Final Report

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Subproject 5
OXYTUNA – A model for the oxygen dynamics in a southern bluefin tuna sea-cage system

Anthony C. Cheshire and Maylene G. K. Loo

March 2008

Aquafin CRC Project 4.5
FRDC Project No. 2003/226

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TUNA
SBT AQUACULTURE SUBPROGRAM

SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

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Executive Summary

The aim of this subproject (“Enhancement of a dissolved oxygen diffusion model to provide a predictive capacity to industry to evaluate fouling management systems”) was to develop a model to illustrate and predict changes in the oxygen concentration in a tuna aquaculture sea-cage. The model provides a platform to investigate the oxygen dynamics of alternative cage configurations and stocking levels, in response to seasonally varying tidal currents, water quality and fouling loads.

The specific objectives of this subproject were:

1. To calibrate the model using the results obtained from Subprojects 3 and 4 to provide a basis for cost:benefit[1] analyses of alternative fouling management systems.

2. To provide farmers and managers with an educational tool that enables them to better visualise the relationship between the level of net fouling, water flow, stocking rate and environmental dissolved oxygen levels.

The OxyTuna© model has been developed to assist farm managers in making better decisions about the management of finfish sea-cage systems. In particular it will help them to better understand the relationship between net fouling and oxygen concentration in cages and how this responds to various management interventions including changes in cage configuration and fouling management (e.g. net cleaning).

The model provides a quantitative prediction of the changes in oxygen concentration through time for different sea-cage configurations (cage size, net type, stocking density, fish species) in response to changes in ambient conditions (temperature, salinity, ambient oxygen concentration and current speed). The dynamic nature of the model allows users to better understand the interplay of factors that control oxygen concentration in a sea-cage, and it can therefore be used not only as a management tool but also as a teaching tool.

By implementing OxyTuna© as a Visual Basic for Applications (VBA™) program developed to run within Microsoft EXCEL™, the model outputs can be easily captured and incorporated into other programs by anyone with a basic understanding of EXCEL™. This feature is expected to improve the utility of the model and the opportunity for individual users to develop their own enhancements.

[1] Where the improvement in oxygenation of the water inside the cage is a quantitative measure of benefit.

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We also thank Steven Clarke (FRDC Aquaculture Subprogram leader) whose unflagging support and hard work made a substantial difference in keeping the project on-track and moving forward, and Jason Tanner for his extensive feedback.

Thank you also to Quinn Fitzgibbon, Kirsten Rough and David Ellis for the provision of data and support during the experimental components of the work.

Chapter 1 Background

This is the final report of the work carried out for "Subproject 5 – Enhancement of a dissolved oxygen diffusion model to provide a predictive capacity to industry to evaluate fouling management systems" of the "Aquafin CRC SBT Aquaculture Subprogram: Net fouling management to enhance water quality and southern bluefin tuna performance" (Aquafin CRC 4.5/FRDC 2003/226).

The aim of the Net Fouling Management project was to better understand the impact of net fouling on the management of tuna sea-cage systems. A build-up of fouling biota is likely to have numerous effects on the environment within a sea-cage and therefore impacts on the management and operation of the system. Typically the effects of net fouling include:

- Changing patterns of water flow through the nets and thereby the supply of oxygen and removal of wastes from cages.
- Changing the weight (and therefore buoyancy) of farming structures.
- Changing the surface area of cages, which in turn affects the potential for growth and attachment of pathogens.
- Reducing the longevity of nets.

The Net Fouling Management project comprised a total of six sub-projects including the work presented in this report which provides an overview of the development and implementation of the OxyTuna© model. OxyTuna© was developed to address the requirements of Subproject 5 of the Net Fouling Management project, the aim of which was to understand how net fouling influences oxygen supply to cages (cage ventilation).

Importance of oxygen supply to sea-cages

Oxygen supply is a fundamental condition for intensive aquaculture, and sea-cage systems are no exception (Edwards and Edelsten 1976, Madenjian 1990, Silvert 1992). A number of factors, including the oxygen demands of the fish, the plankton, fouling biota on cage nets, and sediment-associated flora and fauna, all interact to deplete oxygen concentrations to levels below that required to optimise fish growth. In sea-cages, mass water flow provides for the exchange of oxygen-depleted water from inside the cage with oxygenated water from outside the cage. The effectiveness of this exchange is substantially reduced when net fouling impedes water flow (Inoue 1972, Lee *et al.* 1985, Sliskovic and Jelic 2002, Yokoyama *et al.* 2004), which can lead to a reduction in oxygen concentrations to levels that negatively impact upon the cultured organism. This depletion may in turn lead to increased stress on the fish and susceptibility to disease.

Need

Historically, when farming was conducted in Boston Bay, nets showed obvious fouling after only 4 weeks (Bond 1993), quickly becoming heavily covered by fouling organisms. In a previous study (Cronin *et al.* 1999), typical fouling rates of between 2 and 4 kg wet weight/m^2 were observed on sea-cages. More recent work (Svane *et al.* 2006), also conducted on experimental sea-cages in Boston Bay, largely confirmed these results and has shown that nets, even when treated with anti-foulant, may accumulate substantial fouling loads over relatively short periods[2]. Svane *et al.* (2006) showed that fouling load increased on both treated and untreated nets over the course of their five-month study, reaching levels of 81% in untreated nets compared with only 66% for treated nets[3]. Work carried out in Subproject 2 of this project, where a range of anti-foulants were tested on nets in the Boston Island East farming zone, largely confirmed the overall trend (i.e. less fouling on treated nets). Fouling on untreated nets after 155 days (~5 months) resulted in occlusion of 68% whilst treated nets were typically around 41% (Rough pers. comm.).

It is important to manage net fouling because, by occluding the net, it causes a reduction in water flow and therefore limits oxygen supply to cages. This subproject was developed in order to assist farm managers to make better decisions about the management of net fouling. The work detailed in the following focuses on quantifying the relationship between net fouling and the dissolved oxygen concentration in sea-cages, and understanding how this responds to various management interventions including changes in cage configuration (e.g. stocking density) and fouling management (e.g. cage cleaning).

More specifically, the OxyTuna© model that has been developed in this subproject provides a quantitative prediction of the changes in oxygen concentration through time for different sea-cage configurations (cage size, net type, stocking density, fish species) in response to changes in ambient conditions (temperature, salinity, ambient oxygen concentration and current speed).

[2] Note that prior to the work undertaken in the Net Fouling Management project there have been no quantitative studies of net fouling on cages outside of Boston Bay.

[3] In this study 81% is the amount of space occluded by the net and the associated fouling organisms. This implies that the area of open space in the net is reduced from (typically) 92% in clean nets down to only 19% in these fouled nets. The treated nets (with 66% occlusion) therefore had 34% open space, which provides close to double the area for water to move through the treated net compared to the untreated (heavily fouled) net.

The specific objectives of this subproject were:

1. To calibrate the model using the results obtained from Subprojects 3 and 4 to provide a basis for cost:benefit[4] analyses of alternative fouling management systems.

2. To provide farmers and managers with an educational tool that enables them to better visualise the relationship between the level of net fouling, water flow, stocking rate and environmental dissolved oxygen levels.

[4] Where the improvement in oxygenation of the water inside the cage is a quantitative measure of benefit.

Chapter 2 The OXYTUNA© Model

This chapter will detail the conceptual schema, model construction and the workings of the model.

Overview of model construction

OxyTuna© is a dynamical model that illustrates the changes in dissolved oxygen concentration in a sea-cage through time. The model is based upon a previously published model developed by Emma Cronin (Cronin 1995) that has been substantially modified and upgraded in this subproject. Cronin's model used a relatively simple algorithm to describe changes in the dissolved oxygen concentration in a sea-cage (Equation 1).

Equation 1 **-** General model for oxygen dynamics in a sea-cage.

$$
\begin{aligned}
[\text{Mass Oxygen In Cage}]_{(t+\delta t)} = \; & [\text{Mass Oxygen In Cage}]_{(t)} \\
& + [\text{Mass Oxygen Transported Into Cage}]_{(\delta t)} \\
& - [\text{Mass Oxygen Transported Out From Cage}]_{(\delta t)} \\
& - [\text{Mass Oxygen Respired By Fish In Cage}]_{(\delta t)} \\
& - [\text{Mass Oxygen Respired By Fouling Or Other Biota}]_{(\delta t)}
\end{aligned}
$$

The model calculates a mass-balance for oxygen by which the amount of oxygen in a sea-cage at a time δt from now will be equal to the mass of oxygen currently in the cage, plus any extra oxygen that is transported into the cage over the time period (δt), minus any oxygen that is either transported out of the cage or that is consumed through respiration by fouling or other biota over that time period.

In developing the new model the aim was to incorporate a number of necessary improvements including:

- An enhanced user interface that provided:
    - a simple method for constructing scenarios specifically including changes in cage configuration;
    - graphical illustrations of the model outputs;
- An improved model engine that overcame a serious limitation with the time-stepping algorithms in the earlier model (which resulted in aberrant behaviour under moderate-high current flow rates);
- Incorporation of a sub-model that quantified the change in fouling load through time and which can be used to illustrate the merits of anti-foulant treatment of nets;

- Incorporation of a sub-model that quantified ventilation rate (dissolved oxygen exchange for sea-cage) based on tidally induced current flow and variable fouling load;

- Incorporation of a fish respiration sub-model parameterised using recent results from research on tuna respiration;

- Incorporation of a sub-model that characterises seasonal changes in water quality specifically including changes in temperature, salinity and ambient oxygen concentrations.

The revised OxyTuna© model has been implemented as a Microsoft EXCEL™ add-in using Visual Basic for Applications (VBA™). This strategy means that model outputs can be easily captured by anyone with a basic understanding of EXCEL™, thereby improving the utility of the model and the opportunity for individual users to develop their own enhancements.

Model description

OxyTuna© provides a prediction of the concentration of dissolved oxygen in the water, inside a tuna sea-cage over time. The model achieves this by calculating the mass of oxygen inside the cage and then representing this as a concentration (mass/volume; mg/L). The volume of the cage is calculated from a simple sub-model using the physical cage dimensions (diameter and depth).

A generalised schema for the model is provided in Figure 2.1. This figure uses a modified set of Forrester symbols (Forrester 1961; Appendix I) to represent the relationship between state and forcing variables. A state variable describes the state of the system; in this case the concentration of dissolved oxygen within the sea-cage. A forcing variable refers to factors controlling the state of the system (e.g. current speed, ambient temperature or salinity). Arrows represent the material flows (e.g. oxygen moving into cage, thick lines; ➡) and control flows (e.g. temperature/salinity, thin lines; ⟶) that have been used to construct the algorithms and subroutines used in developing the visual basic code for the EXCEL™ implementation of the model.

A number of terms used in the model proposed by Cronin (1995), atmospheric diffusion and respiration by the fouling biota, have been excluded from the present model. In general, the mass transport of oxygen and the amount of oxygen consumed through fish respiration are orders of magnitude greater than that consumed through diffusion or fouling consumption (Cronin *et al.* 1999) and so these terms can be ignored[5].

[5] For land-based ponds, where the only source of oxygen is either via passive diffusion or active oxygenation, these terms would still be required. However, in a marine sea-cage the effect of oxygen transport by water flow is so great that diffusion becomes irrelevant over the time scales that the model runs.

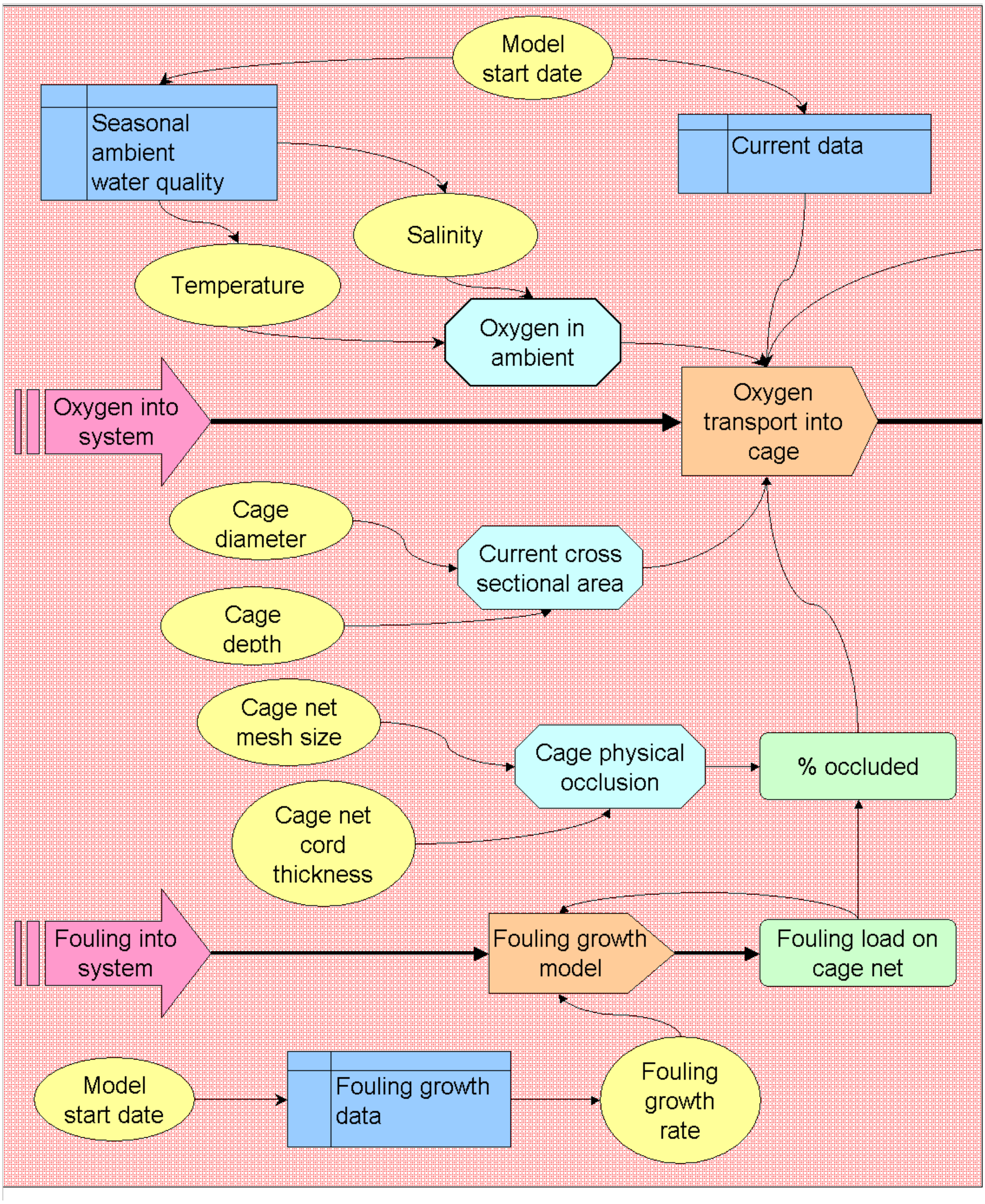


Figure 2.1a Schematic representation of the OxyTuna© model illustrating transport of oxygen into the sea-cage. See Appendix I for explanation of the symbols (note arrows leaving to the right of the diagram are picked up in Figure 2.1b).

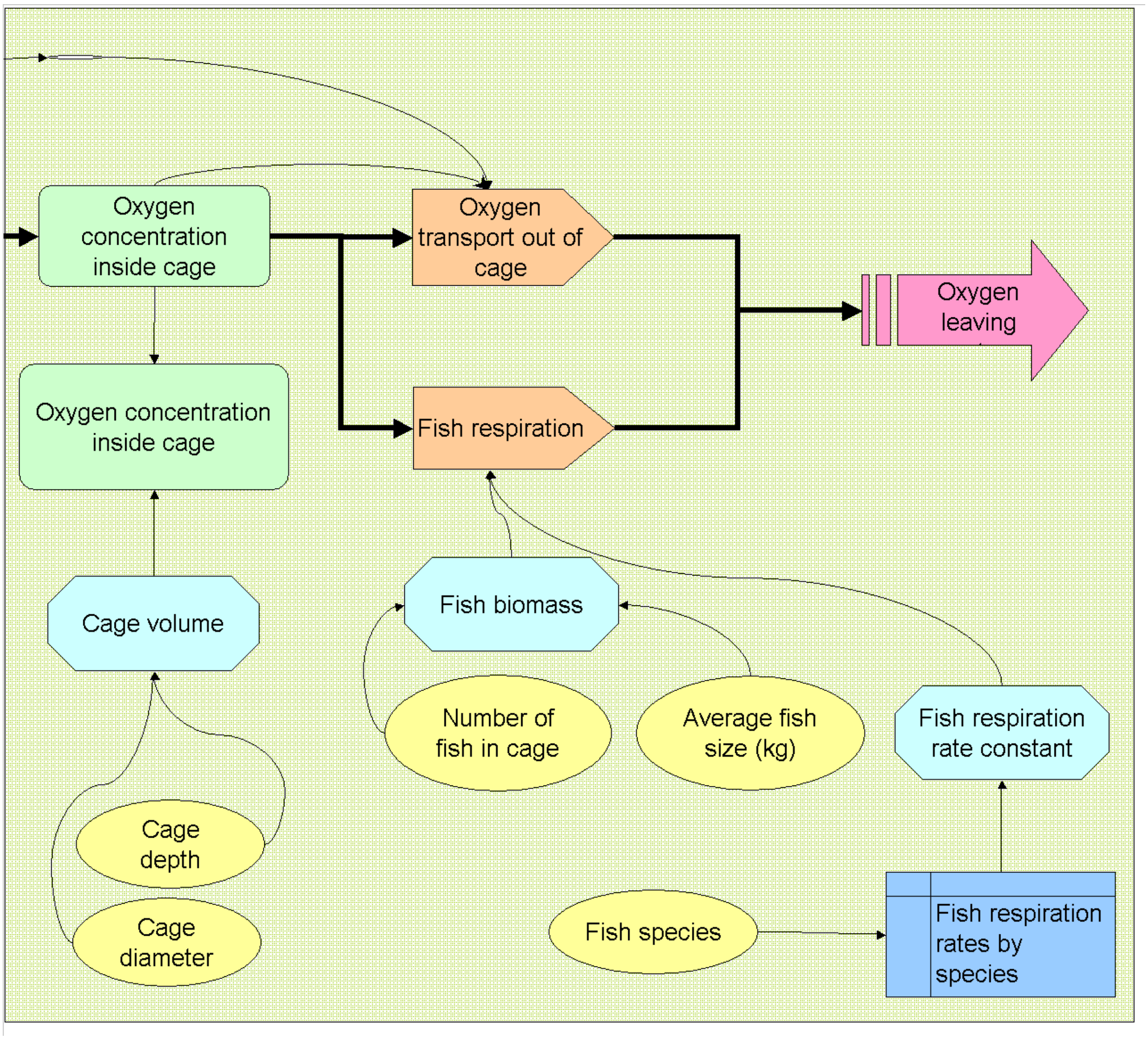


Figure 2.1b Schematic representation showing oxygen concentration inside the sea-cage and transport processes out of the sea-cage.

Model construction

OxyTuna© uses a simple press-button interface that allows the user to navigate through the process for setting the various run-time parameters (see below) and then executing and saving alternative scenarios. The Command screen provides a pictorial representation of the information required to run the model as well as a single graphical display that shows a time series of modelled oxygen concentration based on the user selected parameter values (Figure 2.2).

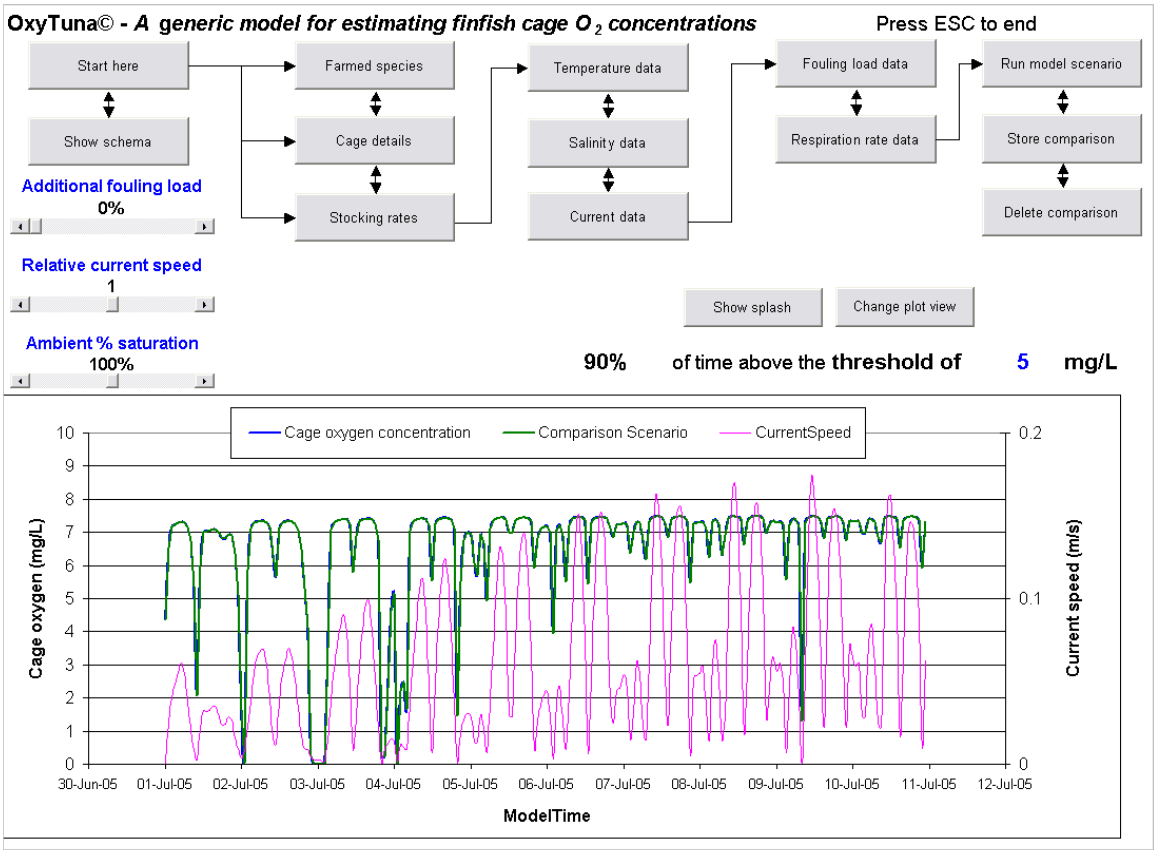


Figure 2.2 Command screen for OxyTuna© showing the buttons that guide the user through the data entry process that is required to set up the parameter sets for a model run. The graphical display in the bottom half of the screen illustrates a time series showing current speed and modelled dissolved oxygen concentration for the sea-cage.

The user navigates through the model by moving the mouse over and pressing any given button (generally starting with “Start here”; Figure 2.3).

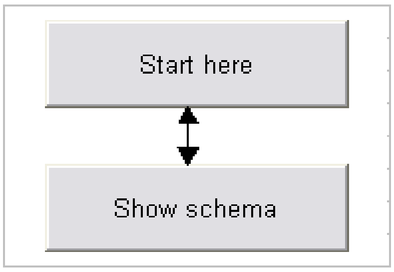


Figure 2.3 Illustration of typical command buttons. Pressing these buttons allows the user to interact with the model, change or check model parameters and execute functions (such as Run the model).

Left clicking the mouse activates the function programmed into that button while right clicking the mouse provides help information to the user (see for example Figure 2.4). Generally, when pressing any button, a default value will be shown. The default value is simply a re-iteration of the current value stored for any given parameter.

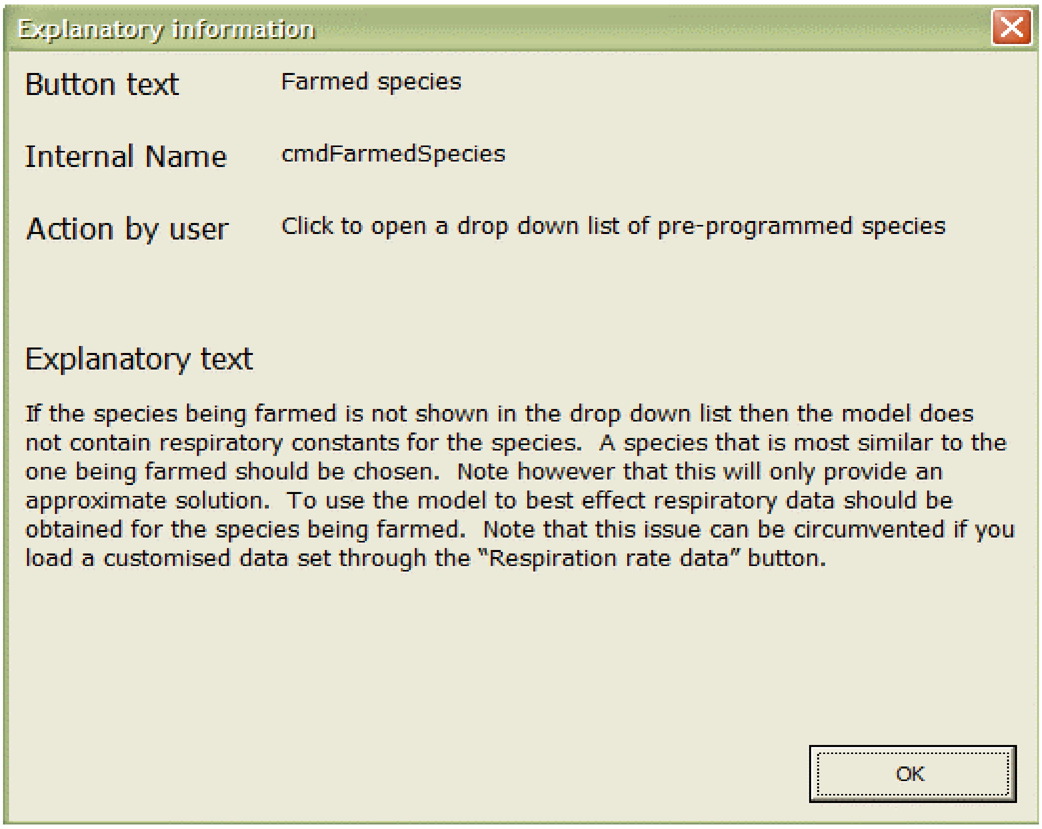


Figure 2.4 Illustration of typical help screen. This information is accessed for any given button by clicking the right-mouse button.

Additional functions include the slider bars that can be used to manipulate data on fouling load (to review the effect of lower or higher fouling load), current speed (to quickly review the effect of lower or higher water flow) and ambient dissolved oxygen concentration (to review the effects of periods of depressed ambient oxygen) (Figure 2.5).

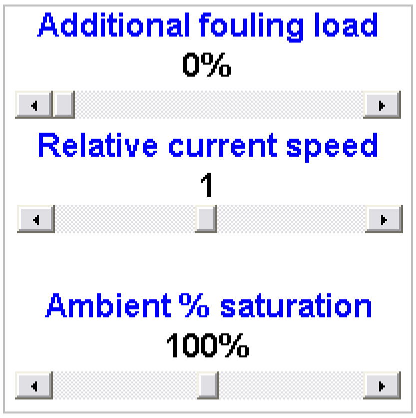


Figure 2.5 Slider bars for additional fouling load, relative current speed and ambient dissolved oxygen (% saturation).

The text showing the percent time above a user-defined dissolved oxygen threshold value (set at 5 $mg.L^{-1}$ - in the illustration; Figure 2.2) provides a simple way of evaluating whether the settings used for any given run are appropriately bounded. The user can change the threshold value simply by overtyping the value currently shown.

The graphical display (bottom of Figure 2.2) shows the dissolved oxygen concentration in ppm or $mg.L^{-1}$ through time for the latest model run (blue line; scale on left hand y-axis), the green line provides a view of the oxygen concentration for a previously saved run (typically using different parameter values) and the magenta line represents current speed in $m.s^{-1}$ through time for the latest model run (scale on right hand y-axis).

The following is a detailed description of the role of each button and how these link to the underlying data requirements for the model to run.

Model initialise – Start Here

Click to enter run time data - start date, deltaT and period of model run.

The user will be asked to provide three values; the start date for the model run, the value for deltaT (the time interval at which to report the results) and the number of days for the model to run. These data will be used to align the model time with sub-models or data sets for water temperature, salinity, current (tidal) flow, fouling load and respiration rates. Note that if these subsidiary datasets do not provide data to cover the period entered via this button then the model run will fail. At some time in the future we may incorporate an additional input for *Location* to allow the user to access different built-in sub-models for temperature, salinity etc. This will allow users from other industry sectors (e.g. salmon) to use the model more easily[6].

Show Schema

Click to review the model "Schema".

The schema allows the user to review the way in which the model is constructed (shown in Figure 2.1a and b). It provides a representation of the material flows (oxygen) in the model and details how the movement of dissolved oxygen into and out of sea-cages is controlled by the setting of the other model parameters (cage and net configuration, ambient water quality and fouling load).

Farmed species

Click to open a drop down list of pre-programmed species.

If the species being farmed is not shown in the drop down list (see illustration in Figure 2.6) then the model does not contain a respiratory constant for that species. A species that is most similar to the one being farmed should be chosen. Note however that this will only provide an approximate solution. To use the model to best effect, respiratory data should be obtained for the species being farmed. This issue can be circumvented by loading a customised data set through the “Respiration rate data” button (see below). If the user enters respiration rate data, then this overrides the default data in the model for the farmed species selected.

[6] Note however that the model can still be used for other farming systems but users need to provide their own data for changes in temperature, salinity, current flow, etc rather than using the built in model functions.

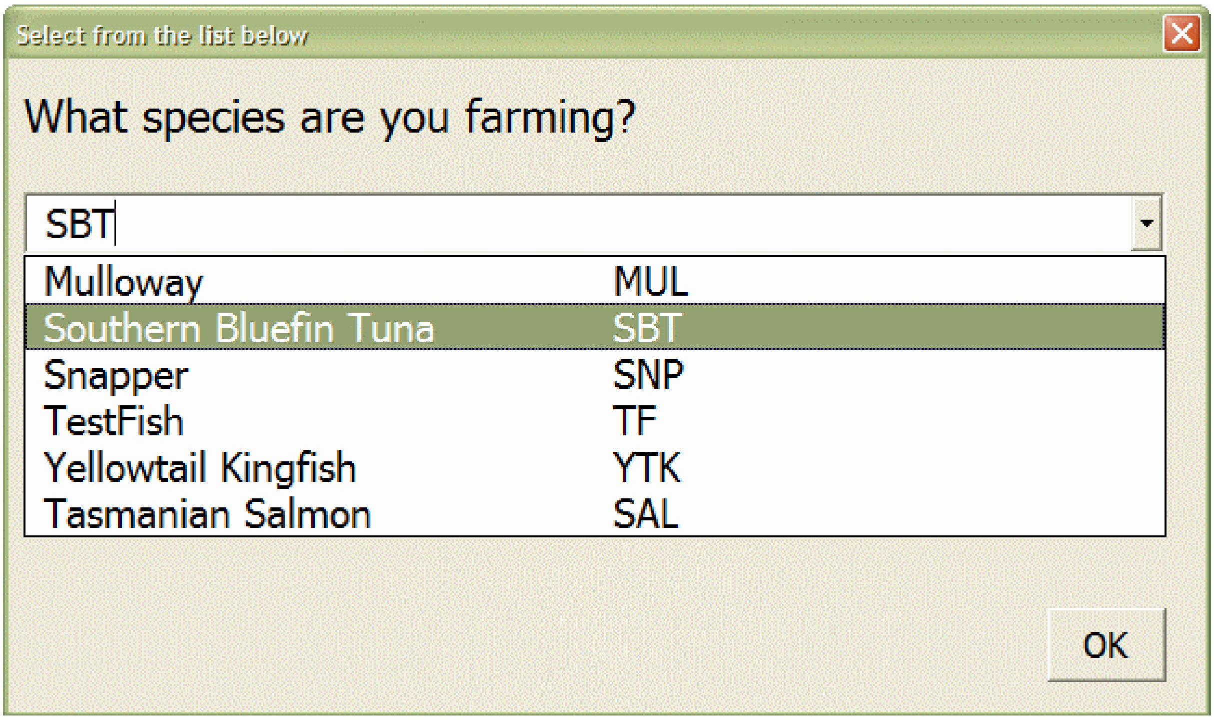


Figure 2.6 Example of a typical dialogue box where the user is asked to provide information. In this example the user has selected SBT.

Cage details

Click to open a series of dialogue boxes that will ask the user for information about the size of the sea-cage and the type of net being used.

The user is asked to provide data for four parameters; the Cage diameter (inside distance across the top of the sea-cage measured from one side of the pontoon to the other running through the middle - measured in m); the Cage depth (distance from the pontoon down through the water column to the base of the cage in the middle - measured in m); the mesh size of the net (length of one side measured in cm) and the cord thickness of the net (measured in mm). Note that the cage details are used to calculate the CageVolume parameter, which is used in the "Stocking rates" function (see below). It is assumed that cages are circular in cross-section.

Stocking rates

Click to open a series of dialogue boxes that will ask the user for information about stocking rate of the sea-cage.

The user will be asked to provide data for the average fish size (measured in kg) and the number of fish in the sea-cage (total count). These data will be used to compute the biomass of fish in the cage (Biomass = AvgSize*Number) and the stocking density (StockDens=Biomass/CageVolume). If these values are not known then the user should provide their best estimate, as the model is very sensitive to these data.

Temperature data

Click to open an option box where you can indicate the source of temperature data for the model (Figure 2.7).

This value will determine whether the model will calculate a value for temperature based on a model of Port Lincoln seasonal sea surface temperatures or utilise a lookup table, showing temperature through time, provided by the user (Figure 2.8). Novice users should use the internal modelled temperature values that are based on data for Lower Spencer Gulf (Port Lincoln region) provided by the Directorate of Oceanography and Meteorology, Australian Government Department of Defence Online data service[7].

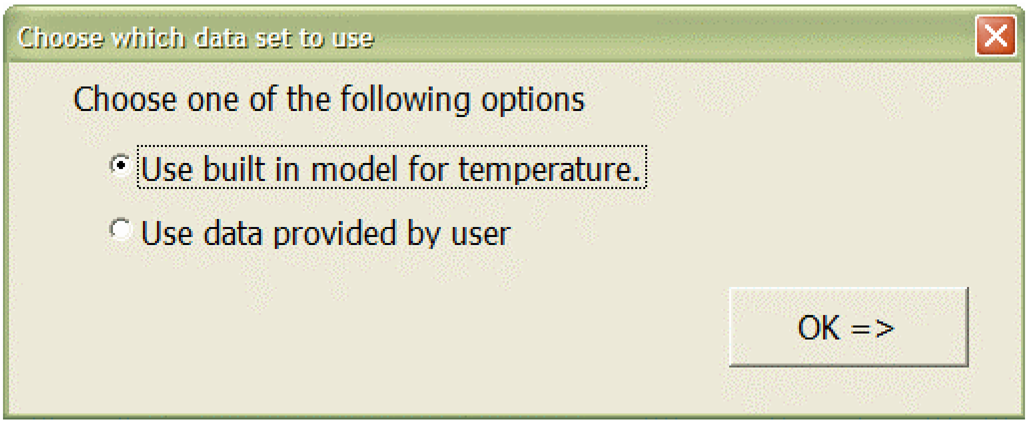
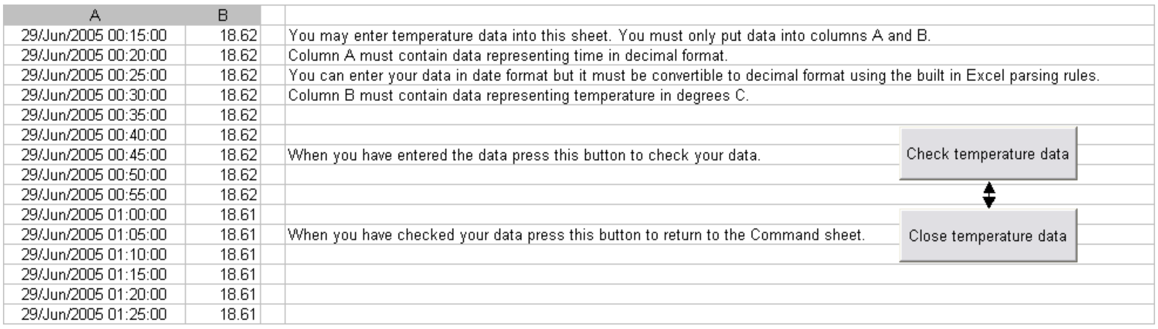


Figure 2.7 Typical dialogue box for options where the user can either use the built in sub-model (in this case for ambient temperature) or alternatively provide their own data.

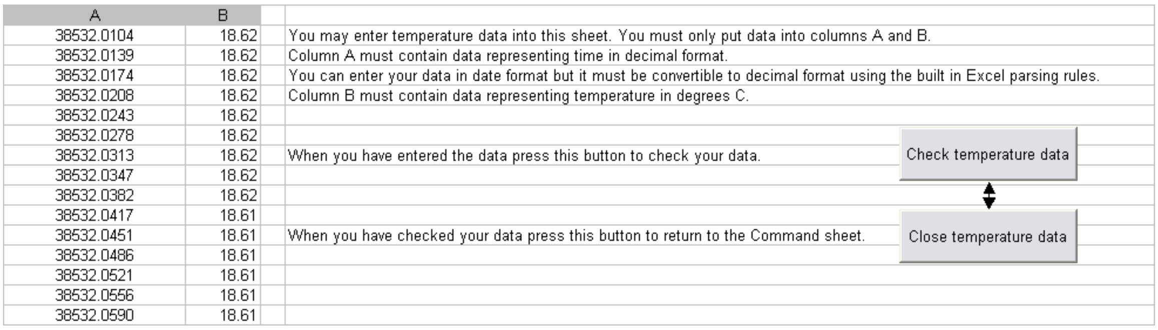
[7] Source – http://www.metoc.gov.au/products/data.html

(a)



A	B	
29/Jun/2005 00:15:00	18.62	You may enter temperature data into this sheet. You must only put data into columns A and B.
29/Jun/2005 00:20:00	18.62	Column A must contain data representing time in decimal format.
29/Jun/2005 00:25:00	18.62	You can enter your data in date format but it must be convertible to decimal format using the built in Excel parsing rules.
29/Jun/2005 00:30:00	18.62	Column B must contain data representing temperature in degrees C.
29/Jun/2005 00:35:00	18.62	
29/Jun/2005 00:40:00	18.62	
29/Jun/2005 00:45:00	18.62	When you have entered the data press this button to check your data.
29/Jun/2005 00:50:00	18.62	
29/Jun/2005 00:55:00	18.62	
29/Jun/2005 01:00:00	18.61	
29/Jun/2005 01:05:00	18.61	When you have checked your data press this button to return to the Command sheet.
29/Jun/2005 01:10:00	18.61	
29/Jun/2005 01:15:00	18.61	
29/Jun/2005 01:20:00	18.61	
29/Jun/2005 01:25:00	18.61	

(b)



A	B	
38532.0104	18.62	You may enter temperature data into this sheet. You must only put data into columns A and B.
38532.0139	18.62	Column A must contain data representing time in decimal format.
38532.0174	18.62	You can enter your data in date format but it must be convertible to decimal format using the built in Excel parsing rules.
38532.0208	18.62	Column B must contain data representing temperature in degrees C.
38532.0243	18.62	
38532.0278	18.62	
38532.0313	18.62	When you have entered the data press this button to check your data.
38532.0347	18.62	
38532.0382	18.62	
38532.0417	18.61	
38532.0451	18.61	When you have checked your data press this button to return to the Command sheet.
38532.0486	18.61	
38532.0521	18.61	
38532.0556	18.61	
38532.0590	18.61	

Figure 2.8 EXCEL™ worksheet where the user can provide their own temperature data (similar sheets are available for salinity, current (tidal) flow, fouling load and respiration rate). (a) data in date format, (b) date converted to decimal format.

Salinity data

Click to open an option box where you can indicate the source of salinity data for the model.

This value will determine whether the model will calculate a value for salinity based on a model of Port Lincoln seasonal salinities or utilise a lookup table, showing salinity through time, provided by the user (similar to the Temperature data button). Novice users should use the internal modelled salinity values that are based on data for Lower Spencer Gulf (Port Lincoln region) provided by the Directorate of Oceanography and Meteorology, Australian Government Department of Defence Online data service[8].

[8] Source – http://www.metoc.gov.au/products/data.html

Current data

Click to open an option box where you can indicate the source of current (tidal) flow data for the model.

This value will determine whether the model will calculate a value for tidal flow based on a model of Port Lincoln seasonal tidal flows or utilise a lookup table, showing tidal flow through time, provided by the user (similar to Temperature and Salinity data buttons)[9]. Novice users should use the internal modelled tidal flow values that are based on tidal height data for Port Lincoln in the year 2005 provided by the National Tidal Centre[10].

Fouling load data

Click to open an option box where you can indicate the source of fouling load data for the model.

This value will determine whether the model will calculate a value for fouling load based on a model of Port Lincoln seasonal changes in fouling growth rates or utilise a lookup table, showing fouling load through time, provided by the user (similar to Temperature, Salinity and Current data buttons). Novice users should use the internal modelled fouling load values that are based on empirical data obtained from the Boston Island East Farming Zone (now Lincoln Offshore Aquaculture Zone).

Respiration rate data

Click to open an option box where you can indicate the source of data on respiration rates used in the model.

This value will determine whether the model will calculate a value for respiration rate based on a model for the various fish species selected (via the Farmed species button) or utilise a lookup table, showing respiration rates through time, provided by the user (similar to the above buttons). Novice users should use the internal modelled respiration rate values for the fish species they have chosen.

Run model scenario

Press this button to run the model using the values you have provided at the preceding steps.

[9] OxyTuna© has been developed using a modularised series of sub-routines for the various sub-models. This means that future developments can be easily incorporated (for example the inclusion of tidal flow models from other SBT projects such as Risk and Response).

[10] Source – http://www.bom.gov.au/oceanography/tides/MAPS/lincoln.shtml#form

The model will be run. Firstly the user will be provided with an estimate of the likely time to complete the run, which can be halted if the estimated time is too long for the user's purposes. If this is the case, increase the time-step in the model or reduce the number of days over which the model is run. Once the user has chosen to continue, the model will begin execution. The results will be presented in graphical form on the chart at the bottom of the screen. Observe the blue line, this is the estimate of oxygen concentration at any point in time over the modelled period. The magenta line represents the tidal current over the same period of time.

Users should note that under a typical run the oxygen concentration (blue line) is more likely to fall during times when current flow (magenta line) is also low. This illustrates the simple fact that when sea-cage ventilation (which is driven by current flow) is low, respiration by fish will draw down the dissolved oxygen level in the sea-cage. When cage ventilation rates are higher (higher current flow), oxygen level stays close to the ambient value (largely determined by saturation percent). This behaviour is strongly influenced by fouling level (higher draw down when fouling is high) and by fish respiration rates (less draw down for lower respiration rates).

Store comparison

Click to store the results from the last model run.

The data from the last run of the model will be stored. You will now have a green line on the chart that represents the results from the stored run. You can use this to compare the effect of changing the model parameters. Typical scenarios that can be used to illustrate the utility of this function could include changing parameters about cage configuration (e.g. reducing the size of the cage) or by changing parameters associated with stocking density (e.g. by increasing the number of fish in the cage). Having done this the model can be re-run. The blue line will represent the prediction based on the new set of parameters while the green line represents the results from the previous scenario. All model results are stored in a separate worksheet and experienced users may export them for use in other programs.

Delete comparison

Click to remove the data stored for a previous scenario.

You do not have to remove the data to store the results from a new run. You can just press the "Store comparison" button to over-write a set of previously stored results. Pressing this button just removes the green line from the graphical display.

Built-in sub-models

Seasonal water quality sub-model

Data on temperature and salinity can be modelled using the equations provided with the model. These data are shown in Table 2.1 and have been obtained from the Directorate of Oceanography and Meteorology[11].

Table 2.1 Average temperature and salinity data predicted for Lower Spencer Gulf (Port Lincoln region) by month, as provided by the Directorate of Oceanography and Meteorology.

Month	Temperature (^{o}C)	Salinity (ppt)
January	20.5	35.6
February	20.7	35.6
March	20.8	35.7
April	20.7	35.7
May	19.4	35.9
June	18.4	35.7
July	17.8	35.6
August	17.8	35.8
September	18.4	35.3
October	17.9	35.5
November	20.2	35.3
December	20.2	35.6

Using these data, an empirical model of temperature (T_{day}) or salinity (S_{day}) for any date during the year can be interpolated from a simple Cosine function using the formulae shown in Equations 2 and 3.

$$T_{day} = R \times \left\{ Cos\left(\frac{2 \times \pi * [day + lag]}{365} \right) \right\} + T_{Base} \qquad \text{Equation 2}$$

The model for salinity is more or less identical in form (Equation 3) to the temperature model but the values for the various model constants (Table 2.2) are different.

$$S_{day} = R \times \left\{ Cos\left(\frac{2 \times \pi * [day + lag]}{365} \right) \right\} + S_{Base} \qquad \text{Equation 3}$$

An explanation for each of the constants and the values applied for Port Lincoln are provided in Table 2.2.

[11] Source – http://www.metoc.gov.au/products/data.html

Table 2.2 Parameter values used for the built-in ambient temperature and ambient salinity sub-models. Parameter values refer to values used in Equations 2 and 3.

Parameter	Temperature sub-model	Salinity sub-model	Explanation of the parameter
T_{day} S_{day}			Temperature or salinity on any given day of the year; *day* is a number between 1 and 365 (or 366 for leap years) corresponding to January 1 through December 31.
R	1.6028	-0.1797	A simple cosine function varies between -1 and +1. The value for R changes the scale of this variation. For temperature the value of R provides for an annual variation of 3.2 degrees (between maximum and minimum values i.e. ± 1.6).
Lag	-60.33	41.06	A simple cosine (scaled over 365 days) would have a maximum value on days 0 and 365 with a minimum value on day 183. The lag value moves the curve to the left or right so that the maximum and minimum values can occur earlier or later in the cycle. For the temperature model the value provides for a maximum 60 days after the start of the year (i.e. in early March).
T_{Base} S_{Base}	19.4	35.61	The base value is the annual mean value and, by definition, the annual fluctuation will increase or decrease relative to this value (determined by the value for R – see above).

These models provide a good fit to the original data (Figure 2.9). The scale of variation in salinity at Port Lincoln is very small, and changes over the course of the year will have no real effect on oxygen concentrations. Nevertheless, incorporation of these sub-models provides for changes in the OxyTuna© model if applied to other regions (e.g. Upper Spencer Gulf), where salinity values undergo large annual fluctuations.

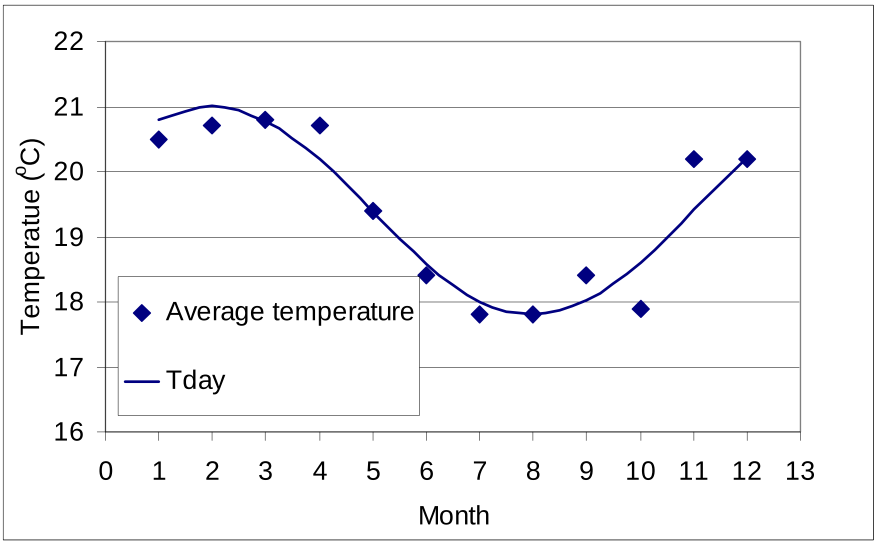


Figure 2.9 Illustration of the goodness of fit between temperature data and temperature sub-model parameterised for Port Lincoln.

Current speed sub-model

The current speed sub-model actually uses a lookup table for current speed at Port Lincoln in the calendar year 2005. The values in this lookup table have been calculated using the published tide tables for Port Lincoln (National Tidal Centre[12]). The current speed in the lookup table was modelled using an empirical equation (Equation 4) calibrated against data from the Tuna Farming Zone under the Aquafin CRC Regional Environmental Sustainability (RESA) project[13] (Bierman *et al.* 2007) over the period 29th June 2005 through 9th August 2005. The goodness of fit between the modelled and actual currents for this period is reasonable ($r^2 = 0.585$; Figure 2.10).

$$C_t = \left| \frac{H_{t+\partial t} - H_t}{\partial t} \right| \times Fh \qquad \text{Equation 4}$$

In this model C_t represents the Current Speed at model time t, H_t is the tidal height (obtained from published tide tables) at model time t, $H_{t+\delta t}$ is the tidal height at a time δt after the current model time. Fh is a constant that relates current speed to time dependent tidal height differences. The model takes no account of wind-forced currents and has only been calibrated against data (as detailed above) for part of the year. Alternative configurations of the equation that incorporate data on ambient wind conditions have been

[12] Source – http://www.bom.gov.au/oceanography/tides/MAPS/lincoln.shtml#form

[13] Aquafin CRC/FRDC Project 2001/104: Aquafin CRC - Southern Bluefin Tuna Aquaculture Subprogram: Tuna environment subproject - Development of regional environmental sustainability assessments for tuna sea-cage aquaculture.

evaluated in developing the model. While this provides a better fit to the data, it also increases the overall complexity of the model and therefore has not been included into this implementation.

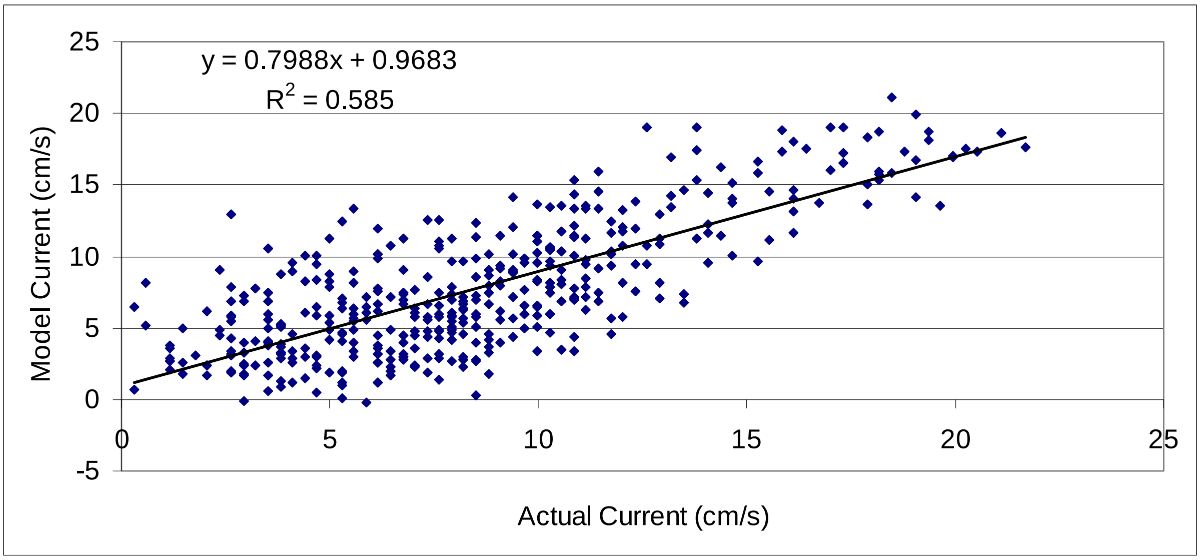


Figure 2.10 Goodness of fit between actual and modelled current using the model specified in Equation 4.

Fouling load sub-model

Sea-cage net fouling changes through time as organisms recruit onto the surface and grow. The data available on changes in fouling load through time are limited to a single set of experimental observations undertaken as part of this project. A simple sub-model for the development of a fouling community has been implemented based on these data (Equation 5). The sub-model provides for an initial rapid phase of colonisation of the net followed by a period where the level remains constant (Figure 2.11). Although the data show an apparent decline in fouling load we have chosen not to incorporate this into the model because we have no basis for extrapolating this behaviour beyond the bounds of the available data.

$$F_t = BaseLevel + \left\{F_{\max} \times \left(1 - e^{[-t/t_k]}\right)\right\} + FoulAdd \qquad \text{Equation 5}$$

F_t is the occlusion of the net (due to fouling and the presence of the net) at time t. At time zero the model assumes a base level of occlusion (*BaseLevel*), which is simply a measure of the obstruction to water flow presented by the physical structure of the net (lines and knots). This parameter will change depending on the type of net used and can be derived directly from the measurements of the net rope thickness and the mesh size (see above section on ***Cage details***). F_{max} is the maximal level of net fouling, t is the model time and t_k is a constant that determines the rate at which fouling will develop on the net. Smaller values for t_k give faster rates for the development of the fouling community and larger values provide for a longer period for fouling to develop. *FoulAdd* is an arbitary constant added to the value derived by the setting on the "Additional fouling load" slider bar (see above). *FoulAdd* allows the user to look at the effect of increased levels of fouling for the purposes of simple scenario analyses. F_t is bounded to ensure that occlusion of the net associated with the fouling community and any arbitrary additional amount from the user setting of *FoulAdd* cannot exceed 100%. While different forms of fouling (hard e.g. mussels versus soft e.g. algae) may have differing effects on water flow no attempt has been made to account for this.

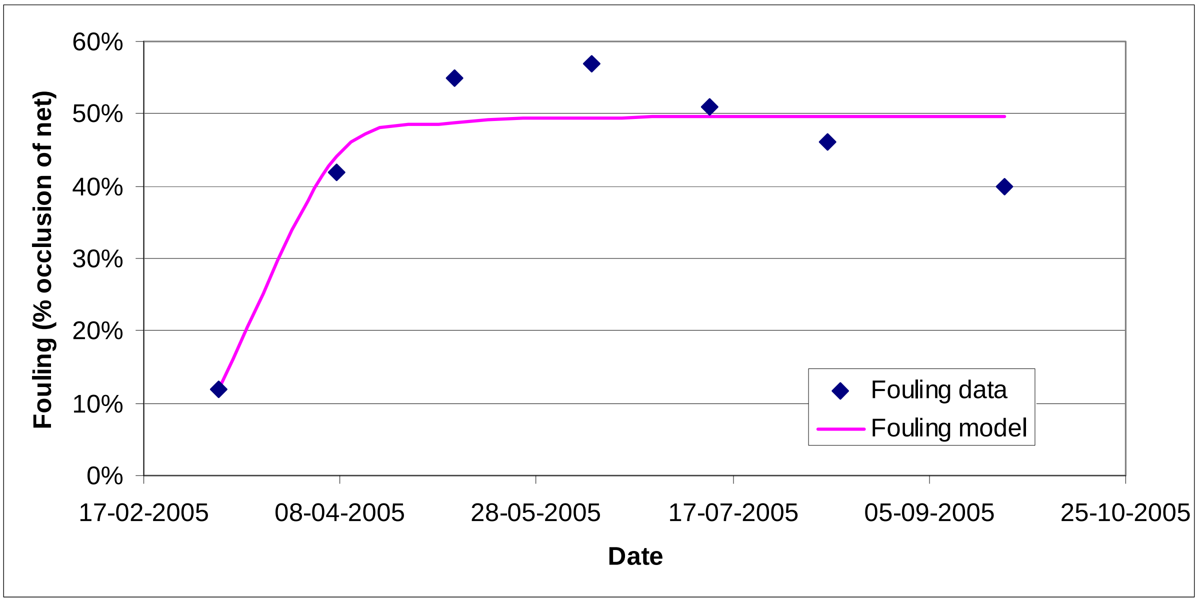


Figure 2.11 Model (magenta line) of fouling load through time based on empirical data from a sea-cage system in the Boston Island East Farming Zone (now Lincoln Offshore Aquaculture Zone) fitted to Equation 5.

Cage ventilation sub-model

Mass transport of dissolved oxygen into the sea-cage (ventilation) is fundamentally linked to the volume of water moving through the net over any given time. Volume flow into a sea-cage is a function of three key variables:

1. Current speed (Current – measured in metres per second);

2. Extent to which fouling and the physical structure of the net obstructs the flow (Occlusion – measured as a percent of the cage area);

3. Cross-sectional area of the cage measured perpendicular to the direction of water flow.

Theoretically, if we take a 1 m^2 area of net hanging vertically and oriented perpendicular (across) the current then the calculation of mass transport through the net is relatively simple; multiply the current speed ($m.s^{-1}$) by the cross-sectional area (m^2) and this provides us with the volume moving through the net ($m^3.s^{-1}$). In reality the calculation is slightly more complex. Firstly we need to determine the cross-sectional area of the cage that is perpendicular to the current and secondly we need to calculate the extent to which the net and any attached fouling organisms will impede the flow of water.

Area of cage net perpendicular to current flow

The cross-sectional area of the sea-cage can be calculated by taking the projected area of the cage along the perpendicular plane at right angles to the direction of current flow. In effect the cross-sectional area of the net perpendicular to the flow is therefore the diameter of the cage (m) multiplied by the depth of the cage depth (m). This calculation also accounts for the change in cross-sectional area of the net (perpendicular to current flow) associated with curvature of the cage.

Effect of net and fouling on water flow

The presence of the net and any associated fouling results in an effective reduction of the cross-sectional area through which water can flow into and out of the cage. However, the effect of occlusion is not a simple linear reduction in water flow. Rather a complex process of turbulence in and around the net modifies the rate at which water flows through the net. Models of turbulent flow are beyond the scope of this study so an alternative strategy was to develop a simple mathematical model of the relationship between measurements of current speed and the flow rate through nets. Volume flow rates were obtained from the flume tank experiment carried out in Subproject 4.

Measurements of the flow through net panels with different levels of fouling were made and these data were then used to develop an empirical model of the effect of fouling on water flow (Equation 6). No data are available for nets with an occlusion greater than 72% so the model has been constructed in two parts:

1. A goodness of fit analysis for the flow rate through a net with up to 72% occlusion (Equation 6).

2. A simple linear reduction model for flow rate through a net with more than 72% occlusion (Equation 7).

In this way the model produces data that are consistent with the experimental data for the range of panels used for measurement.

$$FR_t = C_t \times (Flow_A \times [1 - F_t]^{Flow_B}) - \left(Flow_C \times C_t\right) - Flow_D \qquad \text{Equation 6}$$

Where FR_t is the flow rate through 1 m^2 of the net ($m^3.s^{-1}$) at time t, C_t is the Current Speed at time t, F_t is the fouling (% of the net occluded) at time t, $Flow_A$, $Flow_B$, $Flow_C$ and $Flow_D$ are constants.

For fouling loads greater than 72% the model assumes a linear decline in flow rate (Equation 7) from the rate achieved at a fouling load of 72% (defined as $FR72_C$ calculated from equation 6 where F_t = 0.72) to a value of 0 at a fouling load of 100%. The slope of this line is defined as $FR72_m$ = -$FR72_C$ / (1-0.72).

$$FR_t = FR72_m \times [F_t - 0.72] + FR72_c \qquad \text{Equation 7}$$

Application of the formulae in Equations 6 and 7 over a fouling range (0-100%) and current speeds of 0-1 $m.s^{-1}$ yields the plot shown in Figure 2.12. For any given current speed low levels of fouling (<20%) have little effect on volume flow rate through the net (volume is limited only by current speed). As fouling level increases the volume flow rate decreases until at a loading of 100% volume flow is reduced to zero (the net is effectively impermeable). This model provides a good fit to the experimental data (r^2 = 0.87; Figure 2.13).

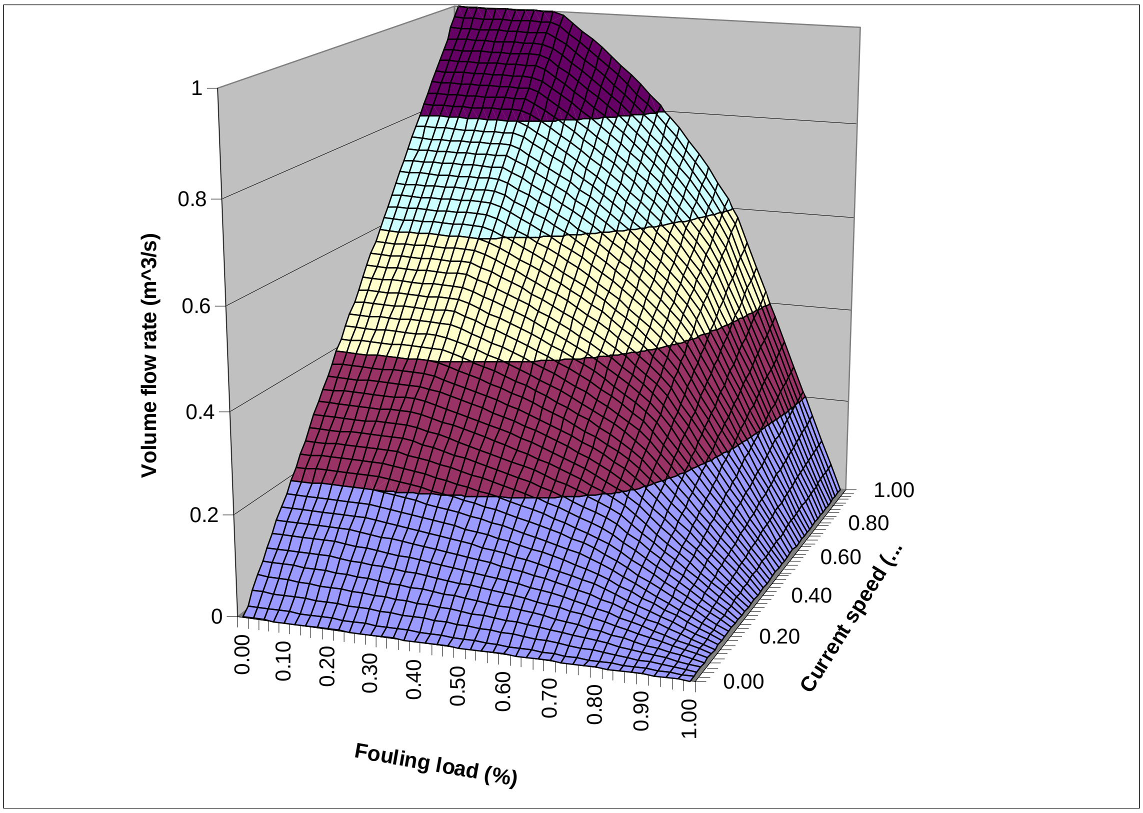


Figure 2.12 Effect of sea-cage net fouling load (x-axis) and current speed (y-axis) on volume flow rate through 1 m^2 cage panel (z-axis). In general terms flow rate increases with increases in current speed and/or decreases in fouling load.

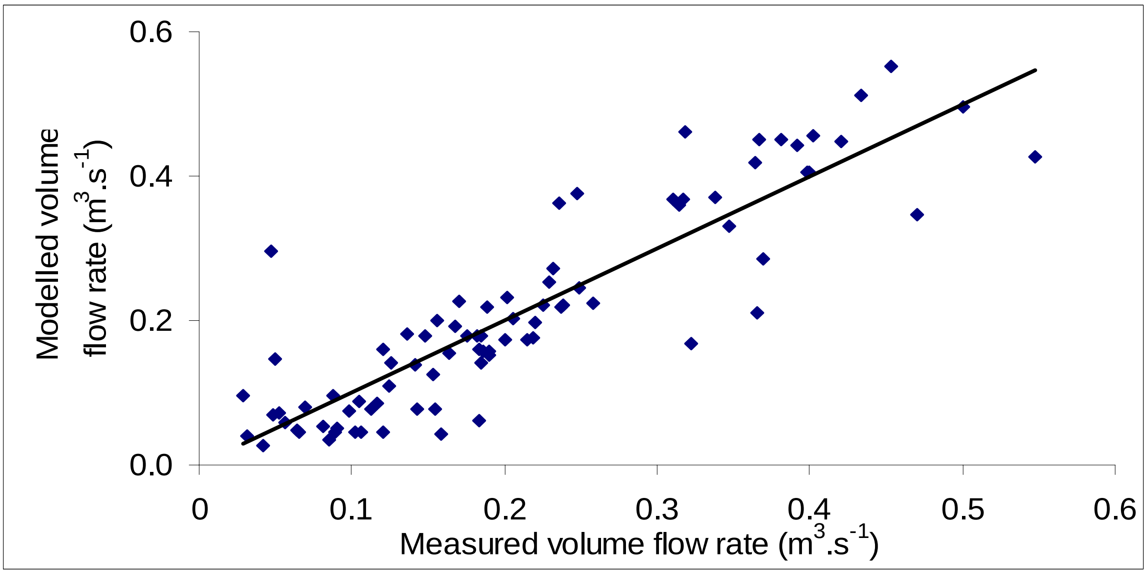


Figure 2.13 Goodness of fit between actual volume flow rates through the net (x-axis) as measured in the flume tank versus the modelled flow rate through the net (using the model developed above; y-axis).

Fish respiration sub-model

The fish respiration sub-model currently uses a simple respiration constant for each species of fish (chosen via the "Farmed species" button). Values have been abstracted from the literature or estimated based on comparisons with similar species. Implicitly the model assumes that respiration rate is constant through time. For southern bluefin tuna, this assumption is not correct (Musgrove and Fitzgibbon 2005) (and this is probably the case for other species) but until more highly resolved data are available on changes relative to feeding rates, water temperature, ambient oxygen, etc, it is the best assumption that can be made. Notwithstanding, the user can still provide their own data on respiration rates via the "Respiration rate data" button. This allows advanced users to build their own models for respiration through time and feed it to the model directly (see Scenario 4 below for an applied example).

Chapter 3 Scenario analysis

This chapter is intended to illustrate the utility of the model through a number of simple scenarios. These scenarios comprise an illustration of the effects of:

1. A 20% reduction in ambient dissolved oxygen concentration with all other parameters being held constant.

2. A 40% increase in stocking density with all other parameters being held constant.

3. A 30% increase in net fouling load combined with a 30% drop in current speed and all other parameters being held constant.

4. A run in which the fish respiration rate increases with current flow (assuming for example that the farmer feeds only during periods of high flow) compared with a run in which the respiration rate is assumed to be constant through time.

The first 3 scenarios can be run quite easily using only the buttons and slider bars provided on the command interface.

Scenario 4 requires the user to enter their own data for respiration rate, which can be modelled based on current flow (see below).

Background scenario – basis for comparison

Scenarios 1 to 4 were run against a standard model run. The standard model run had model parameters set as detailed in Table 3.1. With these values the time series for oxygen concentration, as predicted by the model, is shown in Figure 3.1.

Table 3.1 Model parameters against which scenarios 1 to 4 were compared.

Parameter	**Value**	**Units**	**Explanation of variables**
CageDepth	12.0	m	Depth from surface to bottom of side net
CageDiameter	40.0	m	Diameter measured at the surface
MeshSize	10.0	cm	Distance measured from inside of net rope across mesh to outside of next rope
RopeDiameter	6.0	mm	Net rope thickness
DeltaT	1	hours	Model time step in hours
ModelTimeStep	0.042	days	Model time step in days
RunFor	10	days	Total period to run model over
StartDate	01-Jul-2005 00:00:00	date	Determined by user
StartDay	181.000	day	Day of the year 1-Jan-05 = day 1
EndDay	191.000	day	Day of the year
EndDate	11-Jul-2005 00:00:00	date	End date of model run
TimeEst	0.2	minutes	Estimated time to run model given parameter choices
FoulAdd	0%	%	Obtained from slide bar on command sheet
AveFishSize	20.0	kg	Average size of fish
FishNumber	1000	fish	Number of fish in cage
FishBiomass	20000	kg	Calculated from AveFishSize X FishNumber
FishResp	650	$mgO_2.kg^{-1}.h^{-1}$	Literature derived value (Clarke and Johnston 1999)
FishSpecies	SBT		Species being farmed
StockDens	1.3	$kg.m^{-3}$	Calculated from FishBiomass/CageVolume

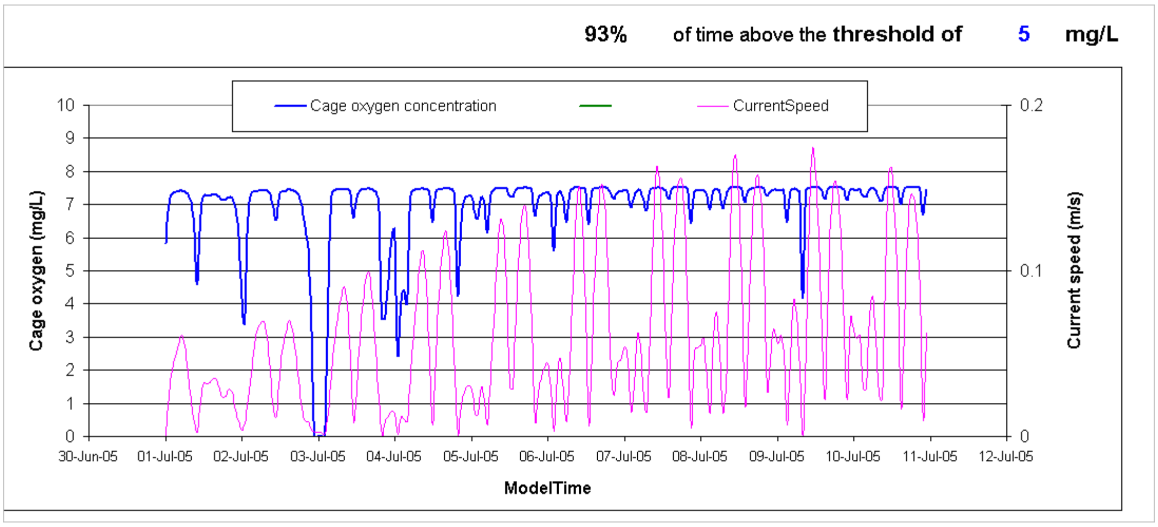


Figure 3.1 Time series prediction using parameter values shown in Table 3.1. The blue line shows dissolved oxygen concentration ($mg.L^{-1}$ or ppm) and the magenta line current speed ($m.s^{-1}$) due to tidal flow.

Scenario 1 – 20% reduction in ambient oxygen

Scenario 1 is enacted with the user dragging the "Ambient % saturation" slider to the left to set the saturation value at 80%. All other parameters remain the same as the background scenario as detailed above.

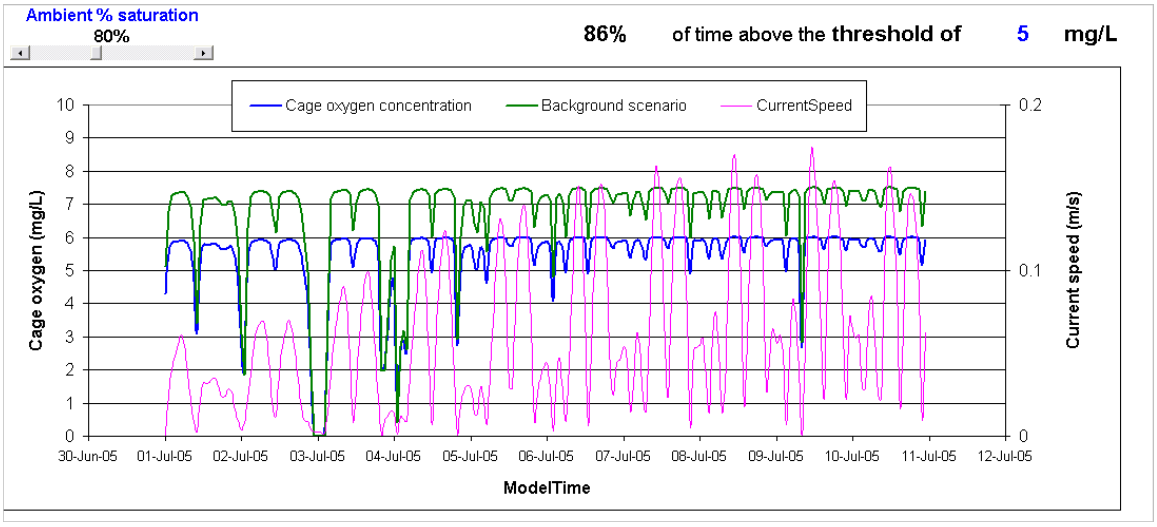


Figure 3.2 Scenario 1 – the plot shows the results with the ambient % saturation set at 80%. The green line on the plot is the background scenario as detailed above and the blue line is the results of Scenario 1.

The scenario predicts a simple downward shift in the oxygen level of around 1.5 $mg.L^{-1}$ (or ppm) over the entire period of the model run. Both this scenario and the background scenario show a precipitous drop in dissolved oxygen in the sea-cage (around 3rd July 2005) associated with a low current flow event when tidal flow was reduced to around zero for a period of 2 hours.

The utility of the "% of time above the threshold" calculator is illustrated by the comparison between the background scenario (Figure 3.1) where dissolved oxygen levels in the sea-cage were above 5 $mg.L^{-1}$ for 93% of the time compared to this scenario (Figure 3.2) where oxygen values were above the threshold for only 86% of the time.

Scenario 2 – 40% increase in stocking density

Scenario 2 is enacted by pressing the "Stocking rates" button and changing either the value for the average size of fish or the number of fish to a value 40% higher. In the background scenario run, the stocking density was set at 1.3 $kg.m^{-3}$ while in Scenario 2 the stocking density was set at 1.9 $kg.m^{-3}$.

The results of this scenario (Figure 3.3) shows that stocking density only has a significant effect during periods of low current flow when mass water exchange is limited relative to the rate of oxygen consumption by the fish.

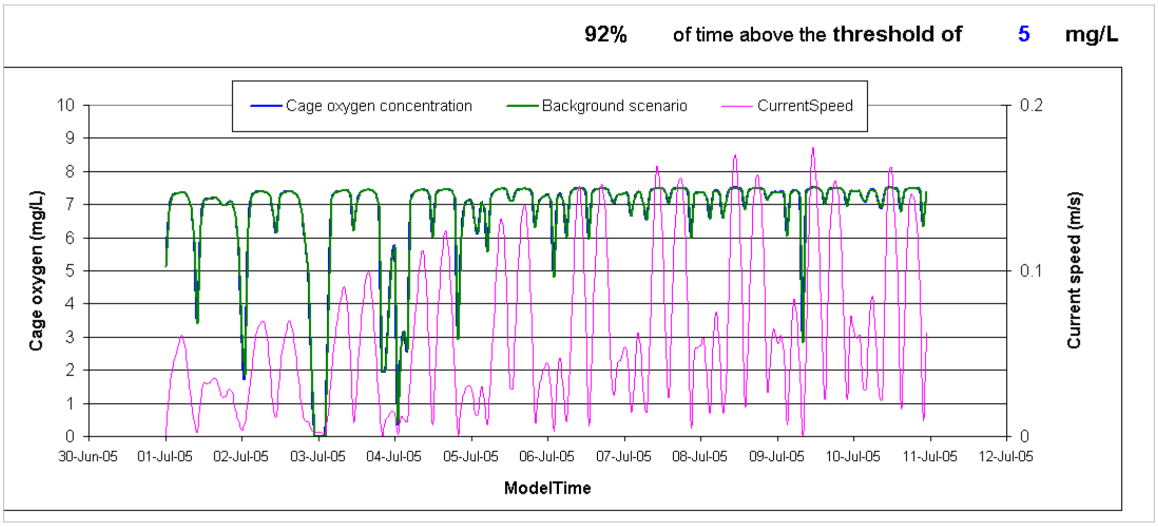


Figure 3.3 Scenario 2 – the plot shows that an increase in stocking density has little impact on sea-cage dissolved oxygen level except during the periods of low flow (note the period around 4-Jul-2005).

Scenario 3 – 30% increase in fouling load combined with a 30% drop in current speed

Scenario 3 is enacted by setting the "Additional fouling load" slider to 30% and the "Relative current speed" slider to 0.7.

The scenario shows that water flow rates (determined by current speed and the level of fouling on the cage) have a substantial influence on dissolved oxygen status inside the sea-cage. During periods of high tidal flow oxygen levels are maintained close to the ambient conditions (Figure 3.4) but oxygen levels fall substantially (relative to the control situation) during periods of low flow. The period of time spent below the 5 $mg.L^{-1}$ threshold is 87% which is only slightly less than that for the control run (93%; Figure 3.1).

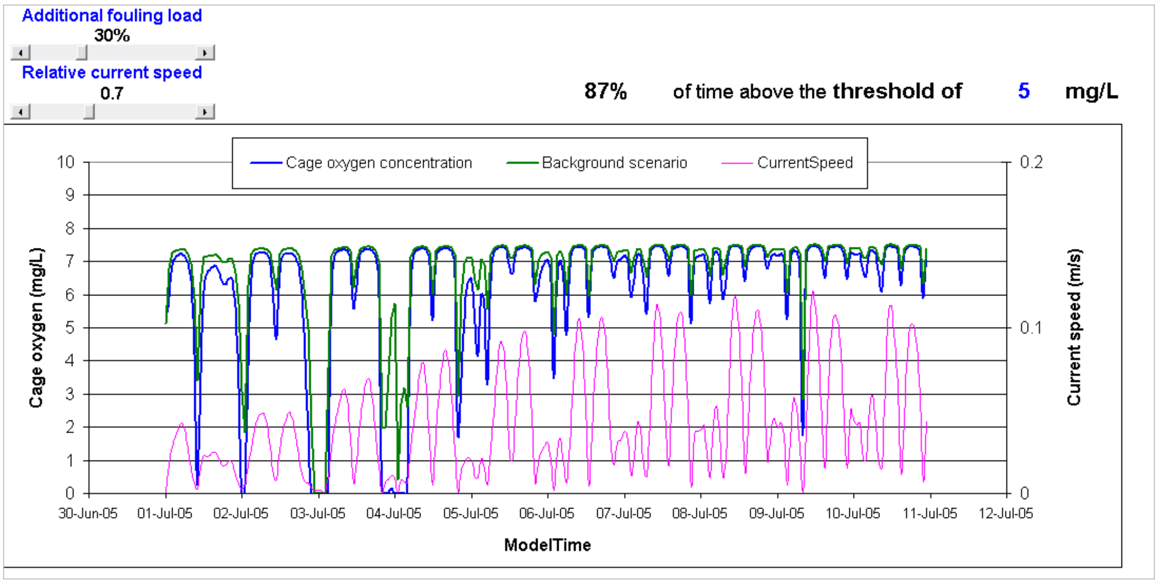


Figure 3.4 Scenario 3 – the plot shows that changes in flow rate and fouling load have a substantial effect on sea-cage dissolved oxygen level during periods of low flow but relatively little effect during periods of moderate-high flow.

Scenario 4 – Comparison of respiration rates linked to current flow

Finfish respiration rates are known to change through time, and particularly in relation to feeding activity by the fish (Musgrove and Fitzgibbon 2005, Seymour *et al.* 2007). Scenario 4 provides a comparison of the effect on cage oxygen when fish respiration rate is assumed to vary in response to feeding. This can be compared to the background scenario in which the respiration rate is assumed to be constant through time.

As detailed above, OxyTuna© was developed to allow scenarios that make use of the built-in sub-models for selected parameters (temperature, salinity, current flow, fouling load and fish respiration rates). Alternatively users may provide their own data for these parameters. Importantly, user supplied data may be derived either from field based observations (i.e. empirical observations) or from new models developed by the user. This scenario has used the latter approach.

Research under Aquafin CRC project 1A.7 (Phase 1 and 2) has shown that respiration rates are unlikely to be constant through time (as assumed in the basic OxyTuna© sub-model); rather, respiration rates are maximised after feeding and then fall through time to the base level (Musgrove and Fitzgibbon 2005, Seymour *et al.* 2007). A simple time-series model was developed in EXCEL™ to illustrate this behaviour. The model assumed that immediately after feeding the respiration rate increased to 1200 $mgO_2.kg^{-1}.h^{-1}$ and then fell, over a period of 12 hours, back to the base rate of 600 $mgO_2.kg^{-1}.h^{-1}$ (this is somewhat faster than the empirical data suggests). Feeding times were selected to coincide with the period of maximum current flow, once every day and during daylight hours. Application of this model provides a time-series for respiration rate as shown in Figure 3.5.

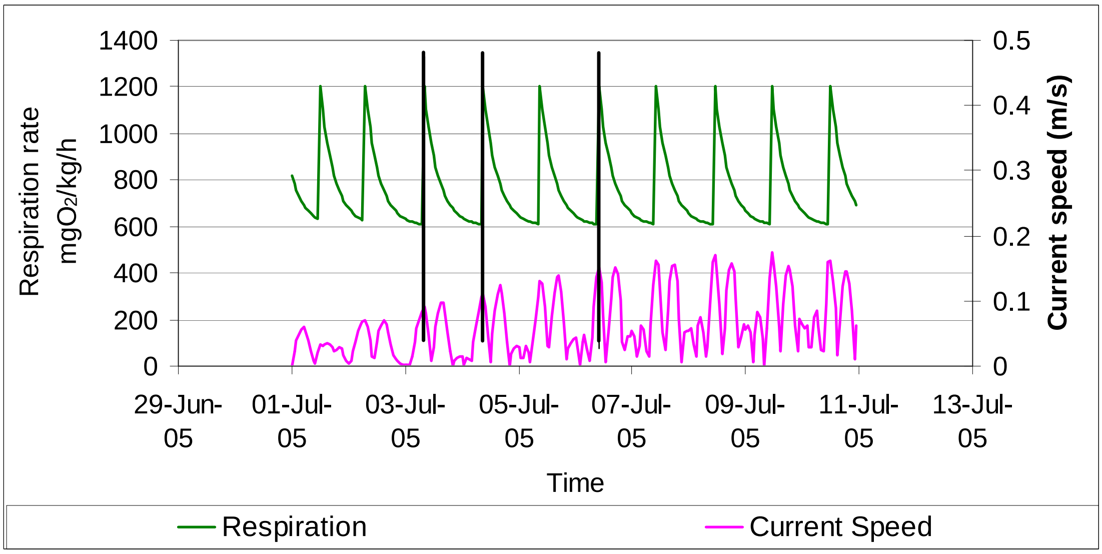


Figure 3.5 Time series plot showing current flow (lower magenta line) and respiration rate (upper green line) used for Scenario 4. Vertical black lines illustrate selected examples of the linkage between periods of higher current flow and the increase in respiration due to feeding.

When OxyTuna© was run using this user-defined model for respiration there was almost no effect on sea-cage dissolved oxygen dynamics (Figure 3.6). This provides a good demonstration of the very low sensitivity of the model to the value for the respiration rate parameter. This result contrasts strongly with those from Scenario 3, which demonstrates a high sensitivity to current flow and fouling (both of which relate to volume transport of water through the net).

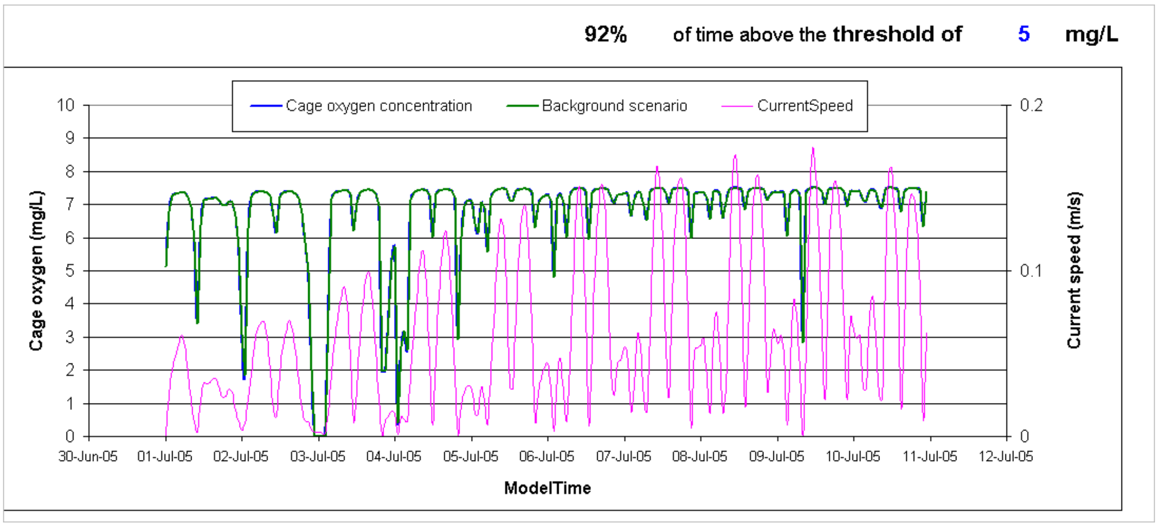


Figure 3.6 Scenario 4 – the plot shows that a periodic doubling of respiration rate has almost no perceptible effect on overall sea-cage dissolved oxygen concentration. The blue line (scenario 4) is almost perfectly superimposed over the green line (background scenario) demonstrating a very low sensitivity to respiration rate.

Chapter 4 Conclusions

The OxyTuna© model has been developed in order to assist farm managers to make better decisions about the management of finfish sea-cage systems and in particular to better understand the relationship between net fouling and dissolved oxygen concentration in cages and how this responds to various management interventions including changes in cage configuration, stocking density and fouling management (e.g. cage cleaning).

The model provides a quantitative prediction of the changes in dissolved oxygen concentration through time for different sea-cage configurations (cage size, net type, stocking density, fish species) in response to changes in ambient conditions (temperature, salinity, ambient oxygen concentration and current speed).

The dynamical nature of the model allows users to better understand the interplay of factors that control dissolved oxygen concentration in a sea-cage, and it can therefore be used not only as a management tool but also as a teaching tool.

The model provides a number of sophisticated features including:

- An enhanced interface that allows the user to quickly and simply develop and analyse simple scenarios relating to changes in stocking density and sea-cage configuration.
- A set of simple sub-models that simulate changes in fouling load, sea-cage ventilation rates (based on tidally induced current flow and fouling load), fish respiration rates for different species and seasonal changes in water quality (including temperature, salinity and ambient oxygen concentration).
- An advanced facility that allows the user to incorporate more sophisticated time series data (or user developed models) that quantify changes in ambient water quality, tidal flow, fouling load and fish respiration rates.
- A simple graphical output that provides a clear representation of the predicted time series.

By implementing OxyTuna© as a Visual Basic for Applications (VBA)™ program developed to run within Microsoft EXCEL™ the model outputs can be easily captured and incorporated into other programs by anyone with a basic understanding of EXCEL™. This feature is expected to improve the utility of the model and the opportunity for individual users to develop their own enhancements.

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Appendix I Explanation of the modified Forrester symbol system

The design of the OxyTuna© model has been represented schematically in Figure 2.1. This figure uses a series of symbols that were based on the Forrester symbols (Forrester 1961). Forrester symbols allow the modeller to provide a schematic representation of material flows, control flows, control variables and parameters, rate equations (processes) and state variables. These symbols are summarised below.