ASSESSMENT OF THE CARRYING CAPACITY OF BOSTON BAY SOUTH AUSTRALIA WITH A VIEW TOWARDS MAXIMISING THE SOUTHERN BLUEFIN TUNA RESOURCE

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EXECUTIVE SUMMARY

This report deals with determination of the "environment carrying capacity" of Boston Bay, South Australia. In this instance, the "environment carrying capacity" is defined as the maximum fish biomass which can be produced within a marine coastal system without exceeding recommended water quality guidelines specified for that system. The determination was carried out using two independent mathematical simulation techniques which incorporated physical and biological processes in Boston Bay. The water quality parameters used were dissolved nitrogen and phytoplankton. These have been proposed by the Australian and New Zealand Environment and Conservation Council (ANZECC) as being suitable water quality guidelines for estuarine and coastal waters environments. ANZECC (1992) guidelines for coastal waters recommended dissolved nitrogen (as NO_3-N) and phytoplankton (as chlorophyll-*a*) levels to be between 10-60 mgm^{-3} and about 1 mgm^{-3} respectively. For estuarine situations, dissolved nitrogen and phytoplankton levels were recommended to be 10-100 mgm^{-3} and 1-10 mgm^{-3}.

The hydrodynamics of Boston Bay was investigated using a two dimensional depth averaged model driven by monthly wind speed and wind direction and mean sea level data for Port Lincoln. Resultant water circulation patterns and mass transport calculations indicated that Boston Bay can be considered as a separate hydrodynamic unit de-coupled from Proper Bay. A combined numerical model, consisting of a model used in Big Glory Bay, New Zealand to simulate dissolved nitrogen and phytoplankton levels was combined with a two dimensional depth averaged tide and wind driven circulation model.

The exchange period for Boston Bay was derived from mass transport estimates using monthly data. The exchange period varied between about 7 and 9 days. The higher value of the exchange period occurred during summer to early autumn (December-March). The lower values of the exchange period occurred in mid late autumn to winter (May-July). The higher exchange periods experienced between summer and early autumn corresponded to periods when the water temperatures in Boston Bay are higher and the level of biological activity in the region may be greater than in the winter when water temperatures are lower and the exchange period is higher.

Simulations of dissolved nitrogen and phytoplankton were carried out for two cases: (1) all nitrogenous compounds formed as a result of feed and fish waste being dissolved in the water column and (2) approximately 33% of nitrogenous compounds being absorbed/adsorbed by sediments and about 66% left in the dissolved form. The simulations were conducted over a period of 360 days and spatially averaged dissolved nitrogen and phytoplankton concentrations were computed for Boston Bay as a function of annual fish production. Production varied between 600 and 4200 tonnes and simulations were carried out with respect to ambient levels of dissolved nitrogen and phytoplankton corresponding to 8.7 mgm^{-3} and 0.5 mgm^{-3} respectively.

Based on existing stocking regime in Boston Bay a peak in the level of nitrogenous compounds due to feed and fish waste occurred in April and corresponded to the peak in fish imports into Boston Bay in April.

Maximum values of dissolved nitrogen for zero uptake by sediments ranged between about 35 mgm^{-3} and 180 mgm^{-3} for fish production levels between 600 and 4200 tonnes. For the same fish production levels and including uptake by sediments the levels of dissolved nitrogen ranged between about 25 mgm^{-3} and 120 mgm^{-3}. The upper levels of simulated dissolved nitrogen are about an order of magnitude greater than reported from field surveys by South Australian Research Development Institute.

From a hydrodynamic point of view Boston Bay can be considered as an isolated system with only one opening to Spencer Gulf and therefore could be treated as an estuarine system. However, as a conservative approach, Boston Bay was considered to be intermediate between a coastal and estuarine system. Under these circumstances the ANZECC (1992) recommendations for NO_3-N for coastal (60 mgm^{-3}) and estuarine (100 mgm^{-3}) water quality criterion were used in an average mode to derive the following sustainable annual production levels.

	Mean environmental sustainable level	**Range**
NO_3-N criterion	1750 tonnes	1300-2400 tonnes
Chlorophyll-*a* criterion	1600 tonnes	upper 3100 tonnes

Simulation of dissolved nitrogen levels in Boston Bay incorporating a loss of approximately 33% of nitrogenous compounds (the particulate form) to the sediments were made. The corresponding environmentally sustainable production levels for an intermediate embayment-coastal waters classification were estimated to be

	Mean environmental sustainable level	**Range**
NO_3-N criterion	2600 tonnes	2000-3400 tonnes

Simulated dissolved nitrogen and phytoplankton levels at the end of the 360 day simulation period showed residuals which increased as a function of fish production levels. For an annual production level of about 1700 tonnes, which corresponded to an environmentally sustainable level, 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% with respect to ambient levels. Simulations were conducted to examine fish stocking factors which may favour reduction of dissolved nitrogen and phytoplankton residuals. It was found that if stocking levels were reduced to zero by end of October dissolved nitrogen and phytoplankton levels were reduced to within 1% of ambient levels in Boston Bay. After 330 days the levels of dissolved nitrogen and phytoplankton were reduced to 8.76 mgm^{-3} and 0.507 mgm^{-3} which represented an increase of 0.6% and 1.4% with respect to ambient respectively. In practice, detection of residual values of this magnitude would not be possible due to the wide variation in ambient levels of dissolved nitrogen and phytoplankton in Boston Bay.

An alternative approach using a mass balance model used in freshwater ponds but adapted to a marine application and based on Boston Bay being a nitrogen limited system was used to derive the carrying capacity of Boston Bay. The underlying assumption was that the carrying capacity of a body of water is dependant on the difference between the productivity of the water body prior to use and the final desired level of productivity. The model included a factor to account for sediment retention based on regression between flushing period and sediment retention. Simulations were performed for a number of food conversion ratio (FCR) values and for the following values of dissolved nitrogen, $N_{initial} = 20\ mgm^{-3}$, $N_{final} = 50\ mgm^{-3}$. The outcome was

FCR	**Production (tonnes)**
15:1	2597
20:1	1944
25:1	1554

Parallel with the numerical simulation of the carrying capacity of Boston Bay the development of a prototype telemetry logging system designed to measure water properties associated with tuna cages in Boston Bay was carried out and has led to completion of a successful working prototype system. The principal objectives were to design a system which can be used to measure critical water quality parameters (dissolved oxygen, water flow and stratification processes) associated with individual tuna cages. In addition to provision of real time data which may be used in farm management practices the system was designed for measurement of oceanographic and meteorologic parameters which can be used in real time numerical simulation of nutrient status in Boston Bay.

The present capability to measure wind strength, direction and water elevation and with the ability to relay such information to computer processing facilities provides a method which, in conjunction with tuna feed information, allows modelling of nutrient status in near real time.

The principle of design has been on simplicity and cost effectiveness through use of standard off-the-shelf data logging hardware coupled with commercially available state-of-art cellular communications system. The system was designed to be used in remote marine environment and has been manufactured accordingly including robustness, storm proof housing and solar panels. The development of prototype working system is estimated to be less than $10000.

The determination of the environmental carrying capacity of Boston Bay was carried out using numerical models driven by bulk wind (most frequently occurring) and tidal data. It is recognised that the models used are idealised and simplified representations of the environment and produced estimates of the oceanographic and biological processes in Boston Bay. Not withstanding this fact numerical models provide useful tools which can be used to estimate various processes and outcomes and highlight issues which require greater understanding. During the course of this investigation the following issues have emerged which could benefit from further investigation and therefore improve numerical simulation of carrying capacity of coastal aquaculture systems;

. the efficiency of fish feeding as a function of oceanographic/ meteorologic conditions to estimate feed loss to the seabed.

. the percentage and rate of feed waste conversion to nitrogenous compounds.

. the need to incorporate a lag in the numerical model.

. the significance of residual levels of dissolved nitrogen and phytoplankton in comparison to the variability of ambient levels in Boston Bay.

. the percentage of nitrogenous compound uptake by sediments.

. quantification of nutrient water quality standards for estuarine and coastal regions used for aquaculture.

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1.0 Introduction

Aquaculture is an increasing use of coastal resources in South Australia. In Port Lincoln, Figure 1, the principal focus of aquaculture is cage culture of southern bluefin tuna *(Thunnus maccoyii)*, Bond (1993). The methods used in tuna farming in Port Lincoln include use of large, approximately 30-50 metre diameter, open water sea-cages into which captured tuna are grown to commercial size. Fish are generally hand fed a pilchard/mackerel/vitamin mixture. Based on experience with salmon farming, particulate wastes from fish cages consist of uneaten food and faecal material some of which is lost in the water column by dissolution and settlement to the seabed, Gowen et al (1988).

It is generally accepted that cage farming of fish is a significant source of nutrients, solids and other waste products (Seymour and Bergheim ,1991). Intensive fish culture can result in the production of wastes which can promote growth of algal communities and alter the biotic characteristics of the water body. This can alter the value of a resource to other users and to the fish farmer. Serious degradation of water quality can stress or even cause mortalities amongst fish stocks and encourage disease organisms to thrive. Hence profitability or even viability of an industry can be affected. It is important that information regarding sustainable levels of fish, consistent with recommended levels of water quality for a given coastal system, can be made which can be used by managers as guidelines for production levels.

The primary source of dissolved nitrogen associated with fish farming is due to fish feed and faeces . The nutrient, including dissolved nitrogen, pathways associated with fish feed for salmonoid farms were considered by Gowen and McLusky (1988), Figure 2. The following division of fish food is suggested, Gowen and Bradbury (1987).

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

That is, approximately 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). In Australian marine waters adjacent to the coast, NO_3-N concentrations can range between 16 mgm^{-3} and 56 mgm^{-3} and NH_3-N concentrations generally less than 3 mgm^{-3} (ANZECC). For purposes of this investigation dissolved nitrogen will be assumed to be of the form NO_3-N

1.1 The concept of carrying capacity

1.1.1 Background

Despite much debate and proliferation of coastal zone policies and water quality guidelines 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)

In this instance, the term "environmental carrying capacity" is advanced as an appropriate concept and is defined as maximisation of tuna biomass in Boston Bay without exceeding recommended water quality parameters for Boston Bay. The 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 recommend 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 are 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 through the northern entrance suggest a coastal regime.

The approach taken in this investigation is based on the use of computer modelling techniques to calculate dissolved nitrogen and phytoplankton concentrations with respect to ambient levels in Boston Bay as a function of tuna stocking levels. The resultant levels of dissolved nitrogen and phytoplankton levels were compared with ANZECC (1992) recommended levels to derive environmentally acceptable production levels.

1.2 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. A modelling package called 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, called 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. Figure 3. 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 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, it must be remembered that 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 consequently it was necessary to develop new modelling techniques.

2.0 PHYSICAL ASPECTS OF BOSTON BAY

2.1 Description of the Bay

Boston Bay is a shallow, maximum depth of about 16-17 metres, north-south aligned bay approximately 15 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 a channel about 4 km wide located north of Boston Island. Boston Bay is physically connected to the relatively shallower Proper Bay and Spalding Cove and Spencer Gulf. Figure 4.

2.2 Wind Regime of the region

The annual wind regime of the Boston Bay was derived from Bureau of Meteorology wind records for Port Lincoln Post Office. Table 2. Wind strength-direction matrices for 0900 hrs and 1500 hrs were examined to obtain representative wind regimes for January, April, July and October. These months represented mid summer, mid autumn, mid winter and mid spring periods respectively.

2.2.1 Summer conditions

The dominant wind direction in the morning and afternoon during the summer 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}) with less than 1% exceeding fresh breeze conditions (> 38kmh^{-1}). Approximately 1-2% of the time, and mostly in the mornings, calm periods prevail over the region.

2.2.2 Autumn conditions

During the mornings the dominant wind direction is from the west (15%) and south-west (11%). In the afternoons the winds maintain a westerly aspect (13%) in addition to east-south-easterlies (11%). During the mornings a relatively (9%) large number of calm periods occur, by the afternoon the number of calm periods are less than 2%. For about 75% of the time the winds are gentle breezes (< 18 kmh^{-1}). Less than 1% of the time winds approach near gale (60 kmh^{-1}) conditions.

2.2.3 Winter conditions

In the mornings winds are from the west (18%), north-west (11%) and north (11%). In the afternoons, the dominant wind direction is from the north-west (15%) and south-west (14%). In the mornings the winds are gentle breezes (< 18 kmh^{-1}) for about 78% of the time with less than 1% exceeding strong breeze (40 kmh^{-1}) conditions. In the afternoon the winds are gentle breezes for about 72% of the time with less than 1% exceeding near gale (60 kmh^{-1}) conditions. The number of calm periods in the morning are about 7% and in the afternoon about 3%.

2.2.4 Spring conditions

East-south-east (13%) and south-west (12%) winds are present during the mornings whereas south-west winds (34%) dominate in the afternoon. In the mornings, about 63% of the winds are gentle breezes (<18 kmh^{-1}) and with about 1-2% near strong breeze (40 kmh^{-1}). In the afternoons a large amount (72%) of the winds are gentle breezes with about 2-3% of the winds approaching strong breeze (40 kmh^{-1}) conditions. In the mornings the number of calm periods are about 10% whereas in the afternoon the number of calm periods are only about 1-2%.

2.3 Gale strength wind events

Gale strength winds can occur in the region, these winds are defined as wind speeds greater than 60-72 kmh^{-1}. These are referred to as Force 8 winds on the Beaufort wind scale.

Analysis of wind speed-direction data from the Port Lincoln Post Office observation station up to 1973 indicated that 93% of Force 8 or greater winds were north-westerlies while about 7% were north-easterlies. The largest number (79%) of Force 8 winds occurred in the spring, 14% in the summer and 7% in the winter.

2.4 Wave regime in Boston Bay

Force 8 wind speeds were used to illustrate typical significant wave heights and periods that may be experienced in Boston Bay under these conditions. The fetch lengths are representative distances that may be experienced during the wind conditions listed.

Wind Duration =3 hours (assumed)

Wind Direction	**Wind Strength** (kmh^{-1})	**Fetch Length** (kms)	**Significant Wave Height** (metres)	**Significant Wave Period** (secs)
South west	60	15	1.46	4.7
North west	60	15	1.46	4.7
North east	60	200	2.1	5.7

2.5 Currents in Boston Bay

Current speeds in Boston Bay are highly spatially variable (Petrusevics et al, 1993). Figure 5. For example, based on current meter deployments during winter of 1993 west, south and east of Boston Island it was found that currents in the region between Boston Island and the mainland were the weakest. In this region, maximum current speeds were found to be about 12 cms^{-1} for less than 1% of the time. Majority (91%) of current speeds were less than 5 cms^{-1}. Major (33%) direction of flow in this region was in a south-westerly direction.

The currents on the eastern side of Boston Island were stronger than on the western side of the island. In this region maximum current speeds attained were 17.5-20 cms^{-1}, however such speeds occurred for less than 0.05% of observations and the majority (42%) of current speeds were in the range 2.5-5.0 cms^{-1}. The dominant (27%) direction of the currents were south-westerly

The strongest currents recorded during the period of the survey were found south of Boston Island where maximum currents in excess of 27.5 cms^{-1} were measured. However the majority (65%) of current speeds were in the range 2-10 cms^{-1} . The major direction of flow was west south-west (32%) and east north-east (29%).

Analysis of current records indicated that large non-tidal residuals were present. For example, in excess of 50% of the observations from the three sites showed non-tidal components which are likely to be attributed to wind.

2.6 Temperature-salinity properties.

Temperature-salinity surveys conducted in Boston Bay during August 1992 (Petrusevics et al 1993) and March 1993 (Petrusevics pers com.) indicated that the water column was well mixed both vertically and horizontally.

Typical mean mid winter temperature and salinity values were 13°C and 35.75 ppt respectively. Corresponding values for late summer were about 20°C and 36.70 ppt

3.0 MODELLING METHODOLOGY

3.1 Delineation of the hydrodynamic boundaries of Boston Bay

Water circulation patterns in Boston Bay and Proper Bay were examined using the numerical model FLOW described by Bye (1977). This was done to examine the degree of hydrodynamic coupling between Boston Bay and Proper Bay and thus delineate the southern boundary of the Boston Bay model. For example, if the degree of hydrodynamic coupling between the two bays was large then it would be necessary to treat Boston Bay and Proper Bay as one isolated unit. There had not been any previous studies attempted to address this matter. The area considered is shown in Figure 4. The seaward boundary of the model was a line from Point Boston, passing through the centre of Boston Island to Stamford Hill.

3.2 Modelling the carrying capacity of Boston Bay

3.2.1 The Coupled model

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 by Bye (1977).

The various processes in the coupled model are shown in Figure 6. Boston Bay is considered as an isolated system which is well mixed. Conductivity-temperature-depth surveys conducted by the South Australian Department of Fisheries (Petrusevics, pers com) in winter 1993 and summer 1994 indicated that the region was well mixed vertically and laterally. Nutrient loading to the system is assumed to derive from feed waste and excreted material from the fish in cages. Removal of nutrients from the bay occurs primarily due to the flushing action of the bay.

Monthly stocking numbers in Boston Bay were derived from information supplied by the tuna farming industry. Table 1. The monthly stocking information was used to calculate monthly food consumption levels which provide, through conversion factors outlined in section 1.0 above, the amount of available nitrogen within the model domain. Portion of the available nitrogen, considered to be in the form NO_3-N, was assumed to be dissolved in the water column and portion taken up by the sediment.

The flushing action of the bay is caused by tidal and wind action. The flushing period, defined as the time required for renewal of the volume of the bay, was calculated using monthly wind speed data. Bureau of Meteorology surface wind analysis data, Table 2, were used to derive monthly values of most frequently occurring wind speeds and most frequently occurring wind direction corresponding to observations at 1500 hrs at the Port Lincoln Post Office. Table 3.

The model was run for a period of 360 days, with monthly averaged feed, wind and tidal data as input. The output, consisted of _spatially averaged_ dissolved nitrogen and phytoplankton values. These data were compared with ANZECC (1992) guidelines for dissolved nitrogen and phytoplankton to derive a mean and a range of production levels in Boston Bay.

3.3 Computation of volume exchange period

Model FLOW was used to calculate exchange periods for the model domain for representative monthly tidal and wind conditions. The volume exchange was derived from mass transport computed across the seaward boundary of the model domain. Mass transport data in conjunction with the surface area and mean depth data from Boston Bay allowed exchange periods to be calculated

3.4 Computation of dissolved nitrogen levels

The computation of dissolved nitrogen levels involved input of exchange period data derived from model FLOW into a sub-model called FARM which was used to compute spatially averaged levels of dissolved nitrogen in Boston Bay. Simulations 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 (pers com.,1996)

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

The simplified mass balance model is

$$V\,dN/dt = I - QN + QN_0$$

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. The time dependent solution was used to calculate dissolved nitrogen levels in Boston Bay.

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

This relationship between observed concentration of nitrogen and chlorophyll-*a* was based on data from a number of marine and freshwater publications which were analysed by Pridmore and Pritchard (1992) and are available on request.

Chlorophyll-*a* levels reported for Boston Bay from surveys conducted during 1991 and 1992 by the South Australian Research 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 using the regression recommended by Pridmore and Pritchard (1992) was = 8.68 mgm^{-3} .

These values are in reasonable agreement with spatially averaged values 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 for dissolved nitrogen of 5-11 mgm^{-3} (ANZECC, 1992)

The nitrogen input to Boston Bay (I) was obtained by use of the empirical relationship;

Nitrogenous compounds = Tuna feed quantity x 0.024

This 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).

3.5 Computation of phytoplankton level

The approach used for calculating phytoplankton levels followed that outlined in Pridmore and Rutherford (1992). It is based on the differential equation

$$dB/dt = D(b-B) + uB$$

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 computational procedure for calculation of dissolved nitrogen and phytoplankton levels involved incorporation of the analytical solutions for determination of dissolved nitrogen and phytoplankton outlined above into a sub-model called FARM. The sub-model incorporated facilities which allowed the fish production level, food consumed by the fish and waste food to nitrogenous compound conversion factor to be set. The exchange period generated by the main model FLOW was linked to model FARM. For each time step, the exchange period generated by the main model was used to calculate dissolved nitrogen and phytoplankton levels with respect to ambient levels which were set to dissolved nitrogen = 8.68 mgm^{-3}, phytoplankton = 0.5 mgm^{-3}.

3.6 Simulation variables

Computer simulations were performed for a range of fish production levels ranging between 600 and 4200 tonnes in 300 tonne increments. The stocking regime listed in Table 1 was used. The simulation period was 360 days.

3.7 The Mass Balance Model

An alternative approach to investigate the carrying capacity of Boston Bay involved use of a mass balance model reported by Beveridge (1984) for freshwater ponds but adapted in consultation with the author to a marine application. The underlying principle adopted in this method is the assumption that the carrying capacity of a body of water depends on the difference between the productivity of the water body prior to use and the final desired level of productivity. Beveridge (pers com, 1995) indicated that this method was suitably applicable to marine embayments for either nitrogen or phosphorus limited nutrient situations.

Primary production growth rates are determined by a variety of factors, including light, temperature and nutrient supply. The amount of plant growth is limited by the factor which is in least supply, which leads to the concept of a limiting nutrient factor. In the case of Boston Bay, the limiting factor is not clearly defined. The temperature range is not small (12-20°C) and the waters are not clear, typical Sechi disc depths vary between 5-8 metres in total depths 12-15 metres. In the event where growth is not limited by temperature or light the nitrogen to phosphorus ratio may provide an indication of the limiting nutrient. As general rule, if the N:P ratio is greater than 20:1 the system is limited by phosphorus, and if less than about 16:1, it is limited by nitrogen (ANZECC, 1992)

Water quality surveys conducted in Boston Bay by SARDI during 1992-1993 indicated that the system appeared to be nitrogen limited. However this is not entirely conclusive. There is increasing opinion (ANZECC, 1992) that the use of N:P ratios is inappropriate or the limitations have not been sufficiently considered. A number of factors have been advanced which suggest that caution should be exercised in using N:P ratios. These concerns include the assumption that the cellular composition of phytoplankton is relatively constant and that the cellular N:P ratio is about 16-20:1 for optimum growth. There is opinion that the ratio may have greater limits and it has been suggested that the N:P ratios can range between 7 and 87 for optimum growth of about 14 freshwater and marine phytoplankton types, (ANZECC, 1992).

There is also some degree of uncertainty what measures of nitrogen and phosphorus should be used in calculating N:P ratios. Most commonly the ratio of total-N and total-P is used. However the critical ratio is the ratio of algal available nitrogen to algal available phosphorus (aN:aP). In turbid coastal waters estimation of these quantities that are available to algae and under what conditions is difficult to assess.

In this case, the mass balance considerations were conducted for a nitrogen limited case. The model is based on the assumption that the concentration of nutrient within an embayment is determined by the nutrient loading, the volume of the embayment, the flushing rate and the fraction of nutrient lost to the sediments

The general form of the model is

$[N] = L\,(1 - R)\,/\,z\,F$ Beveridge (1984)

$[N]$ = Nitrogen concentration of embayment gm^{-3}

L = total N loading $gm^{-2}yr^{-1}$
z = mean depth in metres
R = fraction of N retained by sediments and
F = flushing rate (the number of volumes per year)

Step 1

To determine the potential of a coastal embayment for aquaculture the productivity of the water body prior to use by industry must be assessed through knowledge of the steady state nutrient concentrations.

In the case of Boston Bay, water quality surveys conducted by the Engineering and Water Supply Department (1989) between 1970-1988 provided an indication of nitrogen concentrations levels for the pre-tuna farm industry period.

Typical mean $N_{initial}$ values were

NO_3-N <20 mgm^{-3} (North Shields and Fanny Point)

For purposes of this investigation it was assumed that NO_3-N levels were equal to 20 mgm^{-3}

Step 2

The carrying capacity of an embayment for intensive cage culture is the difference between the productivity of the water body prior to use and the final desired level of productivity. It is difficult to recommend a single set of nitrogen concentrations that will prevent production to the extent where phytoplankton blooms occur. Recommended concentration levels can only be used as indicators of levels at or above which problems have been known to occur (ANZECC,1992).

Values for nitrogen concentration can be site specific. For Boston Bay, to date, there are no guidelines to the levels of dissolved nitrogen, for example, that are tolerable to maintain a desired level of productivity. It is also recognised that the values used in the following simulation may not be entirely representative of average values for the bay, however in the absence of spatially averaged values they represent best approximations.

Value chosen for N_{final} was

NO_3-N= 50 mgm^{-3} This value was recommended by Beveridge (1984) for intensive salmonoid culture and represents a value below the maximum dissolved nitrogen level (60 mgm^{-3}) recommended by ANZECC (1992) for coastal waters.

Step 3

The carrying capacity of a water body is the difference dN between initial value, $N_{initial}$, of the water body prior to use and final acceptable value, N_{final} .

$dN = N_{initial} - N_{final}$

dN is related to nutrient loadings from the fish enclosures L_{fish}

$dN = L_{fish} \times (1-R_{fish}) / z F$

F = the flushing period of the water body; R_{fish} = the fraction of the loading from the fish enclosure retained by the sediments, .

therefore $L_{fish} = dN z F / 1-R_{fish}$

Multiple regression analysis of data from temperate water bodies indicated that the retention factor R and flushing period F are highly correlated by the approximation

$R = 1 / 1 + (0.747 F)^{0.507}$

Consequently the loading L_{fish} associated with fish enclosures can be calculated.

Step 4

Once the acceptable total loading for the area of the water body has been calculated then the intensive cage fish production, tonnes per year, can be estimated by dividing L_{fish} by the average nutrient value associated with wastes per tonne of fish production.

4.0 RESULTS AND DISCUSSION

4.1 The hydrodynamic boundary of Boston Bay

The results of simulations of water movement patterns in Boston Bay and Proper Bay corresponding to peak (3 hours after low tide) flooding tide and peak ebbing tide (3 hours after high tide) for the summer (January-March) are shown in Figure 7 and Figure 8 respectively. The regions of strongest currents occurred in the northern and southern channels where depth averaged current speeds up to 25-30 cms^{-1} can be noted. The current speeds in Boston Bay are appreciably lower (5 cms^{-1} or less). A significant and important region of current divergence (and divergence) was noted in the southern portion of Boston Bay. The feature can be identified clearly in the region of row 22 in Figure 7 and 8. This represents a watershed phenomena where the currents are small, less than 5 cms^{-1} in magnitude, and flow in opposite direction. This phenomena occurs as a result of meeting of two tidal fronts entering Boston Bay through the northern and southern entrances and creating a watershed phenomena in the southern region of the bay. This has been observed in other locations, for example in Barker Inlet-Port Adelaide River where a similar phenomena referred to as the "partings" has been reported (Petrusevics, 1986; MFP, 1996)

The simulations were conducted with a tidal amplitude of about 1 metre and wind strength of 15 kmh^{-1}. For these conditions, the effect of tides is more significant than the effect of winds. The region of the watershed or "partings" in southern Boston Bay emerged as feature previously not reported and acts to effectively separate Boston Bay, in a hydrodynamic sense, from the rest of the waters in the region including Proper Bay.

The persistence of this phenomena throughout the year was examined by conducting simulations for tidal and wind speed data specified in Table 3 to examine seasonal trends. The results corresponding to wind conditions to April (easterly); May-September (westerly); October-November (south-westerly) and December (southerly) are shown in Figure 9 to Figure 12 inclusively. Excepting for minor changes in the current direction associated with low current speeds, the main features of water movement in the region, including the watershed phenomena in the southern portion of Boston Bay remain unchanged. This confirmed that for purposes of modelling, Boston Bay may be treated as a separate hydrodynamic unit for mean seasonal conditions.

For oceanographic (1 metre tidal amplitude) and meteorologic (approximately 15 kmh^{-1}) the degree of coupling between Boston Bay and the remaining waters of the region was calculated by computing the mass transport at various sections in the model domain. It was found that about 40% and 60% of the combined Boston Bay-Proper Bay region waters flow through the northern and southern entrances but only about 14% of the flow through the southern entrance can be attributed to outflow from Boston Bay. Figure 13.

Based on the water movement patterns and estimate of mass transport a reduced model domain was defined which covered only the region of Boston Bay north of the watershed. Computer simulations were conducted for this region for tidal and wind conditions identical for simulations on the combined Boston Bay-Proper Bay region. The resultant simulation for summer (January-March) is shown is shown in Figure 14.

Apart from a minor diference in current speeds at the southern boundary, the overall water movement pattern and magnitude of the currents in the region is similar to that obtained for Boston Bay region previously. Figure 8.

As a result of these findings, the region north of the watershed feature in Boston Bay was used for subsequent carrying capacity simulations. Figure 15.

4.1.1 The influence of wind on currents in Boston Bay

Varying reports on the influence of wind on currents in Boston Bay have been made.
In analysis of current meter data from deployment of current meters at three sites around Boston Bay, Petrusevics (1992) reported that some records showed residuals (observed data-predicted data) as high as 50% of the observed values. This was particularly noticeable in records of current meter deployed inside Boston Bay. Analysis of the source of the residuals is being investigated and it is suspected that a large portion of the residuals may be accounted by wind. Stevens (1995) reported that from numerical simulation of depth averaged currents over a two day period at a site east of Boston Island wind did not have an important effect on currents in the region.

The relative importance of wind on currents in Boston Bay can be estimated from dimensional analysis approach using a one dimensional equation of flow. In this case Boston Bay can be considered as a channel and the main driving forces for currents are the surface slope and the surface stress. These terms are given by

Surface slope = g A x Rate of change of elevation with distance

where g = acceleration due to gravity= 10 ms^{-2}
A = Channel cross-section=25000 m^2

Assume a 1 metre tide range with a phase difference of 10 minute between the northern and southern sections of Boston Bay a distance of about 10 kms. The water level changes approximately by 0.16 mh^{-1}. Hence a lag of 10 minutes represents 0.026 metres over a distance of 10km.

Thus surface slope= 10 x 25000 x(0.026/10000)

$$= \underline{6.5 \times 10^{-1}}$$

The wind stress $F_w = T_s / p_w$

where T_s is surface stress and p_w is the water density

$T_s = p_a C_d W^2$ where p_a =density of air, C_d =drag coefficient and W wind speed

For a wind speed of 20 knots (10 ms^{-1})

$$T_s = 1.3 \times 1.4 \times 10^{-3} \times 10^2$$

$$= 1.8 \times 10^{-1}$$

Therefore $F_w = 1.8 \times 10^{-1} / 10^3$

$$\underline{1.8 \times 10^{-4}}$$

For the range of tide and wind speeds considered, dimensional analysis indicated that water elevation has at least three orders of magnitude greater effect on currents than wind stress. As the tidal amplitude decreases and wind speed increases the effect of the wind will be greater. This will be pronounced during storms and time of dodge tide conditions in Boston Bay. For example, the effect of a strong easterly wind of 45 kmh^{-1} and ebbing tide of 0.2 amplitude is shown in Figure 16. In this case the watershed feature can be noted however the magnitude of the currents are reduced as a result of the easterly wind stress on the water column. The effect of zero tidal amplitude and same wind speed and direction as in previous example resulted in wind driven circulation, including anti-clockwise gyres being set up in northern Boston Bay and Proper Bay. Figure 17.

4.2 The Exchange Period

The exchange period of the re-defined Boston Bay region was computed by calculation of the mass transport across a section between Boston Point and Boston Island. The exchange period was determined for mean monthly wind speed, direction and tidal data as shown in Table 3.

For the specified wind and tidal conditions, the exchange period of Boston Bay varied throughout the year between about 7 and 9 days. Figure 18. The larger value of the exchange period occurred during summer to early autumn (December-March). The smaller values occurred in mid late autumn to winter (May-July). The larger exchange periods experienced between summer and early autumn correspond to periods when the water temperatures in Boston Bay are higher and the level of biological activity in the region may be greater than in the winter when water temperatures are lower and the exchange period is greater.

4.3 Nitrogen input to Boston Bay

Figure 19, illustrates the general nature of the distribution of nitrogen released into Boston Bay as a result of the feeding regime indicated in Table 1. Due to fish import levels peaking in April a corresponding peak in the level of nitrogen in Boston Bay can be noted to occur in April. The close correspondence of nitrogen levels in Boston Bay and the number of fish imported is due to zero lag in the model. This is a an inherent property of the present model and may be contrary to what occurs in practice, where a delay between input of waste into Boston Bay and formation of nitrogenous compounds occur.

4.4 Dissolved nitrogen/phytoplankton simulations

Simulation of dissolved nitrogen and phytoplankton concentrations in Boston Bay follow closely the levels of nitrogen input as a result of waste food. The levels of dissolved nitrogen and phytoplankton shown illustrate the general shape of the distribution that was found for a range of production values between 600 and 4200 tonnes. The major difference in subsequent simulations at different values of fish production was the value of the maximum dissolved nitrogen and phytoplankton concentrations attained. The results shown Figure 20 and Figure 21 corresponded to a production level of 600 tonnes and waste to nitrogen conversion factor of 0.024 as outlined in section 1.0. The resultant maximum level of dissolved nitrogen and phytoplankton concentrations in this case were about 35 mgm^{-3} and 2.4 mgm^{-3} respectively. These levels, as were all subsequent simulations for different production levels, relative to ambient levels of 8.7 mgm^{-3} and 0.5 mgm^{-3} of dissolved nitrogen and phytoplankton.

Simulations were carried out for two cases: (1) all nitrogenous compounds formed as a result of feed waste and fish waste being dissolved in to the water column and (2) approximately 33% of nitrogenous material being absorbed/adsorbed by sediments and about 66% in the dissolved form. In both cases the simulations were conducted over a period of 360 days to determine the maximum value of dissolved nitrogen and phytoplankton.

The classification of Boston Bay either as an embayment or open coastal water system is subject to debate and requires stricter interpretation. From a hydrodynamic point of view Boston Bay can be considered as an isolated embayment with only one opening to Spencer Gulf. However, as a conservative approach Boston Bay was considered to be an intermediate case between the embayment and coastal waters classification cases. Under these conditions water quality guidelines intermediate for NO_3-N and chlorophyll-*a* recommended by ANZECC (1992) for coastal and estuarine waters were used to derive sustainable annual production levels. Figure 22 and Figure 23.

The outcomes are summarised below

	Mean environmental sustainable level	**Range**
NO_3-N criterion	1750 tonnes	1300-2400 tonnes
Chlorophyll-*a*	1600 tonnes	upper 3100 tonnes

4.5 Allowance for sediment losses

A factor of approximately 33% was used to allow for losses to the sediments of nitrogenous compounds formed as result of waste loading to Boston Bay. The resultant maximum levels of dissolved nitrogen corresponding to this condition, together with the no-sediment loss case, are shown in Figure 24. The corresponding environmental sustainable annual production range for an intermediate embayment-coastal waters classification was estimated to be

	Mean environmental sustainable level	**Range**
NO_3-N criterion	2600 tonnes	2000-3400 tonnes

4.6 Residual levels

The levels of simulated dissolved nitrogen and phytoplankton at the end of 360 days are shown in Figure 25 and Figure 26. The levels showed an increase as a function of fish production levels. For an annual production of about 1700 tonnes, which corresponds to an environmentally sustainable level, the residual values for dissolved nitrogen and phytoplankton were about 8.95 mgm^{-3} and 0.52 mgm^{-3} which represents an increase of about 2.9% and 4% per annum respectively. Presence of residual values suggests that production levels need to be reduced marginally if the production levels are to be kept within environmental water quality guidelines.

Simulations were conducted to determine conditions which may favour reduction of dissolved nitrogen and phytoplankton residual levels. It was found that if stocking levels were reduced to zero by end of October the dissolved nitrogen and phytoplankton levels were within close to ambient levels at the end of the year. For example, the levels of dissolved nitrogen and phytoplankton were reduced to 8.76 mgm^{-3} and 0.507 mgm^{-3} which represents increase with respect to ambient of 0.6% and 1.4%.

4.7 Mass balance model simulations

Area of Boston Bay = 60×10^{6} m^{2}
Mean depth Boston Bay = 10 metres
Food Conversion Ratio = Variable 15:1-25:1
N content of food = 50kg per tonne
Mean flushings = 45 $year^{-1}$
Sediment retention factor = 0.14

Beveridge (1984) showed that the sediment retention factor is highly correlated to the flushing period by the approximation $R = 1 / 1 + (0.747\ F)^{0.507}$. This relationship, in the absence of sediment retention values for Boston Bay, was used to calculate a sediment retention factor.

Simulations were performed for a number of food conversion ratio (FCR) values and for the following values of dissolved nitrogen.

$N_{initial}$ = 20 mgm^{-3}

N_{final} = 50 mgm^{-3}

FCR	**Production(tonnes)**
15:1	2597
20:1	1944
25:1	1554

4.8 Comparison of Boston Bay water quality criterion

The water quality criterion used for Boston Bay to derive environmentally sustainable production levels can be compared to the water quality standards used elsewhere in Australia. For example, the water quality standards used for the Marmion Marine Park (MMP) located north of Perth. The dimensions of this region (5 km x 10 km), and (mean depth, 10 metres) are similar to that of Boston Bay. Flushing of the MMP is effected by mass transport across two boundaries similar to that of Boston Bay. In the case of the MMP a series of water quality criterion have been adopted which relate to various levels of ecosystem health.

For dissolved inorganic nitrogen (DIN) and chlorophyll a the following levels were adopted for the condition of the MMP ecosystem in the summer.

Ecosystem Condition	**DIN** **mg^{-3}**	**Chlorophyll a** **mg^{-3}**
Background	13-23	0.4-1.2
Healthy Level 1	20-30	0.6-1.5
Healthy Level 2	25-40	0.7-2.0
Mildly Degraded	30-60	1.0-2.5
Moderately Degraded	40-100	2.0-5.0
Grossly Degraded	60-180	5.0-20.0

For Boston Bay a value of NO_3-N between 50-80 mgm^{-3} was used in setting an acceptable water quality level. This classifies Boston Bay in the category of a mildly-moderately degraded or in a mesotrophic condition.

In general, there are few published surveys of nutrient concentration in estuarine and coastal regions of Australia. Survey of nutrient concentration in Cockburn Sound, Western Australia , during summer of 1989-90 found mean NO_3-N concentrations in the range 5-11 mgm^{-3}. Considerable spatial variation in nutrient concentration in Australian marine waters has been reported, for example, NO_3-N concentrations between 16-56 mgm^{-3} are common ANZECC (1992). The level adopted for setting water quality standard for Boston Bay appears reasonably valid in light of water quality levels recommended for other similar type of coastal eco-systems.

This study has provided quantification of the carrying capacity of Boston Bay using numerical models which are based on mean or bulk oceanographic and biological processes in Boston Bay. The test of the model outcomes will be provided by data collected by other programs presently on-going and planned for Boston Bay.

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APPENDIX A

APPENDIX A

THE DEVELOPMENT OF A CELLULAR PHONE BASED TELEMETRY SYSTEM TO MONITOR TUNA CAGE WATER QUALITY

A1. Overseas experience on the need to monitor aquaculture impacts

The majority of information cited in the following text refers to experience in Europe and mainly with salmonoid aquaculture. The following information reflects issues encountered by overseas organisations with respect to the aquaculture industry. The information provides a suitable framework from which important water quality parameters requiring monitoring were identified. This information was particularly useful in considerations for development of a remote logging monitoring system for Boston Bay, a region of expanding aquaculture industry.

An assessment of the compatibility between fish farming and the Norwegian coastal environment was made by Raa (1992). Pollution from industry, sewage systems, and agriculture was identified a threat to commercial fish farming. The process of fish farming itself has environmental impacts. In sheltered bays sludge depositions under the cages have been observed. If the sediment also contains residual antibiotics, bacterial pathogens resistant to antibiotics may develop. The use of antibiotics can be reduced by prophylactic actions; proper management and operation. New and robust cage systems have made it possible to move farms from sheltered bays to more exposed localities. Combined with improved feed composition and feeding routines, the problem with sludge deposition has been reduced. In Norwegian coastal water, phosphorus, nitrogen and organic matter released from fish farms was compared with the loads from decomposition of roe and milt from wild stocks of fish, and nutrients from industrial, domestic and agricultural discharges. Feed for farmed fish was mainly a marine origin. Nutrients from land-based activities transported from the German Bight and the Baltic Sea appeared to alter the concentration ratio of nitrogen to phosphorus in southern Norwegian coastal waters. A shift in this ratio favoured growth of some algae species and increased toxin production.

Hensey (1992) reported that with the introduction of the first large-scale salmon farm on the west coast of Ireland in 1984, environmental monitoring requirements were imposed by local authorities. A program was set up to carry out sampling as a base-line prior to the introduction of fish and later for continuous monitoring at the site. As well as providing the required data for the government, the monitoring provided the salmon farmers valuable information. Parameters measured included temperature, salinity, transparency, oxygen, ammonia, chlorophyll, phytoplankton counts, and nutrients.

Impacts of aquaculture on surrounding sediments were considered by Holmer (1992). Fish farming generates large amounts of particulate organic waste products, and surrounding sediments are affected by this surplus of organic matter. The extent of impacts was determined from the **quantity and quality of the input and environmental conditions** at the location. The affected area was often limited to the immediate vicinity of the farm.

Development of organic-rich sediments resulted in changes in benthic fauna community structure towards impoverished fauna populations, and the decomposition of organic matter become more dependent on microbial activity. Fish farm sediments were reduced and anaerobic mineralisation processes became important. The cycling of nutrients and other elements was rapid, and the efflux from these sediments to the water column was high. The natural seasonal cycling of elements was disturbed. Use of antibiotics against diseases in the farms developed resistant bacteria in the sediments and the microbial activity was reduced for a long time after medication. Surrounding sediments were subjected to significant alterations due to fish farming.

Braaten (1992) reported on the impact of pollution from aquaculture in six Nordic countries. During the last 20 years fish farming has developed into a major industry in the Nordic countries, with Norway as the leading country. The Norwegian sales statistics constituted 63% of a Nordic production of 190 000 tonnes in 1989. Denmark was the second biggest and produced 17%, followed by Finland 11%, and Sweden 4%, Faroe Islands 4%, and Iceland 1%. The gross production, which is the basis for pollution, was estimated at 272 000 tonnes. Atlantic salmon is the dominating species (Norway, Faroe Islands, Iceland), but production of rainbow trout is equally important in Sweden and dominated in Finland and Denmark. A total amount of 3 523 tonnes of phosphorus and 19 262 tonnes of nitrogen was released in the region in 1989. In addition, a variety of chemicals including antibiotics, organophosphates, disinfectants, antifouling agents, chemicals for water treatment and anaesthetics were released from each country.

Eutrophication from fish farming was estimated to be a small problem on the west coast of Norway, Iceland, and the Faroe Islands, although local problems did arise in narrow fjords and enclosed areas. Overloading of nutrients was considered to be a major problem in the Baltic, the Belts and parts of Skagerrak and Kattegat. Sedimentation below net-pens affected the bottom fauna, and created anoxic sediments in all areas with insufficient water exchange. Oxygen deficiency in the bottom water was a potential problem in fjords with a narrow sill. Release of antibiotics and chemicals was considered to be a serious environmental threat to both the wild stocks of fish, and the bottom fauna. Studies showed that oxytetracycline and oxolinic acid were practically undegradable in sediments, and 60-98% of the chemicals were not absorbed by the gut of the fish. The amounts of nutrients released per tonne of fish produced are decreasing due to improved diets, feeding technology, and stricter governmental regulations. The use of antibiotics and some chemicals seemed to be a necessity, but were reduced by increased use of vaccines, improved husbandry practice, reduced fish density, and overall attention to environmental and hygienic conditions. The introduction of a landbased technology made it possible to reduce the output of organic material both from smolt- and production farms. New methods of collecting surplus food and dead fish were developed. Overfeeding was monitored and controlled by sonic equipment. The environmental problems caused by fish farming were different in the Nordic countries due to geographical, topographical, and physical conditions.

Toxicity and excretion of nitrogenous compounds by marine fish were reported by Handy and Poxton (1993). Dissolved oxygen (DO) levels > 90% saturation, water pH values between 6.0 and 9.0 depending on the cultured species, and concentrations of suspended solids below 15 mg/l are preferable in culture systems. Sufficient water flow (volume per unit time) through the system is also required to minimise the deleterious effects on water quality of oxygen consumption, carbon dioxide and ammonia excretion by the fish.

The environmental effects of aquaculture manifest themselves on **different space and time scales,** ranging from internal effects which affect only a single cage or farm site to regional impacts covering an entire body of water (Silvert, 1992). These distinct effects lead to different types of analysis and require different mitigation strategies. Even though complete scientific data on environmental impacts are seldom available, models based on existing scientific theory provide a better basis for regulation of aquaculture than ad hoc guidelines. Several models corresponding to different scales and types of impact were developed. The emphasis was on marine systems, although the models and analyses can also be adapted to freshwater aquaculture.

Ackefors and Enel (1990) examined phosphorus and nitrogen loads resulting from Swedish fish-farming operations. The nutrient loads from the actual 1986 fish production of 3,945 tons, from the licensed production of 17,323 tons, and from a scenario of 40,00 tons were calculated. The phosphorus and nitrogen loads from Swedish farming in 1986 were about 35 tons of phosphorus and 260 tons of nitrogen. These loads corresponded to 0.6% and 0.2% of the total Swedish phosphorus and nitrogen load on the surrounding sea areas. Compared to the total load from all surrounding countries, including atmospheric deposition, the share of the Swedish fish-farming activities to the adjacent seas was shown to be 0.05% for phosphorus and 0.02% for nitrogen. The overall nutrient load from aquaculture was shown to be negligible in comparison with other nutrient sources.

A2. The Perceived Need in Boston Bay

The ability to monitor water properties during periods of stress in fish farms allows physical factors to be placed in perspective for clinical diagnosis of diseased fish. Also model simulation of the nutrient status of waters associated with tuna fish farming is greatly enhanced through access to real time data on oceanographic and meteorologic conditions of the site. Such data in conjunction with fish feed information provides all the necessary information to run numerical models in near real time. If such information can be relayed to a remote computer facility then real time simulations of nutrient status associated with either a single cage or a region can be conducted.

In nearly all numerical simulations of water quality associated with fish farm operations mean or bulk oceanographic and meteorologic conditions are assumed. For example, depending on the specific objectivity , it is usual that mean seasonal, monthly or weekly averaged values of wind strength, direction and tidal elevation are used in numerical models. Such assumptions are justified if corresponding time scales are of interest are acceptable.

In practice, meteorologic and oceanographic conditions act on time scales of days or even hours and thus render invalid the assumption of stationarity of these variables which is an inherent assumption of using mean parameters. The use of bulk or mean values tend smooth the variability encountered in practice. For example, the use of weekly averaged values would not reveal the effect of a dodge tide, low wind strength and high solar radiation which may result in stratification of the water column and little water flow through the cages. Such conditions may provide the catalyst for onset of factors which may in the short term lead to increased stress on the cage environment including the captive fish. Such conditions remain to be tested for potential to pose threat to fish farms. However, having knowledge of onset of such conditions would provide some warning to managers of fish farms that potentially unfavourable environmental conditions may occur. Such information can be relayed to all fish farm managers through a central reporting facility.

In addition to provision of information for enhancing the simulative integrity of models and dissemination for management purposes the establishment of a real time measurement system offers other benefits. Deployment, for example, of a simple thermistor chain in a fish cage, can provide the response of the water column to potentially unfavourable oceanographic and meteorologic factors such as onset of thermal stratification which can be a pre-cursor to increased primary production. Such information, can be quickly ascertained and disseminated to farm managers.

Furthermore, in light of advances in sensor technology, there is no technical reason why a remote data acquisition system may not provide information on dissolved oxygen levels or information on phytoplankton bloom forming factors. Sashaug et al (1991) used multi-band (blue, green and red) spectral techniques to distinguish between main groups of bloom forming phytoplankton. Multi-channel fluorometry was used by Richardson etal (1986) to demonstrate the ability to detect chlorophyll a levels and hence phytoplankton production.

A3. Methodology to Boston Bay system development

The bulk of advances in remote monitoring technology has been conducted in Norway where satellite data acquisition systems have been used. This has required construction of expensive moored buoy installations housing instruments which provide via a satellite link such as the NOAA/ARGOS system daily information of environmental conditions in remote localities.

In the case of development of the Boston Bay system the principle of design has been on simplicity and cost effectiveness through use of standard off-the-shelf data logging hardware coupled with commercially available state of art cellular communications system. This has resulted in development of prototype working system for less than $10000.

The system design is based around a data logging system using the UNIDATA product line. A microprocessor controlled logger is connected to a series of sensors which at this stage include the following

. wind strength and direction sensor
. bottom mounted pressure gauge and
. a thermistor chain incorporating 3 temperature sensors

The capacity of the data logger allows for expansion of up to 8 sensors.

The output of the logger is interfaced to a telemetry unit and a cellular phone which provides a dedicated communications link to a computer system to process the field data. At the present the processing computer facility is hard wired to a standard TELSTRA telephone line. Options are available to establish a data link between two cellular phones and processing of the field data on a notebook computer which also accommodates the numerical simulation algorithm. This would allow data acquisition, processing and numerical simulation to be conducted anywhere within the cellular phone network in Australia.

All of the electronics are housed inside a PVC container which is sealed to the marine environment. The data logger and cellular phone system in the field unit are powered by separate power supplies which are supported by solar panel trickle charge systems. The expected duration of operation of the field unit, under normal circumstances, is about 12 months.

A4. Status of system

The system has been assembled, fitted inside an operational field unit, and is presently undergoing performance testing at the Flinders University of South Australia to ensure that program loading and data recovery aspects are satisfactory before deployment in the field. It is proposed to attach the field unit to one of the SARDI/TBOAA fish cages in Boston Bay. The system is illustrated in Figure 26.

APPENDIX B

APPENDIX B

B1. THE BASIC MODEL FLOW

The model used in this investigation is based on Bye (1977). Vertically averaged quantities are formed by surface to bottom integration in the equations of motion and the continuity equation. This leads to a set of equations which can predict the components of mean transport velocity (u,v) and mean elevation (n). That is, a two dimensional depth integrated transport model.

The three basic prognostic variables "u,v" the components of the current and the surface elevation "n" are linked by the differential equation

$$dn/dt + du/dx + dv/dy = 0$$

and the solutions for u,v are given by the momentum equations on page 25 (Bye,19977)

The model is strictly valid for a sea with the following properties

1. The elevation of the surface is always much less than the depth.

2. The current velocities are small that the inertial term in the momentum equations may be neglected.

3. The density of the sea is constant.

4. The general circulation of the sea is driven by wind stress and tide generating forces.

The basic model is called FLOW . To operate it also requires knowledge of the bathymetry and bottom friction. The latter for sandy bottom in a shallow sea is 2.5×10^{-3} .

FLOW can produce displays over a selected grid of currents and elevations for specified times. Additionally the model allows for "instruments" to be located at particular grid points in order to obtain a time series of currents and elevations.

B2. THE EXTENDED CONCENTRATION MODEL

The model FLOW was updated to provide information with respect to diffusion and advection of pollutants. The updated model is known as FLOWC and it also can provide full displays of the concentration of pollutant information and a time series of concentrations at a selected "instrument" location.

Thus, knowing the concentration of a point source and the flow rate into the sea at a given site (instrument site) a full display over the model grid will show over what area the pollutant has spread. Further, if an instrument is placed at the point source, a time series of pollutant concentration at the instrument will show when the pollutant has reached equilibrium.

For FLOW the right hand side of the equation was previously set to zero. In FLOWC the new sea surface equation is

$$dn/dt + du/dx + dv/dy = R - E + Q/SIGMA$$

where R, E are rainfall, evaporation respectively (ms^{-1})

Q (m^3s^{-1}) is flow rate

SIGMA (m^2) is the surface area of one grid element

The equation defining the concentration becomes

$$(dn/dt+du/dx+dv/dy)c = (R-E)c + P/p - lambda\ cdz$$

where lambda (t^{-1}) is a decay factor

K (m^2s^{-1}) is the diffusion coefficient

P (kgs^{-1}) is the mass flux and $P/p = Qc_i\ 10^{-s}$

where c_i and s is the input concentration and scaling factor respectively.
The updated model FLOWC allows for up to ten different pollution locations with differing flow rates and input concentrations.

A diffusion/advection time step can be set to speed up the running time of the program. This has little effect on the results.

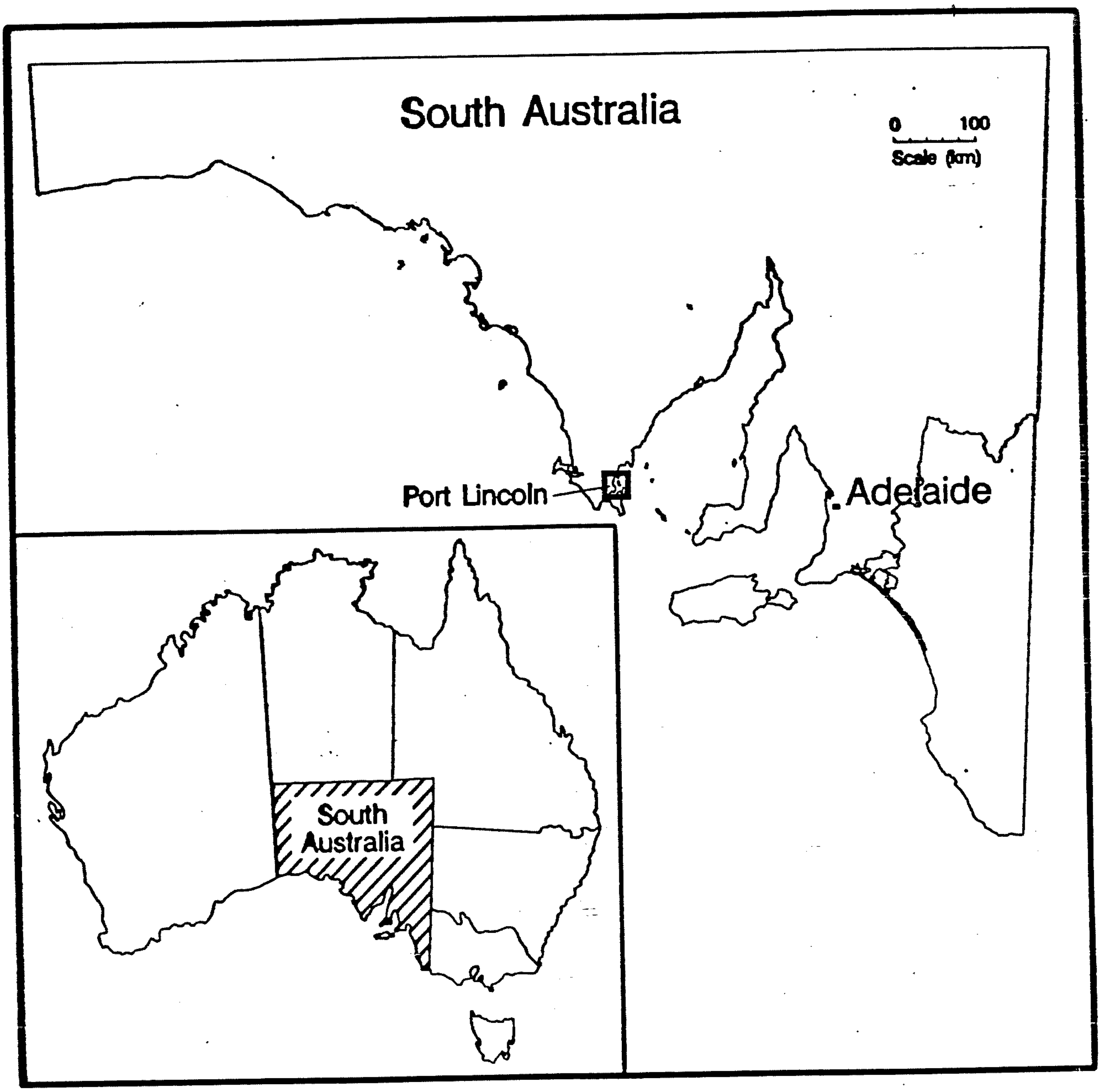


FIGURE 1

Location of the study area

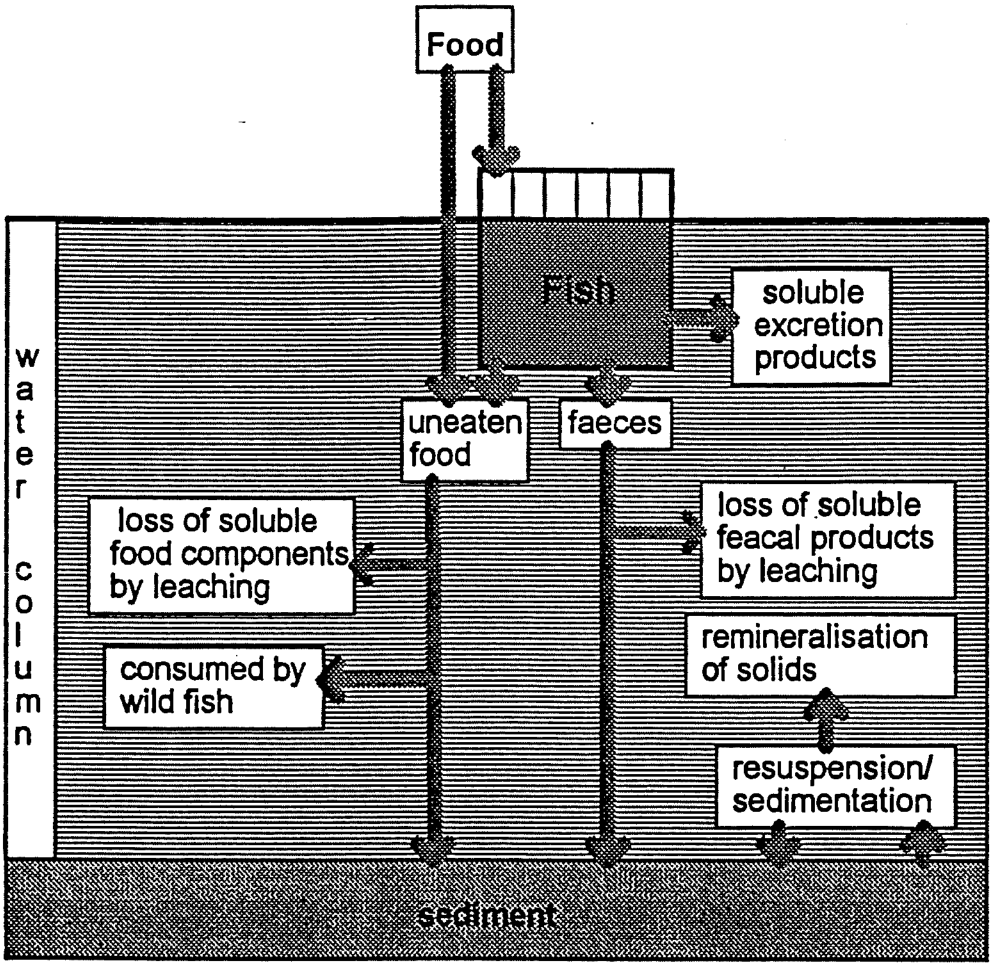


FIGURE 2
Nutrient pathways
(After Gowen and McLusky, 1988)

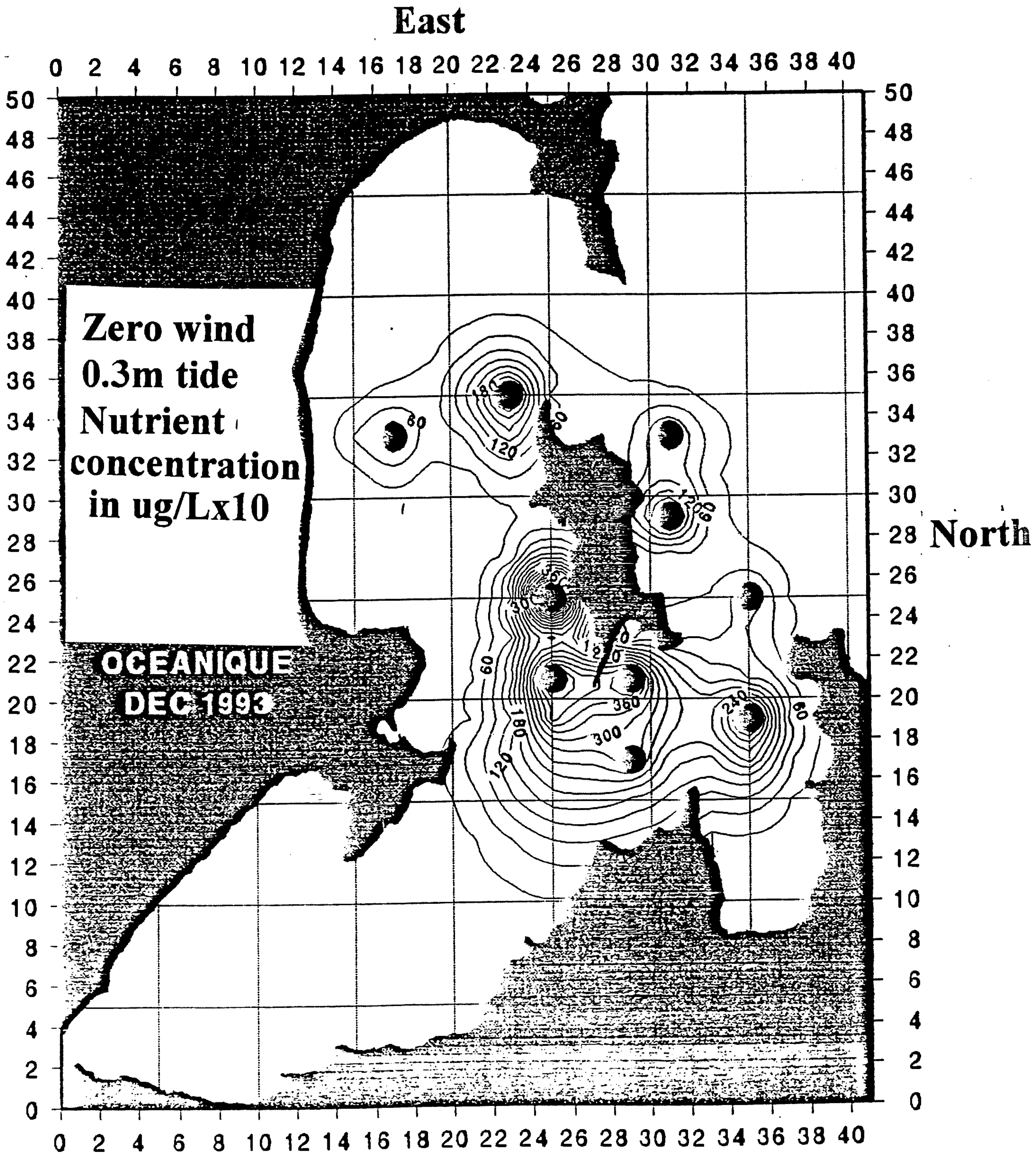


FIGURE 3
Modelled distribution of nutrient levels due to multiple tuna pontoons in Boston Bay
(After Petrusevics, 1992)

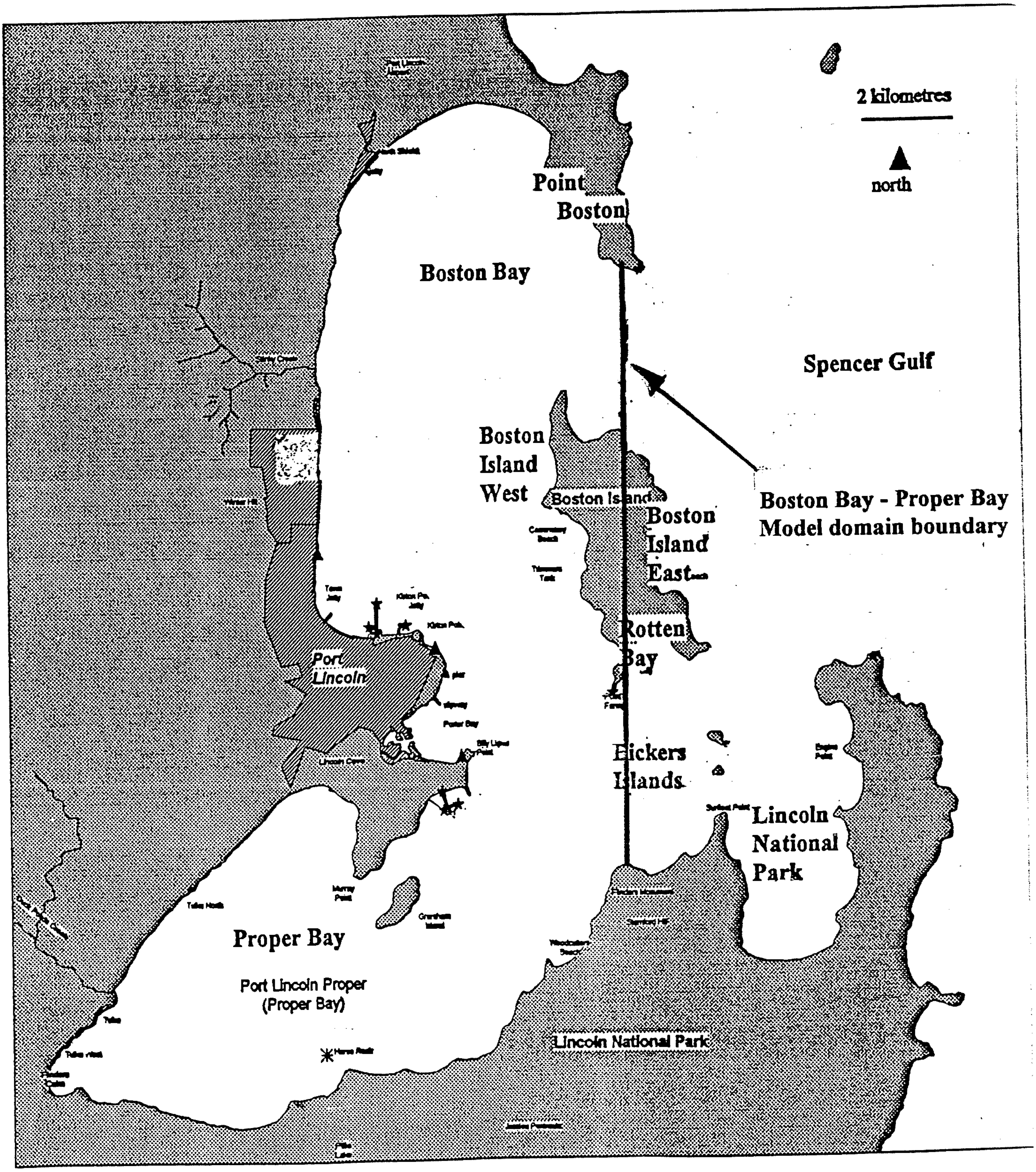
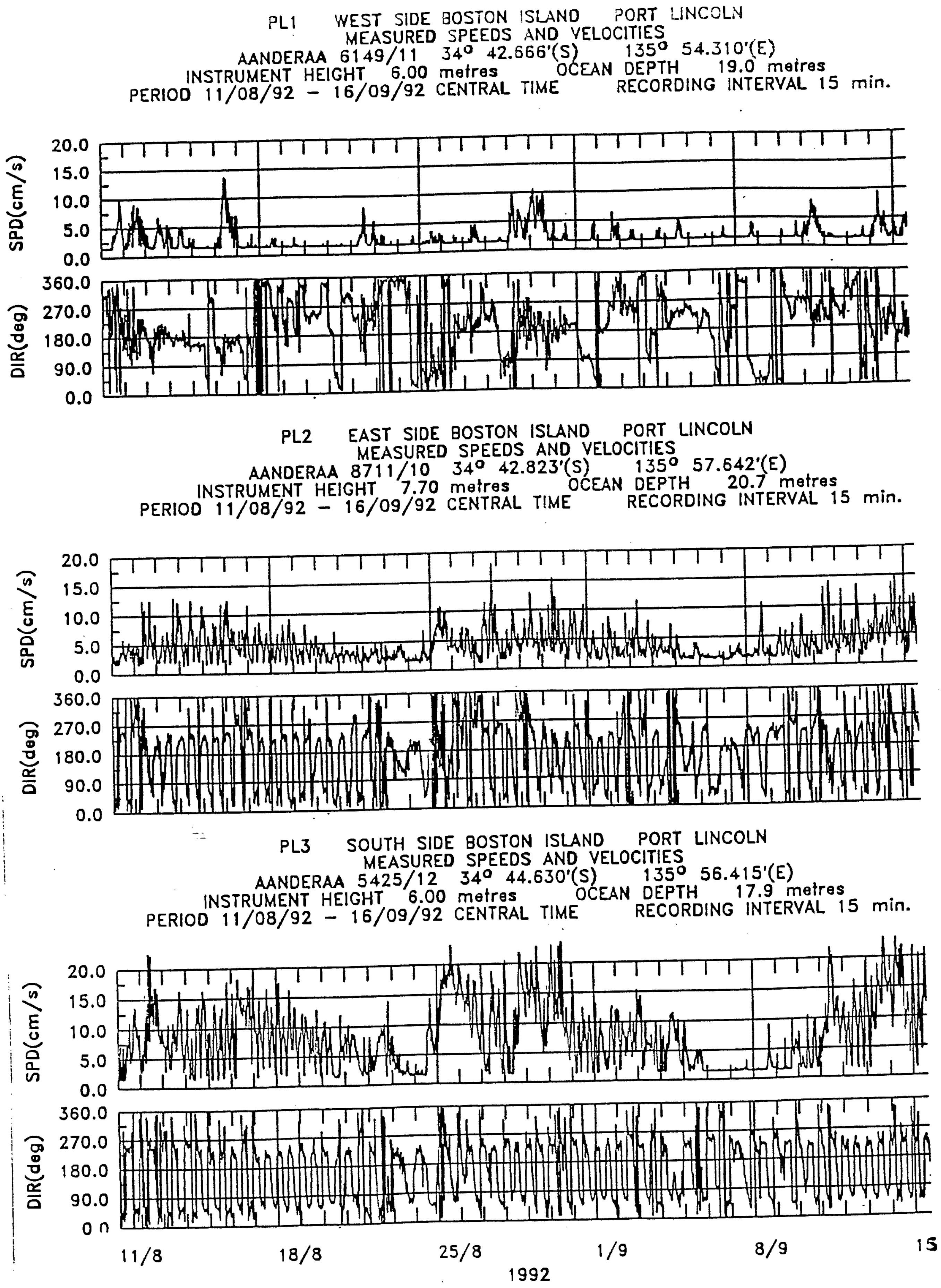


FIGURE 4
Boston Bay region and boundary of Boston Bay and Proper Bay model domain



PL1 WEST SIDE BOSTON ISLAND PORT LINCOLN
MEASURED SPEEDS AND VELOCITIES
AANDERAA 6149/11 34° 42.666'(S) 135° 54.310'(E)
INSTRUMENT HEIGHT 6.00 metres OCEAN DEPTH 19.0 metres
PERIOD 11/08/92 – 16/09/92 CENTRAL TIME RECORDING INTERVAL 15 min.

PL2 EAST SIDE BOSTON ISLAND PORT LINCOLN
MEASURED SPEEDS AND VELOCITIES
AANDERAA 8711/10 34° 42.823'(S) 135° 57.642'(E)
INSTRUMENT HEIGHT 7.70 metres OCEAN DEPTH 20.7 metres
PERIOD 11/08/92 – 16/09/92 CENTRAL TIME RECORDING INTERVAL 15 min.

PL3 SOUTH SIDE BOSTON ISLAND PORT LINCOLN
MEASURED SPEEDS AND VELOCITIES
AANDERAA 5425/12 34° 44.630'(S) 135° 56.415'(E)
INSTRUMENT HEIGHT 6.00 metres OCEAN DEPTH 17.9 metres
PERIOD 11/08/92 – 16/09/92 CENTRAL TIME RECORDING INTERVAL 15 min.

FIGURE 5
Current regimes-Boston Bay

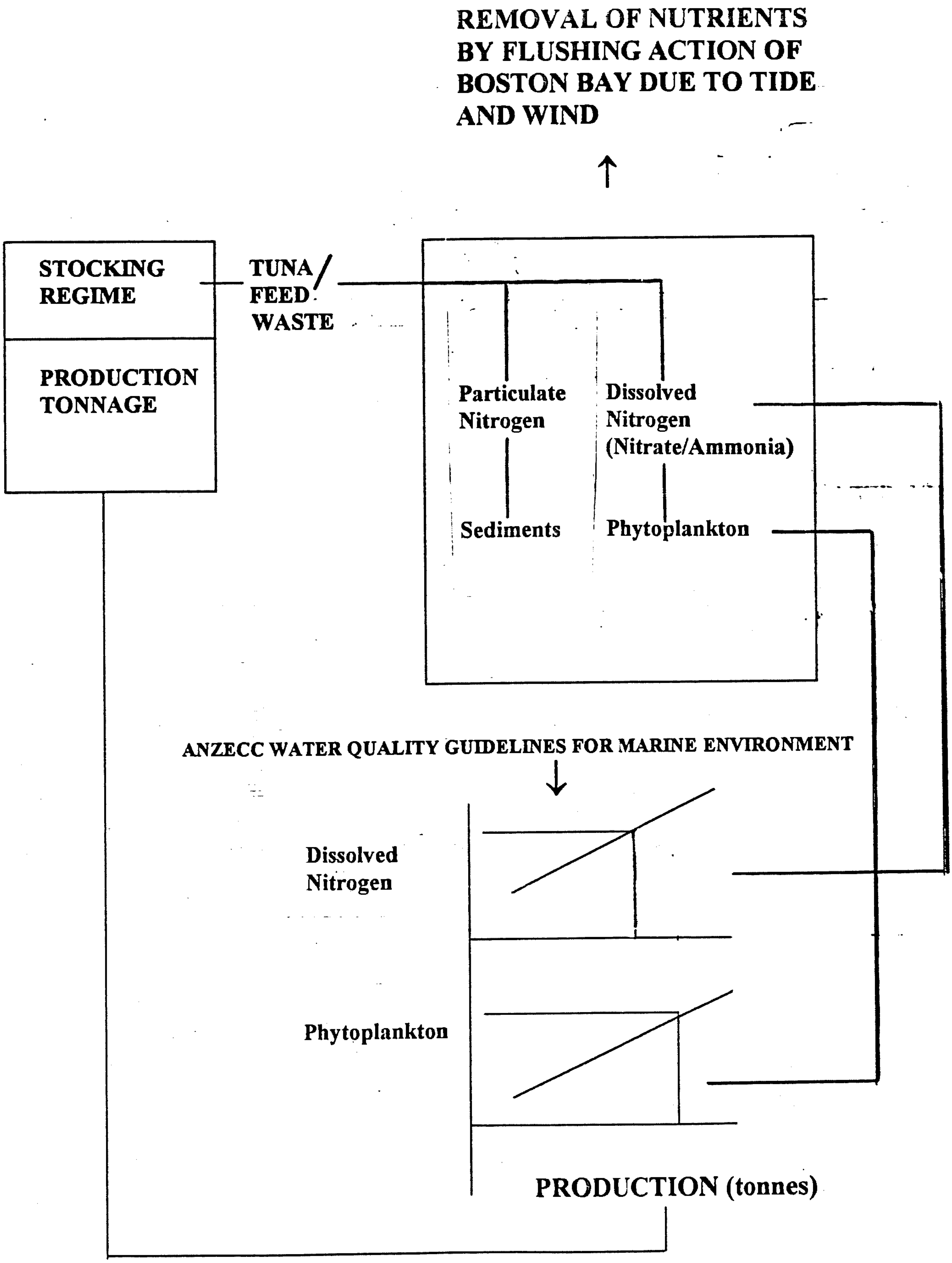


FIGURE 6
Schematic representation of the coupled model.

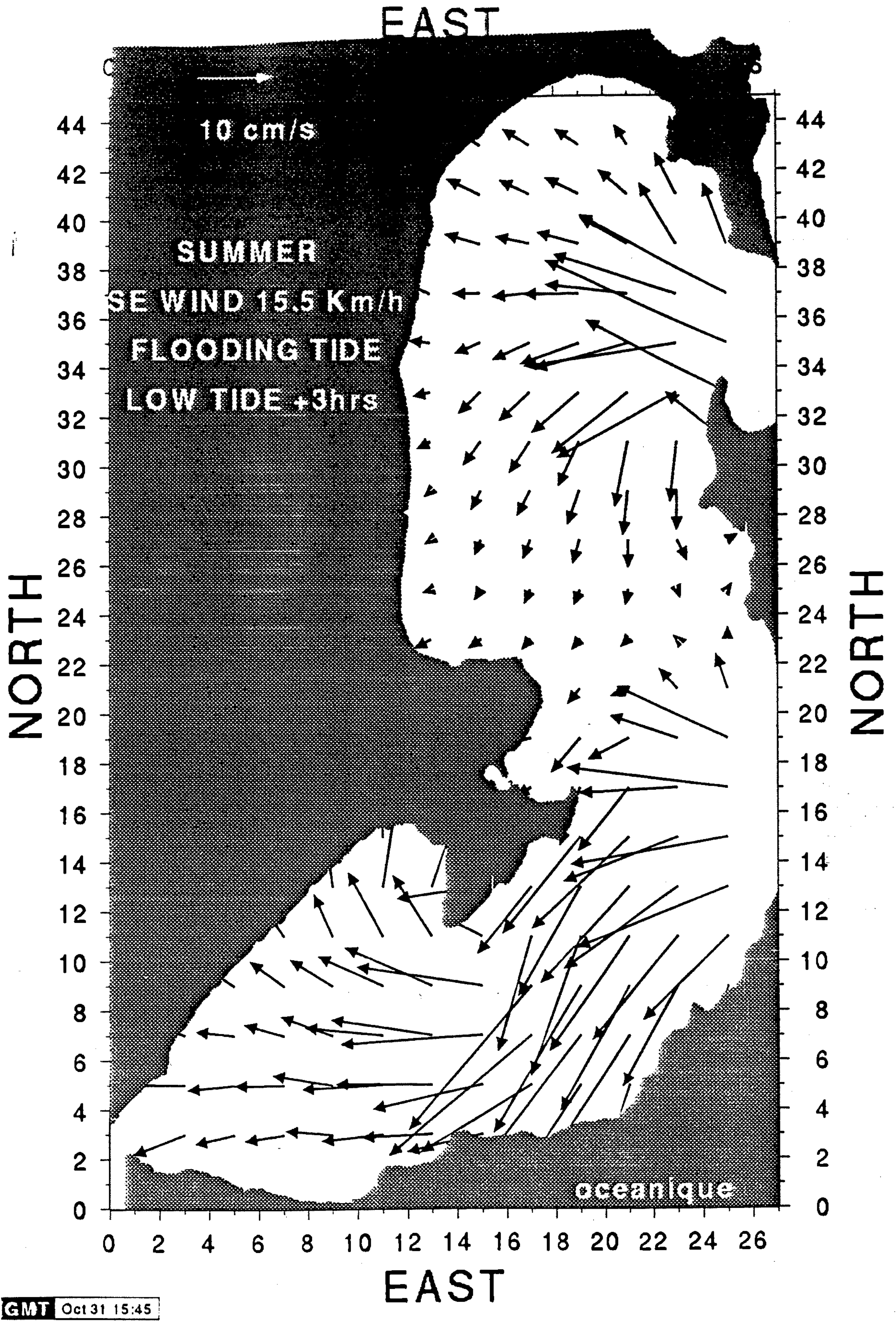


FIGURE 7
Peak flooding tide Boston Bay - Proper Bay
January - March

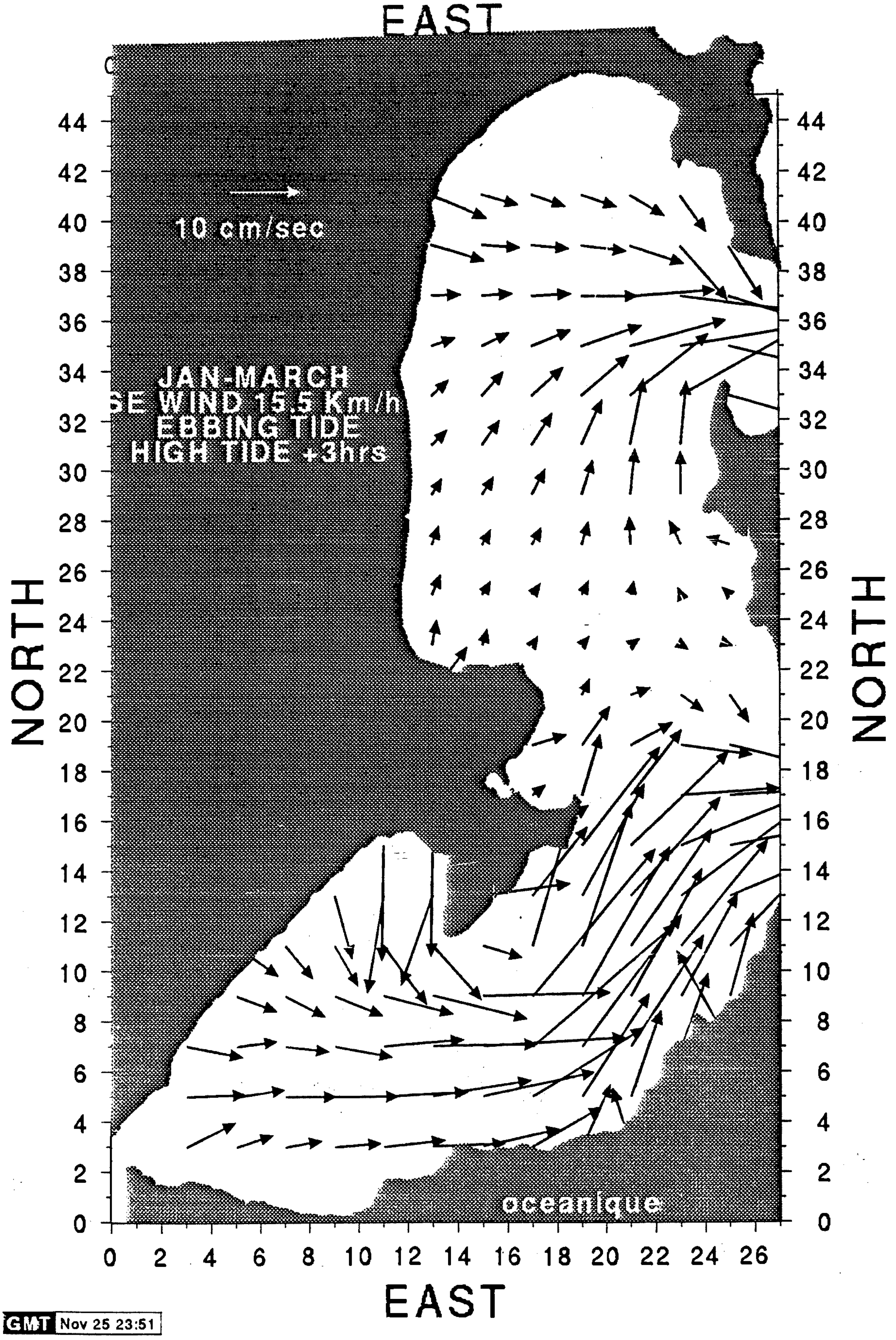


FIGURE 8
Peak ebbing tide Boston Bay - Proper Bay
January - March

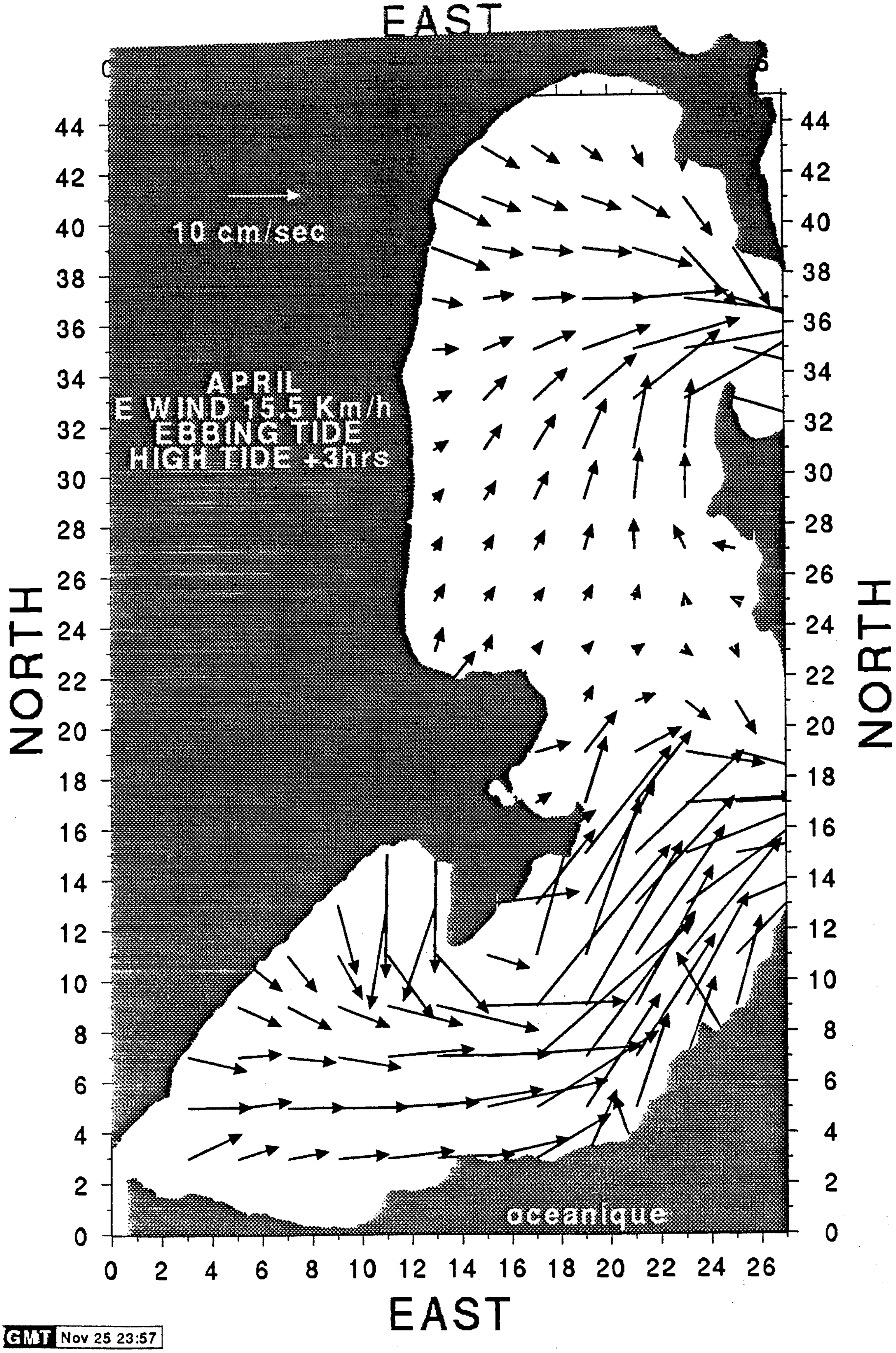


FIGURE 9

Boston Bay - Proper Bay

April (easterly wind)

Ebbing tide

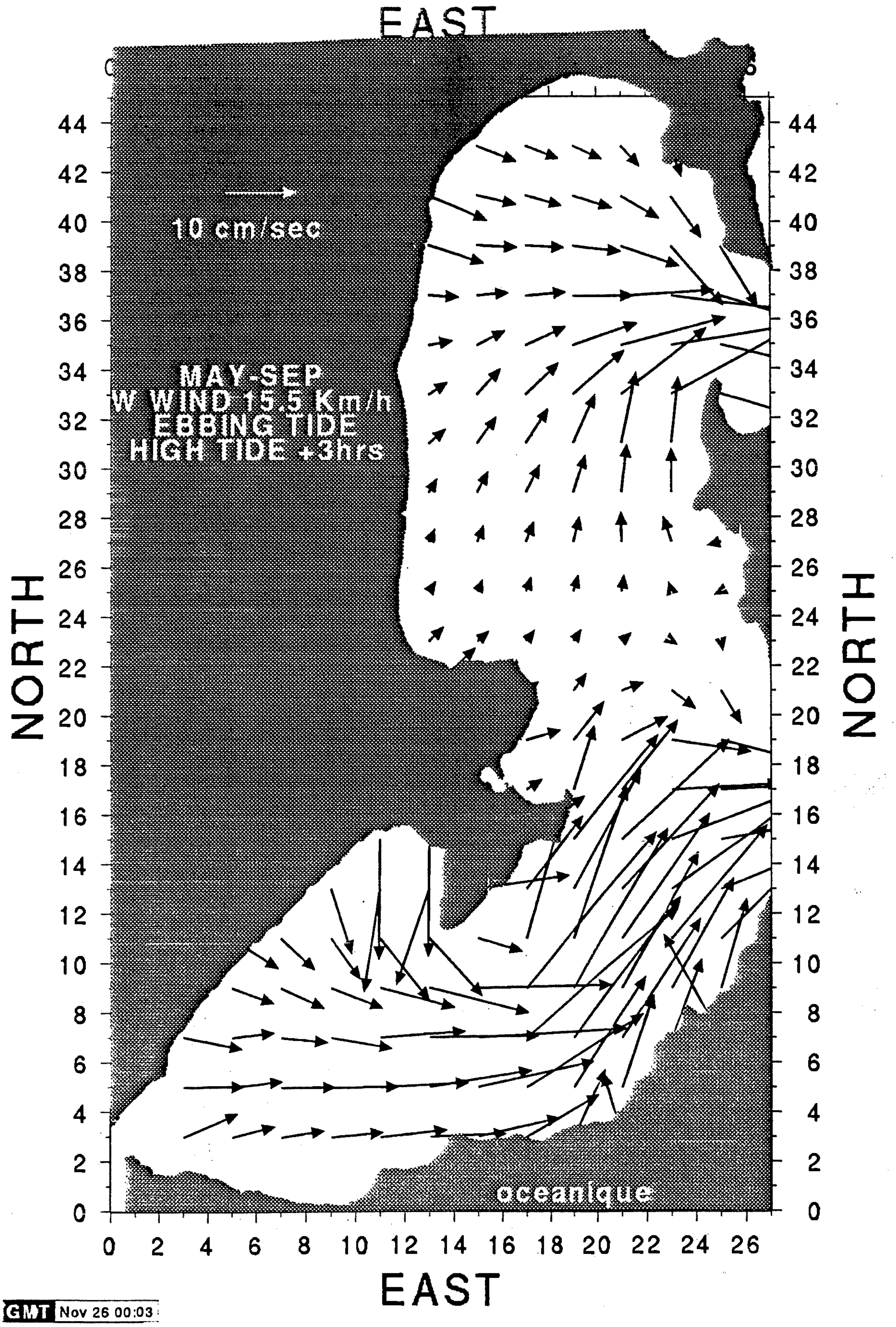


FIGURE 10
Boston Bay - Proper Bay
May - September (westerly wind)
Ebbing tide

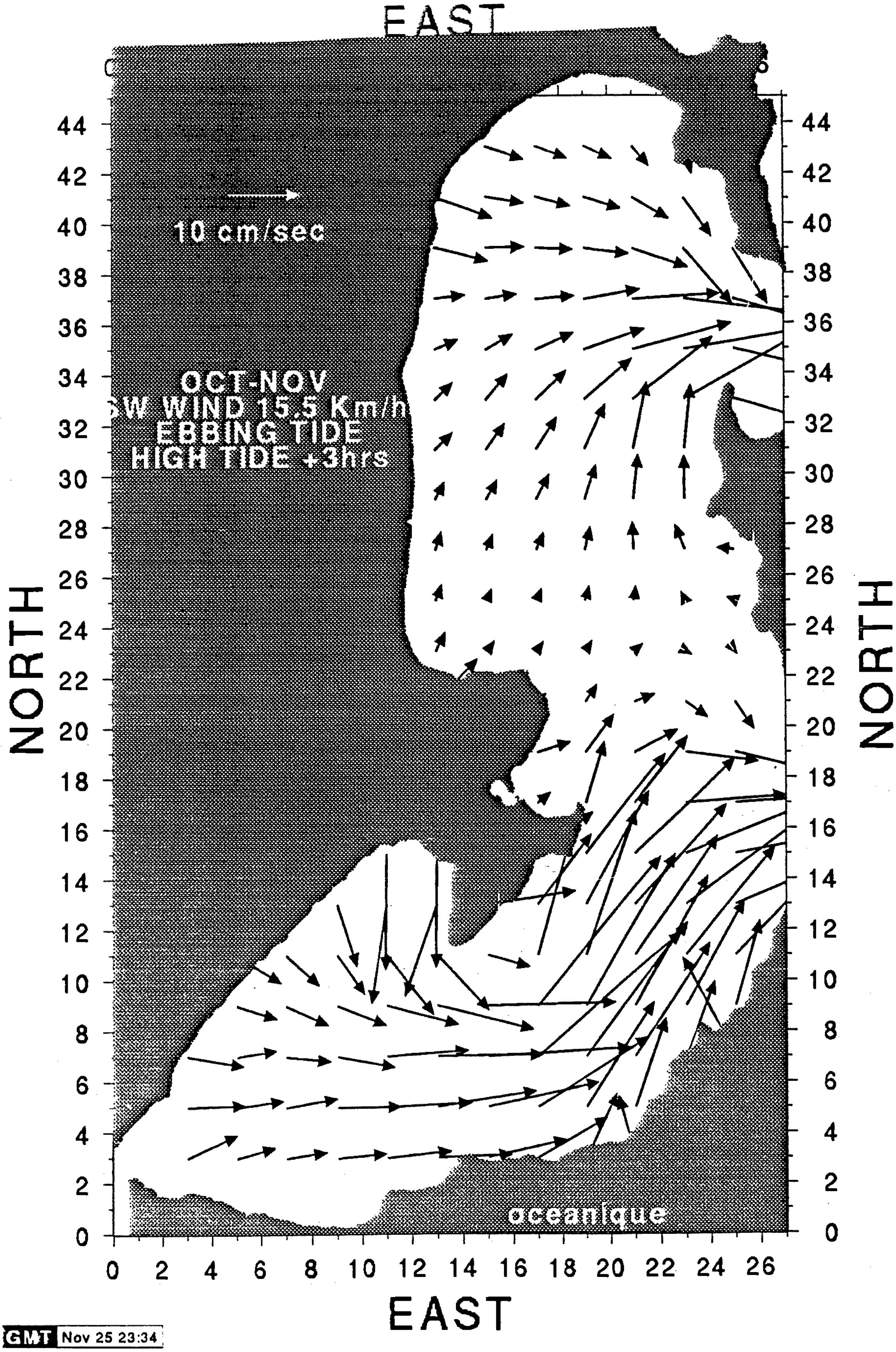


FIGURE 11
Boston Bay - Proper Bay
October - November (south-westerly wind)
Ebbing tide

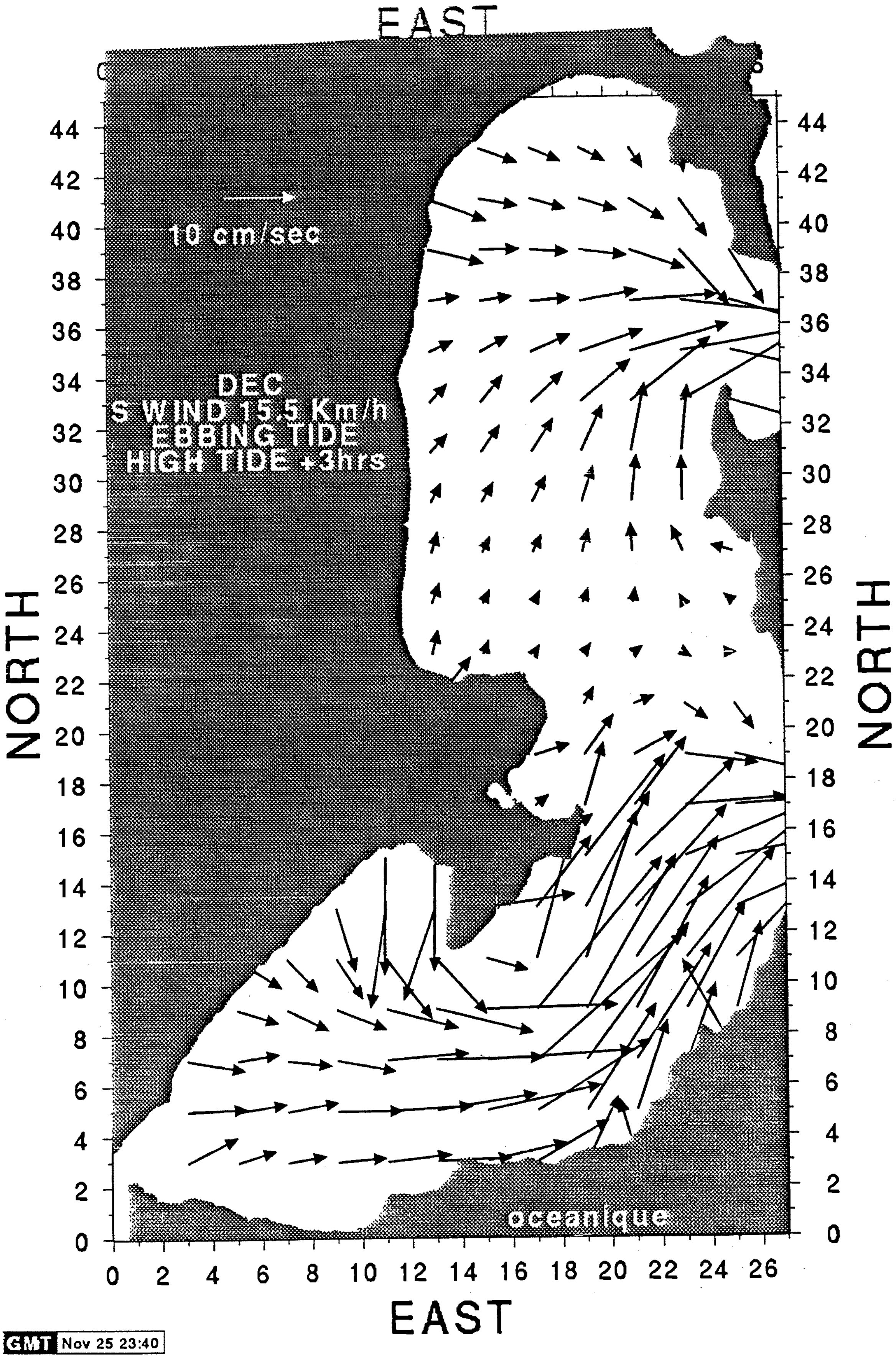


FIGURE 12

Boston Bay - Proper Bay
December (southerly wind)
Ebbing tide

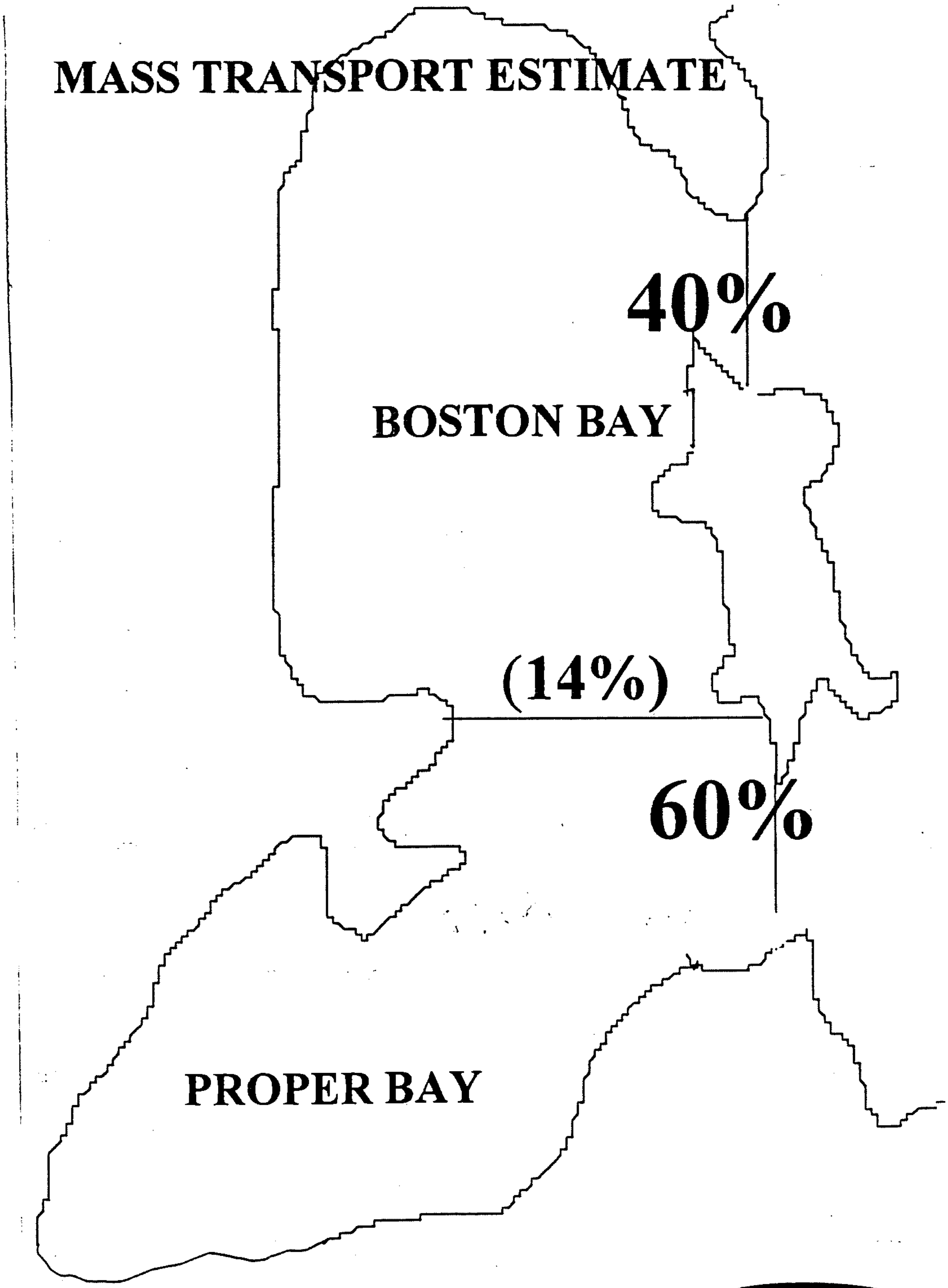


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FIGURE 13
Mass transport in Boston Bay

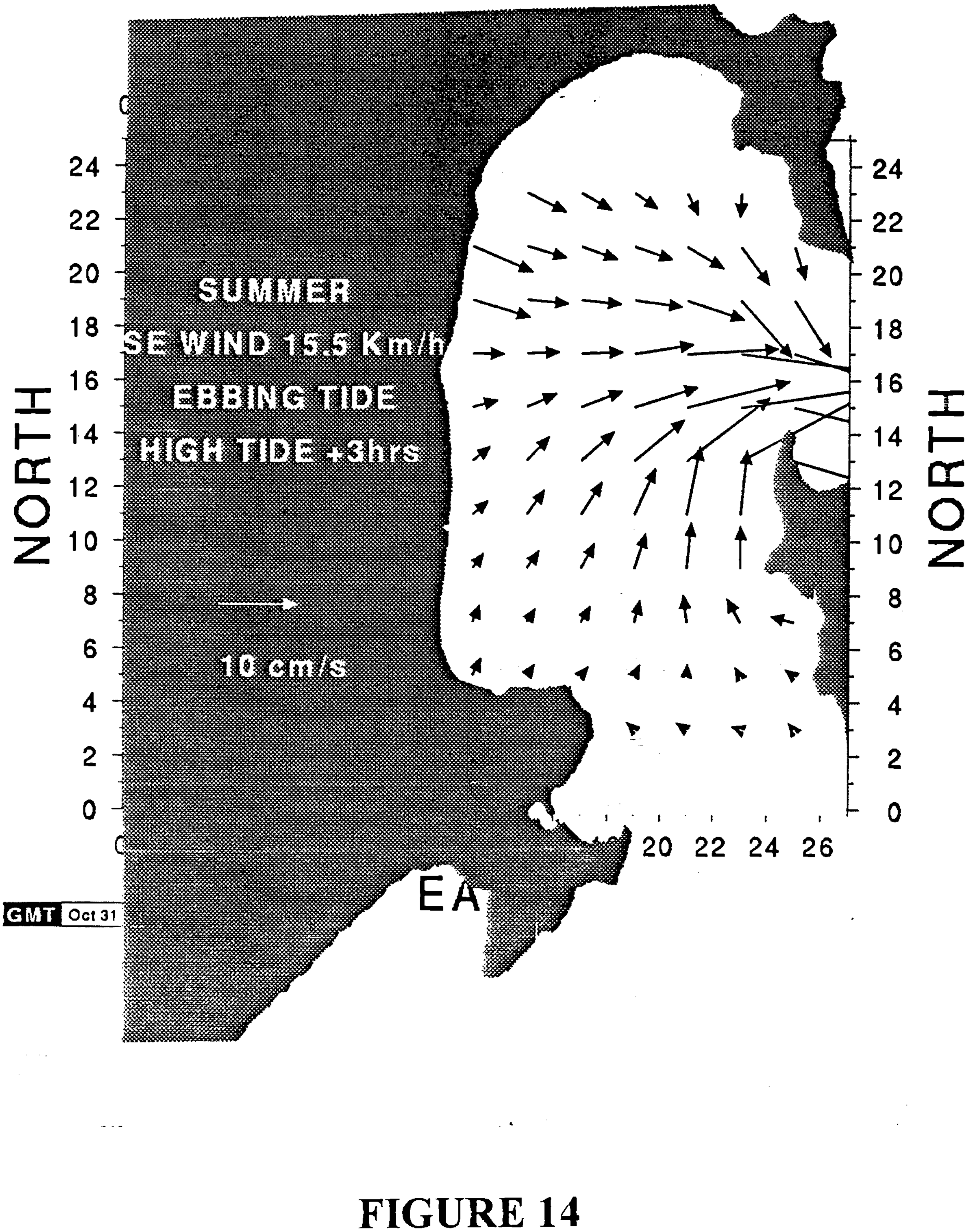

FIGURE 14
Water circulation in reduced model domain - Boston Bay
January - March (south easterly wind)

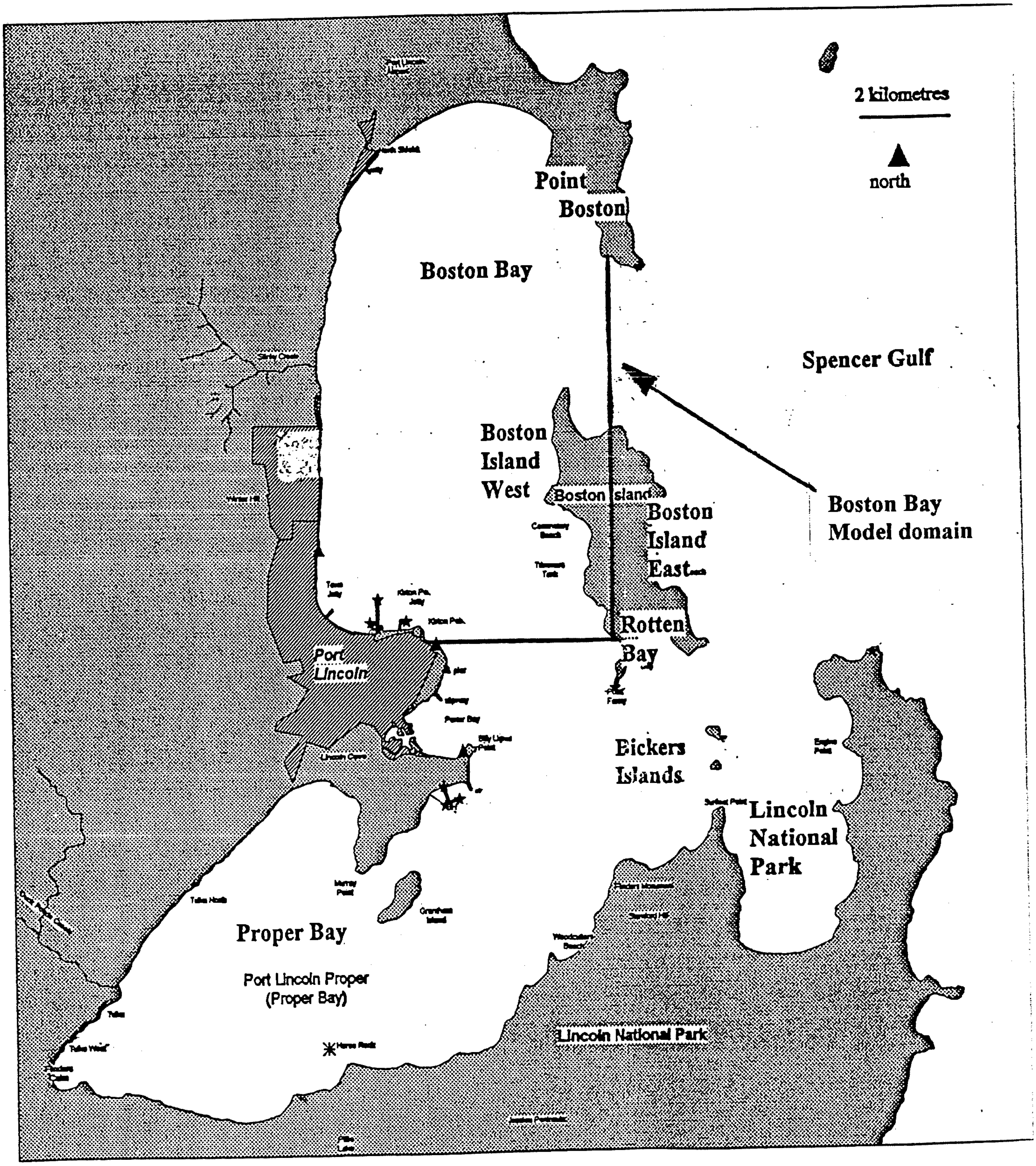

FIGURE 15
The Boston Bay model domain

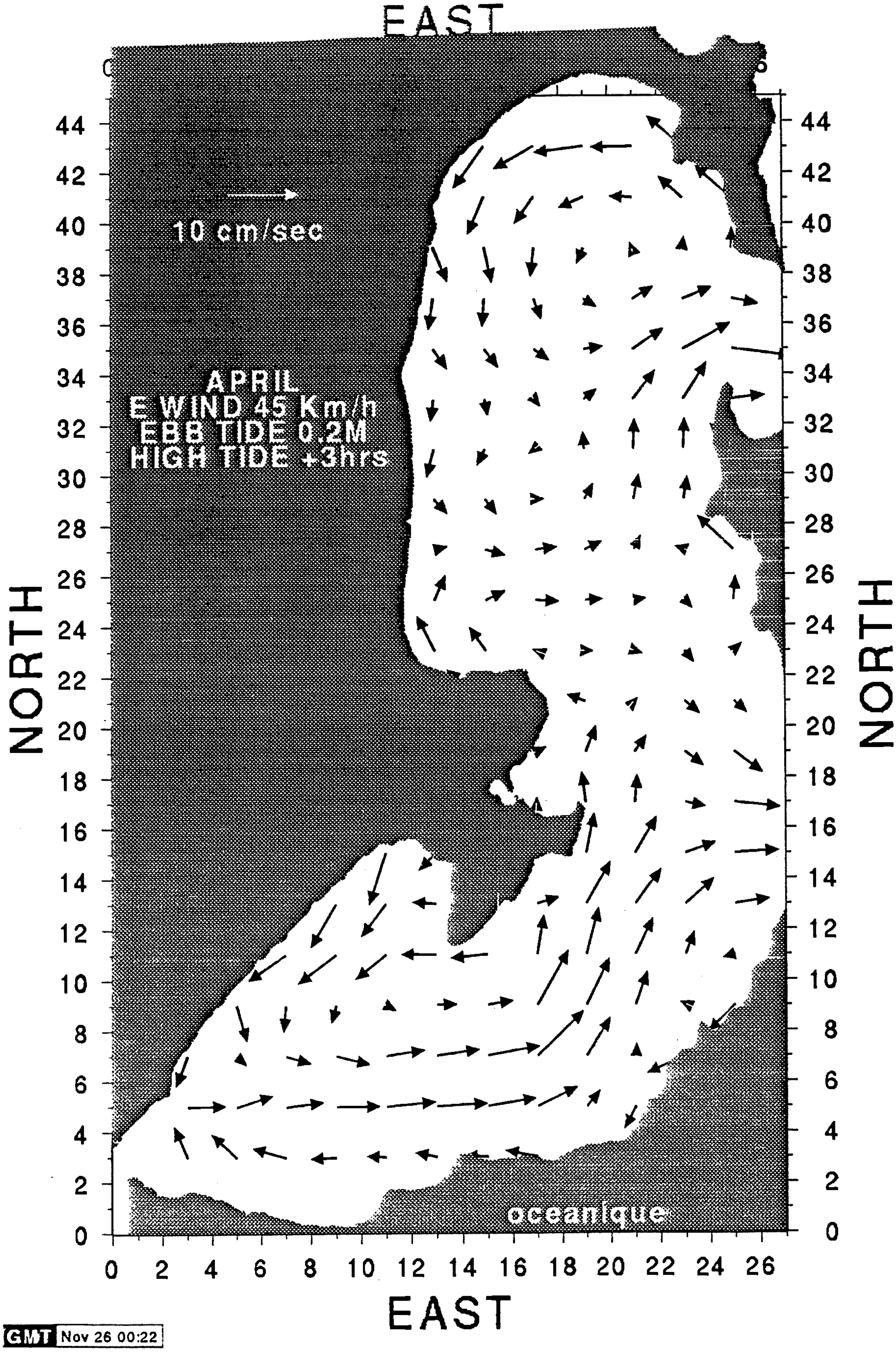

FIGURE 16
Boston Bay - Proper Bay
Easterly wind 45km/h wind
Ebbing tide 0.2 metre amplitude

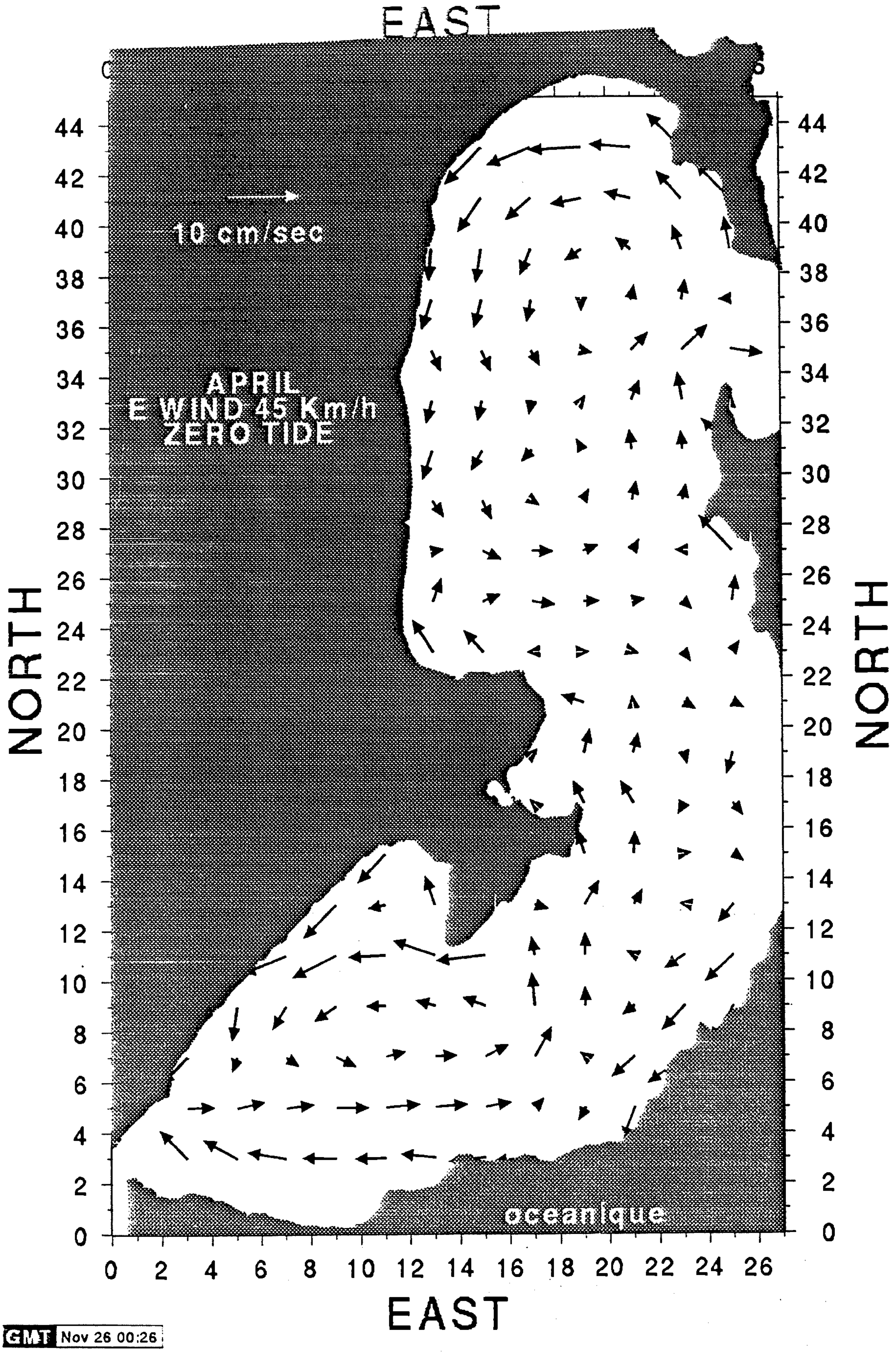

FIGURE 17
Boston Bay - Proper Bay
Easterly wind 45km/h wind
Zero tide

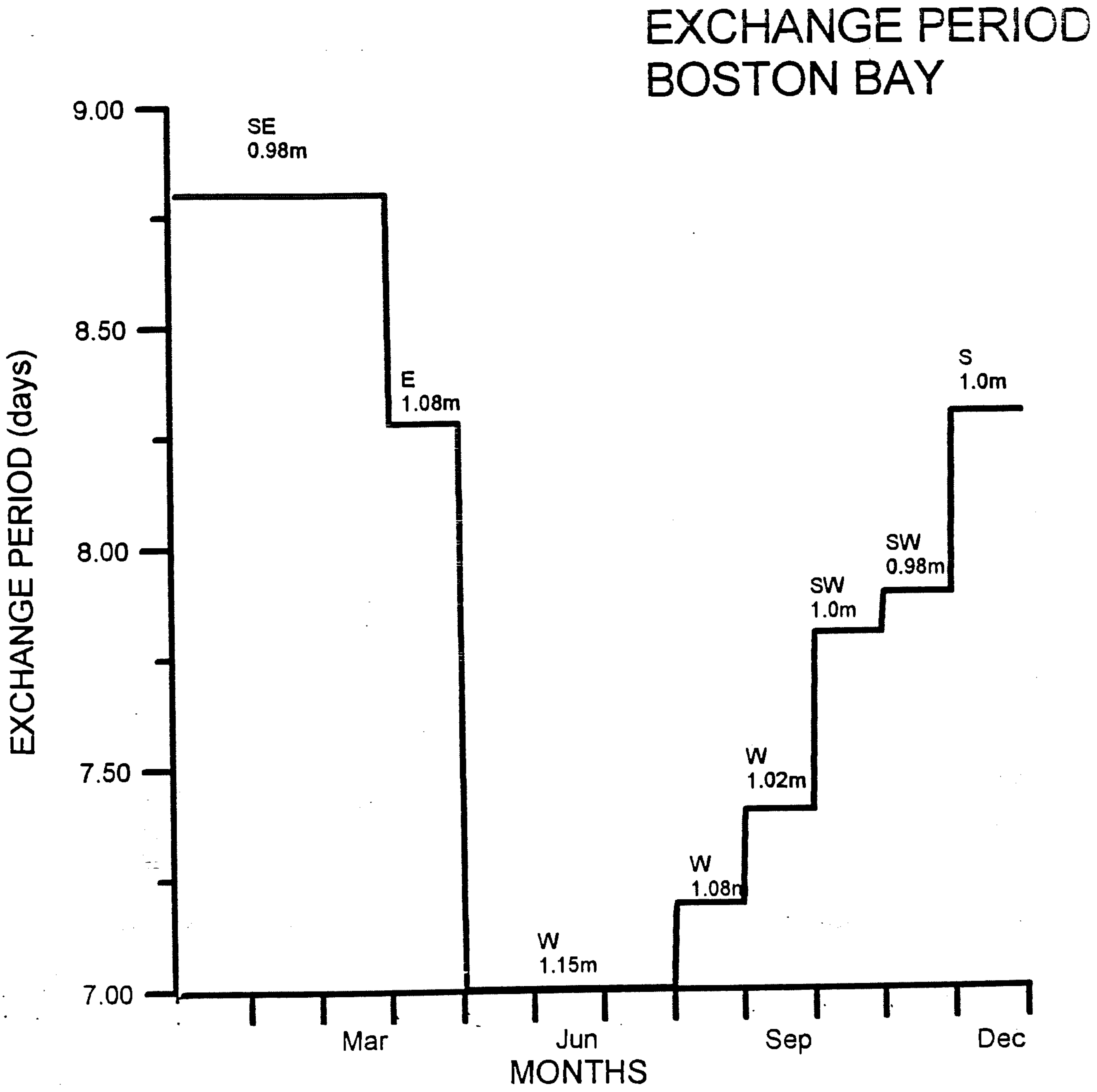

FIGURE 18
The exchange period of Boston Bay (the mean wind and mean tidal data are shown for each month)

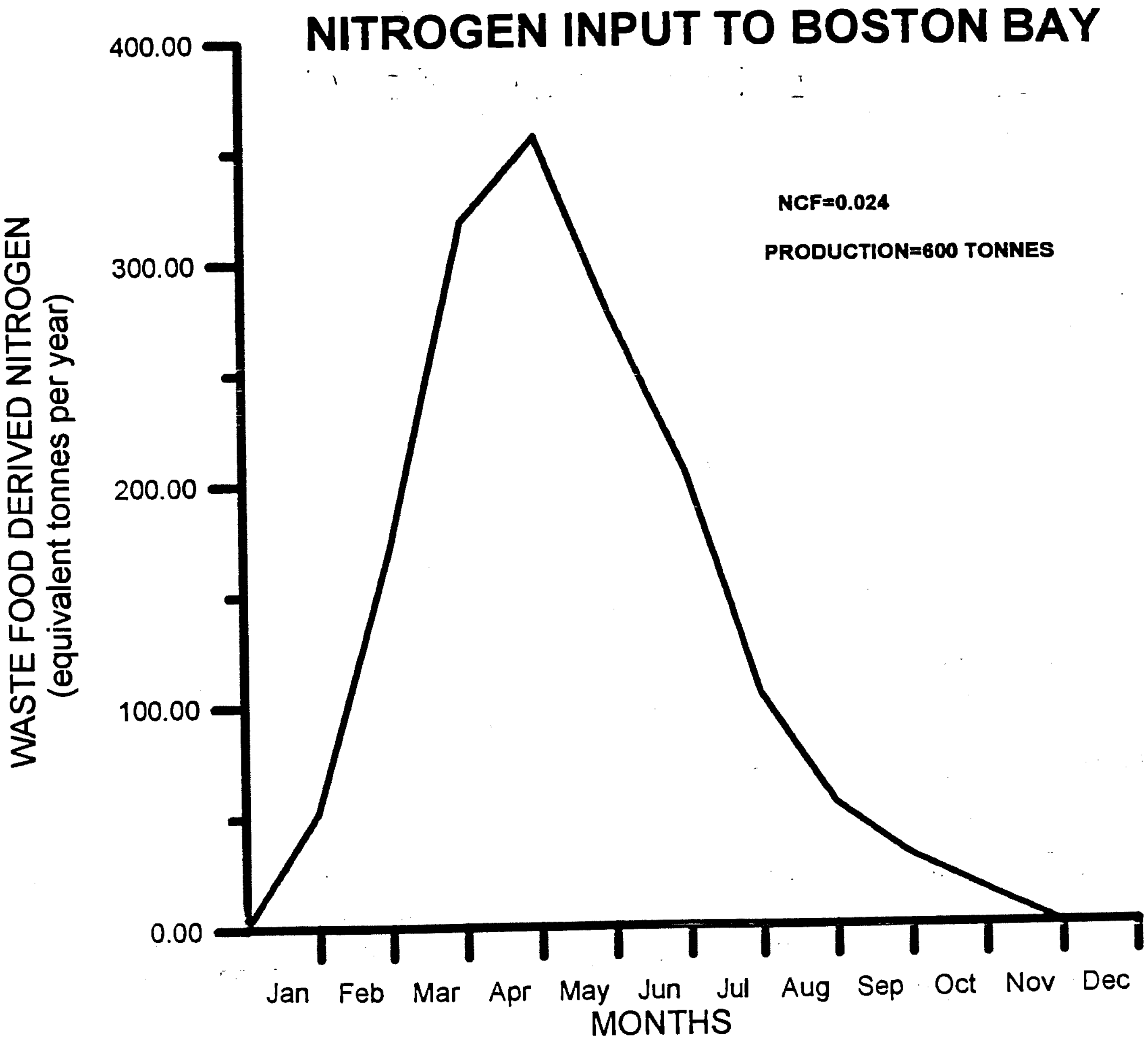

FIGURE 19
Nitrogen input to Boston Bay due to feed waste and fish waste

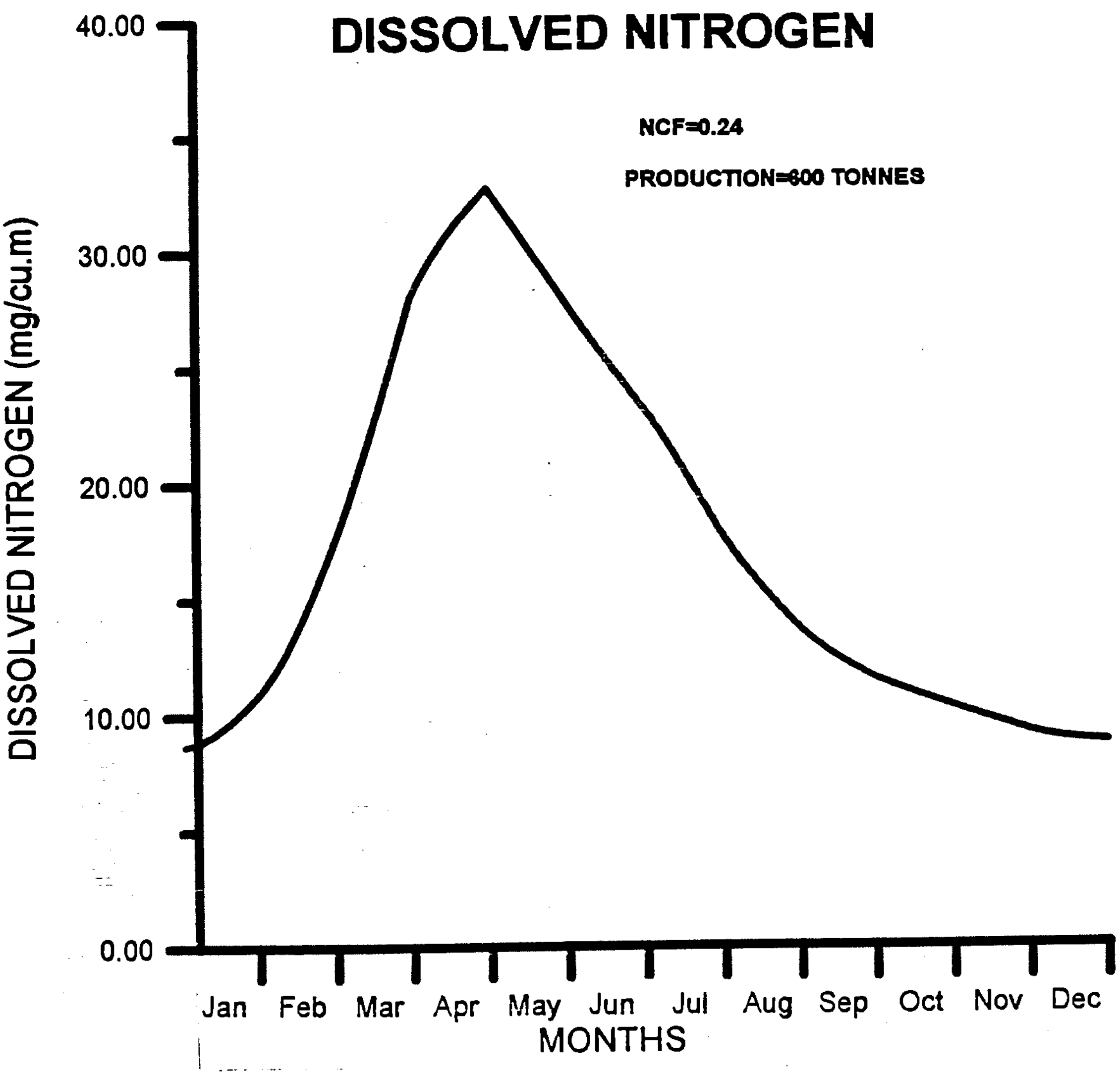

FIGURE 20
Dissolved nitrogen levels in Boston Bay

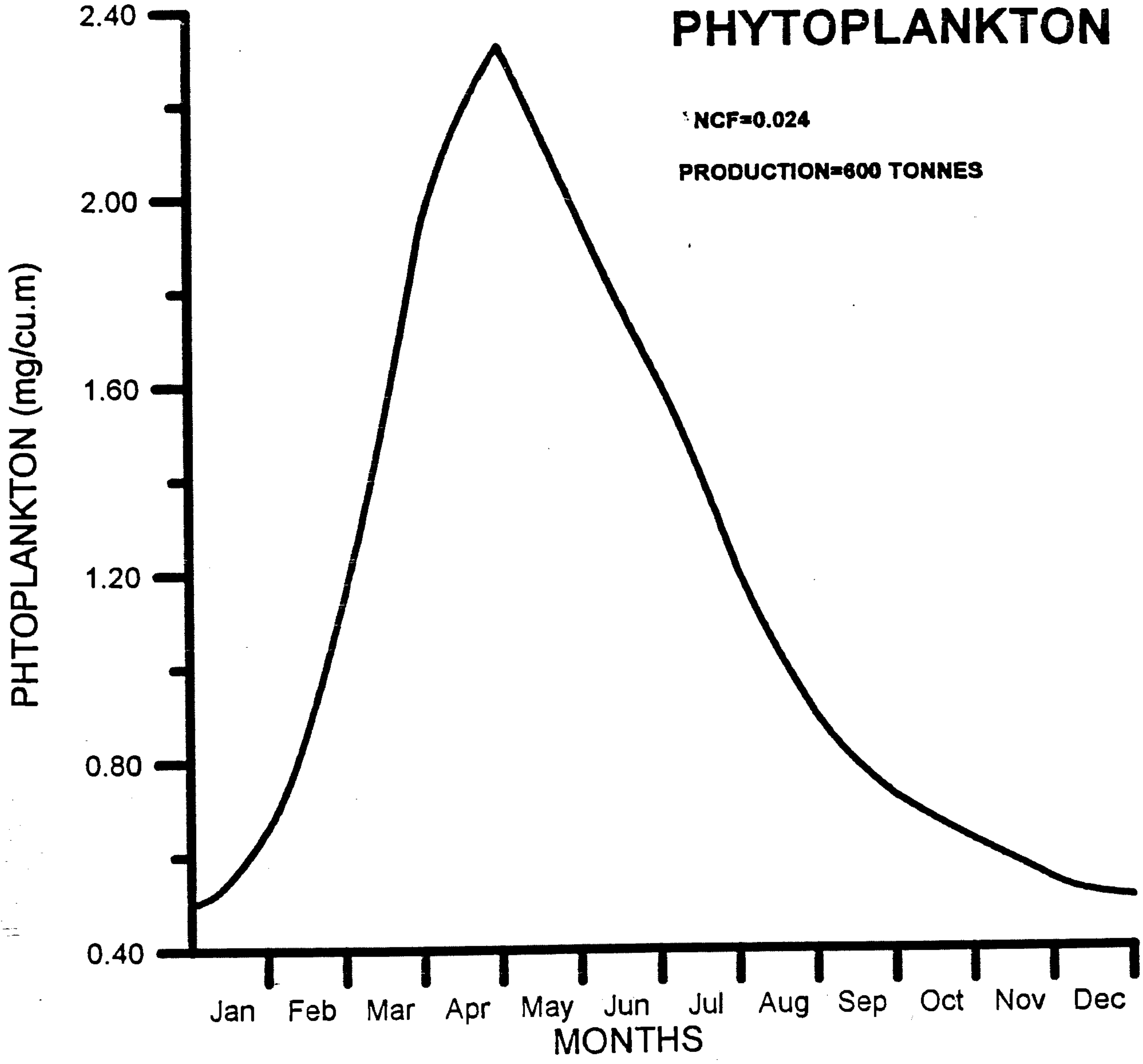

FIGURE 21
Phytoplankton levels in Boston Bay

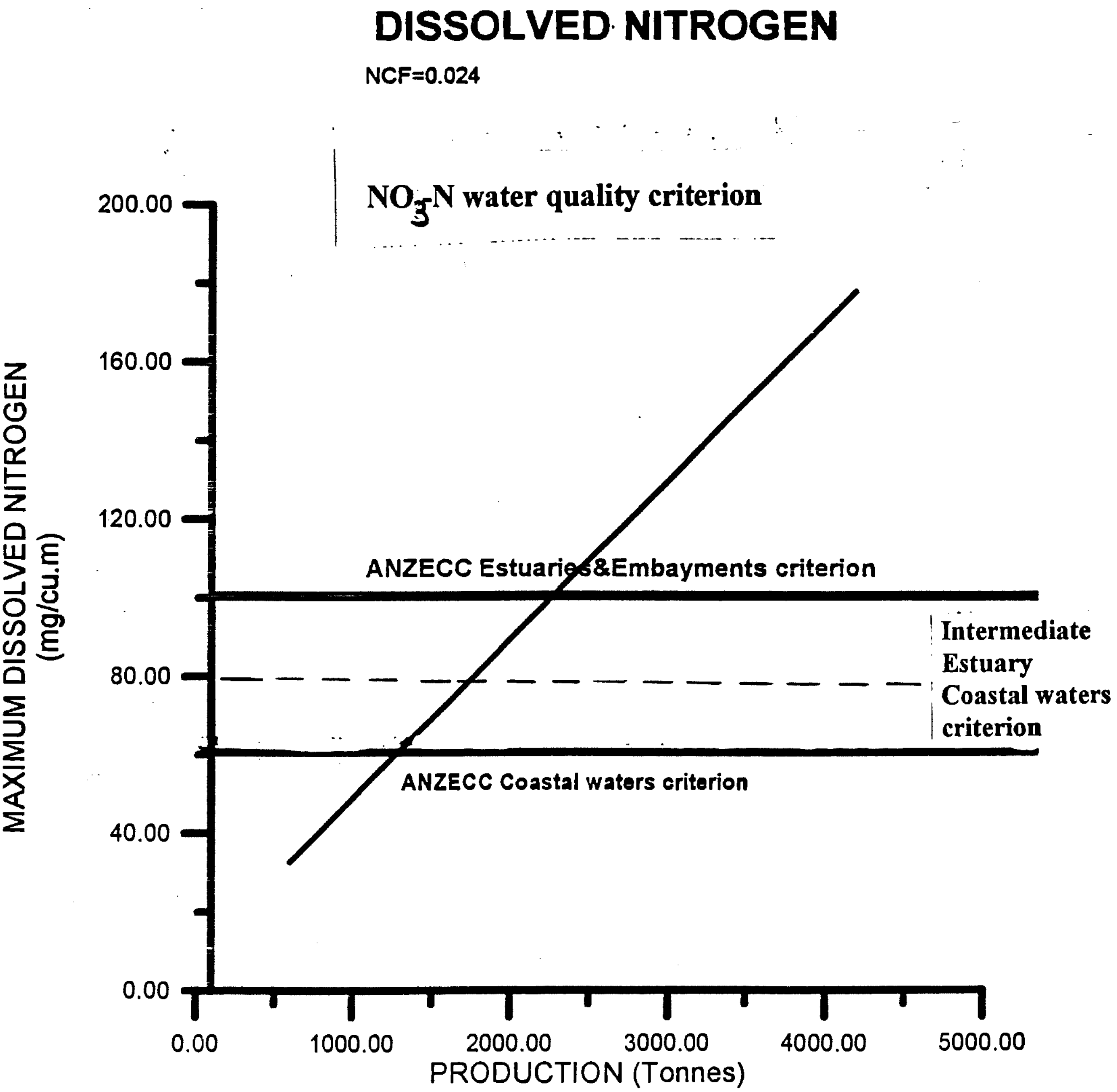

FIGURE 22

Estimate of sustainable fish production levels for intermediate estuary - coastal waters classification

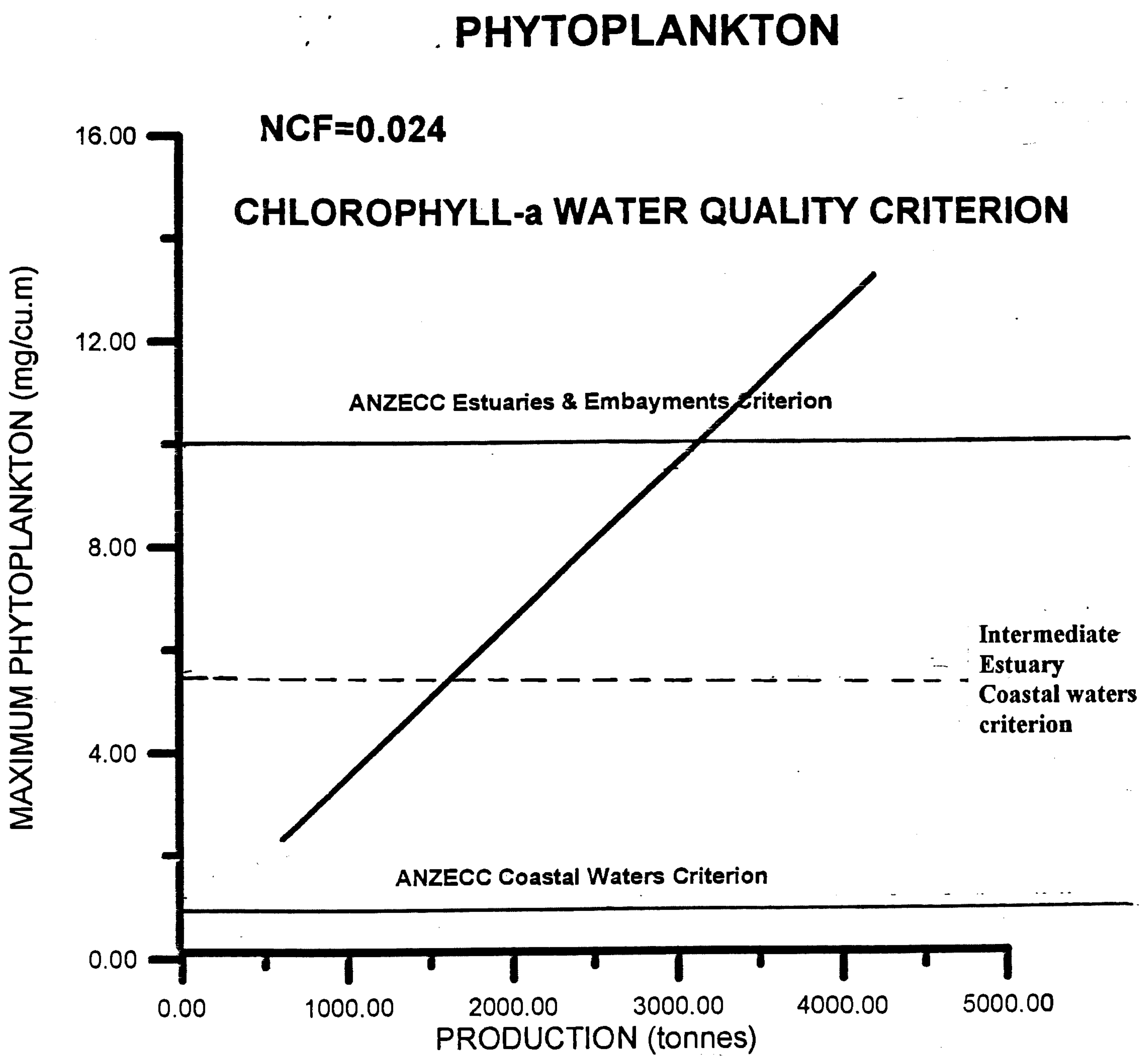

FIGURE 23
Estimate of sustainable fish production levels for intermediate estuary - coastal waters classification

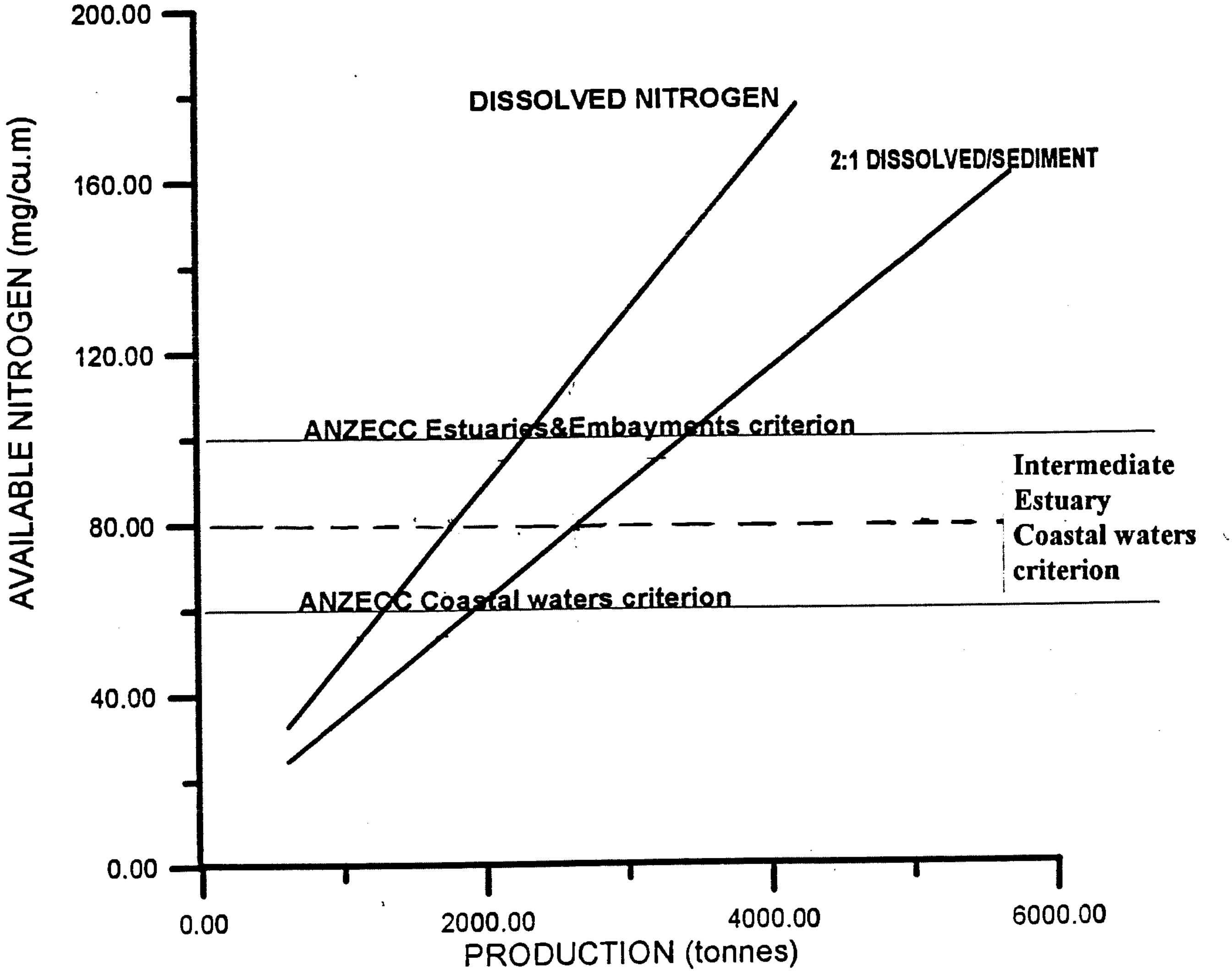

FIGURE 24

Estimate of sustainable fish production corresponding to 33% sediment uptake

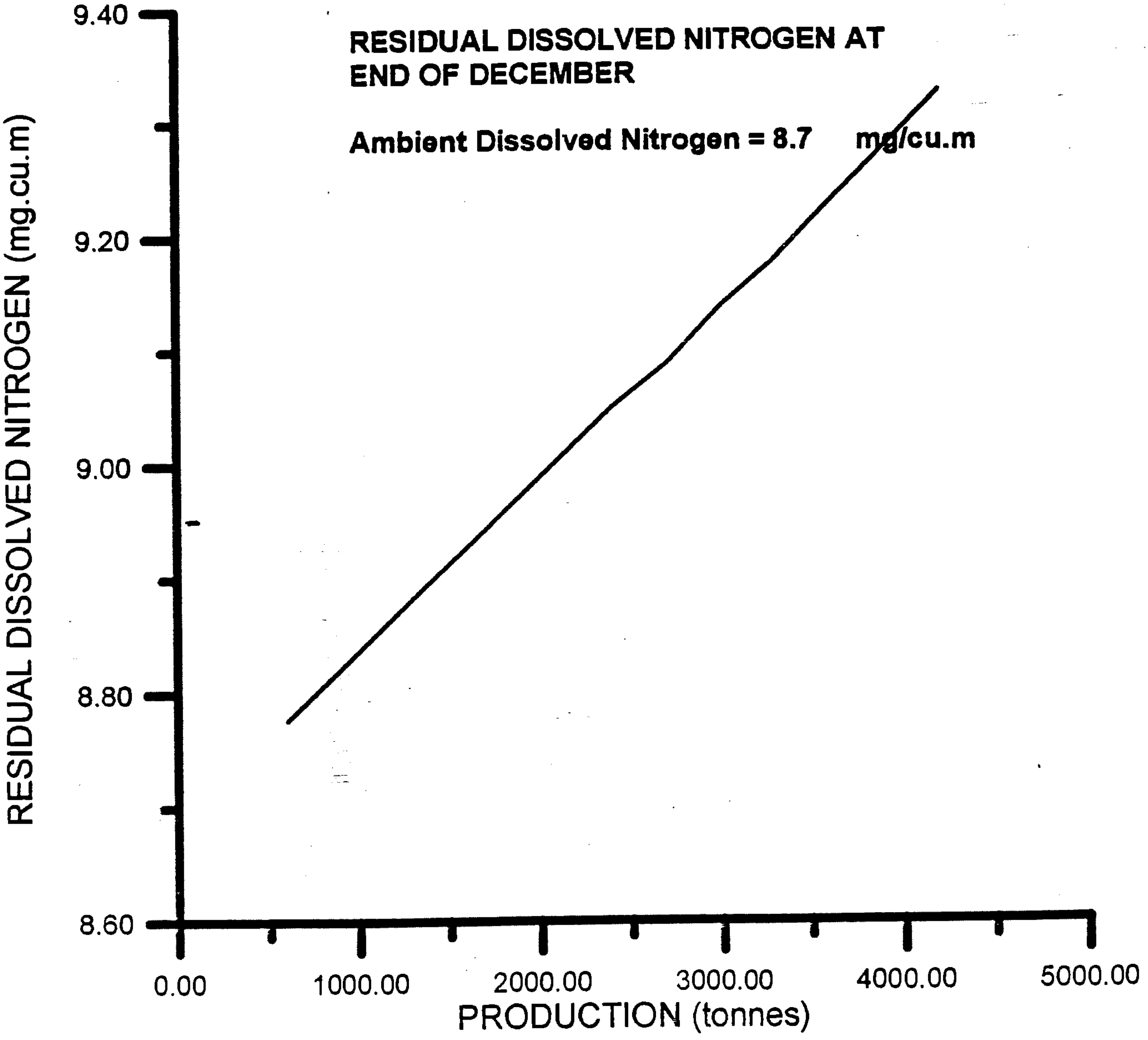

FIGURE 25
Residual dissolved nitrogen at end of 360 day simulation period - no sediment loss

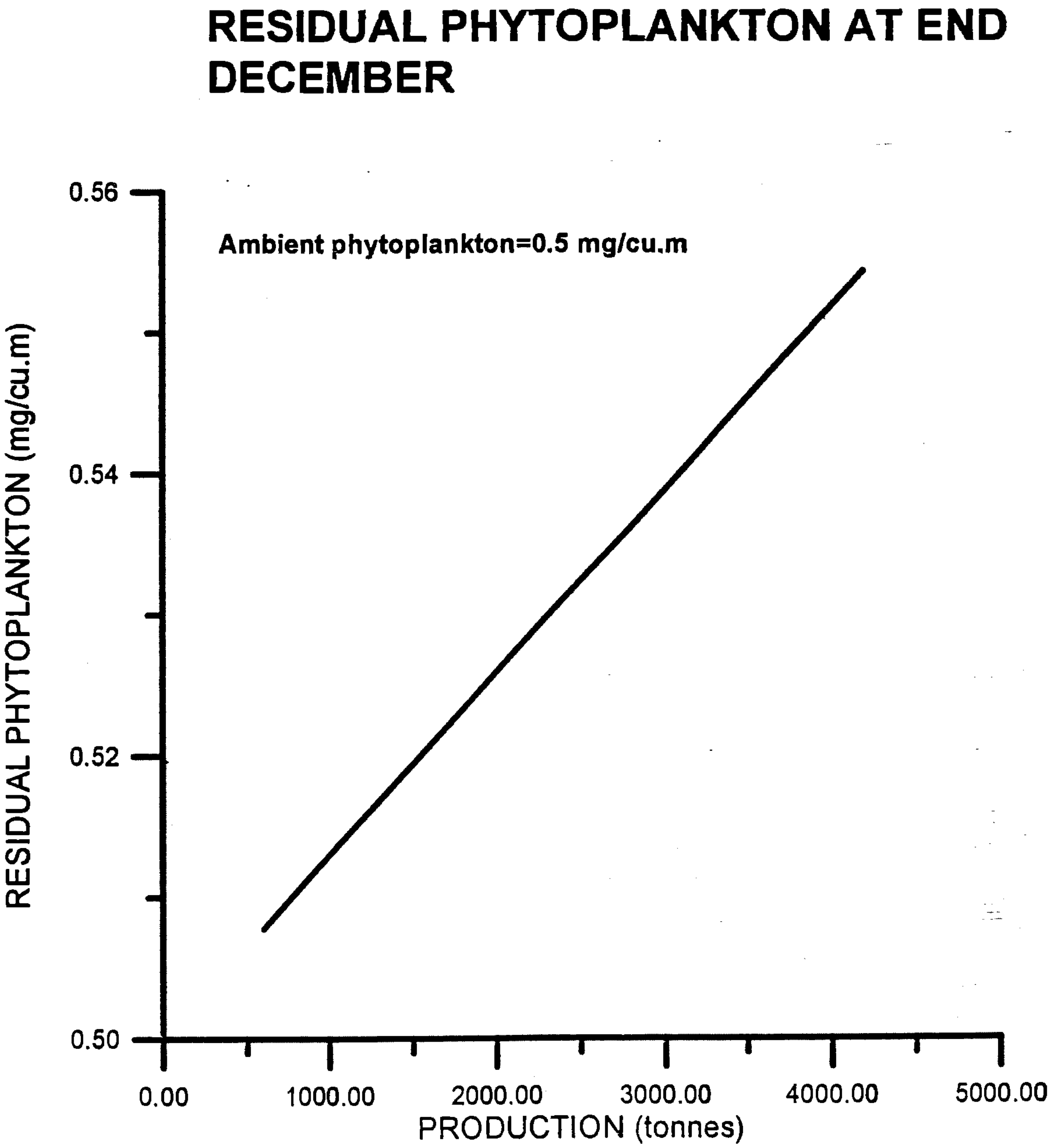

FIGURE 26
Residual phytoplankton level at end of 360 day simulation period - no sediment loss

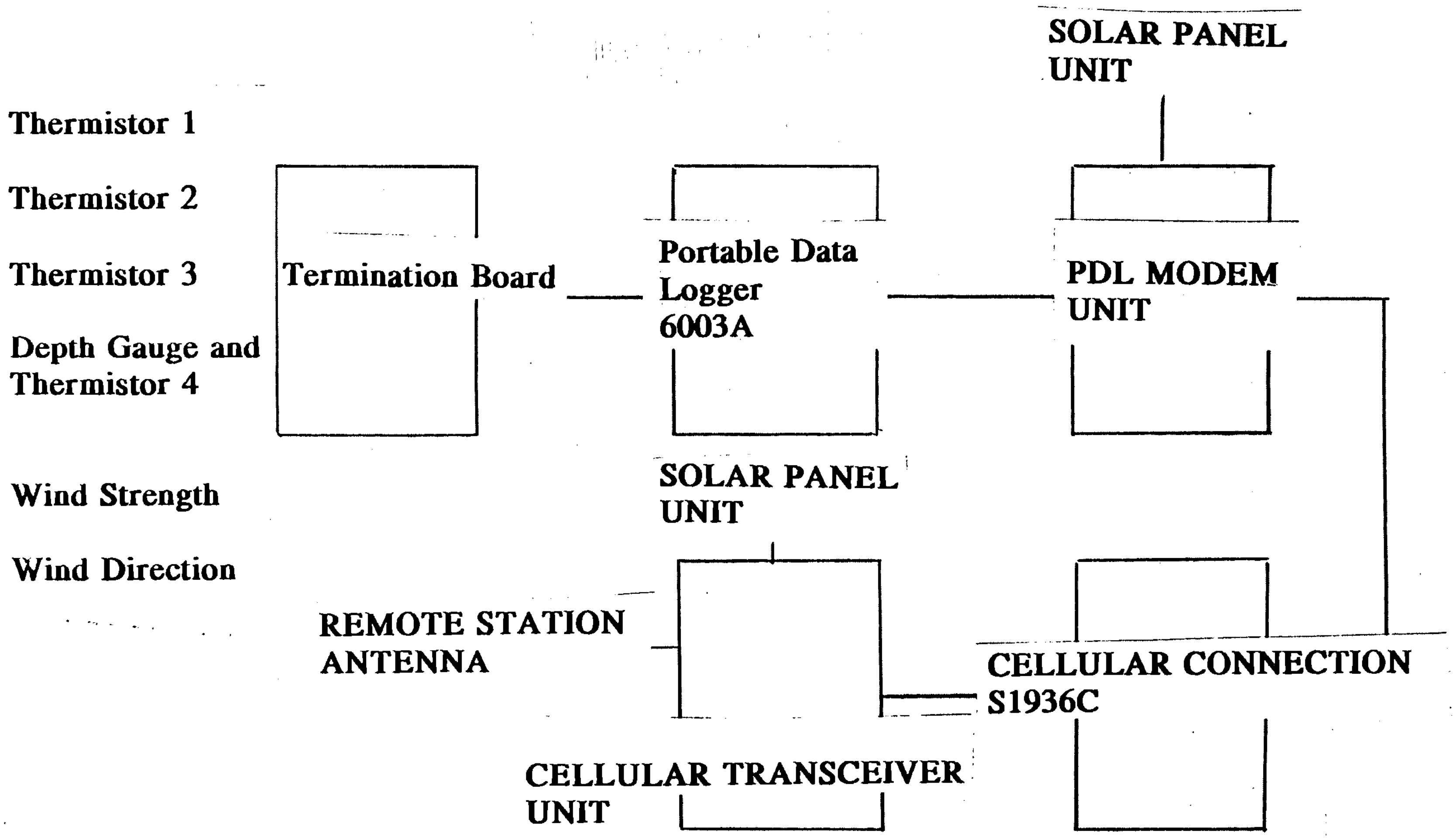

FIGURE 27

Block diagram of tuna cage environmental status monitoring system-remote station

TABLE 1
Tuna Farming Information (Obtained April 1996 in consultation with Industry)

MONTH	FISH IN (%)	TOTAL FISH IN (%)	FISH OUT (%)	TOTAL FISH OUT (%)	FOOD CONSUMPT. (% BODY WT/DAY)
JANUARY	10	10	0	0	10
FEBRUARY	25	35	2.5	2.5	10
MARCH	40	75	5.0	7.5	9
APRIL	25	100	7.5	15	8
MAY			10.0	25	7
JUNE			10.0	35	6
JULY			15.0	50	4
AUGUST			15.0	65	3
SEPTEMBER			15.0	80	3
OCTOBER			15.0	95	8
NOVEMBER			5.0	100	0
DECEMBER					

TABLE 2
Surface wind analysis 1500 hrs Port Lincoln

JANUARY 1500 HOURS LST

SPEED (KM/HR)

CALM 1

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
N	1	1	1	■	■			3
NE	3	3	4	■		■		11
E	3	7	19	4	■	■		25
SE	1	2	6	5	■	■		14
S	2	5	8	7	1	■		23
SW	1	2	5	6	1	■	■	16
W	■	■	1	2	1	■	■	6
NW	1	■	■	1	1	■		2
ALL	12	20	36	25	5	1	■	

NO OF OBS.1104

FEBRUARY 1500 HOURS LST

SPEED (KM/HR)

CALM 2

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
N	2	1	1	■	■		■	3
NE	3	4	4	1	■	■		11
E	3	6	11	4	■	■		24
SE	1	3	9	6	■	■		19
S	1	5	7	7	1	■		23
SW	1	3	5	5	1	■		14
W	■	■	1	1	1	■		3
NW	■		■	■	■	■		1
ALL	11	21	36	25	3	1	■	

NO OF OBS 1015

MARCH 1500 HOURS LST

SPEED (KM/HR)

CALM 1

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
N	2	■	■	■	■	■		3
NE	3	3	4	1	■			11
E	3	6	10	3	■			21
SE	1	3	9	4	■			18
S	2	4	8	5	1	■		20
SW	1	3	7	4	1	■	■	16
W	1	1	2	2	1	1	■	7
NW	1	■	■	1	■	■		2
ALL	13	21	39	20	4	1	■	

NO. OF OBS.1115

APRIL 1500 HOURS LST

SPEED (KM/HR)

CALM 2

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
N	1	1	1	1	1	■	■	4
NE	4	5	5	1	■	■		15
E	3	6	8	1				19
SE	1	2	6	2	■			11
S	2	3	5	2	1			13
SW	1	4	6	4	1	1	■	16
W	1	1	4	4	2	1	■	13
NW	■	1	2	2	1	■	■	6
ALL	14	23	35	17	5	2	1	

NO OF OBS 1077

MAY 1500 HOURS LST

SPEED (KM/HR)

CALM 2

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
N	2	2	2	1	1	■		8
NE	3	5	5	1	1			15
E	2	4	4	1	■			11
SE	■	2	2	1	■			5
S	1	3	3	2	■	■	■	10
SW	3	4	6	4	1	1	■	19
W	1	3	5	5	1	■		16
NW	2	2	4	4	1	1		14
ALL	15	24	31	19	6	2	■	

NO. OF OBS.1113

JUNE 1500 HOURS LST

SPEED (KM/HR)

CALM 4

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
N	3	3	4	2	1	■	■	13
NE	4	4	4	2	■	■	■	15
E	2	2	2	■	■			7
SE	1	1	1	■				3
S	1	2	3	1	■		■	7
SW	2	4	6	3	■	■		16
W	3	3	6	5	1	1	■	18
NW	2	3	6	4	1	1	■	17
ALL	18	21	31	18	5	2	1	

NO. OF OBS.1075

JULY 1500 HOURS LST

SPEED (KM/HR)

CALM 3

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
N	2	3	3	3	■	1	■	12
NE	3	3	3	1	■	■		12
E	1	1	1	■	■			4
SE	1	1	1	■				3
S	2	2	2	1	■	■	■	7
SW	2	4	6	4	2	■	■	19
W	2	4	6	6	2	1	■	21
NW	2	3	4	6	2	1	■	19
ALL	15	22	27	22	7	4	1	

NO. OF OBS.1112

AUGUST 1500 HOURS LST

SPEED (KM/HR)

CALM 2

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
N	2	3	3	2	■	■		11
NE	3	4	4	1	■	■		12
E	2	2	1	■	■			5
SE	1	1	1	■	■			3
S	2	3	3	2	■			10
SW	2	4	7	5	2	1	■	20
W	2	3	5	6	3	1	■	20
NW	2	3	5	5	2	1	■	17
ALL	14	21	29	22	8	2	■	

NO OF OBS.1113

TABLE 2 (continued)
Surface wind analysis 1500 hrs Port Lincoln

SEPTEMBER 1500 HOURS LST

SPEED (KM/HR)

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
CALM 1								
N	3	2	2	1	■	■	■	9
NE	3	4	6	2	■	■		16
E	2	3	3	1	■	■		9
SE	■	1	2	1				4
S	1	3	4	3	■	■	■	11
SW	2	5	7	6	2	1	■	22
W	1	2	4	5	3	1	■	16
NW	1	2	3	3	1	1	■	12
ALL	13	21	31	22	7	4	1	

NO. OF OBS. 1073

OCTOBER 1500 HOURS LST

SPEED (KM/HR)

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
CALM 1								
N	2	2	2	1	■	■	■	7
NE	3	5	5	1	■	■		15
E	2	5	7	2	■			15
SE	■	1	4	2	■			7
S	1	2	5	3	■	■		12
SW	1	3	7	6	2	1	■	21
W	1	1	3	5	4	1	■	15
NW	1	1	1	2	1	■	■	7
ALL	11	20	34	22	8	3	1	

NO. OF OBS 1110

NOVEMBER 1500 HOURS LST

SPEED (KM/HR)

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
CALM 1								
N	2	1	1	1		■	■	5
NE	3	5	6	1	■	■		15
E	3	5	9	2	■			19
SE	1	2	4	2	■			9
S	1	4	6	5	1	■		17
SW	1	3	7	6	2	1	■	20
W	■	1	3	4	2	1	■	11
NW	1	1	1	1	■	■	■	4
ALL	11	21	36	22	6	3	1	

NO. OF OBS. 1075

DECEMBER 1500 HOURS LST

SPEED (KM/HR)

DIRN	1 TO 5	6 TO 10	11 TO 20	21 TO 30	31 TO 40	41 TO 50	51 & UP	ALL
CALM 1								
N	2	1	1	■		■	■	4
NE	3	4	4	1				12
E	2	5	8	2	■			18
SE	1	2	5	2	■	■		11
S	1	5	8	6	1	■	■	22
SW	■	4	7	6	2	■	■	21
W	■	1	2	3	2	1	■	9
NW	1	■	■	■	■	■	■	3
ALL	10	21	37	22	6	2	1	

NO OF OBS. 1111

TABLE 3
Derived wind and tide data Port Lincoln

NOTES

1. Wind data are 1500 h observations
2. Wind data are based on 36 year data record Port Lincoln Post Office produced by the Bureau of Meteorology. The speeds shown for each month represent the average of the largest (by percentage) occurring wind speed range. For example, the range of wind speeds which occur most frequently are in the range 11-20 km/h, thus 15.5 km/h represents the mean of the range.
3. Wind direction is the mean of the sector range in which occurs the most frequently occurring winds. For example, in January, 62 % of the time the wind is between east and south, hence south-east was taken as the mean direction.
4. Tidal data is mean sea level (MSL) from 20 year data record at Port Lincoln produced by National Tidal Facility, Flinders University of South Australia.

MONTH	WIND SPEED (km/h)	Occurrence %	DIRECTION	Occurrence %	MSL (m)
JANUARY	15.5	36	SE	62 E-S	0.98
FEBRUARY	15.5	36	SE	66 E-S	0.97
MARCH	15.5	39	SE	59 E-S	0.99
APRIL	15.5	35	E	45 NE-SE	1.08
MAY	15.5	31	W	49 SW-NW	1.14
JUNE	15.5	31	W	51 SW-NW	1.15
JULY	15.5	27	W	59 SW-NW	1.14
AUGUST	15.5	29	W	57 SW-NW	1.08
SEPTEMBER	15.5	31	W	50 SW-NW	1.02
OCTOBER	15.5	34	SW	45 S-W	1.00
NOVEMBER	15.5	36	SW	48 S-W	0.98
DECEMBER	15.5	37	S	54 SE-SW	1.00