Appendix A

A.1. Scott Reef surveys

In Scott Reef, there are three nested sites at each reef location and one observation has been collected from each site for a given survey time. The number of samples collected for each survey time at Scott Reef is summarised in Table A.1. For example, 21 observations have been collected for survey time 1994.83 using three sites at each reef location. It can be seen from the table that there are some variations in survey practices over time. In particular, site replication has been abandoned after the bleaching event in 2016.

A.2. Distribution of hard coral cover

We visualise the distribution of coral cover at Scott Reef to see how it varies over time (Figure A.1). Accordingly, it exhibits a nonlinear trend with a sudden shift around the 1998 bleaching event. In addition, the distribution of hard coral cover by reef locations is shown in Figure A.2. The years of cyclone events be provided Table A.2. It can be seen from the individual figures that different reef locations have been impacted differently due to bleaching and cyclone disturbances.

A.3. Posterior estimation

The joint posterior distribution of model parameters and random effects can be expressed in a Bayesian framework as follows: 

\[ p(\theta, \xi \mid y_h, Z_h, V_h, d_h) \propto \]
Table A.1: Survey variations over time at Scott Reef. The first column represents survey times used at Scott Reef where the decimal places indicate the survey times within the given year. The next three columns represent three sites at each reef location. The value seven for a particular site index means that the corresponding site has been surveyed at all the seven reef locations. The last column represents the total number of observations collected over the seven reef locations using three sites which are located at each reef location. Starting from 2016.08, only the first site has been surveyed at each reef location which results in the total number of seven observations for the corresponding survey times.

| Site index | Survey times | 1 | 2 | 3 | Total number of observations |
|------------|-------------|---|---|---|-------------------------------|
| 1994.83    | 7           | 7 | 7 | 7 | 21                            |
| 1995.83    | 7           | 7 | 7 | 7 | 21                            |
| 1996.83    | 7           | 7 | 7 | 7 | 21                            |
| 1997.92    | 7           | 7 | 7 | 7 | 21                            |
| 1998.58    | 3           | 0 | 1 |   | 4                             |
| 1998.90    | 7           | 7 | 7 | 7 | 21                            |
| 1999.92    | 6           | 5 | 5 |   | 16                            |
| 2001.90    | 6           | 6 | 6 | 6 | 18                            |
| 2004.00    | 6           | 6 | 6 | 6 | 18                            |
| 2004.33    | 3           | 0 | 1 |   | 4                             |
| 2004.83    | 7           | 7 | 7 | 0 | 14                            |
| 2008.08    | 7           | 7 | 7 | 7 | 21                            |
| 2010.83    | 7           | 7 | 7 | 7 | 21                            |
| 2012.92    | 7           | 7 | 7 | 7 | 21                            |
| 2014.83    | 7           | 6 | 7 | 7 | 20                            |
| 2016.08    | 7           | 0 | 0 | 0 | 7                             |
| 2016.33    | 7           | 0 | 0 | 0 | 7                             |
| 2016.83    | 7           | 0 | 0 | 0 | 7                             |
| 2017.92    | 7           | 0 | 0 | 0 | 7                             |

\[
p(y_h \mid \beta_0, \beta_1, \beta_t, \beta_d, \beta_s, \gamma_{sr}, \delta, Z_h, V_h, d_h)p(\gamma_{sr} \mid \lambda_r, \log \sigma_s)p(\lambda_r \mid \log \sigma_r)p(\delta \mid \log \sigma_\delta)p(\theta)
\]

where the first term on the right hand side is the conditional likelihood (i.e. conditional on the random effects), and then, \(p(\delta \mid \log \sigma_\delta)\) is the distribution of random coefficients, and \(p(\theta)\) is the prior distribution (Table A.3). In this study, all historical data at Scott Reef were analysed within a
ADAPTIVE MONITORING OF CORAL HEALTH

Figure A.1: Distribution of hard coral cover at Scott Reef over time. The fitted blue line is the mean curve produced using `geom_smooth` function in ggplot2 package in R using the default smooth method (i.e. “loess”). The shaded red area represents the corresponding 95% confidence interval for the mean. The sudden shift in hard coral cover due to 1998 bleaching event is marked using a light blue colour box.

Table A.2: The years of reef location specific cyclone events. Here, C represents Cyclone or multiple cyclones and SC represents Severe Cyclone.

| From   | To    | SL1 | SL2 | SL3 | SL4 | SS1 | SS2 | SS3 |
|--------|-------|-----|-----|-----|-----|-----|-----|-----|
| 1994.83| 1995.83|     |     |     |     |     |     |     |
| 1995.83| 1996.83|     |     |     |     |     |     |     |
| 1996.83| 1997.92|     |     | C   |     |     |     |     |
| 1997.92| 1998.90|     |     |     |     |     |     |     |
| 1998.90| 1999.92|     |     |     |     |     |     |     |
| 1999.92| 2001.90|     |     |     |     |     |     | C   |
| 2001.90| 2004.00|     |     |     |     |     |     |     |
| 2004.00| 2004.83| C   |     |     |     |     |     |     |
| 2004.83| 2008.08|     |     | SC  | C   |     |     |     |
| 2008.08| 2010.83|     |     |     |     |     |     |     |
| 2010.83| 2012.92| C   |     | SC  | SC  |     |     |     |
| 2012.92| 2014.83|     |     |     |     |     |     |     |
| 2014.83| 2016.08|     |     |     |     |     |     |     |
| 2016.08| 2016.83|     |     |     |     |     |     |     |

Bayesian framework using WinBUGS to sample from the posterior distribution for the purpose of model selection.
Figure A.2: Distribution of hard coral cover by reef locations at Scott Reef. The fitted blue lines are the mean curves produced using `geom_smooth` function in ggplot2 package in R using the default smooth method (i.e. “loess”). The shaded red areas represent the corresponding 95% confidence intervals for the means. Some badly affected reef locations due to 1998 bleaching event are marked using light blue colour boxes. Here, the impact of a bleaching event can last for years after the event so some locations have been highlighted after the year 1998.
Table A.3: The individual components of the adopted prior distribution $p(\theta)$.

| Parameters                                     | Prior distributions          |
|------------------------------------------------|-----------------------------|
| Each component of $\beta_i$ and $\beta_d$     | $N(0, 100^2)$               |
| Regression coefficients $\beta_0$, $\beta_1$, and $\beta_s$ | $N(0, 100^2)$               |
| Random coefficients $\delta_k$                | $N(0, \sigma^2_\delta)$    |
| Random effects for reef locations $\lambda_r$ | $N(0, \sigma^2_r), r = 1, \ldots, 7$ |
| Random effects for sites $\gamma_{sr}$        | $N(\lambda_r, \sigma^2_s), r = 1, \ldots, 7; s = 1, 2, 3$ |
| linear log $\sigma_\delta$                    | $N(5, 1)$                   |
| Reef random effects log $\sigma_r$            | $N(-1, 1)$                  |
| Site random effects log $\sigma_s$            | $N(-1, 1)$                  |

A.4. Model selection

We used the $\mathcal{M}$-closed perspective to determine the most appropriate model to describe the historical data at Scott Reef. The model selection results using DIC criterion for the formulated models is provided in Table A.4.

Table A.4: Model selection results using DIC criterion. The “+” and “-” imply whether respective component/covariate is included or excluded from the model. The components and covariates dropped at each stage are shown using bold text.

| Components in the model                                      | DIC       |
|-------------------------------------------------------------|-----------|
| ALL COV+NRE+SC                                             | 8897.710  |
| ALL COV+NRE-SC                                             | 9343.130  |
| ALL COV-NRE+SC                                             | 11525.400 |
| ALL COV-NRE-SC                                             | 11998.300 |
| ALL COV+NRE+SC -interaction-Bleaching Loc-Cyclone Loc2     | 17367.400 |
| ALL COV+NRE+SC -interaction-Bleaching Loc-Cyclone Loc2-Intteruppted98 | 27588.400 |
| ALL COV+NRE+SC -interaction-Bleaching Loc-Cyclone Loc2-Intteruppted98-Cyclone hours | 27686.800 |
| ALL COV+NRE+SC -interaction-Bleaching Loc-Cyclone Loc2-Intteruppted98-Cyclone hours-Bleaching | 28061.200 |
| Null model                                                 | 28742.200 |
A.5. Posterior summary

The posterior summary statistics including 95% credible intervals are reported in Table A.5, for the final model choice. Accordingly, all parameters are significant (i.e. credible intervals do not contain zero) except the coefficients for Bleaching. This Bleaching covariate represents bleaching occurrences except for the mass bleaching event in 1998 that was accounted for using ITS approach. Except for that mass bleaching event, Scott reef has undergone only a few bleaching events. As Bleaching is an indicator variable in the model, it may be that bleaching present does not contrast with the bleaching absent; thus, it could result in a non-significant bleaching effect. Furthermore, it should be noted that bleaching is involved in a significant interaction with cyclones in the model. Thus, this disturbance is having a significant effect depending upon the value of the cyclone variable. In terms of random effects, the posterior distribution summary is provided in Table A.6. Accordingly, all reef random effects are non-significant. This indicates that there is not a lot of variability in hard coral cover trajectories at the reef location level. However, there are some significant site random effects indicating that there are distinguishable hard coral cover trajectories at the site level.

A.6. Goodness-of-fit

To assess the goodness-of-fit of the model defined above, a posterior predictive check was used. This involved comparing the observed data with data
Table A.5: Summary of the posterior distribution of the model parameters.

| Parameter          | Mean  | Standard deviation | Lower bound of 95% credible interval | Upper bound of 95% credible interval |
|--------------------|-------|--------------------|--------------------------------------|--------------------------------------|
| Log $\sigma_\delta$ | 1.150 | 0.490              | 0.360                                | 2.218                                |
| Log $\sigma_r$     | -1.992| 0.476              | -2.969                               | -1.122                               |
| Log $\sigma_s$     | -1.704| 0.192              | -2.054                               | -1.304                               |
| Intercept          | 0.656 | 0.093              | 0.470                                | 0.826                                |
| Time               | -9.657| 0.711              | -11.000                              | -8.107                               |
| Bleaching          | 0.032 | 0.025              | -0.017                               | 0.080                                |
| Cyclone hours      | -0.038| 0.002              | -0.042                               | -0.035                               |
| BLE98              | -1.649| 0.026              | -1.700                               | -1.598                               |
| Time98             | 7.216 | 0.448              | 6.233                                | 8.068                                |
| Cyclone loc        | -0.418| 0.014              | -0.444                               | -0.391                               |
| Severe cyclone loc | 1.426 | 0.022              | -1.469                               | -1.382                               |
| Bleaching loc      | -1.010| 0.019              | -1.047                               | -0.973                               |
| Bleaching $\times$ Cyclone | -0.331| 0.022              | -0.376                               | -0.288                               |
| Random coefficient 1| -2.113| 0.167              | -2.433                               | -1.751                               |
| Random coefficient 2| 1.092 | 0.059              | 0.976                                | 1.207                                |
| Random coefficient 3| 2.821 | 0.145              | 2.522                                | 3.089                                |

simulated from the posterior predictive distribution (Gelman and Hill, 2007). This comparison is shown in Figure A.3 where the derived model appears to describe the trends and variability in the data well. Similarly, we checked the posterior predictive distribution at each of the seven reef locations (Figure A.4). From the individual figures, it can be seen that the trends and variability of the data are well captured by the model at the reef location level.

A.7. Extrapolation results

To investigate the appropriateness of the proposed (Graham et al., 2007) Taylor series approximation to the mean response, this approximation was
**Table A.6: Summary of the posterior distribution of the random effects.** The first row represents random effects related to the seven reef locations. The second row represents random effects related to the 21 sites locations nested within reef locations.

| Random effect | Mean   | Standard deviation | Lower bound of 95% credible interval | Upper bound of 95% credible interval |
|---------------|--------|--------------------|--------------------------------------|-------------------------------------|
| SL1           | -0.0150| 0.1001             | -0.2146                              | 0.1917                              |
| SL2           | 0.1848 | 0.1251             | -0.0254                              | 0.4585                              |
| SL3           | -0.0139| 0.1005             | -0.2133                              | 0.1903                              |
| SL4           | -0.1195| 0.1090             | -0.3546                              | 0.0764                              |
| SS1           | 0.0445 | 0.1029             | -0.1523                              | 0.2631                              |
| SS2           | -0.0824| 0.1046             | -0.3053                              | 0.1133                              |
| SS3           | 0.0287 | 0.1019             | -0.1609                              | 0.2441                              |
| SL1-1         | 0.0533 | 0.0803             | -0.0958                              | 0.2235                              |
| SL1-2         | -0.0639| 0.0806             | -0.2133                              | 0.1074                              |
| SL1-3         | -0.0724| 0.0808             | -0.2238                              | 0.0979                              |
| SL2-1         | 0.1278 | 0.0805             | -0.0209                              | 0.2982                              |
| SL2-2         | 0.4847 | 0.0807             | 0.3345                               | 0.6561                              |
| SL2-3         | 0.2874 | 0.0806             | 0.1377                               | 0.4586                              |
| SL3-1         | -0.0450| 0.0805             | -0.1959                              | 0.1251                              |
| SL3-2         | 0.3075 | 0.0805             | 0.1579                               | 0.4801                              |
| SL3-3         | -0.3332| 0.0807             | -0.4847                              | -0.1618                             |
| SL4-1         | -0.2825| 0.0805             | -0.4321                              | -0.1120                             |
| SL4-2         | -0.0817| 0.0805             | -0.2325                              | 0.0887                              |
| SL4-3         | -0.2322| 0.0807             | -0.3836                              | -0.0618                             |
| SS1-1         | -0.0068| 0.0805             | -0.1548                              | 0.1646                              |
| SS1-2         | 0.1826 | 0.0804             | 0.0322                               | 0.3527                              |
| SS1-3         | 0.0349 | 0.0807             | -0.1163                              | 0.2038                              |
| SS2-1         | -0.1777| 0.0805             | -0.3264                              | -0.0064                             |
| SS2-2         | -0.0882| 0.0804             | -0.2383                              | 0.0817                              |
| SS2-3         | -0.1483| 0.0810             | -0.2990                              | 0.0222                              |
| SS3-1         | 0.0284 | 0.0808             | -0.1212                              | 0.1978                              |
| SS3-2         | 0.2382 | 0.0807             | 0.0892                               | 0.4092                              |
| SS3-3         | -0.1311| 0.0814             | -0.2816                              | 0.0417                              |

used to predict future but known hard coral cover in our data set (akin to a leave-one-out cross validation approach), we visualised the extended curves for each of the seven reef locations. For instance, Figure A.5 shows simulated values when the considered design included one site per reef location. As can be seen, the approximation appears to be reasonable for the next sampling
Figure A.3: Overall posterior predictive pattern based on the final model choice. The red lines represent the median and the lower and upper bounds of the 95% credible intervals for the prediction.

point (i.e. 2016.33). Given this, we propose the approach can be used to simulate supposed future data (line 4 in Algorithm 1) when determining adaptive designs.

A.8. Disturbance scenarios

Representatives from AIMS provided us with two disturbance scenarios (i.e. two values for $z$) for which we evaluated designs (Table A.7). In Table A.7, the first row includes the covariates at the last survey time used for modelling where the covariate values represent the existing disturbance conditions between 2014.83 and 2016.08. The changes to the disturbance conditions when moving from the last survey time considered in this study (i.e. 2016.08) to the next survey time (i.e. 2016.33) under disturbance Sc-
Figure A.4: Posterior predictive patterns based on the final model choice at each reef location. The red lines represent the median and the lower and upper bounds of the 95% credible intervals for the prediction.

scenarios (a) and (b) are provided in the second and third rows, respectively.
Figure A.5: Extrapolation of mean curves by reef locations to the next survey time. The red curves represent the median (i.e. median of mean values) and the corresponding lower and upper bounds of the 95% credible intervals for the “seen” data. Extrapolated curves up to the next survey time are shown in green colour.
ADAPTIVE MONITORING OF CORAL HEALTH

Table A.7: Covariate values at the last survey time considered for modeling (i.e. 2016.08) and under two disturbance scenarios adopted in this study. Here, covariates at a given sampling time point have been defined based on what happened in between sampling times. Accordingly, the changes occurred in the covariates under each scenario compared with the last survey time are highlighted in red colour.

| Survey times/Scenarios | Reef location | Bleaching location | Cyclone hours | Cyclone Loc | Severe Bleaching | Bleaching Loc | Bleaching × Cyclone |
|------------------------|--------------|--------------------|---------------|-------------|-----------------|---------------|---------------------|
| The last survey        | SL1          | 1                  | 6.928         | 0           | 0               | 1             | 0                   |
|                        | SL2          | 1                  | 6.928         | 0           | 0               | 1             | 0                   |
|                        | SL3          | 1                  | 6.928         | 0           | 0               | 1             | 0                   |
| Historical data (i.e. 2016.08) | SL4 | 1                  | 6.928         | 0           | 0               | 1             | 0                   |
|                        | SS1          | 1                  | 6.928         | 0           | 0               | 1             | 0                   |
|                        | SS2          | 1                  | 6.928         | 0           | 0               | 1             | 0                   |
|                        | SS3          | 1                  | 6.928         | 0           | 0               | 1             | 0                   |
| Scenario (a)           | SL1          | 1                  | 0             | 0           | 0               | 1             | 0                   |
| New disturbances at time 2016.33 | SL2 | 1                  | 0             | 0           | 0               | 1             | 0                   |
|                        | SL3          | 1                  | 0             | 0           | 0               | 1             | 0                   |
| Changes occurred:      | SL4          | 1                  | 0             | 0           | 0               | 1             | 0                   |
| Removed cyclone impacts | SS1 | 1                  | 0             | 0           | 0               | 1             | 0                   |
|                        | SS2          | 1                  | 0             | 0           | 0               | 1             | 0                   |
|                        | SS3          | 1                  | 0             | 0           | 0               | 1             | 0                   |
| Scenario (b)           | SL1          | 1                  | 6.928         | 1           | 0               | 1             | 1                   |
| New disturbances at time 2016.33 | SL2 | 1                  | 6.928         | 1           | 0               | 1             | 1                   |
|                        | SL3          | 1                  | 6.928         | 1           | 0               | 1             | 1                   |
| Changes occurred:      | SL4          | 1                  | 6.928         | 1           | 0               | 1             | 1                   |
| Added cyclone location impacts | SS1 | 1                  | 6.928         | 1           | 0               | 1             | 1                   |
| and an interaction     | SS3          | 1                  | 6.928         | 1           | 0               | 1             | 1                   |

A.9. Utility evaluations

In the case where the prior and the posterior distributions both are Multivariate Normal, then the KLD utility function can be defined as follows:
ADAPTIVE MONITORING OF CORAL HEALTH

\[
u(d, y|d_h, y_h) = \frac{1}{2} \left( \text{tr}((\Sigma^*_m)^{-1}\Sigma^*_m) + (\theta^*_m - \theta^*_{m_0})^T \times (\Sigma^*_m)^{-1} \right.
\]

\[
\left. \times (\theta^*_m - \theta^*_{m_0}) - q_m + \ln \left( \frac{\det \Sigma^*_m}{\det \Sigma^*_m} \right) \right),
\]

where \( \theta^*_m, \theta^*_{m_1} \) and \( \Sigma^*_m, \Sigma^*_m \) are the means and variance-covariance matrices of the prior and posterior distributions, respectively and \( q_m \) is the dimension of the parameter space.

A.10. Informative sites at each reef location

We determine the optimal design that comprises of the most informative site at each reef location subject to two disturbance scenarios under Objective (ii). The selected sites from each reef location into the optimal designs and expected utility values under the two scenarios are provided in Table A.8.
Table A.8: The optimal designs selected sites and expected utility values under Scenario (a) and (b) for Objective (ii). The red and green colours represent sites selected into optimal designs under Scenario (a) and (b), respectively.

| Reef locations | Scenario (a) | Scenario (b) |
|----------------|--------------|--------------|
|                | Optimal design | Expected utility | Optimal design | Expected utility |
| SL1            | 1             | 50.05         | 1             | 66.16         |
|                | 2             | 49.63         | 2             | 63.82         |
|                | 3             | 49.46         | 3             | 64.86         |
|                | 4             | 50.05         | 4             | 66.16         |
| SL2            | 5             | 49.70         | 5             | 65.77         |
|                | 6             | 49.55         | 6             | 64.77         |
|                | 7             | 50.05         | 7             | 66.16         |
| SL3            | 8             | 49.36         | 8             | 64.82         |
|                | 9             | 49.09         | 9             | 64.66         |
|                | 10            | 50.05         | 10            | 66.16         |
| SL4            | 11            | 49.45         | 11            | 65.71         |
|                | 12            | 49.29         | 12            | 65.47         |
|                | 13            | 50.05         | 13            | 66.16         |
| SS1            | 14            | 49.76         | 14            | 65.02         |
|                | 15            | 50.03         | 15            | 64.51         |
|                | 16            | 50.05         | 16            | 66.16         |
| SS2            | 17            | 49.81         | 17            | 64.22         |
|                | 18            | 49.48         | 18            | 63.88         |
|                | 19            | 50.05         | 19            | 66.16         |
| SS3            | 20            | 49.41         | 20            | 65.64         |
|                | 21            | 49.38         | 21            | 66.11         |