Environmental Monitoring and Modelling of Aquaculture in the Philippines (EMMA)

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Abstract

The project "Environmental Monitoring and Modelling of Aquaculture in the Philippines" Known as EMMA was undertaken by National Integrated Fisheries Technology Development Centre (NIFTDC) Bureau of Fisheries and Aquatic Resources (BFAR) and Akvaplan-niva AS, from Tromso, Norway. The project was funded by Norad.

The goal of the study was to develop suitable aquaculture monitoring techniques and adapt predictive models to assist in identifying risk areas for aquaculture and to allow planned development of sustainable aquaculture. Three different locations were chosen as case studies. A marine site (Bolinao), a brackishwater site (Dagupan) and a freshwater site (Taal lake)

The objective of the study was to undertake environmental surveys of selected aquaculture areas at risk from eutrophication and adapt a mathematical model for the prediction of impact of the fish cages on the recipient water. The objective was also to strengthen BFAR capabilities for surveying impact of aquaculture in other areas of the Philippines

This paper describes some of the findings of the impacts of aquaculture and recommendations for mitigation of impact

1 Introduction

1.1 Background and scope of the investigations

Under the project 'Environmental monitoring and Modelling of aquaculture in risk areas of the Philippines" environmental surveys ware undertaken of a marine area in Bolinao, a brackishwater area in Dagupan and a freshwater area in Lake Taal. Seven field surveys were carried out from April 2005 to April 2006. This paper describes the field investigations that were carried out and initial findings on the observed environmental impacts.

The main goal of the investigation was to determine to what extent the fish farming activities had detectable impact on the local environment and to test and train the users in the donated survey equipment and methodology. The environmental conditions in the different areas were described using sediment quality parameters and water quality. These data, together with hydrographical and water current measurement and registrations of local bottom topography will be able to provide recommendations for the mitigation of impact in the areas.

1.2 General environmental issues related to aquaculture

The spatial extent and level of local environmental impact caused by a fish farm is determined by natural conditions such as bottom topography, sediments and currents, in combination with the size of fish production and operational practices. A major factor in preserving environmental quality is an optimal location and operation of the farm, conforming to the existing environmental conditions.

Organic enrichment in the sediments is one of the most important environmental effects associated with fish farming. The primary causes are wasted food pellets and fish excrements. In areas with water currents insufficient to remove of spread this material over a larger area, organic material may accumulate on sea floor below or in the vicinity of fish farms and there can be a build up of nutrients leading to eutrophication and possibly algal blooms.

Bacterial decomposition may lead to anoxic conditions in the sediments and overlying water and to formation of methane (CH_4) and hydrogen sulphide (H_2S) gas. Both low oxygen concentrations and the presence of methane and hydrogen sulfide have detrimental effects (eg. Reduced growth rates, increased disease frequencies) on fish in the cages near the impacted areas.

Under extreme conditions, anoxic water and the toxic gasses may even cause mortality and algal blooms to develop.

2 Environmental survey

The most important parameters for environmental monitoring and modelling are:
- Bathymetry (depth recordings) of the area
- Tidal range and current speed, direction and dispersion
- Physical parameters - Temperature, turbidity, salinity, oxygen, profile through the water column
- Water quality – chlorophyll, phosphorous, nitrite, ammonia
- Sediment analysis (biological and chemical)
- Weather data - wind direction, speed, temperature

2.1 Bathymetry measurements

Detailed knowledge about the bathymetry in an area is vital information for being able to model the water exchange in an area. For all the investigated areas there existed maps with some depth recordings. However, the resolution (number of recordings) was not good enough for the modelling. Therefore a Garmin echo-sounder which contains a GPS and a chart plotter (GPSmap 178C sounder) was set up on one of the BFAR boats so that we could collect more depth readings from the area. This setup measures and stores water depth and tracks automatically tagged with the date and time of creation, as well as water temperature. This setup is part of the equipment that is donated to BFAR for use in future projects. All the collected data were used for the modelling. In Figure 2 transects of the new depth recordings from Bolinao Bay are illustrated. A detailed map of the northwest entrance of the Bolinao Bay is shown in Figure 3. The data collected from the three areas can be put straight into the model or be used for making new bathymetry maps for the areas.
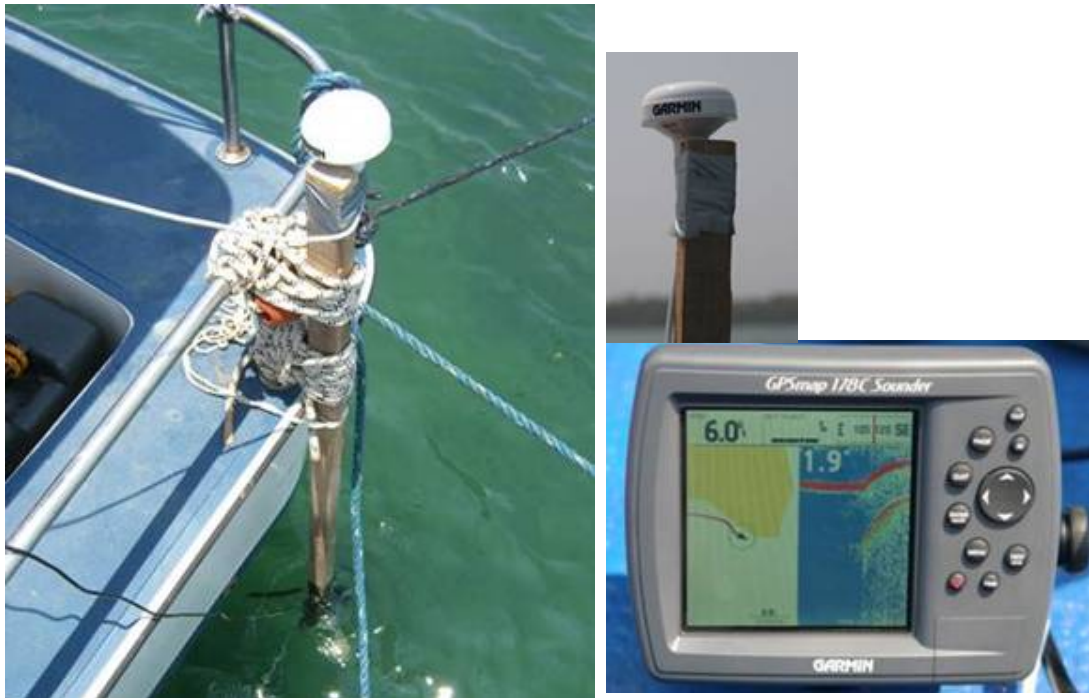
Figure 1. Pictures of the setup with the Garmin GPSmap 178C sounder and the GPS antenna.
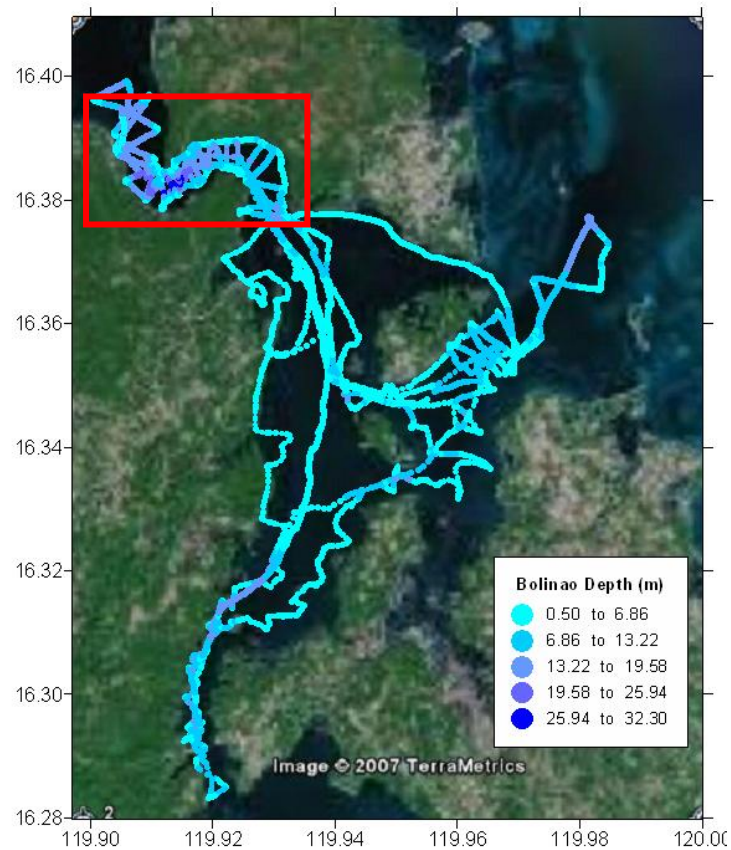

Figure 2. Map of Bolinao Bay demonstrating the new depth recordings. Dark blue illustrates deep areas while light blue illustrates shallower areas. The rectangular indicates the area for the detail illustration in Figure 3.
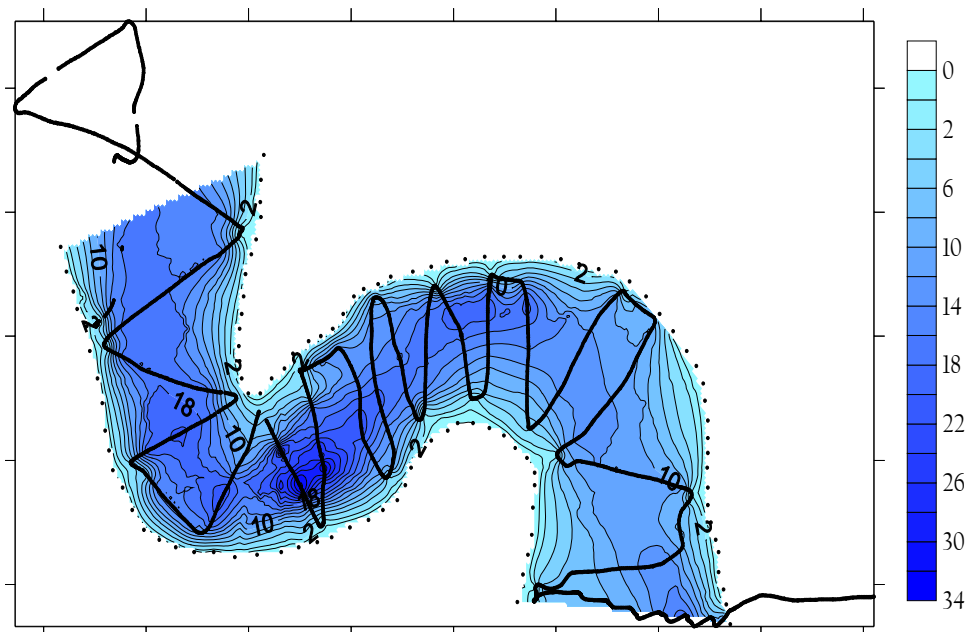
Figure 3. Detailed Bathymetry map of the northwest channel (entrance) of Bolinao Bay. Light blue illustrates deep areas while light blue illustrates shallower areas.

Surveying of the area was undertaken by driving the survey vessel in a series of tracks. The objectives of the survey are to obtain as good coverage as possible of an area. The density of the tracks is dependent on the topography of the area. Areas with a lot of variance in depth needs more tracks compared to an area were the depth is more or less the same. It is further important to make tracks as close as possible to the shoreline, so that shoreline also is included in bathymetry maps (e.g. minimum depth 2 m). In areas with a lot of aquaculture activity it can be difficult to manoeuvre the boat between the cages but recordings as close as possible to cage groups and if possible between cages are important data for the bathymetry and the modelling. It is important that the speed of the boat is not too high and adjusted so that the recordings are correct.

It is really important that the transducer is mounted in a vertical position and that the transducer is not disturbed by the turbulence caused by the vessel or the propeller. Attention was paid to the orientation of the transducer head and the frequency appropriate for the expected survey depth. The transducer is sensitive and could easily be damaged if it comes in contact with any drifting material (wood, rots, rope, etc) during the recordings.

2.2 Current meters

Information about the currents (speed, direction, volume) in an area is vital for doing the modelling. This information is used for modelling water exchange which again give information about how often fresh oxygenated water are coming in to an area, how the waste from the aquaculture activity is dispersed, etc.

MINI current meters model SD-6000 were used in the first survey. This is a compact vector averaging current meter with memory capacity for up to 6000 combined data sets of current speed, direction and temperature. For the second and third field survey, the new current meters, RCM 9 LW from Aanderaa in Norway, were used (Figure 5).

The RCM 9 LW (Light Weight) utilizes the well-known Doppler Shift principle as basis for its measurements. Four transducers transmit short pulses (pings) of acoustic energy along

narrow beams. The same transducers receive backscattered signals from scatters that are present in the beams, which are used for calculation of the current speed and direction. The scattering particles are normally plankton, gas bubbles, organisms and particles stemming from man-made activity.
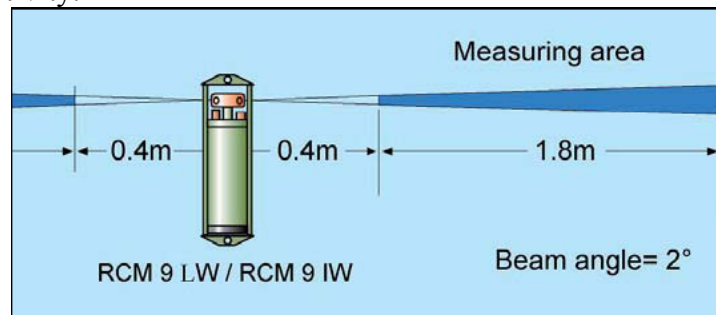

Figure 4. Illustration of the measuring area for the RCM 9 LW current meter.

Two of these current meters have additional sensors to measure conductivity, turbidity, oxygen and pressure (depth).

The current meters were programmed to measure temperature, current-speed and current-direction every 5 minutes. Ideally the current meters should be recording between 2 – 6 weeks per station to get a really good picture of the current in an area. However due to time limitation most of the current meters were deployed approximately 24 hours at each station. Most of the investigated areas were relatively shallow so only one current meter was used at each station. For most of the stations the current meters were placed in the middle of the water column.

A typical mooring (set up) for the current meter rig is illustrated in Figure 6. The set up is dependent on the depth on the station. When the depth is less than 10 meters usually only one current meter is mounted in the rig (6 meter depth). For areas with 15 meter depth usually two current meters are mounted at respectively 3.5 meter and 7.5 meter from the surface. At 20 meter depth the current meters are mounted at respectively 5 meters and 10 meters from the surface.
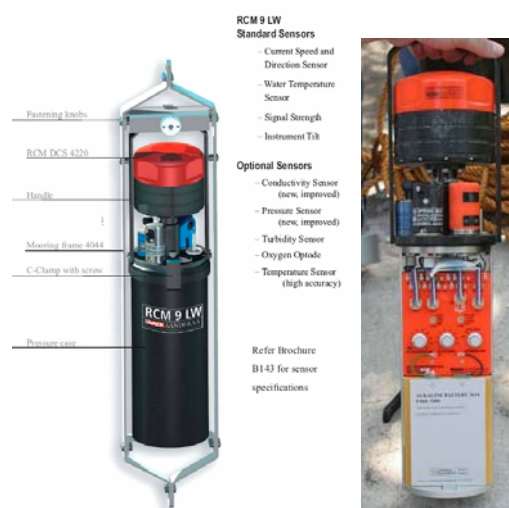

Figure 5. Aanderaa RCM 9 LW current meters equipped with sensors for measuring conductivity, turbidity, oxygen and pressure (depth).
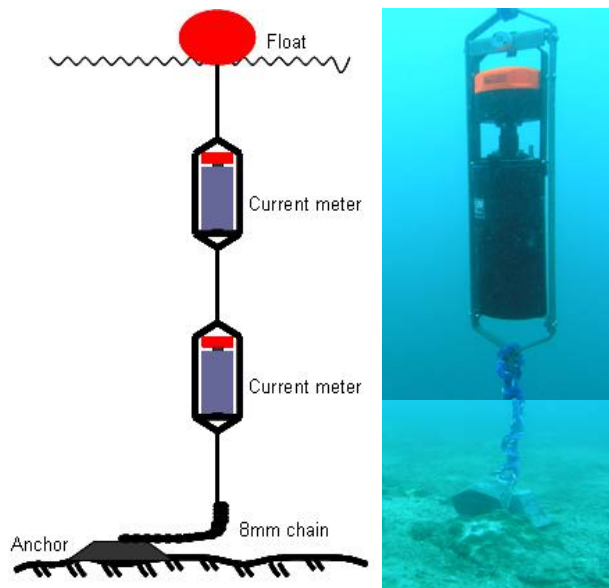
Figure 6. A typical set up (mooring) for current meter rig (Left). Right; picture of a current meter in a rig connected to the leaden weight.

Figure 7. Deploying current meters.

2.3 Drifting Buoy survey

Measurement of the dispersal characteristics was undertaken using GPS and drifting buoys (drogues).

Drifting buoys were manufactured in a local workshop in Dagupan and deployed in Bolinao, Dagupan and Taal Lake to measure current dispersion. This measurement is necessary for the validation of the predictive model.

Figure 8. Left: Pictures of the drogues with the "sail" and the buoy. Right: picture taken of seven drogues minutes after being deployed.

Drifters of various designs to measure physical oceanographic features have been used from oceanic to inshore areas (Yanagi et al., 1982, Burrows et al., 1999). Inshore drifter surveys have been commonly undertaken around long sea outfalls, with surveys around fish farms less common. In this context, although the principles of dispersion measurement are well tested application of this technology around fish farms is novel. Concurrent meteorological measurements of wind speed and direction is desirable.

The system used was with drifting buoys with numbered flags which were tracked at 10 to 30 minute intervals using hand held logging GPS unit by approaching the drifter in a small vessel and fixing position with the hand held unit. This approach limits the accuracy and timing of the positional data. If drifters were grounded or became snagged on moorings or debris then the drifters were recovered and removed from the trial.

One deployment of a CTD (Conductivity Temperature Depth) during the survey if possible is useful to measure the features of the water column in relation to sock depth.

2.4 Water column sampling with the CTDO-probe

Information about conductivity, temperature, salinity and oxygen in the water column is important parameters for understanding the condition and the dynamic of an area. In addition these parameters are sensual for the modelling work. These hydrographic data were measured with an electronic CTDO-probe (Sensordata) (Figure 9). 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 (Figure 10). The probe was programmed to take measurements every five seconds. The measured parameters will have seasonal and day – night changes.

Figure 9. Illustration of the CTDO probe from Sensordata.

Figure 10. Sampling with the CTDO-probe.

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2.5 Secchi-depth and water quality sampling

The Secchi-depth was measured with a standard Secchi-disk (diameter 25 cm).The use of a Secchi-disk is a very well known method for measuring the water-transparency and the colour of the water (Figure 11). These data gives information about the amount of particles in the water. The particles are either related to production in the water column (phytoplankton) or

particles which come from the drainage area or sediments (sand, dust). The Secchi-depth was measured at all benthic and CTDO stations.

Water samples were taken with a Niskin water sampler or a Rutner water sampler at 2 meters depth (Figure 12). In Bolinao, the stations used were the same as the University of Philippines Marine Science Institute (UPMSI) is using in their long trend studies. In Dagupan the same stations as BFAR-NIFTDC are using in their monitoring programme were used. In Taal Lake water samples were taken from some new stations in addition to the stations that BFAR Ambulong Station are using for their monitoring. The samples were analysed by the UPMSI and for the following parameters NH_3, NO_2^-, NO_3^-, PO_4^{-3} and Chlorophyll-a. In Dagupan, water samples were analysed by the NIFTDC laboratories and in Taal Lake by BFAR Ambulong Station laboratories.

Figure 11. Secchi-disk readings in Bolinao Bay 2005.

Figure 12. Left: Water samples taken with a Niskin water sampler in Bolinao Bay. Water sampling in Taal Lake.

2.6 Sediment sampling (Benthic stations)

Sediments are often used as indicators for evaluating the environmental status of an area. It takes much longer time to change the condition of the sediments compared to the water quality parameters. Water quality parameters give a snap shot of the conditions while sediments tell you how the conditions have developed over a longer time period. Therefore sediment samples are very good indicators of the environmental condition.

The distribution and abundance of organisms, numbers of species and community structure were analysed as a pilot faunal registration. These measurements give good indications of the environmental state of the area.

Sampling was carried out with a 0.05 m^2 modified van Veen grab (Figure 13). 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.

At each station one chemical and one biological grab sample were taken (Figure 14). Sub-samples for analyses of grain size, total organic carbon (TOC) and total nitrogen (TN) were taken from the upper 2 cm layer of the chemical samples. Each sample was visually inspected to ensure there was no sediment disturbance. The samples were frozen at -20°C.

The volume of the sediment that contained the biological samples was recorded and gently sieved through a 1mm round hole sieve immersed in sea water. The fauna for the semi-quantitative sample were then preserved in 4 % formaldehyde solution stained with rose bengal and neutralized with borax.

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, feces, fish food etc.). Further samples were taken for chemical analysis, grain size and fauna analysis.
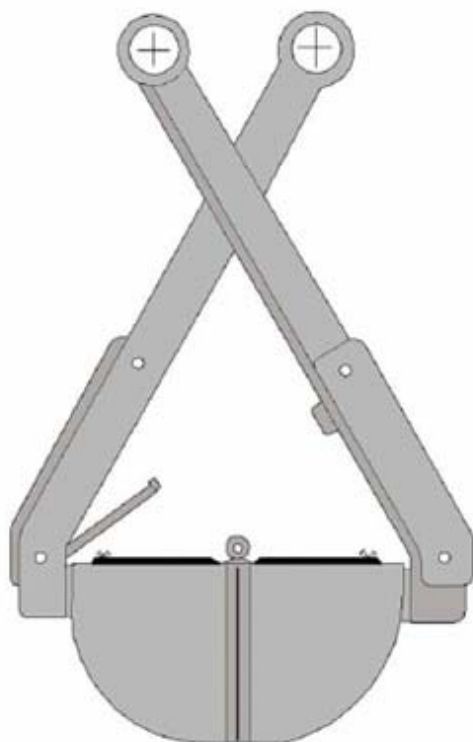

Figure 13. Illustration of the van Veen grab and picture of lowering the grab into the water.

Figure 14. The grab sample is inspected through the lid on top of the grab. A sample for chemical analysis is taken from the upper surface (2 cm).

Figure 15. Biological samples gently sieved through a 1mm round hole sieve immersed in sea water.

In areas with bad environmental conditions the sediments had high organic content and smelled H_2S (Figure 16). In these samples there were no any live animals recorded. 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.

High organic content
- close to a fish cage

Low organic content
- far away from a fish cage

Figure 16. Sediment samples from sites with different environmental conditions. The left picture is of sediments close to a fish cage; the sediments have high organic content, no live animals and smelling H_2S. Right picture is from an area far away from a fish cage; where the sediment is in good conditions.

3 Production survey

A survey of aquaculture production in each of the survey areas was undertaken. This was in order to link aquaculture production to the environmental impacts observed.

The following information was collected from a sample of farms in each area;
- o Species cultured
- o Growth rate
- o Biomass
- o Stocking density
- o Survival
- o Health problems and status

3.1 Fish Farm registration

Fish farms were counted, noted if operational or non-operational and registered with GPS reading (where possible). This method was used for Bolinao and Dagupan.

Figure 17. Data on the number and location of farms was collected by boat.

In Taal Lake the cages were too numerous to count individually by boat so a number of alternative methods for estimating the number of cages were used and their accuracy compared to an aerial survey.

Estimates of the surface area of cage zones were made using satellite imagery. Images were downloaded from Google earth. From the raw images it was not possible to identify areas with cages but with adjustment of the brightness and contrast, the areas with cages were able to be identified (Figure 17).

Figure 17. Left: Image of a cage area. Right: Enhanced image of cage area.

The enhanced image from satellites allowed accurate measurement of surface area but the date of the image used by Google earth is not known. A sub-sample of the number of cages per hectare was measured with a boat in different areas. Density of cages varied between 5 to 25 cages per hectare with an average of 15 per hectare. As the date of the image was not known, this method was discarded.

Another method used to try and estimate the surface area of the cage zones was to follow the perimeter of the cage area with a small boat recording the boat track using a GPS (Figure 18).

Figure 18. Illustration of the boat tracking recorded with a GPS to estimate the surface of the area of fish cages in an area.

This method was accurate for the measurement of surface area of cage zones but took a lot of time.

Another method that was evaluated was the taking a panorama of digital photographs from a vantage point and counting cages from the photographs (Figure).

Figure 20. Panorama photography of fish cages in Taal Lake.

Using this method it was estimated that there were 1,037 cages in the Sampaloc area (1371 counted from the aerial survey). It was difficult to count the cages in the distance accurately. In addition there were very few vantage points high enough to get a full view of the cages on the lake. This method was also discarded.

An aerial survey was undertaken by flying over all the production areas at 100 meters height and taking digital photographs (Figure 19)

Figure 21. Plane used for assessing large numbers of cages by taking digital photographs

This allowed photographs of all the cages to be taken and analysed (see Figures 22 and 23).

Figure 19. Composite of aerial photographs of an area in Leviste, Taal Lake.

Figure 20. Enhanced and zoomed aerial photograph of cages in Leviste, Taal Lake.

It was found that the most accurate method to estimate a large number of cages was by aerial photography.

4 Survey areas and sampling sites

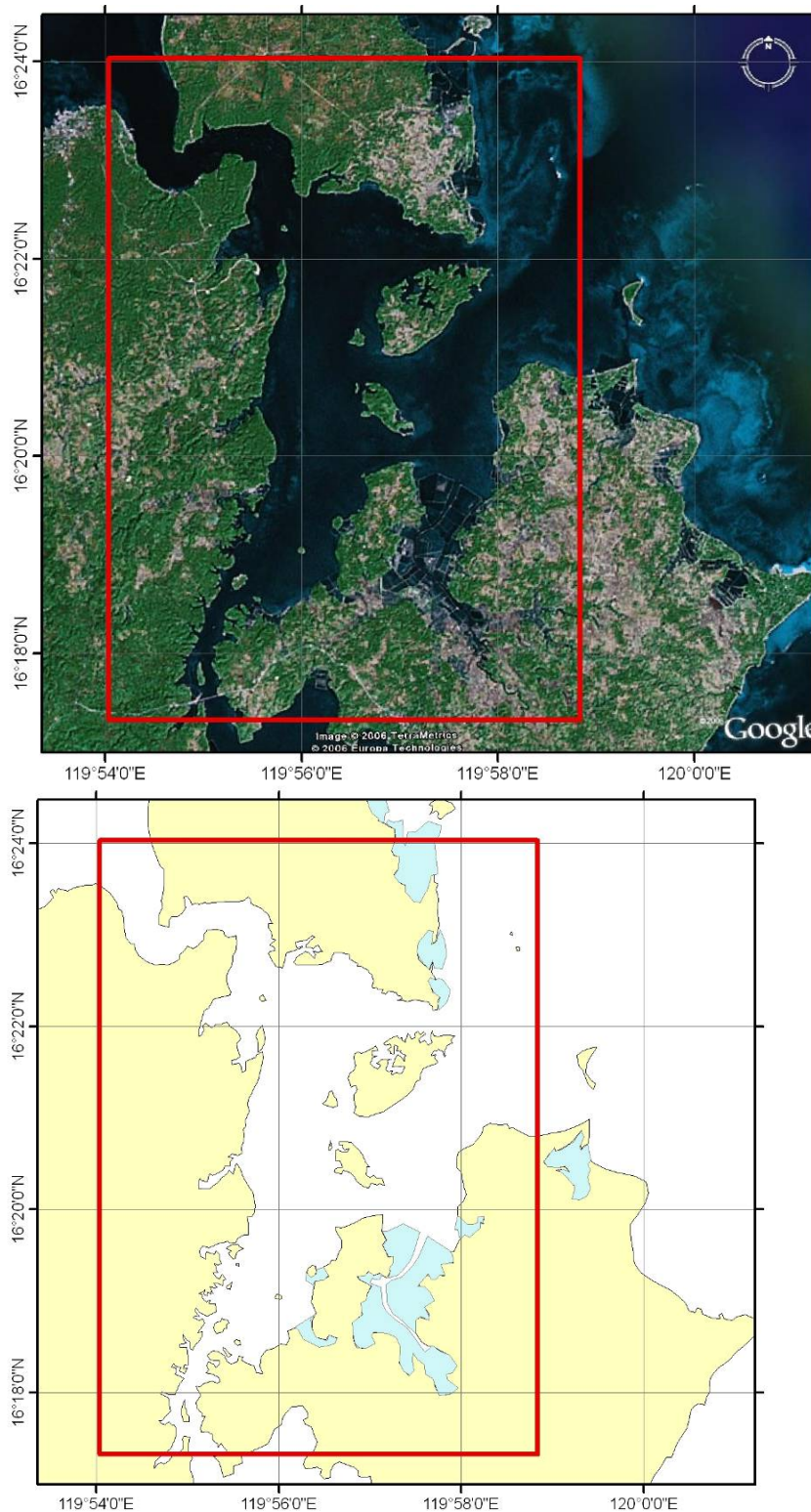## 4.1 Marine - Bolinao survey site – April, October 2005 and February 2006
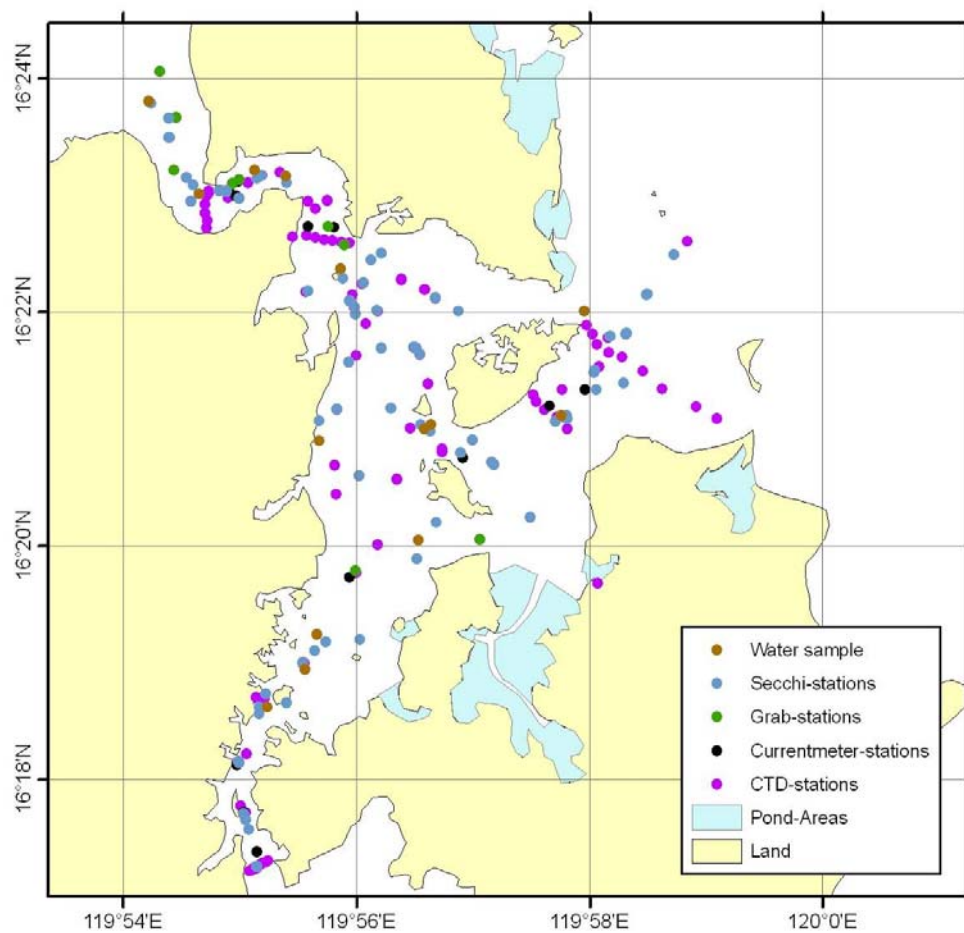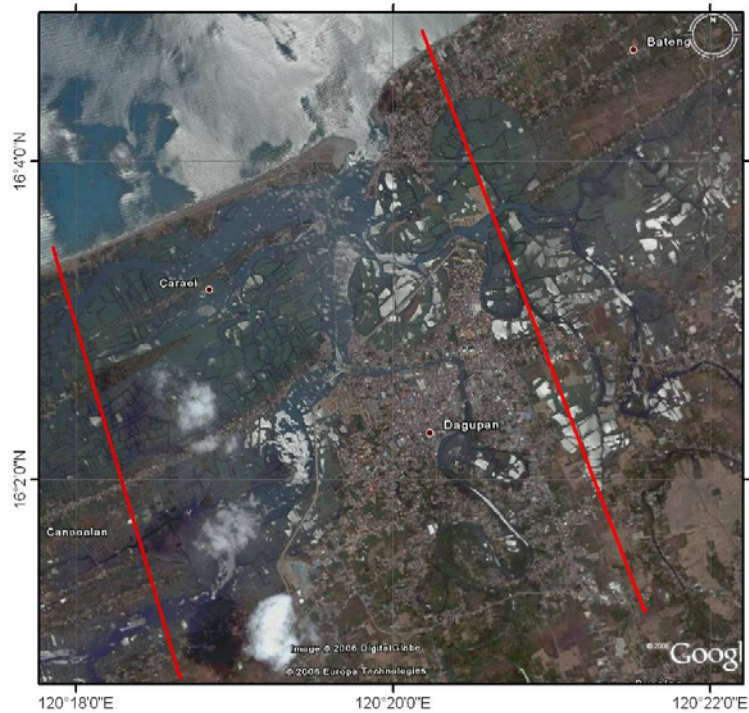

Figure 24. Bolinao map showing limits

Figure 25. Sampling sites in Bolinao

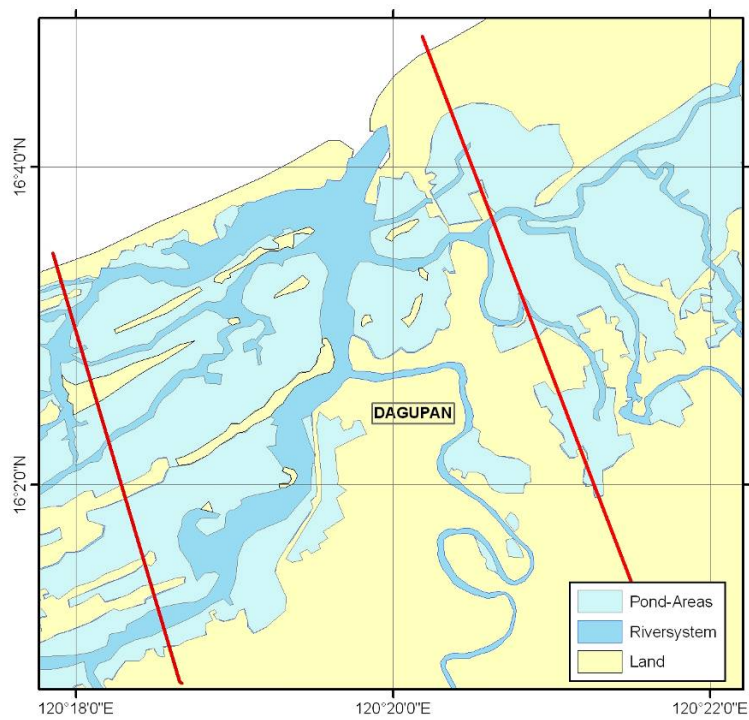## 4.2 Brackish – Dagupan estuary survey site – April 2006

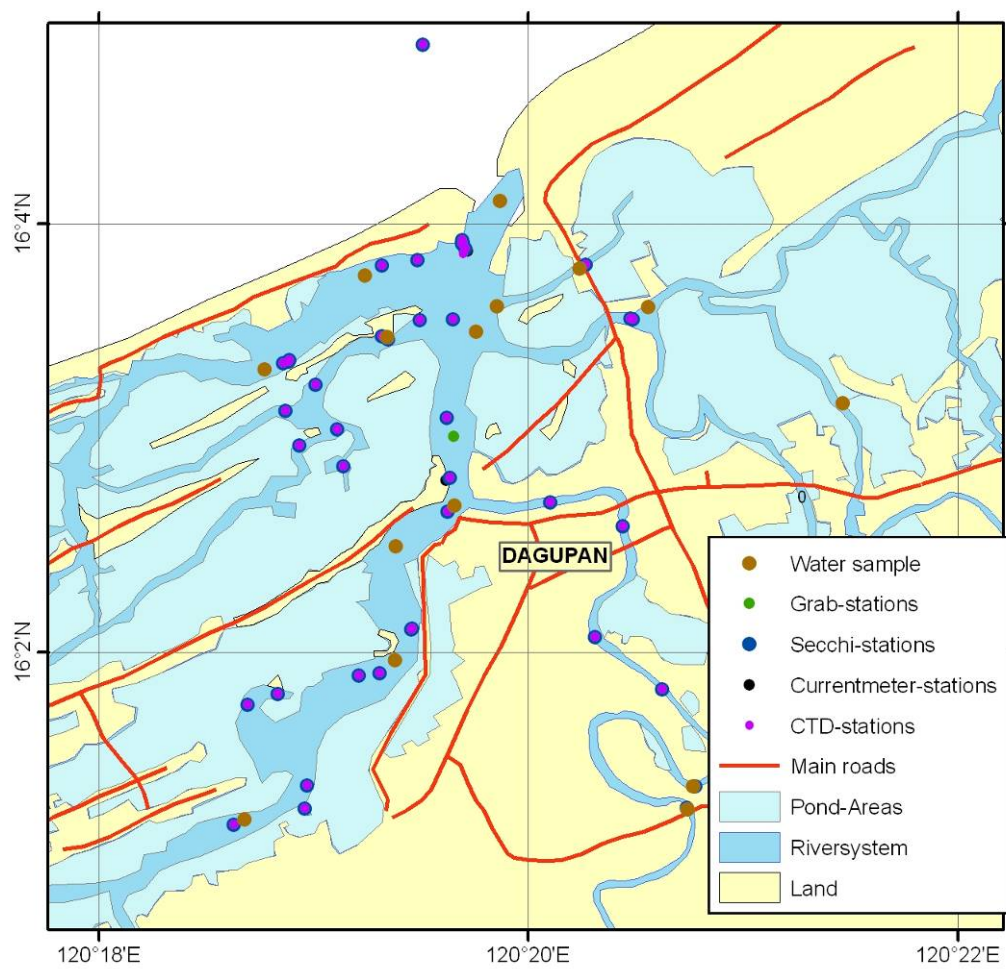**Figure 26**. Dagupan map showing limits.

Figure 27. Sampling sites in Dagupan
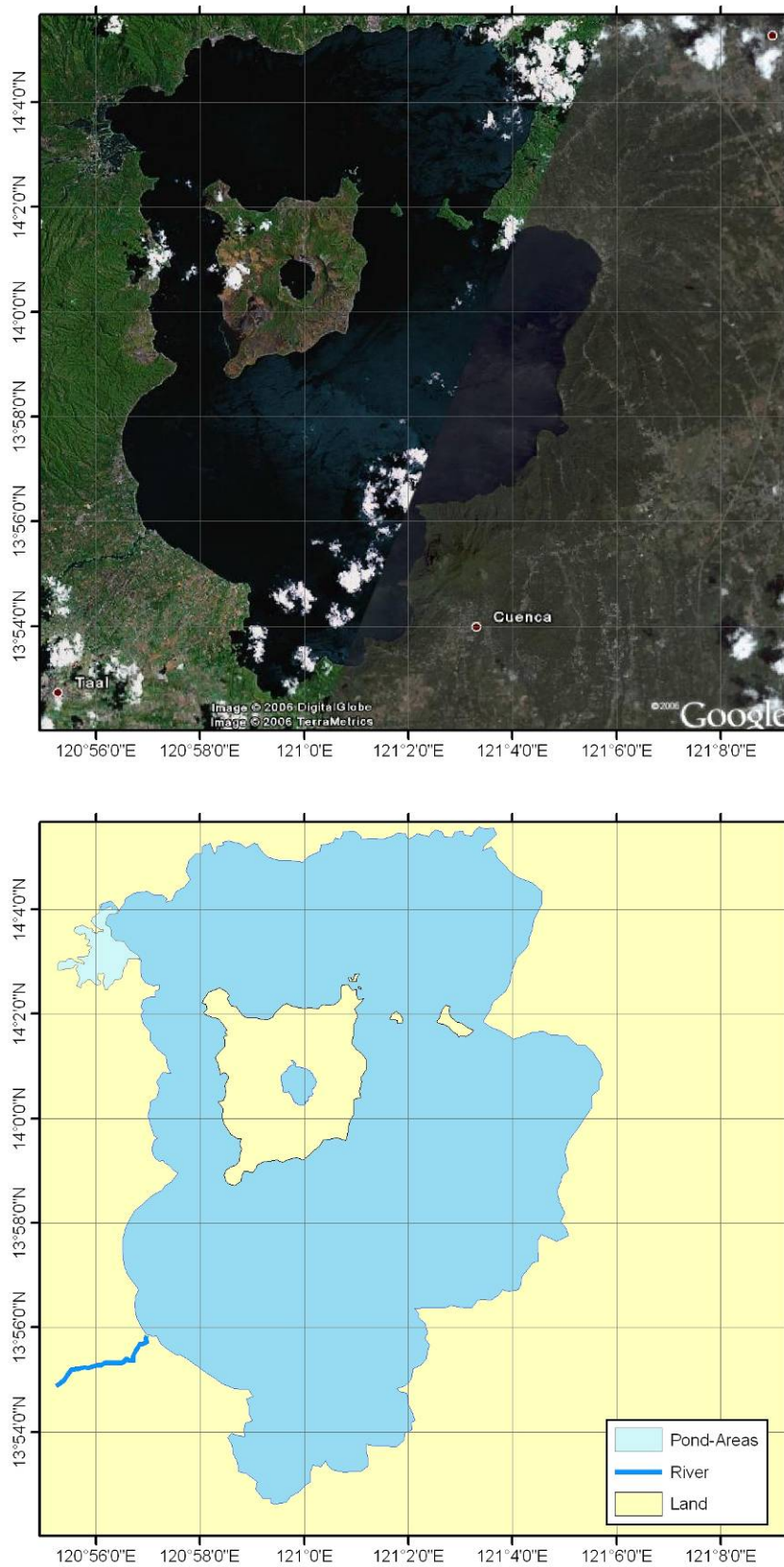
4.3 Taal Lake survey – October 2005 and April 2006

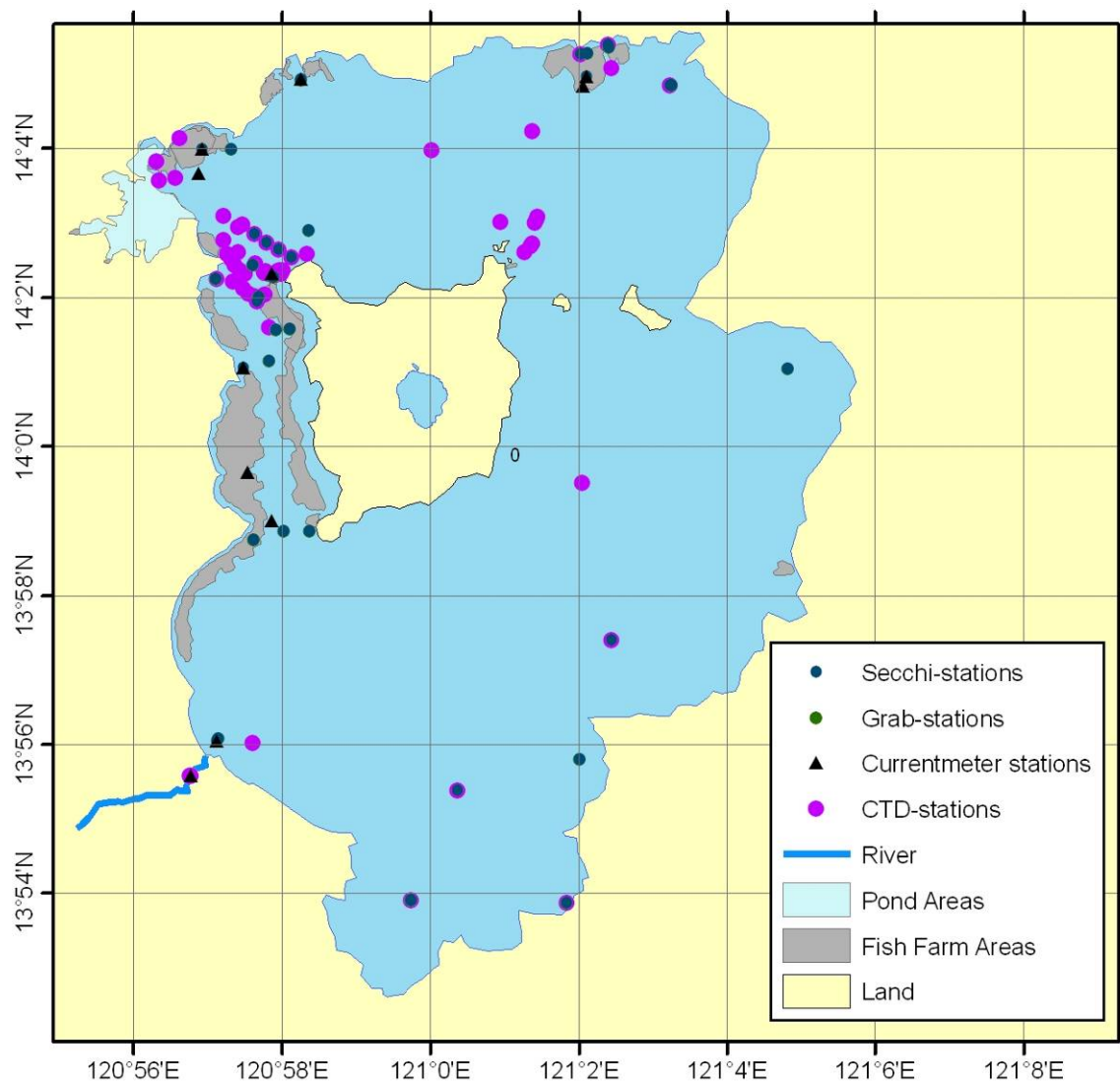

Figure 28. Taal Lake map. The whole lake was sampled

Figure 29. Sampling sites in Taal Lake

Name	Bolinao	Dagupan	Taal
No. Surveys	3	1	2
		Number of stations	
Currentmeter	16	7	11
CTDo	102	42	117*
Secchi depth	86	41	42
Grab sample	63	8	25
Watersample	32		
		* only 57 stations are shown on the map	

Table 1. Number of samples taken.

5 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 water body. 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 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 aquacultures emits its waste to the water body, 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 water body.

Consequently, our strategy to compute carrying capacity is composed of three steps.

Characteristics of a water body.
1) The rate water is exchanged with neighboring water where fish is not grown and hence has higher oxygen content. The concentration and locations of other nutrient sources that enter considered water body. Since fish is usually grown close to the coast, impact of land based sources may be considerable and may cause smaller carrying capacity for fish grown in aquacultures.

2) The growth of phytoplankton and concentration it is able to reach with given external sources. This will give us the remaining concentration of phytoplankton that we may reach by increasing aquaculture size.

3) The fish stock is increased (or decreased) theoretically until critical phytoplankton concentration is reached. So obtained fish stock will define the carrying capacity of the water body for a given species of fish.
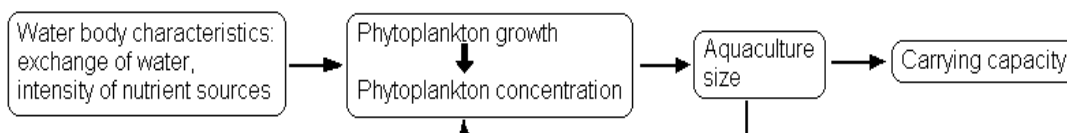
Figure 30. depicts the process graphically.

Figure 30. The process of determining carrying capacity for fish aquaculture based on arriving at the critical phytoplankton concentration.

5.1 Modelling methods

A model of dependence of phytoplankton growth on nutrient

Let us consider a well mixed water body such as an upper layer of a lake or a coastal sea.

Denote the nutrient concentration by S and the nutrient concentration in phytoplankton concentration by X. Nutrient concentration in phytoplankton is proportional to phytoplankton concentration. Inflow of nutrient is: inflow of water, Q, times concentration in the inflow, I. The equivalent rate of change in the concentration is $Q*I/V = D*I$, where V is the volume of the water body. D is the flushing rate because water inflow is assumed to be equal to water outflow. Then, the loss of concentration from a water body is $D*S$. Concentration of nutrient in water is also lost by phytoplankton uptake: $u*X$. Phytoplankton is lost from a water body due to outflow of water. This loss is equal to $D*X$.

Finally, the equations of the model are:

$$dS/dt = D(I - S) - u X \qquad\qquad (1)$$

$$dX/dt = (u - D) X \qquad\qquad (2)$$

where $u = V_{max}S /(h+S)$ = specific uptake rate = specific growth rate. The term u is known as the Michaelis-Menten-Monod uptake. The parameter, V_{max}, is a fixed maximum growth rate = maximum uptake rate, while parameter h is the half-saturation constant. Terms dS/dt and dX/dt denote rates of change of nutrient concentration in water, S, and the nutrient concentration in phytoplankton, X, respectively.

Let us investigate steady states of this model i.e. possible states when $t \to \infty$.

Steady states are solutions of dS/dt = 0 and dX/dt = 0. With this requirement, equations (1) and (2) become a system of two algebraic equations:

$$D(I -S^*) = V_{max} S^* X^* /(h+S^*) \qquad\qquad (3)$$

$$(V_{max} S^*/(h+S^*) - D) X^* = 0 \qquad\qquad (4)$$

where stars (*) denote steady states.

Steady state (S*=0, X*=0) is called the total extinction state and it does not exist. Indeed if we insert these values into (3) and (4) we see that equation (3) can not be satisfied. For equation (3) to be satisfied: $D*I = 0$, which is impossible given that D > 0 and I >0.

Steady state (S*=I , X*=0) exists and it is called the **phytoplankton extinction steady state**. In this state the phytoplankton has been washed out from the reactor.
For this state to be stable, flushing rate D must be greater than the maximum possible specific division rate of phytoplankton which is $V_{max} I /(h +I)$.

Finally, assuming $S^* \neq 0$ and $X^* \neq 0$, from equation (4) we easily find:

$$S^* = D h /(V_{max}-D) \qquad\qquad (5)$$

Hence, S* can be positive only if $V_{max} > D$. $\qquad\qquad (6)$

From (3) and (4) it also follows that:

$$I = X^* + S^*. \tag{7}$$

Anotherwords, in steady state:

the sum of nutrient concentration in water and in the phytoplankton
        is equal to the inflowing concentration.

By substituting (5) into (7) it follows:

$$X^* = I - D h/(V_{max}-D) \tag{8}$$

For $X^* > 0$ the condition $I > D h/(V_{max}-D)$ must hold.
This gives a more stringent condition on V_{max}:

$$V_{max} > D (1 + h/I). \tag{9}$$

Namely, it is not enough that $V_{max} > D$ which ensures that $S^* > 0$, but also $S^* < I$
and hence the condition (9). Anotherwords, even if the condition (6) is satisfied but the
condition (9) is not, as $t \rightarrow \infty$ the system starting with $S(t=0) = So > 0$ and
$X(t=0) = Xo > 0$ will end up in $(S^* = I , X^* = 0=$ i.e. the extinction of phytoplankton. This
will occur because wash out of phytoplankton DX will eventually overcome the growth V_{max}
$S X /(h+S)$.

Hence, the condition (9) must be satisfied if we want that the nonextinction steady state
(i.e. the state in which X persists) be stable (in fact a stable node).

Since we can not control the maximum uptake rate, V_{max} , because this parameter is a property
of existing phytoplankton in the lake, the condition (9) has to be rewritten in terms of D:

$$D < V_{max} /(1 + h/I). \tag{10}$$

Hence, we have a conclusion:

  By controlling flushing rate we can control the
  concentration of phytoplankton in the lake.

Alternatively, since (9) and (10) means:

$$I > D h /(V_{max} - D). \tag{11}$$

We also conclude:

  By controlling the inflow of nutrients in the lake
  we can control phytoplankton in the lake.

In Figure 31 we display dynamics of two systems, each starting with its own initial condition.

The first system starts with a large nutrient concentration So = 200 and a low phytoplankton concentration, Xo = 50. Wee see a phytoplankton bloom and then a tendency to a lower steady state X*.

In the second system which starts with a low nutrient concentration, So = 20, and a very low concentration of phytoplankton, Xo = 10, a transition to steady state is without phytoplankton bloom. Both systems tend to the same steady state since they are characterized with identical flushing rate, inflow of nutrient and phytoplankton characteristics V_{max} and h.
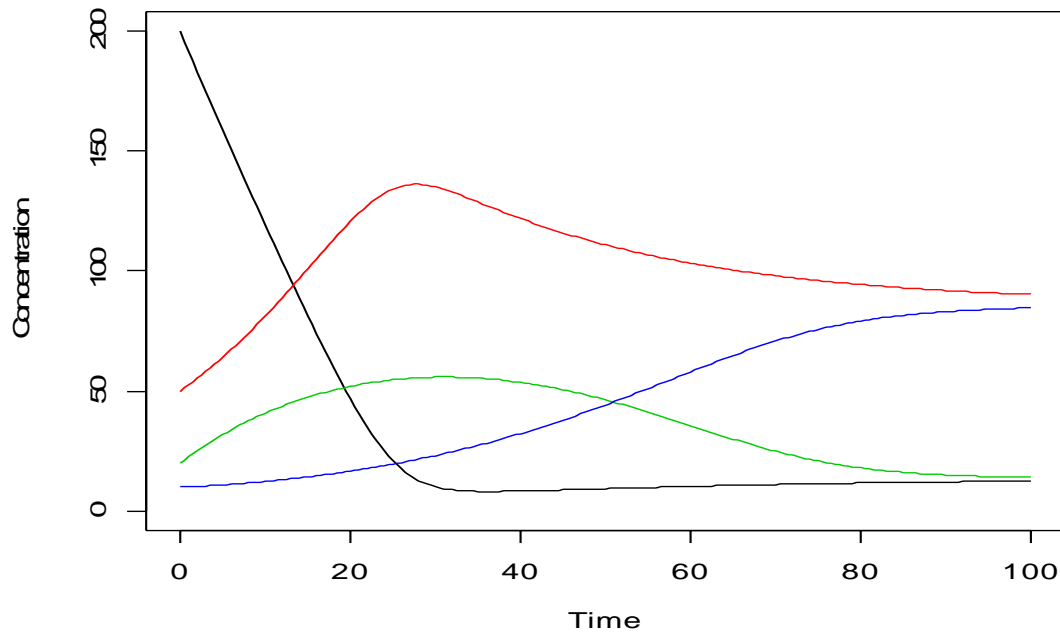

Figure 31. Dynamics of two systems. The first system starts with: So=200, Xo=50. The second system starts with: nutrient So=20 and nutrient in phytoplankton Xo = 10.

Parameters for both systems: I = 100, D = 0.04, V_{max} = 0.1, h = 20.

Consequences for the carrying capacity of a water body for fish farms
The preceding section contains interesting information concerning carrying capacity of a water body for fish aquacultures.

Fish aquacultures emmit nutrients into the lake and this is seen as an increase in the inflow D I. Since the inflow of water to the water body does not change, and hence D is the same, an increase in fish cultures is seen as an increase in average nutrient concentration, I, that enters the reactor.

We see from the expression (5) that as a consequence of an increase in I, the steady state of nutrient concentration, S*, in the reactor does not change. All the benefit of increasing nutrient inflow due to the increase in I goes into the increase of phytoplankton concentration. As the expression (7) shows, **the increase** in steady state **of phytoplankton concentration is linearly related to the increase in nutrient inflow**. Another words, if the nutrient inflow doubles, the phytoplankton concentration will double.

Since we know that there exists a phytoplankton concentration which will induce fish kill due to excessive consumption of dissolved oxygen during night and an overcast day, by limiting phytoplankton concentration we limit the standing stock of fish which are the source of nutrient inflow.

In case that rivers, other land based sources, and atmospheric input, bring so much nutrient that the critical steady state phytoplankton concentration has been reached already, the carrying capacity of the water body for the standing stock of fish is zero. Of course, this conclusion may change if these other sources decrease.

Estimation of the carrying capacity
Let us use the expression (7):

$I = X^* + S^*$.

When fish aquacultures do not exist, we have:

$I_o = X_o^* + S^*$. (12)

In the above expression, I_o is derived from other nutrient sources that drain into the water body and results into the background concentration of phytoplankton X_o^*.

Let us add a contribution from fish aquacultures: I_a. Then the expression (12) changes into:

$(I_o + I_a) = (X_o^* + X_a^*) + S^*$ (13)

But we know that a critically high concentration of X_c^*, call it $X_c^* = X_o^* + X_a^*$ will induce a critically low dissolved oxygen. This will be achieved for a value called the carrying capacity for aquacultures. Carrying capacity of aquacultures translates into a critical increase in nutrient concentration. Denote this value by I_c. Now using (13), we have:

$I_c = X_c^* + S^* - I_o$ (14)

If X_c^* is greater than X_o we have $I_c > 0$.

Note one more property of the expression (14): since the phytoplankton keeps the nutrient concentration, S^*, constant regardless of the increase in I, it is likely that $X_c^* \gg S^*$, so to a good approximation:

$I_c = X_c^* - I_o$. (15)

Application issues

1) The problem of the limiting nutrient
In the above, we assumed that there exists a nutrient which limits the production of phytoplankton. We know that phytoplankton needs many nutrients to grow.
All those nutrients which exist in higher concentration than the one upon which the production depends, are not of our concern. If we would use any of them in the expression 15, we would get a smaller carrying capacity of fish aquacultures.

Hence, to benefit from the above results, we must use the limiting nutrient. It is only for this nutrient that all of the above results are relevant. So it is obvious that somehow we must know the limiting nutrient in advance.

Most oceanographers approach this problem as follows: We know that there exists a Redfield ratio in phytoplankton. This ratio is an optimum ratio of nutrients that phytoplankton needs for growth. Hence, if one has the excess of one nutrient over the other in water than the Redfield ratio dictates in phytoplankton, the other is the limiting nutrient.

Legovic and Cruzado (1997) have shown that this line of reasoning is misleading. They concluded that the Redfield ratio of nutrients in phytoplankton does not translate into the Redfield ratio in water as one to one relationship. The exception is only in the environment where the growth of phytoplankton is negligible (ultra oligotrophic waters). But, in a water body in which we drive phytoplankton to a high concentration, phytoplankton growth is not negligible. Another words, we are on the opposite side of the mentioned exception.

To know which nutrient is limiting at a given time, the correct approach is to do separate experiments for each potentially limiting nutrient. The experiment is to increase one nutrient while keeping the others the same as they occur in the water body, and see if phytoplankton grows faster. The procedure needs to be repeated with all candidates for a limiting nutrient. The candidates 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 we are advised to take phosphorus as the limiting nutrient.
Similar experiments for the seas have resulted into nitrogen being limiting for the Atlantic, while phosphorus is slightly more limiting for the Mediterranean.

According to: Dufour and Berland (1999) and Dufour et al., (1999), south pacific waters are nitrogen limited. However, these results are derived from very oligotrophic sub- tropical Tuamotu archipelago and are probably not valid for Bolinao.

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 area of a dominant impact of aquacultures, the limiting nutrient will be determined by the ratio in which aquacultures emanate nutrients. If we look at the distribution of N and P in fish feed: 73 kg N/ton and P=14 kg N/ton we have the ratio N/P = 5.21. If we were to feed phytoplankton with fish feed, P would be given in excess of N, since the ideal ratio in phytoplankton is N/P = 7 (by weight), and hence N would be limiting. However, fish farms emanate 68 % of N and 28% of P from fish feed into the water column through excretion and soluble feces (Lupatsch and Kissil, 1998). This makes the ratio in emmision: N/P = 13.13 by weight and hence, a fish farm induces P limitation of phytoplankton.

Finally, one more caution. It is possible that bioassay studies show phosphorus limitation at one time instant and nitrogen limitation at another instant, when at both instances the same ratio of nutrients has been emitted to water. The phytoplankton species composition is dynamic in time due to existing seasonal succession of phytoplankton species and hence for the same nutrient ratio in emission one species is limited by nitrogen while another may be

limited by phosphorus or even silica. This latter is due to the fact that different phytoplankton species require different optimum N/P ratio. Hence, bioassay results are a function of phytoplankton composition and dominance for a given time instant.

2) A critical phytoplankton concentration
The critical phytoplankton concentration is one of the key parameters in expressions (14) and (15) which determine the carrying capacity of aquacultures in a studied area.
Hence, our next problem is to determine the highest phytoplankton concentration which guarantees that oxygen concentration will not drop below the healthy level for fish.

Sowles (2005) gives the critical mean phytoplankton concentration as 4 μg Chl-a/l. This concentration would bring dissolved oxygen concentration at the lowest value of 6 mg/l.
Perhaps this is acceptable critical dissolved oxygen content for salmon aquacultures in the Gulf of Maine, USA, but many agree that this dissolved oxygen value is too high as a critical value for freshwater Tilapia species or trophic fish cultures.

Masser (1988) writes: "In general, warmwater species such as catfish and tilapia need a dissolved oxygen concentration of 4 mg/l DO (or ppm) or greater to maintain good health and feed conversion. Healthy warmwater fish can tolerate 1 mg/l DO for short periods of time but will die if exposure is prolonged. Prolonged exposure to 1.5 mg/l DO causes tissue damage, and any prolonged exposure to low dissolved oxygen levels will stop growth and increase the incidence of secondary diseases, apparently by reducing fish ability to resist infection."

According to USEPA the maximum allowable total P should be 0.17 mg/l while the maximum allowable phytoplankton related Chl-a should be 10 μg/l.

If we assume that P in water is found almost exclusively in phytoplankton, then by using a relationship between Total P (TP) and Chl-a we find the upper value of Chl-a that corresponds to total P found in water.

According to Dillon and Rigler (1974):

$$\log_{10} (\mu g \ Chl\text{-}a/l) = -1.134 + 1.5383 \log_{10} (\mu g \ TP/l). \qquad (16)$$

The expression gave excellent correlation of R = 0.975 between the log10 (Chl-a) and log10 (TP) for Canadian lakes.

USEPA total P of 0.17 mg/l would mean 198 μg Chl-a/l. This tells us that there is a gross mismatch between the standard for total P and Chl-a.

As it concerns us, the relationship for Canadian lakes may not hold for tropic lakes.
From 534 Florida lakes, the following relationship has been found by researchers at the Florida Lakewatch (2000, 2):

$$\text{Log}_{10} (\mu g \ Chl\text{-}a/l) = -0.369 + 1.053 \ \text{Log}_{10} (\mu g \ TP/l) \qquad (17)$$

Given total P of 0.17 mg/l we get 95 μg Chl-a/l.

It is instructive to keep in mind (Florida Lakewatch, 2000, 1):

"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."

Hence the above value of 0.17 mg P/l and corresponding 100 μg Chl-a/l we may take as the indication that carrying capacity has been reached.

Let us also mention that:

The Department of Environment and Natural Resources has set the standard for total P as < 0.4 mg P/l. However, when compared to USEPA and the expression (17), the upper limit of 0.4 mg P/l is obviously an overestimate because it would result into unacceptably high phytoplankton concentration. This is an indication that the standard of < 0.4 mg P/l should be changed into < 0.17 mg P/l.

3) Background concentration of nutrient in the inflow, Io
The background concentration of nutrient, Io, means an average value of nutrient concentration in the inflow from other sources. Since there are two seasons, dry and wet: should we take the average value of the limiting nutrient for the dry season or the average value for the wet season? To resolve this dilemma we have to consider time scales of processes responsible for the phytoplankton dynamics and choose the most critical one.

Dry season
In this season the phytoplankton dynamics will be driven by a small value of flushing rate D, small nutrient inflow in terms of D*I, but a high value of I (more concentrated nutrient in small streams that enter the water body). From the expressions (5) and (8) we see that if phytoplankton has enough time to come close to steady state, the steady state would be higher than in case D is higher and I lower. Since dry season is long enough for phytoplankton to grow to whatever value limits its growth, it follows that it is important to measure nutrient concentration in the inflow, because this concentration will determine carrying capacity of aquacultures.

Wet season
Wet season is characterized by much higher precipitation. Direct precipitation contains small concentration of limiting nutrient. The effect on phytoplankton dynamics is basically determined by high flushing and this decreases existing concentration of phytoplankton and presents a weak basis for further phytoplankton growth.

However, wet season is not characterized by a continuous higher precipitation but by a series of storms, sometimes violent ones. Although the dilution phenomenon are more prominent, storms are followed by an increased erosion and flushing of agricultural fields which are rich in nutrients. During such storms up to 80 % of nutrients are flushed into the recipient water

body, estuary, coastal bay or a lake. The first significant storm after the dry season is the one which brings most nutrients into the recipient water body.

A representative total concentration made up of averaging across a series of streams and diffuse inflows is difficult to measure. However, the total inflow of water is usually available since it is equal to the outflow. A single outflow such as in the Taal Lake is not difficult to measure.

The average concentration in such a case would be:

Average I = (Q1*I1 + Q2*I2+…+Qn*In)/(Q1+Q2+...+Qn)   (18)

Where Qi and Ii are the inflow of water through the i-th stream and Ii is the nutrient concentration in the i-th stream, where the number of streams is i = 1, …, n.
Given the fact that the inflow of water through the streams and the concentration of nutrient in each stream are highly variable in time, the problem of precisely estimating the average nutrient concentration is very difficult and time consuming process.
The process is further complicated by the existence of diffuse inflows from agricultural lands, forests and meadows.
The above shows that the precise determination of Io will be difficult to obtain directly, and yet the carrying capacity depends on this determination.
The alternative is to resort to indirect methods. Indirect methods would involve measurements of the nutrient concentration in the water body and possibly extract Io from such measurements. Indeed the expression (13):

(Io + Ia) = (Xo* + Xa) + S*

holds some potential to succeed by assuming much smaller measurement cost.

When one makes measurements of the limiting nutrient in the water body, aquacultures are already there, hence Io is masked by emission from aquacultures.
Now, if we would know the emission of aquacultures and the corresponding nutrient in the phytoplankton, then by using the above expression and neglecting S*, the determination of Io would be straightforward.

4) Emission of nutrients by fish cultures
We start with the expression (15):

Ic = Xc - Io.

All units are in mass nutrient per volume for example µg(nutrient)/l.

In order to apply the expression (15), we need to convert production of fish into the emission of nutrient into the environment.

The fish stock in aquacultures is not constant but varies during the year.
Suppose, we are interested in the maximum stock, say Fm (tons).

This stock of fish emits Fn mass of nutrient in a time interval, for example in kg (nutrient)/day):

$$Fn = a \, Fm. \tag{19}$$

The parameter a specifies how many kg of nutrient are emitted per one ton of standing stock of fish.

From the value of Fn, the equivalent concentration addition in the water body may be calculated from:

$$Ic = Fn/(DV) = Fn \, / \, (Inflow \; or \; outflow \; of \; water \; into \; the \; lake) \tag{20}$$

Now, by imposing the Ic value we may calculate back the value of Fm i.e. the carrying capacity of the water body in terms of tons of fish.

5.2 Modelling Conclusions
The calculations suggest that aquacultures in the Taal Lake have overcome the carrying capacity. Aquacultures in Bolinao Bay are close to carrying capacity during average tidal exchange. This means that during low tidal exchange and no wind, carrying capacity has been overcome. Aquacultures in Dagupan section of the estuary have not overcome carrying capacity even during low flow. However during very low flow and no tidal flushing carrying, capacity has been overcome.

A series of management measures are suggested to decrease environmental impact and increase present carrying capacity for each of the considered areas. Since case studies represent a lake, an estuary and a marine area, the same methods may be applied to many other localities in the Philippines, hence fulfilling the goal of this project to obtain results and arrive at methods that can be applied elsewhere.

6 Recommendations for mitigating impact
Following the collection of data from the environmental surveys, production surveys, an assessment of the impact caused by the level of production in the three areas was possible. This together with an estimation of the carrying capacity allowed and assessment as to whether the present production was above or below the carrying capacity.

Following the analysis of this data and following the participatory workshops, a number of recommendations were drawn up to try and mitigate impact. These recommendations were primarily;
- Reduction of nutrient output by improving food conversion rate
- Utilisation of nutrients from fish production by extractive species such as oysters in marine and brackish water and hydroponics in freshwater
- Zoning of aquaculture into areas away from sensitive habitats and within carrying capacity of that zone
- Farm management and planning solutions to reduce benthic impact

The recommendations are given in more detail below.

6.1 Planning aquaculture within zones and within carrying capacity
Aquaculture production has environmental impact such as organic deposition and dissolved nutrients. The impact is higher close to the farm.

Aquaculture zone should be located away from sensitive habitats such as coral reefs, seagrass beds, fish spawning areas, fry nursery areas, mangroves. In Europe this distance has been determined at around 2 - 400 meters (MedVeg). Until further research has been undertaken in the Philippines on this it is recommended that aquaculture zones are at least 300 meters from sensitive habitats.

There is significant impact to the benthos flora and fauna close to a fish farm. In Europe this distance has been found to be 25 meters (MERAMED). Cages should be placed in such a way that there is no significant impact on the environment outside of the aquaculture zone.

Figure 32. Planning an aquaculture zone.

There should be no significant impact outside the area of the farm or zone (outside of green zone). Therefore it is recommended that there should be a 20 meter buffer between the cages and the edge of the zone (blue arrow).

It is therefore recommended that the minimum distance between large cages (more than 5 tonnes standing biomass) is at least 20 meters or for smaller cages (less than 5 tonnes standing biomass) 1 meter distance between cages (red arrow) and 30 meter distance between rows of cages (green arrow).

When cages are placed close together, there are areas of continuous impact below the cages and if production is high, then continuous azoic areas (See figure 33 below). However if the cages are spaced apart from each other there are pockets of less impacted areas where benthic organisms can survive which improve the ability of the sediment to assimilate the organic matter and recolonise the impacted areas (See figure 33 below).
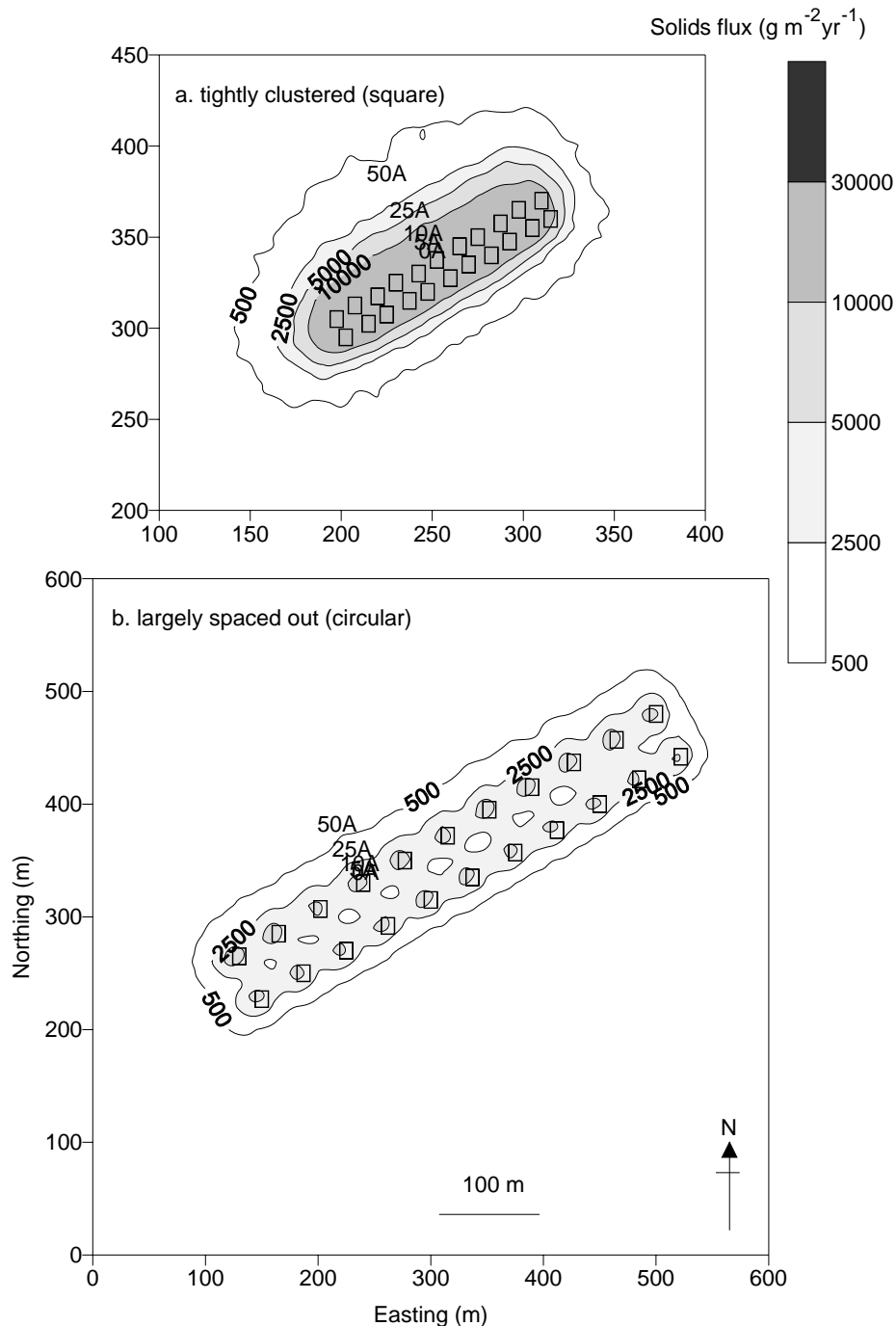
Figure 33. Model predictions of flux (g m-2 yr-1) showing the significant difference in deposition footprint severity and extent when tightly clustered square cages are replaced by circular cages spaced by 30 m. For the spaced out cages, areas of lower flux are shown in between lines of cages which will tend to assist sediment processes (MERAMED).

6.2 Depth of nets in cages

If there is insufficient distance between the bottom of the net and the seabed, the water flow is restricted below the net and the organic matter will build up directly below the net. In Europe the recommended net depth is 1/3 of the water depth to allow sufficient water flow to provide oxygen and to allow sufficient dispersion of the organic sediments.

It is therefore recommended that the depth of cage should be 1/3 (red arrow) of the total water depth (blue arrow).

Figure 34. Recommended depth of cages

6.3 Improvement in feeding strategy

Feed is the most important variable production cost. A simple objective is therefore to minimize waste from uneaten food, which has the added benefit of reducing the risk of environmental degradation. Food conversion rate in farms varies between 2.6:1 (milkfish) and 2.2:1 (tilapia) depending on the feeding strategy and close feed management. This over feeding results in excess nutrients entering the aquatic ecosystem as organic sediments or dissolved nutrients in the water column.

Reported waste loading rates per 1,000 kg of harvested shrimp have ranged widely, from 10 to 117 kg for N and 9 to 46 kg for P, depending upon FCR. For example, according to the Asian Shrimp Culture Council (Anon 1993a), the calculated waste loading rates per 1,000 kg of harvested shrimp would be as follows:

FCR	Organic Matter (kg/tonne)	Nitrogen (kg/tonne)	Phosphorus (kg/tonne)
1	500	26	13
1.5	875	56	21
2	1250	87	28
2.5	1625	117	38

Table 2. Kg per tonne release of organic matter and nutrients

By improving the food conversion rate from 2.5:1 to 2.0:1, the organic matter, nitrogen and phosphorus will be reduced by 30.0%, 34.5% and 35.7% respectively.
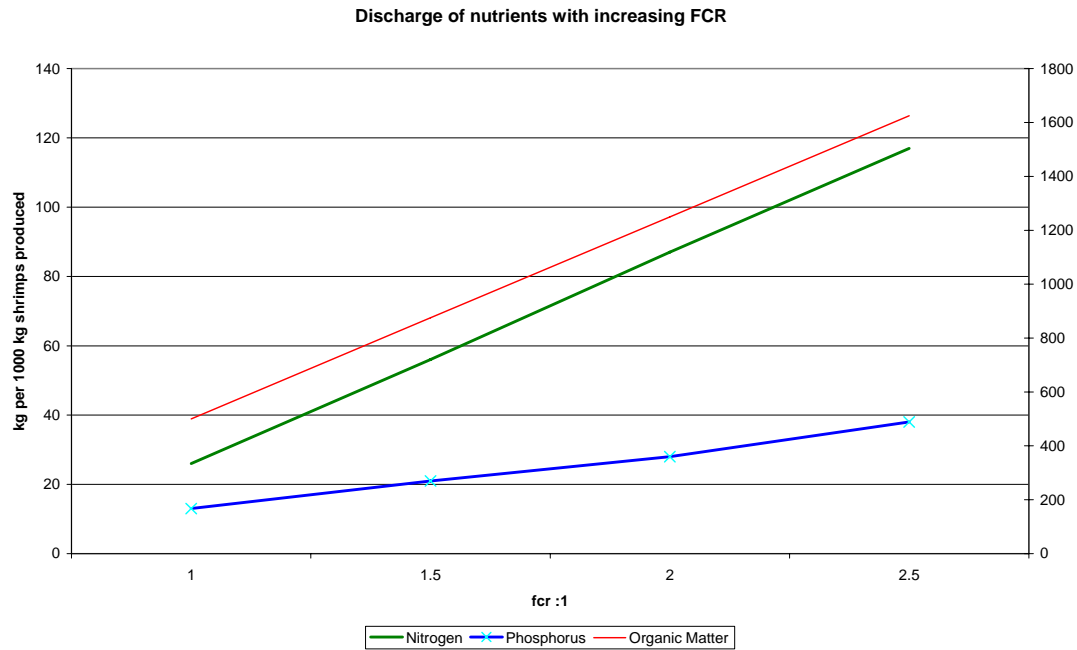
Discharge of nutrients with increasing FCR

Figure 35. Graphical representation of the increase in release of organic matter and nutrients with increasing FCR.

Using modelling the reduction of impact on the sediment can be demonstrated.
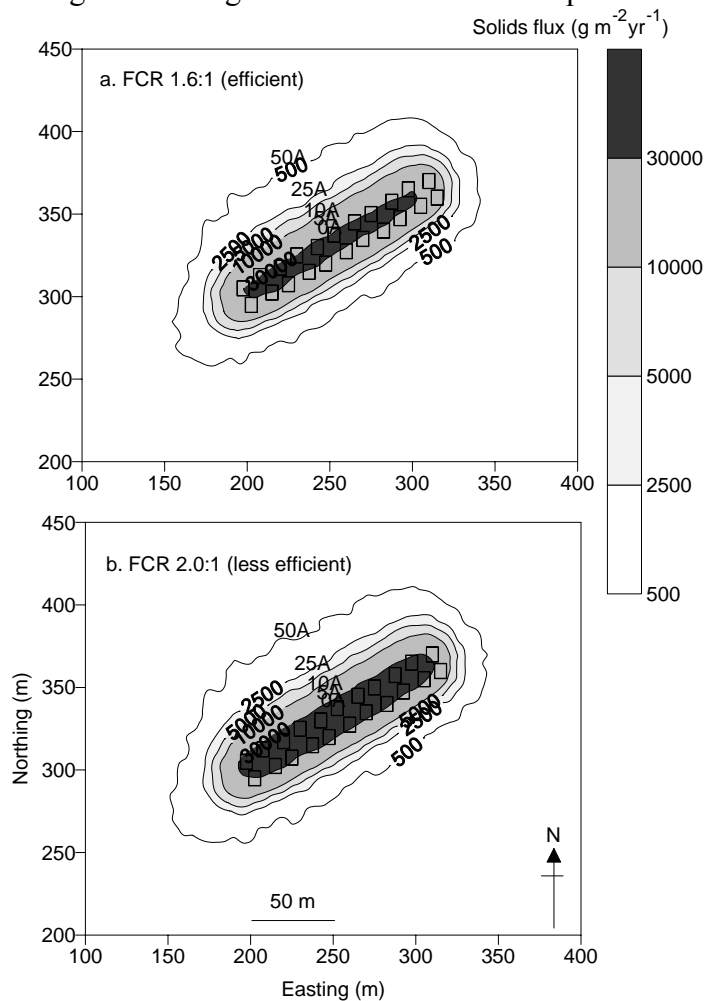
Figure 36 shows the effect between cages with a FCR of 1.6:1 (FI = 111.6 kg cage-1 d-1) and 2.0:1 (FI = 139.5 kg cage-1 d-1). A depth of 15 m was used.

6.4 Methods to improve Food Conversion Ratio

Feed back systems

Traditional hand-feeding uses feed tables and the experienced eye of the operator to adjust the feed quantity to suit the needs of the stock. However, the operator tends to overfeed especially in cages which have become larger and deeper so that accurate visual observations of the stock have become more difficult.

There is a relatively simple method of improving information feedback of feed consumption, by means of a feeding tray. A small feeding tray is made from split bamboo and mosquito mesh similar to the ones used in shrimp ponds

Figure 37. Example of a feeding tray

This has a sting long enough to reach from the bottom of the cage to the surface. The tray is lowered to the bottom of the cage before feeding and then the operator stats to feed. After some time of feeding the tray is lifted out of the water to see if there are any pellets caught on the mesh. If there are pellets then freed would have been escaping from the bottom of the net with being eaten. If there are no pellets, then the tray is lowered again and feeding recommenced. This action is repeated until pellets are found on the tray at which time feeding is stopped for at least one hour.
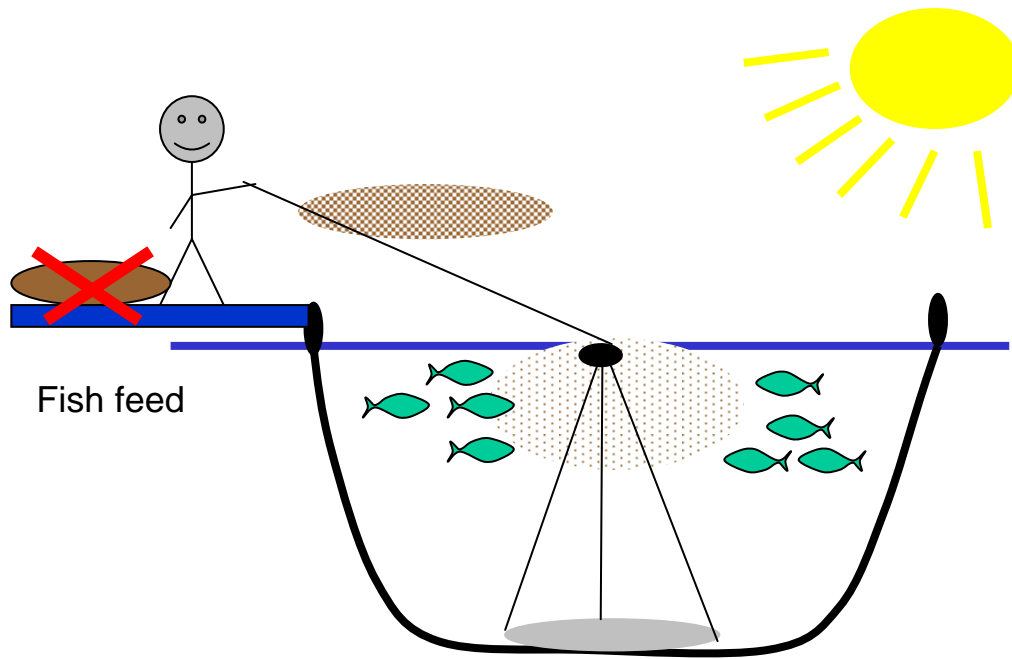
Figure 38. Representation of the use of a feeding tray in a fish cage

The tray could be fitted with a long bamboo to make the lifting easier.

Figure 39. Feeding tray with bamboo pole for ease of lifting

A more sophisticated method is to use airlift pumps. Feed may is given until a significant number of pellets are observed being drawn up through the airlift pump by the operators. Feeding is then stopped.
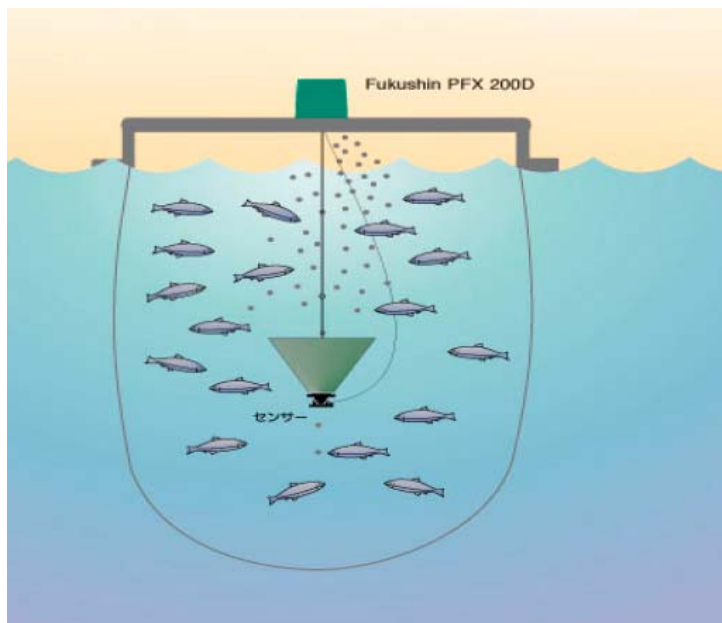
Figure 40. Automated feedback feeding control system

Reducing feed input
Another strategy to reduce feeding is to reduce the amount fed either by reducing daily ration or by not feeding on certain days.

A trial was undertaken on Tilapia reducing feed intake by Jimenez, E., and R. B. Bolivar at the Freshwater Aquaculture Center, Central Luzon State University. Their findings were that with feeding only 67% of the satiation ration, there was only slightly slower growth.
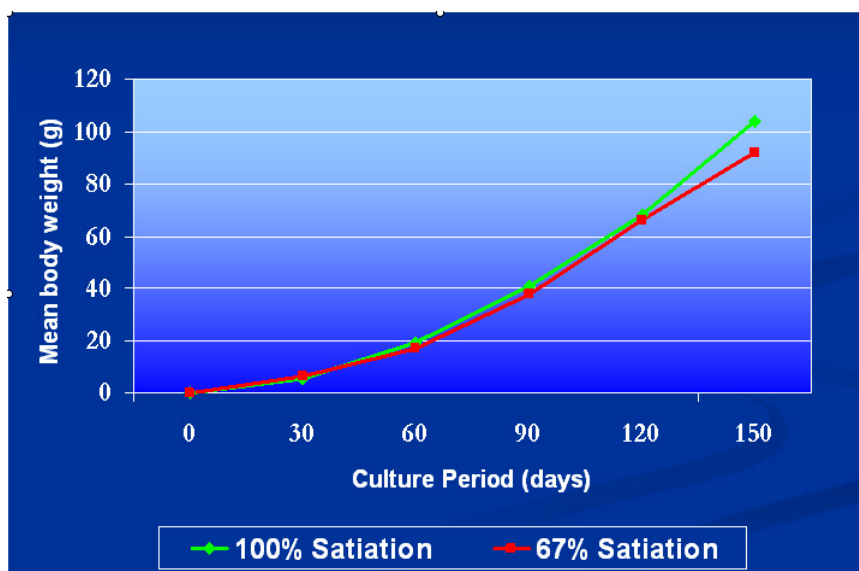

Figure 41. Change in growth rate with decreased feeding level

However Food conversion rate was reduced significantly from 3.5: 1 to 2.7:1

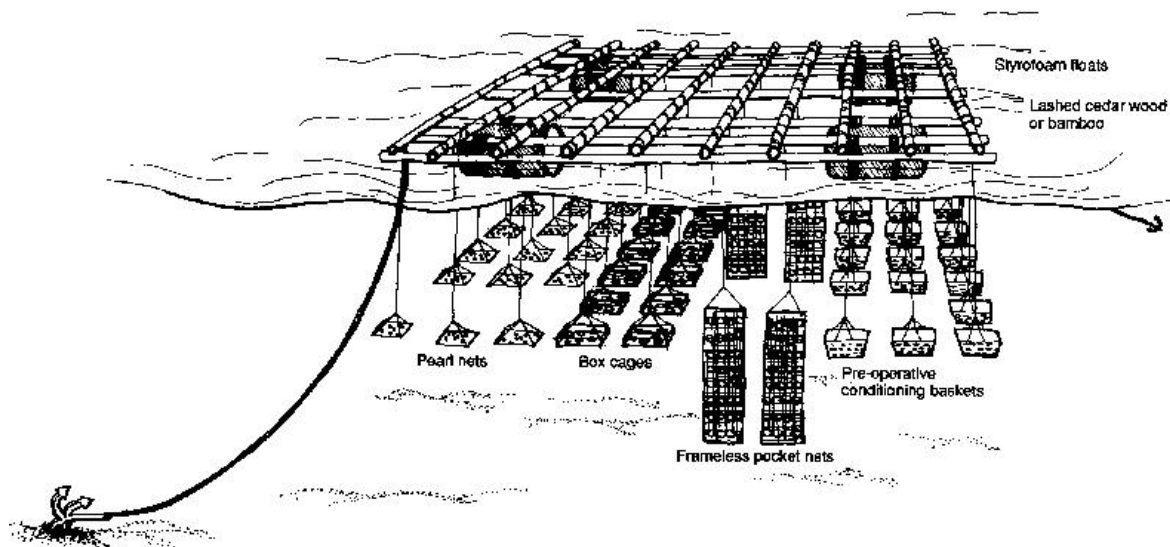| Performance	100% satiation level	67% satiation level
Mean final weight (g)	104.2± 37.1	91.7± 21.6
Mean daily weight gain (g day-1)	0.69±0.25	0.61±0.14
Extrapolated gross yield (kg ha-1)	3,196±1,495	2,815±1,098
Feed conversion efficiency	3.58±1.22	2.73±1.79
Survival (%)	79.7±15	76.7±16
Quantity of feeds (kg ha-1)	10,416±3,642	7,094±2,554

Table 3. Change in growth rate with decreased feeding level

This reduction would be the equivalent of not feeding the fish every third day.

A training course for "Training of trainers" on "Improved feeding and techniques" was scheduled to take place on March 16, 2007 for 20-25 people at Bolinao. The target persons for this course would be a core group of caretakers, LGU (3 persons), NGO, UPMSI (2), Water quality monitoring group. APN will provide the training materials while LGU will be in charged with the venue and food

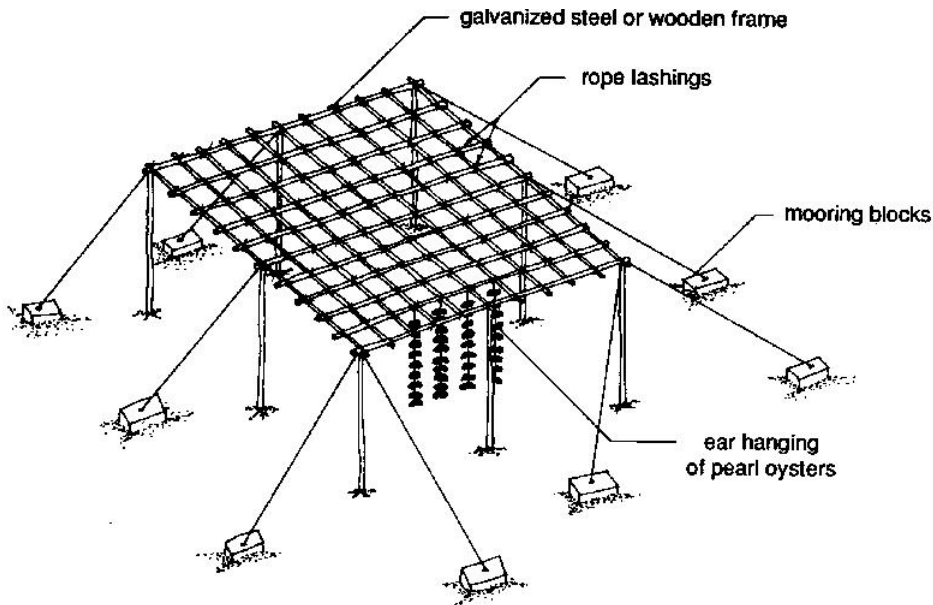## 6.5 Integrated aquaculture: shellfish and finfish

One of the findings from the survey was that where there was a mix of fish and shellfish culture, the impact on the sediments were much less than where there was a monoculture of fish. Therefore a recommendation is to encourage the mixing of fish and shellfish culture.

There are a number of culture methods that would be suitable depending on the depth of the water.

Raft pearl farm structure (from Gervis and Sims, 1992).

Figure 42. Alternative methods for farming oysters on rafts in deep water

Trestle pearl farm structure (from Gervis and Sims, 1992)
Figure 43. Farming oysters on trestles in shallow water

There are number of alternatives for positioning fish cages and mollusc culture.

They can be positioned
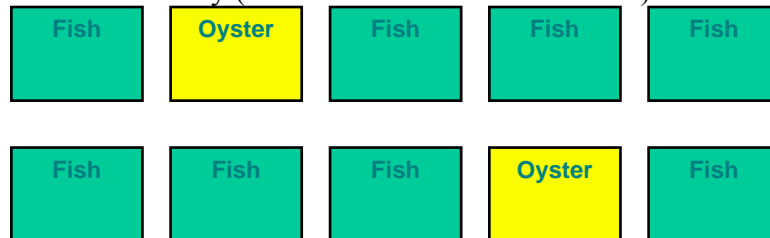- Alternatively (fish – mollusc – fish – mollusc)

| Fish | Oyster | Fish | Fish | Fish |

| Fish | Fish | Fish | Oyster | Fish |

Figure 44. Placing oyster culture alternatively with fish cage culture

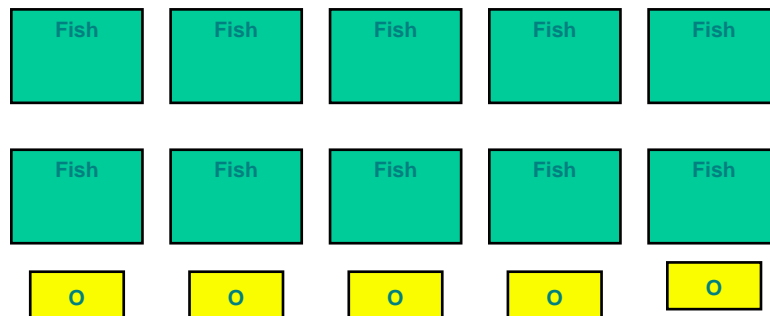- Molluscs within a buffer zone between the cages and the edge of the aquaculture zone

| Fish | Fish | Fish | Fish | Fish |

| Fish | Fish | Fish | Fish | Fish |

| O | O | O | O | O |

Figure 45. Placing oyster culture on the border of a fish cage culture zone

In freshwater there is the possibility to introduce hydroponics to extract nutrients.

6.6 Integrated aquaculture: Aquaponics

Hydroponic systems are designed to grow plant crops without soil using water to supply the nutrients. An aquaponic system is a symbiotic joining of aquaculture and hydroponics. Nitrogen waste from fish metabolites provides needed nutrients to the vegetable or plant crops. By removing these wastes the vegetables remove nutrients from the water improving the environment for the fish promoting faster growth and healthier fish. In aquaponics, nutrient wastes produced by the fish are used to fertilise hydroponic floating production beds. This is good for the fish because plant roots and associated rhizosphere bacteria remove nutrients from the water. These nutrients - generated from fish waste, algae, and decomposing fish feed - are contaminants that would otherwise build up to toxic levels in the water, but instead serve as liquid fertilizer to hydroponically grown plants. In turn, the hydroponic beds function as a biofilter so the water can then be recirculated back into the fish tanks.

Most plants can be grown in hydroponics. This includes trees, shrubs, flowers, herbs, strawberries and most major crops. The most economical crops grown in Australia are lettuce, tomatoes, cucumbers, capsicums, strawberries, egg plants and flowers such as carnations, roses, gypsophilia, chrysanthemums, orchids also a wide range of herbs are grown hydroponically.

In China, floating bed hydroponics have been developed for a number of plants and vegetables.

Rice plants cultivated
on the surface of a fishpond

Canna and umbrella
sedge on floating beds

Flowers grown on floating beds

Figure 46. Examples of floating bed aquaponics.

Plants that will do well in any aquaponics system:
- any leafy lettuce
- pak choi
- spinach
- arugula
- basil
- mint
- watercress
- chives
- most common house plants

There is already a primitive type of aquaponics being practised on Taal lake for coconut tress and abandoned cages filled with grasses and floating water hyacinth.

Figure 47. Coconut trees being grown in association with fish cages in Taal Lake.

A small trial was set up to test the viability of aquaponics in Taal lake using feed sacks, bamboo and coconut matting made into a small floating bed and then a variety of vegetables inserted into the floating structure.

6.7 Early warning systems
IN marine and brackishwater areas where currents are induced by tidal fluctuation, there are times during the tidal cycle that flushing of the bay is reduced dramatically. During these periods, there is greater risk from low oxygenation, build up of nutrients and algal blooms.
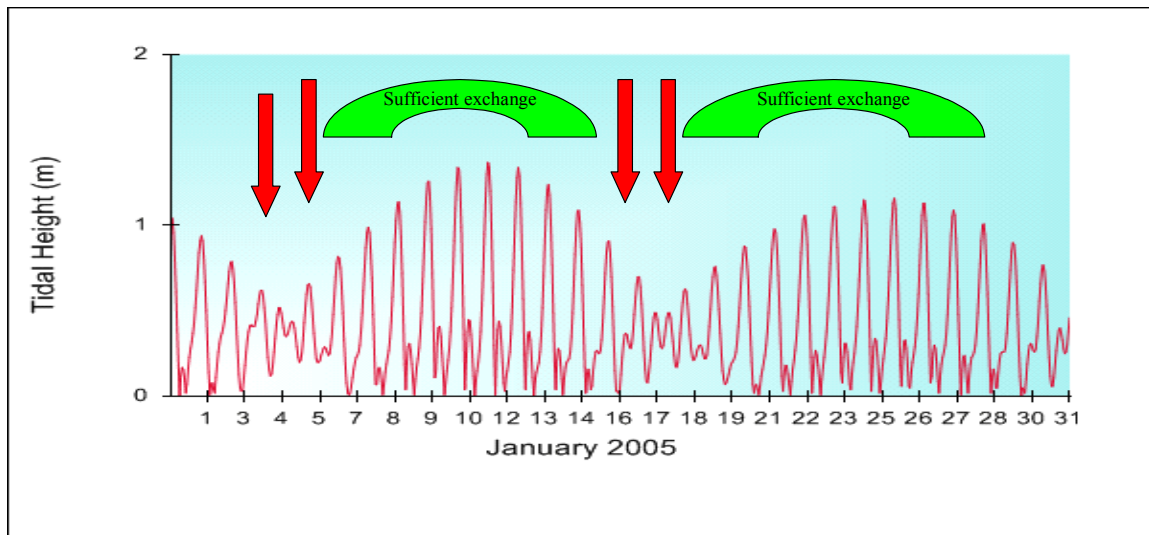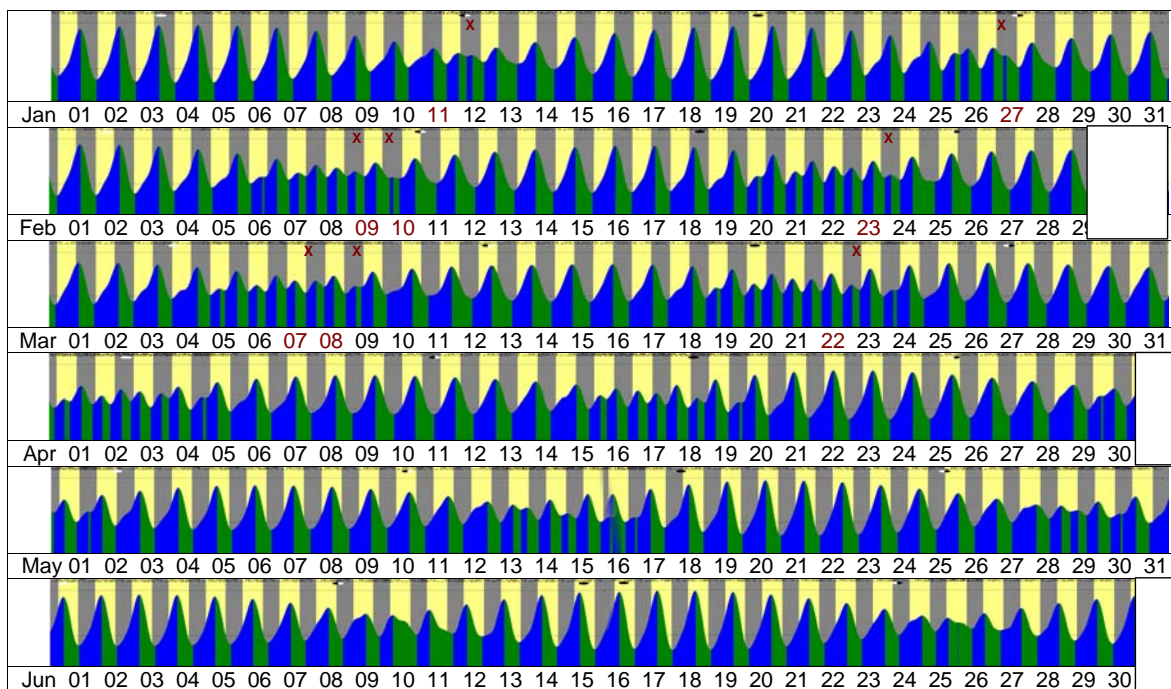
Figure 47. Periods during the month where there are sufficient exchange of water in the bay and periods when there are less exchange and greater risk.

If low exchange occurs at night there is even greater risk from low oxygenation and so fish should not be fed the day before these risk periods and if possible fish harvested from the cage to reduce stocking density and biomass.

As tide tables are available on year in advance, these tidetables can be analysed and a prediction made of the days with higher risks.
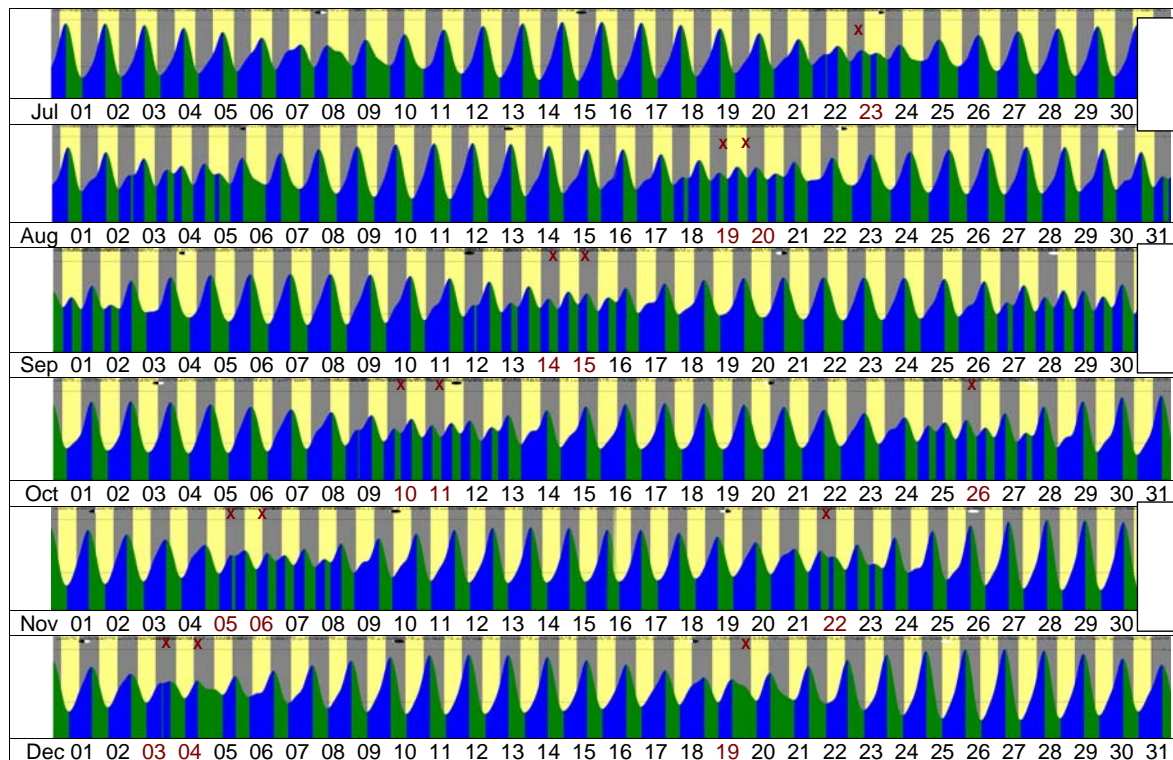
Figure 48. Tidal cycle through the year showing periods of highest risk

Risk periods in Bolinao and Dagupan can then be identified as
- 22 and 23 March 2007
- 23 July
- 19 and 20 August
- 14 and 15 September
- 10, 11 and 26 October
- 5, 6 and 22 November
- 3, 4 and 19 December

If these dates are analysed further critical times can be identified
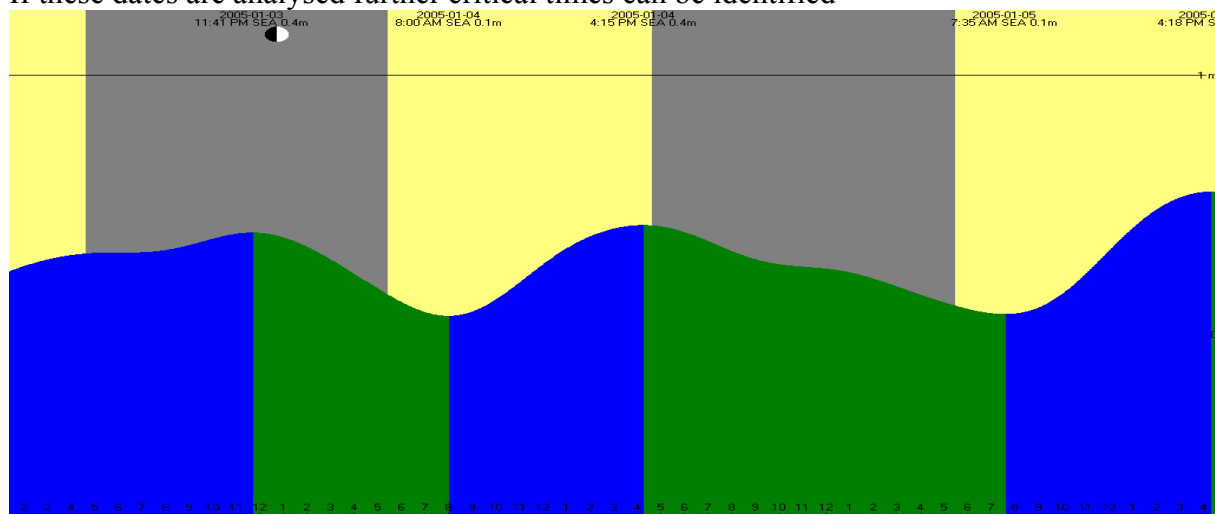

Figure 49. Tidal cycle on 3 and 4 January 2007.

It can be seen from the figure above that the tides vary only 20 cm over 12 hours during the night. If there is high algal levels and high fish biomass, then oxygen levels during the night will reach critical levels.

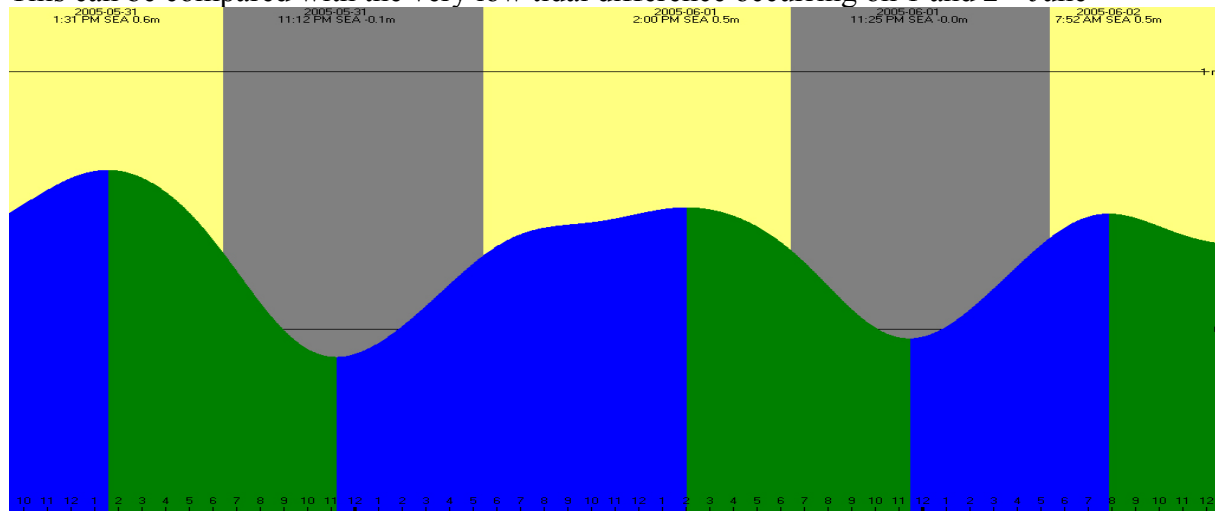This can be compared with the very low tidal difference occurring on 1 and 2nd June

Figure50. Tidal cycle on 1 and 2 June 2007

The low tidal difference of 10 cm over a 12 hour period occurs during daylight when algae are producing oxygen so even with low tidal refreshment, there should be sufficient oxygen for the fish.

If future tide tables are analysed in this way, an early warning calendar can pre prepared in advance showing risk periods and critical risk periods.