FIGURE 15
Secchi-disk measurements from the Bolinao Bay April 2005 and February 2006. The colour of the dot indicates the Secchi-depth in meters

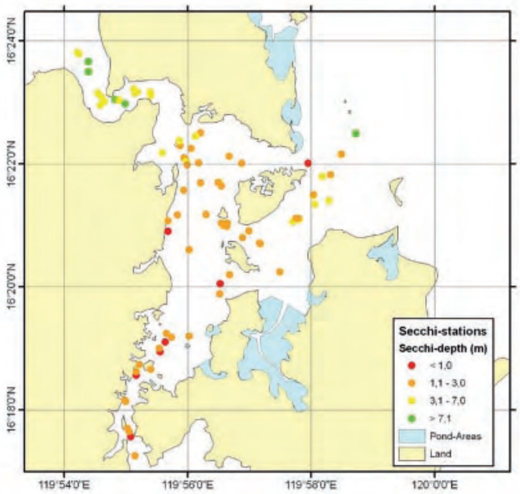
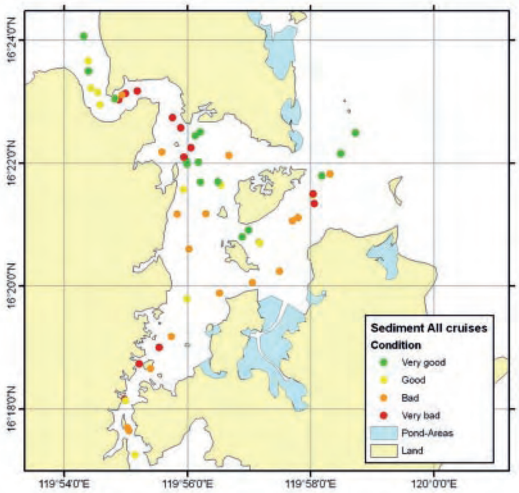


FIGURE 16
Sediment sample collection in Bolinao Bay 2005

FIGURE 17
Illustration of the sediment conditions on 52 stations. Green dot indicates "Very good" conditions while red dot indicates "Very bad" conditions



time period. Therefore the sediment samples are very good indicators of the environmental condition (Figures 16 and 17).

Sampling was carried out with a 0.05 m^2 modified van Veen grab. The grab had hinged and lockable inspection flaps constructed of 0.5 mm mesh. The upper side of each flap was covered by additional rubber flap allowing water to pass freely through the grab during lowering, yet closing the grab to prevent the sediment surface being disturbed by water currents during hauling.

Each sediment sample was described with respect to sediment type, smell, colour, larger living animals and any other obvious features (i.e. visible organic layer, bacteria, faeces, fish food etc.). Further samples were taken for chemical analysis, grain size and fauna analysis.

In Bolinao all the sediment samples were evaluated visually and by smelling the sample. In areas with bad environmental conditions the sediments had high organic content and smelled H_2S. In these samples there was no recording of any live animals. Stations with bad sediment conditions were often related to areas with high fish farming activity. In areas with less fish farming there were no H_2S smell or high organic content and there were also recorded live animals.

Water column sampling with the CTDO-probe

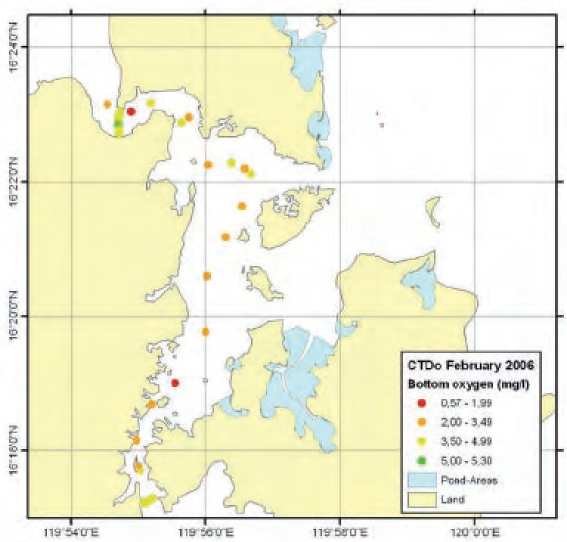
Information about conductivity, temperature, salinity and oxygen in the water column is important for understanding the condition and the dynamics of an area. In addition these parameters are essential for the modelling work. These hydrographic data was measured with an electronic CTDO-probe (sensor data). The probe that was donated to BFAR has sensor for measuring conductivity (salinity), temperature, depth, chlorophyll, turbidity and oxygen. These are all important parameters for evaluating the conditions of the water column.

During sampling the probe was lowered slowly to the bottom and slowly pulled back to the surface. The probe was programmed to take measurements every 5 seconds. The measured parameters will have seasonal and day – night changes. Approximately 100 CTDO readings were collected (Figures 18 and 19).

FIGURE 18
Sampling with the CTDO-probe

The oxygen levels in the bottom water of Bolinao Bay measured in February 2006 varied between 0.57 mg/l and 5.3 mg/l. Generally the lowest levels were found in the southern part of the Bolinao Bay. Low levels of oxygen in the water indicate little water exchange with little new oxygenated water coming in to an area. Further areas with little oxygen are in this case also related to the areas with high aquaculture activity. Release of nutrient (feed spill and fish faeces) to the water increase the production of phytoplankton which again increases the demand for oxygen.

FIGURE 19
Oxygen levels in bottom water of the Bolinao Bay measured with the CTDO in February 2006



MODELLING CARRYING CAPACITY

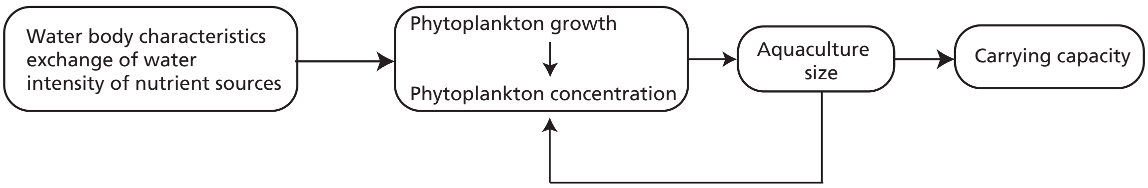
Environmental carrying capacity for fish aquacultures is defined as the maximum number of fish of a given species that may be safely grown in the considered waterbody. The maximum number is limited by a variety of factors. Certainly, if the maximum number exists for a single aquaculture occupying a given area, then the available area for fish cultures induces the upper limit. However, this limit may be much higher than the carrying capacity. Computation of carrying capacity must be based on the condition which limits the stock maximally. In other words, it must be based on the limiting condition.

A well known condition which would limit the maximum number more than the available area is the oxygen content in water. Dissolved oxygen is used by fish and its content must not fall below a certain limit. During a normal sunny day, fish in high density is one of the major oxygen users. However, not all days are sunny. During several overcast days phytoplankton in high concentration is orders of magnitude more intensive user of oxygen and hence one must ensure that phytoplankton is not able to reach very high concentration. Otherwise, within a few days, phytoplankton will decrease oxygen content to a value which will dramatically increase fish mortality. Since fish in aquaculture emits its waste to the waterbody, and this waste contains nutrients used by phytoplankton, increasing the fish stock will cause unacceptably high phytoplankton concentration in water. Hence this will limit the standing stock of fish that we may have in the waterbody.

Figure 20 depicts the process graphically.

FIGURE 20

The process of determining carrying capacity for fish aquaculture based on arriving at the critical phytoplankton concentration



The assumption is that the nutrient concentration in phytoplankton is proportional to phytoplankton concentration.

Residual nutrient levels in the bay will be dependent on

- Inputs of nutrients from aquaculture
- Inputs of nutrients from other sources
- Inflow of nutrient: inflow of water x concentration in the inflow
- Outflow of nutrient: outflow of water x concentration in the outflow
- Loss of nutrients by phytoplankton uptake

Phytoplankton requires many nutrients to grow. It is assumed that there is a single nutrient which limits the production of phytoplankton. In order to find which nutrient is limiting at a given time, the correct approach would be to undertake separate experiments for each potentially limiting nutrient, i.e. by increasing one nutrient while keeping the others the same as they occur in the waterbody, and see if phytoplankton grows faster. The procedure would need to be repeated with all candidates for a limiting nutrient. The candidate nutrients are: reactive nitrogen, reactive phosphorus and reactive silica.

From a number of experiments of the above kind it is known that for lakes and brackish waters the most likely limiting nutrient is phosphorus. Hence for these kinds of environments it is advised to take phosphorus as the limiting nutrient.

Based on short-term responses of coral reef micro-phytobenthic communities to inorganic nutrient loading Dizon and Yap (1999) found that N and P are limiting when added together while neither N nor P seems to be limiting when added alone. In the absence of carrying capacity models validated for this area, the EPA criteria and Florida Lakewatch model were used.

According to US Environmental Protection Agency (EPA), the maximum allowable total P should be 0.17 mg/l while the maximum allowable phytoplankton related Chl-a should be 10 µg/l.

Assuming that P in water is found almost exclusively in phytoplankton, then by using a relationship between Total P (TP) and Chl-a, the upper value of Chl-a corresponds to total P found in water. From an analysis of 534 Florida lakes, the following relationship has been found by researchers at the Florida Lakewatch (2000):

$$\text{Log10}(\mu g\ \text{Chl-a/l}) = -0.369 + 1.053\ \text{Log10}(\mu g\ \text{TP/l})$$

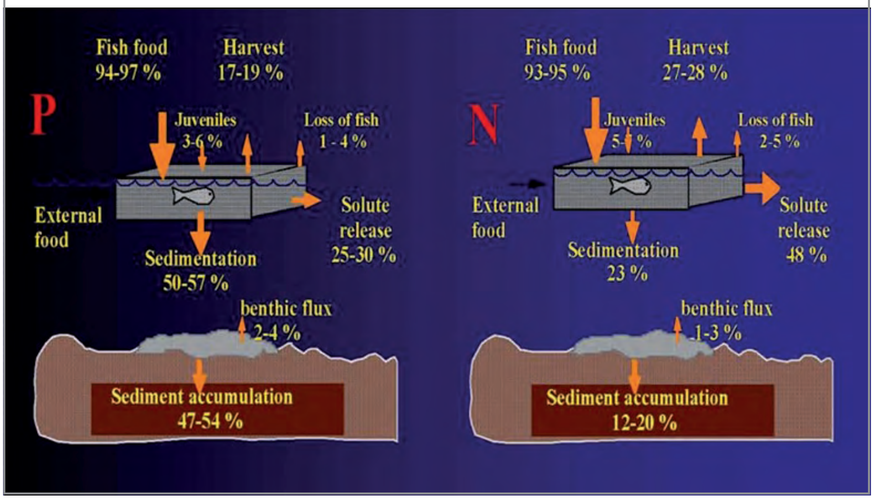
It is instructive to keep in mind (Florida Lakewatch, 2000): "In Florida, when chlorophyll concentrations reach a level over 40 µg/l, some scientists will call it an algae or algal bloom."

"When algal biomass exceeds 100 µg/L (measured as chlorophyll concentrations), there is an increased probability of a fish kill. Fish kills, however, typically only occur after three or four cloudy days. During this time, algae consume oxygen rather than produce it because they don't have sunlight available to help them photosynthesize more oxygen. This can lead to oxygen depletion. Without oxygen, aquatic organisms, including fish, die. Chlorophyll concentrations below 100 µg/l generally do not adversely affect fish and wildlife, but dead fish and wildlife can occasionally be found."

Season variation in carrying capacity

Phytoplankton dynamics will be driven by nutrient inflows to the bay from aquaculture, rivers and human activities. In the dry season, there are low river water flows into the bay but with high nutrient concentrations. In the wet season there will be high river water flows but with lower nutrient concentrations. However, during the first heavy rains of the wet season, there will be high river flows combined with high concentrations of nutrients flushed into the bay (Figures 21 and 22).

FIGURE 21
The theoretical nutrient flow model used for estimating contribution from aquaculture



Estimation of nutrient input by aquaculture was made by using nutrient mass balance modelling.

Excretion of phosphorus from aquacultures was estimated to be 339 kg/day, a contribution from soluble faeces is 143 kg/day and resuspension from the bottom is estimated at 94 kg/day. Together, this amounted to 576 kg/day at maximum production (Unpublished calculation. Personal communication.). Bolinao Bay has a surface area of 28.88 10^6 m^2 with an average depth of 4.8 m leading to the volume V= 138.6 10^6 m^3. Residence time of particles at Bolinao, according to Magdaong and Villanoy (2003) hydrodynamic model, varies from several days to over 25 days, with an average of 20 days. During a neap tidal cycle, the corresponding contribution to the phytoplankton concentration was calculated to be equivalent to of 86 µg Chl-a/l. An estimation was made of the nutrient outputs from aquaculture, rainfall, catchment areas and estimated average nutrient flows in rivers, estimate nutrient outputs from semi-intensive ponds and per capita average nutrient flows for urban areas. The contribution from other sources was estimated to be 37.4 µg Chl-a/l equivalent. Therefore, nutrient contributions were:

- Aquaculture 86 µg Chl-a/l
- Other inputs 37.4 µg Chl-a/l

The total combined nutrient input gave an estimated total algae equivalent of 123.4 µg Chl-a/l which breaches the 100 µg Chl-a/l threshold and indicates that the bay is at high risk from algal bloom formation.

Hydrodynamic modelling

The currents in the bay were modelled. The bay was divided into triangular prisms with variable depth. The prisms are of variable density: finer definition was necessary in straits (smaller prisms). Using these divisions, a hydrodynamic model was run. While moving through the bay, at shallow locations and especially at areas with developed coral reefs, water encounters more friction and hence it goes slower. According to Reidenbach *et al.* (2006) in such areas we expect the friction coefficient to be about 2.5 higher than in the rest of the bay (Figure 23).

FIGURE 22
Other sources of nutrients into Bolinao bay. Rivers and streams (yellow), pond effluent (red) and urban sources (blue)

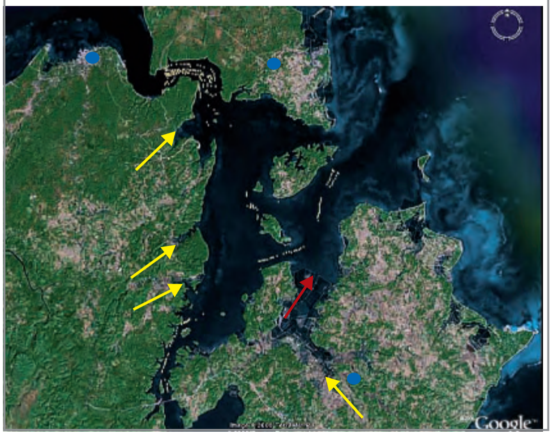
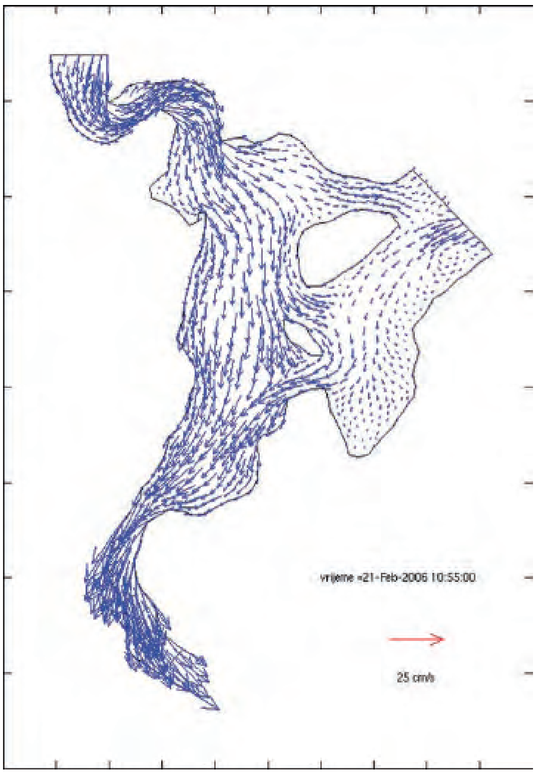


FIGURE 23
A snapshot of the obtained current field. The current field is displayed for 21 February 2006 at 10 h and 55 min



Modelling 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. The model was run for 35 days. Particles close to the openings leave the bay within a day or two while particles released in the central-east side of the bay, take as much as 30 days. In some areas of the bay particles do not leave the bay even after 35 days. However, these locations are very few. Locations of very long residence times of water particles mean higher nutrient levels and smaller carrying capacity (Figure 24).

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 PHILMINAQ project criteria for the selection of zones was that the zones should have sufficient current and short residence time for flushing the cages, sufficient depth and not be located in any critical entrances.

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

FIGURE 24
Residence times of particles released at every location in the bay. X and Y coordinates are in meters. Residence time is colour coded from 5 days (blue) to 35 days (red)

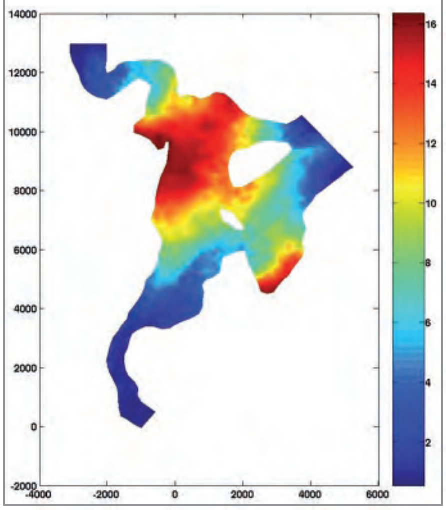


FIGURE 25
Average current speeds and depth

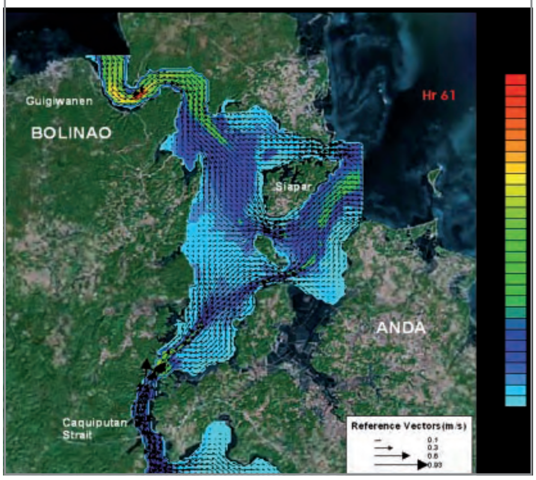
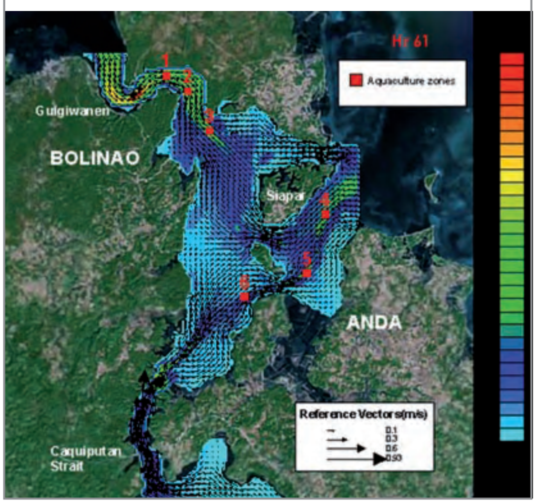


FIGURE 26
Important passages for navigation and flushing



of current speeds and bathymetry in an area can provide useful information in mapping potential mariculture zones.

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 25).

Critical entrances for navigation and water exchange

Critical entrances should be free from aquaculture structures in order to provide enough space for navigation and 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) (Figure 26).

Using modelling to identify Aquazones

The criteria were evaluated and six aquaculture zones identified.

A depositional model TROPOMOD was developed and linked to the hydrodynamic model flow fields provided by Villanoy and Magadong. TROPOMOD is 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 sea bed. This data is used to predict impact on the sediments.

Clusters of cages were modelled using the average size of cages and with typical stocking and harvest rates.

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 28). From the Bolinao sediment trap data sets for waste feed and faeces, 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 prep*).

The threshold of 1 g m^{-2} d^{-1} can be used as a guide for the distance between the cages and sensitive habitats such as corals, posidonia beds etc.

Using TROPOMOD, three rows of cages were tested for each aquaculture zone (Figure 27). 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 (Figure 28). Thus, in all aquaculture zones except zone 4, two rows of 18 cages were found to be optimum. As larger cages were present in zone 4, two rows of 12 cages were recommended.

For the six aquaculture zones, a spacing of 20 m between cages in the same row and 120 m between neighbouring 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 with less wastage, resulted in a reduction in impact at the zones.

The model was also used to predict the change in environmental impact if Food Conversion Rate (FCR) was improved. The model showed that by reducing feed wastage and feeding less, the area of the zone impacted was reduced to around 35 percent in most zones. In most zones also, the area of the zone classed as SEVERE impact was reduced to less than 1 percent when a FCR of 2.0:1 was used (Figure 29).

The model can be used to give an indication of the minimum distance between zones so that there is no overlap between affected areas here called footprints (Figure 30).

FIGURE 27
Aquaculture zones 1 to 6

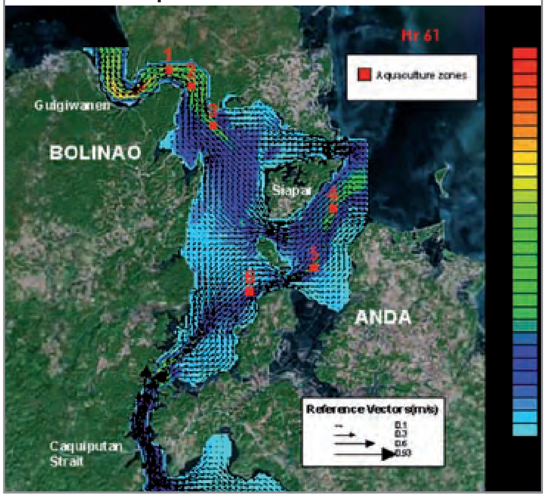
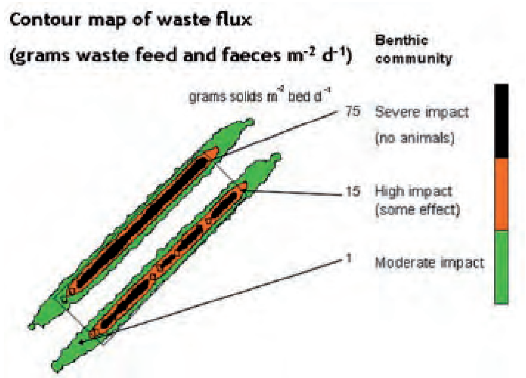


FIGURE 28
Definition of Severe, High and Moderate impact for the SABBAC zone modelling. There are two rows of cages shown and different colours represent different amounts of waste flux (grams waste feed and faeces depositing on the bed per m² per day)



SABBAC = Sual, Anda, Bolinao, Bani and Alaminos City

FIGURE 29
Improvement in severity of impact with improved FCR

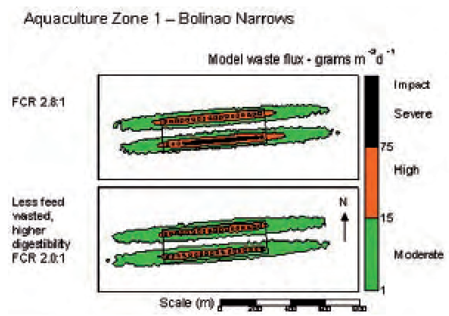
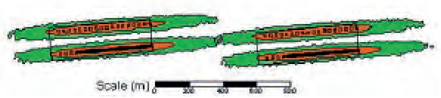


FIGURE 30
Over lap between sediment footprints between zones



As the deposition footprints extend between 200 and 400 m from the edge of each zone, it was recommended that the distance between zones should be a minimum of 600 m.

Monitoring

In addition to the modelling of aquaculture impact, the PHILMINAQ project developed three types of survey for monitoring the impact of aquaculture. These ranged from low cost through intermediate to fully scientific surveys and differ in terms of cost, complexity and accuracy but all give a good indication of the level of aquaculture impact.

The surveys can be used for the following purposes.

- Check level of impact
- Check extent of impact
- Check if
  - production over carrying capacity
  - too many licenses issued
- Check if impact
  - getting worse,
  - staying the same,
  - getting better

Three Categories of surveys were developed. Each category could collect and analyse the necessary parameters but at different capital cost, operational cost and accuracy. The 3 categories were as follows:

Category 1. Low cost simple survey that can be undertaken by local government or larger farmer

Category 2. Medium level survey that requires some dedicated equipment that can be undertaken by Government regional offices, Protected Area Management, IFARMCs, Aquaculture parks and other aquaculture management organisations

Category 3. Comprehensive survey (baseline survey) to be undertaken by government research institutes or similar, scientists for EIA, baseline survey or detailed impact studies.

TABLE 2

Potential users and cost of the different categories of survey

	Category I	Category II	Category III
Level	Simple	Intermediate	Full Quantitative
Client	Large Farmer/LGU	*BFAR Regional IFARMC, PAMBI	Science + Govt Research Institutes
Equipment Cost	USD 1 000	USD 10 000	USD 100 000
Consumables Survey Cost	USD 25	USD 250	USD 2 500

* Bureau of Fisheries and Aquatic Resources (BFAR)
Integrated Fisheries and Aquatic Resources Management Council (IFARMC)
Protected Area Management Board (PAMB)

A field manual of methodology for the 3 categories of monitoring survey was prepared and can be downloaded from www.philminaq.eu.

Conclusions

The conclusions from the two projects were that aquaculture does have an impact on the environment and it can be critical in hot-spot areas of development where the carrying capacity has been exceeded. Mariculture parks are a possible way for governments to control the development of aquaculture by providing zones for clusters of small-scale farmers. Modelling is a good way of identifying zones, estimating the maximum number of cages in a zone, estimating the minimum distance between zones and undertaking scenario testing to identify management options for minimising impact.

Planning aquaculture parks should include Programmatic Environmental Impact Assessment or Statement (PEIA/S) to prevent conflict with other users of the coastline or undue impact to the environment or sensitive fauna or flora. The PEIA/S should also include production carrying capacity estimation for each park. The aquaculture park provides good control of development for the government as it restricts the number of cages to a specific zone that is designated for aquaculture on a long-term basis. It provides a discrete zone that can be monitored on a strategic basis to ensure that production is undertaken in a sustainable manner.

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