Dynamic model; the effects of eutrophication and sedimentation on the degradation of Coral Reefs in Spermonde Archipelago, Indonesia

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Abstract. Coral reef condition is influenced by many physical, biological, and anthropogenic processes. This research was designed to build a model between nutrient enrichment, sedimentation, and the abundance of herbivorous fish on macroalgae and coral reef coverage within the context of coral reef degradation. The research was conducted in the Spermonde Archipelago. The method used was the field survey method. The data were analyzed by using modeling instrument techniques. The results show that if there is no control over nutrient supply and sedimentation and efforts to increase the density of herbivorous fish, then the condition of coral reefs in Spermonde Archipelago is threatened with severe damage. The condition of coral reefs can be improved by decreasing nutrient supply and sedimentation of 6% each and increasing the herbivorous fish population by 5%.

1. Introduction

Some results of coral reef monitoring studies show that damage to the global coral reefs is caused by several factors; natural decease [1-2], overexploitation [3], development in coastal areas [3], anthropogenic activities; pollution [4-6] and sedimentation [3]. One of the anthropogenic wastes in the marine environment is nutrient in the form of Nitrate (N) and Phosphor (P) [4-6].

One of the anthropogenic factors that deteriorate the coral destruction is sedimentation [7]. There are four sedimentation pressures on coral reefs; 1). Smothering (polyp closure) causes coral death. 2) Abrasion (reduction of calcium skeletons on reefs), 3) Shading (decrease in light intensity and reduced photosynthesis), and 4) inhibition of recruitment [8].

Another anthropogenic factor is the increase of N and P elements in the marine environment that will have an impact on coral reefs [9-13]. Nutrient enrichment on coral reefs will cause a "phase-shift", which is marked by the change of a reef which was originally dominated by corals into a reef dominated by algae in a relatively long period [14-15].

Damage to coral reefs will occur quickly if macroalgal growth is not controlled [16-19]. Herbivorous fish are the main controlling agent for macroalgal growth [10, 20]. Littler (1994) and Littler et, al., (2006) [21,22] developed the Relative Dominance Model enabling the dominance of autotrophic benthic on coral reefs that may be predicted from nutrient concentration and herbivorous fish populations. Interactions between herbivorous fishes, nutrient enhancement, biological disturbances, and other physical disorders may influence the community change on coral reefs [9, 10, 23].
Interactions between nutrient enrichment, sedimentation, macroalgae growth, and herbivorous fish populations affect decreasing live coral cover. Therefore, it is necessary to build a dynamic model between these components. This model will be proposed as a recommendation for coral reef management (Figure 1). Case study model development was applied in some islands within Spermonde Archipelago, Indonesia (Figure 2).

**Figure 1.** Row model of interactions between sediments, nutrients, herbivorous fish, and coral reef competition with macroalgae.

The condition of coral reefs within the last two decades in Spermonde Archipelago has decreased [24, 25]. Damage to coral reefs in this region is generally caused by destructive fishing, bombs, cyanide, illegal fishing gear [26], and increasing quantities of domestic and industrial wastes [27-29].

2. **Methodology**
The research method was more emphasized in the development of dynamic models using a research study [30]. Research sites in the Spermonde Archipelago, South Sulawesi Province, (Figure 2). Placement of sampling points was based on zonal representation [31]; i.e. inner zone (Lae-Lae Island and Salemo Island), middle inner zone (Barranglompo and Bontosua Island), outer middle zone (Reang-reang Island), and outer zone (Suranti Island).

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**Figure 1.** Row model of interactions between sediments, nutrients, herbivorous fish, and coral reef competition with macroalgae.
2.1. Causal loop

The built model was prepared using the Spiegelhalter algorithm [32]. The research variables were arranged in several compartments; sedimentation, nutrient, herbivore fish, coral reef, and macroalgae. Interactions among all compartments were connected by causal loops (Figure 3) [33,34].

![Causal Loop model of interaction among each variable in the system.](image-url)
2.2. System identification
The dynamic modeling in this article covered quantitative techniques and simulations used to study the interrelationships of variables using several compartments; herbivorous fish sub-model, nutrient sub-model (Nitrate Concentration), sedimentation rate sub-model, macroalgae cover sub-model and coral cover sub-model (Figure 4).

![Diagram of dynamic model](image)

**Figure 4.** Dynamic model; eutrophication and sedimentation influence on coral damage.

Model simulations applied the following equations:

\[
\begin{align*}
TK &= 100\% - TM - Est\ SK \\
TM &= 0.053N - 4.83IK + 44.274 \\
Est\ SK &= -141.23S + 36.359
\end{align*}
\]

Where TK = Live Coral Coverage (%); TM = Macroalgae Coverage (%); Est SK = Estimation of Coral Reduction Due to Sedimentation; IK = Herbivorous Fish Abundance; N = Nitrate Concentration; and S = Sedimentation Rate

2.3. Model validation
Model was validated using Regression Analysis and the Kalman Filter test. The test was conducted to see the tendency of increased live coral cover from the influence of macroalgae and sedimentation by comparing actual conditions (field data) with the results of simulation models.
3. Results and discussion

3.1. Model validation

The results of Linear Regression Test based on the field data from Faizal's research (2012), reveal that there is a real relationship between actual live coral cover and a simulation value of $R^2 = 0.94$ and likewise for macroalgae cover with a value of $R^2 = 0.95$ (Figure 5). Furthermore, the Kalman Filter test results (Table 1), obtained an accuracy of 50.2% for coral cover and 48.2% for macroalgae.

Figure 5. The results of the regression analysis for the validation test; (a) live coral cover; (b) macroalgae cover between simulation results and field data.

| Table 1. Kalman Filter Statistical Tests on sub-model coral cover and macroalgae. |
|---------------------------------|-----------------|
| Parameters                      | Value           |
| $Va$ = Variant of the actual value of Coral cover | 14.519          |
| $Vs$ = Variant of Coral Cover Simulation Value | 14.670          |
| $KF = Vs/(Vs+Va)$ | 0.502           |
| $Va$ = Variant of the actual value of macroalgae cover | 13.942          |
| $Vs$ = Variant of macroalgae Cover Simulation Value | 13.02           |
| $KF = Vs/(Vs+Va)$ | 0.482           |

Figure 5, shows that the value of determination ($R^2$ Square) has the meaning of the contradiction between the simulation value and the value of the field data, which also shows that there is an influence between the two variables [35-36]. The Kalman filter test results in Table 1 have a matching level of simulation results, according to Eriyatno (1999) [37] that a good level of simulation results is if the accuracy is 47.5 - 52.3%. Based on the two tests, the model is valid for use in research simulations.

3.2. Real model simulation

To predict the condition of coral reefs in Spermonde Archipelago in the next 15 years (2011-2026), assuming there is no effort for the improvement of ecosystem conditions, an actual condition simulation is conducted. Simulation results show that all sampling sites will experience a reduction in live coral cover. Coral cover on Lae-lae and Bontosua Islands will be depleted in the 9th and 12th years, respectively (Figure 6 and Appendix 1)
Figure 6. Prediction of the actual condition of coral cover in the Spermonde Archipelago in 2026; a) Lae-Lae, b) Salemo, c) Barranglompo, d) Bontosua, e) Reang-reang and f) Suranti.

Prediction data shows that if there is no control over nutrient supply and sedimentation and efforts to increase the density of herbivorous fish, then the condition of coral reefs in the Spermonde Archipelago is seriously damaged. This is corroborated by several studies of live coral cover reduction in Spermonde \[24,25,27-29\].

3.3. Model sensitivity
Model sensitivity analysis is a measuring tool to identify variables that influence the response of the model. The level of sensitivity of each variable to changes in coral cover is done by adding a coefficient value of 0.1 to each variable constant. Predictive values are shown in Appendix 2, and the sensitivity test results in Figure 7.
The sensitivity test results in Figure 7, show that nutrient is the most sensitive parameter for ecosystem changes. This explains that nutrient enrichment is a major cause of changes in the composition of ecosystems in the Spermonde Archipelago. Enrichment of nutrients will increase zooxanthellae and chlorophyll-a within coral tissue [38], reduced coral growth, and calcification rate [39]. Various previous studies informed that the influence of nutrients on coral reefs is very significant [40]. On healthy coral reefs, the average concentration of nutrients in water is 0.1-0.5 µM nitrate, 0.2-0.5 µM for ammonium, and less than 0.3 µM for phosphorus [41-42].

The growth of coral reefs that live in ecosystems that experience nutrient enrichment is very different from the condition of ecosystems that do not experience nutrient enrichment. Edinger et.al., (2000) suggested that the characteristics of coral reefs that live in areas that experience nutrient enrichment are as follows: (1). The dispersion rate of individuals is lower (2). Total coral cover and coral species density is low, and coverage of macroalgae is higher and (3). Bioerosion intensity is higher in the enriched reefs.

3.4. Model implementation
The implemented model was a simulation model based on [37] with three scenarios; pessimistic, moderate, and optimistic. The model strategy is influenced by three key factors, as shown in Table 2, with the model scenario as in Table 3. The results of running models for each scenario are shown in Figure 8 and Appendix 3.4, and 5.

Table 2. Prospective key factors for eutrophication control on coral reefs.

| No | Key Factor          | Strategy                        | A              | B              | C              | D              |
|----|---------------------|---------------------------------|----------------|----------------|----------------|----------------|
| 1  | Nutrient Supply     | Constantly                      | Decrease (3%/year) | Decrease (6%/year) | Increase (6% / year) |
| 2  | Herbivorous Fish    | Constantly                      | Increase(2.5% /year) | Increase (5% / year) | Decrease (5%/year) |
| 3  | Sedimentation Supply| Constantly                      | Increase(3% /year) | Increase(6% /year) | Increase(6% /year) |
### Table 3. The scenario of eutrophication control strategies on coral reefs.

| No. | Scenarios   | Factor Sequence |
|-----|-------------|-----------------|
| 1.  | Pessimistic | 1D-2A-3D        |
| 2.  | Moderate    | 1C-2B-3C        |
| 3.  | Optimistic  | 1C-2C-3C        |

**Figure 8.** Prediction of changes in coral cover at each station for each scenario; A1-A2: pessimistic, B1-B2: moderate and C1-C2: optimistic for 15 years (2011-2026) period.

In Figure 8 (A1-A2) for pessimistic scenarios, the modulation predictions produced live coral cover values, which are quite discouraging i.e. 16.38%. All stations in the study area will experience a reduction in live coral cover. Even some stations will lose live coral cover within 15 years. This
condition explains that in pessimistic conditions, without serious efforts from the government in the management of coral reefs, there will be a decrease in total live coral cover.

Figure 8 (B1-B2) with the implementation of a moderate scenario with improved environmental quality, as shown in Tables 2 and 3. The results of the model prediction reveal that there was an improvement in a live coral cover of 9.75% from the average initial condition of 30% to 39.75%. This explains that if the exploitation of the herbivorous fish is controlled, it will increase the grazing of macroalgae [43]. Interactions between herbivorous fish and macroalgae based on a study in Jamaica confessed that restriction of the herbivorous fishing in the period of 1996-1999 had reduced the percentage of macroalgal cover up to 10% of 60% [44]. Herbivorous fish are the only mechanism in controlling macroalgal growth on coral reefs. If macroalgal growth is not controlled, it will automatically dominate coral reefs [10].

Figure 8 (C1-C2), with the application of an optimistic scenario, will produce a system performance that is able to suppress the growth of macroalgae in the future. The optimistic model prediction results obtained improvements in live coral cover in the Spermonde Archipelago from 30% to 50.3% within 15 years. Efforts to improve the quality of the aquatic environment and increase herbivorous fish populations will increase the improvement of live coral cover. If the supply of nutrients to the waters is abundant, the growth of macroalgae will be faster as well. Although herbivorous and grazing fish occur, if these two factors are controlled, between grazing and growth, coral recruitment will increase [45-46], a change in community structure becomes the dominance of coral reefs [14-15].

Figure 8 shows the predicted value of coral reef conditions between the pessimistic, moderate, and optimistic scenarios. Based on the level of probability of coral condition improvement, the best sequence of scenarios is optimistic (50.3%), moderate (39.75%) and pessimistic (16.38%). Figure 9 shows a comparison of the live coral cover of all scenarios with a minimum ratio of the healthy coral cover of 51%. The optimistic scenario is a scenario that is expected to occur because this scenario is very close to the category of healthy coral conditions.

![Figure 9](image)

**Figure 9.** Comparative graph of living coral conditions from pessimistic, moderate, and optimistic scenarios and quality standards for healthy corals.

This study recommends an optimistic scenario. It is based that there are many probable causes of coral damage. The anthropogenic activity was only accounted for 22% of damage to coral reefs, meaning that there are still around 78% of other factors that influence; climate change [2,47], coral exploitation for building materials [12], the use of bombs and cyanide in fish capture [3]. The analysis and model results elaborate three key parameters that may be managed in controlling coral reef damage due to anthropogenic waste, namely; herbivorous fish density, nutrient concentration, and sedimentation rate. If these three factors are able to be controlled, it is possible to
improve the condition of existing coral reefs from damage caused by anthropogenic waste, at least 22%.

4. Conclusion
The interaction model between anthropogenic activities and decreasing live coral cover in the Spermonde Archipelago is valid to be implemented with the greatest sensitivity due to the effect of increased nutrients. Improvement of the condition of coral reefs from an average coral cover of 30.3% to 50.3% may be obtained with a scenario of decreasing nutrient supply and sedimentation by 6% each and increasing of herbivorous fish populations by 5%.

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Appendix

Appendix 1. Prediction of Actual Condition of Live Coral Cover (%) in the Spermonde Archipelago.

| Year | Lae-lae | Salemo | Barranglompo | Bontosua | Reangreang | Suranti |
|------|---------|--------|--------------|----------|------------|---------|
| 0    | 5.47    | 14.22  | 49.06        | 30.78    | 35.78      | 47.19   |
| 1    | 6.95    | 12.37  | 57.9         | 9.18     | 35.64      | 51.03   |
| 2    | 6.56    | 11.7   | 56.05        | 8.53     | 35.48      | 52.58   |
| 3    | 5.66    | 11     | 54.13        | 7.85     | 35.31      | 52.5    |
| 4    | 4.74    | 10.29  | 52.16        | 7.16     | 35.14      | 52.43   |
| 5    | 3.79    | 9.55   | 50.13        | 6.45     | 34.96      | 52.35   |
| 6    | 2.81    | 8.79   | 48.04        | 5.71     | 34.78      | 52.27   |
| 7    | 1.81    | 8.01   | 45.88        | 4.95     | 34.59      | 52.19   |
| 8    | 0.78    | 7.2    | 43.66        | 4.17     | 34.39      | 52.1    |
| 9    | 0       | 6.37   | 41.38        | 3.37     | 34.19      | 52.01   |
| 10   | 0       | 5.51   | 39.02        | 2.54     | 33.98      | 51.92   |
| 11   | 0       | 4.63   | 36.6         | 1.68     | 33.77      | 51.83   |
| 12   | 0       | 3.72   | 34.1         | 0.81     | 33.55      | 51.73   |
| 13   | 0       | 2.79   | 31.53        | 0        | 33.32      | 51.63   |
| 14   | 0       | 1.83   | 28.88        | 0        | 33.09      | 51.53   |
| 15   | 0       | 0.84   | 26.15        | 0        | 32.85      | 51.43   |

Appendix 2. Prediction data for the sensitivity test of the Barranglompo Island case study.

| Year | Actual | sken + fish 0.1 | sken + NO3 0.1 | Sken + Sed 0.1 |
|------|--------|-----------------|----------------|----------------|
| 0    | 49.06  | 49.06           | 49.06          | 49.06          |
| 1    | 57.9   | 57.91           | 54.69          | 57.9           |
| 2    | 56.05  | 56.06           | 52.74          | 56.05          |
| 3    | 54.13  | 54.14           | 50.73          | 54.13          |
| 4    | 52.16  | 52.17           | 48.65          | 52.16          |
| 5    | 50.13  | 50.14           | 46.52          | 50.13          |
| 6    | 48.04  | 48.05           | 44.32          | 48.04          |
| 7    | 45.88  | 45.89           | 42.05          | 45.88          |
| 8    | 43.66  | 43.67           | 39.71          | 43.66          |
| 9    | 41.38  | 41.39           | 37.31          | 41.38          |
| 10   | 39.02  | 39.03           | 34.83          | 39.02          |
| 11   | 36.6   | 36.61           | 32.28          | 36.6           |
| 12   | 34.1   | 34.11           | 29.66          | 34.1           |
| 13   | 31.53  | 31.54           | 26.95          | 31.53          |
| 14   | 28.88  | 28.89           | 24.16          | 28.88          |
| 15   | 26.15  | 26.16           | 21.29          | 26.15          |
|      | Average| 43.416875       | 43.42625       | 39.684375      | 43.416875 |

Appendix 3. Prediction of Pessimistic Condition of Live Coral Cover (%) in the Spermonde Archipelago.

| Year | Lae-lae | Salemo | Barranglompo | Bontosua | Reangreang | Suranti |
|------|---------|--------|--------------|----------|------------|---------|
| 0    | 5.47    | 14.22  | 49.06        | 30.78    | 35.78      | 47.19   |
| 1    | 6.95    | 12.37  | 57.9         | 9.18     | 35.64      | 51.03   |
| 2    | 5.6     | 11.02  | 54.19        | 7.87     | 35.32      | 52.51   |
| 3    | 3.64    | 9.59   | 50.25        | 6.49     | 34.97      | 52.35   |
| 4    | 1.57    | 8.07   | 46.07        | 5.02     | 34.6       | 52.19   |
### Appendix 4. Prediction of moderate Condition of Live Coral Cover (%) in the Spermonde Archipelago.

| Year | Lae-la | Salemo | Barranglompo | Bontosua | Reangreang | Suranti |
|------|--------|--------|-------------|----------|------------|---------|
| 0    | 5.47   | 14.22  | 49.06       | 30.78    | 35.78      | 47.19   |
| 1    | 6.95   | 12.37  | 57.9        | 9.18     | 35.64      | 51.03   |
| 2    | 8.45   | 12.43  | 60.03       | 9.85     | 35.92      | 52.82   |
| 3    | 9.43   | 12.49  | 62.19       | 10.51    | 36.22      | 53.01   |
| 4    | 10.44  | 12.56  | 64.66       | 11.18    | 36.66      | 53.33   |
| 5    | 11.4   | 12.62  | 66.94       | 11.81    | 37.04      | 53.6    |
| 6    | 12.35  | 12.69  | 69.24       | 12.44    | 37.45      | 53.9    |
| 7    | 13.25  | 12.77  | 71.32       | 13.03    | 37.78      | 54.13   |
| 8    | 14.11  | 12.84  | 73.25       | 13.6     | 38.07      | 54.33   |
| 9    | 15     | 12.92  | 75.59       | 14.19    | 38.54      | 54.68   |
| 10   | 15.88  | 13     | 77.94       | 14.76    | 39.02      | 55.05   |
| 11   | 16.77  | 13.09  | 80.5        | 15.33    | 39.6       | 55.52   |
| 12   | 17.59  | 13.19  | 82.63       | 15.87    | 40.03      | 55.84   |
| 13   | 18.41  | 13.29  | 84.87       | 16.4     | 40.51      | 56.21   |
| 14   | 19.25  | 13.39  | 87.42       | 16.93    | 41.12      | 56.7    |
| 15   | 19.98  | 13.5   | 89.2        | 17.41    | 41.45      | 56.94   |

### Appendix 5. Prediction of optimistic Condition of Live Coral Cover (%) in the Spermonde Archipelago.

| Year | Lae-la | Salemo | Barranglompo | Bontosua | Reangreang | Suranti |
|------|--------|--------|-------------|----------|------------|---------|
| 0    | 5.47   | 14.22  | 49.06       | 30.78    | 35.78      | 47.19   |
| 1    | 6.95   | 12.37  | 57.9        | 9.18     | 35.64      | 51.03   |
| 2    | 8.45   | 12.43  | 60.03       | 9.85     | 35.92      | 52.82   |
| 3    | 9.43   | 12.49  | 62.19       | 10.51    | 36.22      | 53.01   |
| 4    | 10.44  | 12.56  | 64.66       | 11.18    | 36.66      | 53.33   |
| 5    | 11.4   | 12.62  | 66.94       | 11.81    | 37.04      | 53.6    |
| 6    | 12.35  | 12.69  | 69.24       | 12.44    | 37.45      | 53.9    |
| 7    | 13.25  | 12.77  | 71.32       | 13.03    | 37.78      | 54.13   |
| 8    | 14.11  | 12.84  | 73.25       | 13.6     | 38.07      | 54.33   |
| 9    | 15     | 12.92  | 75.59       | 14.19    | 38.54      | 54.68   |
| 10   | 15.88  | 13     | 77.94       | 14.76    | 39.02      | 55.05   |
| 11   | 16.77  | 13.09  | 80.5        | 15.33    | 39.6       | 55.52   |
| 12   | 17.59  | 13.19  | 82.63       | 15.87    | 40.03      | 55.84   |
| 13   | 18.41  | 13.29  | 84.87       | 16.4     | 40.51      | 56.21   |
| 14   | 19.25  | 13.39  | 87.42       | 16.93    | 41.12      | 56.7    |
| 15   | 19.98  | 13.5   | 89.2        | 17.41    | 41.45      | 56.94   |
|   |     |     |     |     |     |     |
|---|-----|-----|-----|-----|-----|-----|
| 14| 25.49 | 14.54 | 100 | 20.01 | 59.33 | 72.83 |
| 15| 27.28 | 14.93 | 100 | 21.01 | 62.76 | 75.83 |