Considerations for Longline Culture Systems
Design: Scallops production

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Introduction

Mollusk culture in cages suspended in the water began in Japan with the oyster (Crassostrea gigas) 300 years ago, but only in the middle of this century did the Japanese develop a special culture structure where the main characteristic is to give an artificial environment to grow sessile organisms in a vertical water column. This is a great advance in the optimization of the production per unit of surface area. These structures belong to the general class of culture systems known as longline systems, and they are used commonly for scallops and oyster commercial culture, with some modifications in several countries, but all inspired in the Japanese system (Dupouy, 1983; Imai, 1977; Illanes & Akaboshi, 1985; Barnabe, 1991).

To design and dimension the longline system, it is necessary to know the depth of placement, the current speed, the longline flow exposure area, the respective drag coefficients, and an estimate of the fouling growth on the system (Merino, 1996).

In this work the basic physics and operational concepts for design, dimensioning and installation of a commercial longline for scallop production will be discussed.

Longline Systems and Structures

The spatial disposition of the longline in the water column could be totally immersed or at the surface. The immersed longline is used in unprotected culture areas and in areas with a considerable fouling biomass, because wave and fouling effects are minor under the water surface. The surface longline generally is used in protected areas with a low fouling biomass.
This general rule could reduce investment and operations cost in a commercial mollusk culture (Merino, 1996).

In the “longline culture system,” three subsystems can be found: the mooring-anchor system, the floatation system, and the growing system, each of them are assembled from structures like ropes, buoys, pearl-nets, etc. (Figure 1).

The mooring-anchor system is used to stabilize the system against the effects of dynamic stresses, both vertical and horizontal, to which the longline is continually being subjected within the marine environment.

The floatation system is used to maintain suspension of the culture system, and is usually composed of different kinds of plastic buoys, or other manufactured materials, with varying sizes and capacities.

The growing system is used to grow the mollusk in captivity, and one of several growth structures is used, depending on the step of the culture and also on the selected species. In scallop and oyster cultures, pearl-net, lanterns, bags, ear-hangers, and other basket systems are generally used.

![Figure 1. Typical Chilean aquaculture longline facility setup. 1) culture units, 2) main line, 3) buoy rope, 4) first buoy rope, 5) floats, 6) buoy, 7) mooring line, 8) anchor system, 9) anchor rope, 10) anchor buoy.]

**Knowing the Environmental Forces**

The currents, waves, wind, system weight and management operations are the main variables that determine the dimensions and the magnitude of the stress that acts upon the longline system’s structures.

Marine currents make horizontal tension a maximum in each of the extreme ends of the longline, and they are
quantified through the hydrodynamic resistance of the longline’s structures. The magnitude of this force depends on the current speed and the exposure area of the individual structures. Waves make horizontal and vertical tensions, and both are maximum at the water surface, and are progressively lessened under the surface. Winds also provide a horizontal tension, and its magnitude depends on the wind speed and exposure area of the surface structures. Finally, the system weight (animals, fouling, ropes, etc.) provides gravitational forces, and they can be compensated through the addition of floats during the system design.

Operational management requires the longline to be lifted to the boat for seeding, material changes, or harvest, and also when it is necessary to move or relocate the anchor and mooring systems.

**Design Principles**

The primary design challenge is to identify and evaluate the forces that are present on and in the longline, to determine the strength needed for the longline’s structure to resist the natural forces and to reduce the culture labor risk. With sufficient technical data it is possible to size a longline for a specific goal and the specific environmental conditions of the culture area. This paper will show what is needed to specify a commercial longline system to grow mollusks.

**Buoyancy force**

In accord with the Archimedes Principle, all bodes, either totally or partially immersed in a fluid of density (δ) experience an upwards force commonly referred to as buoyancy force, similar in magnitude to the weight of the liquid volume displaced by the body.

**Floatation or the gravity force on an immersed body**

Floatation is a concept directly related to the buoyancy force, for the floatation of a body will depend on the balance that exists between the buoyancy force (upwards force) and the
body weight (downwards force). Thus, it is possible to obtain the other force, a result of the addition of both forces, which is named floatation. Consequently, for any body:

\[
\text{Floatation} = \text{Dry body weight} \times [1 - (\delta_{\text{fluid}}/\delta_{\text{body}})] \quad (1)
\]

\[
\delta_{\text{fluid}} = \text{fluid density (Kg/m}^3)\]

\[
\delta_{\text{body}} = \text{body density (Kg/m}^3)\]

**Resistance force**

To maintain an object in equilibrium in a moving fluid, there must be applied to the body a force of equal magnitude and opposite in direction to the resultant of the forces exerted by the fluid particles over it. This force, which will maintain the body in static equilibrium, is called “fluid resistance or drag” (R), and it is a function of the speed of the fluid (v), mass fluid density (\(\delta\)), fluid viscosity (\(\mu\)) and by the body geometry and surface roughness. The last two elements can be represented by a drag coefficient (Cd) and the projected body area (A), upon a plane normal to the direction of the flow. Thus the fluid resistance is given by:

\[
R = \frac{1}{2} \text{Cd A } \delta v^2 \quad (2)
\]

These data are determined by observation and experiment (empirical data), not on theory, and upon the evaluation of the body resistance in a fluid. Generally the Cd value depends on the body size and of the Reynold’s number (Re). Knowing the Reynold’s number and the coefficient of drag (Cd), it is possible to obtain the respective resistance coefficient for a given body geometry and body cross sectional area from the numerous and widely published empirical tables.

**Longline Rope Sizing**

To size the structural longline ropes, the following should be considered:

- Evaluation of tensions in the mooring line
- Safety factor
- Characteristics of the materials used
Mooring line:

The recommended length for preliminary design is:

$$n = j * h$$  \hspace{1cm} (4)$$

\(n\) = mooring-anchor rope length (m)  
\(j\) = constant (3.0 < j < 5.5)  
\(h\) = placement depth (m)

It should be noted that for a high length/depth ratio, the natural vertical changes acting on the anchor system are minimal, but at the same time the relative cost for this system is high due to the need for more rope.

Considering the forces on the extreme ends of the main line and the diagonal configuration that will be adopted by the mooring-anchor rope subject to those forces, the tension will be:

$$T_{m-a} = (T_h^2 + T_v^2)^{0.5}$$  \hspace{1cm} (5)$$

\(T_{m-a}\) = mooring line rope maximum tension (N)  
\(T_h\) = maximum horizontal tension in the main line (N)  
\(T_v\) = maximum vertical tension in the main line (N)

Once the maximum tension at the mooring line rope is determined, it is possible to determine the rope diameter (d), using the tension value for an approximate safety factor:

$$d = \frac{(T_{max} * F_s)^{0.5}}{C_r}$$  \hspace{1cm} (6)$$

where,

\(d\) = rope diameter (mm)  
\(T_{max}\) or \(T_{m-a}\) = maximum tension in the rope (N)  
\(F_s\) = safety factor  
\(C_r\) = resistance constant (N/mm²)

Main line:

The main line’s length is determined by the desired production level and the site characteristics. The following are the most important factors (Merino, 1996):

- Production level: This is in function of the investment available, supply of seeds, market demand, marine characteristic of the aquaculture site, etc.
- Productivity: The productivity of the aquatic environment will determine the maximum stocking level; from this one can establish an optimum culture density.
- Economics: Usually the ropes are used completely from anchor to anchor, so it is important not to introduce into the longline any element that could be the cause of structural failure during the period of operation.
- Design aspects: some design parameters, like the separation between each growing culture unit, determine the main line length and factor directly in the stocking density of the culture system.

Also to quantify the forces acting over the main line, it is possible to solve the problem by using coordinates at the one end of the main line:

\[ T_h = R_h + F_h + T_o \]  \hspace{1cm} (7)

- \( T_h \): Horizontal force at the main-line end (N)
- \( R_h \): Hydrodynamic resistance of the main line and culture units (N)
- \( F_h \): Horizontal force due to dynamic forces (N) (waves, winds)
- \( T_o \): Horizontal force due to gravitational forces (N) (rope weight, biofouling weight)

**Buoy ropes:**

For the determination of the buoy rope diameter it is necessary to know the working tension to which they will be submitted. First it is required to calculate the immersed weight that should be lifted by the flotation main-line system.

a) Main-line total weight calculus \( (W_{\text{main line}}) \). The immersed total weight of the main-line system should be calculated from the immersed weights sum of each structural component (PSi). Then, from the equation \( (1) \) results:

\[ W_{\text{main line}} = \sum \text{PSi} \]  \hspace{1cm} (8)

b) Main line weight per unit length calculation \( (w) \). The
main-line weight \( W_{\text{main line}} \) per unit length is simply the \( W \) divided by the main-line length \( s \). Knowing this, it is possible to know how many buoys per unit length will be needed to maintain the main line at the surface. The following equation gives the longline lineal weight:

\[
w = \frac{W_{\text{longline}}}{s} \quad \text{[kg/m]} \tag{9}
\]

c) Buoy rope diameter calculation: Assuming that the adopted configuration by the main line, between two buoys, is like a catenary, it is possible to utilize the catenary expression to determine the tension in the line. Once a maximum is determined, a rope diameter can be chosen and an adequate safety factor incorporated, using a methodology that is similar to that used in other portions of the longline systems (Equation 6).

**Anchor Rope:**

Although one might think that the anchor rope could be smaller than the main line, the working characteristics of the system require this rope diameter to be similar to that of the main-line rope. The reason is that during installation and relocation operations of the system, the anchor rope is used for tensioning the main line. Using this diameter, it is possible to get its length using the catenary principles.

**Buoy Sizing**

The buoy volume can be easily determined by the following equation:

\[
V_b = \frac{W}{[(\delta_{sw} - \delta_b) \cdot g] \cdot F_s} \tag{10}
\]

- \( V_b \) = Buoy volume \( (\text{m}^3) \)
- \( W \) = Weight to lift per buoy \( (\text{N}) \)
- \( \delta_{sw} \) = Seawater density \( (1.025 \text{ Kg/m}^3) \)
- \( \delta_b \) = Buoy material density \( (\text{Kg/m}^3) \)
- \( g \) = Gravity acceleration \( (9.8 \text{ m/s}^2) \)
- \( F_s \) = Safety factor
Anchor System Sizing

During operation, the main factors that generate hydrodynamic resistance are the growing units. In effect pearl-nets and lantern-nets produce a wall-like effect against water flow, and that creates a tension in the system that will be resisted by the mooring-line rope to the anchor system.

Design and sizing of the anchor system must also consider the bottom conditions of the place where the longline system will be located. The slope, substrate type and its sheer strength, are very important in determining the anchor system design characteristic.

The anchor volume could be determined by the following equation:

\[ V_{anchor} = \frac{W_{dry}}{\delta_{anchor}} * g \]  \hspace{1cm} (11)

- \( V_{anchor} \) = anchor volume (m\(^3\))
- \( W_{dry} \) = anchor dry weight (N)
- \( \delta_{anchor} \) = density of anchor material (Kg/m\(^3\))
- \( g \) = gravity acceleration (9.8 m/s\(^2\))

The dry weight anchor should be determined using equation 1.

The following equation describes the immersed weight in relation with the respective forces:

\[ W_{sub} = (T_{m-a} * \cos \phi / \mu) + T_{m-a} * \sin \phi \]  \hspace{1cm} (12)

- \( W_{sub} \) = immersed anchor weight (N)
- \( T_{m-a} \) = mooring line rope tension (N)
- \( \mu \) = drag coefficient
- \( \phi \) = mooring line rope angle

To decide the kind of anchor that is necessary for a specific place, it is possible, from a technical viewpoint to make a pre-selection based upon the concept of a “fixing coefficient” (K). K is the relation between “fixing force” (H) and the anchor dry weight (W), given by:

\[ K = \frac{H}{W_{dry}} \]  \hspace{1cm} (13)
Table 1 shows several anchor and substrate types with their respective K value.

<table>
<thead>
<tr>
<th>Anchor type</th>
<th>Sand substrate</th>
<th>Mud substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stockless</td>
<td>$4.4 &lt; K &lt; 16.0$</td>
<td>$2.0 &lt; K &lt; 7.5$</td>
</tr>
<tr>
<td>Mushroom</td>
<td>$2.0 &lt; K &lt; 2.5$</td>
<td>$5.0$</td>
</tr>
<tr>
<td>Danforth</td>
<td>$14.6 &lt; K &lt; 21.0$</td>
<td>$7.1 &lt; K &lt; 8.5$</td>
</tr>
<tr>
<td>Stato</td>
<td>$20.0 &lt; K &lt; 35.0$</td>
<td>$15.0 &lt; K &lt; 22.0$</td>
</tr>
<tr>
<td>Boss</td>
<td>$30.0 &lt; K &lt; 55.0$</td>
<td>$22.0 &lt; K &lt; 35.0$</td>
</tr>
</tbody>
</table>

Rodriguez, 1996.

Beveridge (1987) also states that it can be shown that K depends upon the angle between the anchor and the seawater surface, and thus the ratio between water depth and line length, and also with the nature of the substrate (Table 2).

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Substrate l:d</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td></td>
<td>0.19</td>
<td>0.53</td>
<td>0.63</td>
<td>0.70</td>
<td>0.74</td>
</tr>
<tr>
<td>Sandy mud</td>
<td></td>
<td>0.10</td>
<td>0.32</td>
<td>0.36</td>
<td>0.36</td>
<td>0.62</td>
</tr>
<tr>
<td>Mud</td>
<td></td>
<td>0.05</td>
<td>0.23</td>
<td>0.27</td>
<td>0.35</td>
<td>0.41</td>
</tr>
</tbody>
</table>


**Conclusion**

The geometry and the spatial configuration of a longline culture system depend on the oceanographic and meteorologic site conditions, the depth of the main line below the surface, and the type of longline that depends on the operating approaches and procedures. Of these, the oceanographic and meteorologic site conditions are probably most important. If they are incompletely understood, the probability of failure is high, or the initial cost may be unacceptably high.
In this paper, means have been formulated to calculate or estimate the forces are acting upon the long-line system. Once they are evaluated, it is then possible to determine the strength that must be built into the long-line's structures by to resist the natural forces and to reduce the risk to laborers during culture. During the design stage it is also necessary to consider the projected levels of biofouling on systems components and the effects of age and sun damage. Biofouling on netting is particularly important for it increases environmental loading over the entire long-line system by added weight and drag but it also reduces water circulation in the lantern-nets and pearl-nets and this could kill the mollusks.

Finally, a word of caution. Always consider adequate safety factors, for this gives you an additional tolerance in your system design and to some degree compensates for unanticipated loading events or even unexpectedly high production.

References
Optimisation of Southern Bluefin Tuna Resource in Semi-Open Ocean Farming, Boston Bay, South Australia, Using Numerical Simulation

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Abstract

Environment Carrying Capacity (ECC) of Boston Bay, South Australia was developed to optimise farming of the southern bluefin tuna resource. Existing and newly developed numerical simulation techniques, in conjunction with mean oceanographic, meteorologic and farm management data were used to derive spatially averaged peak annual levels of dissolved nitrogen and phytoplankton as a function of tuna feed. Simulations were conducted for annual (360 days) production levels (500-5,000 tonnes) and included allowance for uptake of nitrogenous material by sediments. Based on Australian and New Zealand Environment and Conservation Council recommendations for NO$_3$-N (neglecting sediment uptake), the mean value of ECC for Boston Bay was, mean 1,750 tonnes, range 1,300-2,400 tonnes. Corresponding simulations allowing 33% sediment uptake of waste derived products yielded an ECC, mean = 2,600 tonnes, range 2,000-3,400 tonnes.

Background

Southern bluefin tuna (*Thunnus maccroyii*) are caught in the waters of the Great Australian Bight and are transferred to cages in the protected waters of Boston Bay, South Australia, Figure 1. They are nurtured and grown until they reach a marketable condition. The tuna industry in Port Lincoln has
grown from traditional canning to a highly value added commodity. The first experimental tuna farm was established in Boston Bay in 1990 under a tripartite agreement between the Australian Tuna Boat Owners Association, the Japanese Overseas Fisheries Cooperative Foundation and the South Australian Government. Earnings from the industry have risen from about $4 million in 1990 to around $40 million in 1994. Farm sites are located in Boston Bay and surrounding area, Figure 2. Each site is allocated 126,000 m$^3$ of water at a stocking density of up to 4kgm$^3$.

This is equivalent to 10 cages, each holding up to 50 tonnes of tuna per site. The tuna holding cages are made of high density polyethylene plastic floating collars 30-40 metres in diameter from which two nets are suspended. The inner net, which contains the tuna, has sides which drop to a maximum depth of 10 metres. The outer net is used to keep predators away, such as seals and sharks. About 4-9 months is required
Figure 2. Boston Bay region showing approximate location of tuna leases (1994).

for the tuna to reach a marketable size of about 30 kg, after which they are harvested almost on a daily basis. The main market for the tuna is the Tsukiji Fish Market in Tokyo, Japan. (PISA, 1996)

The tuna are fed daily mainly on a diet of pilchards, mackerel and a supplementary vitamin powder. Pilchards have a high water content and about 17 tonnes of pilchards are required to produce about one tonne of tuna. This at the extreme end of commercial feed conversion and marks one of the major expenses associated with tuna farming. Research is currently ongoing into developing artificial feeds for tuna. This should allow for a much more efficient food conversion ratio of about 5:1. (PISA, 1996). Sea-cage farming involves stocking densities and feeding rates in excess of what occurs in the
natural environment which generates large quantities of waste. Uneaten food and faecal material is deposited on the sea floor which leads to nutrient enrichment of the sea floor and the water column. Gowen et al (1988). This has two implications. Firstly, there is a need to maintain the environment under the cages in a healthy environment for the fish thus ensuring productivity of the farms and secondly to address the long term viability of the marine environment on a regional level.

Based on salmonoid farming the primary source of dissolved nitrogenous material associated with fish farming is due to fish feed waste and faeces. The following division of fish food has been suggested. Approximately, 10-20% of feed sinks directly to the sea bed, 80%-90% is consumed by fish which is apportioned as follows, 25% is retained by fish, 65% excreted as urine, 10% excreted as solids, Gowen and Bradbury (1987). As a first approximation, 80% of the feed may be considered as waste material of which approximately 3% is converted to nitrogenous compounds such as organic particulate nitrogen in sediments which can break down and be slowly released into the water and dissolved inorganic nitrogen (mostly nitrate, NO$_3$-N; and ammonia NH$_3$-N).

Despite much debate and proliferation of coastal zone policies and water quality guidelines throughout the world a simple and effective definition of carrying capacity of a coastal region, particularly in relation to aquaculture application, has not yet evolved. Terms such as carrying capacity, assimilative capacity, initially much supported, have not been translated into practical and meaningful definitions that can be applied across a broad spectrum of marine systems. Effective management of coastal resources requires agreement on intended use and type of “acceptable” water quality values. (Lord et al, 1994)

A possible definition suitable for aquaculture may be derived from the concept of sustainable development proposed by Pillay (1996) and defined at the Den Bosch Conference in 1991 (FAO/Netherlands 1991). Sustainable development was defined as “the management and conservation of the natural resource base and orientation of the technological and
institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for the present and future generations. Such development conserves land, water, plant and animal resources; is environmentally non-degrading, technically appropriate, economically viable and socially acceptable."

The term "environmental carrying capacity" is advanced as an appropriate interpretation of the above concept and is defined as "maximisation of tuna biomass in Boston Bay without exceeding recommended water quality guidelines for Boston Bay." The water quality parameters used in this case are a suite of environmental values (dissolved nitrogen and phytoplankton) proposed by the Australian and New Zealand Environment and Conservation Council (ANZECC) for specific classes of the marine environment.

For coastal waters, ANZECC, (1992) guidelines recommended NO$_3$-N and phytoplankton (chlorophyll-a) levels between 10-60 mgm$^{-3}$ and less than 1 mgm$^{-3}$ respectively. For estuarine and embayment cases the corresponding levels for NO$_3$-N and phytoplankton were 10-100 mgm$^{-3}$ and 1-10 mgm$^{-3}$ respectively. Boston Bay can be considered to be intermediate between these classifications. The presence of Boston Island tends to make Boston Bay a semi-estuarine system, however the relatively unrestricted exchange of the bay with the open sea suggested a coastal regime.

The approach taken in this investigation was based on the use of computer modelling techniques to calculate spatially averaged dissolved nitrogen and phytoplankton concentrations with respect to ambient levels in Boston Bay. Computation was made for different tuna stocking levels. The resultant levels of dissolved nitrogen and phytoplankton levels were considered in relation to ANZECC (1992) recommended levels to derive environmentally acceptable tuna production levels.

**Numerical models in aquaculture – recent applications**

Falconer and Hartnett (1993) used deterministic mathematical models for farm optimisation. The models
predicted tidal currents and solute levels. Refined mathematical models for predicting tidal current, biochemical oxygen demand (BOD) and nitrogen levels for a proposed fish-farm configuration in a bay off the Eire coastline were examined. The models accurately predicted field-measured velocities at two sites within the bay and further predicted BOD and nitrogen levels which were known to affect adversely the hydro-ecology of the bay. Silvert et al. (1990) modelled the feeding, growth and metabolism of cultured salmonoids. Modelling package BSIM was used to simulate critical ecological processes that take place within, around and beneath a sea cage filled with salmon (Salmo salar). The derived model, SITE, was tested in the L’Etang Inlet of New Brunswick (Canada), an area of expanding salmon farming. The behaviour of the model was consistent with available field data. Kishi et al. (1991) applied a numerical model to calculate tidal and wind induced currents, spatial distribution of dissolved oxygen and distribution of deposits from mariculture of fish.

Turrell and Munro (1988) studied the dispersal of wastes from a fish farm using a two box model of a hypothetical fjordic sea loch typical of some Scottish west coast fish farm sites. Within the range of production (70-100 tonnes per annum) of fish, the release of ammonia was not considered to add significantly to existing ammonia levels in the loch. Petrusevics (1992) used a two dimensional depth integrated model which included diffusion simulation to examine nutrient distributions associated with a number of tuna pontoons in Boston Bay. The model permitted pontoons to be treated as point sources of nutrients. Nutrient loadings and pontoon location could be varied to demonstrate expected nutrient levels in the bay for variable tuna stocking levels.

Numerical models provide useful tools which can be used to estimate various processes and outcomes. However, irrespective of the complexity of a model, a model is an idealised and simplified representation of the environment and, at the best, produce estimates whose accuracy is a function of the quality of data used in the model and how well the model
simulates known processes. In the case of Boston Bay, approximations of physical and biological processes were made to derive water quality levels resulting from tuna farm activity. The resultant levels were compared to broadly defined water quality criterion to provide an estimate of the “environmental carrying capacity.” Southern bluefin tuna fish farming in Australia is relatively new and there was limited information which could be drawn upon to address various aspects related to the carrying capacity issue in Boston Bay. There was no readily available numerical model which could be applied and it was necessary to develop new modelling techniques.

The Physical Environment of Boston Bay

Boston Bay is a shallow, maximum depth of about 16-17 metres, north-south aligned bay approximately 12 km long and about 5 km wide. Boston Island, located centrally in the bay, is about 5 km long and about 2 km wide. Exchange between Boston Bay and Spencer Gulf occurs mainly through the northern channel which is about 4 km wide. Boston Bay is physically connected to the relatively shallower Proper Bay. Figure 2.

Winds

The summer dominant wind direction in the morning and afternoon is south-east (12.5%) and south (12%) with a relatively large (18%) contribution of easterlies in the afternoon due to the local sea breeze. The majority (75%) of the winds are gentle breezes (<18 kmh⁻¹). During the winter, the prevailing winds are from the west (18%), north-west (11%) and north (11%). The winds are gentle breezes (<18 kmh⁻¹) for about 78% of the time. Winds up to Force 8 (63-74 kmh⁻¹ on the Beaufort wind scale) occur in the area. Approximately 93% of Force 8 or greater winds are north-westerlies while 7% are north-easterlies. The largest number (79%) of Force 8 winds occurred in the spring, 14% in the summer and 7% in the winter.
Wave regime

Wave conditions are mostly locally wind generated. Long period waves from the southern ocean do not generally penetrate into Boston Bay except during extreme storms across the southern continental shelf. Under Force 8 wind speeds and for the following wind directions the significant wave height and wave period are: south-westerly/north-westerly, 1.46 m, 4.7 secs; north-easterly, 2.1 m. 5.7 secs.

Currents

Current speeds in Boston Bay are highly spatially variable (Petrusevics et al, 1993). Currents between Boston Island and the mainland are the weakest. In this region majority (91%) of current speeds are less than 5 cms\(^{-1}\). Major (33%) direction of flow in this region is in a south-westerly direction. The currents on the eastern side of Boston Island are stronger, in this region the majority (42%) of current speeds are in the range 2.5-5.0 cms\(^{-1}\). The dominant (27%) direction of the currents is south-westerly. The strongest currents are experienced in the channel south of Boston Island where majority (65%) of current speeds are in the range 2-10 cms\(^{-1}\). The major direction of flow is west south-west (32%) and east north-east (29%).

The effect of wind on currents

Large non-tidal residuals, as high 50%, have been reported in current records, VIMS (1992). Stevens and Noye (1995) reported that from numerical simulation of depth averaged currents in Boston Bay, wind did not have an important effect on currents in the region. Using dimensional analysis, Petrusevics (1996) showed that, for mean tidal and wind conditions, water elevation has at least three orders of magnitude greater effect on currents than wind stress. However, with decreasing tidal amplitude and increasing wind speed the effect of the wind becomes more important. In Boston Bay, this may occur during storms, and periods of “dodge” tide, a local phenomena when tidal elevations remain constant for a period of about one day every two weeks.
Temperature-salinity properties

Typical mean mid winter temperature and salinity values are 13°C and 35.75 ppt respectively. Corresponding values for late summer are about 20°C and 36.70 ppt (Petrusevics et al. 1993).

Methodology

Modelling considerations

The approach consisted of linking numerical techniques reported by Pridmore and Rutherford (1992) to simulate dissolved nitrogen and phytoplankton levels in Big Glory Bay, New Zealand, to a two dimensional depth integrated model, Bye (1977).

Throughout the year, Boston Bay is well mixed, vertically and laterally (Petrusevics et al, 1993). Further, based on mass transport calculations the major exchange between the combined Boston Bay-Proper Bay system and Spencer Gulf occurs through the northern passage (40%) and southern passage (60%) and only about 14% transport occurs between the southern portion of Boston Bay and the southern channel. This means that the southern channel serves to connect mainly Proper Bay with Spencer Gulf and the main exchange between Boston Bay and Spencer Gulf is through the northern channel. Water circulation patterns under typical seasonal tidal and wind conditions confirm mass transport estimates. A region of divergence can be noted in the southern region of Boston Bay, Figure 3, hence Boston Bay may be considered as a separate hydrodynamic unit. Nutrient loading to the system was assumed to be due to feed waste and excreted material from the fish in cages, Figure 4, and was dependent on stocking levels which varied throughout the year, Table 1.
Figure 3. Peak ebbing tidal currents. Note region of divergence at row 22.
Figure 4. Schematic representation of tuna farm.

<table>
<thead>
<tr>
<th>Month</th>
<th>Fish In %</th>
<th>Total Fish In %</th>
<th>Fish Out %</th>
<th>Total Fish Out %</th>
<th>Food Consumed (% Body Wt/Day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JANUARY</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>25</td>
<td>35</td>
<td>2.5</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>MARCH</td>
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Computation of dissolved nitrogen levels

Simulations of spatially averaged dissolved nitrogen were made for sediment uptake and no-uptake cases. A ratio of 2:1 of dissolved to sediment based nitrogen was assumed. This corresponded to approximately 33% being taken up by the sediments which is in agreement with observations on sediment uptake reported by Cheshire et al (1996).

The steps involved in computation of dissolved nitrogen followed the method outlined by Pridmore and Rutherford (1992).

The simplified mass balance model is, $V \frac{dN}{dt} = I - QN + QN_0$; the steady value is given by $N = N_0 + I/Q$ and the time dependent solution by $N(t) = + (N(t_0) - N_0)\exp(-Q/V(t-t_0)) + I/Q(1-\exp(-Q/V(t-t_0)))$ where $N$ and $N_0$ represent average concentration of dissolved nitrogen levels in Boston Bay and Spencer Gulf respectively; $V$ is the volume of Boston Bay. $I$ is the nitrogen input into Boston Bay due to tuna feed waste and $Q$ is the net exchange between Boston Bay and Spencer Gulf. Figure 5. In the absence of a relationship between dissolved nitrogen and phytoplankton for Boston Bay, the value for ambient nitrogen level $N_0$ was obtained using the regression between nitrogen (N) and chlorophyll-a reported by Pridmore and Rutherford (1992), chlorophyll-a =0.0867(N)-0.250.

Chlorophyll-a levels reported for Boston Bay from surveys conducted during 1991 and 1992 by the South Australian Research Development Institute (SARDI pers comm) are highly variable. Values ranged between 0.17 and 1.26 mgm$^{-3}$. For purposes of this investigation a value of 0.5 mgm$^{-3}$ was used. The corresponding level of nitrogen was = 8.68 mgm$^{-3}$. These values are in reasonable agreement with values reported for dissolved nitrogen and chlorophyll-a for the Marmion Marine Park, Western Australia (13-23 mgm$^{-3}$ and 0.4-1.2 mgm$^{-3}$) and Cockburn Sound, Western Australia for dissolved nitrogen of 5-11 mgm$^{-3}$ (ANZECC, 1992).

The nitrogen input to Boston Bay ($I$) was obtained by use of the relationship; nitrogenous compound value = tuna feed x
WASTE

3% Conversion to nitrogenous material

70% dissolved nitrogen

Q=Exchange period

30% sedimentation

Spencer Gulf

$V \frac{dN}{dT} = I - QN + QN_0$

$V = Volume \ of \ Boston \ Bay$

$I = Nitrogen \ input \ to \ bay$

$N, N_0 = dissolved \ nitrogen \ levels \ in \ Boston \ Bay, \ Spencer \ Gulf$

Figure 5. Schematic representation of processes at bay level.

0.024, which is based on the assumption that 80% of food is converted into waste matter and about 3% of waste matter is converted into nitrogenous compounds, Gowen and McLusky (1988).

Computation of phytoplankton level

The approach used for calculating phytoplankton levels followed that outlined in Pridmore and Rutherford (1992).

$dB/dt = D(b-B) + uB$ where $B$ and $b$ are the spatially averaged phytoplankton concentrations in Boston Bay and Spencer Gulf. $D=Q/V$, $Q=exchange \ period \ of \ Boston \ Bay$, $V=volume \ of \ Boston \ Bay$ and $u$ is the specific growth rate of phytoplankton which is expressed as $u=u_{max} \ ((K-B)/K)$ where $K$ is the maximum phytoplankton concentration that can exist in a given embayment and is linked to dissolved nitrogen (N) level through the relation $K=0.086(N) - 0.25$.

The computation framework

The software program to perform the above calculations runs as a DOS program and consists of separate modules. Module FLOWC (after Bye, 1993) was used to calculate mass transport and flushing period of Boston Bay for mean monthly tidal amplitude and most frequently occurring wind speed. The
module FARM calculated dissolved nitrogen and phytoplankton levels. Figure 6.

The program allows the user to input tidal data, wind data, ambient dissolved nitrogen and phytoplankton levels (in this case, dissolved nitrogen = 8.68 mgm$^{-3}$, phytoplankton = 0.5 mgm$^{-3}$), annual stocking levels (500-5,000 tonnes), feed levels (Table 1), feed waste, feed waste to nitrogenous material conversion factor and percentage nitrogenous material uptake by the sediments. The output, consists of spatially averaged dissolved nitrogen and phytoplankton values. These data were compared with recommended ANZECC (1992) guidelines for dissolved nitrogen and phytoplankton to derive a mean and range of production levels in Boston Bay.

**Results and Discussion**

**The Exchange Period**

The mean exchange period was derived from mass

**Figure 6. Model structure.**
transport calculations across a section in the northern channel. The exchange period throughout the year varied between about seven and nine days.

**Nitrogen input to Boston Bay**

The amount of nitrogen released into Boston Bay varied throughout the year in proportion to the feeding regime. Figure 7a corresponds to a production level of 600 tonnes. The nitrogen level peaked in April.

![Graphs showing nitrogen input, dissolved nitrogen, and phytoplankton concentrations over months.](image)

*Figure 7. (a) Nitrogen input to Boston Bay. (b) Dissolved nitrogen as NO₃-N, (c) phytoplankton as chlorophyll-a.*
Dissolved nitrogen/phytoplankton levels

Peak dissolved nitrogen and phytoplankton concentrations in Boston Bay followed closely the levels of nitrogen input, Figure 7 b and c. For example, for production = 600 tonnes and waste to nitrogenous conversion factor = 0.024, the corresponding concentrations were about 35 mgm$^{-3}$ and 2.4 mgm$^{-3}$ respectively relative to ambient levels of 8.7 mgm$^{-3}$ and 0.5 mgm$^{-3}$. Simulations were carried out for cases where: (1) all nitrogenous compounds due to feed waste material were dissolved and (2) approximately 33% of nitrogenous material being taken up by sediments. Simulations corresponding to bay production levels between 500 and 5,000 tonnes per annum were conducted over a period of 360 days.

Boston Bay the bay was treated as an intermediate case between an embayment and coastal waters. Water quality guidelines for NO$_3$-N and chlorophyll-a (ANZECC,1992) were used to derive the environmental carrying capacity of Boston Bay. The results corresponding to dissolved nitrogen only and 33% uptake by sediments is shown Figure 8. The case for phytoplankton can be represented similarly.

![Dissolved Nitrogen vs Production](image)

*Figure 8. Estimate of sustainable fish production corresponding to 33% sediment uptake.*
The outcomes were, no sediment uptake; NO$_3$-N criterion, mean ECC=1,750 tonnes, range 1,300-2,400 tonnes. Chlorophyll-a criterion, mean ECC=1,600 tonnes. For a 33% sediment uptake; NO$_3$-N criterion, mean ECC=2,600 tonnes, range 2,000-3,400 tonnes.

**Residual levels**

Dissolved nitrogen and phytoplankton at the end of 360 day simulation period, after all fish were removed, showed an increase above ambient levels. For example, for an annual production level of about 1,700 tonnes, the residual values for dissolved nitrogen and phytoplankton were about 8.95 mgm$^{-3}$ and 0.52 mgm$^{-3}$ which represented an increase of about 2.9% and 4% per annum respectively with respect to ambient levels. Residual dissolved nitrogen and phytoplankton levels fell when stocking levels were reduced to zero by end of October, rather than November. The extra time was sufficient, from a numerical simulation point of view, for the bay to recover to near ambient levels.

The study provided one possible way of quantification of the environmental carrying capacity of Boston Bay using numerical models based on mean or bulk oceanographic processes in Boston Bay. Several aspects of the technique could benefit from further investigations. The validity of model outcomes will be provided by data collected by other programs presently on-going and planned for Boston Bay.

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