Dilution and Transport of Discharged Material from a Proposed Abalone Farm

Prepared by: Brian G. Sanderson,

15 Beckwith St, Wolfville, NS B4P 1R3, Canada

email: bxs@eastlink.ca, Phone: 902 697 2592

August 22, 2013

Contents

1 Introduction

It is proposed to develop an abalone farm Pindimar, Port Stephens. Abalone are to be grown onshore. The farm will draw 50 ML of seawater per day from Port Stephens. The abalone farm will modify the nutrient content of the withdrawn water which will then be discharged back into Port Stephens. In the following work we will examine:

- The nutrient loads to be expected from the proposed abalone farm and how these loads compare with existing nutrient loads.
- The extent to which nutrient concentrations change from intake to outlet and how this compares with background values.
- How the discharged water is diluted by tidal mixing within Port Stephens.
- The extent to which the proposed abalone farm can be expected to increase nutrient concentrations within Port Stephens.

Australia is a nutrient poor continent (Flannery 1994) and its waters are infertile (particularly in the vicinity of NSW) as evidenced from the global distribution of chlorophyll (Yoder and Kennelly 2003). It is commonly understood that human population growth in the coastal catchments of NSW has caused nutrient loading of estuaries and lagoons to be increased beyond natural levels. The concern is that such eutrophication might cause changes in estuary ecology (Webster and Harris 2004) that are deemed to be undesirable.

Nitrogen is usually considered to be the macro-nutrient that most limits growth of plants, algae, and phytoplankton in marine and estuarine waters (Ryther and Dunstan 1971, Codispoti 1989).

Harris (2001) finds evidence for nitrogen limitation in many Australian lagoons and estuaries. Plants, algae, and phytoplankton can use nitrogen in either its oxidized states (NO_x) or its reduced state (ammonia). Increased supply of mineralized nitrogen is, therefore, an important consideration in the following work.

Because some organisms can fix nitrogen from the large atmospheric pool, there is an argument that phosphorus is the ultimate limiting nutrient for the ocean as a whole (Tyrrell 1999). In the judgement of the present author, this argument is sound. Further, this argument lays open a possibility that changes to phosphorus input might also influence the ecological state of Port Stephens — although the preponderance of evidence is that nitrogen is expected to be more relevant to ecological state. We will, therefore, also consider phosphorus in the following work.

2 Loads and Discharge from the Proposed Abalone Farm

Let us now consider the conversion of food into abalone and nutrients, following the calculation of Maguire (1996) which is based upon the production of 100 tonnes of live abalone.

2.1 Food conversion to produce 100 tonnes of abalone

- 150 tonnes of dry formulated feed is required to produce 100 tonnes of live abalone. This assumes a 1.5:1 food conversion rate (FCR). Coote et al (1996) achieved a FCR of 1:1 for eaten food but Flemming et al (1996) and Maguire (1996) indicate that 30% of the food will not be eaten. Housefield (pers. com.) has experience feeding abalone by ±10% daily adjustments depending upon whether or not all food was consumed during the previous day. It is anticipated that it will be possible to optimize feeding so that, on average, only 5% of the food will not be eaten. Nevertheless, the present calculations will be based upon 30% not being eaten in order err on the side of caution.

- 150 tonnes of food contains 40.5 tonnes protein or 6.5 tonnes of nitrogen. (Assuming protein is 16% nitrogen.)

  - 30% of the 6.5 tonnes-N of food is not eaten, **contributing 1.95 tonnes-N of particulate waste.**
  - 28% of ingested food (6.5-1.95=4.55 tonnes-N) is not digested, **contributing 1.27 tonnes-N of particulate waste.**
  - 25% of ingested food (4.55 tonnes-N) is used for growth, **contributing 1.14 tonnes-N in abalone tissues.** (Neori and Krom 1991; Peck et al 1987).
  - The rest of ingested food is metabolized, **contributing 4.55-1.27-1.14=2.14 tonnes-N as ammonia.** We will use "ammonia" to represent the sum of NH_3 and NH_4^+. Most (93% at 23 °C) ammonia-N is in its ionized form (NH_4^+) with only 7% not ionized (NH_3).

- Australian abalone feed typically contains 1% phosphorus — consistent with Tan et al (2001) and Maguire (1996b). Thus, 150 tonnes of feed has 1.5 tonnes-P.
  - 30% of food is not eaten (assuming worst case), **contributing 0.5 tonnes-P in particulate waste**.
  - 20% of eaten P is not digested, **contributing 0.2 tonnes-P in particulate waste.**
  - There is about 200 μg-P per g of abalone shell (Tan et al 2002). By weight, approximately 1/3 of the animal is edible meat, 1/3 is offal, and 1/3 is shell (King et al 1996). Thus 33 tonnes of **shell contains 0.007 tonnes-P.**
  - The soft-body of abalone contains about 1500 μg phosphorus per gram of tissue (Tan et al 2002), **contributing 0.10 tonnes-P in abalone tissue.**
  - This **leaves about 0.69 tonnes-P which we assign to filterable reactive phosphorus (FRP).** This contribution *errs on the side of overestimating impact* because it assigns phosphorus to its most bioavailable form, FRP, whereas we expect some phosphorous would be chemically bound to organic material.

2.2 Nutrient Loads from the Abalone Farm

The farm is designed to produce 60 tonnes per year of live-weight abalone from an on-farm biomass of 67 tonnes. Let us now calculate the nutrient loads to be discharged into Port Stephens. Nutrient loads are obtained from the above food conversion calculations, on the assumption that the on-farm biomass of live abalone is 67 tonnes.

- Ammonia (NH_3+NH_4^+) Load: Rescaling ammonia produced by abalone metabolism $2.14 \times 67/100$ results in an **Ammonia Load of 1.43 tonnes-N/year.**

- Total Nitrogen (TN) Load: Uneaten and undigested food produce $(1.95 + 1.27) \times 67/100 = 3.22$ tonnes-N of particulate waste. It is expected that 80% of the waste will be separated/filtered before discharge. Summing the remaining particulate N and ammonia-N gives a **Total Nitrogen load of 2.07 tonnes-N/year.** Total failure to remove particulates would increase the Total Nitrogen load to 4.65 tonnes-N/year.

- **Filterable Reactive Phosphorus (FRP) Load: is** $0.69 \times 67/100 = 0.46$ **tonnes-P/year.**

- Total Phosphorus (TP) Load: There are $(0.5 + 0.2) \times 67/100 = 0.47$ tonnes-P/year of particulate waste. 80% of this particulate waste will be separated/filtered before discharge. Adding the FRP load gives a **Total Phosphorus Load 0.55 tonnes-P/year.** If none of the particulates are separated/filtered, then the Total Phosphorus load will become 0.92 tonnes-P/year.

2.3 Comparison With Other Nitrogen Loads

The nitrogen load from the proposed abalone farm should be put in context with estimates of other loads. DECC undertook an exercise to estimate catchment loads of total nitrogen (TN) for use in the simplified estuary response model of Sanderson and Coade (2010). The TN load from the catchment of Karuah River was estimated to be ≈ 40 tonnes-N/year. TN load from the proposed abalone farm is 5% of this value. (Note, there are additional loads associated with rainfall and groundwater, for example, which are neglected in the DECC calculation.)

Catchment loads are highly variable and difficult to measure. Bartley et al (2012) analysed the limited measurements available for Australian catchments and found mean TN concentrations in catchment runoff of: 6800 μg/L from grazing on modified pasture, 1600 μg/L for grazing on native pasture/savanna/woodland, and 780 μg/L for forest. Given Karuah River has catchment area 1460 km^2 (DECCW 2010), annual rainfall $\approx$ 1100 mm, and setting the runoff coefficient to 0.2, the Bartley et al (2012) concentrations correspond to a TN load in the range 250-500-2200 tonnes-N/year — roughly an order of magnitude higher than the DECC estimate and more than two orders of magnitude higher than the expected load from the proposed abalone farm.

It is pertinent to note that a change in land use from forest to grazing might double the mean nitrogen load in catchment runoff (or increase it by a factor of 8 if the pasture is modified). Similarly, horticulture and other types of farming appear to greatly increase nutrient loads as does urban development (Bartley et al 2012). Clearly such human activity is expected to have already greatly increased nutrient loads into Port Stephens (and many other Australian waterways) relative to loads from the natural landscape. Regardless, nutrient from the proposed abalone farm is minor compared with that due to other human activity.

It should also be noted that upwelling by offshore conditions can substantially modify nutrient concentrations in surface layer on the adjacent shelf (Oke and Middleton, 2001). MHL (1999) give 110^6 m^3/day exchange at the entrance and the volume of the outer harbour (east of Soldiers Point) is 640×10^6 m^3 giving a time scale of about 1 week for elevated offshore nutrient conditions to modify the outer harbour. Given the substantial tidal exchange, nutrient levels in Port Stephens outer harbour might reasonably be expected to be strongly influenced by large scale upwelling and downwelling events on the neighbouring continental shelf — although measurements are scarce.

The Myall Lakes catchment is 818 km^2 (DECCW 2010) and this also represents a substantial nutrient input some of which ultimately flows into Port Stephens (Sanderson 2008). Input from the Myall Lake catchment, like discharge from the proposed abalone farm, is located in the outer harbour and so tidal currents more readily flush it than they do input from Karuah River.

Table 1: Concentration increase from intake pipe to outlet pipe

Nutrient	Load (tonnes/year)	Concentration Increment (μg/L)	ANZECC 2000 trigger (μg/L)
Ammonia	1.43	78	15
Total Nitrogen	2.07	113	100
Filterable Reactive Phosphorus	0.46	25	15
Total Phosphorus	0.55	30	50

The proposed abalone farm would result in a more steady nutrient load whereas many natural sources are highly intermittent. In this regard, the proposed abalone farm will be expected to have TN loads more like those from urbanized portions of the Port Stephens catchment. Base flow from urbanized catchment can have high concentrations of TN (Bartley et al 2012). Runoff from urbanized areas will drain via the foreshore whereas the abalone farm discharges into deeper offshore waters whereby the impact of the latter will be relatively minimized.

In their estuary process study, MHL (1999) calculated annual total phosphorus load of 80.1 tonnes-P/year, of which 38.5 tonnes-P/year was from catchment runoff. This load was calculated for the year of 1997 which had catchment discharge close to the long term average (MHL 1999). Again, the difficulty estimating such loads must be recognized. Nevertheless, the proposed abalone farm would contribute a total phosphorus load that is two orders of magnitude smaller than the existing load.

2.4 Nutrient Concentration Increment: from ocean intake to farm outlet

The proposed abalone farm will pump 50 ML of seawater each day. Thus, the above nutrient loads from the abalone farm can be converted into concentration increases of the outflow water relative to the intake water (Table 1).

Production of abalone will be compromised if ammonia-N concentration approaches 570 μg/L.

Clearly, this will not be an issue. On the other hand, nutrient concentrations within the outlet pipe may exceed ANZECC 2000 trigger values — so mixing and dilution subsequent to discharge will be calculated in Section 6. Relative to ANZECC 2000 trigger values, the ammonia increment is by far larger than the increments of other nutrients so attention should be focused upon the dilution of ammonia. In particular, **if dilution is deemed sufficient for ammonia then dilution will be sufficient for other nutrients**.

Measurements of nutrient concentrations at intake and outlet have been made available from two abalone farms, one in South Australia and the other in Victoria (Housefield, pers. com.). From these we calculate the average increment in nutrient concentration along with the standard error of that increment. Unfortunately, between farm comparisons will still be confounded by variable farming intensity and timing of nutrient measurements relative to feeding. Also, our calculations above did not include an estimate of the oxidized nitrogen (NOx) loads and concentration increments. It is not clear that there is a mechanism from which we could calculate any meaningful increase in NOx from the proposed abalone farm. Measurements from South Australia abalone farm (Table 2) show that increments in NOx are small compared to increments in ammonia and total nitrogen.

Interestingly, the South Australia Farm (Table 2) has total nitrogen (which includes ammonia) increasing by 51 ± 28 μg-N/L which is similar to the 78 μg-N/L increase in ammonia that is anticipated for the proposed farm. Measurements at the Victoria Farm (Table 3) result in ammonia concentration increasing by a smaller amount than for the proposed farm, although both farms cause an increase above the ANZECC 2000 trigger value. Table 3 also shows the increase in total nitrogen at the Victoria farm is only partly attributable to ammonia. Maguire (1996) observes that apart from ammonia, particulate nitrogen is a waste product which can be well removed with appropriate filtering and cleaning of excess food (the abalone food being dense and therefore amenable to separation from the water). The presently proposed abalone farm in NSW will use filtering, settling, and cleaning to remove particulates.

Table 2: South Australia Farm — averages over 6 occassions May-Dec 2003

Nutrient	Intake (μg-N/L)	Outlet (μg-N/L)	difference (μg-N/L)
Total Nitrogen	153 ± 26	204 ± 25	51 ± 28
NOx	5.5 ± 0.5	7.3 ± 0.6	1.8 ± 0.5

Table 3: Victoria Farm — averages over 3 occassions, 2003-2004

Nutrient	Intake (μg-N/L)	Outlet (μg-N/L)	difference (μg-N/L)
Total Nitrogen	178 ± 38	283 ± 38	105 ± 8
Ammonia	13 ± 4	54 ± 9	41 ± 7

2.5 Background Nutrient Concentration

Existing measurements of nutrient concentrations give some insight as to the background nutrient concentrations that might be expected in the water which the abalone farm draws and subsequently discharges with nutrient increments discussed above. Additionally, in Section 6 we will calculate the dilution of the nutrient increment — which should be assessed relative to background concentrations.

It must be understood that obtaining nutrient concentrations is both laborious and expensive. Further, nutrient concentrations are observed to be highly variable. Throughout New South Wales estuaries and lagoons, it is fair to say that knowledge of nutrient concentration suffers from undersampling. Nevertheless, a fair estimate of the general magnitudes and variations of nutrient concentrations can be made.

In their estuary processes study, MHL (1999) reported on all nutrient measurements made in Port Stephens up to that time. Based upon EPA measurements made from 1973-1993, MHL (1999) reported that:

- 80% of NO_x measurements were below 100 μg-N/L and 50% were below 10 μg-N/L.
- 30% of FRP (filterable reactive phosphorus) measurements in Port Stephens exceeded 15 μg-P/L.

Table 4: Nutrient concentrations obtained from offshore sites located within the inner and outer harbours of Port Stephens, for wet and dry weather (MHL 1998).

Nutrient	inner Harbour		outer Harbour	
	dry	wet	dry	wet
TKN (μg-N/L)	NA	200	NA	100
NH4 (μg-N/L)	NA	40	40	< 10
NOx (μg-N/L)	20	20	20	10
TP (μg-P/L)	30	95	10	35
FRP (μg-P/L)	NA	10	NA	13

- 70% of TP (total phosphorus) observations in Port Stephens were below 50 μg-P/L wheres 70% of TP observations in Karuah River exceeded 50 μg-P/L. Relatively high phosphorus and chlorophyll-a indicate a degree of eutrophication in Karuah River.

MHL (1999) also summarize 1995-1998 measurements made by Hunter Water Corporation (HWC) at the southern foreshore of Port Stephens under mostly dry-weather conditions. TP was in the range 5-12 μg-P/L and NO_x 10-4000 μg-N/L.

To assess any impact of the Boulder Bay WWTW, beach sampling was carried out by HWC from January 1985 to March 1998 at five sites between Shoal Bay, Fingal Bay, Boulder Bay and Anna Bay. Sampling site along the Port Stephens foreshore (Jan 1985 - March 1998) gave TP in the range 5-100 μg-P/L and NO_x 10-230 μg-N/L.

MHL (1998) report dry weather sampling 17 and 18 Dec 1997 at various sites in Port Stephens. Wet weather sampling was undertaken 25 and 26 April 1998 at the same sites. Total Kjeldahl nitrogen (TKN) was measured. TKN is the sum of organic nitrogen, ammonia, and ammonium so it is less than TN because it does not include NO_x. Considering sites representative of offshore locations within the inner and outer harbours of Port Stephens, the nutrient concentrations are shown in Table 4. (Here the inner harbour is defined as that portion of Port Stephens that is west of Soldiers Point, the outer harbour being to the east of Soldiers Point.)

Recently (19/1/2011, 09/02/2011, 23/03/2011) the NSW EPA has made nutrient measure-

Figure 1: Locations of NSW EPA nutrient measurements on 19/1/2011, 09/02/2011, 23/03/2011

ments at three sites near the intake and outlet locations for the proposed abalone farm. Specific sampling sites are marked with thumb tacks in Figure 1. The nutrient concentrations averaged over the three sampling occasions are given in Table 5.

Clearly nutrient concentrations within Port Stephens are highly variable. Generally, existing concentrations are comparable to ANZECC 2000 trigger levels. The abalone farm is expected to raise concentrations of total nitrogen and phosphorus, from intake to outlet pipe, by amounts that are within the variability of available measurements of existing concentrations. Ammonia is the nutrient that is most clearly raised above the previously measured values in Port Stephens. Clearly, it is critical to examine the dilution of ammonia after discharge from the outlet from the proposed abalone farm.

Table 5: Nutrient concentrations measured by NSW EPA in 2011.

Nutrient	Mean and SEM
Total Nitrogen, TN (μg-N/L)	137 ± 7
Total Dissolved Nitrogen, TDN (μg-N/L)	110 ± 6
Ammonia, NH3-N (μg-N/L)	4.3 ± 2.3
Nitrate+nitrite, NOx (μg-N/L)	4.5 ± 1.8
Total Phosphorus, TP (μg-P/L)	15.6 ± 0.3
PO34, FRP (μg-P/L)	7 ± 1

3 Long-Term, Large-Scale Change of Ammonia-N

Given that the proposed abalone farm adds small nutrient loads compared to other sources in the catchment, one would expect it to have little impact upon the long-term nutrient concentrations that are presently observed throughout Port Stephens. Box models can serve to illustrate long-term, large-scale distributions of nutrients in semi-enclosed water bodies. Calculations will be made for ammonia-N because this is the nutrient that is most critically impacted by the proposed abalone farm (relative to background levels).

MHL (1998) measured tidal prisms in September 1993. At the entrance to Port Stephens, the ebb tide had a volume of 168×10^6 m^3 and the flood tide transported a volume of 165×10^6 m^3. At Soldiers Point the volumes were smaller, averaging 103×10^6 m^3 on the ebb tide and 110×10^6 m^3 on the flood tide. Currents had peak magnitudes larger than 1 m/s on both the ebb and flood tides.

Freshwater flow into Port Stephens will act to enhance flushing of discharge from the abalone farm out to sea and thereby reduce the impact of the abalone farm. Most of the time freshwater inflow is small compared to the tidal flow. Here, the freshwater flow will be neglected in order to do a worst-case calculation of the average increase in ammonia-N due to discharge from the abalone farm.

MHL (1999) calibrated exchanges in a 13-box model against observations of water level and salinity. Their model used an exchange of 110×10^6 m^3/day at the entrance which can be reconciled with measurements of the tidal prism by using an exchange efficiency of 0.33.

Let us presently divide Port Stephens into 2 boxes. Box 1 has a volume $V_1 = 640 \times 10^6$ m^3 and represents the outer harbour from Soldiers Point to the entrance. Box 2 has a volume $V_2 = 580 \times 10^6$ m^3 represents the inner harbour west of Soldiers Point. Ammonia-N is discharged into box 1 at a rate of $S_1 = 1430/365 = 3.92$ kg-N/d. Let the exchange between box 1 and the ocean be $E_{1,0}$. The exchange between box 1 and box 2 is represented by $E_{1,2}$. Denote the concentration of material due to the source S be: C_1 in box 1, C_2 in box 2, and $C_0 = 0$ in the ocean.

The equation representing conservation of mass in box 1 is

$$\frac{dC_1V_1}{dt} = E_{1,0}(C_0 - C_1) + E_{1,2}(C_2 - C_1) + S_1 \tag{1}$$

and in box 2 conservation of mass is given by

$$\frac{dC_2V_2}{dt} = E_{1,2}(C_1 - C_2). \tag{2}$$

Highest concentrations will result when the system has reached a steady state. Setting the time derivatives to zero gives the following steady-state equations

$$E_{1,0}(C_0 - C_1) + E_{1,2}(C_2 - C_1) + S_1 = 0 \tag{3}$$

$$E_{1,2}(C_1 - C_2) = 0 \tag{4}$$

Solving the above equations gives

$$C_1 = C_2 = \frac{S_1}{E_{1,0}} \tag{5}$$

where we have used $C_0 = 0$. Note, the concentration in the inner harbour is elevated as much as that in the outer harbour because mixing is the only mechanism considered for transporting material between the two boxes. Consideration of river flow would reduce C_1 and also reduce C_2 relative to C_1.

Given $E_{1,0} = 110 \times 10^6$ m^3/day and $S_1 = 3.92$ kg-N/day, the concentration of ammonia-N would be elevated by 3.6×10^{-2} μg-N/L due to the abalone farm. This increase is:

- Insignificant relative to ANZECC guidelines for trigger values.
- Insignificant relative to previous measurements of ammonia in Port Stephens.

It is noteworthy that during the 25-26 April 1998 wet weather event MHL (1999) reported ammonia-N < 10 μg-N/L in the outer harbour, increasing to 30 μg-N/L in the middle of the inner harbour, and to 100-130 μg/L in Karuah River. Karuah River is obviously, on this occasion, a major source of increased DIN (dissolved inorganic nitrogen) within the inner harbour — dwarfing potential impact of the proposed abalone farm.

Although the presently proposed abalone farm is sited within the outer harbour, it is interesting to consider what might happen should it be relocated into the inner harbour. Now the steady equations can be written

$$E_{1,0}(C_0 - C_1) + E_{1,2}(C_2 - C_1) = 0 \tag{6}$$

$$E_{1,2}(C_1 - C_2) + S_2 = 0 \tag{7}$$

where the source from the abalone farm is now represented by S_2 (which will have the same numerical value as S_1 above). Solving the above equations gives

$$C_1 = \frac{S_2}{E_{1,0}} \tag{8}$$

and

$$C_2 = \frac{S_2}{E_{1,0}} + \frac{S_2}{E_{1,2}} \tag{9}$$

where we have used $C_0 = 0$. The concentration in the outer harbour C_1 is the same as before but C_2 is increased. Given the above measurements of tidal volumes $E_{1,2} = 69 \times 10^6$ m^3/day. Substituting into (9) the concentration in the inner harbour becomes $C_2 = 0.09$ μg-N/L. Again, this is still very small compared to background values. Nevertheless, discharging into the outer harbour is more prudent than discharging into the inner harbour.

Except near the point of discharge, the abalone farm is unlikely to cause a measurable change in nutrient concentration in either the inner or outer harbour.

4 Drifter Releases from the New Outlet Position

In the major channels, the vertically-averaged tidal currents have amplitudes in the range 0.45-0.95 m/s (NSW Public Works Department 1987, Report 85045). Currents nearer shore can be quite different, exhibiting great spatial and temporal variability, as previously shown by drifter studies in Salamander Bay (McOrrie, 1984) and in the vicinity of Pindimar (Sanderson 2004).

The proposed abalone farm will have two outlet pipes that are separated by a few metres where they lay over vegetated areas but come to a single position at the deep, unvegetated outlet position. Drifters were deployed from the outlet position in order to measure likely trajectories for discharge from the proposed abalone farm. It is only practical to measure short-term trajectories near the outlet because in the longer term trajectories become most numerous in their variation.

Repeated deployments were made from the outlet position at intervals of about 30 minutes and tracked over the next 20-30 minutes using GPS. Observations of wind and salinity/temperature profiles were also made. Tracking was done at times of mostly light wind when the water column had little vertical stratification. Drifters were drogued at the depth of the edge of the seagrass bed. Measurements were made on: 6-7-14 April 2012, 12 May 2012, 29 July 2012, 4 August 2012. Cumulatively, measurements spanned the tidal cycle.

Drifter displacements for each day are presented in the HTML documentation (Sanderson 2013) where they are incorporated into movies showing tidal currents obtained from modelling. Details of tidal water levels and drifter velocities are also presented in the HTML document.

The duration of each drifter track was somewhat variable. In Figure 2 the drifter displacements have directions as obtained by measurements but the length of the displacement has been normalized to that which the drifter would have made over a 20 minute period. In this way, the variability of the different drifter tracks can be better assessed as a function of current variability as opposed to variations in tracking time. Generally the drifter trajectories are oriented along bathymetric contours and have more of a tendency to track into deeper water than to track into shallower water.

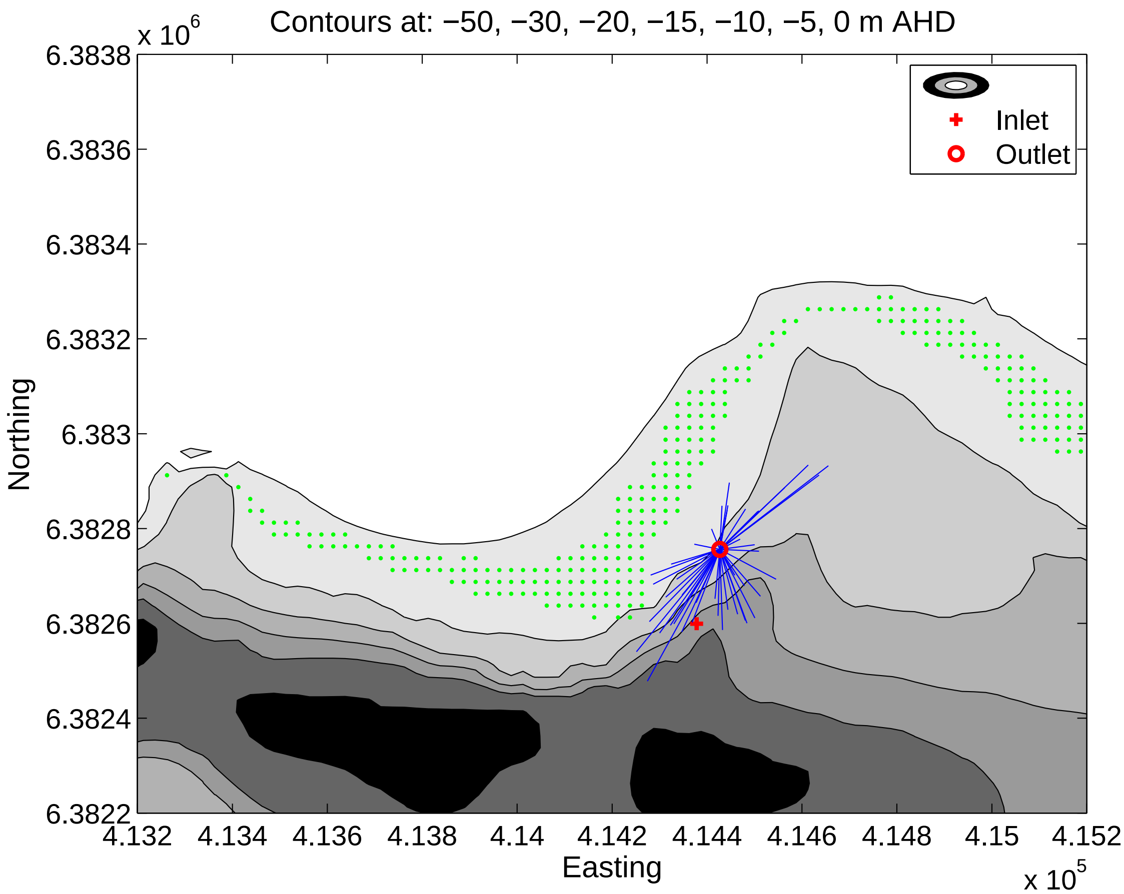


Figure 2: Blue lines show drifter displacements from the outlet position that have been normalized to a 20 minute period. Bathymetric contours are drawn with black lines and filled on a gray scale. The proposed abalone farm will pump seawater with intake (red cross) and outlet (red circle). Green dots indicate the location of *Posidonia*.

5 Current Modelling

A three-dimensional model was used to model tidal currents. The model uses high-order numerics to obtain accurate solutions with low dissipation (Sanderson 1999) which is essential in order to achieve an eddy-admitting solution. Eddies are important for determining the dispersal of material discharged from the outlet pipes. Fundamental features of the model are described by Sanderson and Brassington (2002) and a recent computational advancement by Sanderson (2011). For the present application, nesting capabilities and accurate split-explicit time-stepping were added.

The model was run with a 150 m horizontal grid scale for the domain shown in Figure 3 and forced at its eastern boundary with water level measurements made at Tomaree. Black boxes show nesting to 50 m grid scale and then to a 25 m grid scale in the vicinity of the proposed abalone farm. Vertical grid-scale was 1.5 m for all levels of nesting. Bathymetric measurements were not available for Karuah River. Karuah River and the upper reaches of Tilligerry Creek are represented using simplified geometry in order to fit within the model domain.

The model was used to simulate currents at the times when drifter measurements were made. Such simulations were started 3-4 tidal cycles before the measurements in order to minimize spin-up effects. Detailed movies that compare modelled currents with drifter trajectories are given in the HTML documentation (Sanderson 2013). Generally measurements and model are in agreement considering the intermittent and spatially-complex eddies which are made most evident by the modelling. No efforts were made to tune the model to better match present observations. Such tuning, although a common practice, is not advised because tuning for an *ad hoc* data set does not necessarily improve the model given that the only tunable parameter (bottom drag coefficient) is based upon broader theory and measurement — indeed, such tuning can lead to a false impression for the accuracy of model predictions. In short, improving an interpolation does not necessarily improve an extrapolation.

Figure 4 shows a snapshot (one frame from one movie in Sanderson 2013) of modelled currents for the 25 m nested model. The outgoing tide is strong in the deeper waters offshore. A large scale eddy acts to entrain water from the outlet location towards the strong outflowing tide. Movies in

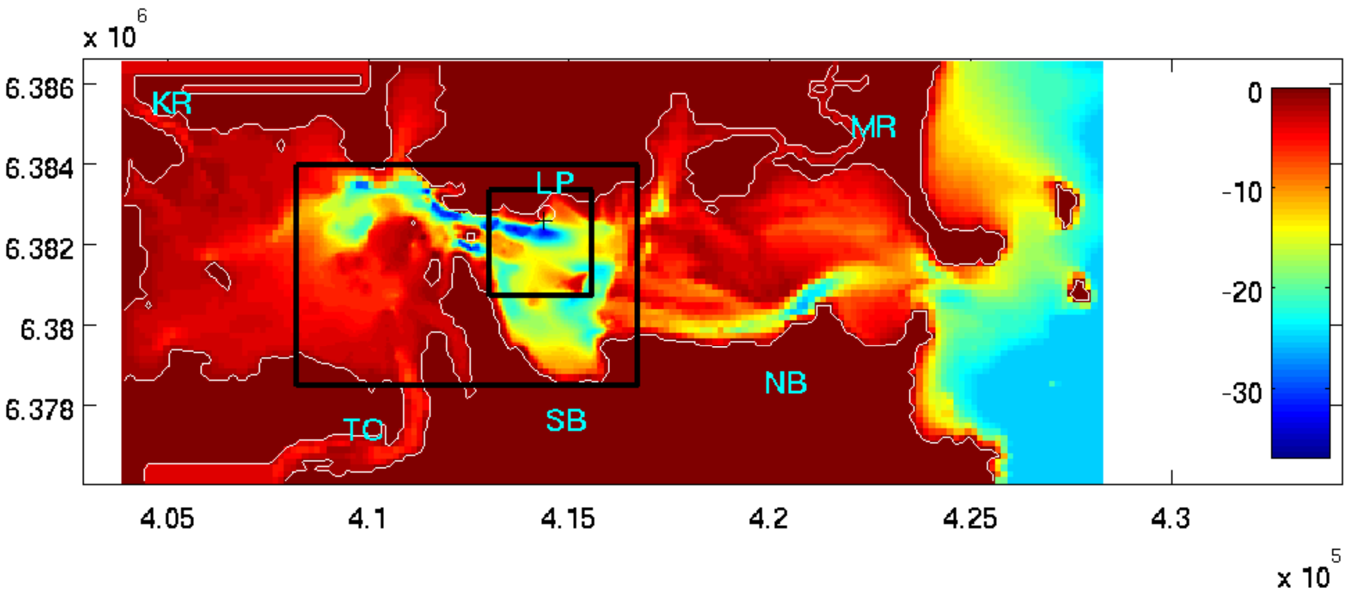


Figure 3: Depth (in metres relative to AHD) of Port Stephens is shown by the coloured map above. The total area of the above map is modelled using a three-dimensional hydrodynamic model with horizontal grid-scale 150 m. The area shown by the bigger black box was modelled using a grid-scale of 50 m with nesting within outer model. The smaller black box shows the area, near Pindimar, which was modelled using a grid-scale of 25 m nested within the 50 m resolution model. Indicated locations are: LP Lower Pindimar, MR Myall River, NB Nelson Bay, SB Salamander Bay, TC Tilligerry Creek, KB Karuah River.

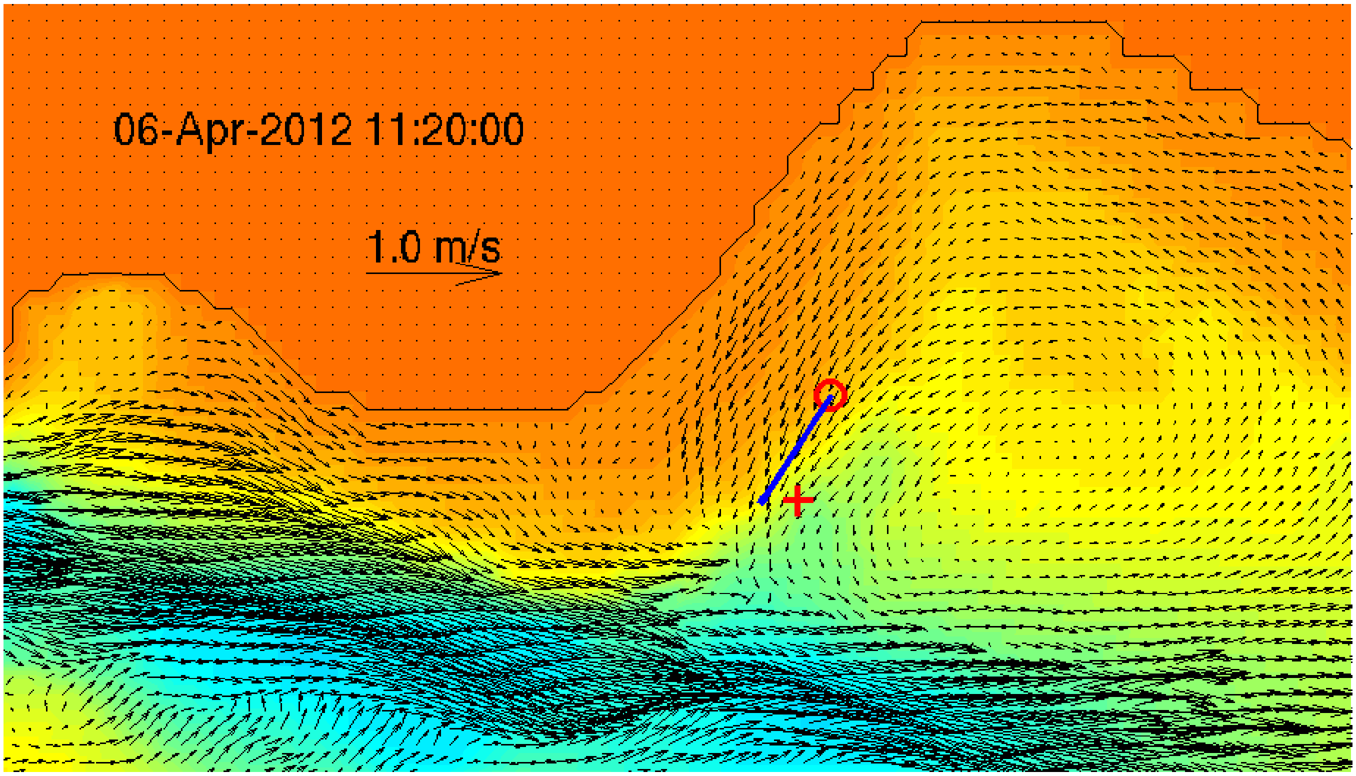


Figure 4: Modelled currents on the outgoing tide.The outlet location is plotted with a red circle and the intake with a red cross. The blue line shows a drifter displacement from the outlet position over a period of 20 minutes.

the HTML documentation (Sanderson 2013) show that the eddy field frequently has much more spatial variability and eddy structures greatly change through the tidal cycle.

6 Dispersion of Discharge

A key question is how would material disperse after it is discharged from the outlet pipes of the proposed abalone farm. This is modelled by adding an inflow (source) to the cell adjacent the bottom at the outlet position. Similarly, an outflow (sink) is added to the cell adjacent the bottom at the intake position. Both flows are constant and are set to 50 ML/day, consistent with the proposed abalone farm. The concentration of material in the outflow pipes is set to 1. Such normalization is applicable for dynamically-passive tracers and has the advantage of directly indicating the dilution fraction as material is transported and mixed in Port Stephens.

Simulations were done using spring and neap tides (Figure 5) to force the open boundary. Figure 4 gives some idea of the spatial complexity of the currents in the vicinity of the intake and outlet for the proposed abalone farm. A full appreciation of the spatio-temporal flow structure is better seen in the movies within the HTML documentation (Sanderson 2013). Fluid mixing can be understood in terms of irreversible stretching and folding mechanisms (Ottino 1985) associated with temporally-varying hyperbolic singularities (Halide and Sanderson 1993) evident in the simulated currents.

The model simulates dispersing material as a function of the three spatial dimensions and time. In Figure 6 the dispersing material has been averaged with respect to time and the vertical dimension. This averaged representation of the spreading material appears patch-like whereas at any particular time the material tends to be distributed as a plume that has considerable spatial structure. Temporal variability is presented in movies within the HTML documentation (Sanderson 2013). Material is more rapidly dispersed from the outlet position during spring tides (Figure 6). Material is more likely to be dispersed into shallow areas (over seagrass meadows) during spring tides — but at extremely diluted average concentrations.

Figure 6 shows concentrations normalized by the outlet concentration which is the most straightforward way to present dilution. To obtain an actual concentration of some material discharged from the outlet pipes, one need only multiply the normalized concentrations by the actual concentration in the outlet pipes. For ammonia-N the concentration in the outlet pipes

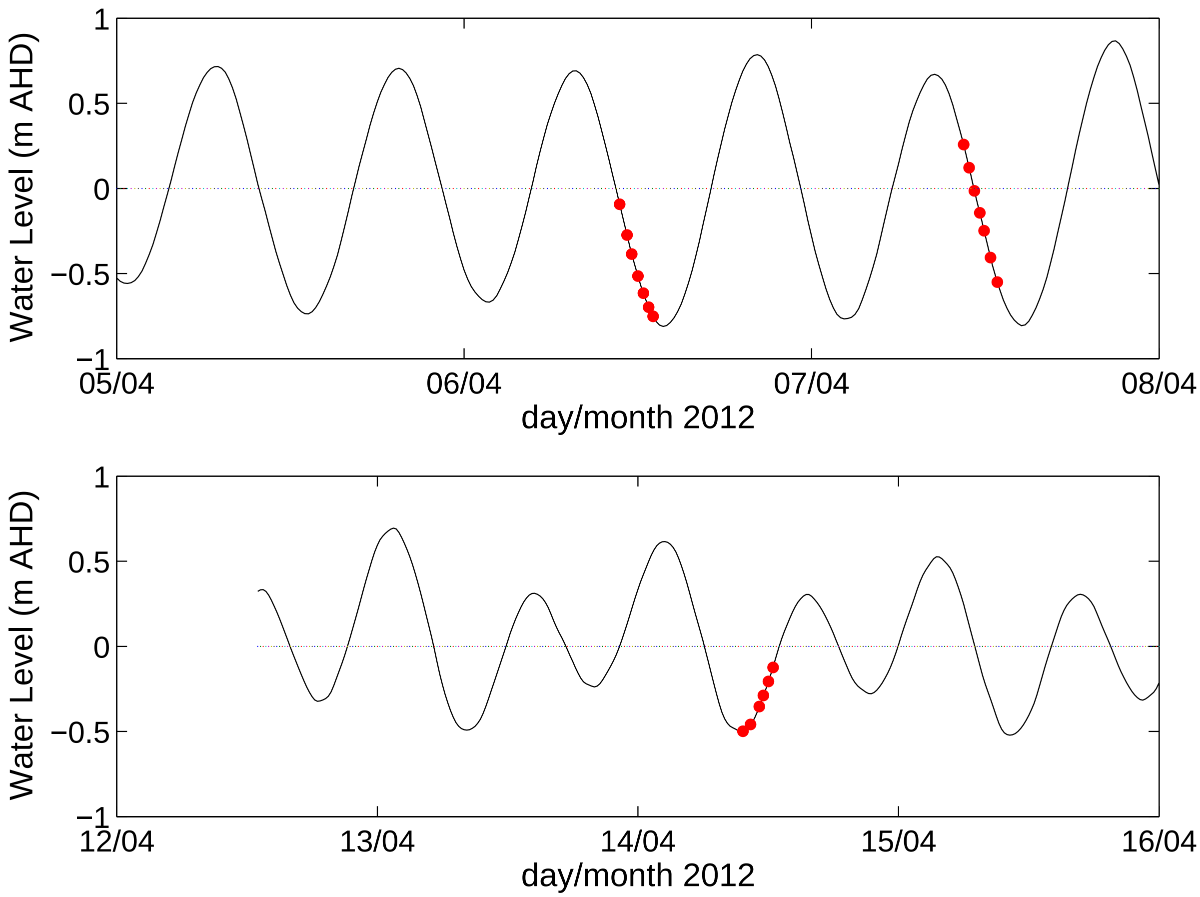


Figure 5: Water level as measured at Tomaree and used as boundary conditions for simulating the dispersion of material discharged from the outlet pipes. Top: spring tides. Bottom: neap tides. Read dots indicate times coincident with some of the drifter measurements.

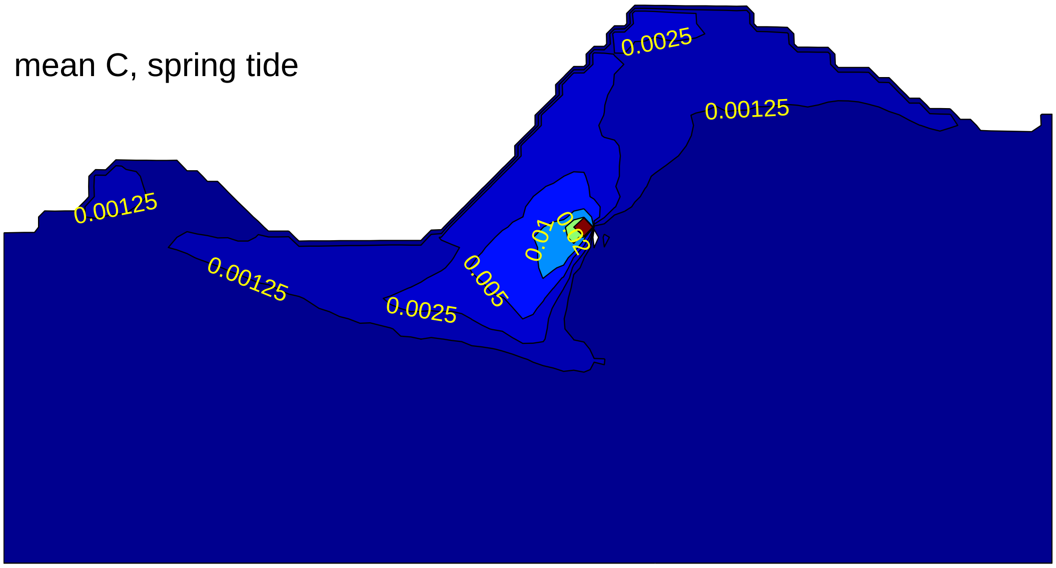
was estimated (in Section 1) to be elevated by 78 μg/L. Thus, on average, the abalone farm can be expected to cause an increment in ammonia-N as presented in Figure 7. These increments are much less than 15 μg/L, the ANZECC (2000) trigger value for ammonia-N. The increments are also much less than background values of ammonia-N, see Section 2.5 and Tables 4 and 5.

The averaged increments plotted in Figure 7 are most relevant for biological growth because such growth happens over time scales longer than the duration of eddies that come and go at different phases within the tidal period.

Obviously, concentrations might be intermittently higher at this or that local position from time to time due to the spatio-temporal structure (Figure 4) underpinning the averaged quantities plotted in Figure 6. Such variability is mostly due to the variation over the tidal cycle. Figure 8 shows the maximum (maximum instantaneous values during the periods modelled) increments in ammonia-N. Maximum values are substantially larger than the average increment, consistent with these peak values having very short duration and being spatially localized at any particular time. Short-lived, maximum values are still below the ANZECC (2000) trigger value. Maximum values are not statistically robust so we also plot contours of the mean plus two standard deviations in Figure 9; nominally ammonia-N falls below this concentration 97% of the time. Increments plotted in Figures 8 and 9 are not expected to be of great biological importance because they are short-lived (time scales typically ∼hour or less) and they are spatially localized (see movies in the HTML documentation, Sanderson 2013). Catchment discharge results in far greater peak values which persist for much longer periods and extend over much greater areas. In wet conditions, observations (MHL 1999) suggest naturally occurring ammonia-N can be in the range 10-40 μg/L in surface waters.

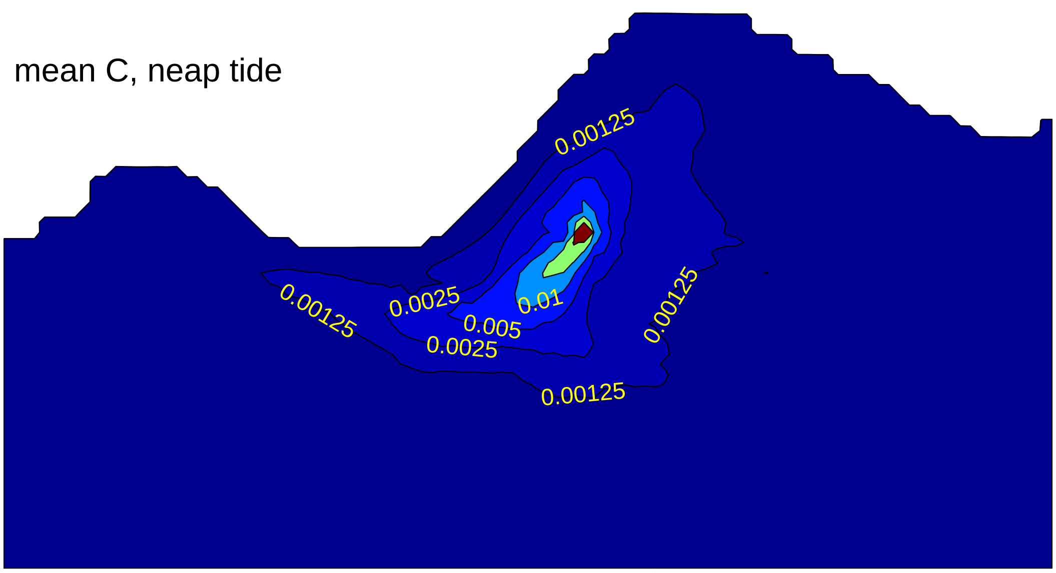
Additionally, concentrations in the outlet pipes might vary if the amount of abalone within the farm varies through production cycles. Concentrations will be reduced from those plotted above whenever stocking density is below maximum production.

The outlet and intake positions are separated by about 165 m in the horizontal and the intake is at greater depth. The question arises whether this separation is sufficient to effectively isolate the intake from the outlet. Figures 10 and 11 show normalized concentrations (representing dilution) mean C, spring tide



Contours: 0.00125, 0.0025, 0.005, 0.01 0.02, 0.04

mean C, neap tide



Contours: 0.00125, 0.0025, 0.005, 0.01 0.02, 0.04

Figure 6: Averaged concentration of normalized discharge from the outlet pipe. Averaging was with respect to depth and times subsequent to a 12 hour spin-up period. The concentration of material discharged from the pipe was 1 (ie normalized). Contours indicate the dilution factor.

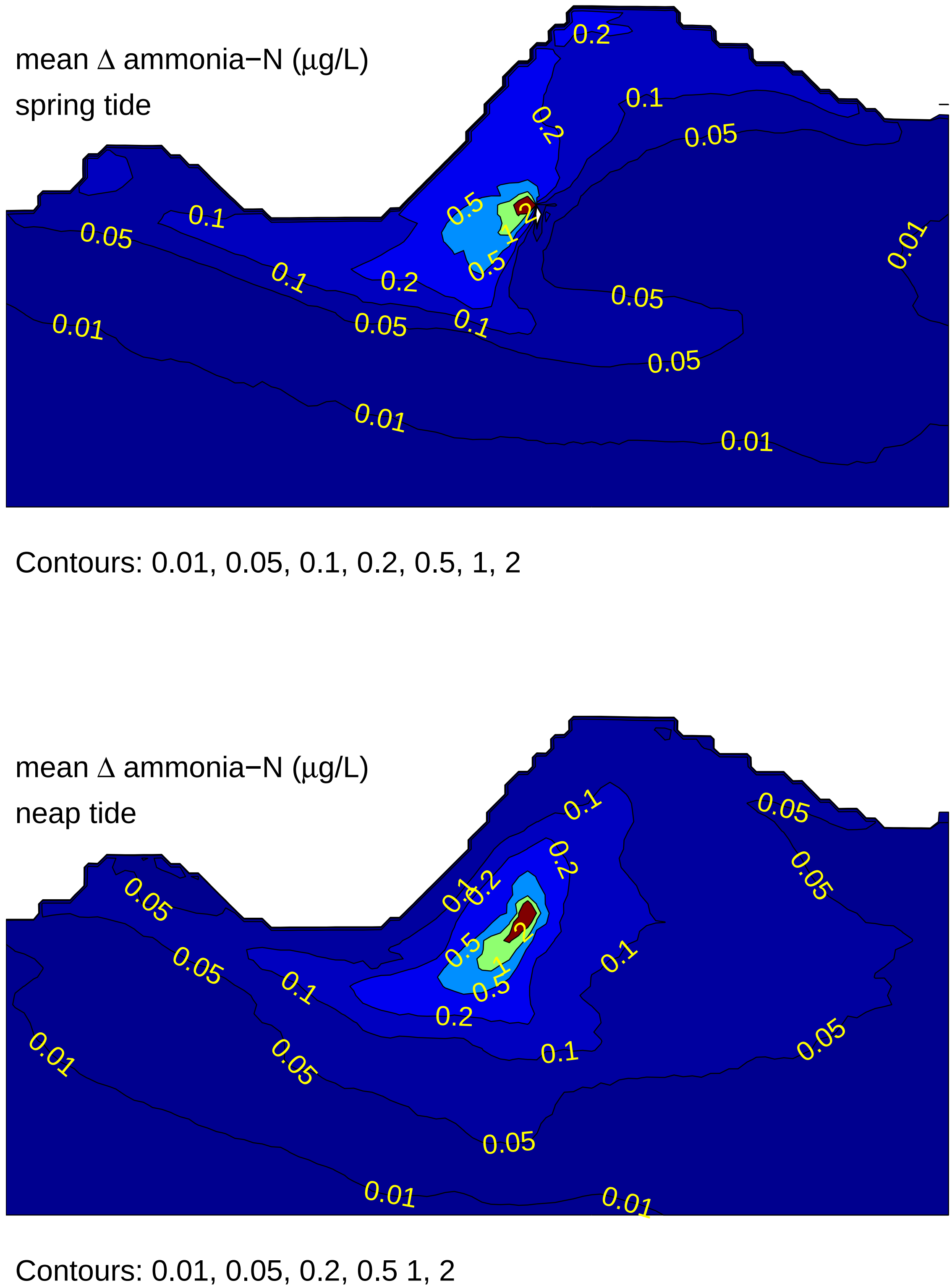


Figure 7: Averaged increment of ammonia-N (μg-N/L) given 78 μg-N/L in the outlet pipe. Averaging was with respect to depth and time subsequent to a 12 hour spin-up period.

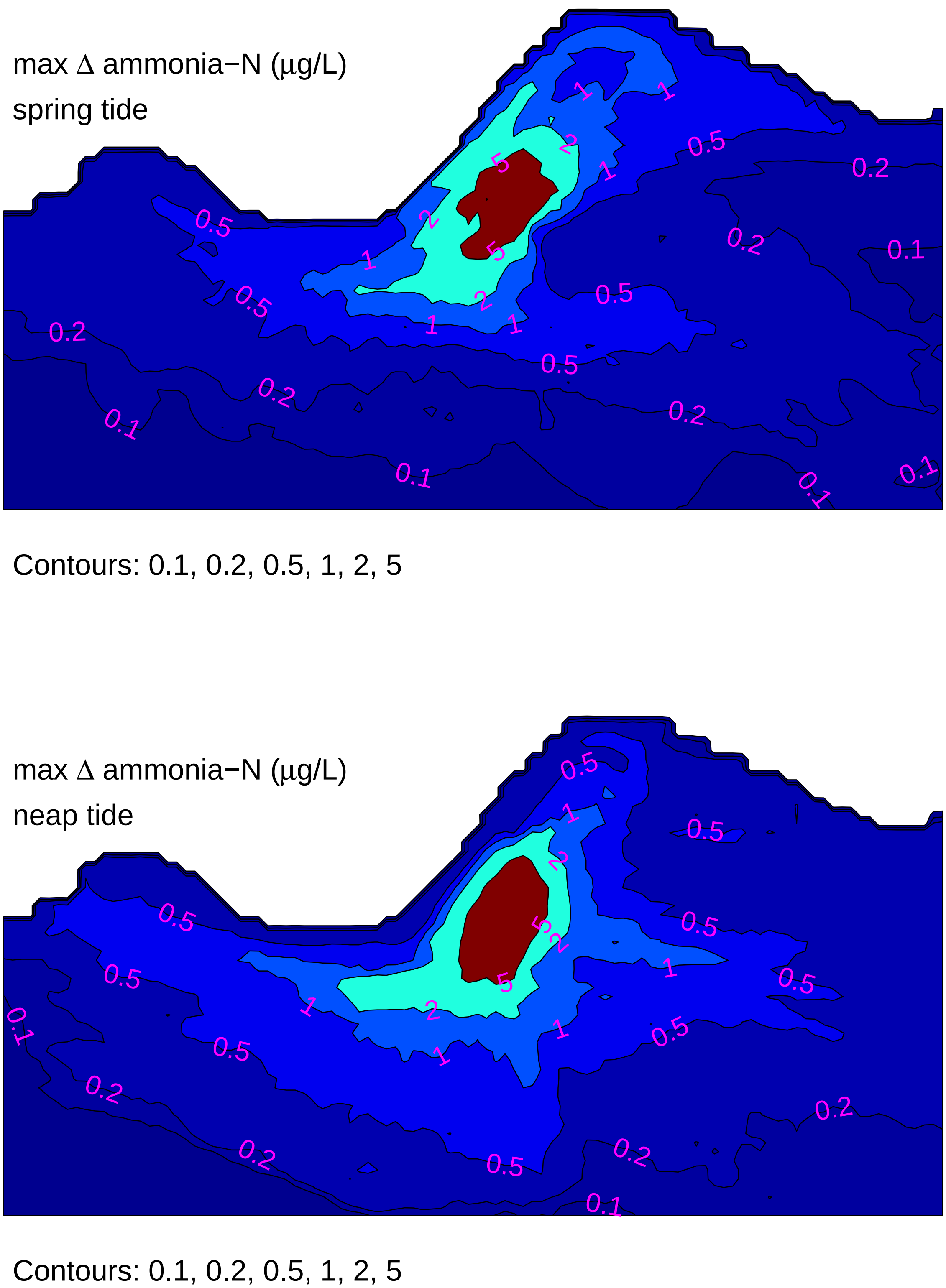


Figure 8: Maximum increment of vertically-averaged concentration of ammonia-N (μg/L) given incremental concentration 78 μg/L in the outlet pipe.

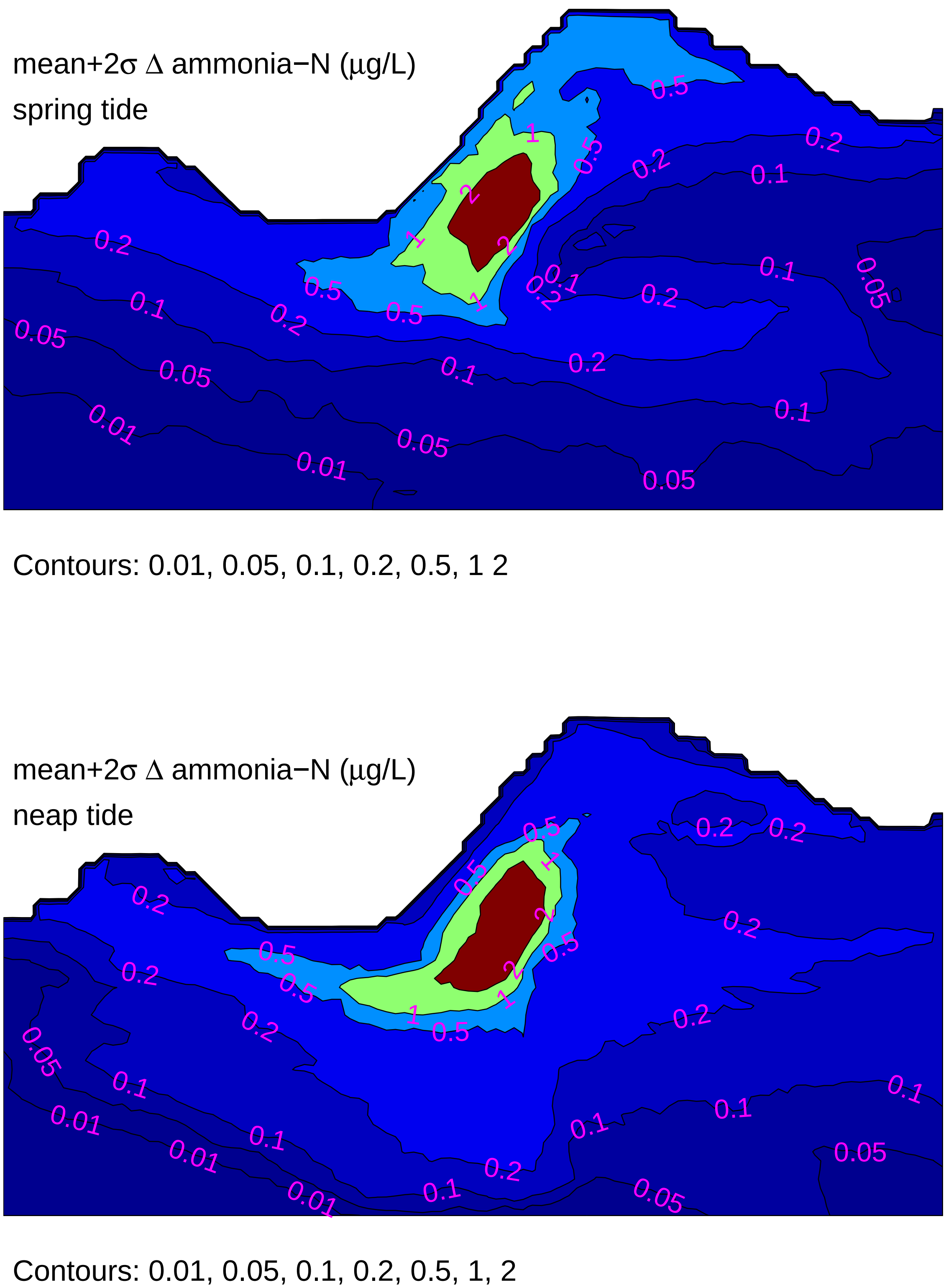


Figure 9: Mean plus two standard deviations for the increment of vertically-averaged concentration of ammonia-N (μg/L) given incremental concentration 78 μg/L in the outlet pipe.

Table 6: Minimum-maximum nutrient measurements in the subtidal zone. Obtained from Table 4.4 of Tanner et al (2007)

Region	site	TP (μg-P/L)	TN (μg-N/L)	ammonia (μg-N/L)	NO_x (μg-N/L)
Smith Bay	Farm	0-0	60-180	3-56	8-26
	Nonfarm	0-0	40-110	2-4	2-15
Streaky Bay	Farm	0-10	90-160	0-27	2-5
	Nonfarm	0-0	50-320	0-8	2-8

in the grid-cells within which the intake and outlet pipes are located. Each grid-cell has volume $25 \times 25 \times 1.5$ m^3 so even the outlet cell has normalized concentrations less than 1 given that discharge flow does not dominate the tidal currents on the scale of a model cell. Normalized concentrations are very low at the intake cell. However, intermittently the plume from the outlet does intersect the intake cell and a very small portion of the discharged material might be recycled through the proposed abalone farm. Generally, interference of the discharged material with the intake is greater for neap tides (Figure 11) than spring tides (Figure 10) — although it is always small in absolute terms.

6.1 Dispersion of discharge for other abalone farms

It is of interest to investigate the extent to which other abalone farms might increase nutrient concentrations within the water to which they discharge. Tanner et al (2007, Table 4.4, Page 116) report nutrient measurements associated with three abalone farms in South Australia at: Smith Bay, Point Boston and Streaky Bay. Results from Point Boston are not relevant because they reflect the application of fertilizer to grow algae. These farms discharge over the inter-tidal zone (whereas the presently proposed abalone farm discharges offshore into the tidal stream in order to maximize the rate of dilution and avoid nearshore flora). Table 6 compares nutrient measurements in the subtidal zone at farm sites and non-farm sites.

In the subtidal zone at the Smith Bay and Streaky Bay regions, it was ammonia-N that was most clearly elevated at farm sites relative to non-farm sites. The measurements of TP appear

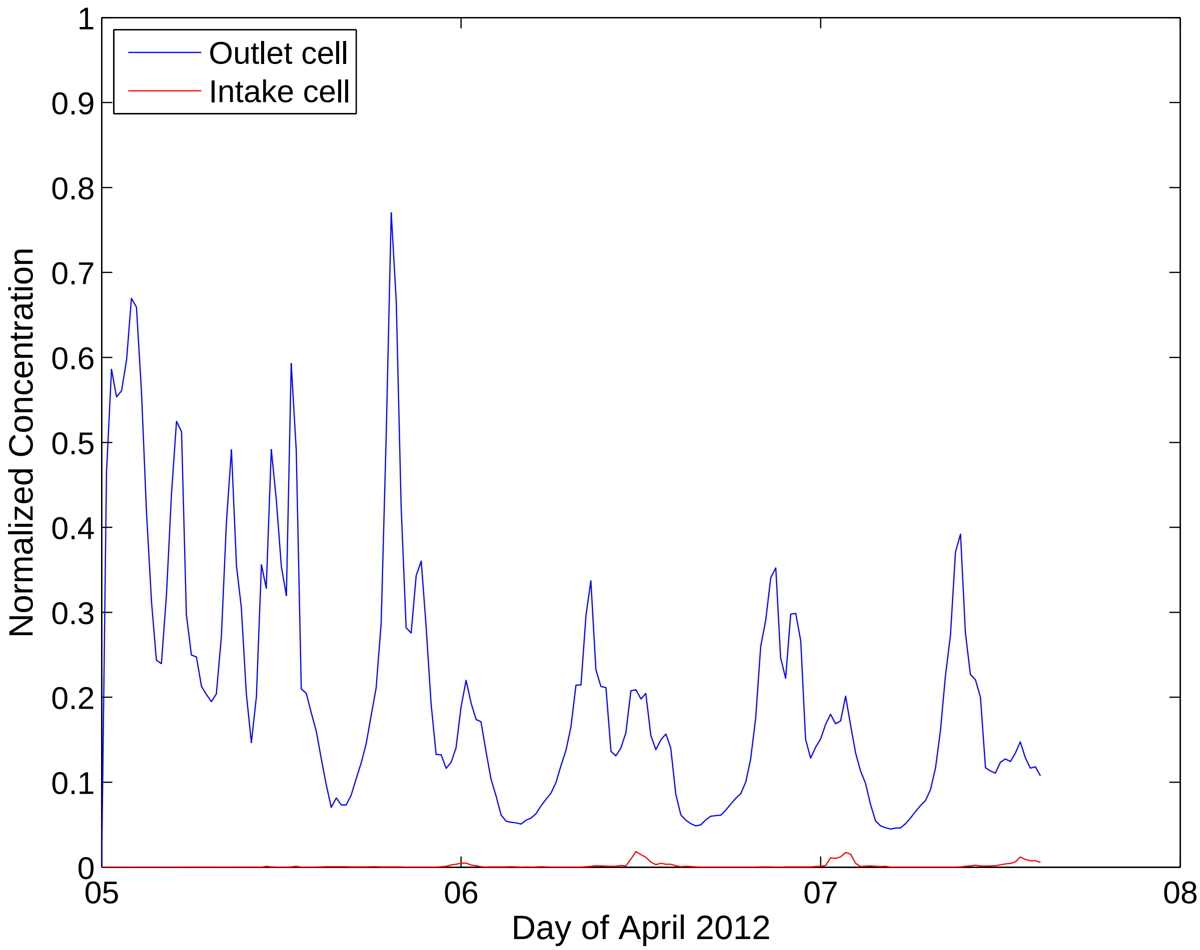


Figure 10: Normalized concentrations at the model cells containing the outlet and intake of seawater for the proposed abalone farm. This spring tide simulation shows that dilution is sufficiently rapid so that a neglible amount of discharged material would be pumped back into the proposed abalone farm.

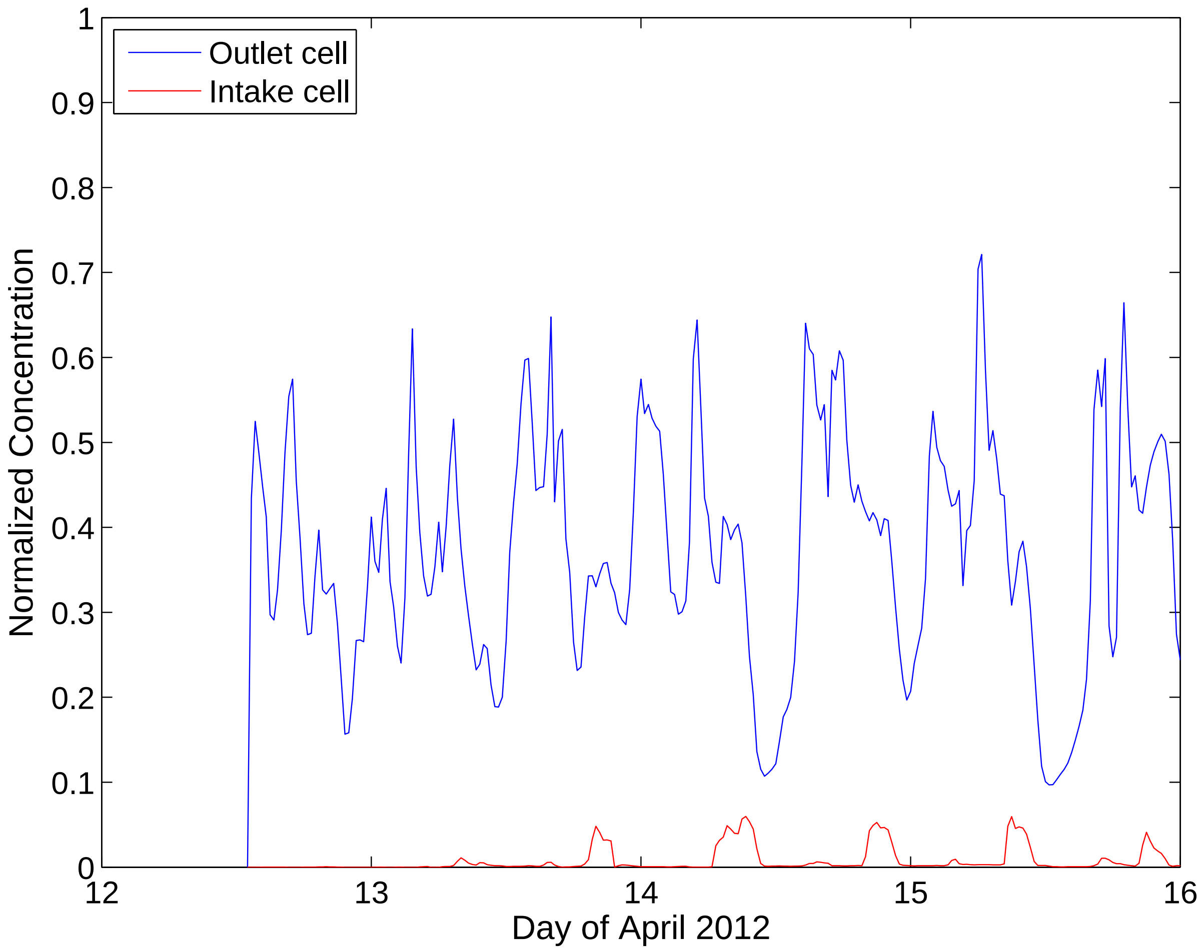


Figure 11: Normalized concentrations at the model cells containing the outlet and intake of seawater for the proposed abalone farm. This neap tide simulation shows that dilution is sufficiently rapid so that very little of the discharged material would be pumped back into the proposed abalone farm.

to lack the resolution that would be required to clearly demonstrate increases due to the abalone farms. TN and NO_x were somewhat elevated at the Smith Bay farm site but at Streaky Bay it was the non-farm site that was somewhat elevated — a mixed result suggesting that the any increase due to farms is not resolved from the natural variability.

Our earlier calculations of nutrient loads also indicate that abalone farms will increase ammonia concentrations far more than concentrations of other nutrients, relative to background levels. The ammonia-N increments implicit in Table 6 are most reasonably compared with increments plotted in Figure 9. Except very close to the outlet pipe, it is expected that the presently proposed abalone farm will cause comparatively small increments in ammonia-N, probably because discharge is into relatively deep tidal water offshore.

7 Wind and Catchment Discharge

The above simulations are all driven by tidal forcing. Wind and catchment discharge will also influence circulation in Port Stephens.

Catchment discharge is usually very small compared with tides, except for infrequent, short-lived events. On those rare occasions when catchment discharge is sufficient to noticably modify the above simulations, the water quality will be overwhelmingly determined by the catchment discharge rather than discharge from the proposed abalone farm. Such catchment discharge events can stratify the water column. The intake for pumping to the proposed abalone farm has been located in relatively deep water (Figure 2) so as to isolate it from such catchment discharge (which often has poor water quality).

Dominant winds are from the west-north-west (Figure 12) giving them an offshore component in the area of interest. When winds are strong they are expected to further increase vertical mixing and horizontal dispersion of the discharge plume — through bathymetric influences on wind-driven circulation and the well-known shear-diffusion mechanism (Csanady 1982). Regardless, tidal mixing is sufficient to rapidly dilute the plume without being augmented by wind.

8 Conclusion

Nutrient loads from the abalone farm are minimal compared to other sources. The abalone farm is located in the outer harbour so discharged material will be more efficiently flushed to the continental shelf than much of the catchment load. Discharged material will be rapidly diluted by tidal currents near the outlet location.

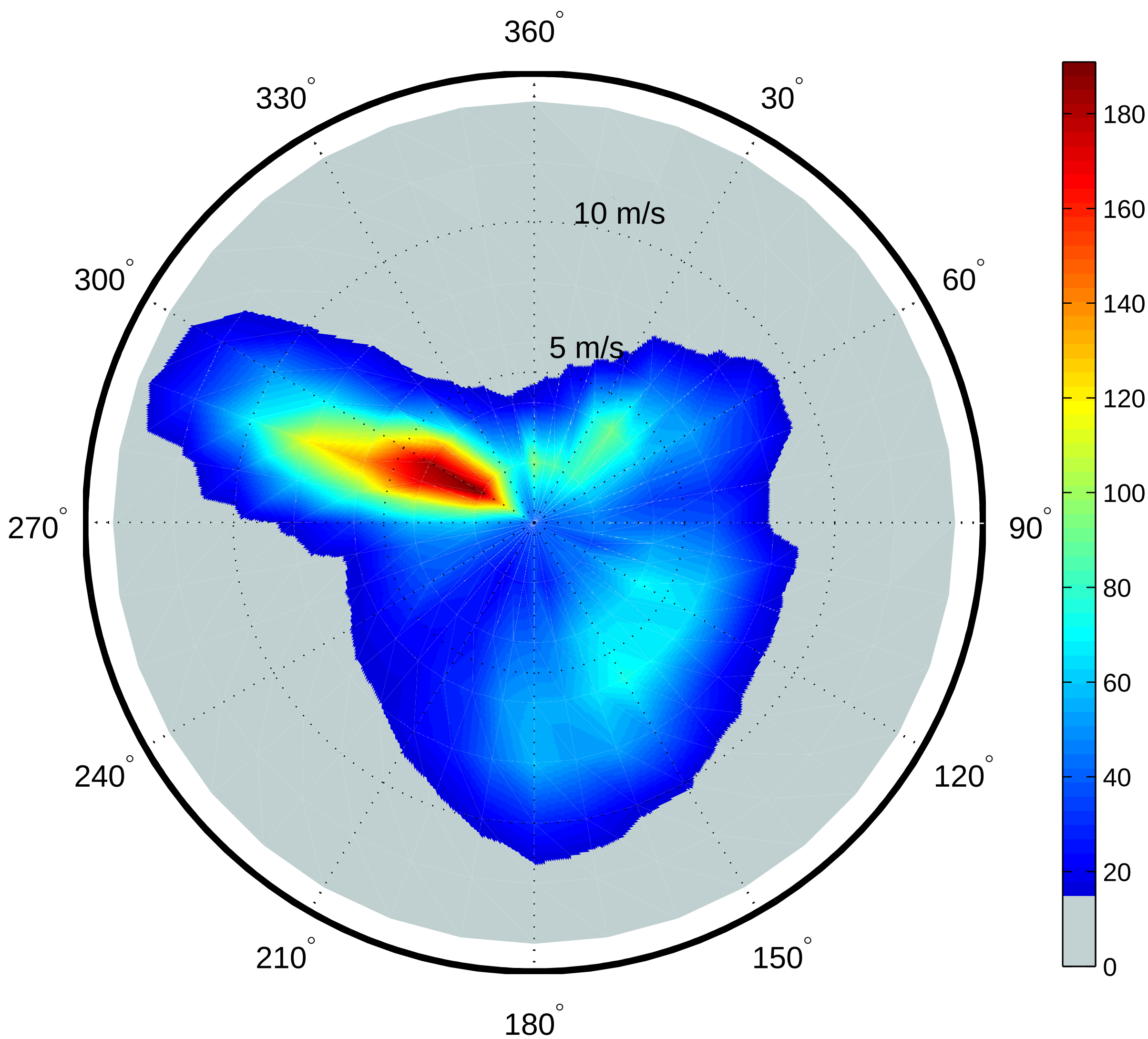


Figure 12: The color-scale of this polar-coordinate plot shows the number of hours each year that the wind blows from each direction ±5 degrees at each speed ±1 m/s. The wind measurements are from BoM station 61078 WILLIAMTOWN RAAF and span the interval Jan 1996 - Dec 2001. Directions are degrees clockwise from true north. Dominant winds are from the west-north-west.

References

[1] Australian and new Zealand Guidelines for Fresh and Marine Water Quality 2000. Volume 1, The Guidelines, Chapter 3 Aquatic Ecosystems, Table 3.3.2. Australian and New Zealand Conservation Council. Agriculture and Resource Management Council of Australia and New Zealand.

[2] Bartley, R., W.J. Speirs, T.W. Ellis, D.K. Waters, 2012. A review of sediment and nutrient concentration data from Australia for use in catchment water quality models. Marine Pollution Bulletin, 65, 101-116.

[3] Codispoti, L. A. 1989. in Productivity of the Ocean: Present and Past (eds Berger, W. H., Smetacek, V. S. & Wefer, G.) 377-394 (Dahlem Conf., Wiley, Chichester, UK).

[4] Coote, T.A., P.W. Hone, R. Kenyon, G.B. Maguire. 1996. The effect of different combinations of dietary calcium and phosphorus on the growth of juvenile Haliotis laevigata. Aquaculture, 145, 267-279.

[5] Csanady, G. T. 1982. Circulation in the Coastal Ocean. D. Reidel Publishing Company, Boston, 279 pp.

[6] DECCW 2010. NSW estuaries and coastal catchments spatial database.

[7] Flannery, T. 1994. The Future Eaters: An Ecological History of the Australasian Lands and People, ISBN 0-8021-3943-4

[8] Fleming, A.E., R.J. Van Barneveld, P.W. Hone, 1996. The development of artificial diets for abalone: A review and future directions. Aquaculture, 140, 5-53

[9] Halide H. and B. G. Sanderson. 1993. Determining flow field singularities from drifter trajectories. J. Geophys. Res. 98, 8413-8423.

[10] Harris, G.P., 2001. The biogeochemistry of nitrogen and phosphorus in Australian catchments, rivers and estuaries: effects of land use and flow regulation and comparisons with global patterns. Marine and Freshwater Research 5, 139149.

[11] King, R.H., C.J. Rayner, M. Kerr, H.K. Gorfine, P.E. McShane 1996. The composition and amino acid balance of abalone (Haliotis rubra) tissue. Aquaculture, 140, 109-113.

[12] Maguire, G.B. 1996. Nitrogen budgets for land-based abalone farms — a discussion document. Fisheries WA, Research Division, PO Box 20 North Beach, WA 6020, Australia.

[13] Maguire, G.B. 1996b. Effects of extended feed immersion, feeding frequency and feed rate on growth of juvenile greenlip abalone *Haliotis laevigata* and on composition and microbial colonisation of a formulated diet. Second FRDC/CRC Abalone Aquaculture Workshop, August 3-4, 1995, Hobart. In: P. Hone and A. Flemming (Editiors), Proceedings 1st and 2nd Annual Abalone Aquaculture Workshops, SARDI, Adelaide, pp. 89-91.

[14] MHL 1998, Port Stephens/Myall Lakes Estuary Processes Study Data Report March 1997-April 1998, report prepared by Manly Hydraulics Laboratory, Report MHL942.

[15] MHL 1999. Port Stephens/Myall Lakes Estuary Process Study. Prepared by Manly Hydraulics Laboratory, January 1999, Report MHL913.

[16] Neori, A., and M.D. Krom, 1991. Nitrogen and phosphorus budgets in an intensive marine fishpond: The importance of microplankton. In: C.B. Cowey and C.Y. Cho (Editors), Nutritional Strategies & Aquaculture Waste. University of Guelph, Guelph, Ontario, Canada, pp 223-230.

[17] Oke, P., and J.H. Middleton, 2001. Nutrient enrichment off Port Stephens: the role of the East Australian Current. Continental Shelf Research 21, 587-606

[18] Ottino, J.M., 1985. The Kinetics of Mixing: Stretching, Chaos and Transport. Cambridge University Press.

[19] Peck, L.S., M.B. Culley, M.M. Helm 1987. A laboratory energy budget for the ormer *Haliotistuberculata* L. Journal os Experimental Marine Biology and Ecology, 106, 103-123.

[20] Ryther, J. G. & Dunstan, W. M. 1971. Nitrogen, phosphorus and eutrophication in the coastal marine environment. Science 171, 1008-013.

[21] Sanderson, B. G. 1998. Order and resolution for computational ocean dynamics. J. Phys. Oceanogr. 28: 1271-1286.

[22] Sanderson, B.G., 2004. Calculation of Dilution and Transport of Nitrogen Discharged from a Proposed Abalone Farm. TUNRA Report, 27 pp.

[23] Sanderson, B. G. 2008. Circulation and the nutrient budget in Myall Lakes. Hydrobiologia, 608:3-20.

[24] Sanderson, B. G. and G. G. Coade, 2010. Scaling the Potential for Eutrophication and Ecosystem State in Lagoons of New South Wales, Australia. Environmental Modelling & Software, 25, 724-736, DOI information: 10.1016/j.envsoft.2009.12.006

[25] Sanderson, B. G. 2011. Long-wave Explicit and Short-wave Implicit (LESI) Treatment of the Barotropic Mode to Accurately Calculate Slow Modes in Ocean Models. Ocean Modelling, 40: 35-41, doi:10.1016/j.ocemod.2011.08.002

[26] Sanderson, B. G., 2013. Movies of Current in Port Stephens. HTML document, take your browser to HTML/PortStephens.html
Also available at: `http://users.eastlink.ca/~bxs/PORT_STEPHENS/PortStephens.html`

[27] Sanderson, B.G., and G.B. Brassington. 2002. Fourth- and fifth-order finite-difference methods applied to a control-volume ocean model, Journal of Atmospheric and Oceanic Technology, 19, 1424-1441.

[28] Tan, B., K. Mai, W. Xu, 2002. Availability of phosphorus from selected inorganic phosphates to juvenile abalone, Haliotis dicus hannai. Chinese Journal of Oceanology and Limnology, 20(2), 118-128.

[29] Tanner, Jason E. & Bryars, Simon (2007) Innovative Solutions for Aquaculture Planning and Management — Project 5, Environmental Audit of Marine Aquaculture Developments in South Australia. FRDC Project 2003/223. Fisheries Research & Development Corporation and South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Aquatic Sciences Publication No F2007/000766-1 SARDI Research Report No.190

[30] Tyrrell, T. 1999. The relative influences of nitrogen and phosphorus on oceanic primary production. Nature, 400, 525-531.

[31] Webster, I.T., Harris, G.P., 2004. Anthropogenic impacts on the ecosystems of coastal lagoons: modelling fundamental biogeochemical processes and management implications. Marine and Freshwater Research 55, 67-78.

[32] Yoder, J.A., and M.A. Kennelly, 2003. Global Biogeochemical Cycles, 17, 1112, doi:10.1029/2002GB001942