PHILMINAQ

Mitigating Impact from Aquaculture in the Philippines

Output from PHILMINAQ

PHILMINAQ modelling outputs.

By

- **Scottish Association of Marine Science**
- **Marine Science Institute, Univ. of the Philippines**

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PHILMINAQ Project Partners

- **Akvaplan-niva AS**
- **Bureau of Fisheries and Aquatic Resources**
- **Scottish Association of Marine Science**
- **Marine Science Institute, Univ. of the Philippines**

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Use of Modelling for zoning and estimating carrying capacity

Description of the Hydrodynamic model

The hydrodynamic model used for the SABBAC area residence time estimation is a 2-dimensional vertically-integrated barotropic tide model. The model grid is 75mx75m and the bottom bathymetry was digitized from topographic maps and navigational charts. (Figure 1). The model is driven by tidal oscillations of sea level at the three open boundaries. This was obtained from deployments of pressure gauges at the open boundaries for 15 days where tide height was measured on an hourly basis. The model was allowed a spinup time of 1 day and then allowed to run for 30 days. Hourly sea surface heights and currents were stored and were used to drive the residence time model.

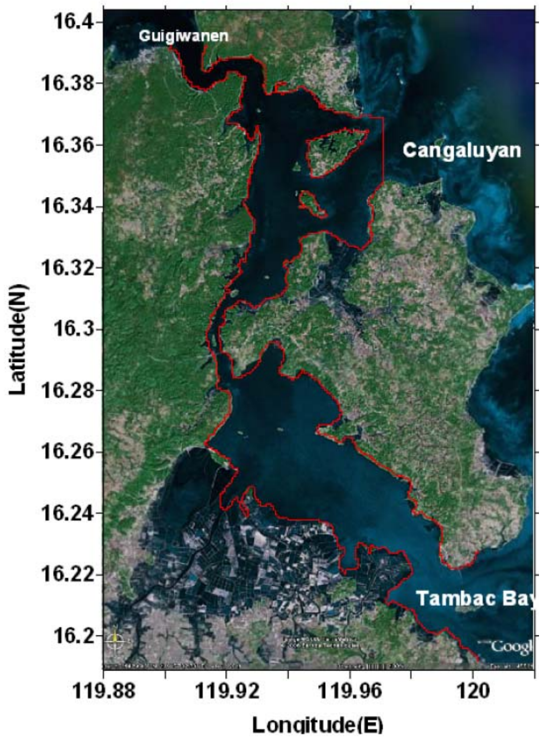


Figure 1. Domain of hydrodynamic model in SABBAC area.

The effect of the fish cages and pens on the flow field was simulated by assuming that the obstruction of the structures was similar to increasing the frictional drag within the grid cell where the cages orpens are located. Measurements of flow reduction within cages were done on the field yielded average reduction of 43% and 59% for cages and pens, respectively.

Numerical experiments with the model show that this reduction is equivalent to a frictional drag (C_D) of 0.0078 for cages and 0.026 for pens. These elevated frictional drag values was only used in cells where cages and pens are found.

Methodology for determining residence times

The velocities generated by the hydrodynamic model were used to simulate the transport of passive particles which form the basis for estimating residence time. Passive particles were initially placed at the center of each model grid. The location of each particle over time was then calculated using the equation of Tartinville et al. (1997) modified for 2D model:

$$r(t+\Delta t)=r(t)+\Delta t\{u+(6k_h/\Delta t)^{1/2}d_h\}$$

where, r is the location of the particle, t is the time of particle of r, Δt is increment time, d_h is a randomly generated dimensionless number, k_h is the eddy diffusivity of grid size, and u is the advective velocities provided by hydrodynamic model. These particles can move freely between grid cells and once a particle exits any of the three open boundaries, it is completely removed in the calculation and never returns. The time from its release to its exit through the open boundaries is the residence time. In a tidally dominated flow, the residence of a particle released close to the open boundaries will vary greatly with the phase of the tide The simulation time is 30days, hence the resulting residence time is averaged to compensate for the stochastic estimation of the position and location of the particles in Lagrangian method. Figure 2 shows the difference between the residence time estimate with and without fish farms.

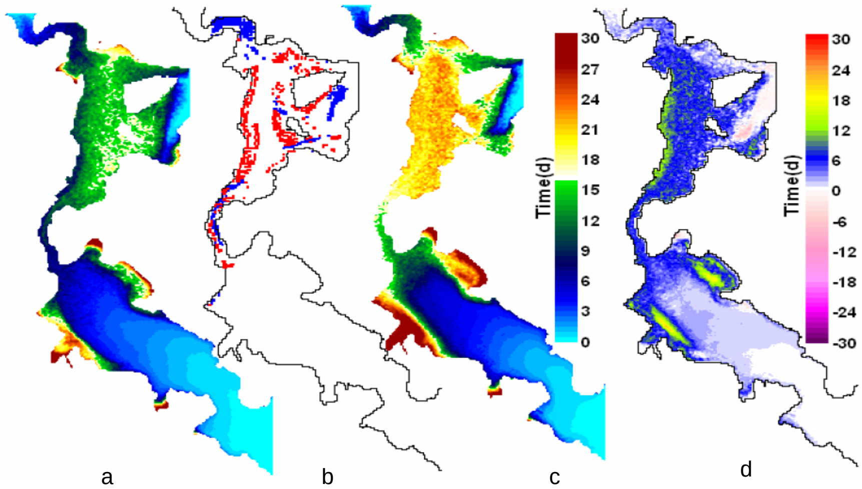


Figure 2. Predicted residence times without structures (a), with structures (b and c) and change in residence time due to structures (d).

The models described above may not necessarily apply for different areas. Other methods of residence times may be used.

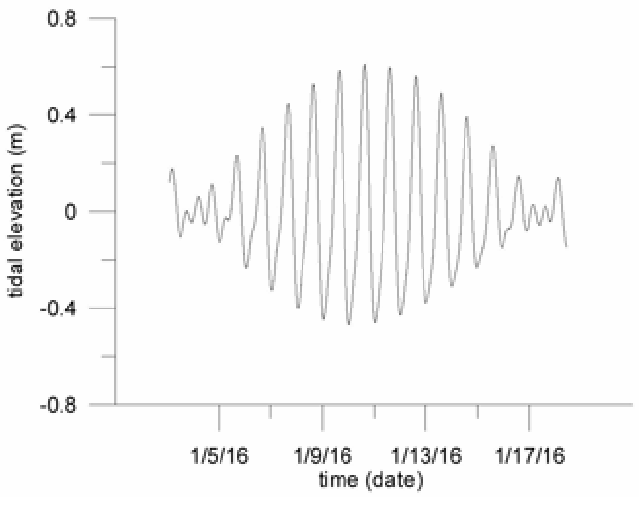
Methodology for determining average current speeds

Water currents influence the fate of dissolved and suspended waste (excess feeds and fecal material) from mariculture cages and pens. Stronger currents can advect mariculture waste material further away from the source allowing for a higher rate of dilution and dispersion. Weak currents can lead to local accumulation of waste particularly on the seabed. The currents must therefore be one of the important criteria in selecting sites for mariculture cages or pens. Most areas being developed for mariculture are sheltered from the open sea. Thus, most of the time, the flow is dominated by the tides. In this note, we describe different ways to measure currents and how to calculate average tidal currents for the purpose of site selection.

Measuring currents
Currents can be measured in a variety of ways ranging from electronic measuring devices to simple surface drogues or drifters. Electronic instruments to measure currents allow continuous measurement over a period of time but can be prohibitively expensive for some mariculture cage or pen operators or even for local government authorities. Surface drogues are relatively inexpensive but require manpower over the period of measurement. Both methods can be used to estimate the average current in a particular area and comparison using hypothetical data will be used.

Averaging of currents
Current variations in the coastal areas are dominated by the tides. The strongest components of the tide contribute to the fortnightly variations known as the spring and neap cycle (see Figure 3). The average current used to characterize a particular area should take into account the current variations at this time scale. One way is to simply average the speed over a 15 day period. If a hydrodynamic model is available, the spatial variation of the average current speeds can be represented as in the map shown in Figure 4.

Calculating the average speed is straightforward if a continuous 15-day time series of the currents is available either from direct measurements or from a hydrodynamic model. However, if none is available, one should be able to estimate the average speed by conducting direct measurements of currents continuously for 24 hours at selected days during a spring-neap cycle. The timing of the spring and neap tides can be determined from the Tide Tables published by NAMRIA (see example in Figure 5). For example, measuring hourly velocities for 24 hours during spring tide and again during neap tide will yield average values which differ only by about 8% compared to averaging currents measured hourly for 15 days (Figure 6). This suggests that in the absence of continuous current measuring instruments, it is possible to represent the average currents over a spring neap cycle using 24-hour measurements of currents conducted for only two days, once during the spring tide and again during the neap tide.



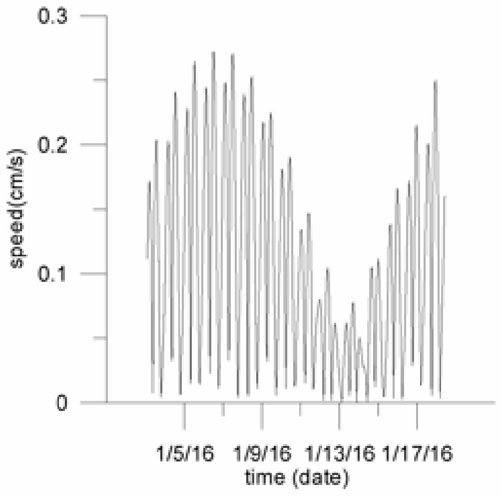


Figure 3. *Example of sea level and current variations over a spring neap cycle.*

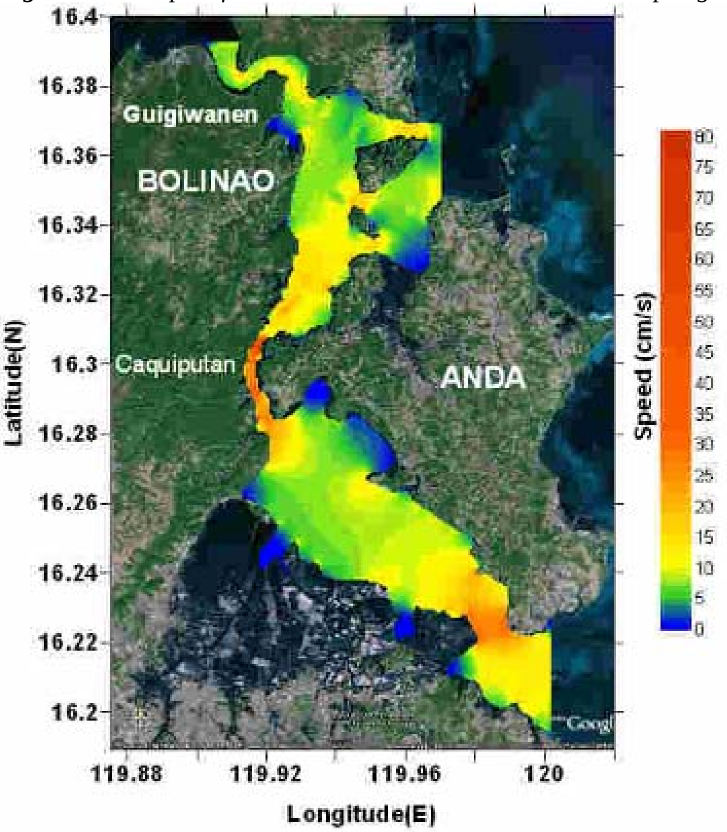


Figure 4. *Average speed over the model domain in the SABBAC area calculated from a hydrodynamic model.*

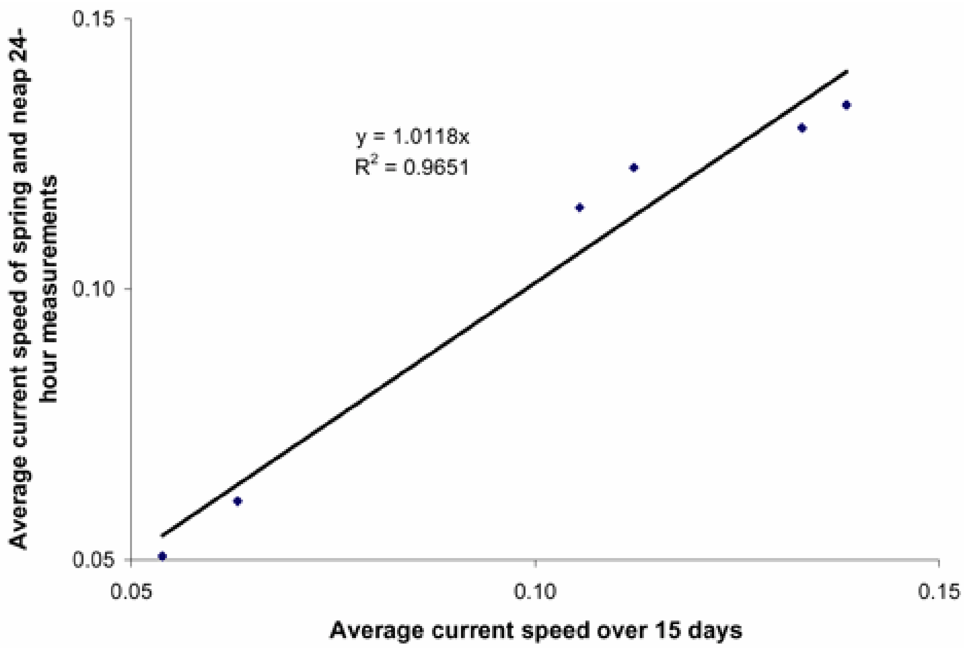


Figure 5. *Correlation between average current measured using a 15-day hourly time series against the average obtained from 24-hour measurements during spring and neap.*

Other ancillary parameters can also be derived from the current measurements or hydrodynamic model data. For instance, the Scottish Environmental Protection Agency (SEPA) requires mariculture operators to provide:

- Mean, maximum, minimum current speeds;
- Ranked percentage of mean current speeds;
- Percentage < 3 cm s-1 (to define whether a site is quiescent or not);
- Percentage > 9 cm s-1 (as this current speed is important for resuspension in the Scottish models);
- A graph of speed percentiles; and
- The length of time this analysis has been undertaken.

Methodology for selecting optimal aquaculture zones

It is difficult to prescribe a standard methodology for mariculture site selection because different sites have their own set of characteristics and one approach that works for one site may not work for another. The amount of available information needed for making an informed decision also varies between sites. For the example shown here, the SABBAC area has been the site of several research projects over the past few decades and relatively more information is known about the site compared to other coastal areas in the Philippines. Nevertheless, an attempt is made here to develop a methodology for selection of mariculture zones based solely on hydrodynamics.

Residence time.

Residence time for an area proposed for mariculture should not be more than 14 days to ensure that the water can be flushed within a spring-neap cycle. This can be estimated using residence time and hydrodynamic models. An example is shown in Figure 10. It is necessary to repeat the residence time calculations every time the configuration (location and numbers) of the cages change.

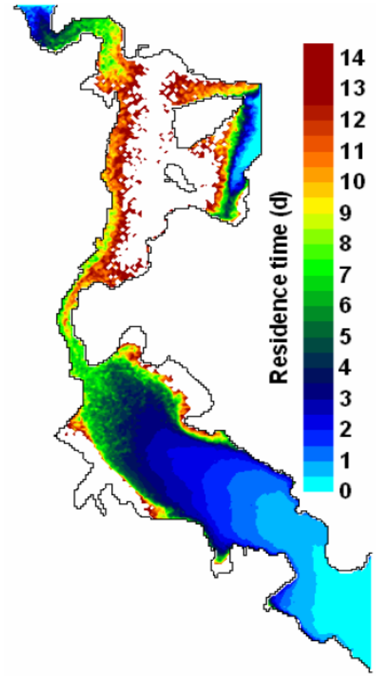


Figure 6. Example of residence time map showing only areas with residence times < 14 days.

Current speeds

Mariculture areas often have muddy substrates which require only small current speeds for resuspension of sediments. Dudley et al (2000) estimates a minimum speed of 0.3ms-1 for resuspension to occur in pens (Figure 11). Cromey et al (2002) suggests even a lower value of 0.095ms^{-1} for resuspension velocities in mariculture areas. Removal of waste from small embayments is also enhanced if threshold velocity for resuspension is surpassed (Panchang et al, 1997). Allowing for resuspension in a tidally dominated area will tend to redistribute deposited sediments over a much large footprint but will reduce sediment flux rates.

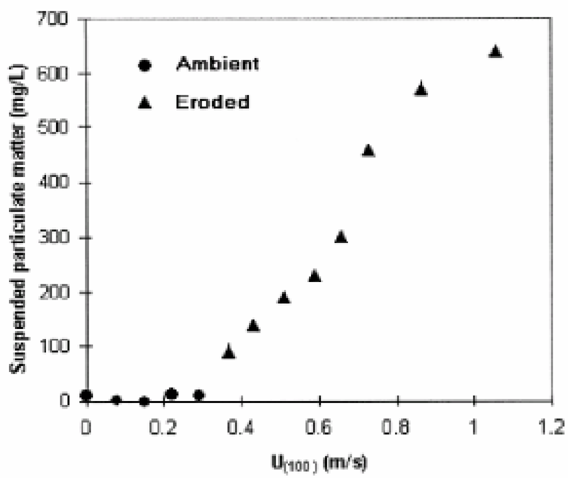


Figure 7. Sediment resuspension as a function of current speeds.

Critical entrances for navigation and water exchange

Provide enough space for navigation especially in narrow passages and keep critical passages free to allow unobstructed flow of water. These passages are typically the entry or exit points of exchange with the open sea. Minimum space for navigation should allow two-way traffic of the widest boats (typically large boats with outriggers).

In addition, critical passages should be free of fish farms to allow unobstructed flow of water. These passages are typically the entry or exit points of exchange with the open sea. Hydrodynamic modeling and residence time calculations suggest that in the SABBAC area, the most critical passages are the Guiguiwanen Channel and the Caquiputan Strait (Figure 12).

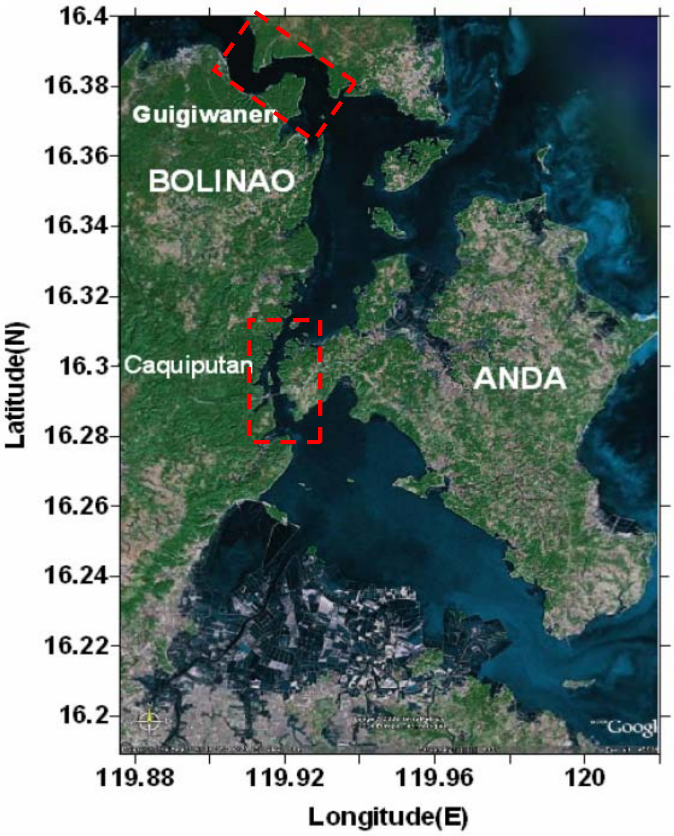


Figure 8. Important passages for navigation and flushing in the SABBAC area.

Current speed and depth

For a tidally-dominated circulation, it is important to note that the magnitude of the flow also depends on the depth. For instance, flow from relatively deep water must speed up to conserve volume once it flows along shallow bathymetry. The availability of current speeds and bathymetry in an area can provide useful information in mapping potential mariculture zones. Depth and current speed can be used as one the criteria and a classification scheme may be adopted. An example is shown below

- Strong currents in deepwater – ideal for cages;
- Weak currents in shallow water – ideal for shellfish culture and not for cage or pen structures

- Strong currents in shallow water – in most instances, shallow areas with strong currents are important passages for water exchange and should be kept free of any structures. Depending on area, may also be suitable for pen culture if it does not interfere with the flushing of the embayment;
- Weak currents in deep water – areas where there is a high tendency for waste material from mariculture to accumulate. It is best that these areas are kept free of pollution sources.

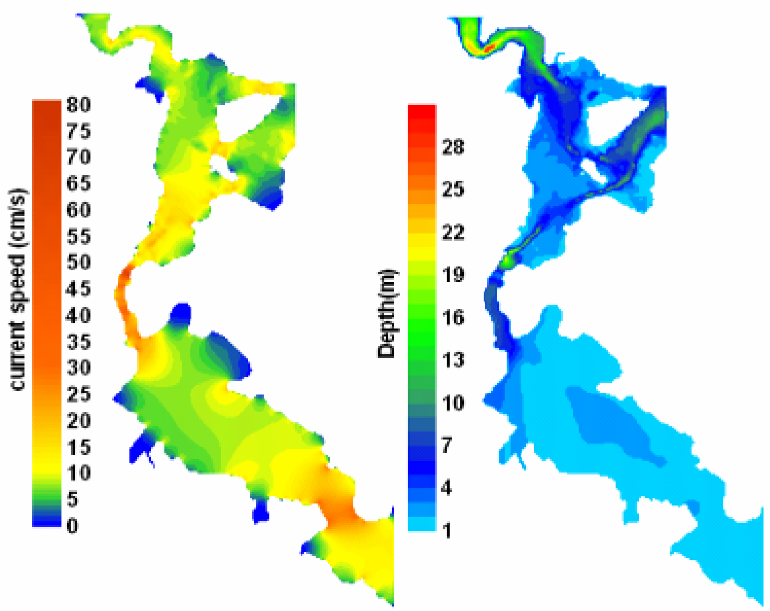


Figure 9.Average current speed (left) and bottom depth (right).

The integration of these variables and finding the optimum combination that is deemed to give the best solution is best done using the tools available in a Geographic Information System (GIS) system.

Siting of aquaculture zones from sensitive habitats.
Results of a study by Pusceddu et al. (2007) indicate that "quantitative and qualitative changes in the organic loads of the sediments that arise from intensive aquaculture are dependent upon the ecological context and are not predictable only on the basis of fish-farm attributes and hydrodynamic regimes. Therefore, the siting of fish farms should only be allowed after a case-by-case assessment of the ecological context of the region, especially in terms of the organic matter load and its biochemical composition."

Mangroves, seagrass beds, and coral reefs are sensitive habitats in coastal areas that can be affected by aquaculture. The environmental impacts on these habitats include habitat loss and/ or modification and release of wastes. Habitat loss happens when mangroves areas are cleared for the development of fish pens, shrimp ponds, salt beds, and reclamation for industrial or other development. Habitat loss also occurs when fish pens and cages are installed above seagrass beds and near coral reefs.

Current fish farming practices result in large amounts of feed wasted that end up in the marine environment (e.g., FCR or feed conversion ratio >2.5). Wasted feed partly dissolve in the water column with the undissolved part end up in the sediments. Hence, the level of nutrients in the water column and sedimentation of particulate material are increased. Moreover, the sediments also become enriched with organic matter (Holmer et al., 2003). Work done on the impact of salmon farming indicated that sedimentation can extend up to 1.2 km from the farm site (Milweski, 2000). In the case of Bolinao, Pangasinan, water quality conditions have become eutrophic over a 10-year period of unregulated fish farming that resulted in a massive fish kill in 2002, when the number of fish pens and cages more than doubled the allowable limit (San Diego-McGlone et al., 2008). The fish kill coincided with the first reported Philippine bloom of a dinoflagellate *Prorocentrum minimum* (Azanza et al., 2005).

The effect of wasted feed on seagrass habitats comes from sedimentation that smother the seagrass beds with particulate matter (http://ec.europa.eu/research/agriculture/projects/qlrt_2000_02456_en.htm). This type of impact has been measured up to 400 m from the fish cages. The large input of organic matter led to high sulfate reduction rates that contributed to sediment anoxia and sulfide toxicity (Holmer et al., 2003). Aquaculture wastes also led to stress on individual plants, as evidenced by the decrease in shoot biomass and seagrass cover closer to the fish cages (Ruiz et al., 2006), changes in physiology as an adaptive response to anoxia, and death, to demonstrate its intolerance to highly reducing sediments (Pérez et al., 2007).

Sedimentation and eutrophication also affect coral reefs. According to Villanueva (2005), there is diminished larval output, growth, survivorship of scleractinian corals after exposure to fish farm effluents.

Given the above environmental impacts, aquaculture activities should be sited far from sensitive habitats. Any prescribed distance from these habitats should be based on flushing, residence time, density of fish farming structures, and allowable levels of water quality parameters.

Aquazones for Bolinao north channel

The modelling activity utilised hydrodynamic model flow fields provided by Dr Villanoy and E Magadong. For the 6 zones, a spacing of 20 m between cages in the same row and 120 m between and cage rows was recommended to prevent severe impact underneath the cages. The exception was zone 4, which had large circular cages so a spacing between cage centres of 30 m was recommended. Also, the spacing between cage rows was adequate to allow impact to be minimised on areas between cage rows, thus allowing remediation of sediments between rows. In addition to spacing recommendations, two scenarios were presented for each zone, one for a high (inefficient) Food Conversion Ratio - the current situation - and one for an improved situation with a lower (more efficient) FCR. These scenarios with a lower FCR showed how the environmental impact could be minimised by using better quality feed. This better quality feed used in the model did not break up so easily and also had better digestibility. This meant that the model could be used to show that careful use of better quality feed so that less is wasted, resulted in a reduction in impact at the zones.

The detailed report for modelling of the 6 SABBAC zones with TROPOMOD is given below.

Depositional Modelling

A particle tracking model used for predicting output, movement and deposition of particulate waste material (with resuspension) and associated benthic impact of fish farms. Simulated particles exiting the fish cage are displaced by currents and random walk eddy dispersion and deposit on the seabed. This data is used to predict impact on the sediments.

Used for:

- Regulating discharges of medicines
- Determining the maximum biomass for a site
- Assisting selection of sites
- Preparation of EIAs

PHILMINAQ project modelling approach with TROPOMOD

Modelling of the SABBAC zones has the following objectives:

- to test scenarios which encourage careful feeding, so waste feed and nutrient input to the environment is minimised; farmers will also save money
- to encourage use of better quality feed, where better digestibility of feed means less feed is needed; better quality feed also breaks up less, so more goes to growth

The modelling approach also aims to:

- maintain enough spacing between cage rows so that remediation of sediments can take place – impact should be low between rows in each zone
- maintain enough space between cage rows to prevent reduction of currents by high aggregation of cages – although not predicted by TROPOMOD, this effect is known to exist and has been shown by MSI models
- prevent overlap of zones by predicting the extent of the zones and recommending minimum spacing between zones

The TROPOMOD model was therefore set up to evaluate the following:

- How severe is the impact – what is the maximum impact underneath cages?
- How far to the boundary of the impact?
- How can husbandry practices be optimised to use the zone most productively?

Bathymetry and current flows

TROPOMOD was set up using flat bathymetry from the MSI model (Figure 14, Table 1).

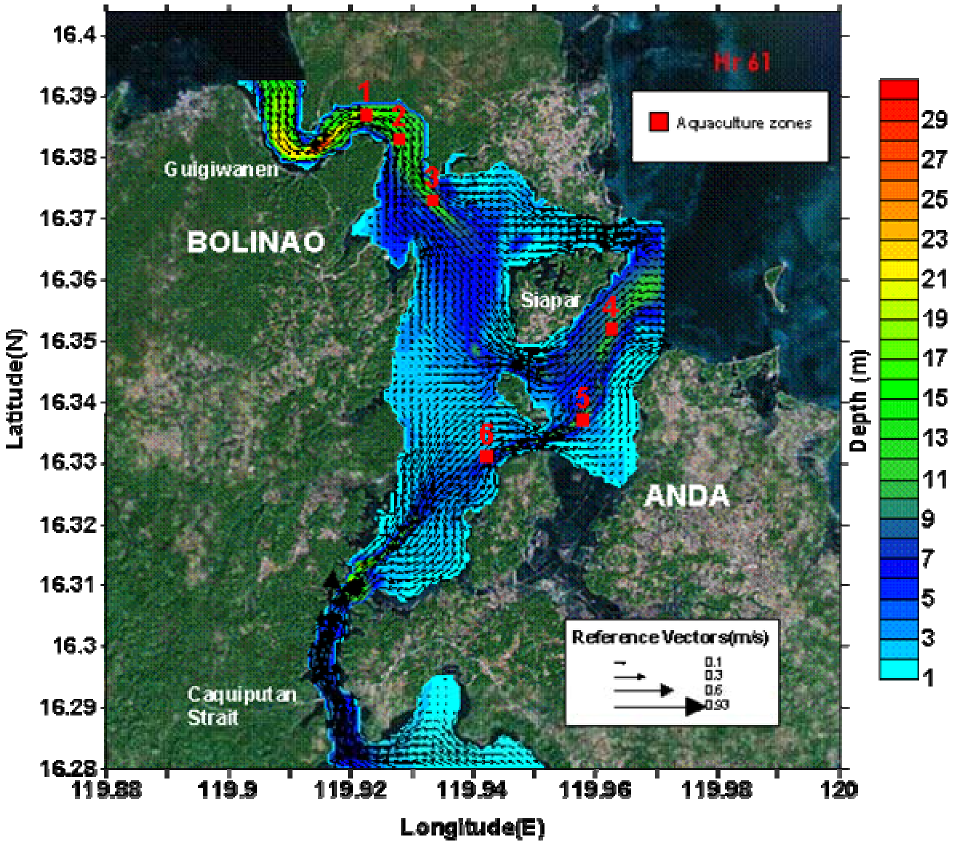


Figure 14. Bathymetry and flow fields from the MSI model of SABBAC zones 1 to 6.

Flow fields of current speed and direction were calculated from model tidal constituents to give a time series of depth-averaged current speed and direction for 1 month for each zone (Figure 15). Summary statistics were compared for each zone and zone 6 in the south of the area had the highest maximum speed, with zones 1 and 2 in the north having the next highest maximum and average current speeds (Table 1). The lowest current speeds were predicted by the MSI model in zones 4 and 5 to the east and south of Siapar. However, zone 4 is exposed to waves from the sea to the east, and the effect of waves on dispersion is not predicted by TROPOMOD. TROPOMOD is therefore likely to underestimate the dispersion and so will underestimate the assimilative capacity of zone 4.

Table 1. Zone depth and mean and maximum current speeds for a 30 day time series taken from the MSI hydrodynamic model of the area.

Zone	Depth (m)	Mean speed (cm/s)	Max speed (cm/s)
1	20	10.8	28.6
2	14	11.5	30.6
3	13	8.9	23.7
4	10	7.9	24.8
5	10	6.0	18.8
6	5	14.2	43.0

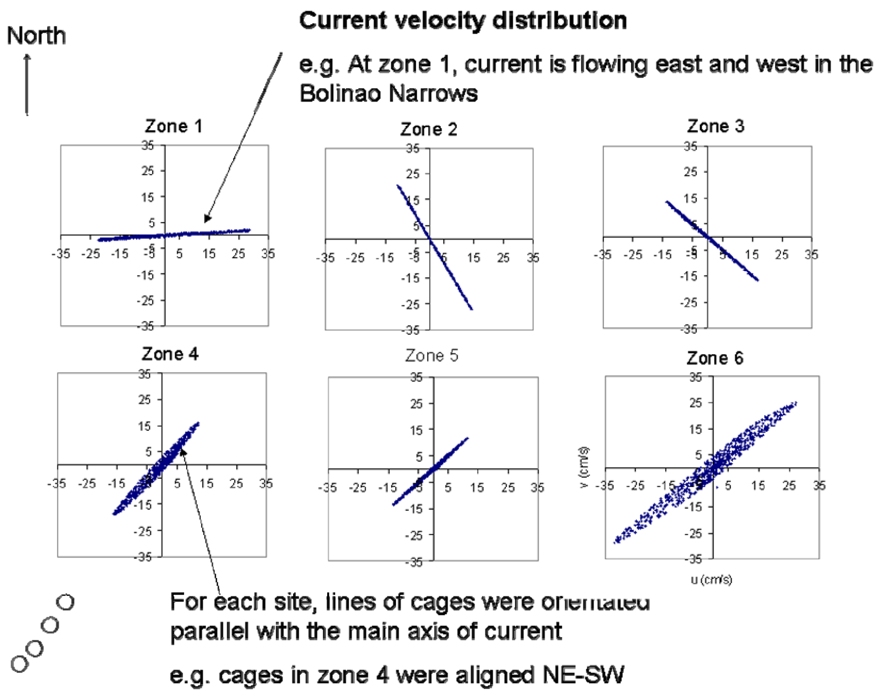


Figure 15. Hydrodynamic model data (x-axis easting cm s^{-1}, y-axis northing cm s^{-1}) used in TROPOMOD modelling of SABBAC zones 1 to 6.

Zone size and cage size

Each zone had a size of 600 m by 200 m (12 ha). In all zones except zone 4, square cages of 12m * 12m with net depth of 8 m were used. Zone 4 is an exposed site and so had larger circular cages of 20 m diameter and 8 m deep in the model. Assuming stocking density was the same between square and circular cages, this resulted in the larger circular cages in zone 4 containing 2.2 times more biomass than square cages.

FCR and settling rates of feed and faecal particles

Two different scenarios were undertaken for each zone with Feed Conversion Ratio (FCR) of 2.8:1 and 2.0:1. The high FCR means 2.8 units of food for every 1 unit of biomass produced and represents the FCR measured at Bolinao by the EMMA project. This high FCR is caused by high feed losses through careless feeding of poor quality feed. This poor quality feed also breaks up quickly as shown by experiments undertaken during the May 2007 training course. Feed settling experiments during the training course measured settling velocity of pellets as 8.9 cm/s for intact pellets. However, with poor quality feed such as the feed in use in Bolinao and Sual, intact pellets quickly broke up to finer particles, resulting in a high loss of nutrient to the environment. For the FCR 2.8:1 scenario, poor feed quality was represented in TROPOMOD by defining feed particles of three different sizes: 5% of particles remaining intact and the remaining particles were smaller particles settling at a slower rate. A scenario using FCR of 2.0:1 was undertaken to represent more careful feeding practices with better quality feed. In this scenario, pellets were assumed to have a higher concentration of binder and so remained intact with a settling velocity of 8.9 cm s^{-1} (Table 2).

UP-MSI measured an average faecal settling rate of 0.84 cm s^{-1} for milkfish. This rate is consistent with the value for Sea Bream and Sea Bass faeces, measured by Magill et al. (2006) of 0.48 and 0.70 cm s^{-1} respectively. Magill et al. (2006) showed the importance of determining faecal particle size in addition to settling velocity, as high numbers of fine particles bias the numerical mean towards slow settling particles, but these particles only represent a small proportion of the faecal mass. Similar video based experiments undertaken by Magill et al. (2006) were undertaken in the PHILMINAQ project but videos were accidentally lost. Thus, the 0.84 cm s^{-1} value used in the modelling is a good first measurement of Milkfish faeces, as no other data existed previously.

Table 2. Zone and cage size and settling velocity data.

Model input data	Value
Zone size	600 m by 200 m (12 ha)
Cage size	12m*12m*8m – square - (all zones except zone 4) 20 m diameter circular – zone 4
Feed settling rate for different scenarios:	
Scenario A - FCR 2.8 – pellet break up (estimated)	8.9 cm/s (5%), 4.5 cm/s (65%), 1.6 cm/s (30 %)
Scenario B - FCR 2.0 – intact pellets (measured)	8.9 cm/s (100%)
Faeces settling rate – measured by PHILMINAQ for Milkfish	0.84 (cm/s)

Feed ration and modelling the different sized fish in cages in a zone

At any time of the year, an aquaculture zone will have cages with different sized Milkfish as farmers stock with small fish at different times of the year. Although modelling the zone with fish at maximum size would give a worse case scenario, this would be unrealistic. Therefore to simulate a more normal situation where fish were at different stages of the growing cycle, several different size fish and feeding rates were used in the same scenario. For all zones except zone 4, eight different types of cages were modelled, where each cage contained one size of fish as shown in Table 3 (data source – EMMA project). For zone 4 which contained large circular cages, the fish numbers, biomass and feed ration were 2.18 times higher than for square cages. For all zones, 1 in every 8 cages is empty.

Table 3. Feed ration used in the model for different cages in all zones except zone 4, where feed ration was 2.2 times higher in the larger circular cages at this site – data source EMMA project.

Fish weight (g)	Fish numbers per cage	Cage biomass (kg)	Feed rate (% day^{-1})	Feed ration (kg $cage^{-1}$ day^{-1})
0	0	0	0	0
20	27247	545	8.5	46
41	26873	1091	8.9	97
91	26498	2406	7.1	171
162	26124	4224	5.1	214
247	25749	6358	4.4	278

386	25375	9799	3.3	323
433	25000	10825	1.8	193

As there is no order to the location of cages with different sized fish in the aquaculture zone, each cage in the model grid was assigned a biomass and feed ration from Table 3 randomly. This ensured that a mixture of fish sizes and feed rations were in use in the modelled zone, as would be the case for an operational zone.

In scenario A, a FCR of 2.8:1, feed wastage of 27 % and a digestibility of 49 % was used. This scenario used three different settling rates for pellets to simulate pellet break up (Table 1). Scenario B used a much lower feed wastage with improved digestibility and only one settling rate for feed pellets.

Table 4. Mass balanced model used for determining feed wasted and faecal outputs. In each of the scenarios, the amount of consumed feed allocated to growth and maintenance is the same (FCR data from EMMA project). TROPOMOD settings are also shown.

Scenario	**A**	**B**
Description	High feed wastage, poor feed quality with low digestibility	Low feed wastage, better feeding quality with improved digestibility
FCR	2.8	2.0
Pellets fed (kg wet wt)	322.6	230.4
Pellets fed (kg dry wt)	**293.5**	**209.7**
Pellet water content (%)	9	9
Total feed lost to environment (kg dry wt)	**77.8**	**21.6**
Feed consumed (kg dry wt)	215.7	188.0
Maintenance (kg dry wt)	26.2	26.2
Growth (kg dry wt)	78.6	78.6
Total (kg dry wt)	104.8	104.8
Faecal output (kg dry wt)	**108.8**	**83.2**
Faecal output (g faeces/kg food)	372.3	396.0
Mass budget (kg dry wt)	**291.4**	**209.7**
TROPOMOD settings		
Pellet digestibility (%)	49	56
Pellet water content (%)	9	9
Feed wasted (%)	27	10

Definitions of environmental impact

Using model validation data sets from MERAMOD and DEPOMOD, the threshold of 75 g m^{-2} d^{-1} was used as the definition for SEVERE impact (Figure 16). From the Bolinao sediment trap data sets, stations which had 114.0 g m^{-2} d^{-1} (0 m) and 148.7 g m^{-2} d^{-1} (25 m) were devoid of fauna. For model predictions of above 15 g m^{-2} d^{-1}, impact has been detected with MERAMOD and DEPOMOD validation data sets. Also, recent data sets from shellfish farms in Canada show that 15 g m^{-2} d^{-1} was a useful threshold, above which moderate impact was measured (Weise et al., In review).

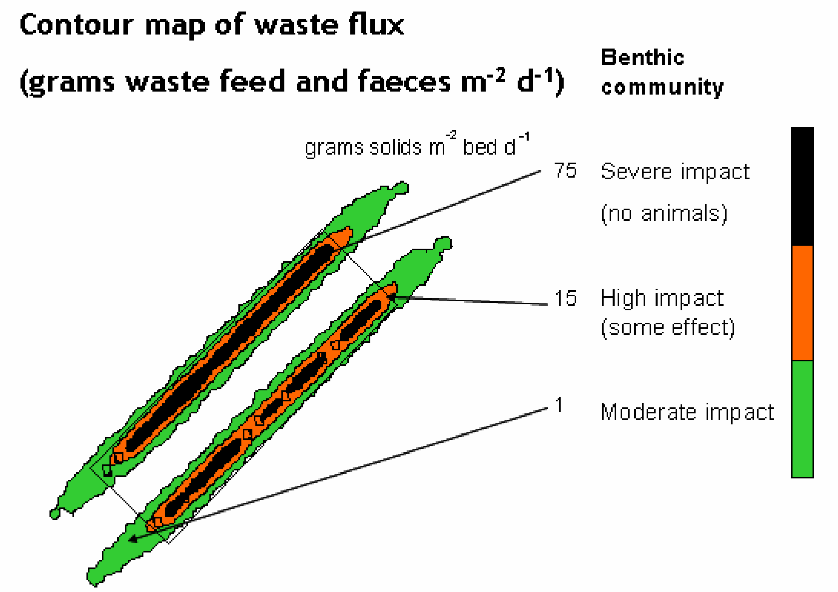


Figure 16. Definition of Severe, High and Moderate impact for the SABBAC zone modelling. There are two rows of cages shown and different colours represent different amounts of waste flux (grams waste feed and faeces depositing on the bed per m^2 per day)

Using TROPOMOD predictions, the zones were divided up into different sub-zones of impact from LOW to SEVERE (Table 5). The percentage area with HIGH or SEVERE impact was predicted with TROPOMOD, as well as the distance to the boundary of moderate impact. This distance to the boundary was used to determine whether adjacent zones would overlap. The extent of the area of SEVERE impact was also evaluated for each zone.

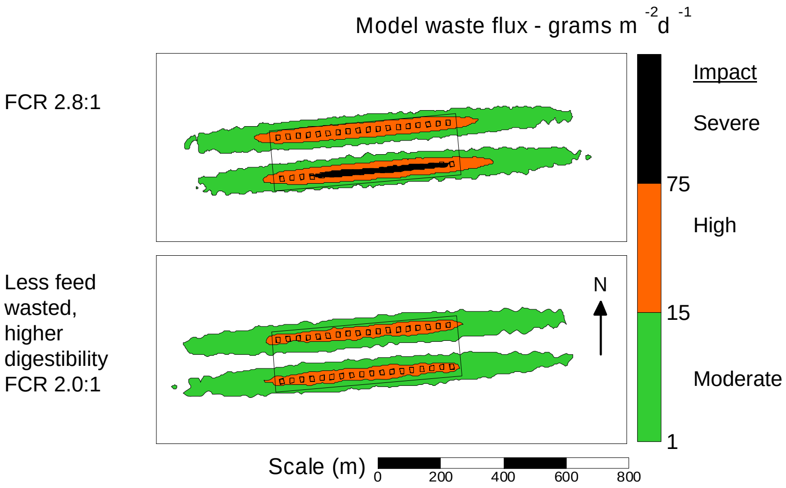
Table 5. Definition of impact areas with the TROPOMOD model using predicted flux as an indicator if impact.

Definitions	Zone colour	Predicted flux (g m^{-2} d^{-1})
Impact areas: Low/None Moderate High Severe	 White Green Yellow Black	 <1 1 – 15 15 – 75 75 +
% of zone area HIGH and SEVERE impact	Orange Black	>15
Is more than 1 % of zone SEVERE impact? Yes or No?	Black	> 75
Distance to boundary of zone of effect - 1 g m^{-2} d^{-1} contour	Green	1

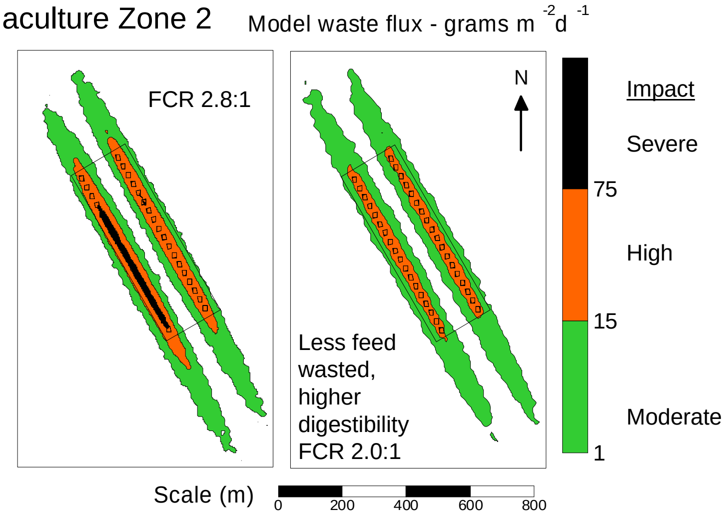
Results

The model results are shown in the next series of figures. The percentage of area with HIGH impact was greater than 50 % for zones 1 to 4 for the current high FCR situation. The model showed that by reducing feed wastage and feeding less, the area of the zone impacted was reduced to around 35 % in most zones. In most zones also, the area of the zone classed as SEVERE impact was reduced to less than 1% when a FCR of 2.0:1 was used,

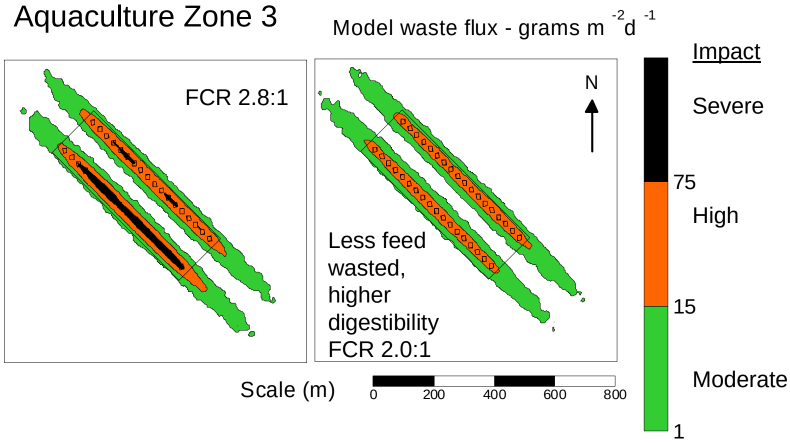
Aquaculture Zone 1 – Bolinao Narrows



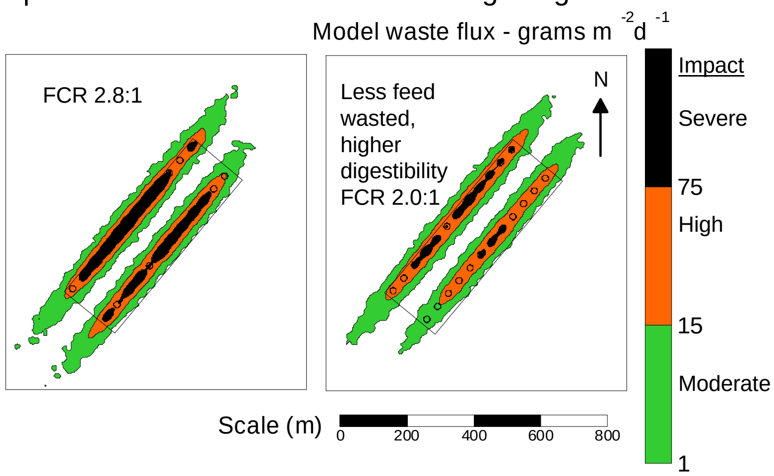
Aquaculture Zone 2

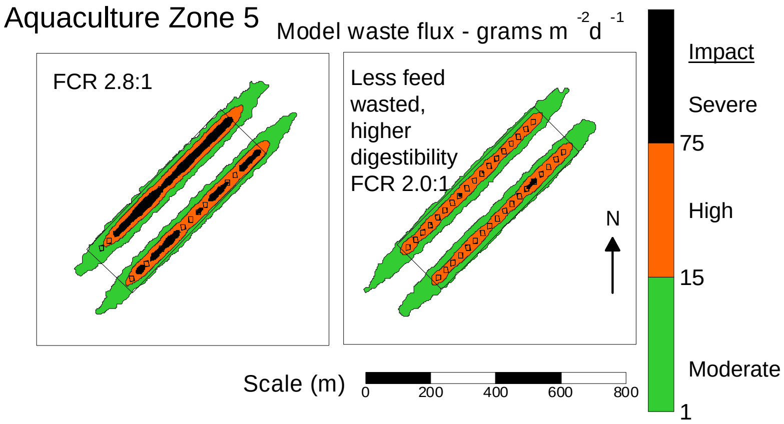


Aquaculture Zone 3



Aquaculture Zone 4 – 2 rows of 12 large cages





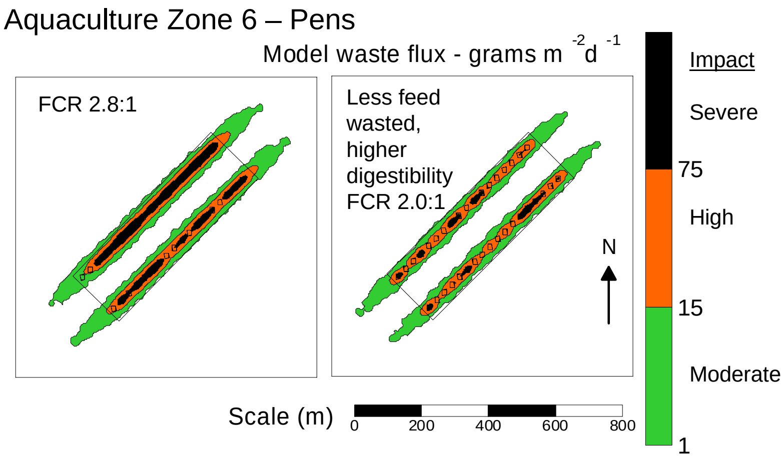


Table 6. The percentage of sea bed area in each zone predicted to be highly impacted for the two different scenarios. As FCR is reduced through better feeding practices, area of sea bed impacted is reduced as is the severity of the impact.

Zone	Scenario	% of zone HIGH and SEVERE impact	SEVERE >1% of zone? (Yes, No?)
1.0	FCR 2.8	54	Y
2.0	FCR 2.8	53	Y
3.0	FCR 2.8	50	Y
4.0	FCR 2.8	53	Y
5.0	FCR 2.8	45	Y
6.0	FCR 2.8	41	Y
1.0	FCR 2.0	36	N
2.0	FCR 2.0	35	N
3.0	FCR 2.0	36	N
4.0	FCR 2.0	44	Y
5.0	FCR 2.0	35	N
6.0	FCR 2.0	31	Y

Using TROPOMOD, 3 rows of cages were tested for each zone and the area of HIGH and SEVERE impact was found to occupy the majority of the zone area and little area was available between rows for remediation of impact. Thus, in all zones except zone 4, 2 rows of 18 cages were found to be optimum (Table 7). As larger cages were present in zone 4, 2 rows of 12 cages were recommended.

Table 7. Predicted cage numbers and spacing between cages and rows, where zone 4 has larger circular cages. The maximum biomass in each zone is also shown, assuming that all cages in the zone contain 386 grams.

Zone	Cages	Spacing between cages and rows	Zone biomass modelled **Average situation with all different fish sizes in zone (EMMA data)**	Zone biomass if all fish 386 grams in all cages **Maximum biomass in zone**
1	2 rows of 18	20 m between cages 120 m between rows	137 tonnes	353 tonnes [A]
2	2 rows of 18	20 m between cages 120 m between rows	137 tonnes	353 tonnes [A]
3	2 rows of 18	20 m between cages 120 m between rows	137 tonnes	353 tonnes [A]
4	2 rows of 12	30 m between cages 120 m between rows	277 tonnes	514 tonnes [B]
5	2 rows of 18	20 m between cages 120 m between rows	137 tonnes	353 tonnes [A]
6	2 rows of 18	20 m between cages 120 m between rows	137 tonnes	353 tonnes [A]

Zone 4 cages are large circular cages (20 m diameter* 8m deep)
Zones 1, 2, 3, 5, 6 are square cages (12m* 12m*8m deep)
[A] 386 gram fish require highest feed, 9.8 tonnes per cage *36 = 353 tonnes in zone (square cages)
[B] 386 gram fish require highest feed, 21.4 tonnes per cage *24 = 514 tonnes in zone (large circular cages)

Ranking of zones in terms of assimilative capacity

The zones were ranked in terms of assimilative capacity by examining the results of TROPOMOD in terms of the magnitude and extent of impact, depth and current. From these assessments, zone 1 was predicted to be the most dispersive, with zone 5 as the least dispersive.

Table 8. Ranking of zones according to impact area, depth and current.

Overall rank	**Zone**	Rank - magnitude of SEVERE impact	Rank - extent of SEVERE impact	Rank - depth	Rank – current
1 (most	**1**	1 (least	1 (least area	1 (deepest)	3

dispersive)		severe impact)	effected)		
2	**2**	2	2	2	2
3	**6**	3	3	6 (shallowest)	1 (fastest speeds)
4	**3**	4	4	3	4
5	**4**	6 (most severe impact)	6 (most area effected)	4	5
6 (least dispersive)	**5**	5	5	5	6 (slowest speeds)

Modelling summary and recommendations
TROPOMOD was set up with bathymetry and current speed and direction data for the six SABBAC zones, feed and faecal settling velocity data for milkfish. The model was ran with 2 different scenarios: scenario A with a Food Conversion Ratio of 2.8:1 simulating high feed wastage and poor quality feed; scenario B with a FCR of 2.0:1 simulating low feed wastage and higher quality feed.

For the following recommendations of biomass and cage spacing, HIGH impact areas were maintained to around 50 % of the total zone area and minimal impact was predicted between rows of cages to allow remediation of sediments.

From the results of the modelling study, the following recommendations are made:

- in all zones except zone 4, 2 rows of 18 cages with 20 m between cages and 120 m between rows (each cage is square – 12m*12m*8m)
- as zone 4 is an exposed site, 2 rows of 12 cages with 30 m between cages and also with 120 m between rows (each cage is circular – 20 m diameter*8m)
- all zones (excluding zone 4) with this cage arrangement would have a maximum standing biomass of 353 tonnes and 514 tonnes for zone 4
- this is equivalent to an average standing biomass of 137 tonnes for all zones and 277 tonnes for zone 4
- as the deposition footprints extend between 200 and 400 m from the edge of each zone, it is recommended the distance between zones should be a minimum of 600 m

Improvement of FCR of 2.8 to 2.0:1 resulted in:

- reducing the feed needed by 29 % without any reduction in production
- minimised or made absent SEVERE impact under cages in each zone
- reduced HIGH and SEVERE impact areas to around 35 % of the total zone area