A model to estimate aquaculture carrying capacity in three areas of the Philippines

Tarzan Legović[1*], Rune Palerud[2], Guttorm Christensen[2]
Patrick White[2], and Regie Regpala[3]
[1]Centre for Marine Research, R. Boškoviæ Institute, P.O. Box 180, Bijenièka 54, HR-10002 Zagreb, Croatia
Tel +385 1 4680230; Fax +385 1 4680242
* Corresponding author; Email legovic@rudjer.irb.hr
[2]Akvaplan-niva AS, Tromsø Polar Environmental Centre, N-9296 Tromsø, Norway
[3]National Integrated Fisheries Technology Development Centre-Bureau of Fisheries and Aquatic Resources (BFAR-NIFTDC), Bonuan Binloc, 2400 Dagupan City, Philippines
Date submitted: August 21, 2007; Date accepted: August 21, 2008

ABSTRACT

A model was developed to estimate the production carrying capacity of water bodies based on nutrient inputs from aquaculture and other sources, flushing rates, and the risk of algal blooms for three different areas of the Philippines – Bolinao (marine site), Dagupan (brackishwater site) and Taal Lake (freshwater site). The results suggest that aquaculture production in the Taal Lake was greater than the sustainable carrying capacity. Aquaculture structures in Bolinao were close to carrying capacity during average tidal exchange but greater than the carrying capacity during low tidal exchange and no winds. Aquaculture production in the Dagupan estuary has not overcome its carrying capacity even during low flow. However, during very low flow and no tidal flushing, carrying capacity has been overcome.

INTRODUCTION

Modeling carrying capacity

Environmental carrying capacity for fish aquaculture 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 factor which could 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 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:

1) Consider characteristics of a water body. How quickly is the water exchanged with neighboring water where fish is not grown and hence has higher oxygen content? What are 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) Consider how the phytoplankton is grown and the 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) Increase (or decrease) fish stock 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 1 depicts the process graphically.

MODELING 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:

$$dS/dt = D(I - S) - uX \quad (1)$$

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

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:

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

$$\left(\frac{V_{max} S^*}{(h + S^*)} - D \right) X^* = 0 \quad (4)$$

where (*) 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) cannot 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 $V_{max}I/(h+I)$.

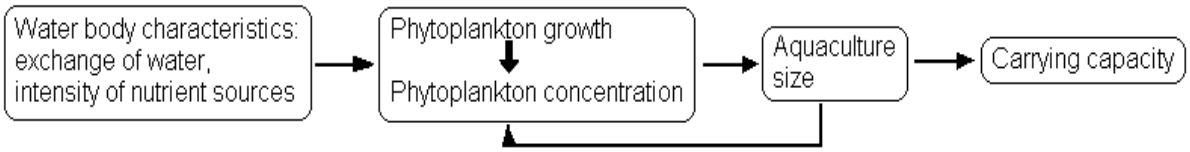

Figure 1. The process of determining carrying capacity for fish aquaculture based on arriving at the critical phytoplankton concentration

Finally, assuming S*≠0 and X* ≠ 0, from Equation (4) we easily find:

$$S^* = \frac{Dh}{(V_{max} - D)} \quad (5)$$

Hence, S* can be positive only if

$$V_{max} > D \quad (6)$$

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

$$I = X^* + S^* \quad (7)$$

In other words,

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

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

$$X^* = I - \frac{Dh}{(V_{max} - D)} \quad (8)$$

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

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

Namely, it is not enough that V_{max} > D which ensures that S* > 0, but also S* < I and hence the condition (9). That is, even if the condition (6) is satisfied but the condition (9) is not, as t → ∞ 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}SX/(h+S).

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

Since we cannot 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:

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

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:

$$I > \frac{Dh}{(V_{max} - D)} \quad . \quad (11)$$

We also conclude:

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

In Figure 2 we display dynamics of two systems, each starting with its own initial condition.

The first system starts with a large nutrient concentration S_o=200 and a low phytoplankton concentration, X_o=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, S_o=20, and a very low concentration of phytoplankton, X_o=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.

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 emit 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 Equation (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 Equation (7) shows, the increase in steady state of phytoplankton concentration is linearly related to the increase in nutrient inflow. In other 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

From Equation (7) when fish aquacultures do not exist, we have:

$$I_o = X^*_o + S^* \qquad (12)$$

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: Ia. Then Equation (12) changes into:

$$(I_o + I_a) = (X^*_o + X^*_a) + S^* \qquad (13)$$

But we know that a critically high concentration of X_c*, call it $X_c^* = X_o^* + X_a^*$ will induce a critically

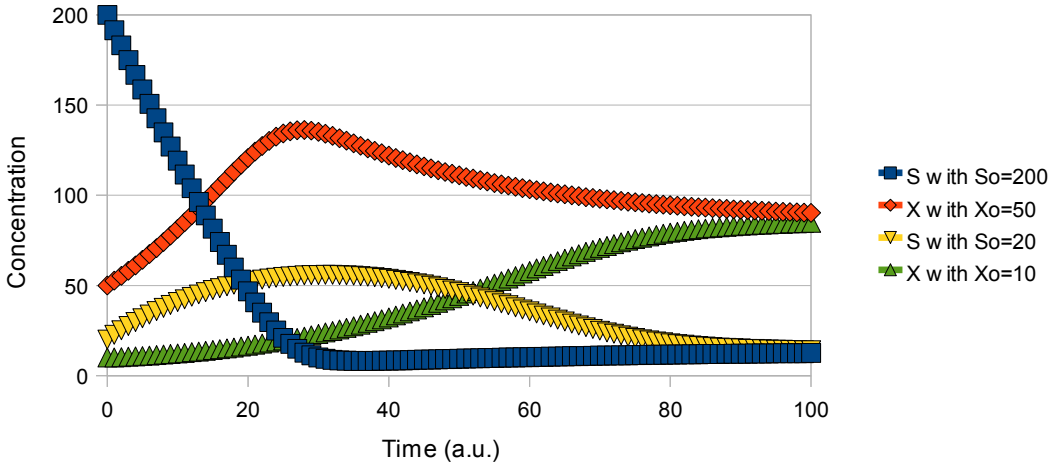

Figure 2. Dynamics of two systems. The first system starts with concentrations of nutrient So=200 and phytoplankton Xo=50. The second system starts with So=20 and phytoplankton Xo=10. Parameters for both systems are I=100, D=0.04, Vmax = 0.1, h=20.

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:

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

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

Note one more property of Equation (14): since the phytoplankton keeps the nutrient concentration, S* , constant regardless of the increase in I, it is likely that Xc* >>S*, so to a good approximation:

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

APPLICATION ISSUES

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 Equation (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. In other 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 microphytobenthic 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 emission: 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.

Critical phytoplankton concentration

The critical phytoplankton concentration is one of the key parameters in Equations (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 U.S. Environmental Protection Agency (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 Phosphorus (TP) and Chl-a we find the upper value of Chl-a that corresponds to TP found in water.

According to Dillon and Rigler (1974):

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

The expression gave excellent correlation of R = 0.975 between the $\log_{10}$ (Chl-a) and $\log_{10}$ (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):

$$\log_{10}(\mu g\ Chl\text{-}a/L) = -0.369 + 1.053 \log_{10}(\mu g\ TP/L) \quad (17)$$

Given TP of 0.17 mg/L we get 95 µg Chl-a/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 100µg/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 Equation (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.

Background concentration of nutrient in the inflow, Io

The background concentration of nutrient, I_o, 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 Equations (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:

$$I_{ave} = \frac{Q_1 * I_1 + Q_2 * I_2 + \ldots + Q_n * I_n}{Q_1 + Q_2 + \ldots + Q_n} \qquad (18)$$

Where Q_i and I_i are the inflow of water through the i^{th} stream and I_i 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 I_o from such measurements. Indeed, Equation (13) 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 I_o 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.

Emission of nutrients by fish cultures

In order to apply the Equation (15) with all units being in mass nutrient per volume, for example, μg(nutrient)/L, 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 F_m (tons). This stock of fish emits F_n mass of nutrient in a time interval, for example in kg (nutrient)/day):

$$F_n = a F_m \tag{19}$$

The parameter a specifies how many kg of nutrient are emitted per one ton of standing stock of fish. From the value of F_n, the equivalent concentration addition in the water body may be calculated from:

$$I_c = \frac{F_n}{DV} = \frac{F_n}{\textit{Inflow or outflow of water into or from lake}} \tag{20}$$

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

MODELING CARRYING CAPACITY IN TAAL LAKE

Volume V of the receiving body of water in Taal is $V = 2.43\times10^9$ m^3. This volume is derived from the surface area of the Taal Lake, which is 2.43×10^8 m^2 and the depth of the upper 10m. Average yearly rainfall is 1882.9 mm and average evaporation is 116.75 mm, so the net water layer entering the Lake is 1766.15 mm over the watershed and the lake. In addition to the lake, the watershed is 4.2×10^8 m^2. Hence the yearly inflow is 1.2×10^9 m^3. Thus D = (inflow=outflow)/V = 0.494/year. Therefore the lake needs two years to renew one volume of water to the depth of ten meters.

The net inflow of aquacultures is: Fn = 2.13×10^3 kg (phosphorus)/day = 730 t/y. This value may be compared to 816 t/y reported by Vista et al., 2006. Hence, the contribution of fish cultures to the nutrient concentration in phytoplankton is:

$$\begin{aligned} I_a &= \frac{730\times10^3 (kg\,P/y)}{(0.494/y)*(2.43\times10^9 m^3)} \\ &= \frac{730\times10^3 (kg\,P/y)}{1.2\times10^9 (m^3/y)} = 608 (mg\,P/m^3) \\ &= 608\,\mu g\,P/L \end{aligned} \tag{21}$$

According to the Florida Lakewatch relationship in Equation (17) the value of total phosphorus translates to 365 μg Chl-a/L.

From the above calculation it would appear that the carrying capacity of the Taal Lake has been overcome due to fish cultures alone by a factor of 3.7.

Let us now assume that nitrogen is limiting. Input of nitrogen to the water column from aquacultures is 26 259.56 kg/day.

$$\begin{aligned} I_a &= \frac{9.6\times10^6 (kg\,N/y)}{1.2\times10^9 (m^3/y)} = 8 (g\,N/m^3) \\ &= 8000 (\mu g\,N/L) \end{aligned} \tag{22}$$

Now using the Lakewater relationship between Total Nitrogen (TN) and Chl-a:

$$\log_{10}(\mu Chl\text{-}a/l) = -2.42 + 1.206 \log_{10}(\mu g\,TN/L) \tag{23}$$

we obtain 193 μg Chl-a/L.

We conclude that if nitrogen were limiting, and other sources of nitrogen are negligible, the carrying capacity for aquacultures in the Taal lake would be

overcome by a factor of 2.

Finally, with N/P of 13.13 (by weight) simultaneous limitation of N and P can not be ruled out. In this case the following relationship would hold (Florida Lakewatch 2000):

$$Chl\text{-}a = 0.628\,TP - 2.402 \quad . \qquad (24)$$

For the Taal lake, with TN = 8000 µgN/L, TP = 609 µg P/L the resulting chlorophyll-a would then be 380 µgChl-a/L.

MODELING CARRYING CAPACITY DAGUPAN ESTUARY

The volume of the receiving body of water is V = 0.3×10^9 m^3. The volume is derived from the surface area of the estuary, which is 68×10^6 m^2 and the depth of 4.4 m. The depth is obtained from detailed bathymetric measurements obtained in the project.

Average inflow of the river feeding the estuary during the most critical period (end of the dry season) is 38.4 m^3/s = 3.3×10^6 m^3/day. This is based on the current measurements within the project. The average current at the center of the measurement station is 10.5 cm/s with a current distribution factor of 0.5, river width of 140 m, the depth of 8.7 m and a cross-sectional shape factor of 0.6.

The flushing rate is D = (inflow=outflow)/V = 0.011 (1/day). The estuary needs 91 days to renew one volume of water.

Net inflow of aquacultures including resuspension is F_n = 146 kg (phosphorus)/day.

Hence, the contribution of fish cultures to the nutrient concentration in phytoplankton is:

$$I_a = \frac{146(kg\,P/day)}{0.011(l/day)*0.3\times10^9 m^3} = 44.2(mg\,P/m^3 = \mu g\,P/L) \qquad (25)$$

Using Equation (17) the value of total phosphorus translates to 23.1 µg Chl-a/L.

From the above calculation it would appear that the carrying capacity of the Dagupan estuary has not been overcome. However, the above contribution to Chl-a value has been derived only from limiting nutrient inflow from fish cultures.

Two other nutrient inflows have not been considered:

a) from people, their agriculture and animal farming activities. This input is very important and it probably contributes as much as the existing fish cultures.

b) nutrient concentration in the river water feeding the estuary. Depending on the activities upstream the estuary, this input could contribute one quarter to one half of fish cultures.

If a) and b) were also taken into account, it would still turn out that the natural carrying capacity of the Dagupan estuary under consideration has not yet been reached.

The above calculation is based on the river inflow of 38 m^3/s. We know that the river inflow feeding the estuary is not constant but varies greatly. During the dry season, the river inflow may be smaller. When the river inflow is half the one that has been measured, the contribution of fish cultures together with other existing inflows, overcome the natural carrying capacity. During this time of the year, fish kills would be imminent.

According to the existing information, this has already happened at the end of the dry season, which is characterized by the lowest river inflow.

MODELING CARRYING CAPACITY IN BOLINAO BAY

Surface area of 28.88×10^6 m^2 with an average depth of 4.8 m leads to the volume V= 138.6×10^6 m^3. Residence time of particles at Bolinao, varies from several days to over 25 days, so it would be reasonable to use 20 days.

Excretion of phosphorus from aquacultures amounts to 339 kg/day, a contribution from soluble feces is 143 kg/day and resuspension from the bottom is

estimated as 94 kg/day. Together, this amounts to 576 kg/day.

$$I_a = \frac{576(kg\,P/day)}{0.05(1/day)*138.8\times10^6 m^3} = 83\,\mu g\,P/L \qquad (26)$$

From Equation (17), we obtain the corresponding contribution to the phytoplankton concentration of 44 μg Chl-a/L

Inclusion of external sources

The above contribution to phytoplankton concentration is on top of all external sources of nutrients: a) land based sources, b) concentration of nutrients entering from Lingayen Bay and c) atmospheric fall out.

If external sources were negligible or even if they are of the same order of magnitude as the contribution from fish cultures, which is unlikely, it would appear that the maximum concentration of 100 μg Chl-a/L has not been reached and hence the carrying capacity of the Bay has not been overcome.

Flushing of the bay

The above calculation is based on a particle residence time of 20 days which is computed from an average including neap and spring tides.

We know that the marine through flow is not constant but varies greatly. During the neap tide, flushing is much slower. If the water through flow is half the one that has been assumed, the contribution of fish cultures alone would get close to natural carrying capacity. Then the inclusion of all external nutrient sources would well overcome the carrying capacity.

According to the existing information, this has already happened at the neap tide, which is characterized by the lowest through flow.

MODELING 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.

REFERENCES

Dillon P.J. & Rigler F.H., 1974. The phosphorus-chlorophyll relationship in lakes, *Limnol. Oceanogr*, 19: 767-773.

Dizon R.M. & Yap H.T., 1999. Short-term responses of coral reef microphytobenthic communities to inorganic nutrient loading, *Limnol. Oceanogr.*, 44(5):1259–1267.

Dufour P. & Berland B., 1999. Nutrient control of phytoplanktonic biomass in atoll lagoons and Pacific ocean waters: studies with factorial enrichment bioassays. *J. Exp. Mar. Biol. Ecol.*, 234:147-166.

Dufour P., Charpy, L., Bonne, S. & Garcia, N., 1999. Phytoplankton nutrient control in the oligotrophic South Pacific sub tropical (Tuamotu archipelago). *Marine Ecology Progress Series*, 179:285-290.

Florida Lakewatch, Beginner's Guide to Water Management – Nutrients Information Circular, No. 102 2000. University of Florida.

Legovic T. & Cruzado A., 1997. A model of phytoplankton growth on multiple nutrients. *Ecological Modelling*, 99:19-31.

Lupatsch I. & Kissil G.W., 1998. Predicting aquaculture waste from gilthead seabream (Sparus aurata) culture using a nutritional approach. *Aquat. Living Resources*, 11: 265-268.

Masser M., 1997. Cage Culture: Site Selection and Water Quality, Oklahoma Cooperative Extension Service, SRAC- 161, http://srac.tamu.edu/

Sowles J.W., 2005. Assessing nitrogen carrying capacity for Blue Hill Bay , Maine : A management case study. In Hargrave B., ed., Environmental Effects of Marine Finfish Aquaculture, Springer, pp 359-380.