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Carrying capacity for finfish aquaculture, Part II – Rapid assessment using hydrodynamic and semi-analytic solutions

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ABSTRACT

The carrying capacity for aquaculture cage farming in Spencer Gulf (South Australia) is based in part on guidelines that the maximum feed rates and nutrient flux into the lease regions are determined such that the maximum nutrient concentration c does not exceed a prescribed value (say c_P) to ensure ecosystem health – ecological carrying capacity. The goal of this study is to allow the rapid estimation of maximum nutrient fluxes and feed rates at new lease sites. Spencer Gulf is chosen as a case study although the methodology should find application in other regions around the world. In part I of this study, semi-analytic solutions were obtained to show that to a good approximation the maximum nutrient flux (feed rate) F can be simply estimated from: $F = c_P/T^*$ where T^* is a flushing time scale of the cage or lease region. In this study a 3-dimensional hydrodynamic model for Spencer Gulf is used to determine the parameters needed to estimate T^* and thus F and feed rates at every model cell in the gulf. The parameters needed include the vector mean speed (U), r.m.s. tidal amplitude (U_K) and the mean shear dispersion diffusivity (K_S). As a case study, these parameters and T^*, are estimated by three-monthly, winter averages. Results show the vector mean speed to be very small ($U \sim 0.01$ m/s), tidal velocities large ($U_K \sim 0.3$–1 m/s) and the associated shear dispersion coefficients very large ($K_S \sim 10$–$100\ \text{m}^2/\text{s}$). Flushing at the scale of the lease (600 m) and in the upper gulf is generally dominated by diffusive affects for which the maximum nutrient flux (and feed rates) is largest. The results should find application in other finite source flux problems in the coastal oceans including desalination plants and ocean outfalls.

1. Introduction

The world's coastal oceans are subject to increased exploitation through developments in aquaculture. In Spencer Gulf of South Australia (Fig. 1), finfish cage aquaculture of Southern Bluefin Tuna and Yellowtail Kingfish is well developed and planned to expand over the next decade. In Australia and elsewhere, the management of these "outfalls" often invokes the concept of ecological carrying capacity. The carrying capacity of farmed fish biomass is guided by the concentration of nutrients discharged and which are formally limited to be less than a government prescribed maximum concentration c_P (ANZECC/ARMCANZ, 2000), set to ensure ecosystem health (Gecek and Legovic, 2010). This definition of carrying capacity differs from that based on ensuring farmed fish health – production carrying capacity The limits here may well include oxygen concentrations which if too low can adversely impact on farmed fish health (Stigebrandt, 2011). In addition carrying capacity of fish biomass can be limited by socio-economic conditions such as availability of ports, labour, stock feed, lease entitlements and the availability of young fish to be farmed.

In South Australia, the government issues licenses for lease sites within zones (Fig. 1). These zones can consist of 10–20 leases. Each lease typically is stocked with six or so cages over an approximate area 600 m × 600 m. The government advises aquaculture lease holders on finfish biomass based on feed rates, expected nutrient levels and other criteria. Information on monthly feed rates per lease is provided by the industry to government. One model used by government to indicate nutrient levels and associated feed rates is based on a simplified advective flushing model for zones and ecological carrying capacity. The carrying capacity estimates have a direct impact on feed rates, fish growth and market value.

Since information of feed rates and nutrient fluxes is only available at the scale of the lease, the focus here will be on carrying capacity at this scale. Fortuitously, the lease scale is also the grid scale of the hydrodynamic model results used below.

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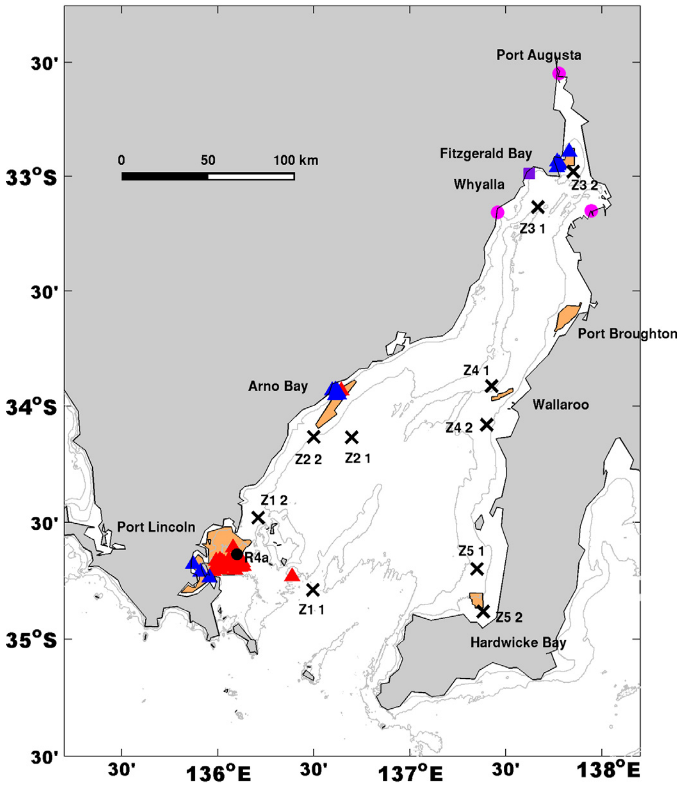

Fig. 1. Map of Spencer Gulf showing the location of: the six aquaculture zones (brown shaded regions), 2010/2011 field survey sites (black crosses), tuna (red triangles) and Yellowtail Kingfish finfish (blue triangles) aquaculture leases, waste water treatment plants (pink circles) and the Onesteel steel works (blue square). The location (S.W. gulf) of the 2005 R4a mooring is indicated by the black circle. The location of aquaculture leases is plotted for the 2010/11 period. The 10, 20 and 40 m depth contours are plotted.

In Part I of this study (Middleton and Doubell, 2014), the near field concentration was detailed for a cage (or lease) subject to a constant nutrient input flux F. The maximum concentrations found near the downstream edge of the cage, were generally found to lie in the interval

$$C_{\max} = FT^*[0.6, 1.2] \quad \text{for}\, t \gg T^*, \tag{1.1}$$

for a wide variety of flow regimes. Here, T^* is a time scale of flushing of the lease that depends on mean properties of the oceanographic circulation including the vector mean speed (U), r.m.s. tidal amplitude (U_K) and the mean shear dispersion diffusivity (K_S). T^* can vary by a factor of 10 depending on the relative importance of advection and diffusion in flushing the region of the cage. This variability is much larger than the range of uncertainty indicated in (1.1).

The significance of (1.1) is that it can be easily used to determine carrying capacity for aquaculture once the important oceanographic scales (U, U_K, K_S) have been estimated. In the case study here, we will estimate these parameters and T^* for the whole of Spencer Gulf (by season) using a high resolution hydrodynamic model. Indeed, a primary goal of the study here is to provide environmental scientists and managers with a simple tool for estimating maximal ecological carrying capacity and associated feed rates and nutrient fluxes for finfishlease sites in Spencer Gulf. The methodology can be extended to other finfish aquaculture sites where the oceanographic parameters (U, U_K, K_S) can be estimated. Moreover, we note below that the approach outlined below might also be used for proposed sewage, waste water and desalination plant outfalls.

There are limitations to this approach. The relation (1.1) is only valid at times much larger than T^* and is not exact: Eq. (1.1) itself is based on the assumptions that there exists only one lease site that contributes to nutrient concentrations–the analysis here does not address the cumulative impact of many lease sites. The effects of coastal boundaries a distance L from a lease/cage site can be included in the exact solutions for nutrient concentration derived in Part I (Middleton and Doubell, 2014). As a rule of thumb, (1.1) should be valid provided L is much larger than the width of the source region itself.

It is also assumed below that the nutrients are conserved and that uptake through biological recycling is relatively small. In Section 5, this is shown to be a reasonable assumption for Spencer Gulf at the scale of the lease and over the flushing time scales determined below.

The use of a hydrodynamic model to estimate flushing scale T^* has parallels with other studies where flushing estimates or residence times are estimated using particle tracking (e.g., Gecek and Legovic, 2010; Ali et al., 2001; Dudley et al., 2000). What is unique here is that we adopt the model for T^* that needs information only on seasonally averaged currents and the horizontal diffusivity. This obviates the need for ensembles of particle tracking.

In Section 2, the result $c_{\max} = FT^*$ is detailed and the time scale T^* related to times scales of advection and diffusion and then the oceanographic parameters (U, U_K, K_S, etc.), using a simple parabolic model for shear dispersion.

In Section 3, a hydrodynamic model for Spencer Gulf developed by Luick and Middleton (2013) is briefly described. The estimates of the oceanographic parameters are then presented along with the various time scales for carrying capacity. Only results for winter are presented so as to illustrate the approach taken, However, it is noted that the results for summer are qualitatively similar to those found here, so that the analysis provides an overview of what is expected for a full 12-month period.

In Section 4, the relationship between maximum concentrations obtained at the scale of the lease, cage and zone are discussed. These are important since concentration maxima averaged over the scale of the zone may differ considerably from those at the scale of the cage.

In Section 5, a summary is presented and further limitations of the analysis are discussed.

2. Carrying capacity and time scales: the needed parameters

In the following, an outline is given of the relations established by Part I of this study (Middleton and Doubell, 2014), between maximum concentration of an arbitrary nutrient $c_{\max}$, the nutrient flux for a lease (F) and the time scales of advection (T_a) and diffusion (T_d). Next, the time scales are related to the principal oceanographic parameters including the vector mean speed (U), r.m.s. tidal amplitude (U_K) and the associated mean shear dispersion diffusivity (K_S). This is done by considering a simple model for the strong tides of the region.

2.1. Scale estimates for carrying capacity

First consider a square source region of nutrients defined by the square centred upon the origin:

$$\left\{ \frac{-W}{2} < x < \frac{W}{2}, \frac{-W}{2} < y < \frac{W}{2} \right\} \tag{2.1}$$

The focus will be on results at the scale of the lease (W = 600 m) although the formalism below applies to any flux region. It is assumed that a constant flux F (kg/(m^3 s)) is applied over this region and at the surface after time t = 0. The depth of the ocean