CASE STUDY 6.6

RISK ANALYSIS OF COASTAL AQUACULTURE : POTENTIAL EFFECTS ON ALGAL BLOOMS

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6.6.1 Introduction

In this case study, waste effluents released from a fish farm are assessed for their capacity to significantly increase phytoplankton production in Tolo Harbour, Hong Kong SAR, China.

6.6.1.1 Issue of concern

The demand for seafood increases as the world's population grows. Because wild fish stocks are stable or declining, commercial fish aquaculture has become an increasingly common activity in developed (*for example*, Norway, Chile, Scotland/UK and Canada) and developing countries (for example, China and many countries in Southeast Asia). These fish farms discharge nutrients and organic wastes into the surrounding waters. The cultured fish are fed trash fish or manufactured feeds. The conversion of these feeds to fish (the ratio of feed supplied to the fish versus the increase in fish weight) is never 100%. Particulate matter in the form of feed not consumed by the fish or in the form of fish faeces is released, sinks and is deposited on the seabed sediment. This unused solid material breaks down into small particles that are decomposed by bacteria into dissolved organic matter and inorganic nutrients. Dissolved organic matter is eventually remineralised to inorganic nutrients. Dissolved organic and inorganic nutrients are also excreted directly by fish. Phytoplankton growth can be stimulated by the release of these nutrients, and may then result in a number of environmental consequences such as an increased frequency of phytoplankton blooms, a change in phytoplankton species diversity, and the depletion of dissolved oxygen in the bottom waters, as summarised in Figure 6.6.1.

Fish farm effluent may be an environmental hazard if it causes undesirable environmental changes. For many countries, the changes in water colour are associated with other undesirable changes in the aquatic environment such as a loss of fish, reduced property values, closures of swimming beach, etc. This study assesses one particular fish farm site to determine if the conditions there would be capable of generating a significant change in phytoplankton abundance.

A simple conceptual model for possible environmental consequences of nutrients effluent from fish farm on phytoplankton growth is presented in Figure 6.6.1. In this analysis, it serves as the basis for the risk assessment. The model consists of release, exposure, and consequence assessments, and risk estimation. The process begins with the identification of question as 'Is there a fish farm development in the area of interest?' and the endpoint to the assessment is: 'Are probable changes in phytoplankton biomass large enough to cause a visible discolouration of the water…an algal bloom?'.

6.6.1.2 Formation of a phytoplankton bloom

A phytoplankton bloom is a rapid accumulation of phytoplankton biomass in a water body. The bloom is an outcome of the balance between growth and loss rates in phytoplankton population. The growth rate is determined by light, nutrients, temperature and other physiological factors affecting phytoplankton, while the loss rate is driven by physical dilution processes (horizontal exchange and vertical mixing), sinking and grazing (Cloern 2001). A sufficiently slow exchange rate with surrounding waters (for example, a long residence time) helps to minimise the constraints on the growth of the algal population. A stable water column (stratification) can also help prevent light limiting algal growth. Both conditions are generally required for a bloom to occur (Mann and Lazier 1991). When stratification of the water column is relatively shallow, the concentration of the most limiting nutrient determines the amount of phytoplankton biomass (Parsons *et al.* 1984). Thus, fish farms can act as a source of nutrients and may result in algal blooms when the surrounding waters are not flushed or vertically well mixed. In any algal bloom, a concentration of chlorophyll a (chl *a*) exists above which discoloration of the water is apparent to the naked eye. When this happens, people residing in the area generally express concern and consider it to be an indication of poor water quality.

6.6.2 Hazard Identification

6.6.2.1 Sources of nutrients

Caged fish farming releases uneaten fish feeds, faeces, and soluble fish wastes into the environment (Tacon *et al.* 1995), as shown in Figure 6.6.2. Feeds are usually made of dry pellets or trash fish (small, low commercial value fish). The dominant type of feed varies among fish farms. On farms where feeds are usually

Figure 6.6.1 : A simple conceptual model for environmental consequences on phytoplankton resulting from nutrients from fish farm operations.

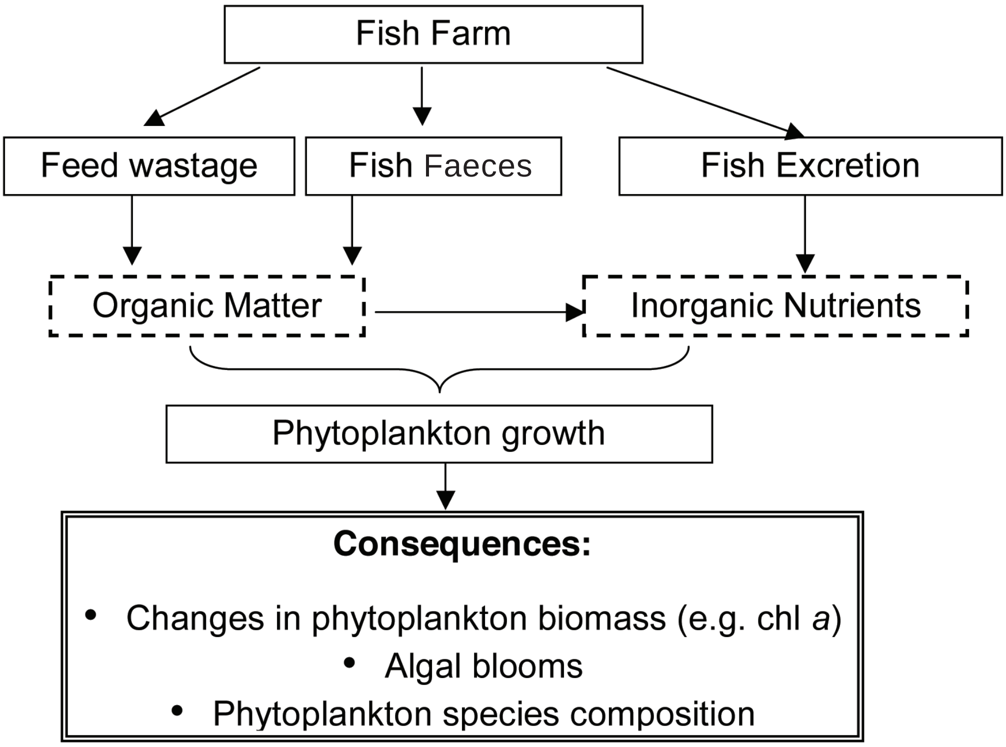
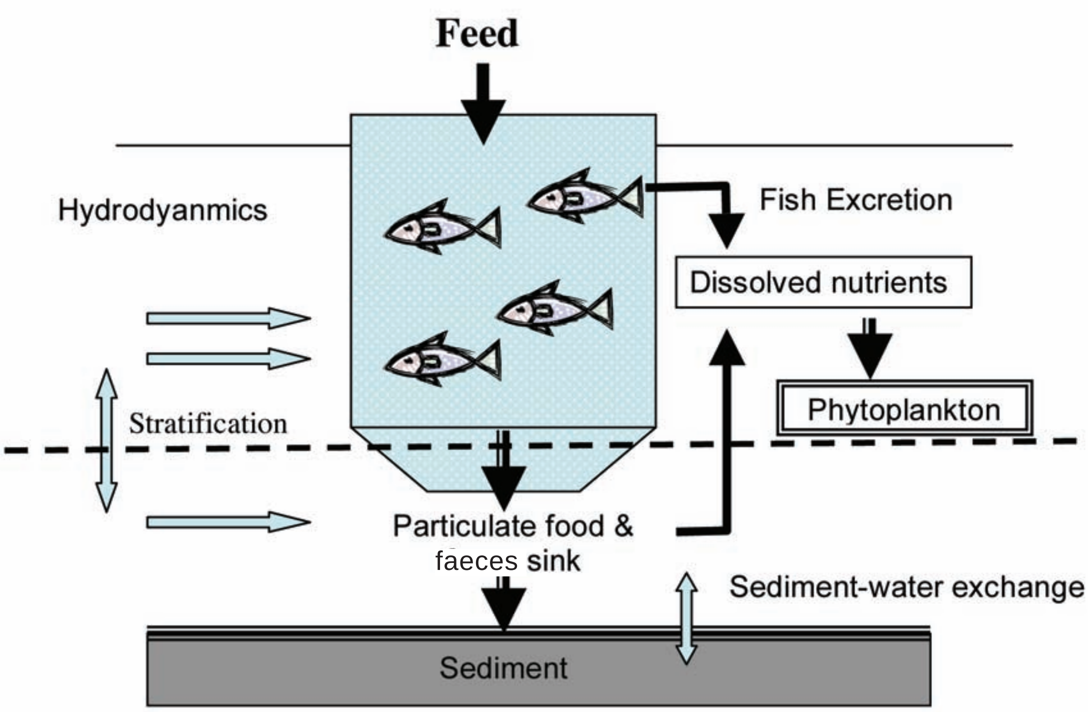


Figure 6.6.2 : Pathways of nutrients by fish farm operations to phytoplankton in water column. Exposure of nutrients depends on hydrodynamics, stratification and sediment-water exchange.



not of high quality and feed delivery systems tend to be imprecise, resulting in relatively poor feed conversion (Islam and Tanaka 2004). Marte *et al.* (2000) described fish cultivation in the Philippines, using trash fish as the main ingredient of feed for caged grouper, sea bass and snapper. FCR (feed conversion ratios = weight of feed supplied/harvest weight) values were generally between 2 and 2.8. The FCR varies depending on management practice and technology, with an average of two being common.

Feeds are generally supplied twice per day for adult fish, and 3 or 4 times daily for small fish. Some of the feed supplied is not captured by the fish and not all of the feed that the fish capture is digested. Faeces and uneaten feed are lost to the environment. Loss rates can be as high as 75–80%, depending on the culture system and the degree of feed management applied (Islam 2005). The waste feed and faeces sink in the water column, settle to the seabed, and are decomposed by bacteria and converted into dissolved organic matter that is remineralised into inorganic nutrients. Fish also excrete nutrients such as ammonium and urea directly into the water. These solid and soluble wastes form the basis for potential changes in water quality, sediment geochemistry, and aquatic and benthic ecology.

6.6.2.2 Changes in water quality and Phytoplankton biomass

The environmental effects of nutrient enrichment are site-specific and largely depend on the prevailing physico-chemical and biological features of the receiving environment. The input of soluble nitrogenous and phosphorous compounds from urban and agricultural runoff have been shown to cause hypernutrification (increases in nitrogen above ambient levels in the environment) in coastal waters as a precursor to algal blooms. The influence of fish farming is less clear. The effects of effluents from cage culture on phytoplankton depend primarily on the annual level of production, volume of the water body, depth of the water column, and water residence time (Phillips *et al.* 1985; Huang 1997). When the residence time of water near fish farms is longer than the doubling times of a phytoplankton population, phytoplankton biomass can accumulate and form blooms, which may cause discolouration of the water.

Waste food and faecal material contain organic nitrogen and phosphorus. That waste feed and faecal material sinks to the bottom in the vicinity of a farm (Figure 6.6.2) and is remineralised. Studies in many parts of the world have shown elevated levels of nutrients such as nitrate, nitrite, ammonium and phosphate associated with higher phytoplankton densities near fish culture (Wu 1995, Leung *et al.* 1999). Enell (1987) also showed that about 80% of the nitrogen input from fish farms was in the dissolved form (ammonium and urea). Ammonia and urea are readily taken up by phytoplankton and therefore most of the dissolved nitrogen released to the environment is readily available for phytoplankton growth in the photic zone. While nitrogen is generally considered the limiting nutrient in marine waters, enhanced levels of dissolved inorganic phosphate have also contributed to eutrophication of waters (Cloern 2001; Islam and Tanaka 2004). The phosphate in fish farm wastes is mainly held in the solid wastes on the bottom and is released by bacterial activity. Under conditions where algal growth is P limited, that phosphate may stimulate increases in algal abundance (Porrello *et al.* 2003).

Given this background, it is reasonable therefore to consider that nutrient wastes from fish farms represent an environmental hazard that in some circumstances might result in augmentation of algal abundances and possibly lead to an undesirable discolouration of waters.

6.6.3 Risk Assessment

Increased nutrient concentrations around fish farms may result in increased phytoplankton biomass (chlorophyll a can be used as a proxy), that may lead to algal blooms (Smith *et al.* 1999). The probability and magnitude of these risks depends on the natural nutrient assimilation capacity of the water column. That assimilation capacity is determined by the coupling between biological and physical processes. The biological processes include natural variability of nutrients, dissolved oxygen, phytoplankton biomass and species composition. The physical processes involve horizontal exchange between waters in which the caged fish are situated and open waters where exchange is less restricted, as well as the vertical mixing of the water column. Phytoplankton growth rate depends on water clarity and inorganic nutrients concentrations, derived either directly from fish excretion or from the decomposition of organic nutrients (feed waste and fish faeces). Since high concentrations of phytoplankton biomass can cause a change in water quality, plankton ecology and potential bottom water hypoxia, large increases in phytoplankton biomass are also a significant environmental phenomenon.

6.6.3.1 Study site

6.6.3.1.1 Tolo Harbour fish production

Fish are a major source of animal protein in Hong Kong. In 1997, the annual per capita fish consumption in Hong Kong exceeded 33 kg, compared to the world average of 16.1 kg (FAO 2000). Fish farms in Hong Kong consist of fish cages and the farms are small, covering about 250 m^2. Fish start as fry and grow to marketable size in about 1.5-2 years (Li 1996). During the annual production cycle of the farm, the fish biomass on site increases and nutrient releases increase along with the biomass. Common species cultured include green grouper, brown-spotted grouper, Russell's snapper, mangrove snapper, cobia and pompano (AFCD 2006, Chau 2004). Currently, there are 26 fish culture zones (Fig. 3) occupying a total sea area of 206 ha with some 1,125 licensed operators. Total marine fish culture production in 2005 amounted to 1,539 tonnes, valued at $76 million (AFCD 2006; June press release on www.afcd.gov.hk).

Tolo Harbour has two fish culture zones (Fig. 6.6.3, numbers 25 and 28) Also there is fish culture zone No. 10 in Tolo Channel. Fish Culture Zone No. 25 (FCZ25) is Yim Tin Tsai, which is separated from No. 28 by land and there is no direct water exchange between them

(Fig. 3). It has an area of 134,400 m^2 (480 m x 280 m) and between 2001 and 2005 produced 175, 133, 220, 126 and 149 tonnes of fish respectively, with an average production of 160.6 tonnes (data provided by AFCD).

6.6.3.1.2. Tolo Harbour geographic features

Tolo Harbour is a semi-enclosed bay connected to Mirs Bay via Tolo Channel to the east of Hong Kong (Fig. 6.6.3). The main harbour and channel is about 16 km long and 3 km wide, on average. The total surface area is about 50 km^2 and the water column is up to 10 m deep in the harbour. There are two fish farms in the Tolo Harbour designated as the Fish Culture Zone (FCZ) under the Marine Fish Culture Zone Ordinance and the Fish Culture Zone No. 25, Yim Tin Tsai FCZ, is used as the case study in this document. Water quality is good in Mirs Bay, but is poor in the inner harbour which receives riverine inputs and sewage effluent. Fresh water input and tidal cycles drive the flushing process and the average residence time is estimated to be 28 days (Lee and Arega 1999).

6.6.3.2 Release Assessment

The maximum nutrient input to Tolo Harbour from the farm may be estimated from : (1) annual fish production (AFP), (2) feed conversion ratio, FCR, (3) total N or P concentration in the feed (this value depends on the type of feed used), (4) total N or P concentration in fish, and (5) a seasonal modifyer, which adjusts for the fact that there is a seasonal pattern in fish growth and feeding. In this analysis, we divide the year into only two periods 'summer' and 'winter', each six months long.). Total nutrient loadings can also be estimated as the total feed nutrient minus the nutrients in the harvested fish.

6.6.3.2.1 Fish Farm Feeds in China,Hong Kong Special Administrative Region

In many temperate and developed regions, cultured carnivorous fish like salmon and cod depend on expensive, high-protein feeds. The protein for that feed is commonly derived from catches of small pelagic fish. In other regions, feeds derived from low-cost, low-protein agricultural by-products or wastes are widely used to reduce the cost of production. The feed conversion ratio (FCR) is an important indicator of how much waste is released to the environment.

The type of feed used and the feeding practices vary with different regions, for example, Korea RO (Kim 2000), Philippines (Marte *et al.* 2000), and Tasmania (Gooley *et al.* 2000). Fish farms in Hong Kong use three main types of fish feed: mixed feed, moist pellet feed and dry pellet feed. Mixed fish feed is composed of trash wild fish, mainly relatively small juveniles of commercially important fish species, or other adult pelagic fish (Willmott 2000). They typically include clupeidae, carangidae, leionathidae, engraulidae, siganidae and scombridae (Wilson 1997; Sadovy 1998). Moist pellet feed consists of mixed fish, fish meal, a vitamin mixture and binder (Wong 1996; Chu 2002). Dry pellet feed is the dried form of moist pellet feed. Mixed fish feed is the most common feed used at Tolo Harbour fish farms, with nearly 99% of farms using mixed fish feed, composed mostly of small fish (Chau 2004). For this reason, mixed fish feed will be used as the basis for estimates in this case study.

Chau (2004) estimated the average feeding frequency and feeding volume by interviewing fish farmers. He found that feeding frequency varied from daily to weekly and he estimated that average weekly feeding frequency was 3.7 times in summer and 2.2 times in winter. The weekly feeding volume also varied with seasons. The average feeding volume per cage of fish per 'meal' was 84 (2.1 pans) and 56 kg (1.4 pans) in summer and winter respectively. Information on feeding volume per cage per week was calculated by multiplying the feeding frequency and volume. The weekly feeding volume per cage was estimated to be 8.8 and 3.3 pans of mixed fish feed in summer and winter respectively, which is equal to 213 and 80 kg, respectively. Thus, each cage received, on average, 30.4 kg of mixed trash fish per day in summer and 11.4 kg per day in winter. Over a full year, 73% of the feed was delivered in one half of the year and 27% in the other half. These two percentages will be used to estimate the release of nitrogen during summer and winter periods in the next section.

6.6.3.2.2 Discharge of nitrogen from fish farms

Areolate grouper, *Epinephelus areolatus*, is the most common fish species cultivated in fish farms in Hong Kong. Leung *et al.* (1999) conducted a detailed study on N budgets in both laboratory experiments and at open-sea fish cages. They gave a structured account of the N budget, which is shown in simplified form in Figure 6.6.4.

The maximum possible loading of nutrients from a fish farm would occur if all nutrients not retained in the fish were discharged to the environment. In a typical open cage farm in Hong Kong, this would amount to losses of approximately 320.6 g N/kg dry fish production (2, Table 6.6.I). Fish Culture Zone No. 25 in Tolo Harbour produced 160.6 tonnes annually (C in Fig. 6.6.4) on average during 2001-2005 (AFCD). This fish production is equivalent to 160,600 kg x 30.8% = 49,464.8 kg as dry weight. Using this amount x 320.6 g N/kg =15,858.4 x 103 g N y-1 (3, Table 6.6.I), gives the amount of N that is potentially discharged annually (D+E in Figure 6.6.4) to the surrounding waters of the fish farms. Based on the feeding practice in Hong Kong (Chau 2004), the relases in summer and winter would be 11,580 x 103 and 4,280 x 103 g N 0.5y-1 (4, Table 6.6.I) respectively.

We do not know exactly the nutrients loadings from other sources. We do however, know ambient concentrations of nutrients, and from this we can estimate the potential maximum effect of nutrient releases from fish farms on nutrient levels in the surrounding waters. If we take the inner Tolo Harbour area to be roughly 1/4 of the total Tolo Harbour area, for example, 50 km^2 (Lee and Arega, 1999), and assume that the N additions are evenly mixed into the top 4 m (5, Table 6.6.I), then the annual fish farm contribution would be about 22 µM (6, Table 6.6.I). This breaks down as 16.5 and 6.1 µM, respectively, for the summer and winter periods (7, Table 6.6.I). When these two values are divided by 180 days,

Figure 6.6.3 : Yim Tin Tsai Fish Culture Zone (No. 25) in Tolo Harbor, connected with Tolo Channel (separated by the dotted lines). Other numbers 1-29 show other designated fish culture zones. The sampling stations, TM2, TM3 and MM17 are also shown.

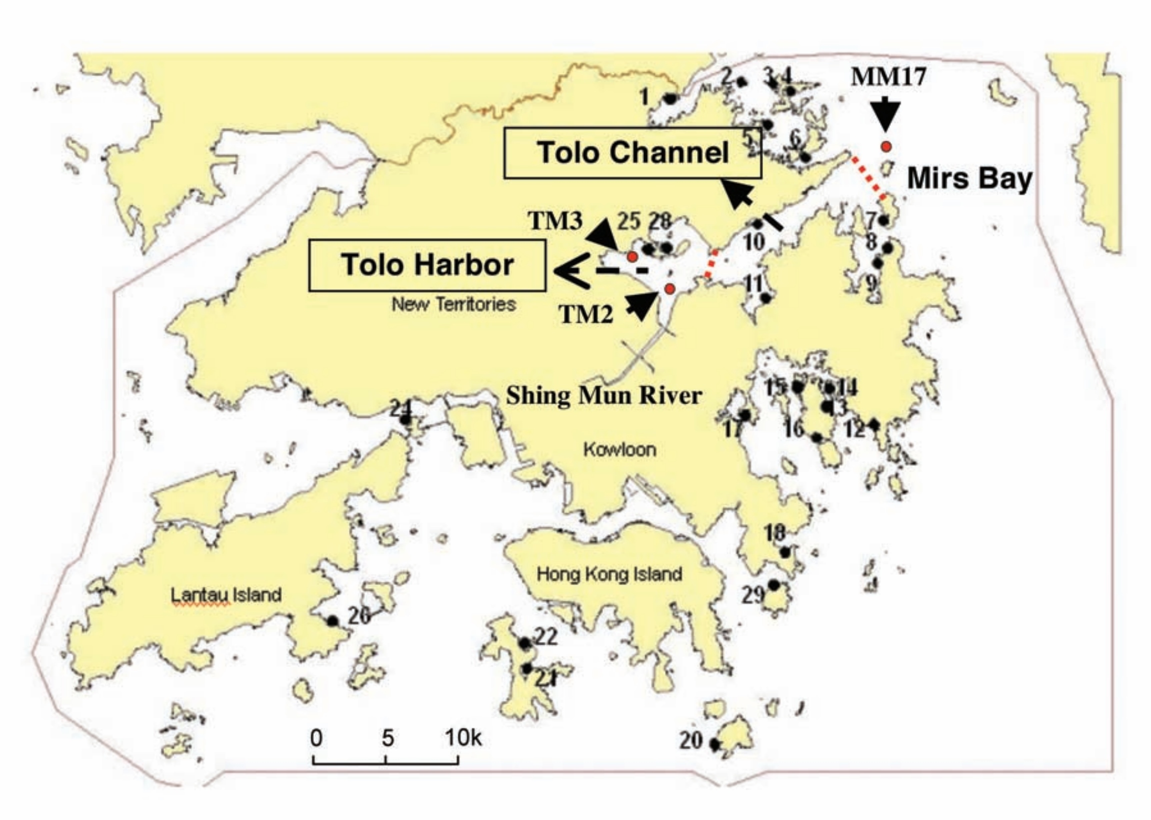


Figure 6.6.4 : A simple conceptual flow diagram for a nutrient budget for a cage fish farm.

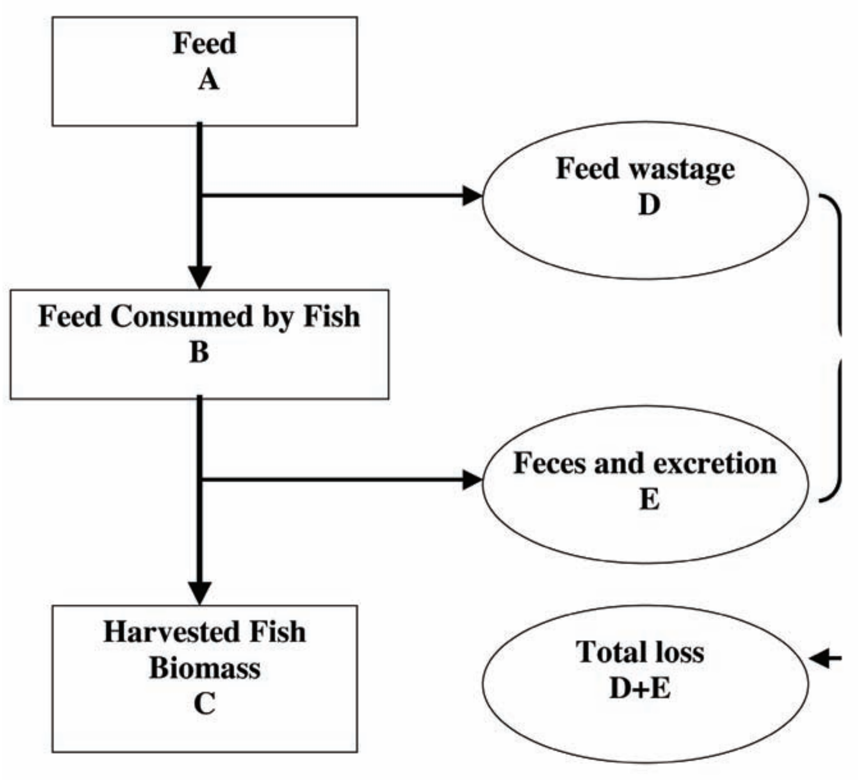


Table 6.6.I : Estimate of N additions (final concentrations) from fish farms FCZ25 to the surrounding waters. Letters, B, C, and D+E in the bracket correspond to ones in Figure 6.6.4. Final N additions are based on the assumption: N additions are distributed evenly in the top 4 m of the Tolo Harbour (1/4 of the Tolo Harbour and Channel area 50 km²).

	Parameters	Quantity	Unit
1	Fish Production	160.6	Tonnes/yr
	Wet weight	160.6×10^3	kg/yr
	Dry weight (x 30.8%) (C)	49,465	kg/yr
2	N loss /kg fish production	320.6	g N / kg fish production
3	Total N loss to the environment (D+E)	$15{,}858 \times 10^3$	g N/yr
4	Feed Addition Summer (73% B) Winter (27% B)	$11{,}576.6 \times 10^3$ $4{,}281.8 \times 10^3$	
5	Tolo Harbor volume in top 4 m (1/4 x 50 km² x 4 m)	50×10^9	Litre
6	Annual N addition	22.6	µM/year
	Summer addition 73% Winter addition 27%	16.5 6.12	µM/0.5 year
7	Annual daily N addition	0.063	µM/day
	Summer daily	0.092	
	Winter daiy	0.034	

the daily added N concentration is 0.092 and 0.034 µM for summer and winter, respectively. This means that fish farms in No. 25 fish culture zone contribute daily, 0.092 and 0.034 µM N in summer and winter, respectively, to the top 4 m of Tolo Harbour. Relative to phytoplankton half-saturation uptake coefficients for N and P discussed below, this is a very low value. It is worth pointing out that waste feed N, which comprises 43% of the total N loading (Leung *et al.* 1999), may not be totally dissolved in the water column and therefore may not be fully available to phytoplankton. In reality, the water in Tolo Harbour will also exchange to a small degree with adjacent waters. Therefore, the estimates used here are the potential maximum assuming no water dilution occurs.

6.6.3.3 Exposure Assessment

Exposure depends on the spatial scale and intensity of the nutrient addition, the residence times (tidal flushing and dilution), and vertical mixing. Fig. 6.6.2 provides a schematic illustration of basic concepts related to the nutrient effluents from fish farms and their dispersion, which may lead to a visible change in the pelagic ecology including increased phytoplankton biomass (see, for example, Enell 1994; Håkanson *et al.* 1988; Holby & Hall 1991; Mäkinen 1991; Stigebrandt *et al.* 2004).

The contribution of fish farms to ambient conditions of nutrients needs to be examined. Whether an increase in phytoplankton biomass arising from nutrient inputs from fish farms is significant depends on the ambient nutrient concentrations from other sources. Fortunately, the Environmental Protection Department (EPD) of Hong Kong maintains a regular monitoring program, which provides nutrient data that can help in this analysis.

6.6.3.3.1 Environmental conditions in Tolo Harbour

During the summer, there is a two-layer circulation in Tolo Harbour; a surface water outflow of less saline waters and a deep return inflow of more saline water from Mirs Bay (Yin 2002). This is evidenced by the high salinity in August at MM17 (Fig. 6.6.5). The circulation is probably driven by fresh water (lowest salinity in July, Fig. 5) collected from the Tolo Harbour watershed when rainfall is high in summer. Mirs Bay is also subject to the southwest monsoon in summer, and therefore receives pulsed inputs of oceanic waters from South China Sea (Yin 2002). The deep bottom oceanic waters are relatively poor in nutrients and may serve as a within-season flushing mechanism that reduces cumulative eutrophication effects (Yin 2002). This oligotrophic flushing, and the stratification, is likely to limit the impact of phosphorus in bottom waters on algae in surface waters.

The Environmental Protection Department has maintained a water quality monitoring program in Tolo Harbour and Mirs Bay since 1986. Station TM3 is near the fish culture zone, and water quality at TM2 is more likely to be dominated by the effects of waters from the Shing Mun River. MM17 in Mirs Bay at the entrance of Tolo Channel (Fig. 6.6.3) was selected to reflect conditions of the incoming waters. The following water quality parameters are monthly averages during 1986-2000 and describe the conditions in the fish culture zone and provide background conditions for assessing fish farm effects.

Salinity (Fig. 6.6.5): The monthly average surface salinity At MM17 is 32.3 in January. It starts to decrease in April and drops to the lowest value of 30 in July. At TM2 and TM3, the salinity in January is 30.4 and 31, respectively. The lowest salinity is 27 at TM3 in July, and 27.5 at TM2 in May. The salinity can occasionally decrease to 16 (data not shown) at TM2 and TM3, but generally does not go below 28. Salinity near the bottom at all three stations is higher in most months and stratification is present, though weakest in the October-March period and strongest during April-September. The salinity in Tolo Harbour appears to fluctuate synchronously at TM2 and TM3, except for June and July. As the correlation in salinity between the two stations is significant (r=0.86 n=310), this suggests that the two stations may be subjected to the influence of the same waters. This could be important for the distribution of nutrients.

NO_3 (Fig. 6.6.6 - 6.6.7): At MM17, NO_3 is generally below 4 µM in the water column. At TM2, NO_3 is >13 µM in January, and decreases to the lowest concentration (6 µM) during summer (June-September). At TM3, the temporal distribution of NO_3 is very similar to TM2, with the lowest concentration in May when bottom NO_3 is generally <2 µM. NO_3 often decreases below 2 µM at the 3 stations, mostly at MM17, and less frequently at TM2 (Fig. 7). When NO_3 is the sole source of N, concentrations of 1 - 2 µM NO_3 are usually considered to be limiting for marine phytoplankton growth (Parsons *et al.* 1984).

NH_4 (Fig. 6.6.8 - 6.6.9): At TM2, surface NH_4 in winter (December-March) is about 18 µM at TM2, and 8-10 µM in summer months (Fig. 8). At TM3, surface NH_4 is 16 µM in winter, and decreases to 8 µM in summer except for July with a peak of 12 µM. The temporal distribution of surface NH_4 is very similar between TM2 and TM3 (if the July peak is omitted). NH_4 at MM17 is low (<4 µM) all the times. NH_4 frequently decreases to <2 µM, mostly at MM17, and much less frequently at the other two stations (Fig. 9). An NH_4 concentration of 1 µM is considered to be the limiting level for phytoplankton growth if NH_4 is the sole source of N (Parsons *et al.* 1984).

Chl *a* (Fig. 6.6.10 - 6.6.11): Between 1986 and 2001, the monthly average for chl *a* in waters surface at MM17 was <3 µg l^{-1} during all months. Although average chl *a* is higher (around 20 µg l^{-1}) at TM2 than at TM3 (around 16 µg l^{-1}), chl *a* appears to vary synchronously between the two stations. Also, chl *a* at the bottom is approximately 10 µg l^{-1} at TM2, and approximately 5 µg l^{-1} at TM3. Yearly average chl *a* at the surface is the highest at TM2 and the lowest at MM17. However, while chl *a* >20 µg l^{-1} occurs frequently at both TM2 and TM3, there are only two occasions when chl *a* exceeded 20 µg l^{-1} at MM17.

TIN/P (Fig. 6.6.12): The average cellular N:P ratio for phytoplankton is 16:1 (the Redfield ratio). When the ambient N:P ratio is >16:1, P is potentially limiting and when N:P<16:1, N is potentially limiting, the surface TIN/P ratio remains around 16:1 at TM2 and TM3, but there is a peak of 64:1 in July at the other two stations. However, this is the period of lowest algal concentrations, suggesting that P availability does not increase algal abundance. TIN/P at MM17 is usually <16:1.

6.6.3.3.2 Contribution of fish farms to ambient N concentrations

The Total N loading from two urban wastewater treatment plants in Shatin and Taipo was approximately 4,000 kg d^{-1} in 1995 (Lee and Arega 1999). This rate of input would be 28 times the release of N from fish farms in the fish culture zone No. 25 (Table 6.6.I, 51,488 kg N per year) if, as in the past, this was released into Tolo Harbour. The total N loading in Tolo Harbour has been reduced since the treated effluent from the treatment plants is now diverted to other areas in Hong Kong. However, TM2 still has high nutrient concentrations. TM2 receives Shin Mun River Channel water which is heavily polluted. NO_3 N in the river near Tolo Harbour is over 100 µM most of the year, as shown in the water quality monitoring data and sometimes NO_{3-}N can reach about 250 µM (3.5 mg l^{-1}) (http://epic.epd.gov.hk.htm).

The riverine flux of nutrients was estimated to be 58,450 kg y^{-1} for total inorganic nitrogen (TIN), and 6280 kg y^{-1} for PO4-P from four streams entering Tolo Harbour in 1986 (Hodgkiss and Chan 1986). The TIN input from the streams was over three times that of the annual fish farm N loading of 15,860 kg N y^{-1}. The riverine flux may have been reduced since there were no livestock farms remaining in the catchment areas of any of the ten rivers in the Eastern New Territories by the mid 1990s after the implementation of the Waste Disposal Ordinance of the Livestock Waste Control Scheme introduced in 1988, which banned livestock farming in the new towns and urban areas (EPD 2006, 20 Years of Marine Water Quality Monitoring in Hong Kong, http://www.epd.gov.hk/epd/misc/river_quality/1986-2005/textonly/eng/4_eas_nt.htm).

6.6.3.4 Consequence Assessment

There are different sources of nutrients, such as runoff, river channels and discharges which carry sewage effluent. The nutrients from the different sources are eventually distributed in the coastal waters, and increase the ambient concentrations. Therefore, it is important to compare the N additions from a fish farm with ambient concentrations in order to assess potential consequences of nutrients introduced by fish farms in comparison with contributions by the other sources. This way, we can evaluate the incremental change in risk arising from the releases from fish farms, how effective our regulative management of fish farms is, and whether there is any advantage to be gained from implementing risk management or mitigation measures.

6.6.3.4.1 Comparison between ambient concentrations of nutrients from others sources and additions from fish farms

Tidal flushing is weak in Tolo Harbour. Some water from Mirs Bay moves into Tolo Harbour and 70% of that comes back out (Lee and Arega 1999). In other words, 30% of tidally-driven intruding waters remains in the harbour and dilutes the Tolo Harbour water during a tidal cycle. The yearly average total N concentration in

Figure 6.6.5 : Monthly average salinity at the surface and bottom during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

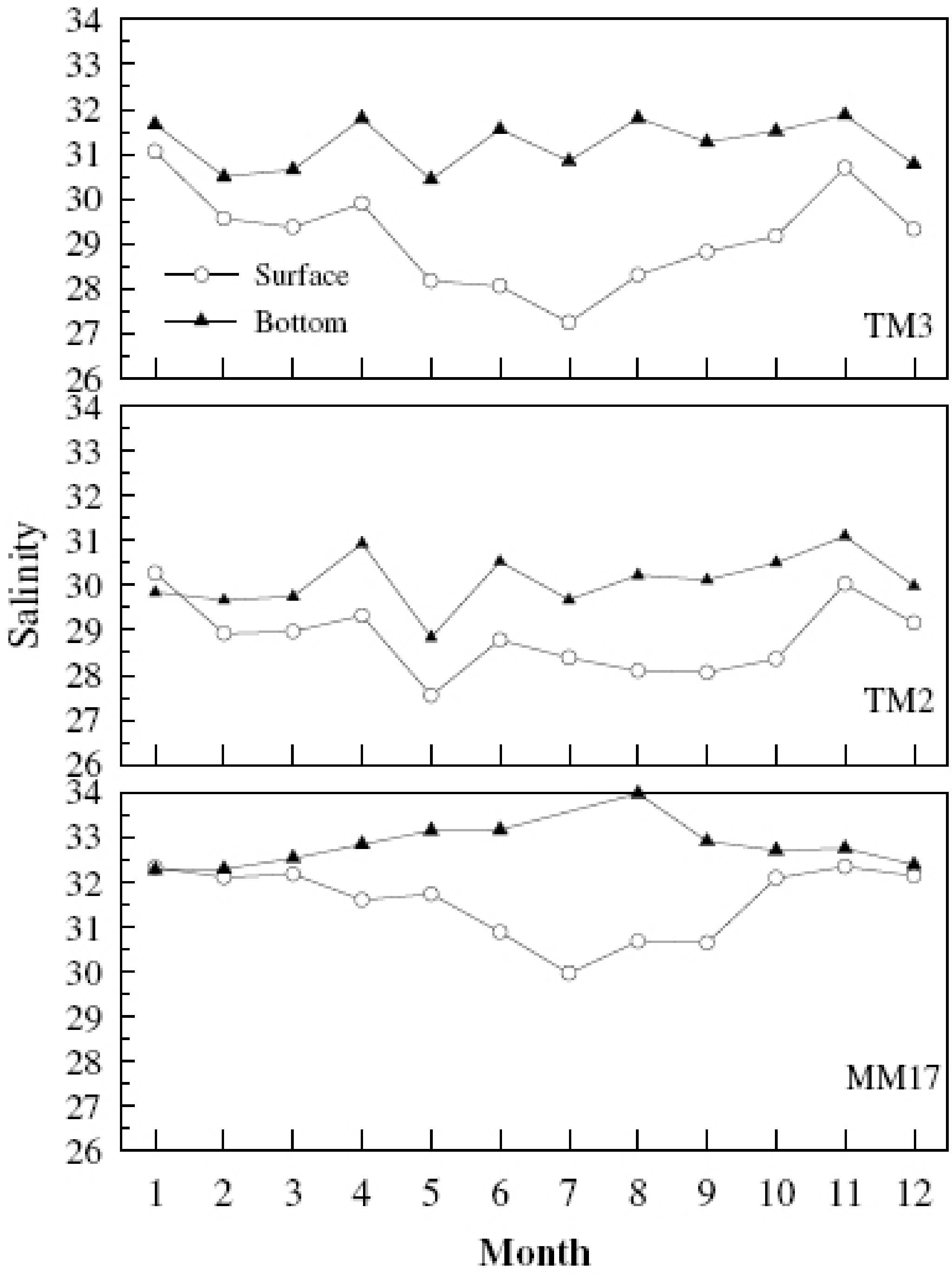


Figure 6.6.6 : Monthly average NO_3 at the surface and bottom during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

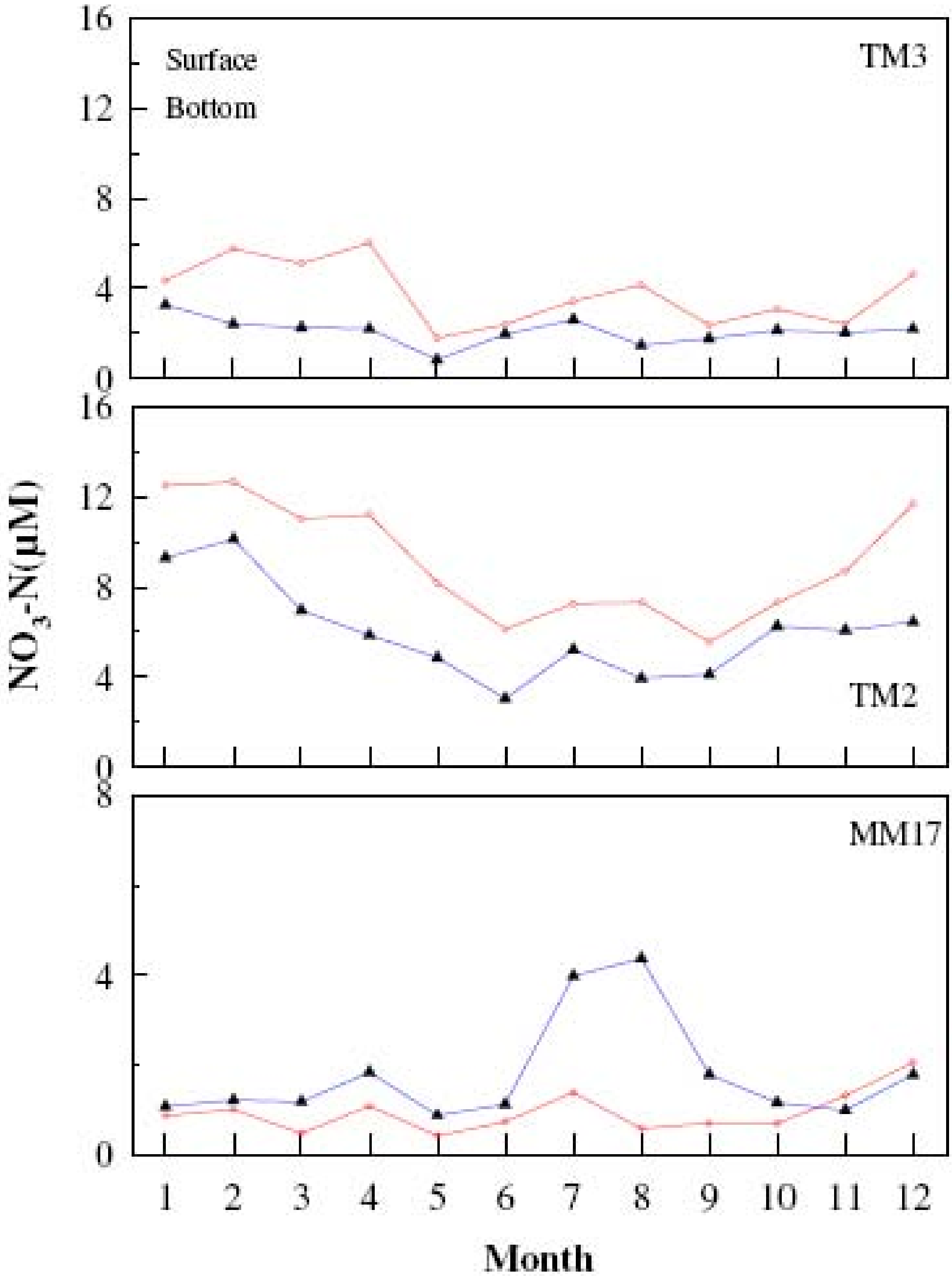


Figure 6.6.7 : Time series of NO_3 showing concentrations < 5 µM at the surface during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

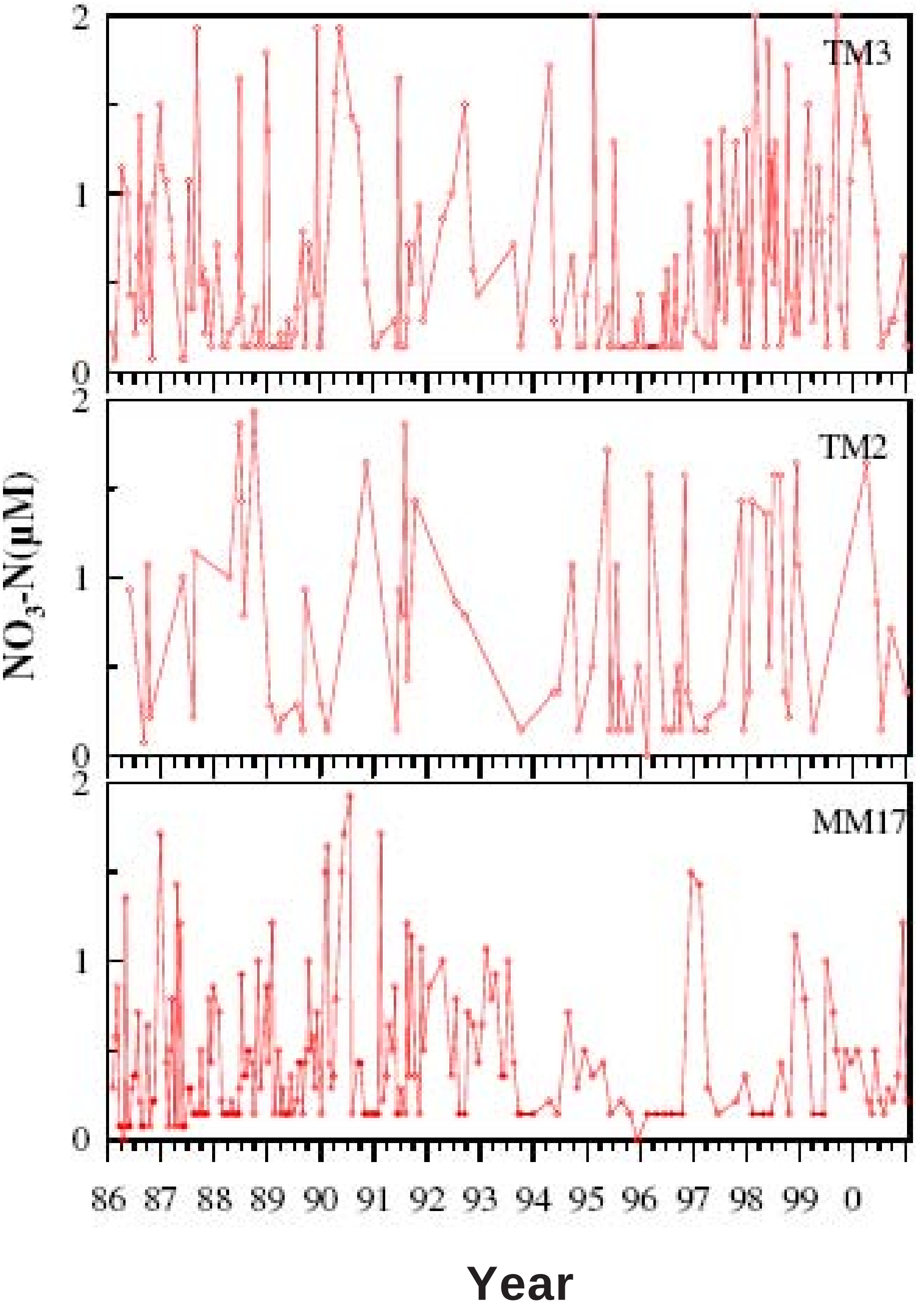


Figure 6.6.8 : Monthly average NH_4 at the surface and bottom during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

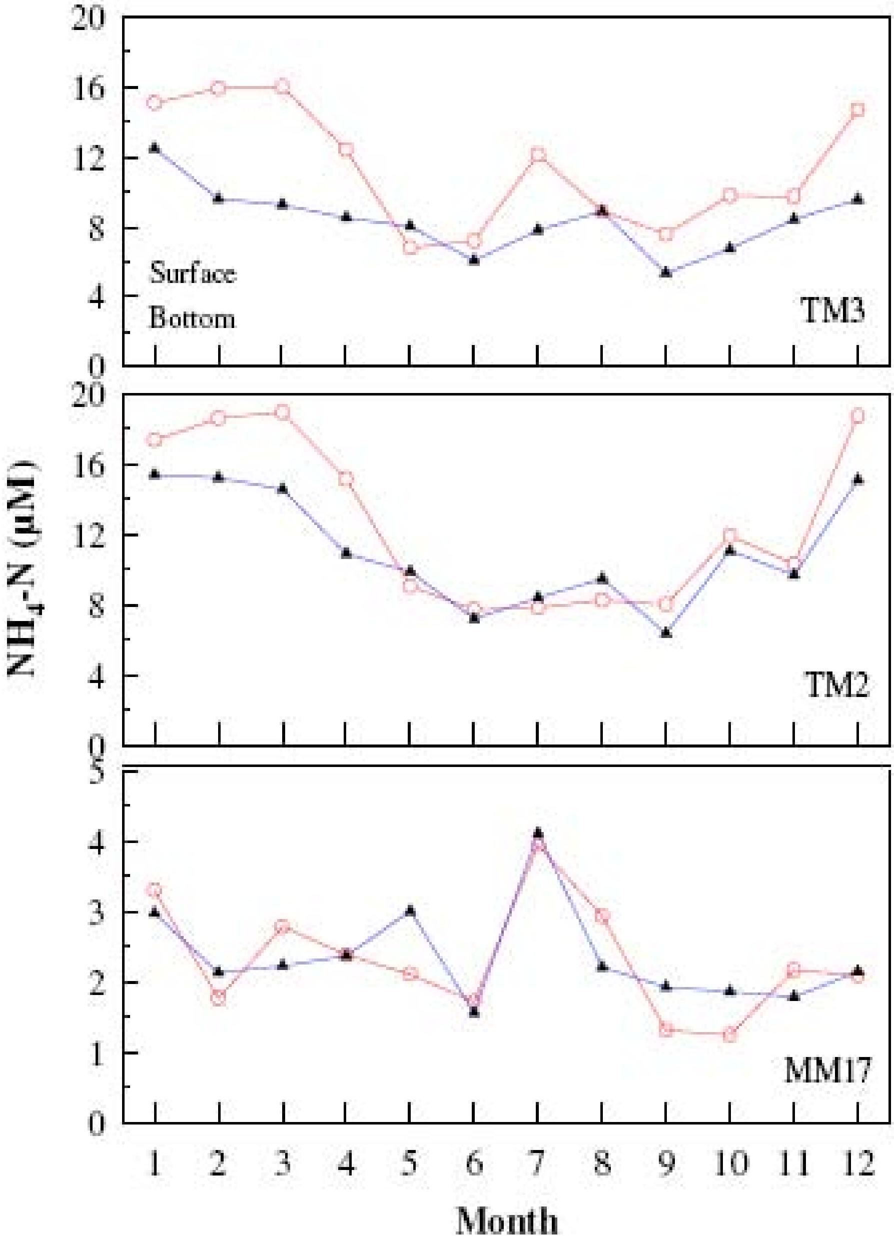


Figure 6.6.9 : Time series of NH_4 showing concentrations < 5 µM at the surface during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

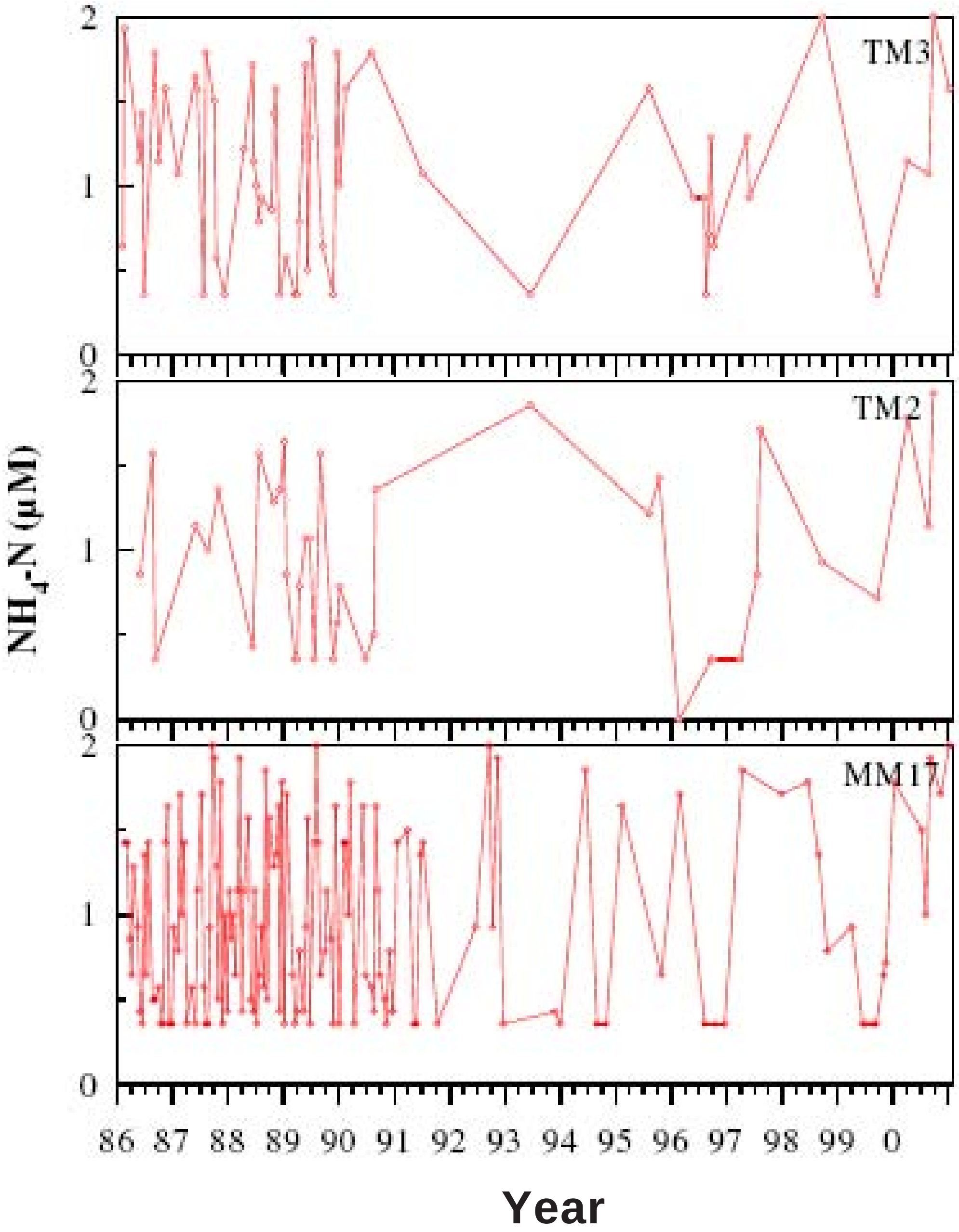


Figure 6.6.10 : Monthly average chl a at the surface and bottom during 1986-2000 at TM3 (near the fish farms), TM2 and MM17.

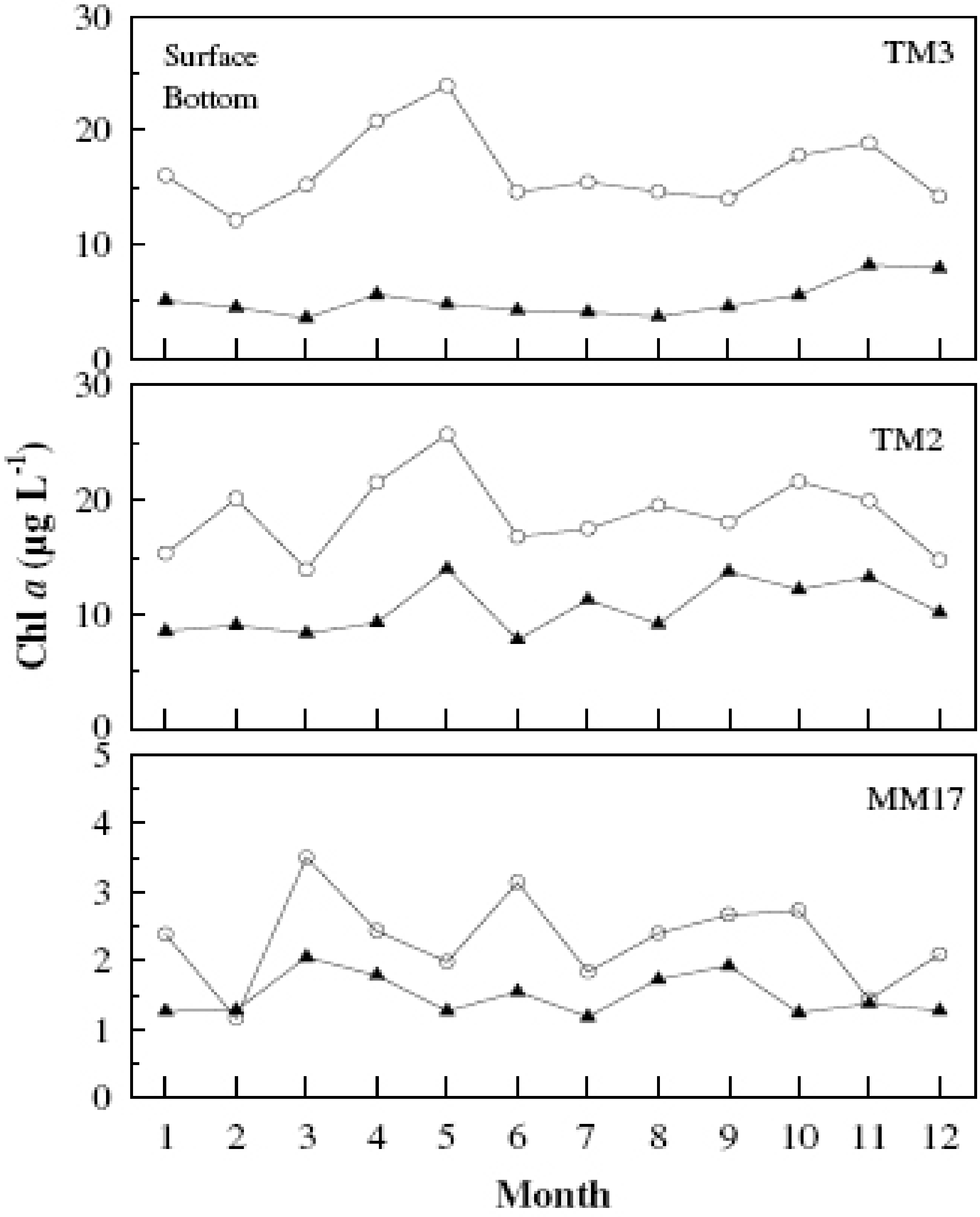


Figure 6.6.11 : Time series of Chl a showing concentrations >20 µg L-1 at the surface during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

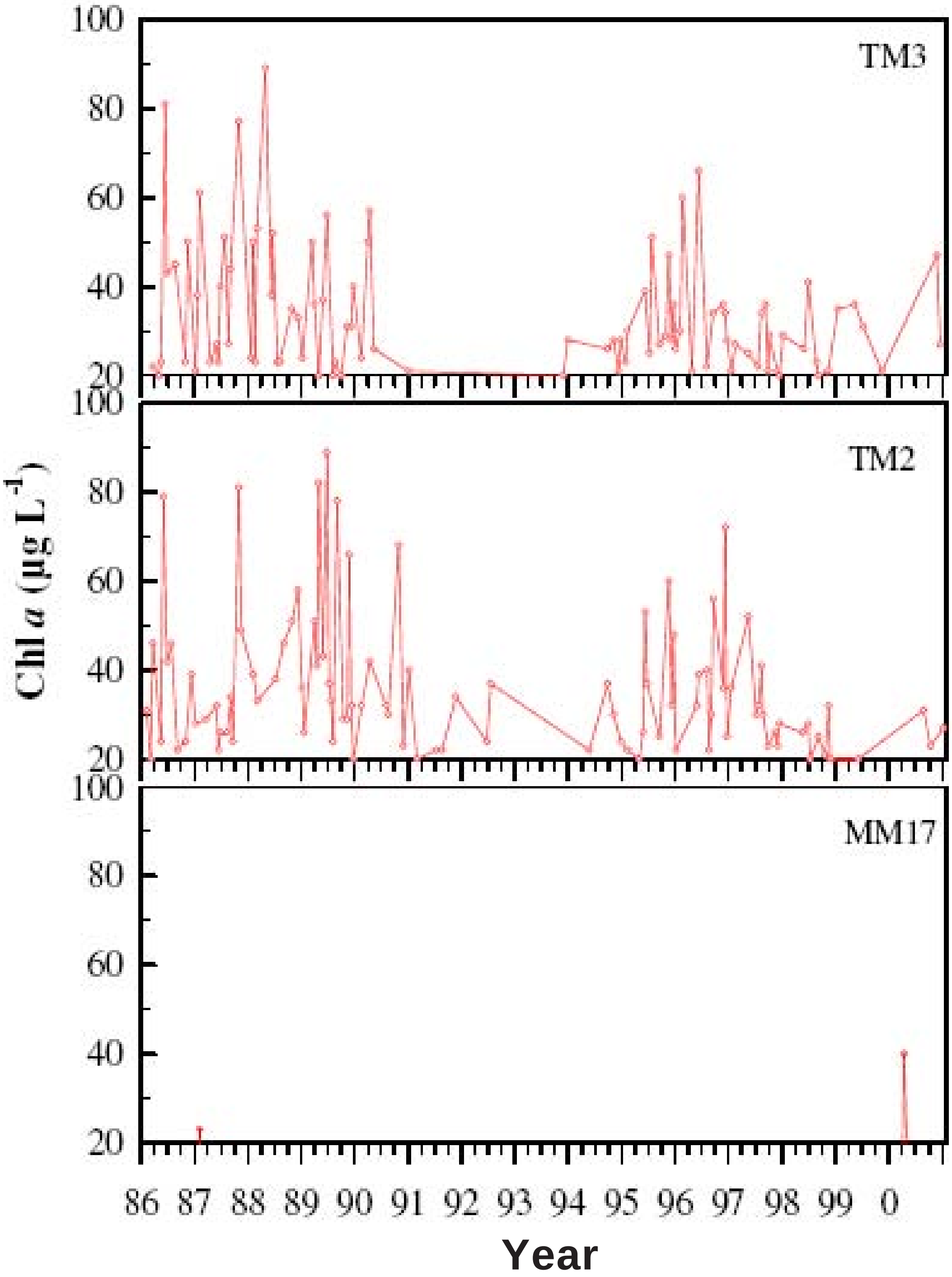
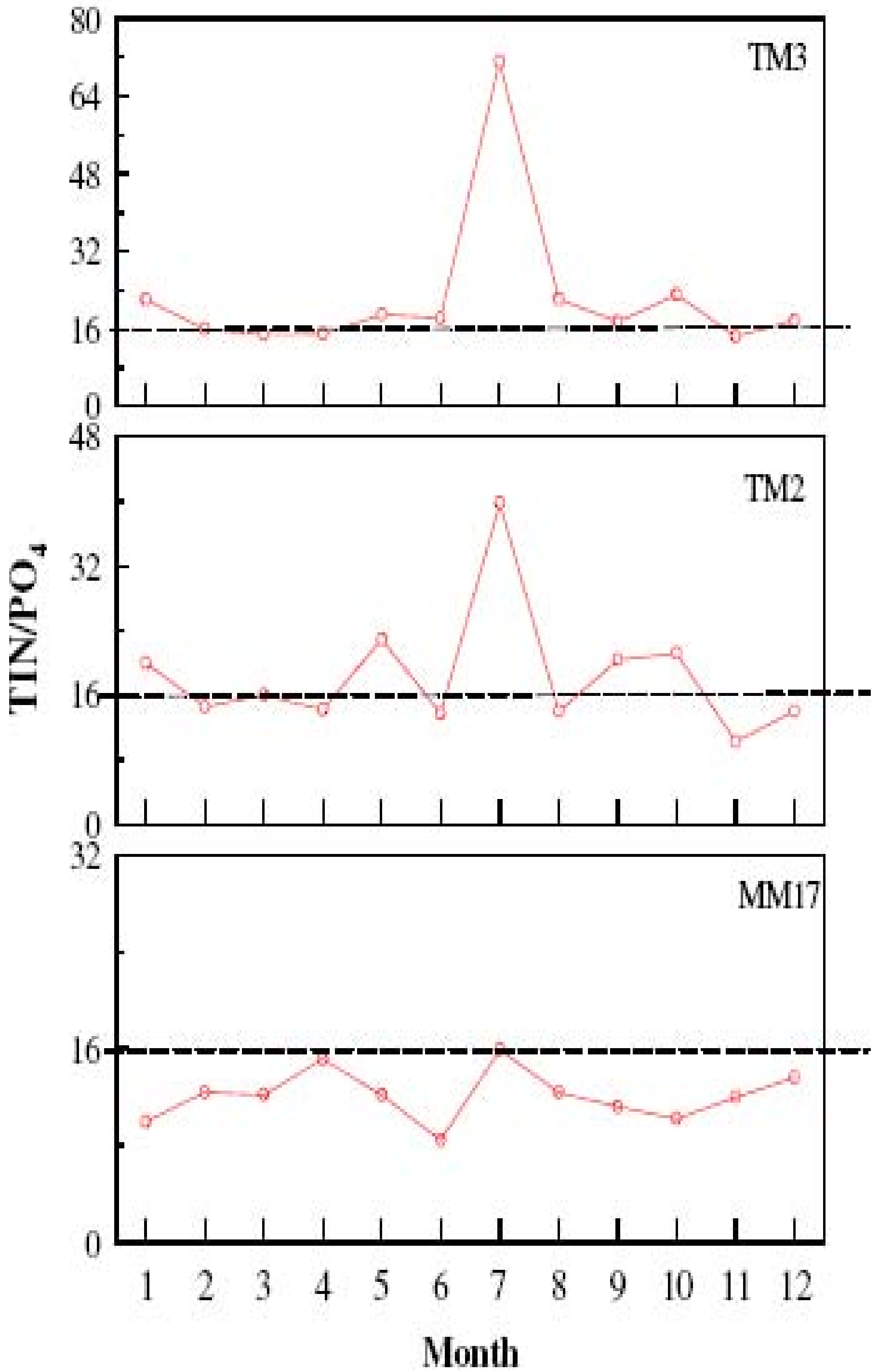


Figure 6.6.12 : Monthly average TIN/PO_4 ratio at the surface and bottom during 1986-2000, at TM3 (near the fish farms), TM2 and MM17. The dashed line is the N:P ratio = 16:1 required for phytoplankton growth.



the water column in Mirs Bay is 4.1 µM with only a small seasonal difference and chl *a* is 1.76 µg l^{-1}. Even if the Mirs Bay water is used as the background water for the fish farms in Tolo Harbour, the background ambient N concentration of 4.1 µM from Mirs Bay is still high compared to the fish farm daily input concentrations of 0.09 and 0.03 µM in summer and winter, respectively. Fish farms contribute only about 0.7 – 2.2% in winter and summer respectively, when compared to Mirs Bay ambient N concentrations. Mirs Bay concentrations are also high in comparison to the phytoplankton half saturation uptake concentrations of 1-2 µM.

Based on the monthly average of TIN at TM3, the average ambient total dissolved inorganic N in the water column (surface-bottom average) near the fish farm is 11.9 µM and 15.5 µM in summer and winter, respectively. These values represent daily concentrations present in ambient waters near the fish farms and can be used as ambient N concentrations for comparisons with N additions from the fish farm. Thus, fish farm FCZ25 contributes only 0.8% (summer) and 0.2% (winter) to the ambient concentrations resulting from all other sources.

Background concentrations of N are also high compared to the nitrogen uptake half saturation coefficients of 2µM that are common for phytoplankton species, suggesting that nitrogen is unlikely to limit phytoplankton growth in Tolo Harbour.

The N/P ratios do not suggest P limitation except in July. Stratification in Tolo harbour is strongest, and Chl *a* are near their lowest at this time. The substantial supply of P from the rivers does not seem to elicit a numerical response in the phytoplankton population. This would support a supposition that phosphorus generated by fish farm effluents is likely to be primarily generated in the sediments below the pycnocline and be largely isolated from phytoplankton in the euphotic zone.

Tidal flushing is weak in Tolo Harbour, and the residence time of 28 days is sufficient for phytoplankton blooms to occur. Phytoplankton blooms do occur frequently in Tolo Harbour, as phytoplankton biomass frequently exceeds 20 µg L^{-1} chl *a* (Fig. 6.6.12). Red tides frequently occur in Tolo Harbour and Tolo Channel (Fig. 6.6.13) (Yin 2003). Our estimates indicate that fish farms contribute very little to the ambient nitrogen concentrations in Tolo Harbour, as the maximum estimated accumulative concentration is a very small fraction of monthly average N concentrations. This conclusion agrees with other studies which found that the spatial footprint for nutrients from fish farms are usually confined to a rather small area. Marine aquaculture cages are generally located from 100 m to 1.5 km offshore in water depths ranging from 15 to 30 m (Gooley *et al*. 2000). These would be the areas primarily susceptible to the effects of cage aquaculture (Pe´rez *et al.* 2002). The spatial scale of the effects of aquaculture effluents depends on a number of factors including the area used for culture, the degree of intensification, production level and the profile of the water body. Guo and Li (2003) reported that the effect of cage culture only extended 20 m outside the cage area in a lake in China with a fish production of 16 metric tonnes using 20,000 m^2 of cage area.

In the consequence assessment, a logic model can be used to describe sequential steps in the mechanism that links specific exposures to nutrients in wastes (the hazard) produced by fish farming to the specific effect of fish farming on overall phytoplankton abundance. The logic model demonstrates how each step contributes to the potential development of bloom conditions.

The steps in the logic model are illustrated in Figure 6.6.14, and summarized below:

6.6.3.4.2 Logic model

The risk: fish farm causes an increase in nutrients, leading to a significant increase in algal biomass, leading to discoloration of the water body.

End point: Chlorophyll a increases to above 20 µg l^{-1}.

Logic model steps:

1. Establishment of fish farms
2. Feed usage by fish farms
3. Release of nutrients
4. Phytoplankton growth
5. An increase in phytoplankton population biomass
6. On the basis of fish farm nutrients, phytoplankton blooms occur

6.6.3.4.3 Evaluation of consequence using the logic model

In the consequence assessment, using the logic model each step in the process is assessed for severity, probability and duration of change (Table 6.6.II).

1. Establishment of fish farms.

Fish farms either already exist, or are in the proposal stage. The intensity of fish farm establishment is thought to be high, their geographic extent is spreading and, once established, fish farms tend to remain in operation for a long time. Consequently the severity of this step is judged as high (H). Therefore, the probability for an establishment of a fish farm is high(H) with low uncertainty (L) in general.

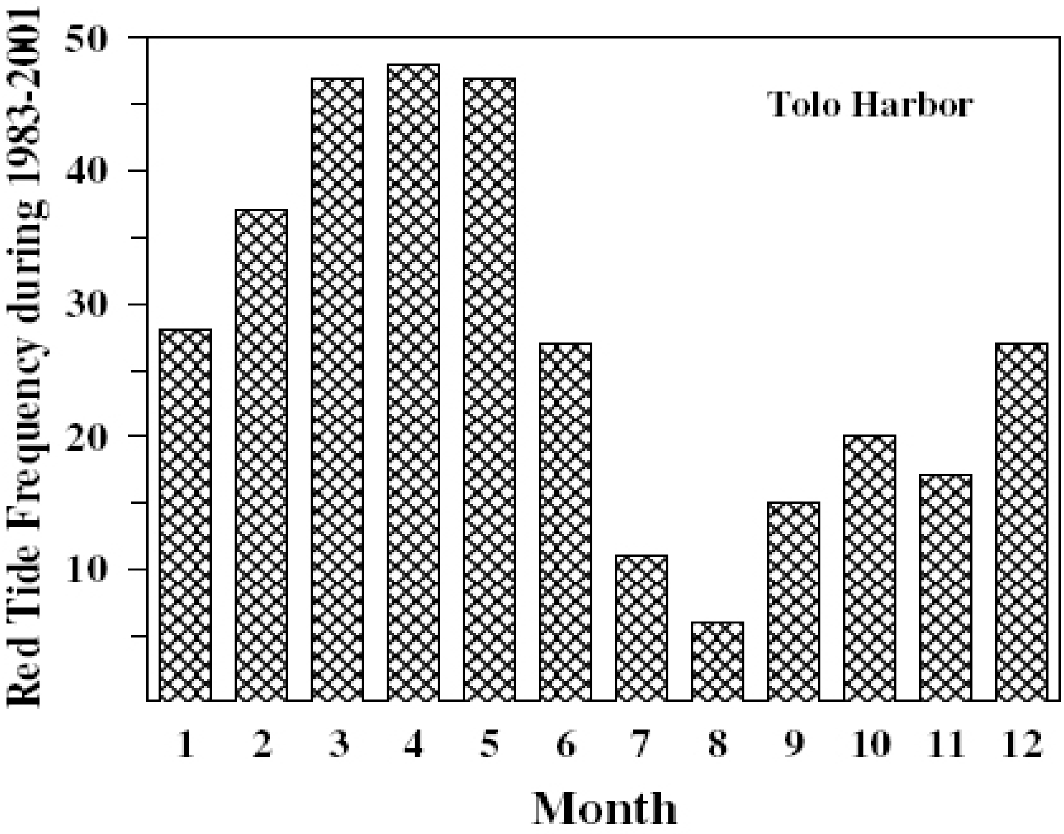
2. Feed usage by fish farms

All operating fish farms provide feed to fish. Intensity/quantity of feed is daily (H), limited to fish farms (geographic extent, L) and feeding continues as long as the fish are in cages, although once the farm ceases to operate feeding ceases (temporal duration, L). The severity of feeding is therefore considered Low(L), and the probability is very high (H). Uncertainty is low (L).

3. Release of nutrients

Intensity (H) of the release is high. The geographic extent (H) of feed wastage distribution can be large as the uneaten feed is quickly

Figure 6.6.13 : Monthly average occurrences of algal blooms (red tides) reported by AFCD (Agriculture, Fisheries and Conservation Department) during 1983-2001, in Tolo Harbor and the Tolo Channel.



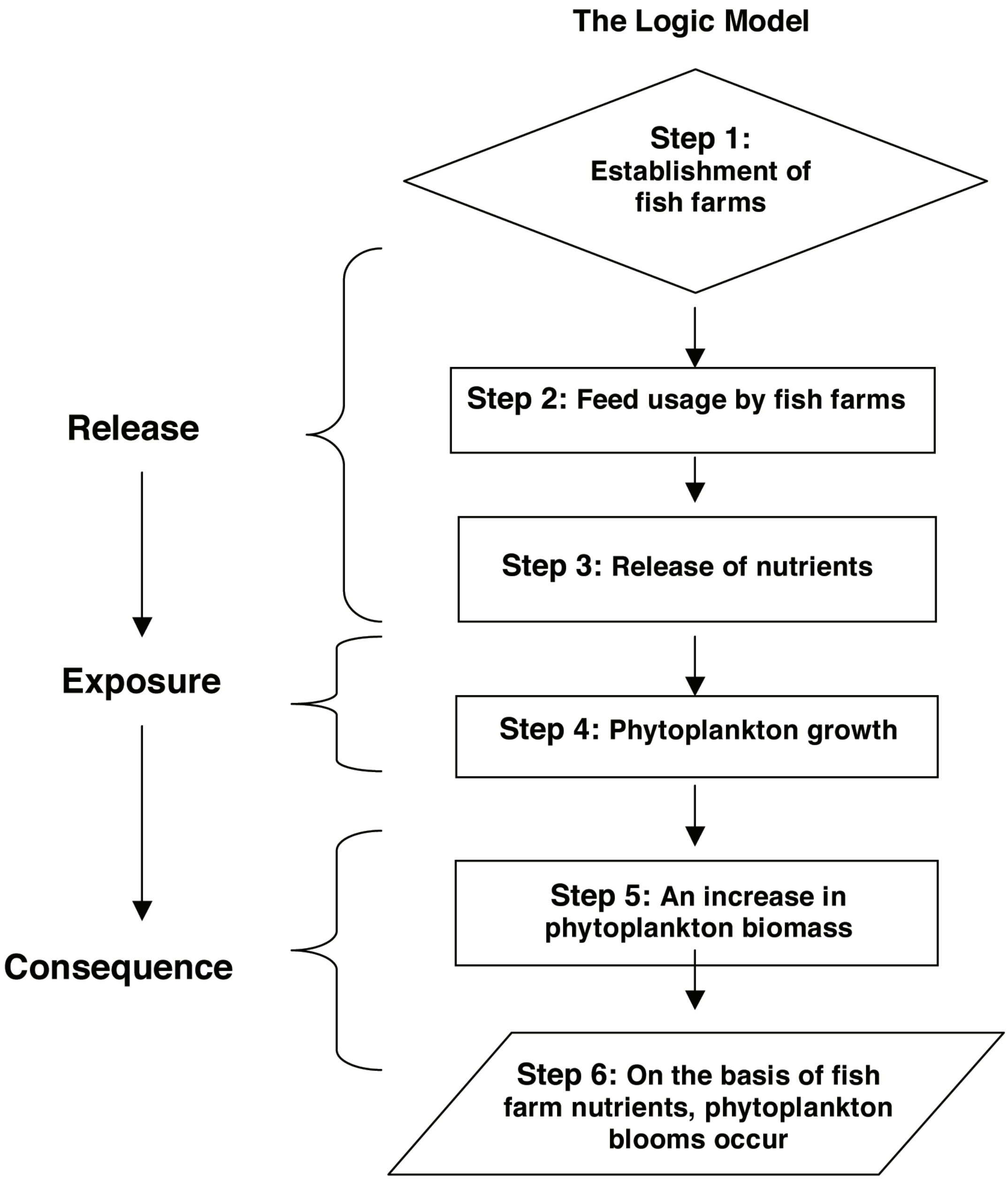
distributed over a large area of the surrounding water before settling on the seabed, and thus there is a constant release of nutrients via fish excretion. The duration of nutrients in the harbour after removal of the fish farm would likely be in the order of a year or two, a relatively moderate length of time (M). The severity of this step of the logic model is therefore high (H); there will be a release of nutrients in active fish farms (probability is H) and uncertainty is low (L).

4. Phytoplankton growth

Phytoplankton will be exposed to nutrients released from fish farms. Nutrient ratios are an indicator of which nutrients are likely to limit phytoplankton growth. For phytoplankton, the nominal N:P ratio (by atoms) is 16 N:1 P (called the Redfield ratio) whereas N:P ratios in fish feeds are generally lower than the Redfield ratio, i.e. are relatively rich in P (Islam 2005). In marine waters, N is usually considered to be the limiting nutrient for phytoplankton growth (Hecky and Kilham, 1988). Further, most of the P in fish farm waste is in the solid component which can be trapped below the pycnocline in stratified waters and be unavailable for phytoplankton growth. Thus, nitrogen excreted by fish will probably enhance phytoplankton growth. In Mirs Bay, the N:P ratio is <16:1, suggesting potential for N limitation of phytoplankton growth. Therefore, we focus on the N budget in Tolo Harbour.

Using N concentration as the basis for phytoplankton growth, the potential intensity of phytoplankton growth is high because of exposure to pre-existing high nutrient concentrations. The farm's proportional contribution to the total supply of nutrients is however not significant (L). The geographical extent of the contribution will in all likelihood remain close to the farm and is judged to be low (L). Temporal persistence of the nutrient contribution after the farm ceases operation will arise from sediment remineralisation, which will probably continue over a time scale of a few years. Only a proportion of the nutrients remineralised from sediment will enter the photic zone and contribute to phytoplankton growth. The duration is thus judged to be medium (M). In this case study, the severity is judged as low (L). The probability of fish farm nutrients contributing to individual alga will be proportional to their contribution to the nutrient pool (L). The uncertainty of whether some phytoplankton will use farm nutrients is low (L).

Figure 6.6.14 : The logic model steps for risk assessment of fish farms. The assessment of severity, probability and uncertainty for each step of the logic model is presented in Table 6.6.II.



5. An increase in phytoplankton biomass

An increase in the biomass or abundance of the phytoplankton population requires a stable water column, for example, long residence time of the water column with little horizontal dilution and weak vertical mixing. When tidal flushing is strong, the phytoplankton biomass gained will be diluted either via horizontal exchange or vertical mixing. When flushing and vertical mixing are not significant, phytoplankton growth and densities will be determined by the most limiting growth factor (nutrients or light).

N and P in Tolo Harbour are only occasionally drawn down to levels that would be considered to be growth limiting. The average water residence time of 28 days permits considerable accumulation of biomass if nutrients are not limiting. However, the frequency of red tides (visible discolouration of the water) (Fig. 6.6.13) suggests that, at high phytoplankton biomass, light may occasionally become a limiting factor for phytoplankton growth. Even so, there are many periods when chlorophyll levels are lower and there may be potential for further population growth.

The intensity of likely increases in phytoplankton biomass is low (L) as nutrients do not seem to be generally limiting. The geographical extent of the increase, in the same fashion as proportion of contribution of farm nutrients to population growth, is expected to be low (L). The duration of the contribution after the farm ceases operation is at best moderate (M) and will regulated by physical processes affecting stratification of the water column. The consequent severity is therefore low (L) and probability is low (L), and the uncertainty is moderate, as we can not predict physical processes or state with absolute authority that light is the limiting factor.

6. On the basis of fish farm nutrients, phytoplankton blooms occur

When phytoplankton biomass accumulates to a certain level, it can discolour the water. Blooms have frequently occurred in Tolo Harbour since 1983 (Fig. 6.6.13). If chl *a* > 20 µg l^{-1} is considered to represent a phytoplankton bloom, phytoplankton blooms have occurred every year at the fish farm (TM3) except for 1991-93, and every year except 1993 at the Tolo Harbour control site (TM2). There is no evidence that the time averaged concentration at these sites is different. In the same period, blooms have occurred only twice at the oceanic control site MM17.

When a phytoplankton bloom occurs, nutrients, including NO_3, and NH_4, can be temporally drawn down to limiting levels (Fig. 6.6.7 and 6.6.9). However, this high concentration of chl *a* > 20 µg l^{-1} is not primarily supported by N concentrations released from fish farms. Therefore, nutrient input from fish farms does not appear to be related to the occurrences of large phytoplankton blooms or to a significant increase in phytoplankton biomass in Tolo Harbour.

Once the factor supporting blooms development (in this case possibly the fish farm) ceases to be present, blooms of phytoplankton last on time scales of days to weeks and so the duration is considered low (L). The contribution of the farm to the intensity of a bloom under the conditions present in Tolo Harbour is low (L) and the geographic extent is low (L) as nutrients are diluted rapidly at most farms. Consequently, the severity and probability of fish farm nutrients leading to a bloom in Tolo Harbour are both low (L), but there is considerable uncertainty in this prediction (H). When water near the fish farms is not moving due to the lack of currents or wind, the nutrients from the fish farm may accumulate and result in a highly localised rapid increase in phytoplankton biomass. If those conditions persist for a week in a subtropical environment, a bloom may occur at the farm site.

Natural waters surrounding the fish farms in Tolo Harbour have background nutrients and phytoplankton biomass that have temporal (seasonal) fluctuations. Even so, fish farm operations in the Tolo Harbour contribute a small nutrient load to Tolo Harbour compared to the loading from other sources of nutrients. The additional nutrient load from fish farms may pose an environmental risk to phytoplankton biomass in Tolo Harbour only when N or P is exhausted during phytoplankton blooms, but rather than contributing to the development of a bloom directly it may only contribute to a longer duration of a very small portion of possible phytoplankton blooms.

6.6.3.5 Risk Estimation

In the earlier discription of the new expansion of farming activities, no special technologies were identified to be used nor were specific regulatory requirements mentioned that might reduce the effect of that farm from that which might be anticipated based on the experience used to development the consequence assessment.

In order to reduce nutrient pollution in Hong Kong waters, the Water Pollution Control Ordinance was enacted in 1980 and was amended in 1990 and 1993. It provides the main statutory framework for the declaration of water control zones to cover the whole of Hong Kong and the establishment of water quality objectives. A licence is granted, with terms and conditions specifying requirements relevant to the discharge, for example, the discharge location, provision of wastewater treatment facilities, maximum allowable quantity, effluent standards, self-monitoring requirement and keeping records. In 1982, the Marine Fish Culture Ordinance was implemented. The ordinance requires all marine culture operations to be conducted at sites within gazetted fish culture zones.

Table 6.6.II : Severity, probability and uncertainty for each step of the logic model. (NA = not applicable)

	Logic Model Step	Intensity or degree of change	Geographical extent	Permanence or duration	Severity	Probability	Uncertainty
1	Establishment of fish farms	H	H	H	H	H	L
2	Feed usage by fish farms	H	L	L	L	H	L
3	Release of nutrients	H	H	M	H	H	L
4	Phytoplankton growth	L	L	M	L	L	L
5	An increase in phytoplankton population biomass	L	L	M	L	L	M
6	On the basis of fish farm nutrients, phytoplankton blooms occur	L	L	L	L	L	H

Probability = H - High, **M** - moderate, **L** - Low, **EL -** Extremely Low, **N -** Negligible
Severity = C - very intense, **H** - high, **M** - Moderate, **L -** Low, **N** - Negligible. There are three components of severity that should be considered: the duration of the activity, the degree of change, and the geographic extent of the change.
Uncertainty = H- Highly certain, **M** - Moderately certain, **L** - Low Uncertainty
The final rating for the **Probability** is assigned the value of the element with the **lowest** level of probability.
The final rating for the **Severity** (intensity of interaction) is assigned the value of the step with the **lowest** risk rating

In Tolo Harbour and the Channel water control zone, the water quality objective is <20 µg chl *a* l^{-1}. There does not appear to be a water quality objective for total inorganic nitrogen, but only a reference level between 0.2 and 0.4 mg N l^{-1}, which is equal to 14.3 and 28.6 µM, respectively.

EPD acknowledges the need for a mixing zone around outfalls of other types of effluents where pollutants are first diluted and accepts that the water and seabed are changed from their normal state within this area, known as an allowable zone of effects (AZE). It is defined as: 'The area (or volume) of seabed or receiving water body in which EPD will allow some exceedance of the relevant environmental quality standard or some damage to the environment'. The concept is fundamental to the Hong Kong system of environmental management. It follows that any modeling approach used in regulating effluent discharges must allow appropriate boundaries to be set, defining the extent of the AZE and therefore where EPD expects the EQS to be achieved, taking into account the natural processes of dispersion and degradation of the various types of wastes. In the case of fish farms, AZE is usually quite small compared with that typical for domestic sewage effluent discharge.

These controls alone seem unlikely to limit phytoplankton proliferation in Tolo Harbour. For that reason, the risk level identified in the consequence assessment is the same as that for the risk evaluation. Should any of the recommended risk management activities be undertaken, that level of risk may be modified.

6.6.4 Risk Management

Risk management addresses what might be done to reduce the probability of a risk being expressed, or to reduce the uncertainty in the prediction of the expression of a risk. This can be addressed through consideration of the series of steps in the logic model discussed above. For each step, the process identifies what could be done to reduce the probability of it occurring. These actions would directly mitigate possible effects. A further contribution to increasing the effectiveness of the risk analysis would be to reduce the uncertainty associated with predicting that the step will happen. Usually this involves further research or development. Table 6.6.III identifies both mitigation and research or development steps that could be employed in addressing risks associated with algal blooms arising from fish culture.

Although Tolo Harbour is a special case where ambient concentrations appear to exceed nutrient concentrations contributed from fish farms, in order to assess these risks, we need to set up a set of criteria for those parameters and address questions such as, at what level is a change in each parameter considered to be a risk and what is the probability (how frequently) that this level will be achieved.

Table 6.6.III : Possible mitigation and research activities to reduce the probability of steps in the logic model occurring, or reduce the uncertainty in the estimate of that probability.

	Logic Model Step	Probability	Mitigation (regulate/design/ modified practices)	Uncertainty	Research/Development
1	Establishment of fish farms	H	Where feasible move to land-based production	L	Develop economically competitive land-based technologies with appropriate waste treatment.
2	Feed usage by fish farms	H	Intercept and recover solid wastes before they are decomposed and dissolved	L	Improve cage designs to allow *in situ* waste recovery
3	Release of nutrients	H	Use more efficient feed to increase FCR, practice efficient feeding frequency and intensity	L	Improve hydrodynamic modeling dispersal of particles near fish farms Investigating rates of decomposition from feed particles to dissolved form
4	Phytoplankton growth	L	No feasible mitigation	L	Conducting physiological ecological study to understand dominant species growth characteristics
5	An increase in phytoplankton population biomass	L	No feasible mitigation	M	capability of predicting the depth of euphotic zone and its residence times
6	On the basis of fish farm nutrients, phytoplankton blooms occur	L	No acceptable mitigation, but clays have been used in Korea and Japan.	H	Develop biological-physical coupling model to understand the bloom dynamics and to project occurrences of blooms

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