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Implementation of the Atlantis ecological model in the Westernport Scoping Study

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1. Introduction

The Westernport Scoping Study is being conducted by the Victorian State Government and CSIRO to scope the development of support tools for improving balanced economic, social and environmental decision making. The Westernport Bay and catchment region is an ideal place for development of such tools: it is undergoing extensive urban development and significant change in catchment land practices; it provides important marine and coastal habitats for supporting biodiversity, conservation, recreation and commercial use; and it also provides catchment and storage of water for domestic and industrial use. In combination with those of the Mornington Peninsula, its unique attributes have also been recognised through the declaration of a UNESCO Biosphere for the region.

In order to develop decision support tools for such a region, it is necessary to use a well-organised framework. This involves establishing the key issues through stakeholder engagement, the collection of data and background information, and initial modelling, to ascertain knowledge gaps and to scope scientific capability for providing decision support.

2. The Atlantis modelling platform

Initial modelling for the marine component of the Westernport region has been done using the Atlantis ecological model. Atlantis is a modelling framework that includes a deterministic biogeochemical ecosystem model (Fulton *et al*. 2004).[1] The model tracks the nutrient flow through the main biological and detritus groups found in temperate marine ecosystems. The invertebrate and primary producer groups are simulated using aggregate biomass pools, while the vertebrates are represented using age-structured models. The primary processes considered in Atlantis are consumption, production, migration, recruitment, waste production, habitat dependency, predation and (natural and fishing) mortality. The outputs of the model consist of deterministic time series for each component in the modelled ecosystem.

This model has been used in the Westernport Scoping Study to determine data requirements and knowledge gaps, and to demonstrate where and how science can support natural resource management and policy.

3. Physical implementation

3.1 Box design

Polygons are used to define the groupings of the modelled system (Figure 1). Horizontally, boxes were defined, considering:

- the major geographic segments based on previous studies of water movements and sediment (Marsden et al. 1979)
- bathymetry (particularly the distinction between channels and tidal flats)

[1] This is the only part of Atlantis that was used at this stage of the modelling study of Westernport Bay.

Vertically, only one sediment, and one water column layer were considered.

This implementation of Atlantis is not yet designed to represent tidal variations of sea level and the subsequent emersion-immersion of some of the boxes.

3.2 Hydrodynamics

Atlantis does not include an explicit hydrodynamics model. Instead it uses a transport model. It is therefore necessary to specify, as a forcing condition, the water fluxes between the different boxes making up the modelled system.

Some significant hydrodynamic studies were carried out in Westernport (WP) in the past (Nihoul (ed) 1979, Jenkins *et al.* 1992 and Black pers. com.). Some work nevertheless is required to adapt the available information to our model spatial structure. Given the available time, in this scoping study a simple approach was used: a set of fluxes between the boxes was constructed, assuming a global flushing rate of 1000 $m^3.s^{-1}$ (net incoming water flux in WP = net outgoing water flux from WP). The requisite information regarding the bay's circulation scheme and current velocities came from Sternberg 1979; Hinwood and Jones 1979; and Marsden 1979. A schematic of the resulting flows is given in Figure 1.

As little supporting information was available, a constant circulation scheme is assumed throughout the simulated period. We did not consider tidal variations or neap-tidal or other seasonal variations.

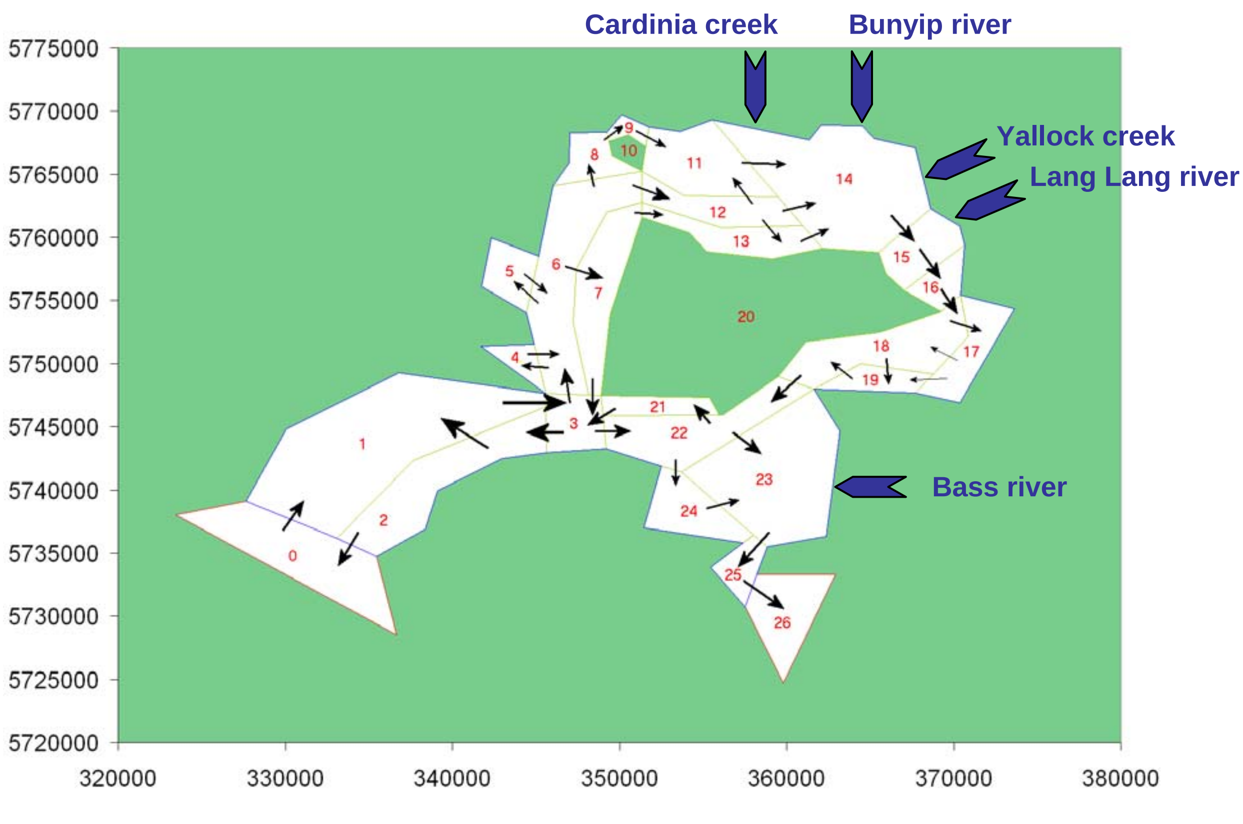


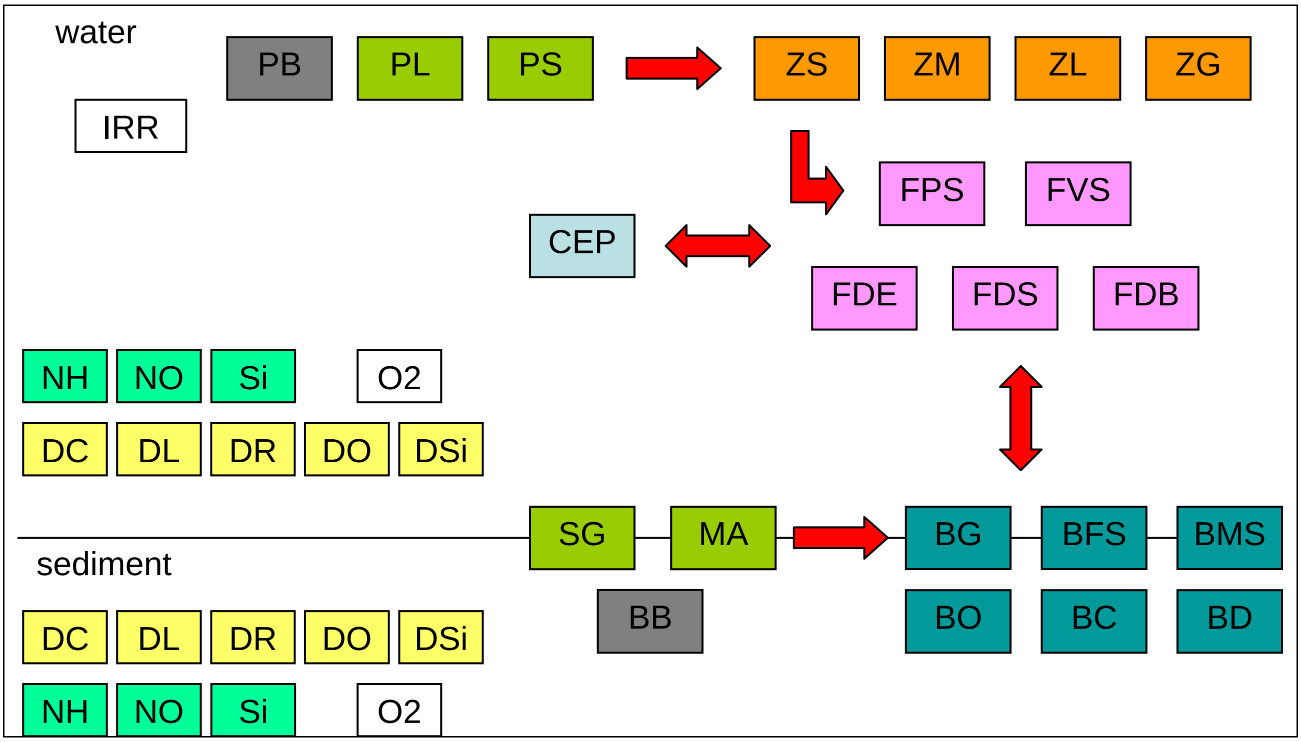
Figure 1: Box design, water circulation and terrestrial inputs in the Westernport Atlantis model.

3.3 Terrestrial inputs

Only the most important water flux inputs were considered at this stage. These were Cardinia creek, Bunyip river, Yallock creek, Lang Lang river, and Bass river (Marsden *et al*. 1979). The river flow and input data available to run the model are detailed below in Section 5.1.

4. Biological implementation

The Westernport biocenosis is represented in the model as depicted in Figure *2*. The functional groups were picked from a pre-existing list in Atlantis. The dynamics of upper predators, such as sea and shore birds, as well as sharks and mammals, were not considered explicitly in the scoping model. Nevertheless, the fish and invertebrates' mortality due to predation by these higher trophic levels was estimated and included (see *Appendix 1*). An average daily mortality due to fishing activities is included in the same manner (see *Appendix 2*).



Small planktivores	FPS	(abundance and weight)
shallow piscivores	FVS	(abundance and weight)
Sh. demersal sedentary	FDS	(abundance and weight)
Sh. demersal casual 1	FDE	(abundance and weight)
Sh. demersal casual 2	FDB	(abundance and weight)
Large phytoplankton	PL	mg N m-3
Picophytoplankton	PS	mg N m-3
Cephalopods	CEP	mg N m-3
Gelatinous zooPK	ZG	mg N m-3
Large carnivorous zooPK	ZL	mg N m-3
Copepods (mesozooPK)	ZM	mg N m-3
Small zooplankton	ZS	mg N m-3
Pelagic assoc. bacteria	PB	mg N m-2
Dissolved oxygen	O2	mg O m-3
Light	IRR	W m-2
Temperature	T°	° C

Microphytobenthos	MB	mg N m-2
Seagrass	SG	mg N m-2
Macroalgae	MA	mg N m-2
Sedimentary bacteria	BB	mg N m-2
Meiobenthos	BO	mg N m-2
Deposit feeders	BD	mg N m-2
(also defined as Benthic Deposivores)		
Benthic infaunal carniv.	BC	mg N m-2
Benthic grazers	BG	mg N m-2
Shallow filter feeders	BFS	mg N m-2
Macrozoobenthos	BMS	mg N m-2
Labile detritus	DL	mg N m-3
Refractory detritus	DR	mg N m-3
Diss. organic nitrogen	DON	mg N m-3
Biogenic silica	DSi	mg Si m-3
Ammonia	NH	mg N m-3
Nitrate	NO	mg N m-3
Dissolved silica	Si	mg Si m-3

Figure 2: Functional groups representing the Westernport biocenosis in Atlantis and main trophic relationships.

4.1 *Definition and parameterisation*

4.1.1 Fish groups

Biological surveys of WP indicate the presence of 91 fish species (Edgar and Shaw 1995a;Edgar and Shaw 1995b). These were divided into 4 groups: 'common', 'commercial', 'rare' or 'normal'. The list of fish considered in the model was built from the common and commercial groups, with some modifications as advised by an expert panel.

The selected species were then aggregated into 5 functional groups according to their ecological characteristics (habitat, diet, size). The initial abundance and weight structure of each functional group was defined from the data available as well as expert judgement (see *Appendix 3*).

4.1.2 Benthos groups

The benthic community of Westernport has been the subject of several studies over the last 30 years (Coleman and Cuff 1980; Coleman et al. 1978; Edgar and Shaw 1995b, 1995c; Edgar *et al.* 1994). The data available in Coleman's paper (1978) were most suitable, due to the strata-based approach employed in that study.

Six functional groups were used to describe the Westernport environment in the model: meiobenthos, benthic grazers, filter-feeders, deposit feeders, infaunal carnivores and macrozoobenthos. The epifauna (grazers, macrozoobenthos and filter feeders) are represented in the model by their mean weight per unit area (mg $N.m^{-2}$) at the seabed-water interface; and the infauna (meiobenthos, deposit feeders and carnivores) by their mean weight per unit volume (mg $N.m^{-3}$) in the sediment layer. The parameterisation of these groups is detailed in *Appendix 4*.

4.1.3 Other groups

Specific data for Westernport were also available for seagrass and macroalgae (see *Appendix 5*), as well as for some of the non-living groups of the ecosystem (see *Appendix 6*). The other groups (mainly plankton) were initialised and parameterised based on expert judgement, the results being reported in Table 1.

Groups	**Concentration in all boxes** (mg.m^{-3} N)
Large phytoplankton	3
Small phytoplankton	3
Large zooplankton	1
Mesozooplankton	5
Small zooplankton	2
Gelatinous zooplankton	0.5
Pelagic bacteria	50
Benthic bacteria	700
Cephalopods	50

Table 1: Initial conditions for the planktonic, cephalopod and bacteria groups

4.1.4 The diet matrix

A matrix of potential trophic interactions defines the links between the different functional groups. Thus, the value 0 means that there is no potential trophic relationship between one group and another. The other values define the availability of each food source to each consumer (i.e. the proportion of the stock of a given food source that is actually accessible by a given consumer at any one time).

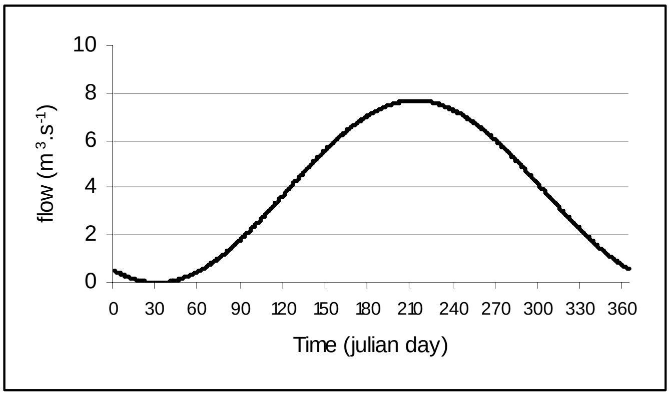
Table 2: Diet matrix, representing the trophic relationships between the functional groups. The consumers are listed vertically and the food sources horizontally. The colours correspond to 3 different levels of availability: green for values below 0.001, yellow for values between 0.001 and 0.1, and red for values above 0.1.

5. Scenarios and runs

5.1 The scenarios

The utility of models such as Atlantis is that they provide a tool for the consideration of "what if" scenarios. At this stage, the tested scenarios consist only of different nitrogen input levels. These inputs were estimated from the results of the simulations from the MUSIC catchment model (Condina and Associates, pers. comm.). These annual results were apportioned to obtain a seasonal input of freshwater and nitrogen of different sorts (Figure *3*).

	Inputs	
	Freshwater (ML.yr^{-1})	Nitrogen (kg.yr^{-1})
Bass river	1.21E+05	2.54E+05
Bunyip river	3.04E+05	5.26E+05
Cardinia creek	6.65E+04	1.67E+05
Lang Lang river	1.57E+05	3.80E+05
Yallock river	1.05E+05	2.56E+05



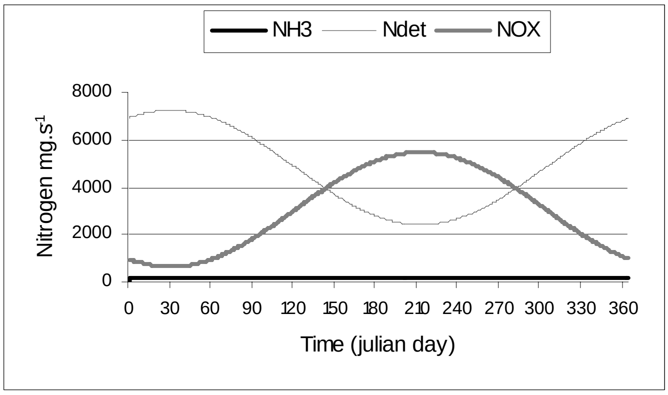


Figure 3: Current annual input estimates from the MUSIC model, and decomposition into a seasonal signal (cosine function adjusted on the basis of the available sampled data).

Four scenarios were then constructed from these estimated inputs:

Scenarios	Definition
A	Actual N values from MUSIC model
B	MUSIC N values x2
C	MUSIC N values x5

Table 3: List of the investigated scenarios

The increase or decrease in the nitrogen inputs are applied progressively during 60-year simulations. In each case, the model runs with the basic values (equivalent to scenario A) during the initial 8 years, and then the nitrogen inputs increase or decrease linearly during the next 16 years. The model continues to run for another 36 years after the stabilisation of the seasonal pattern of terrestrial inputs.

5.2 Results

Figure 4 shows the evolution of the labile detritus concentration in the water column of box 14, (the one that receives most of the terrestrial inputs - see Figure 1). It clearly shows the increase of nutrients that are imposed on the system, from year 8 to year 24, and the stabilisation at new seasonal values.

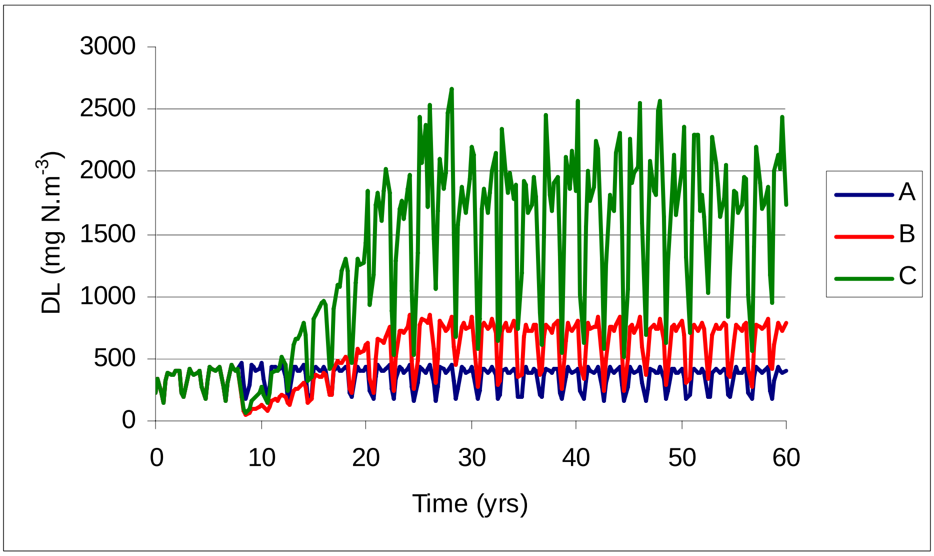


Figure 4: Evolution of the labile detritus concentration in the water column of box 14 for all scenarios.

Some of the living groups (eg benthic deposit feeders and infaunal carnivores) react strongly to the changed conditions (Figure 5). The deposit feeders feed mainly on the detritus, algae and bacteria available at the sediment-water interface, and therefore they benefit directly from an increase in ecosystem productivity (due to nutrient increase). In turn, the deposit-feeders group contributes key prey for benthic predators such as the infaunal carnivores: this is the reason for the strong relationship observed between infaunal carnivores and deposit feeders (see Figure 5).

The results obtained for the whole modelled ecosystem are synthetised in Figure 6. Each square corresponds to a functional group, with the size of the square proportional to its relative biomass in the modelled ecosystem. Note that the global weight of nitrogen contained in the whole modelled ecosystem, and its distribution through the different functional groups, changes with the scenarios. The global weight of nitrogen contained in the whole modelled ecosystem increases by 1.08 between scenarios A and B, and by 1.32 between scenarios A and C. The most substantial changes in the modelled ecosystem are centred around detrital and inorganic nitrogen. The inorganic nitrogen increased by a factor of 7.46 and detritus by a factor of 2.07 between scenarios A and C.

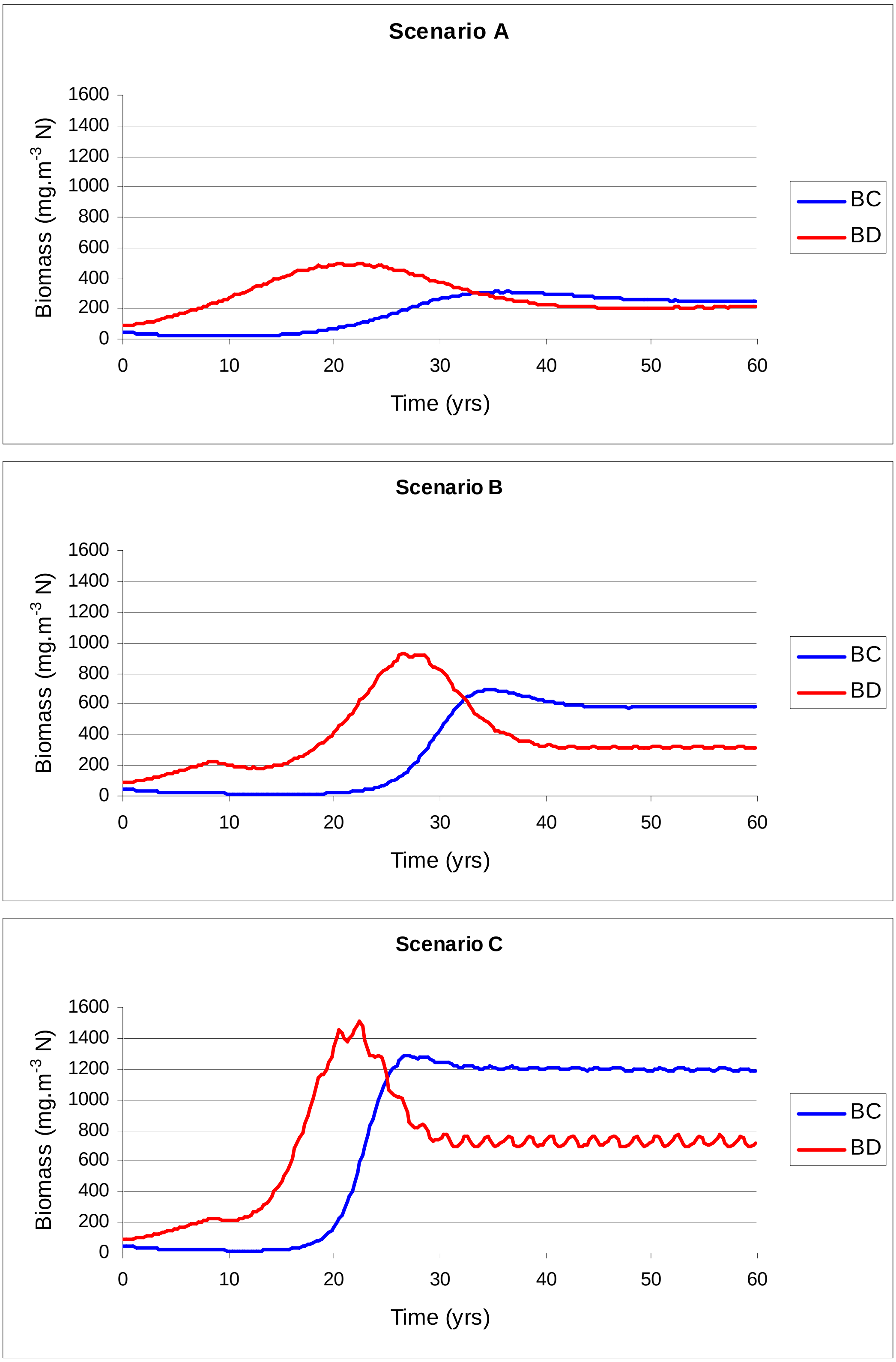


Figure 5: Evolution of benthic deposit feeders (BD) and infaunal carnivores (BC) biomasses through time for all the scenarios.

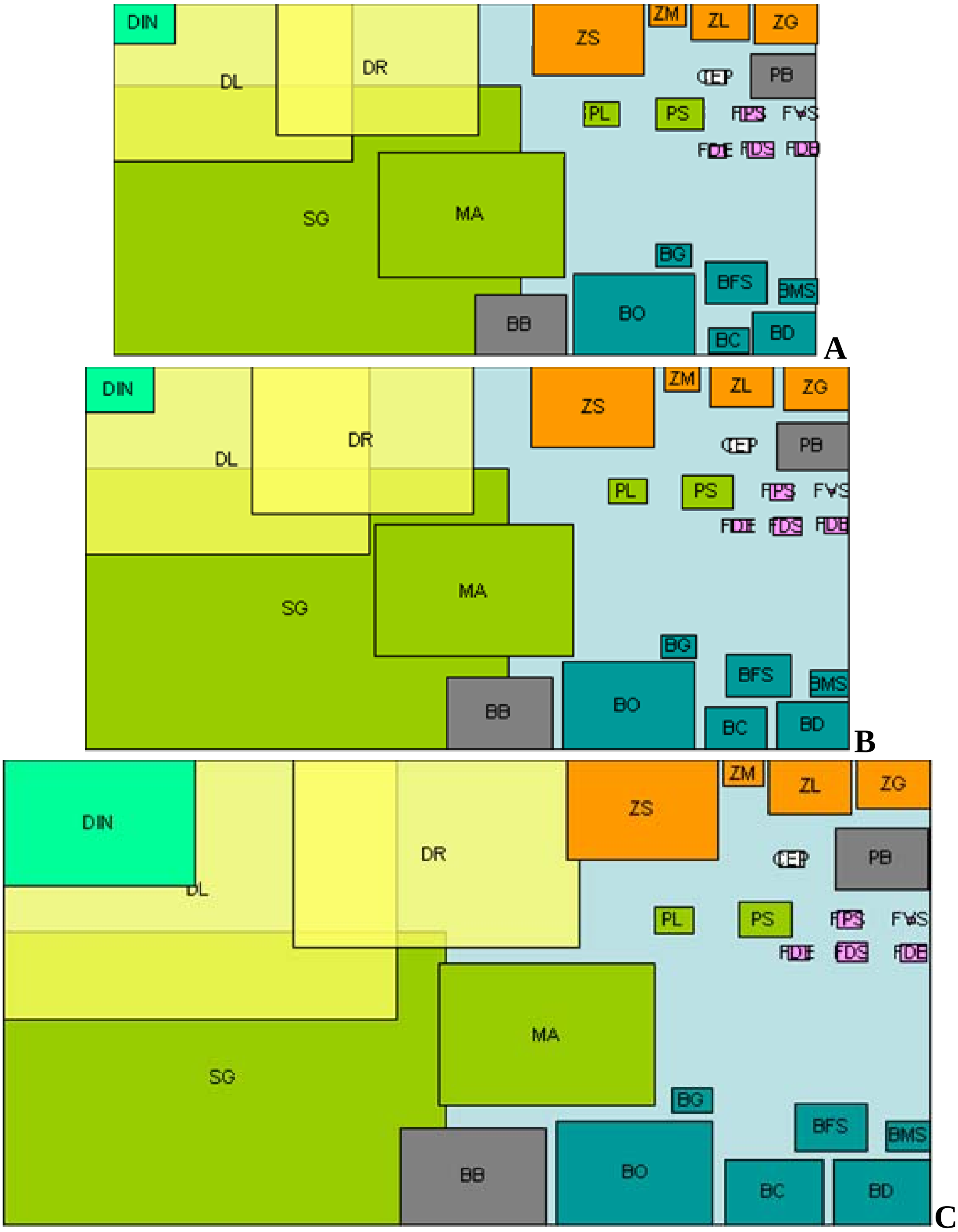


Figure 6: State of the modelled WP ecosystem at the end of each scenario (60th day of the 60th year). Refer to Figure 2 for definitions.

Among the living groups, important modifications of the benthic communities can be observed. This is most noticeable with the infaunal carnivores, benthic bacteria and deposit feeder stocks which increased by 4.65, 1.98 and 1.71, respectively, between scenarios A and C. There is also an increase in the large and small zooplankton stocks which rise by a factor of 1.48 and 1.41, respectively, between scenarios A and C. The seagrass stock decreased marginally, dropping by 10% between scenarios A and C.

6. Perspectives

These results were obtained with an extremely schematic representation of the Westernport ecosystem. Therefore they cannot be considered as particularly reliable projections of the consequences of an increase in terrestrial nitrogen inputs in the area. However, they provide a demonstration of the Atlantis model's abilities to investigate the consequences of human-induced changes in a complex ecosystem. Further, the scoping exercise has allowed us to realise a first list of available data for modelling needs, as well as to specify the further developments required in the Atlantis framework for a full study of the Westernport environment.

The remainder of this section points to the necessary model developments and data acquisition (and/or treatment) for an investigation of environmental outcomes in WP due to the functional importance of nutrient fluxes, turbidity, fisheries activities, modification of the bathymetry (dredging, sifting and sediment deposition) and climatic changes on the WP ecosystem dynamics and productivity. Many of these factors will be influenced strongly in the future by urbanisation and changes in catchment land use practices.

6.1 The physical environment

Because WP is a tidally-driven shallow bay, the hydrodynamic dataset is a key component to obtaining a good representation of ecosystem dynamics. The available data (references cited in Section 3.2) would reasonably allow us to develop and validate a simple hydrodynamic model. This option would allow us to calculate the sea circulation, sea level and bottom shear strength in a great range of conditions. Given the underlying uncertainty, this information constitutes input data for Atlantis in order to:

- better consider the sea circulation and tidal variations in the ecological model; and
- employ a more sophisticated model to describe the processes of erosion-resuspension – deposition, thus allowing a good estimation of the turbidity due to suspended sediment, as well as a better representation of the movements of detrital and algal particles in such shallow waters.

Although the sediment dynamics would not be modelled explicitly, different scenarios about changes in bathymetry due to sifting or dredging of some part of the bay could be investigated. The influence on the circulation pattern of these events can be calculated with the hydrodynamic model, and then the influence on the ecosystem dynamics can be determined with Atlantis. The hydrodynamic model also allows an investigation of a range of climate change scenarios.

The acquisition of a more accurate bathymetry would also be advantageous. The bathymetry used to create the current model geography lacks precision in some areas. Moreover, it is likely there have been some substantial modifications over time due to the dredging of shipping channels and as a result of sediment settlement (Condina and Associates, pers. comm.).

The model geography will also require refinement vertically (with more than one box for the water column) to more effectively model the erosion-deposition processes. Modifications to the horizontal geometry may also be needed, depending on the form of tidal modelling used, as well as the details and structure of updated submodels of benthic and shore habitats.

6.2 The terrestrial inputs

A significant database of physical characteristics such as temperature, nutrient concentrations and turbidity in the rivers around Westernport is available from the Victorian EPA (Victorian Water Resources Data Warehouse). However, the measures are generally realised upstream, sometimes above locations where streams join or divide. These data will require careful analysis to estimate the inputs at the river mouth, or some new measures will be needed.

Some additional inputs beyond the 5 rivers currently considered would desirably be included, since significant nutrient and sediment inputs were estimated from French and Phillip Islands, as well as other places around the bay (Condina and Associates, pers. com.). Ideally, it would be useful to include temperature, nitrogen, phosphorus and silica concentrations (or fluxes) under mineral and detrital form, as well as suspended sediment concentration (or fluxes, or turbidity).

6.3 Living groups

6.3.1 Shore and benthic plants

A more specific parameterisation of the seagrass sub-model, using the local studies (Bearlin *et al.*; Bulthuis 1983; Bulthuis *et al*. 1992; Bulthuis and Woelkerling 1981; Bulthuis and Woelkerling 1983a, 1983b; Campbell *et al*. 2003; Campbell and Miller 2002; Clough and Attiwill 1980; Kerr and Strother 1989; Kerr and Strother 1990; Bulthuis *et al*. 1992), as well as some further development, particularly on spatial-related processes, would be highly recommended. The modelling of the mineral turbidity will allow a more realistic treatment of seagrass in the ecological model. It is also important to note that the distribution and abundance of seagrass used so far corresponds to the nineties (Blake *et al*. 2001), whereas the great variations in seagrass cover occurred in the seventies and eighties (Jenkins *et al*. 1992). A deeper treatment of the existing data would allow reconstitution of the evolution of the seagrass beds over the last 20 to 30 years, and provide a solid basis for attempts at reproducing this historical trajectory in the model.

The mangroves and salt marshes are also thought to play a great role in the nutrient recycling in Westernport. These groups are not currently present in Atlantis and need to be included as new functional groups in the modelling framework of the full study. This implies the development of additional submodels, as well as a parameterisation based on local data (Bird 1986; Boon and Cain 1988; Boon and Cain 1988; Cain and Boon 1987; Davey and Woelkerling 1985; Harty 2004; Van der Valk and Attiwill 1984).

6.3.2 Top-predators

Mammals and birds are not considered explicitly in the model thus far. The predation pressure of these groups on the fish and invertebrates was estimated and included in the preliminary model, however.

In the full study, it will be necessary to expand the existing model of WP and include these high order trophic levels as explicit functional groups. This would not require any further development of Atlantis. Moreover, the collection and treatment of data has already been done in large part.

Sharks were also not included in the first version of the WP Atlantis model. This would need to be rectified as for the other higher trophic groups. In particular, because of its commercial interest, the elephant shark (*Callorhinchus milii*) would need to be included as a separate functional group. Westernport Bay is thought to be a key site for its reproduction. Again, this would not require any further development of Atlantis.

6.3.3 Fish

It is critical that a better estimate of fish abundance be obtained for Westernport. As explained above, the data currently available do not allow reasonable estimates of fish abundance, while the model (and particularly the benthos groups) are sensitive to the demersal fish abundance. The consideration of fish movement (for the appropriate functional groups) inside and outside Westernport would also improve model performance. Different options are already available to model the fish migrations in Atlantis, but it requires accurate parameterisation.

The fisheries effects on the ecosystem are considered in a rudimentary way so far. Different options are already available to model these activities in Atlantis. Access to more detailed data will clearly be necessary for the full study.

6.3.4 Benthos

Some difficulties were experienced with the modelling of the benthos biomass during this scoping stage. The shallow depths in the bay, as well as the artificial permanent emersion of the tidal flats in this first version of the ecological model, make the ecosystem extremely sensitive to the benthic activities, generating instabilities within the benthos as well as in some trophically related groups. This would be improved once the tidal variations are considered. Nevertheless, some further development of the formulation of the benthic processes is recommended.

6.4 Bio-chemical processes in general

The consideration of tidal variations in the ecosystem model would require some additional developments of Atlantis. It will be necessary to consider two sets of processes during tidal flat emersion and immersion. This is particularly relevant to the feeding activities of the benthos, the deposition-suspension of living and non-living particles, and the occurrence of nekton and demersal fauna.

Finally, because it is a shallow environment with a soft sediment cover, where nutrient cycling is an important issue, it would be useful to consider whether improvements or alternative representations of remineralisation and aeration processes in the sediment layer (particularly the burrow-edge processes) would be beneficial.

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Appendix 1: Estimation of fish and benthos predation by birds and marine mammals

1. Introduction

Estimates of the average daily quantity of fish and benthos (as biomass) consumed by birds and mammals feeding in Western Port were obtained by basic heuristic methods using data collected from scientific literature and other sources. Whereas there is considerable scope to develop more sophisticated statistical approaches to determine these estimates (see Section 1.1 below), the central purpose was to obtain estimates of the daily quantities of biota consumed using straightforward deterministic calculations. In all cases, a maximal predation estimate was determined by assuming the entire daily food requirement was taken only from Westernport, as opposed to further out at sea or elsewhere. The corresponding parameters were determined and imported into the Atlantis model for the Westernport Scoping Study. There were two daily average quantities requiring estimation:

(a) population sizes of the main bird and marine mammal species present in Westernport based on counts made there,

(b) quantity of food consumed and the diet composition of an individual of each species.

These were determined by using published survey data and the estimated average metabolic rate of an individual of each of the main species present.

1.1 Future refinements

Statistical modelling approaches can be developed to more accurately incorporate the following biological complexities into the model;

- Seasonal abundances of bird populations in Westernport, which are in general species dependent. In particular, this applies to some of the more numerous species such as short-tailed shearwaters. Associated predation pressures on various prey biota will therefore also be seasonal. Since different bird populations are not synchronised with each other, the net seasonal predation effect is a complex one. Statistical methods can be developed to evaluate this as an average predation effect.

- Estimation of seabird population abundances can be elaborated by the use of GAMS (General Additive Methods) as for example, elaborated by Clarke *et al*. 2003).

- The energy intake from food can be determined more accurately by taking greater account of population age structure, diet composition and energy content of the various types of prey consumed: for example, by adapting some of the approaches of Tierney *et al.* (2002).

- More sophisticated methods for estimating field metabolic rates can be developed which take into account factors other than body mass, such as major hydrodynamic and thermal processes (Hind and Gurney, 1997).

2. Birds

2.1 Seabirds

Daily predation of fish, cephalopods, molluscs and crustaceans by seabirds in Westernport was estimated by considering the daily food requirement of the most abundant seabird species (including the Little Penguin) in each of the three arms of Westernport (Western, Northern and Eastern). This was determined by a twofold calculation which consisted of estimating average population abundance and individual consumption rates. Table A1-1 lists the 14 seabird species included.

Population abundances

It was assumed that dynamic seabird populations occurred uniformly across each of the three arms and that, therefore, the population in any of these sub-regions would be directly proportional to the sea surface area. The sea surface areas of the 26 Westernport boxes defined for the Atlantis model were calculated and grouped in accordance with the three arms in which they were located. Within each box, seabird populations were estimated using bird count data published in a recent paper by Dann *et al.* (2003) which described the results of a monthly survey conducted in each arm of Westernport between 1991 and 1994 (36 months in total). It was assumed that negligible prey would be taken from the shallow inter-tidal and sub tidal (< 2m depth at high tide) areas of the north eastern part of Westernport, because few seabirds are found there. For this reason no seabird counts were performed in that region by Dann *et al.* (2003).

The bird counts described in Dann *et al*. (2003) were conducted by observers on boats travelling at a mean speed of 22.5 knots, on specific transects within the western, northern, and eastern arms of Westernport, totalling 43 nautical miles (81 km).

These count data were used to estimate average daily bird populations expected in the ‘observation tunnel’ traced out by each transect taken by the vessel from which the observations were made. The daily population in each arm was then estimated by assuming abundance to be directly proportional to the basal area of transects within the arm. Similar scaling factors based on the area of each box in the model were applied to find a daily population estimate for that box. Average abundances were calculated as a mean daily value taken across the entire four year survey period and, hence, did not display any seasonal component.

Daily food consumption

The daily quantity of food consumed by an individual seabird was assumed to be directly proportional to its field metabolic rate (FMR) which was, in turn, assumed to be directly proportional to its existence metabolic rate M. For all birds at 0ºC, Kendeigh (1970) states that M, defined as the minimum resting metabolism required to exist, scales with body mass by the power law

$$M = 18.1295\, W^{0.53} \qquad (1)$$

where *M* is existence metabolism [KJ per day] and *W* is body mass [g]. The constant 18.1295 is the product of 4.3372 [given by Kendeigh (1970)] and the conversion factor of 4.18 from [Kcal to kJ]. Since this equation is based on observations at 0ºC, which is much lower than the average annual temperature in Westernport, any predation estimates derived from it should provide an upper bound on the actual energy requirement of an individual.

Hence an upper estimate for the field metabolic rate *F* of any bird is given by

$$F = kM \qquad (2)$$

where *k* is a constant to be determined. Chiaradia *et al* (2002) state that a crested tern of body mass 310g would require 406.3 kJ per day at 0ºC to meet its daily energy expenditure. This would take 96 minutes of foraging time assuming a foraging rate of 8 fish weighing 5.5g per hour. Hence it would need to consume 96/60 x 8 x 5.5g= 71g of fish per day to meet its FMR requirement. Combining equations (1) and (2) we obtain

$$k = F / M = F / (18.1925 W^{0.53}) \qquad (3)$$

and on inserting *F*= 406.3 kJ and *W* =310g we find that *k* = 1.0679. Hence the field metabolic rate at 0ºC as a function of body mass is obtained by combining equations (1) and (2) to obtain

$$F = kM = 19.4278 W^{0.53} \qquad (4)$$

Equation (4) closely matches the field metabolic rate equation $F = 16.69\, W^{0.651}$ for seabirds described by de L. Brooke (2004).

Since the quantity of food consumed *Q* is assumed proportional to *F*,

$$Q = cF \qquad (5)$$

and on inserting *Q*= 71g and *F*= 406.3kJ into equation (5), we find that *c*= 71/406.3 =0.1747 . Combining equations (1), (2) and (5)

$$Q = cF = c\,(kM) = ck(18.1925 W^{0.53}) \qquad (6)$$

Hence in equation (6) the constant of proportionality is *c* x *k* x 18.1925 =0.1747 x 1.0679 x 18.1925=3.395 so that the daily consumption of food *Q* [g] by an individual bird of mass *W* [g] required to meet field metabolic rate, as a function of body mass is

$$Q = 3.395 W^{0.53} \qquad (7)$$

The mean adult body mass of an adult of each of the 14 species of bird was obtained from the Handbook of Australian, New Zealand and Antarctic Birds (HANZAB 2003) and equation (7) was used to obtain an estimate of daily food consumption of an individual of each species. Information from HANZAB (2003) on the composition of species diet was used to broadly categorise daily food intake into fish, cephalopods, molluscs or crustaceans. To simplify the calculation, it was assumed that the energy content obtained from each type of prey was equivalent to that of fish. The daily predation (g) exerted by each bird population in each box was taken as the product of average population abundance and average daily consumption rates, with values shown in Table A1-1.

Short-tailed shearwaters, which breed in large numbers on Phillip Island, are the most numerous species recorded in Westernport. The literature suggests that most of their prey items (especially crustaceans such as krill) are taken from regions as far away as Antarctic waters (HANZAB 2003). For this species in particular, the prey quantities calculated to be taken from Westernport are therefore likely to be greatly over-estimated. If the consumption of krill by short-tailed shearwaters is excluded from Table A1-1, fish would (unsurprisingly) be estimated to be the largest component of seabird diet. However, these maximal values for krill have been included, in line with the purpose of deriving upper predation limits for the parameter values imported into the Atlantis model. As a side note, it can be seen that very few Little Penguins, which also breed in large numbers on Phillip Island, were observed to enter Westernport, preferring instead to forage in Bass Strait or further a field (Dann *et al*. 2001).

	Seabirds	**WESTERNPORT TOTAL CONSUMPTION (g/day)**				
Perennial seabirds	Mean population	fish	cephalopods	molluscs	crustaceans	Total
Black-faced cormorant	8.825	1894.46	0	0	0	1894.46
Little pied cormorant	36.158	2846.6438	0	0	938.78678	3785.4306
Pied cormorant	38.719	6350.0643	0	0	529.74534	6879.8096
Pelican	6.673	1723.6188	430.904706	0	0	2154.5235
Seasonal seabirds						
Short-tailed shearwater	4185.528	17018.844	0	3491.045	415870.73	436380.62
Fluttering shearwater	306.232	22221.223	0	0	0	22221.223
Australian gannet	22.623	4627.7718	18.585429	0	0	4646.3572
Pacific gull	23.399	1159.5142	0	1231.9839	1231.9839	3623.4819
Silver gull	280.848	4811.9693	4811.96934	4811.9693	4811.9693	19247.877
Crested tern	153.365	6533.4248	2177.80826	0	2177.8083	10889.041
Fairy tern	13.514	436.0505	0	0	0	436.0505
Black-browed albatross	3.127	344.53916	172.26958	0	344.53916	861.3479
Shy albatross	1.191	161.87946	161.879458	0	0	323.75892
Penguins						
Little penguin	62.881	8305.4004	0	0	0	8305.4004
TOTALS	5143.089	78435.404	7773.41677	9534.9982	425905.56	521649.38

Table A1-1. Estimated daily predation rates of the main seabirds in Westernport

In summary, the total quantity of fish consumed in Westernport by the mean daily population of 5143 seabirds is estimated as 78 kg per day, equivalent to approximately 28.6 tonnes per year. This value is similar to the total quantity of fish (28.7 tonnes) previously estimated to be consumed by the 4100 crested terns breeding on Phillip Island during the annual breeding period of 3 months (Chiaradia *et al*. 2002).

2.2 Shorebirds

Shorebirds differ significantly from seabirds in terms of their diet and foraging behaviour. In general, their main prey items are small benthic animals to be found in sub-tidal and inter-tidal areas. During the periods between feeding, shorebirds gather in static groups for extended periods at specific ‘roost’ sites. It is during these roosting periods that they may be relatively easily counted.

Population abundances

Meticulous counts have been performed since 1973 at the various shorebird roost sites in Western Port by the Bird Observers Club of Australia (BOCA 2003). The extensive data collected from these counts have been analysed and are thought to accurately reflect population abundances of the different shorebird species to be found there (Dann *et al*. 1994, Loyn *et al*. 1994). These data, as described in Lane (1987), were used to estimate the mean daily populations in each model box taken across a year, of the main species present (listed in Table A1-2).

It was assumed that shorebird predation would only occur in the largely sub-tidal and inter-tidal model boxes, where they would have the opportunity to feed. Average daily populations, as with seabirds, were assumed to be distributed uniformly throughout such boxes and hence were taken as proportional to box area, without incorporating seasonal fluctuations in abundance. This also implied the boxes encountering highest shorebird predation were in general different to those with highest seabird predation.

Daily food consumption

Predation estimates were calculated by the same approach applied to seabirds, by deriving the mean adult body mass (HANZAB 2003) and then determining the daily food consumption required to meet field metabolic rate based on body mass as described by equation (7). The results suggest that molluscs make up the greatest component of shorebird diet and more interestingly, that the average daily consumption of these invertebrates (109 kg) exceeds the average daily consumption of fish by seabirds (78 kg).

	Shorebirds	WESTERNPORT TOTAL CONSUMPTION (g/day)				
Perennial shorebirds	Population	worms	molluscs	crustaceans	insects	Total
Pied oystercatcher	160	8746.4482	8746.4482	0	0	17492.896
Red-capped plover	80	0	927.12084	927.12084	0	1854.2417
Seasonal shorebirds						
Red-necked stint	3750	17527.471	17527.471	17527.471	17527.471	70109.884
Curlew sandpiper	3100	22426.172	22426.172	22426.172	22426.172	89704.689
Eastern curlew	1020	0	42468.53	42468.53	42468.53	127405.59
Double banded plovers	500	4033.2185	4033.2185	4033.2185	4033.2185	16132.874
Sharp-tailed sandpiper	310	2404.2829	2404.2829	2404.2829	2404.2829	9617.1314
Bar-tailed godwit	290	5489.5134	5489.5134	5489.5134	5489.5134	21958.054
Greenshank	260	3356.5341	3356.5341	3356.5341	3356.5341	13426.136
Ruddy turnstone	70	734.59452	734.59452	734.59452	734.59452	2938.3781
Lesser golden plover	50	598.70042	598.70042	598.70042	598.70042	2394.8017
TOTALS	9590	65316.935	108712.59	99966.138	99039.017	373034.68

Table A1-2. Estimated daily predation rates of the main shorebirds in Westernport

3. Marine mammals

The number of marine mammals entering Westernport is thought to be extremely low. However, because of their high individual body mass and field metabolic rate, the presence of marine mammals could give rise to relatively high associated predation rates. Hence rough estimates for predation rates in Westernport which might be due to marine mammals were calculated. It was assumed as with birds, that the entire food requirement would be taken from Westernport, so that all estimates would be upper limits for the possible prey quantities actually captured there.

Population abundances

Dann *et al.* (1996) provide counts of Australian fur seals and bottlenose dolphins observed during monthly surveys conducted between 1991 and 1994 in Westernport. The surveys were performed on vessels travelling on identical transects to those in the seabird abundance surveys described by Dann *et al.* (2003). The mean recorded sightings of seals and dolphins over 34 trips were respectively 1.7 and 1.4 individuals per trip and showed no seasonality. These two species were the only marine mammals recorded in the entire survey period ranging from 1991 to 1994.

Estimates for predation rates in each box were calculated from the count data of Dann *et al.* (1996) by assuming that marine mammal populations would be distributed uniformly in the three arms of Westernport (Northern, Eastern Western). As with seabird populations, it was assumed that negligible predation would occur in the shallow north eastern region of Westernport.

The average daily population of each marine mammal species was estimated for each arm by assuming abundance to be directly proportional to the total surface area of all transects lying within the arm. Populations for each box within the arm were in turn estimated by assuming abundance within the box to be proportional to box area.

Daily food consumption

The daily food requirement to meet field metabolic rate was estimated using the relationship between field metabolic rate and body mass for all marine mammals, irrespective of ambient temperature, given by Williams *et al* (2004)

$$F = 1697.76\, W^{0.756} \qquad (8)$$

where F is field metabolic rate [kJ per day] and W is body mass [kg]. The constant of proportionality 1697.76 used here is the product of 19.65 [given by Williams *et al.* (2004)] and the conversion factor of 86.4 from W [J per second] to kJ.

A comparison of equation (8) with the field metabolic rate estimated for birds in equation (4) shows that the metabolism of marine mammals scales more rapidly. An interesting illustration is provided by considering the Little Penguin. Assuming a body mass of 1 kg (=1000g), by equation (4) the estimated field metabolic rate is 705 kJ per day, whereas by equation (8) the same estimate would be more than twice as high at 1698 kJ per day. This would be consistent with the greater energy intake required to counter heat loss when any homeotherm is in continual contact with water (Hind and Gurney 1997).

Using the Table IV of Tierney *et al.* (2002), an estimate for the wet weight average calorific content of pelagic fish consumed was obtained at approximately 10 kJ per gram. Hence the estimated quantity of food Q [kg] required by a marine mammal of body mass W [kg] each day to meet its field metabolic rate F [kJ per day] is given by (F/10) / 1000, or in other words

$$Q = 0.1698\, W^{0.756} \qquad (9)$$

According to Dann *et al.* (1996), only juvenile or female fur seals were observed in Westernport, which have a mean body mass of 74.5 kg (Zoos Victoria Fact Sheet 2004). The average weight of a bottlenose dolphin is 200 kg (www.seaworld.com.au).

Applying equations (8) and (9) to these body masses, the estimated daily food consumption Q required by a fur seal and a dolphin would be respectively 4.418 kg (with field metabolic rate 44,180 kJ per day) and 9.321 kg (with field metabolic rate 93,208 kJ per day). These values are similar to those obtained by applying the general approximation of 5% body mass per day to marine mammals to estimate their daily food consumption (respectively this would give 3.725 kg and 10 kg).

The composition of the diet for both these mammal species is mainly fish followed by cephalopods, with some crustaceans also consumed by bottlenose dolphins (www.parks.tas.gov.au, www.seaworld.com.au). A suitable apportionment of food intake as fish:cephalopods:crustaceans to reflect this would therefore be 60%: 40%: 0% for a fur seal and 50%: 40%: 10% for a dolphin.

Table A1-3 shows the calculated daily predation (g) exerted on Westernport as the product of average population abundance and average daily consumption rates based on the above estimates.

Mammals	WESTERNPORT TOTAL CONSUMPTION (g/day)				
	Mean population	fish	cephalopods	crustaceans	Total
Seals					
Australian fur seal	21.641	57366.08	38244.05045	0	95610.126
Dolphins					
Bottlenose dolphin	17.464	81392.69	65114.15259	16278.53815	162785.381
TOTALS	39.105	138758.8	103358.203	16278.53815	258395.507

Table A1-3. Estimated daily predation rates of the main mammals in Westernport

The results in Table A1-3 suggest that the daily quantity of fish consumed by seals and dolphins (139 kg) in Westernport is approximately twice that of seabirds (78 kg, Table A1-1). The corresponding estimate for the quantity of cephalopods consumed (103 kg) is more than an order of magnitude higher than for seabirds (8 kg, Table 1).

The above calculations thus suggest that although very few marine mammals may enter Westernport, their greater individual body mass and metabolic rate could contribute a greater predation impact on fish and cephalopods than that exerted by the far more abundant seabird populations.

Appendix 2: Estimation of average mortality of fish and cephalopods due to fisheries

1. Introduction

Mortality of fish and cephalopods from commercial fisheries was incorporated into the Westernport Atlantis scoping model using average daily catch values calculated from annual fisheries wet weight catch records (kg) forwarded by the Victorian DPI. This data gave the reported catches of the main commercial species taken in Westernport from December 1978 to mid-2004 (approximately 25 years) and were forwarded as both annual and seasonal data sets.

The annual data set gave annual reported catch figures by calendar year, whereas the seasonal set gave reported catch for quarterly (3 monthly) fishery seasons that commenced in June of each year. No other data were available, so it was not possible to evaluate the influence of trawling effort, or management controls that may have been historically applied to conserve the various fish stocks. Therefore it was not possible to derive a meaningful catch per unit effort (CPUE) index to reflect changes in the commercial fish stocks abundance occurring over the same time period.

In view of these limitations on fisheries data, it was decided that commercial fisheries mortality would be most appropriately incorporated into the Atlantis model by way of a constant daily catch rate imported for each of the five fish and cephalopod functional groups. These values were calculated simply as the average daily value using the catch data for the main commercial species, taken across the entire 25 year record period, as shown in Table A2-1.

1.1 Future refinements

More extensive information on the following aspects would enable more sophisticated development of the fisheries model component.

- Information on fishing effort would permit more accurate estimation of changes in fish stock abundance to be determined and hence the effect of a range of different possible future fishery scenarios could be evaluated.

- The recreational fishery in Westernport is likely to be significant, with the three main recreational fish species Elephant fish, King George Whiting and Snapper also being commercially taken. However, there appears to be few data available on the quantities of recreational fish caught, although a recreational fish survey for the year 2000 was apparently conducted. Such data once forwarded could be used in combination with an estimate for growth of the local human population to obtain projections for recreational fishery catches in the future.

- Complete itemisation of all commercial fish species and especially pelagic fish such as anchovy and pilchards would enable a more accurate representation of fisheries mortality pressure to be incorporated into the respective functional groups within the model.

Functional group	26 YEAR TOTALS	26 YEAR MEANS	Kg per day
Pelagic			
Australian salmon	286,011	11000.42	
ANNUAL TOTALS	286,011	11000.42	
SEASONAL TOTALS	71502.75	2750.106	7.534536
Demersal sedentary			
Mullet, Yellow-Eye	502,211	19315.81	
Flathead, Sand	153,114	5889	
Ling, Rock	2,080	80	
ANNUAL TOTALS	657,405	25284.81	
SEASONAL TOTALS	164351.3	6321.202	17.31836
Demersal casual (mostly hebivorous)			
Garfish, Southern sea	482,736	18566.77	
Stranger	52,642	2024.692	
Leatherjacket	8,557	329.1154	
ANNUAL TOTALS	543,935	20920.58	
SEASONAL TOTALS	135983.8	5230.144	14.32916
Demersal casual **B**			
Whiting, King George	327,882	12610.85	
Flathead, Rock	229,100	8811.538	
Flounder, Unspecified	65,510	2519.615	
Snapper	43,094	1657.462	
Trevally	12,317	473.7308	
ANNUAL TOTALS	677,903	26073.19	
SEASONAL TOTALS	169475.8	6518.298	17.85835
Sharks (most abundant)			
Shark, Gummy	204,065	7848.654	
Shark, Elephant	95,016	3654.462	
ANNUAL TOTALS	299,081	11503.12	
SEASONAL TOTALS	74770.25	2875.779	7.878846
Cephalopods CEPH			
Calamary, Southern	181,246	6971	
Squid, Goulds	3,313	127.4231	
ANNUAL TOTALS	184,559	7098.423	
SEASONAL TOTALS	46139.75	1774.606	4.861934

Table A2-1: Commercial fish and cephalopod fisheries mortality estimates incorporated into the Westernport Scoping Study model. Species are shown under their respective functional group within the Atlantis model. The values shown are the total reported catches (kg), together with mean annual and mean daily values across the period December 1978 to June 2004. Values from the rightmost column were imported into the Westernport scoping model to reflect fisheries mortality pressure.

2.0 Preliminary fisheries data analysis

A preliminary analysis of the data was performed to investigate fluctuations in total commercial fish catches reported in each of the four fishery seasons, over the 25 year period since December 1978. The purpose was to identify any significant periodic or general trends that may have been apparent historically.

Annual catch totals

The total annual commercial catches in Westernport for each of the 25 years were plotted as a time series shown in Figure A2-1. As evidenced by the fitted regression line, annual total catches show a clear downward trend. However, because no information on associated fishing effort was included, this plot may not necessarily reflect actual changes in fish stock abundances.

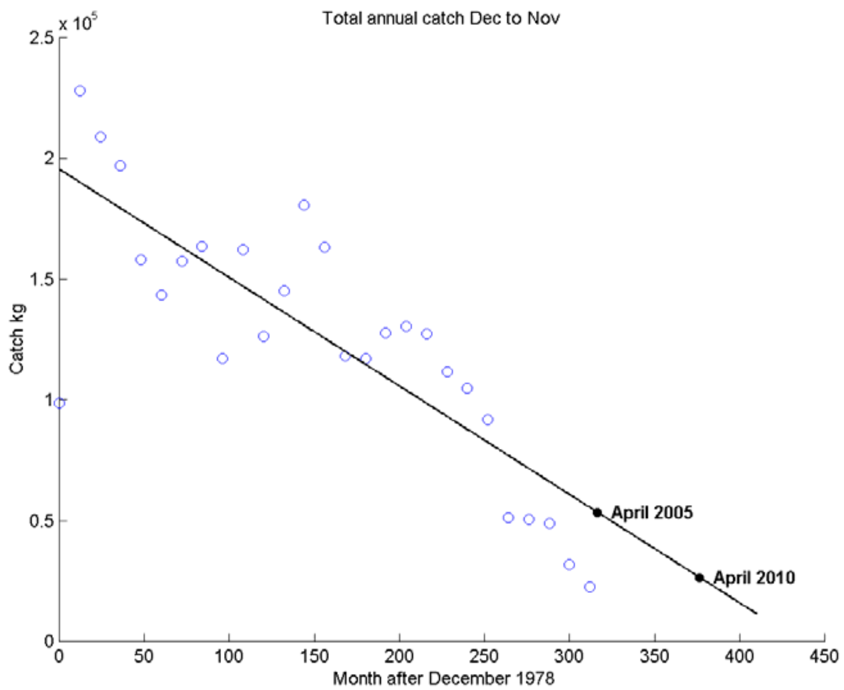
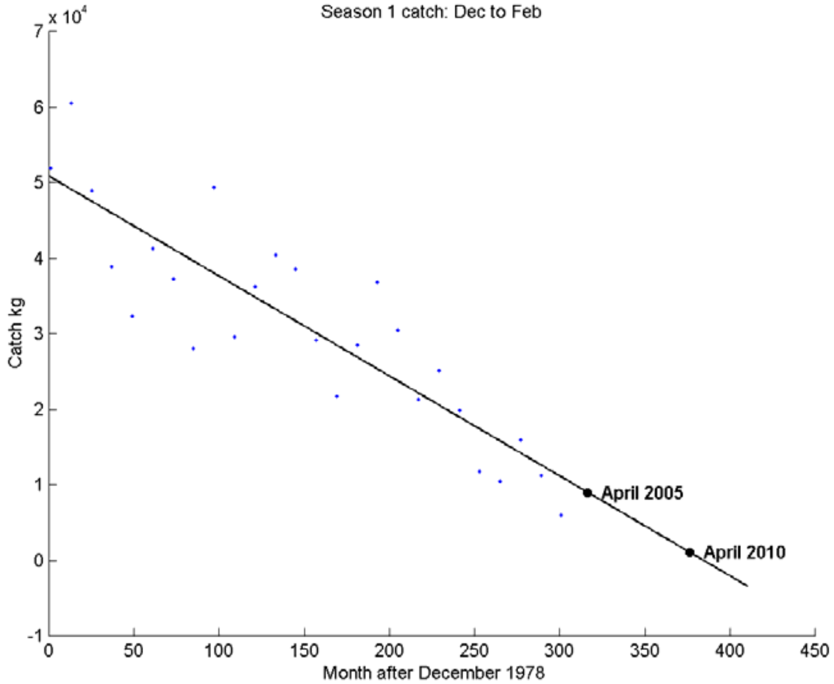
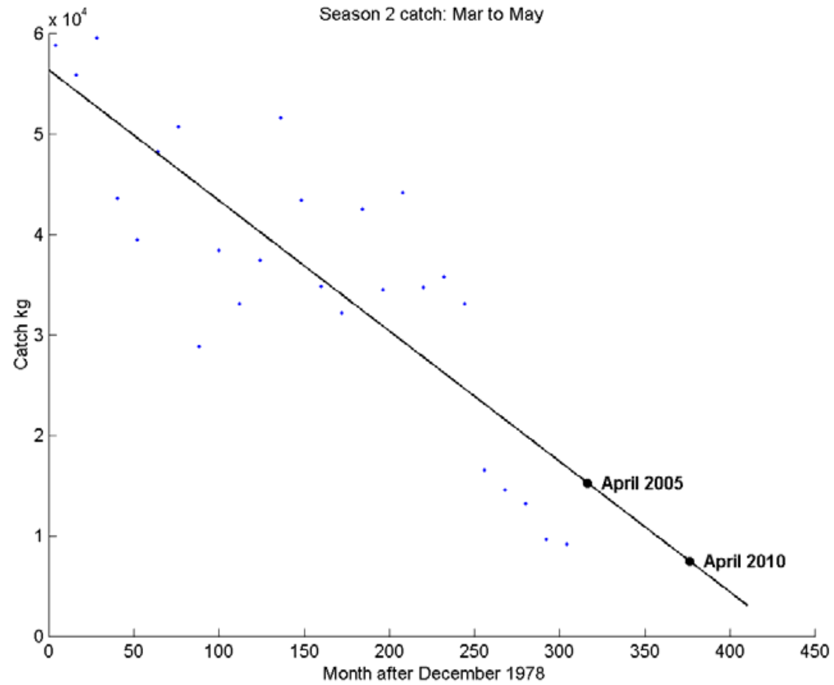


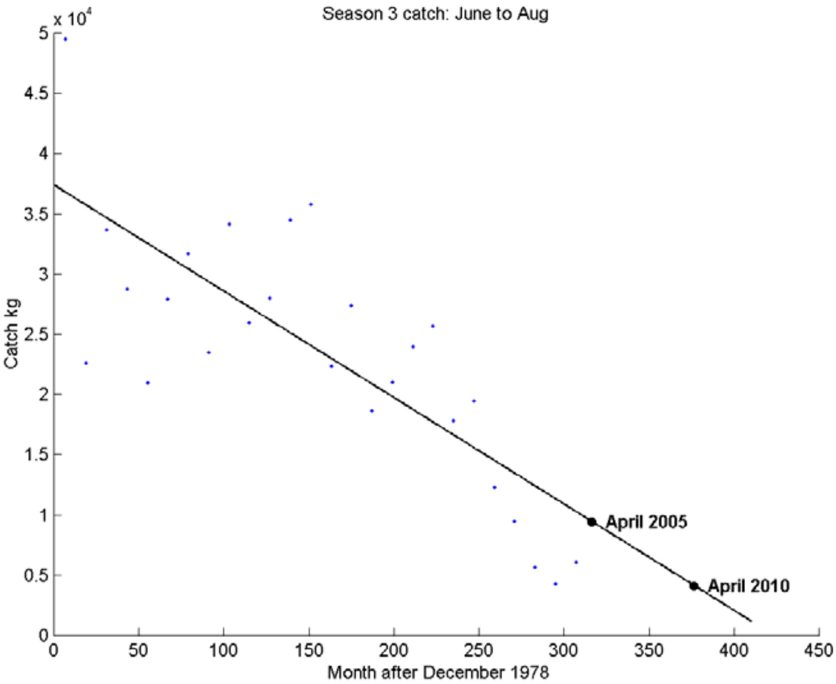
Figure A2-1: Reported annual total commercial fish catches (kg) since December 1978 (open circles) in Westernport. The projections for April 2005 and April 2010 (solid circles) are based on the least squares regression line of best fit. Data forwarded by the Victorian DPI.

Seasonal catch totals

The annual total catch time series was decomposed into four separate seasonal catch time series and plotted similarly, as shown in Figure A2-2. These plots again show a consistent decline in the total seasonal catch with the greatest overall catch decline having occurred in season 4 (September to November).







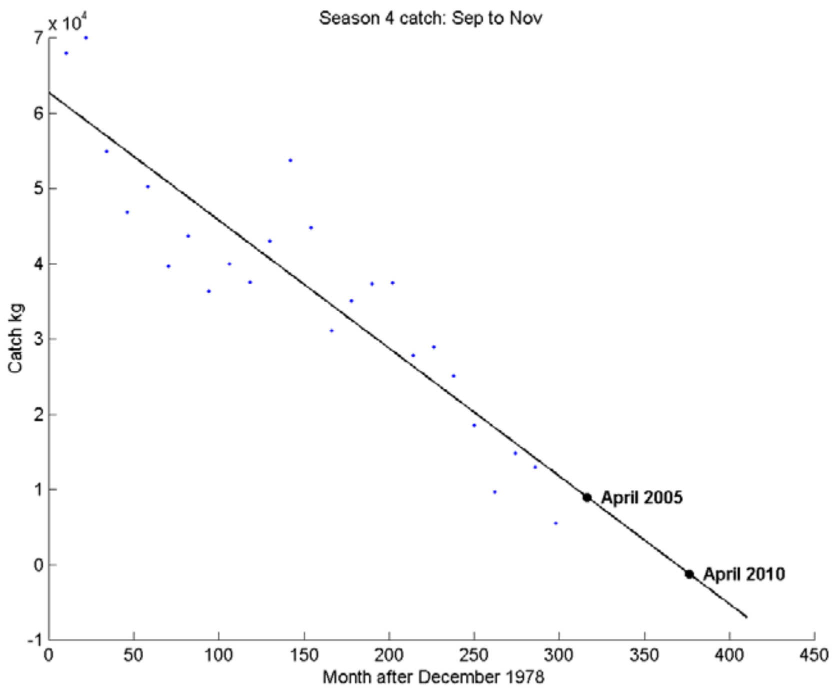


Figure A2-2: The reported annual total commercial fish catches of Figure 1 decomposed into quarterly fishery seasons, running from (1) December to February, (2) March to May, (3) June to August and (4) September to November. Data forwarded by the Victorian DPI.

Appendix 3: Definition and parameterisation of the fish groups

Table A3-1 (over page) summarises the information collected about the main fish species in Westernport, and their grouping into 5 functional groups.

Weight calculations:

Combined utilization of Von Bertalanffy growth curves and classic length-weight relationships allowed for the estimation of the average individual wet weight as a function of age for each fish group. The wet weights were then converted into structural and reserve weight, using wet weight estimates and the parameters in Table 3.2. The converted weights are displayed in Table A3.3.

Parameters	units	Values
Wet weight / C-weight ratio	g WW . g CW^{-1}	20
C-weight / N-weight ratio	g CW . g NW^{-1}	5.7
N-weight / structural weight ratio	g NW . g sW^{-1}	3.65
Structural weight / reserve weight ratio	g rW . g sW^{-1}	2.65

Table A3-2: parameters for weight conversion

Abundance calculations:

Initially, biomass estimates were made by extrapolating the results obtained by Edgar and Shaw (1995) in terms of fish abundance, to the whole Westernport area, box by box. Unrealistically high abundances were obtained; therefore, given time constraints it was decided to define the initial abundances with expert judgement, on the basis of what was calculated in the Port Philip Bay study (Fulton pers. comm.). The values are shown in the Table A3-4.

Functional Groups	Common name	Scientific name	Lmax (cm)	habitat 1	depth range	habitat 2	Migrate	predators	prey
FPS	Australian pilchard ($)	*Sardinops neopilchardus*	27	marine pelagic	0-200 m		oceanodromous	finfish, bony fish, mammals	zooPK, phytoPK, plants
Small pelagic planktivores	Australian anchovy ($)	*Engraulis australis*	12	marine and brackish pelagic	65 m	bays, inlets and estuaries	Spring in WP	fish, dolphins, birds	PK
	Silverfish ($)	*Leptatherina presbyteroides*	25	marine pelagic	0-728 m			finfish, bonyfish	zooplantkon, zoobenthos
	Sandy Sprat	*Hyperlophus vittatus*	10	marine and brackish pelagic	10-13m		amphidromous	finfish, bonyfish	zooPK
FVS Small pelagic piscivores	Eastern Australian salmon ($)	*Arripis trutta*	55	marine and brackish pelagic	30m	continental shelf W including estuaries, bays and inlets	anadromous	finfish, bony fish, sharks, mammals	fishes and pelagic crustaceans (crust.)
FDS	Half-banded pipefish	*Mitotichthys semistriatus*	27	marine demersal	3m	eelgrass	sedentary	finfish bony fish	zooPK
Shallow demersal	Port Phillip pipefish	*Vanacampus phillipi*	18	marine and brackish demersal	24m	rock pools and estuaries among vegetation	sedentary	finfish, bony fish	zooPK, zoobenthos
sedentary	Hairy pipefish	*Urocampus carinirostris*	10	marine and brackish demersal	-3m	lower reaches of rivers, estuaries or other protected inshore habitats	sedentary	finfish, bony fish	zooPK
	South Australian cobbler	*Gymnapistes marmoratus*	23	marine and brackish demersal	2-26m	inshore W	sedentary	finfish, bony fish	zoobenthos, crabs, fish
	Rock Ling ($)	*Genypterus tigerinus*	120	marine and brackish demersal	60 m	caves and rocky recesses	sedentary	finfish bony fish	
	Heteroclinus perspicillatus	*Heteroclinus perspicillatus*	20	marine demersal		rocky reefs, on sand with sparse algae growth or weeds		finfish, bony fish	zoobenthos
	Yellow Eye Mullet ($)	*Aldrichetta forsteri*	40	marine, brackish and FW demersal	0-50 m	sandy and muddy bottoms of coastal W, bays, estuaries	sedentary	finfish, bony fish, birds	benthic detritus, algae and small invertebrates
	Sand Flathead ($)	*Platycephalus bassensis*	46	marine and brackish demersal	100m	coastal W from shallow bays and inlets to 100 m depth over sand, mud substrates	sedentary		crustaceans and fish
FDE	Southern Sea Garfish ($)	*Hyporhamphus melanochir*	52	marine and brackish pelagic	0-20 m		out of WP in winter	finfish bony fish	seagrass (SG) and algal filaments
Shallow demersal casual	Luderick ($)	*Girella tricuspidata*	71	marine and brackish benthopelagic	20m	estuarine (including mangroves), rocky reef and inshore, coastal W habitats, SG	out WP spring summer	finfish, bony fish	SG, algae
(mostly herbivorous)	Bridled Goby	*Arenigobius bifrenatus*		marine and brackish demersal		muddy coastal areas to upper estuaries, rocky reefs, in SG beds and mangroves			
	Blue weed whiting ($)	*Haletta semifasciata*	29	marine and brackish demersal		sheltered W with sand and seagrass bottoms	out WP autumn Winter		polychaetes, gastropods, crust., algae and SG
	Six-spined leatherjacket ($)	*Meuschenia freycineti*	60	marine demersal	100 m	continental shelf			plants
	Glass Goby	*Gobiopterus semivestitus*	2.5	brackish and freshwater demersal		quiet coastal estuaries, fresh water	catadromous		
FDB	Swan river goby	*Pseudogobius olorum*	6	brackish and freshwater demersal		brackish estuaries. Usually over mud and rock bottoms, sometimes among weeds	catadromous	finfish, bony fish, birds	insects, crustaceans and algae
Shallow demersal casual	Tamar River goby	*Favonigobius tamarensis*	11	brackish and freshwater demersal		quiet waters of brackish estuaries; sand, silt or mud bottoms	catadromous	finfish, bony fish	
(other diet)	Longsnout flounder ($)	*Ammotretis rostratus*	30	marine and brackish demersal	1-80 m	sandy regions of bays and offshore areas	casual		zoobenthos
	Greenback flounder ($)	*Rhombosolea tapirina*	45	marine and brackish demersal	100 m	silty sand substrates from estuaries and inshore waters down to 100 m depth	casual		zoobenthos
	Ruddy gurnard perch ($)	*Neosebastes scorpaenoides*	40	marine demersal	2-140 m	continental shelf	casual	finfish, bony fish, sharks,rays, birds	
	Bluefin gurnard ($)	*Chelidonichthys kumu*	60	marine and brackish demersal	1-200m	estuaries to edge of continental shelves over sand and sandy shell seabed	casual		zoobenthos
	Rock Flathead ($)	*Platycephalus laevigatus*	50	marine demersal			casual		zoobenthos, fish
	King George whiting (or Spotted sillago) ($)	*Sillaginodes punctatus*	72	marine and brackish demersal	2-200 m	Inhabit shallow inner continental shelf waters, including bays and inlets	casual non-migratory		benthic crustaceans and worms, molluscs
	White trevally ($)	*Pseudocaranx dentex*	122	marine and brackish demersal	10-200 m		casual	finfish, bony fish	PK and bottom invertebrates, fish
	Snapper ($)	*Pagrus Auratus*	120	brackish demersal	0-200 m	Inhabit rocky reefs. Also occur in estuaries.	casual		zoobenthos
	Elephant Fish ($)	*Callorhinchus milii*	125	marine demersal	200 m	continental shelves to 200 m. Migrates inshore bays in the spring	spring in WP		zoobenthos
	Smooth toadfish	*Tetractenos Glaber*	15	marine, brackish and FW demersal		coastal bays on sandy flats, often in very large schools, entering FW in estuaries		fisnfish, bonyfish	zoobenthos, shellfish

Table A3-1: Fish grouping (ecological data mainly from fishbase FAO website,and Kailola et al. (1993).

FPS	wet W (g)	structural W	reserve W
1	20.942438	50.3303	173.753
2	178.22853	428.331	1135.08
3	330.84361	795.106	2107.03
4	456.16211	1096.28	2905.16
5	545.74012	1311.56	3475.63
6	605.39637	1454.93	3855.57
7	643.61932	1546.79	4098.98
8	667.56587	1604.34	4251.5
9	682.37487	1639.93	4345.82
10	691.4625	1661.77	4403.7

FVS	wet W (g)	structural W	reserve W
1	76.60984	184.114	452.901
2	578.7077	1390.79	3685.58
3	1287.284	3093.69	819.827
4	2093.199	5030.52	1333.09
5	2886.952	6938.12	1838.6
6	3607.321	8669.36	2297.38
7	4228.45	10162.1	2692.96
8	4746.12	11406.2	3022.63
9	5167.504	12418.9	3291
10	5504.837	13229.6	3505.84

FDS	wet W (g)	structural W	reserve W
1	42.68978	102.595	27.1876
2	365.44378	878.2595	207.388
3	723.46267	1738.675	632.489
4	1207.2064	2901.241	1328.29
5	1605.9346	3859.492	2277.65
6	1788.481	4298.2	3440.24
7	2079.8925	4998.54	4766.12
8	2180.8883	5241.26	6204.35
9	2250.5309	5408.63	7707.87
10	2365.645	5685.28	9235.98

FDE	wet W (g)	structural W	reserve W
1	90.2937	217	1902
2	181.0035	435	3804
3	1046.075	2514	17264
4	1187.549	2854	23465
5	1291.574	3104	26777
6	1569.113	3771	28545
7	1551.221	3728	29489
8	1588.67	3818	29994
9	1589.502	3820	30263
10	1611.971	3874	30407

FDB	wet W (g)	structural W	reserve W
1	132.23658	317.8	1902
2	305.8335	735	3804
3	569.6409	1369	7074
4	1145.1072	2752	15243
5	1549.5564	3724	20470
6	2074.6746	4986	23814
7	1994.7834	4794	25954
8	2209.491	5310	27323
9	2347.2201	5641	28200
10	2435.4333	5853	28760

Table A3-3: Initial individual weight for each functional group. Structural and reserve weight are expressed in mg N per individual, whereas wet weight is expressed in g per individual.

FPS	1	2	3	4	5	6	7	8	9	10
1	223	165	122	91	67	50	37	27	20	15
2	77	57	42	31	23	17	13	9	7	5
3	78	58	43	32	23	17	13	10	7	5
4	2877	2132	1579	1170	867	642	476	352	261	193
5	2088	1547	1146	849	629	466	345	256	189	140
6	149	110	82	60	45	33	25	18	13	10
7	606	449	332	246	182	135	100	74	55	41
8	2962	2195	1626	1204	892	661	490	363	269	199
9	4549	3370	2497	1850	1370	1015	752	557	413	306
11	762	565	418	310	230	170	126	93	69	51
12	235	174	129	95	71	52	39	29	21	16
13	2188	1621	1201	890	659	488	362	268	198	147
14	1058	784	581	430	319	236	175	130	96	71
15	610	452	335	248	184	136	101	75	55	41
16	452	335	248	184	136	101	75	55	41	30
17	975	722	535	396	294	218	161	119	88	66
18	236	175	129	96	71	53	39	29	21	16
19	1089	807	598	443	328	243	180	133	99	73
21	1627	1205	893	661	490	363	269	199	148	109
22	138	102	76	56	42	31	23	17	13	9
23	441	327	242	179	133	98	73	54	40	30
24	2458	1821	1349	999	740	548	406	301	223	165
25	399	296	219	162	120	89	66	49	36	27

FVS	1	2	3	4	5	6	7	8	9	10
1	3	3	2	1	1	1	1	1	0.4	0.3
2	2	2	1	1	1	1	0.4	0.3	0.2	0.2
3	2	2	1	1	1	1	0.5	0.4	0.3	0.2
4	17	13	10	8	6	4	3	3	2	2
5	12	9	7	5	4	3	2	2	1	1
6	3	2	2	1	1	1	1	0.4	0.3	0.3
7	5	4	3	2	2	1	1	1	1	0
8	20	15	12	9	7	5	4	3	2	2
9	124	95	72	55	42	32	25	19	14	11
11	15	11	9	7	5	4	3	2	2	1
12	4	3	2	2	1	1	1	1	0.5	0.3
13	9	7	5	4	3	2	2	1	1	1
14	13	10	7	6	4	3	2	2	1	1
15	19	15	11	9	7	5	4	3	2	2
16	14	11	8	6	5	4	3	2	2	1
17	29	22	17	13	10	8	6	4	3	3
18	6	5	4	3	2	2	1	1	1	1
19	14	11	8	6	5	4	3	2	2	1
21	6	4	3	2	2	1	1	1	1	0.5
22	3	3	2	2	1	1	1	1	0.4	0.3
23	6	4	3	2	2	1	1	1	1	0.5
24	7	6	4	3	2	2	1	1	1	1
25	6	5	4	3	2	2	1	1	1	1

FDE	1	2	3	4	5	6	7	8	9	10
1	46	34	25	19	14	10	8	6	4	3
2	19	14	10	8	6	4	3	2	2	1
3	20	15	11	8	6	4	3	2	2	1
4	503	373	276	204	151	112	83	61	45	33
5	362	268	199	147	109	81	60	44	33	24
6	33	24	18	13	10	7	5	4	3	2
7	111	82	61	45	33	25	18	14	10	7
8	527	390	289	214	158	117	87	64	48	35
9	1134	840	621	461	341	251	187	137	102	76
11	169	126	93	69	51	38	28	21	15	11
12	50	37	27	20	15	11	8	6	5	3
13	369	274	203	150	111	82	61	45	33	25
14	207	153	113	84	62	46	34	25	19	14
15	161	119	88	65	49	36	27	20	15	11
16	119	88	65	49	36	27	20	15	11	8
17	253	187	139	103	76	56	42	31	23	17
18	58	43	32	24	17	13	10	7	5	4
19	218	161	119	88	65	48	36	27	20	15
21	270	200	148	110	81	60	45	33	24	18
22	33	25	18	14	10	7	5	4	3	2
23	87	65	48	36	26	19	14	11	8	6
24	403	299	221	164	121	90	67	49	37	27
25	84	62	46	34	25	19	14	10	8	6

FDS	1	2	3	4	5	6	7	8	9	10
1	177	131	97	72	53	39	29	22	16	12
2	44	33	24	18	13	10	7	5	4	3
3	38	28	21	16	12	9	6	5	3	3
4	2810	2082	1542	1142	846	627	464	344	255	189
5	2055	1523	1128	836	619	458	340	252	186	138
6	105	78	58	43	32	23	17	13	10	7
7	564	418	309	229	170	126	93	69	51	38
8	2844	2106	1561	1156	856	634	470	348	258	191
9	2496	1849	1368	1015	749	557	411	303	225	166
11	538	398	295	219	162	120	89	66	49	36
12	178	132	98	73	54	40	29	22	16	12
13	2212	1639	1214	899	666	494	366	271	201	149
14	909	673	499	370	274	203	150	111	82	61
15	283	210	155	115	85	63	47	35	26	19
16	210	155	115	85	63	47	35	26	19	14
17	482	357	265	196	145	108	80	59	44	32
18	135	100	74	55	41	30	22	17	12	9
19	909	673	499	369	274	203	150	111	82	61
21	1672	1239	918	680	504	373	276	205	152	112
22	82	61	45	33	25	18	14	10	7	6
23	372	275	204	151	112	83	61	45	34	25
24	2551	1890	1400	1037	768	569	422	312	231	171
25	308	228	169	125	93	69	51	38	28	21

FDB	1	2	3	4	5	6	7	8	9	10
1	100	70	49	34	24	17	12	8	6	4
2	59	41	28	20	14	10	7	5	3	2
3	67	47	33	23	16	11	8	5	4	3
4	576	402	280	196	136	95	66	46	32	22
5	396	276	193	134	94	65	46	32	22	15
6	85	60	42	29	20	14	10	7	5	3
7	160	111	78	54	38	26	18	13	9	6
8	661	461	322	225	157	109	76	53	37	26
9	3600	2512	1752	1221	852	595	414	290	200	140
11	438	306	213	149	104	72	51	35	25	17
12	117	82	57	40	28	19	14	9	7	5
13	334	233	162	113	79	55	38	27	19	13
14	383	267	187	130	91	63	44	31	22	15
15	554	386	269	188	131	91	64	45	31	22
16	410	286	200	139	97	68	47	33	23	16
17	845	589	411	287	200	140	97	68	47	33
18	179	125	87	61	42	30	21	14	10	7
19	433	302	211	147	102	71	50	35	24	17
21	210	147	102	71	50	35	24	17	12	8
22	100	70	49	34	24	17	12	8	6	4
23	170	118	83	58	40	28	20	14	10	7
24	284	198	138	96	67	47	33	23	16	11
25	192	134	94	65	46	32	22	15	11	8

Table A3-4: Abundance of fish for each functional group expressed in 10^{-6} ind.m^{-3}

Appendix 4: Parameterisation of the benthos groups

The mean number of individuals per station for each of the main taxa and for each stratum (Table 5 of (Coleman *et al*. 1978)) were converted to mean biomass per stratum, with the following conversion factors:

mean AFDW of crustaceans = 3.7 mg
mean AFDW of molluscs = 4.4 mg
mean AFDW of polychaetes = 3.3 mg

These weight estimations were calculated using the regressions proposed by (Edgar 1990) considering a mean sieve mesh size of 4 mm (Coleman used sieves of 1, 3 and 5 mm). Biomasses of the three main taxa were decomposed into biomass of main species, using the list of species and their proportion given in Table 2 of Coleman *et al.* (1978).

These biomasses were converted to nitrogen biomass with the conversion factor N weight = 9% of the AFDW (Jorgensen 1979) and then distributed into functional groups: deposit feeders, infaunal carnivores, grazers, filter feeders and macrozoobenthos, depending on their ecology (diet, habitat, size) as displayed in Table A4-1. This work was done more with groups than with species, due to the difficulty and time required to find precise information about each indicated species.

Taxa	species	functional groups
Polychaeta errantia	*Platynereis sp.* *Nepthys australiensis* *Eunice sp.* *Dorvillea sp.*	BC
Polychaeta sedentaria	*Mediomastus sp.* *Isolda sp.*	50% BFS - 50% BD
Mollusca gastropoda	*Sigapatella calyptraeformis*	BG
Mollusca Bivalvia	*Pronucula concentrica* *Nepotrigonia margaritacea* *Lepton frenchiensis* *Mysella donaciformis* *Notocallista diemenensis* *Katelysia rhytiphora* *Tellina deltoidalis* *Tellina mariae*	50% BD - 50% BFS
Crustacea Tanaidacea	*Leptochelia sp.*	BG
Crustacea Isopoda	*Leptanthura diemenensis*	BD
Crustacea Amphipoda	*Lembos sp. 4* *Amaryllis macrophthalmus* *Tethygenia sp* *Marea mastersi*	BG
Crustacea Decapoda Crustacea Brachyura	*Pontophilus intermedius* *Macrobrachium intermedium* *Halicarcinus ovatus* *Litocheira bispinosa*	BMS

Table A4-1:Allocation of the different taxa listed by Coleman et al. (1978) into the pre-defined functional groups.

Once these estimates had been made, the strata were compared to our boxes, and for each box, percentages of cover by each of the strata were estimated. These percentages of cover allowed us to calculate the mean biomass of each functional group for each box.

Five of our boxes are not covered at all by any stratum. We then considered the most appropriate strata for each box, having regard to the characteristics (bathymetry, position in WP, and sediment type) of the box. The resulting biomasses per box are given in Table A4.2.

Boxes \ mg.m-2 N	BC	BFS	BD	BG	BMS
0	0.00	0.00	0.00	0.00	0.00
1	62.87	54.80	62.15	133.03	57.79
2	64.05	55.78	63.12	132.81	57.68
3	58.64	48.79	54.54	103.82	45.12
4	94.19	80.76	87.74	127.01	54.85
5	94.19	80.76	87.74	127.01	54.85
6	56.01	49.11	56.54	134.36	58.44
7	77.56	66.98	74.16	130.21	56.41
8	94.19	80.76	87.74	127.01	54.85
9	94.19	80.76	87.74	127.01	54.85
10					
11	94.19	80.76	87.74	127.01	54.85
12	56.01	49.11	56.54	134.36	58.44
13	94.19	80.76	87.74	127.01	54.85
14	94.19	80.76	87.74	127.01	54.85
15	82.11	72.44	78.38	108.37	46.66
16	131.12	103.68	109.36	103.71	44.69
17	94.19	80.76	87.74	127.01	54.85
18	147.70	114.45	120.44	108.92	47.00
19	94.19	80.76	87.74	127.01	54.85
20					
21	156.99	117.67	122.03	79.61	34.28
22	178.20	134.29	140.81	118.52	51.26
23	195.17	154.89	160.50	103.41	44.07
24	70.86	112.90	114.77	41.99	14.69
25	178.20	134.29	140.81	118.52	51.26
26	0.00	0.00	0.00	0.00	0.00

Table A4-2: Initial abundance of the benthic functional groups in $mg.m^{-2}$ N

Appendix 5: Parameterisation of seagrass and macroalgae

The values of the initial conditions for seagrass biomass in each box were calculated using the following steps:

1. The surface area of dense, medium and sparse seagrass beds (m^2) in each box of the model was estimated from GIS files associated with Blake *et al.* (2001).

2. These surface areas were then converted into "above ground" seagrass biomass using the following values: 50, 200 and 500 g DW/m^2, respectively for sparse, medium and dense beds. These values were estimated from the average biomass indicated by Edgar *et al.* (1994).

3. The "below ground" biomasses were estimated from the "above ground" biomasses, using the average ratio (above/below) of 1.1, calculated from Plus *et al.* (2001).

4. Both "below ground" and "above ground" biomasses were converted into g of N, using a nitrogen content of 1.95% of dry weight for above ground biomass (leaves) and 0.85% for belowground parts (roots and rhizomes) (Plus *et al.* 2001).

5. The obtained biomass was then divided by the box area to obtain an average density within each box ($mg.m^2$ N).

This treatment is, of course, responsible for an artificial homogenisation of the seagrass density within the area of each box recognised as containing seagrass. This is a standard representation in patch models though fine scale variation may be captured in future benthic production formulations.

boxes	Seagrass beds areas (m^2) total dense	total medium	total sparse	Biomass $mg.m^{-2}$ N
0	0	0	0	0.00
1	18834369	0	0	2397.33
2	1611150	0	0	491.78
3	85868	0	0	76.58
4	1270865	1445058	143020	4044.37
5	3725885	642586	1666820	4493.70
6	3513296	1692170	772980	1100.20
7	8449436	1385890	1553461	3974.34
8	680247	2667055	1519165	2248.73
9	0	68245	39487	124.05
10				
11	264680	2766982	557288	618.71
12	1278011	944886	646215	1208.42
13	3686263	2363398	1090212	3314.79
14	4892869	4307015	4371510	1200.42
15	0	0	0	0.00
16	0	0	0	0.00
17	14021	149419	0	53.55
18	320139	412946	489817	204.50
19	1856309	157767	232541	2572.23
20				
21	4161113	538705	1507874	6196.53
22	1114818	94380	363151	441.73
23	8654689	821581	1807732	1806.81
24	11304804	299802	2042895	7654.71
25	885471	17311	134116	1354.23
26	0	0	0	0.00

Table A5-1: Seagrass bed areas and biomass in the WP boxes

Appendix 6: Parameterisation of nutrients and detritus

The 1984-2003 data for the survey stations 709 (western arm), 716 (upper arm) and 724 (eastern arm) (Victorian Water Resources Data Warehouse), describe the evolution of the following parameters: temperature, salinity, dissolved oxygen, silica, ammonia, nitrate, and total kjeldahl nitrogen.

The simulated period starts on 01/01/1970, therefore:

- The available summer data were plotted (Jan-March);
- The detrital nitrogen were calculated from: Total Kjeldahl nitrogen - ammonia
- A linear trendline was used to extrapolate a value for 01/01/1970, if any trend was detected, otherwise a summer average was used;
- The DON and labile detritus concentration were estimated from the detrital nitrogen using the following ratio: 95% labile detritus, 5% DON (Murray and Parslow 1997).
- These three survey stations were distributed in our WP box set, and the values in the other boxes were determined arbitrarily.

The results are shown in Table A6-1. The values in sediment had to be defined arbitrarily, as well as values for refractory detritus and biogenic silica, both in the sediment and the water column (Table A6-2).

boxes	**DON** (µg.l-1)	**Ndet** (µg.l-1)	**NO3** (µg.l^{-1})	**Si** (µg.l^{-1})	**S‰** (mg.l^{-1})	**Tº** (ºC)	**dO2** (mg.l^{-1})
0	8	152	4	70	35	20	7
1	8	152	4	70	35	20	7
2	8	152	4	70	35	20	7
3	8	152	4	70	35	20	7
4	8.15	154.85	4.1	71	34	20	6.9
5	8.15	154.85	4.1	71	34	20	6.9
6	8.15	154.85	4.07	70.59	33.69	19.92	6.89
7	8.15	154.85	4.1	71	34	20	6.9
8	9.5	180.5	5	72	33	20	6.7
9	9.5	180.5	5	72	33	20	6.7
11	11	209	6	74	31.5	20	6.5
12	11	209	6.03	73.83	31.41	19.85	6.46
13	11	209	6	74	31.5	20	6.5
14	11.4	216.6	7.3	131	31.5	20	6.4
15	11.75	223.25	8.55	188	31.5	20	6.3
16	12.1	229.9	9.8	245	31.4	20	6.2
17	12.45	236.55	11	358	31.4	20	6.1
18	12.45	236.55	11.16	358.50	31.38	20.25	6.09
19	12.45	236.55	11	358	31.4	20	6.1
21	10.3	195.7	7.6	215	32.5	20	6.5
22	10.3	195.7	7.6	215	32.5	20	6.5
23	10.3	195.7	7.6	215	32.5	20	6.5
24	10.3	195.7	7.6	215	32.5	20	6.5
25	9	171	5.8	143	33.8	20	6.8
26	8	152	4	70	35	20	7

Table A6-1: Initial conditions for nutrients and detritus, defined on the basis of the data available for the survey stations 709, 716 and 724, located in the boxes 6, 12 and 18. The detrital nitrogen corresponds to the variable labile detritus.

Variables	**water**	**sediment**
Labile detritus (µg.l-1)	See above	Water values x 10
Refractory detritus (µg.l-1)	200 everywhere	2000 everywhere
Dissolved Organic Nitrogen (µg.l-1)	See above	= water values
Nitrate (µg.l-1)	See above	= water values
Silica (µg.l-1)	See above	= water values
Detrital Silica (µg.l-1)	1 everywhere	1 everywhere
Salinity (mg.l^{-1})	See above	= water values
Temperature (ºC)	See above	= water values
Dissolved oxygen (mg.l^{-1})	See above	= water values

Table A6-2: Arbitrarily defined initial conditions.