monitoring Site Planner. A spatial moving average filter was used to fill these holes with estimates from surrounding pixels.



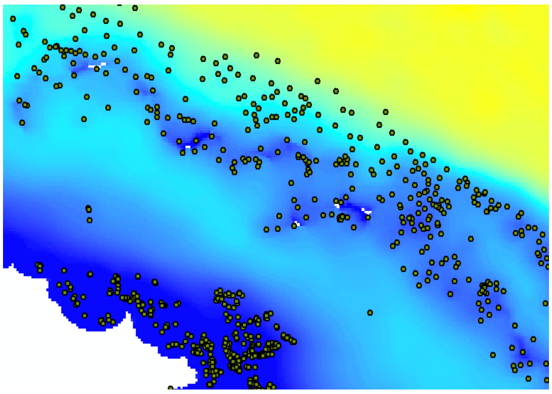
Example close up view of the raw SSTAARS temperature showing that the pixels around islands and the mainland have been excluded. This is presumably to remove contamination from land temperatures in the water temperature estimates.



A 3 pixel radius mean filter was used to infill the data around islands and along the mainland.



Close of the raw mean annual secchi before infilling. The holes in the data correspond with reef areas that are excluded in the remote sensing to due to contamination from shallow water reflections.



A 5-pixel radius mean filter was used to fill in nearly all the holes. The dots correspond with reef centroids where the data is sampled for the reef database. The infilling approximates sampling the waters surrounding each reef.

Figure 11. Infilling of the temperature and secchi source data to ensure that all reefs have an estimate of these environmental gradients.