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Minimising Impacts of the North Pacific Seastar in Australia

Final Report May 2004

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CONTENTS

EXECUTIVE SUMMARY

This report provides the results of the initial implementation of the Management Strategy Evalaution (hereafter MSE) for *Asterias amurensis*. It presents the results of stakeholder and managers workshop and examines management options for the vector ranked as the highest threat by that workshop – ballast water. Several reballasting scenarios are explored as a method of reducing the potential spread of *Asterias* throughout southern Australia and the consequences of uncertainty in biological parameters considered.

The MSE framework requires the explicit definition of management options, performance measures to determine the efficiency of the management options and a base model that simulates possible “real-world” scenarios to which the management options are applied. Uncertainties in the functional relationships and parameters in the base model can be simulated and the performance of management options across the range of uncertainties can be examined.

A scoping workshop in May 2002 included managers, scientists and industry representatives. Participants agreed that management actions should be initiated on the most significant vectors of *Asterias* using the precautionary principle. Participants used six criteria to qualitatively score 18 identified vectors that could potentially spread *Asterias* larvae and non-larvae (adults and juveniles) beyond the Derwent River and Port Philip Bay. Vectors were ranked based on the six criteria on their threat in spreading *Asterias* larvae and non-larvae as well as a measure of the vector strength. The likelihood of a vector leading to the establishment of *Asterias* larvae and non-larvae at a recipient site was based on four criteria -- frequency, volume, entrainment and discharge. The likelihood of dispersion of *Asterias* larvae and non-larvae by a particular vector was based on two criteria scores -- promiscuity and range.

Ballast water was ranked the most important vector for spreading *Asterias* larvae (overall score 4.4). Commercial fishing vessels were ranked as the most important vector for spreading *Asterias* non-larvae but its vector strength(1.4), was much lower than that obtained for spreading larvae with ballast water. Less important vectors for spreading *Asterias* non-larvae were ballast water (overall score = 0.7), barges and dredges, and mariculture baskets (overall score = 0.5). Vectors having the greatest likelihood of dispersing of *Asterias* (both adult and larvae) were cruising yachts and trailered boats. However, although these vectors were highly promiscuous and covered long ranges, the likelihood of entraining and discharging *Asterias* larvae and non-larvae by these vectors was considered low (trailered boats) to medium (cruising yachts), and therefore they were not considered important vectors. Gaps in vector knowledge were recognised for exploratory oilrigs and barges & dredges.

The base model is arranged into two components -- physical and biological. The physical component comprises of an oceanographic model linked with estuarine input, where appropriate, and anthropogenic inputs. The anthropogenic inputs are currently limited by data to the movement of shipping with associated ballast water. Future updates of the model will include further anthropogenic vectors. The ships transport ballast water, with entrained *Asterias* larvae, recreating the patterns of movement between ports in southern Australia.

The biological component comprises a complete population model for *Asterias*. Estimates of mortality, growth, density, and fertilisation success are derived from either data or published literature. The population dynamics of adult *Asterias* are modelled using an age-structured constant hazard model. Estimates for larval mortality and settlement are lacking and were derived by calculating the range of larval mortality and settlement rates required to keep the known population of the Derwent estuary steady, given the other known demographic parameters.

Six management scenarios were examined: (1) no ship movement; (2) current ship movements with no exchange of ballast water; (3) current ship movements with 95% exchange at least 5nm from the coast; (4) current ship movements with 95% exchange at least 33nm from the coast; (5) current ship movements with 95% exchange in at least 200m water; and (6) current ship movements with exchange where possible at least 5nm from the coast. Scenario (1) can also be interpreted as current ship movements with freshwater ballast or 100% effective ballast water treatment. The performance of the management options was assessed by examining the probability that population of at least 100 individual seastars would establish for a period of two years at a particular site.

The no ship movement scenario (1) defines the natural potential range of *Asterias*, throughout Bass Strait, and on the northern Tasmanian and south-eastern Victorian coasts. Scenario (2) of current shipping movements with no exchange was consistently the least effective at preventing the spread of *Asterias* beyond its potential natural range. The effectiveness of reballasting options were very similar to one another, but their effectiveness compared to the no-reballasting option changed depending on the rates of larval mortality. When larval mortality was high (low total number of larvae), reballasting reduced the spread of *Asterias* compared to the no-reballasting scenario, as a consequence of relatively smaller numbers of *Asterias* reaching the coastline. However, when larval mortality is low (hence total number of larvae remains high), sufficient numbers of larvae reach recipient ports to facilitate an easy establishment of a population and sites between ports are more easily infected due to increased numbers.

This report summarises the initial work on the MSE for *Asterias amurensis*. The model will be improved over the coming year. Additional meetings with managers and stakeholders will help refine the management objectives and performance criteria. Additional data inputs will help refine the outputs of the model and extend management scenarios to additional vectors.

1. Introduction

The invasion process can be broken down into discrete phases: the pre-border, border and post-border phases (Figure 1). Once inside a border, local mechanisms can further spread the invader. The border can be the border of a region, country, State or local jurisdiction i.e. any place on the transport pathway where jurisdiction or an administrative boundry exists or could be developed to protect areas inside the border. For *Asterias amurensis*, which has already established in Australia, the border that we are concerned with in this report is any boundary with a semi-enclosed water body which could maintain an established population[1].

In the pre-border phase, the potential introduced species must be available to be taken up in a suitable transport pathway that will move it from its native (or existing introduced) range to a new area. The risk posed by a vector is theoretically a function of its frequency, the density of the threatening species at the time and place of contact, the likelihood that the species will be taken up by the vector, and the likelihood that the species will survive the journey. Consequently, any action that reduces the availability (abundance, likelihood of being taken up) or its survival rate in transit, or restricting the transport pathway, will reduce the risk of the potential introduced species arriving at the border.

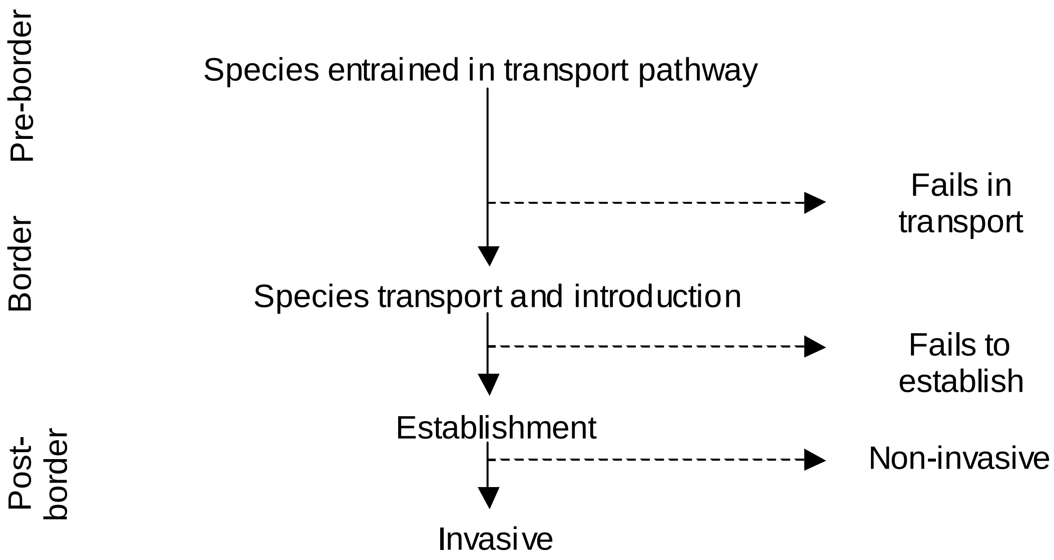

Figure 1. Schematic of invasion process showing steps necessary for an alien species to become invasive. (after Kolar and Lodge 2001).

At the border, the transport vector must be permitted to cross the border and the potential introduced species discharged in a healthy enough condition to establish itself. The species carried by the vector must be discharged, dislodged, discarded with other cargo or waste, drop off, divide, or spawn and release gametes or offspring. There are a variety of mechanisms available, and more being developed, to reduce the possibility of a species being discharged. In

[1] The direct introduction of Asterias amurensis from an international source is briefly considered but not developed in the body of this report.

all cases, there will be a cost in implementing and managing actions and ideally this should only be done when there is a realistic risk of a viable potentially invasive organism being introduced. Ideally, a species-specific risk assessment would be in place to estimate the risk posed by an individual vector arriving from a given destination, in a particular season after journey of known duration, and to a particular location. When the risk level has been estimated, appropriate management actions can be implemented. This has been the approach taken to regulating overseas ballast water discharges into the Australian environment and is being recommended as part of the developing National System for Prevention and Management of Marine Pest Incursions (‘National System’).

Upon release into a new environment, a new species must still establish a viable, reproducing population. To become an introduced pest, it must not only establish, but also reach reproductively viable population densities where the pest characteristic become manifest. The likelihood of this happening is a function of the species’ physiological tolerance, biotic and abiotic variables, environmental resistance and stochastic events.

Once an introduced marine species has established in a new region, it is available to be transported by new and probably a more diverse set of local vectors and it may well adapt physiologically, ecologically or genetically to the local environment, further increasing the risk of spread. Increasing spread increases the risk that habitats of high conservation and/or economic value (marine parks, aquaculture sites, ports) will be impacted. Sensitive habitats (i.e. marine parks and aquaculture) are typically not directly impacted by international shipping and so are relatively immune from introduced marine species until introduction occurs via local vectors (Wasson *et al.* 2001). Managing the risk at this level is complicated by the diversity of local vectors and may on occasion be reduced to the protection of particularly sensitive or valuable habitats.

Given that at any one time there is estimated to be 10,000 organisms moving around the world in the ballast water of ships (Carlton 1999), it might be expected that the rate of species introductions would be extremely high and that by now all suitable species would have been distributed rapidly around the globe. That this is not the case (a new species establishes in busy ports like San Francisco and Port Phillip Bay on average every 3-6 months; Cohen and Carlton 1995; Hewitt *et al.* 1999), shows that despite frequent arrival of organisms taken up in ballast water, the frequency of species failing to complete the set of steps to become introduced, let alone invasive is high. This is encouraging and emphasizes the point that managing the risk of introduced species does not have to be about preventing the entry of an individual of a species, but is more usefully directed at reducing the risk of entry and establishment by increasing the already high failure rate at each step. Kolar and Lodge (2001), in a metanalysis of published studies on pest invasions, found the strongest result was that the probability of bird establishment increases with number of individuals released and the number of release events. They extrapolated this result to suggest that therefore even if impossible to halt ballast water releases completely, "reducing the number of individuals released and the frequency of releases will, however, reduce the probability of establishment."

When evaluating the potential for vectors to transport *A. amurensis* around southern Australia, it is important to recognise that some spread will be expected to occur by natural transport in ocean currents. For example, the population that established at Andersons Inlet in southeastern Victoria appears most likely to have resulted from larval transport in prevailing currents from Port Phillip Bay, although transport on small vessels has been suggested an another possible vector (Don Hough, DSE Victoria*, pers. comm.*). Prevailing currents around southern Australia are complicated (Figure 2) and will need to be part of the underlying simulation model.

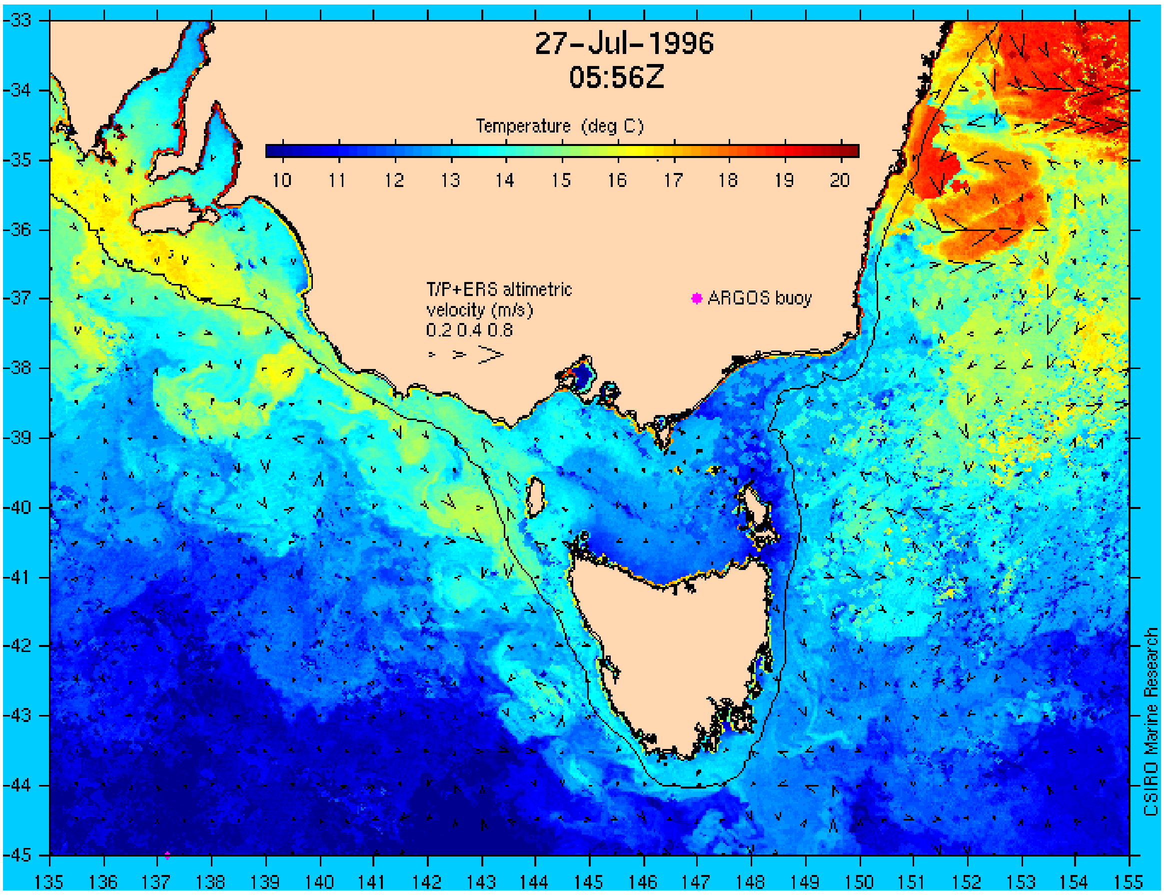

Figure 2. Example of small-scale variability in ocean currents off western Victoria during the larval residence period for *A. amurensis*.

There are other management options available in addition to the control of vectors. If a potentially invasive species is identified early on, then it can be eradicated. The likely success of eradication will depend on the stage of the invasion at which the species is detected and size of the water body infected. To date, attempts have been (are being) made to eradicate *A. amurensis* from Hendersons Lagoon (Northeast Tasmania) and Andersons Inlet (Southeast Victoria), small semi-enclosed water bodies where the seastar was identified in the first season, but there were no attempts to eradicate the seastar from the Derwent Estuary, a large water body where the seastar was only discovered after many generations, and attempts to eradicate the seastar in Port Phillip Bay were abandoned when the size of the first generation was established[2]. The opportunity for eradication is limited (Figure 3).

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[2] In August 1995, the first adult Northern Pacific seastar was caught off Point Cook, in Port Phillip Bay. Despite a major effort to find and remove it from the Bay, which covers 1950 km^2, only 3 more adult seastars were found in the next 30 months. In 1998 there was evidence that the seastar was breeding in the Bay. In January that year four juveniles were found off Dromana and by the end of April over 100

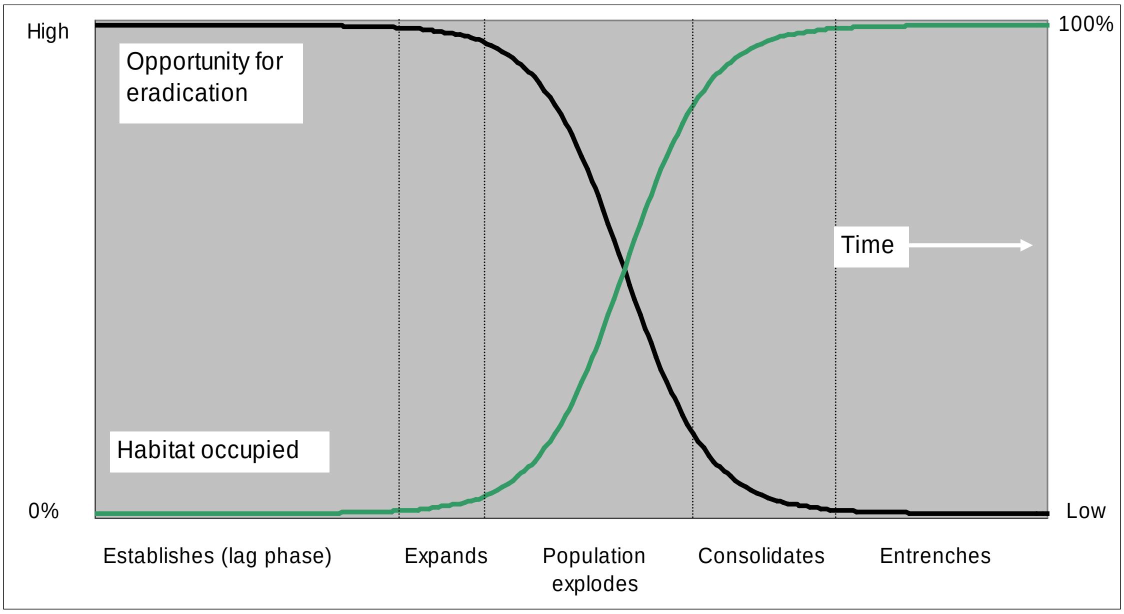

Figure 3. Schematic of establishment of an invasive species and the corresponding opportunity for eradication.

Management intervention can take place at the pre-border stage, the border or post-border. Each opportunity for intervention will have costs and benefits to a variety of stakeholders. If the risk of invasive species is to be managed effectively then we need a mechanism to compare and contrast alternative management interventions to determine which, or which combination, is most likely to achieve the desired management objectives and goals. Management strategy evaluation is an approach that simulates the biological, physical, management and operational systems, using this systems approach to determine how management interventions may satisfy declared management objectives through meeting specific performance criteria (Figure 4). Australia's first National Control Plan is for Asterias amurensis. The work contained in this report helps implement actions, listed in the plan, to deal with this invasive species.

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juveniles had been caught in the same area. The initial response was an intensive effort to find and remove the seastar. However, by February 1999, the seastar covered about a 100 km^2 area in the eastern and central area of the Bay.

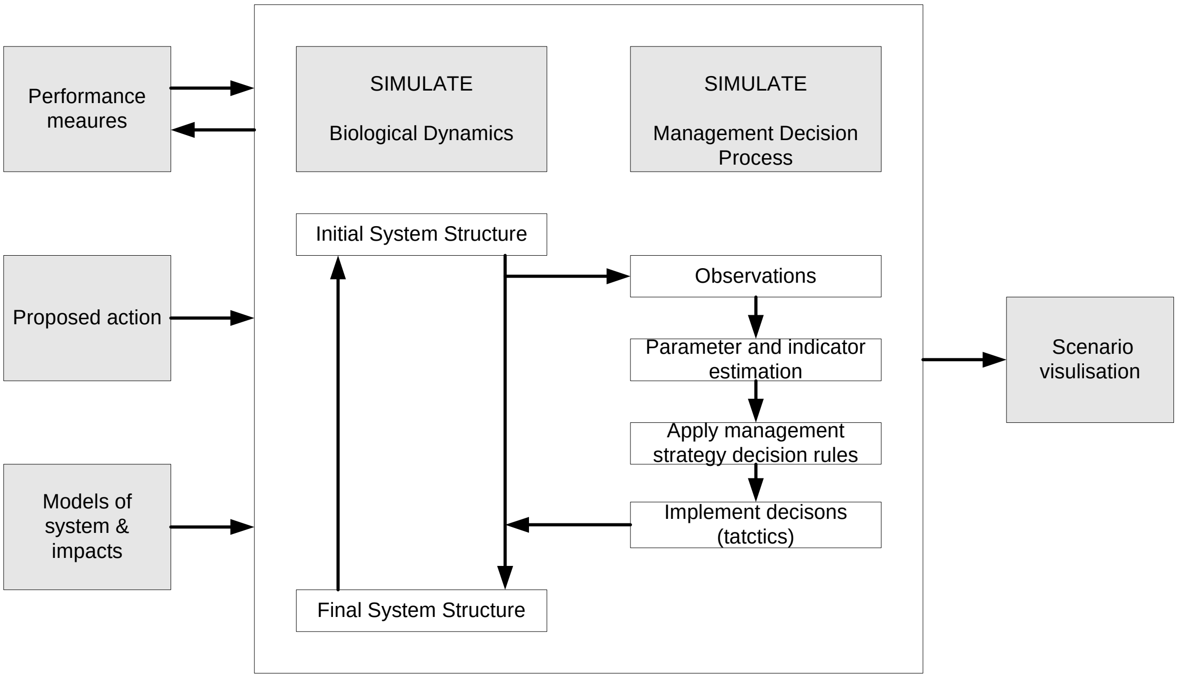

Figure 4. General framework for monitoring/management strategy evaluation (from Sainsbury pers. comm.)

1.1 Objectives

The objectives of this project were to:

1. Develop a simulation model to represent movement of *A. amurensis* by all known and potential vectors; the risks of successful establishment; and the reduction of risks provided by regular professional surveys and community monitoring.

2. Determine the role of international and domestic ballast water management (as well as other vectors) in reducing the overall impacts of *A. amurensis* to Australia.

3. Provide public and private sector managers the information to target management intervention at the vectors, times and places that will provide the highest reduction in overall impacts.

2. METHODS

2.1. Physical model

The physical model includes:

- natural dispersal
- anthropogenic dispersal

The first question to be resolved in the physical model is the spatial scale. In the original specification, the spatial environment that needed to be represented by the MSE model was restricted to key ports, marinas and reballasting areas. However, once it became clear that we would also have to represent the dispersal of the *Asterias* larvae in ocean currents, then the representation of spatial scale became more involved.

2.1.1 Natural dispersal

Oceanic Cells

Available oceanographic models for the area work on cells with area 22000 m x 22000m across a total area of 1034km x 2992km (47 x 136 cells). The flows between cells have been provided by Scott Condie (CSIRO Marine Research) from a hydrodynamic model of southeastern Australia. The grid covers a large part of the potential natural dispersal of *Asterias* larvae from existing populations (Figure 5). Present simulations have been conducted using currents from 0-10m depth as *Asterias* are most commonly found in this depth layer.

Data on the distribution of *Asterias* and asteroid larvae in the Derwent Estuary and Spring Bay are available from studies of the broad scale and vertical distribution of larvae in September 1993 and September 1995 (Bruce *et al*. 1993 and CSIRO unpublished data). Seasonal availability of asteroid larvae around the Hobart docks is available from CSIRO for the period March 1995 to 1997 (Sutton, unpublished data); although there was only limited positive identification of *A. amurensis*.[3]

Asteroid larvae are available throughout the Derwent Estuary and Spring Bay at the peak period of abundance for *Asterias*. Larval densities were highest in the samples taken at 0 and 5 m, with few larvae in samples taken at 10m depth. There were significantly fewer larvae at the surface on the Eastern shore where low salinity water occurs – larvae were found at the 2m halocline and deeper (6 or 10 m). No consistent variation in the depth distribution with respect to day/night or tide was found, although variability was high and sample size low

Asterias larvae are modelled as passive particles.

[3] See also Project # 35601 – Controlling the Northern Pacific Seastar (*Asterias amurensis*) in Australia

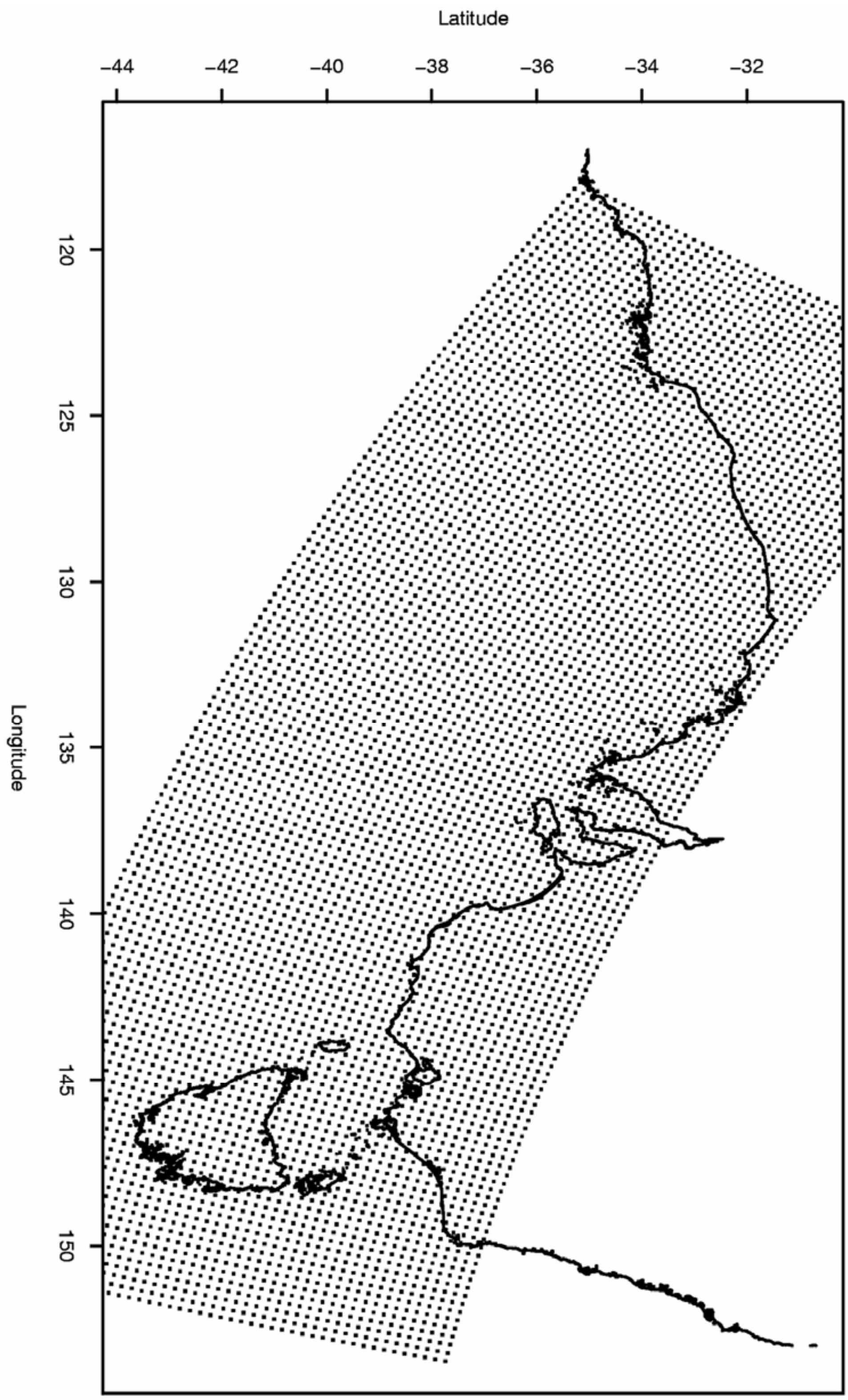

Figure 5. Distribution of cells across southern Australia.

Estuaries

Different embayments or nodes will be more or less likely to support the development of self-sustaining populations of *Asterias*. Factors such as available habitat, depth, productivity, and exchange with the ocean would be expected to influence, initial establishment probability, development of a self-sustaining population and, ultimately, population size.

Data on the residence time and volumes of estuaries in the south east have been obtained from the SERM II model (CSIRO; http://www.per.marine.csiro.au/serm2/index.htm) and the OzEstuaries database (Geoscience Australia; http://www.ozestuaries.org/). The names, positions, residence time and volumes for the estuaries used in the model are shown in Table 1.

Table 1 Estuaries included in MSE model

Estuary ID	Estuary Name	Latitude	Longitude	Volume (m^3)	Residence Time (days)
78	NULLICA RIVER	-37.092	149.872	2800000	9.58796
77	CURALO LAGOON	-37.048	149.921	660000	6.86781
79	TOWAMBA RIVER	-37.112	149.913	15100000	5.144398
538	TOURVILLE BAY	-32.170	133.495	105200000	74.8116
537	SMOKEY BAY	-32.397	133.915	7085000	12.6794
528	THIRD CREEK	-33.180	137.920	700000	155.9045
531	NORTHERN SPENCER GULF	-32.768	137.848	6774250000	1713.157
529	SECOND CREEK	-33.158	137.949	5250000	387.22576
530	PORT PIRIE	-33.149	138.016	58600000	237.61306
527	FISHERMAN CREEK	-33.206	137.848	3000000	255.40706
526	PORT DAVIS CREEK	-33.249	137.823	1540000	9.387094
	BROUGHTON RIVER ESTUARY				
80	WONBOYN RIVER	-37.250	149.966	32700000	13.9231
81	MERRICA RIVER	-37.297	149.951	280000	6.414152
536	BLANCHE PORT	-32.750	134.218	14180000	13.5518
532	FRANKLIN HARBOUR	-33.731	136.977	114280000	3.37846
602	MALLACOOTA INLET	-37.569	149.763	56321000	92.2953
603	BETKA RIVER	-37.585	149.742	702000	52.1249
535	BAIRD BAY	-33.152	134.360	21830000	3.96702
534	VENUS BAY	-33.229	134.660	141280000	6.77748
604	WINGAN INLET	-37.749	149.513	2700000	54.7797
525	PORT RIVER BARKER INLET SYSTEM	-34.761	138.528	99280000	150.69838
608	YEERUNG RIVER	-37.791	148.775	315000	8.41172
607	SYDENHAM INLET	-37.781	149.017	27100000	82.2894
606	TAMBOON INLET	-37.779	149.148	14105000	73.8375
610	LAKE TYERS	-37.859	148.088	14366000	103.399
609	SNOWY RIVER	-37.805	148.557	98100000	18.673

611	GIPPSLAND LAKES	-37.889	147.971	4855600000	32.6561
533	PORT DOUGLAS/COFFIN BAY	-34.526	135.366	235180000	9.31245
524	THE COORONG AND LOWER LAKES	-35.561	138.890	4715750000	13.1033
612	JACK SMITH LAKE	-38.497	147.040	107400000	94.3662
617	PORT PHILLIP BAY	-38.297	144.632	3035872000	156.595
616	WESTERN PORT BAY	-38.429	145.216	4694500000	50.9496
613	CORNER INLET	-38.781	146.484	264320000	34.8159
627	BARWON RIVER	-38.286	144.501	75000000	59.5562
615	ANDERSON INLET	-38.650	145.721	54386400	5.19464
614	SHALLOW INLET	-38.871	146.184	5030000	97.9718
628	THOMPSON CREEK	-38.305	144.377	300000	7.330632
636	GLENELG RIVER	-38.061	140.984	5460000	12.1887
634	FITZROY RIVER	-38.263	141.850	840000	7.657456
633	LAKE YAMBUK	-38.337	142.040	1900000	22.5484
629	AIRE RIVER	-38.807	143.461	2920000	42.3608
635	SURREY RIVER	-38.260	141.704	850000	5.496752
561	LITTLE MUSSELROE RIVER	-40.763	148.038	220000	0.9000674
560	RINGAROOMA RIVER	-40.861	147.888	980000	0.3361054
559	TOMAHAWK RIVER	-40.865	147.761	700000	0.258439
562	GREAT MUSSELROE RIVER	-40.829	148.173	34314000	8.19661
558	BRID RIVER	-41.001	147.398	2000000	2.241538
563	ANSONS BAY	-41.063	148.298	46900000	22.4124
541	MOSQUITO INLET	-40.624	144.952	18120000	15.924012
557	LITTLE FORESTER RIVER	-40.970	147.364	340000	1.391732
556	PIPERS RIVER	-41.010	147.158	2500000	1.47085
564	GEORGES BAY	-41.276	148.331	33200000	12.59644
542	WEST INLET	-40.787	145.261	17775000	133.03872
544	BLACK RIVER	-40.836	145.316	850000	4.28334
545	DETENTION RIVER	-40.871	145.449	296000	0.8003304
543	EAST INLET	-40.789	145.277	2960000	13.7419
547	CAM RIVER	-41.039	145.840	220000	1.22893
548	EMU RIVER	-41.042	145.880	1608200	1.911584
546	INGLIS RIVER	-40.987	145.740	520000	2.953802
549	BLYTHE RIVER	-41.074	145.985	1300000	1.13676
551	FORTH RIVER	-41.157	146.250	6100000	1.47849
552	DON RIVER	-41.160	146.335	2250000	4.85712
553	MERSEY RIVER	-41.168	146.370	46100000	16.0146
550	LEVEN RIVER	-41.168	146.370	18440000	7.49039
554	PORT SORELL	-41.139	146.555	187500000	26.3593
555	TAMAR RIVER	-41.069	146.776	917100000	182.0514
601	ARTHUR RIVER	-41.054	144.663	20600000	1.423616
599	PEDDER RIVER	-41.405	144.778	1925000	8.367972
569	LITTLE SWANPORT	-42.312	148.000	42800000	22.8564
598	PIEMAN RIVER	-41.667	144.924	38100000	3.432238
596	HENTY RIVER	-42.061	145.251	1475000	3.5008
597	LITTLE HENTY RIVER	-41.949	145.196	650000	1.529424
570	SPRING BAY	-42.549	147.923	51100000	57.49
571	PROSSER RIVER	-42.553	147.881	1900000	0.488752
572	EARLHAM LAGOON	-42.655	147.957	4900000	23.22352
595	MACQUARIE HARBOUR	-42.213	145.219	2975700000	115.345
574	BLACKMAN BAY	-42.845	147.886	258500000	15.8096
575	CARLTON RIVER	-42.877	147.641	14600000	6.51088

576	PITT WATER	-42.849	147.615	149485000	9.23513
594	SPERO RIVER	-42.636	145.335	310000	0.5157186
593	WANDERER RIVER	-42.733	145.387	375000	1.035486
579	DERWENT RIVER	-42.944	147.383	705300000	15.433962
591	LEWIS RIVER	-42.951	145.494	870000	1.0463848
592	MAINWARING RIVER	-42.870	145.436	930000	2.40973
582	ESPERANCE RIVER	-43.341	147.060	197100000	16.653918
581	HUON RIVER	-43.281	147.124	304612000	23.964624
637	STOKES INLET	-33.855	121.136	57850000	13.9944
590	GIBLIN RIVER	-43.067	145.684	340000	0.8601618
583	CLOUDY BAY LAGOON	-43.440	147.202	5850000	45.867
585	SOUTHPORT LAGOON	-43.489	146.982	20120000	46.3315
584	SOUTHPORT	-43.447	146.961	21200000	15.76782
589	PAYNE BAY	-43.298	145.943	42020000	27.736932
588	BATHURST HARBOUR	-43.327	145.984	334100000	29.73836
587	NEW RIVER	-43.554	146.601	24920000	41.6028
639	WELLSTEAD ESTUARY	-34.392	119.399	5120000	20.5811
640	BEAUFORT INLET	-34.472	118.902	13620000	18.9062
641	OYSTER HARBOUR	-35.000	117.949	45850000	1.66343

Estuarine exchange occurs between the estuary and the oceanic cell adjacent to the estuary position. Daily exchange is calculated as 1/residence time and gives the proportion of estuarine volume exchanged per day assuming that the volume of water in the estuary will be replaced completely after the residence time. Movement of water out of and into the estuary occurs at the same rate, determined by the residence time such that the total volume of water in the estuary does not change from day to day. In this way, larvae can both leave and enter an estuary from the adjacent oceanic cell.

Ports

A total of 104 ports[4] in the south east are included in the MSE model. The ports are the nodes for movements of ships. Ports can be either in estuaries (with associated residence times) or in oceanic cells, where larvae can be moved away from the port in oceanic currents (Table 2). Each port included information on the associated vector movements and probabilities.

Table 2 Ports included in MSE model. Estuary ID corresponds to the ID number of an estuary (Table 1)

Port ID Number	Port	Estuary ID
1	ADELAIDE	525
2	AMERICAN RIVER	0
3	ANSON'S BAY	563
4	APOLLO BAY	0
5	ARDROSSAN	0

[4] A list of ports was derived from the Client Place Move (CPM) data from Lloyds Maritime Information Unity (LMIU) from 1998 to 2002 and from AFMA commonwealth fisheries records. A port is defined as any location at which a vessel may be moored or launched.

6	Bairds Bay	535
7	Ballast Head	0
8	Barry Beach	613
9	Barwon heads	617
10	Beachport	0
11	Beauty Point	555
12	Bell Bay	555
13	Bichneo	0
14	Bremer Bay	639
15	Bridport	558
16	Burnie	0
17	Carpenters Rocks	0
18	Ceduna	537
19	Coles Bay	0
20	Corinella	616
21	Cowell	532
22	Devonport	553
23	Dover	582
24	Dunalley	0
25	Eaglehawk Neck	0
26	Eden	77
27	Edithburgh	0
28	Esperance	0
29	Flinders	0
30	Fowlers Bay	0
31	Geelong	617
32	Georgetown	555
33	Grassy	0
34	Hobart	579
35	Inspection Head	555
36	Inverloch	615
37	Kettering	0
38	King Island	0
39	Kingscote	0
40	Klein Point	0
41	Lady Barron	0
42	Lake Tyers	610
43	Lakes Enterance	611
44	Launceston	555
45	Macquarie Hbr.	595
46	Margate	0
47	Marion Bay	574
48	Melbourne	617
49	Mornington	617
50	Nelson	636
51	Nelson Bay	0
52	Newhaven	0
53	Nubeena	0
54	Pirates Bay	0
55	Point Turton	0
56	Pondalowie Bay	0
57	Port Adelaide	525
58	Port Albert	613

59	Port Arthur	0
60	Port Augusta	531
61	Port Bonython	0
62	Port Fairy	0
63	Port Franklin	613
64	Port Giles	0
65	Port Huon	581
66	port kenny	534
67	Port Latta	0
68	Port Lincoln	0
69	Port MacDonnell	0
70	Port Melbourne	617
71	Port Neill	0
72	Port Phillip Bay	617
73	Port Pirie	530
74	Port Stanvac	0
75	Port Vincent	0
76	Port Welshpool	613
77	Port Wilson	617
78	Portland	0
79	Queenscliffe	617
80	Rapid Bay	0
81	Risdon cove	579
82	Robe	0
83	San Remo	617
84	Smithton	0
85	Southend	0
86	Southport	584
87	Spring Bay	570
88	St. Helens	564
89	Stanley	0
90	Stenhouse Bay	0
91	Strahan	595
92	Streaky Bay	536
93	Swansea	0
94	Tamboon	606
95	Thevenard	538
96	Triabunna	570
97	Twofold Bay	77
98	Vivonne Bay	0
99	Wallaroo	0
100	Waratah Bay	0
101	Welshpool	613
102	Westernport	616
103	Whyalla	0
104	Wynyard	546

2.1.2 Vectors

A critical component of this project is the extent to which data are available for the different vectors. Likely vectors for *A. amurensis* were identified at a Joint Commonwealth/State workshop on developing a control plan for *A. amurensis*, held in Adelaide, May 2001 (Table 4)[5]. Vector data for this project were to be collected and mapped in the BRS NHT Project "Focusing Management Action To Reduce Secondary Invasions Of Marine Pests By All Vectors" (Kinloch et al. 2004). While the Kinloch et al. project did identify and rank the important vectors and their characteristics, it did not identify the strength of linkages between nodes. These data could not be used in this model.

[5] http://www.dse.vic.gov.au/dse/nrencm.nsf/9e58661e880ba9e44a256c640023eb2e/ecab8c42702384624a256dea0015c859/$FILE/MayWorkshop.pdf

Table 3 Potential transport/incursion vectors for marine pests (From joint Commonwealth/State workshop on developing a Control Plan for *Asterias,* Adelaide, May 2001, extended for the MACC High Level Group by AFFA January 2003)

Transport Vector	Known or estimated scale of vector activity, (pa)	Relative Risk Posed (Frequency/Volume/ Connectivity/ Viability)	Actual and potential management option[s]	Adequacy/ effectiveness of option[s] (indicative only - for discussion)	Implementation (indicative only, for discussion)	Potential management conflicts of option[s] (indicative only, for discussion)	Generality of assessments to other pest classes (indicative only, for discussion)				Accountabilities (indicative only - for discussion)	
							molluscs	crustacae	algae	polychaetes	Jurisdictional	Who is responsible
Commercial Ships Ballast Water ***International*** ***Coastal***	11,000* 14,000*	High	Exchange, Treatment, DSS, Formatted Risk Matrix (for evaluation by harbour master)	Potentially good but data intensive. Requires port surveys and open access data base May create significant operational cost impacts on coastal shipping & ports	legislation	Cwlth/State jurisdictional issues. Requires balancing of acceptable environmental risk and trade disruption. Treatments may have broader effects than intended	Good	Good	Good	Good	Cmwlth/ State	Shipping industry and ports
Bio-Fouling **hulls, sea-chests, internal systems, etc.** *International* *Coastal*	11,000* 14,000*	High	Certification, (antifouling schedules), Inspections, treatments, Formatted Risk Matrix(for evaluation by harbour master)	Potentially good though this may require improved/other methods for seachests etc. Inspection difficult Requires open access data base.	legislation	Cwlth/State jurisdictional issues Treatments may have broader effects than intended	Good	Good	Good	Good	Cmwlth/ State	Shipping industry and ports

Marine Engineering- 1. **Oil&gas rigs** 2. **Dredges** 3. **Barges** 4. **Pontoons**	? ? ? ?	High High High High	Antifouling, bw exchange/ treatment, local quarantine mgt zones inspection, Formatted Risk Matrix (for evaluation by State agency)	Consistency of legislative backing Antifouling may be ineffective on sedentary vessels Requires open access data base.	legislation or codes of practise	Cwlth/State jurisdictional issues, consistency. Treatments may have broader effects than intended	??	??	??	??	??	Industry sectors and ports
Navigation Buoys		Low	Antifouling, Inspection	Consistency of legislative backing	Codes of practise	Habitat issue, consider with emergency response issues	??	??	??	??	State	States/ports
Recreational yachts & boats 1. International 2. Domestic 3. Racing 4. Trailer sailors	800* ?????? ??? ??????	high high low low	Registration,/inspection protocols, antifouling, cleaning, certification, education, quarantine mgt zoning and monitoring	Consistency of legislative backing Antifouling may be ineffective on sedentary vessels.	Regulation/inspection and protocols or codes of practise, education campaigns	Consistency of state/territory approaches	??	??	??	??	Cwlth State State State	Yachting & recreational sectors
Apprehended illegal entry vessels	??	Limited to specific areas	Inspections, treatments, quarantine, destruction	Actions while under bond difficult	Inspection and protocols	Consistency of approach across jurisdictions	??	??	??	??	Cwlth and State	Responsible Cwlth agencies
Commercial fishing vessels and gear 1.Vessels *Cwlth* *State* 2. Wet nets 3. Traps 4. Holding tanks	 ?? ?? 	 high high high high	Treatments, inspection, exchange, management & quarantine mgt zones, education.	Consistency of legislation Antifouling gear may increase residue risks	Regulation/inspection and protocols or codes of practise, education campaigns	Consistency of state/territory approaches. Variable approaches for vessels and gear	??	??	??	??	Cmwlth and/or State	Fishing sector, ports.

Mariculture Ropes Spat Bags Sea Cages Baskets	??	 High High High High	Treatment, inspection, management & quarantine zones, *National Policy for the Translocation of Live Aquatic Biota* (incl. risk matrix)	Consistency of legislation Antifouling gear may increase residue risks Monitoring and enforcement difficult	Inspection and protocols, Codes of practise	Consistency of approaches across jurisdictions	??	??	??	??			Cmwlth/ State	Responsible agencies and relevant vectors
Aquarium trade	??	Moderate to high	Regulation, education *National Policy for the Translocation of Live Aquatic Biota* (incl. risk matrix)	Consistency of legislative backing Monitoring and enforcement difficult	Inspection and protocols, import regulation, Codes of practise	Consistency of approaches across jurisdictions	??	??	??	??			Cmwlth/ State	Aquarium trade
Live fish trade	??	Moderate to high	Regulation, management & quarantine zones, education *National Policy for the Translocation of Live Aquatic Biota* (incl. risk matrix)	Consistency of legislative backing Monitoring and enforcement difficult		Consistency of approaches across jurisdictions	??	??	??	??			Cmwlth/ State	Live fish trade
Floating Rubbish/Debris		Low	Marpol, education, collection	marginal	In port inspections Education campaigns	Consistency of approaches across jurisdictions	??	??	??	??			Cmwlth/ State	Community(Responsible agencies)
Natural dispersal mechanisms		Variable	Monitoring and clean up activities	Limited to closed systems	In port inspections Education campaigns	Consistency of approaches across jurisdictions	??	??	??	??			Cmwlth/ State	Community(Responsible agencies)
Intentionally introduced or Bioterrorism		Low	Monitoring and clean up activities	??????		Consistency of approaches across jurisdictions	??	??	??	??			Cmwlth/ State	Community(Responsible agencies)
Other?														

* based on AQIS inspection figures and advice of overall port activity from AAPA

Fortunately, complete commercial shipping records are available through Client Place Move (CPM) data from Lloyds Maritime Information Unity (LMIU). CMR Marine Pests has purchased 5 years of Lloyd's data that record all arrivals to Australian ports between 1998 and 2002 for vessel greater than 100 GT. These data provide information on the dead weight, port of origin, port of arrival, probability of exchange, and frequency of exchange for the ports in the south east (Table 2). Information on these variables is input into the MSE model for each port.

The distributions of ship dead weight (DWT) were also calculated from the Lloyds database for vessels operating in southeast Australia. An empirical kernel distribution for each ship type (i.e. Bulk Carrier, Container, General Cargo, Ro/ro, Tanker and Woodchip carrier) was calculated using a Gausian kernel (Silverman 1986). For each vessel leaving a port in the MSE model, a random DWT is calculated using a rejection method (Devroye 1986)on the empirical kernel distribution and assigned to the new vessel. This DWT is used to calculate the ballast water uptake and discharge and the rate of reballasting.

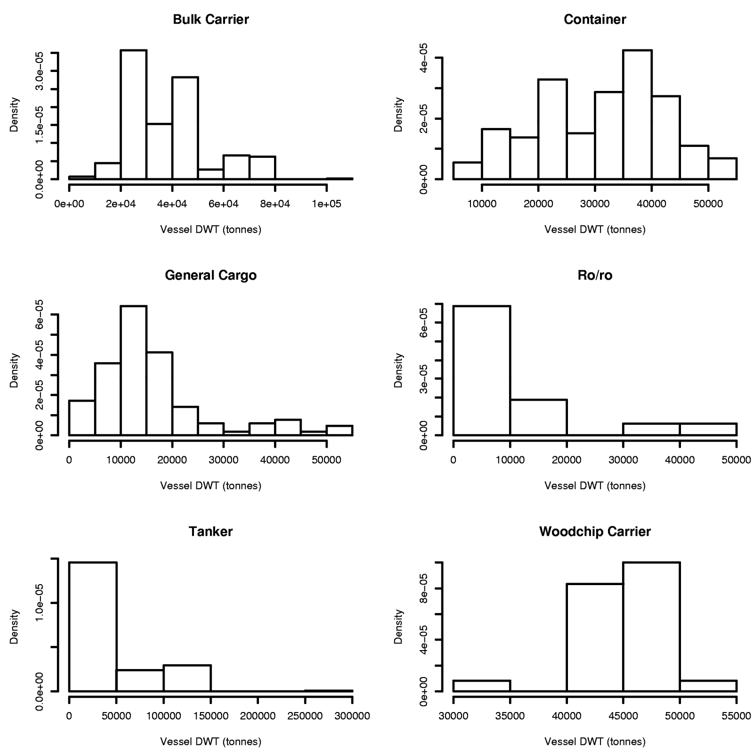

Figure 6. The empirical distributions of ship dead weight

From 1998 to 2001, the Australian Quarantine Inspection Service (AQIS) collected data on the ballast water discharge from international vessels entering Australian ports (Vessel Management System, Australian Quarantine and Inspection Service). This information was used to calculate an expected discharge for each of the ship types (Bulk Carrier, Container, General Cargo, Tanker, Ro/ro, Woodchip carrier). For Bulk Carriers, General Cargo, Tankers and Woodchip Carriers the relationship was:

$$Discharge = m \times DWT^2 + c \times DWT + \varepsilon \qquad \text{eq(1)}$$

where $\varepsilon = PERT(a,b,c,w)$, a pert distribution (modified beta) a = minimum value, b= most likely value, c = maximum value and w = weight of the distribution.

For Container Carriers and Ro/ro the relationship was:

$$Discharge = (m \times DWT + c + \varepsilon)^2 \qquad \text{eq(2)}$$

and ε is distributed as above.

For ports were traffic was high for a particular vessel type, it as possible to calculate values for m, c, a, b, c, w for that particular port for use in the MSE model. However, where traffic was low, values for these parameters are estimated from a generalised relationship calculated across all ship discharges in the AQIS database.

2.1.3 Uptake by vectors

There are limited data available on the uptake of *Asterias* by vectors. Presence of adult *Asterias* on a variety of vectors is the focus of the NHT study being conducted by Victorian DSE[6]. Presence of newly settled *Asterias* on a variety of small vessel and marine equipment is the focus of an ongoing NHT project being conducted by CSIRO. Larval *Asterias* can be picked up in ballast water and a relationship between larval density in the water column and ballast tanks has been developed from the limited data (Figure 6 from Martin and Sutton 2000).

[6] Natural Heritage Trust Project # 35601 – Controlling the Northern Pacific Seastar (*Asterias amurensis*) in Australia

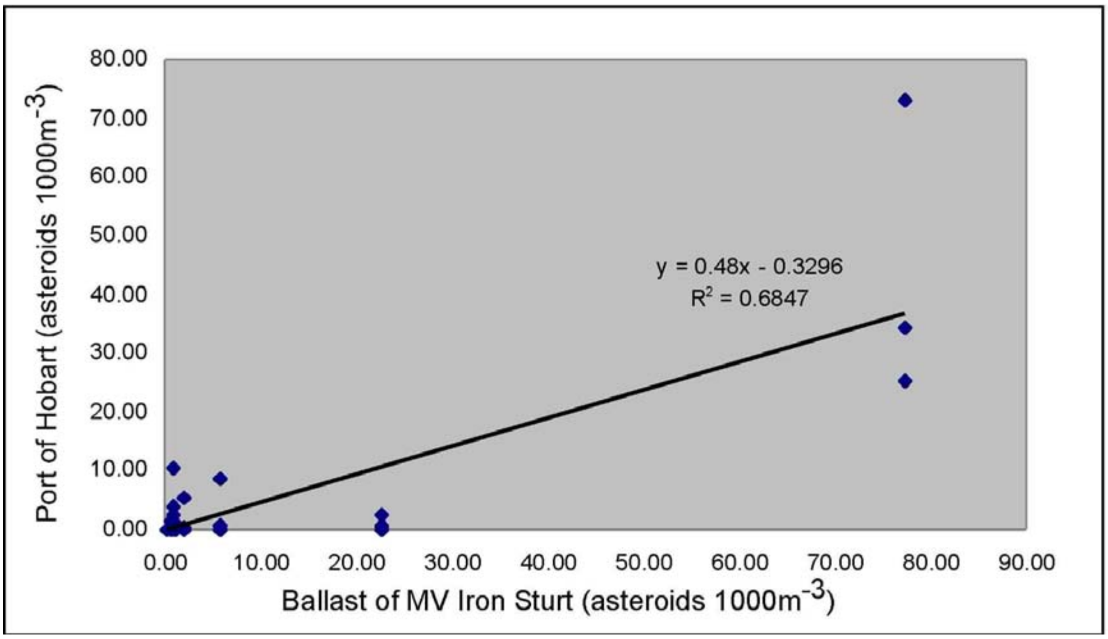

Figure 6 Comparison of the density of asteroid larvae between the Port of Hobart and the ballast tanks of the MV Iron Sturt.

Larvae in the MSE model in oceanic cells and estuaries are distributed as well-mixed particles. Uptake is modelled as a 1:1 proportion of the volume of water to be discharged at the next port to the volume of the estuary in the uptake port (from the OzEstuaries database) or the volume of the oceanic cell to a depth of 10m ($4.84 * 10^9$ m^3). Thus if the ship uptakes 1,000 m^3 of water and the estuary contains 100,000 m^3 with 1,000 larvae, the ship will contain 10 larvae.

Upon arrival at the destination port, 80% of the ballast water is discharged along with 80% of the transported larvae, simulating the behaviour of ships that do not completely discharge all water in their ballast tanks.

2.1.4 Journey survival

There are few data available on the survival of planktonic organisms in ballast water. These data may provide initial estimates or probability ranges given that no *Asterias* specific data are available. However, journey time in the MSE model was between 1 to 2 days, although this may extend on some reballasting options. Over this period, mortality due to extended ship transport is unlikely to vary from the background mortality rate. Thus larval mortality due to journey time is not explicitly modelled here.

2.1.5 Larval retention during reballasting

There are few data available for the retention of *Asterias* larvae (or any other life history stages) by vectors. It is a commonly accepted (though not generally proven) wisdom that 3 times volumetric ballast water exchange will lead to the loss of 95% of planktonic organisms assuming that the larvae are distributed randomly throughout the ballast tanks. *Asterias* was one of the species tested for in the study of Type II errors in the NHT/Victorian EPA Port of Hastings project. Results from that study indicated the presence of *Asterias* in a few ships that had either reballasted or come from areas prior to their last port of call that may have contained *Asterias* larvae.

In the current MSE model, reballasting occurs as described in Rigby and Hallegraeff (1994). It is the perfect situation. The proportion of ballast water exchanged is determined from:

$$Exchange = 1 - e^{\frac{-22 \times 800}{speed \times DWT \times 0.34}} \qquad \text{eq(3)}$$

where 800 is the expected pumping capacity of the ship in m^3/hr (Teresa Hatch *pers comm.*) and 0.34 is the proportion of ship's DWT carried as ballast water.

At the beginning of a journey between two ports, a route is selected according to the ballast water management rules. The route selection algorithm choses the two points closest to each port and then plots a route between them that minimises journey distance but preferentially moves in a direction that satisfies the management rule where possible. In each cell that satisfies the management criteria, a proportion of ballast is exchanged according to eq(3) and the vessel speed. For some management options, the speed of the vessel is varied to ensure that the full 95% is reballasted but in others the speed is held at a constant 13 knots, resulting in an exchange of less than 95%.

2.2 Biological model

The biological model includes:

- a population model of established populations
- availability of *Asterias* for uptake by vectors
- establishment probability

2.2.1 *Population Dynamics in established populations*

The vast majority of larvae entering virgin territory will originate from either the Derwent Estuary or Port Phillip Bay[7]. The dynamics of established populations and the consequent spawning dynamics need to be determined so that the numbers of larvae leaving the Derwent estuary and Port Phillip Bay through natural advection and anthropogenic vectors can be estimated.

In 2000, CSIRO, with help from community groups, held a seastar cleanup around the docks in the Derwent Estuary. Seastars were collected by divers, and the ray length of each starfish (to the nearest 5mm) was measured for a proportion of those collected. This data set provided the best data to assess the growth and mortality of *A. amurensis* in the Derwent. Data on starfish from Belrieve yacht club, CSIRO docks and Kings Wharf were used in this analysis.

[7] See Jenkins, G and Hatton, D 2003. the use of hydrodynamics modelling for the management and early detection of *Asterias amurensis* in Port Phillip Bay and Western Port. Marine and Freshwater Resource Institute No. 58.

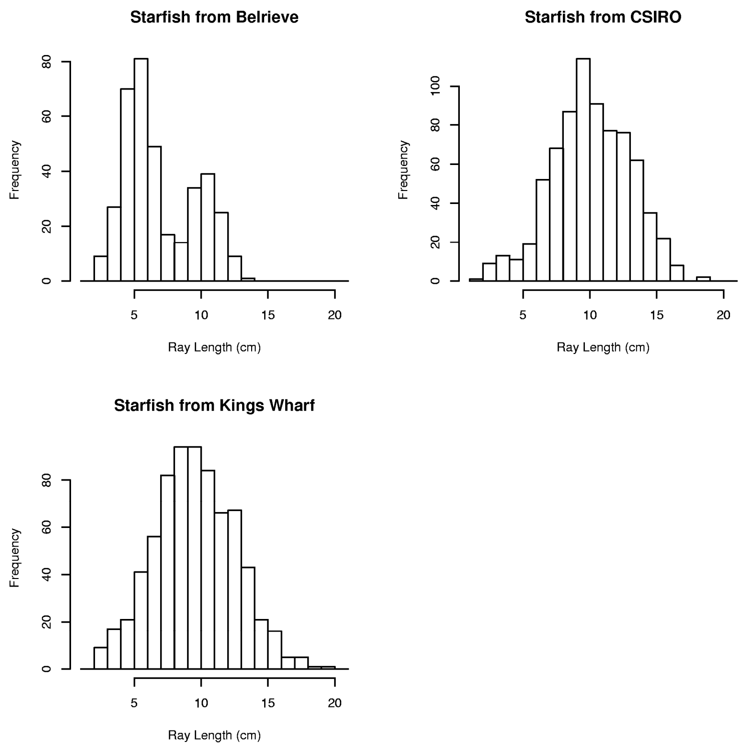

Figure 7 Size Frequency Distributions from three sites in the Derwent Estuary

Only starfish from Belrieve showed multiple modes in the size frequency distribution (Fig.7). It was assumed that starfish in the first mode were up to one year old. It was further assumed that the spread of starfish sizes around the first mode represented varying growth rates. The von Bertalanffy growth coefficient, K,

$$K = \log\left(\frac{L_\infty - l_t}{L_\infty - l_{t+1}}\right) \qquad \text{eq(4)}$$

was calculated for the data in the first mode, limited to a minimum of 3 cm and a maximum of 8.5cm (L_∞ = maximum size, l_t = length a time t, l_{t+1}=length at time t+1). Bootstrapped values of K (1000 bootstraps) were generated from the distribution of sizes in the first mode (Figure 8a). Because the initial data are not continuous (i.e separated into 5mm bins) the distribution of K values is noticeably stepped.

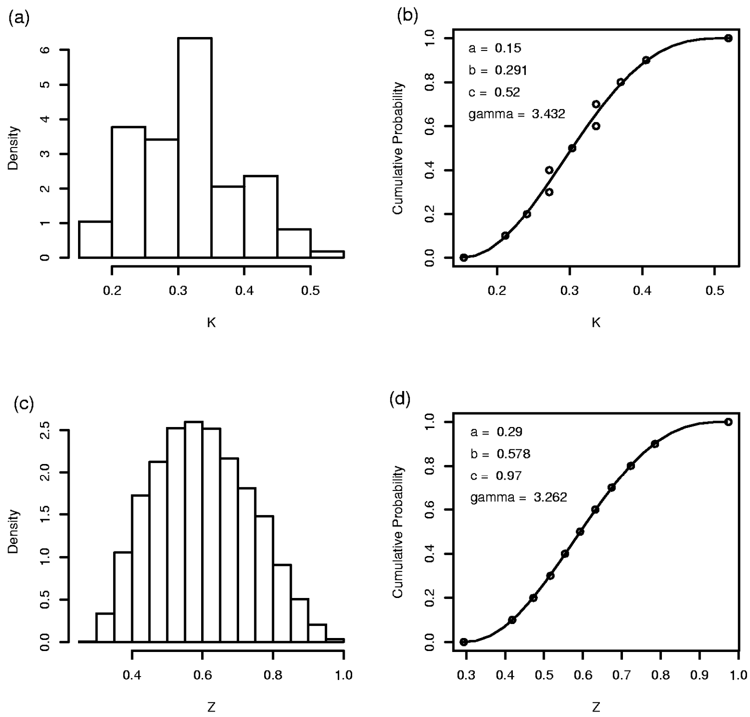

Figure 8. Bootstrapped K and Z values with fitted pert distributions derived from size frequency data. (a) bootstrapped K values; (b) pert distribution fitted to the quantiles of a; (c) bootstrapped Z values; (d) pert distribution fitted to the quantiles of c.

A pert distribution (modified beta distribution), was fitted to the boot strapped K values. The minimum and maximum values were specified (a and c respectively; Fig. 8b) and the values of b and weight (most-likely value and the spread of the distribution) were fitted to the quantiles of the bootstrapped K values. This distribution was then used to define the range of growth rates for *Asterias*.

The dynamics of established populations were modelled as

$$N_t = N_c e^{-Z(t-t_c)} \qquad \text{eq(5)}$$

where N_t is the population at time t, N_c is the population at the time when all individuals will be caught, and Z is the mortality rate. Solving the von Bertalanffy growth equation for age and inserting into the population model yields

$$N(l) = N_c \left(\frac{L_\infty - l}{L_\infty - l_c} \right)^{\frac{Z}{K}} \qquad \text{eq(6)}$$

This equation was fitted against the total size frequency distribution (Belrieve + CSIRO + Kings) with 10000 K values drawn from the pert distribution to yield a distribution of Z values (Fig. 8c). The quantiles of the Z distribution were fitted to values of b and weight from the pert distribution, specifying values of a and c (Figure 8d).

The pert distribution can be used to define the dynamics of established and new populations using equation (5). This approach has many assumptions, but in the absence of any other developed population model and without any additional field data, offers the best estimate of population dynamics.

For an established population N_c must also be calculated. The abundance of Asterias with a ray length > 5.5cm in the Derwent is estimated at 4,000,000 (Ling *et al.* unpublished manuscript). For this population the N_c is the abundance at age 0. Equation (5) can be integrated for starfish between a ray length of 5.5cm (using the mode of the K pert distribution to convert length to age) and an age of 8 years and the result can be optimized by varying N_c and holding all other parameters constant so that the integral equals 4,000,000.

This process is repeated for Port Phillip Bay, assuming that the number of starfish greater than 5.5 cm is 50,000,000.

The abundances for age classes 0 to 8 year, within a specified number of bins in each year can then be calculated by integrating over the inter-bin ranges for all age classes, using the parameters calculated (N_c and Z).

2.2.2 Availability of *Asterias*

There are several dimensions to the availability of *Asterias* to vectors:

Larval availability and production

A. amurensis spawn small pelagic eggs approximately 150µm in diameter that hatch and develop through a series of stages (coeloblast, gastrula, bipinnaria, brachiolaria) typical of asteroids with planktotrophic larvae.

For established populations it is possible to estimate the total number of eggs produced by the population. Each female seastar releases 106000*(0.14*weight (gm) – 2.59) Morris (2002). The relationship between length and weight can be calculated as weight = $e^{0.231*\text{length} + 1.98}$ (taken from Hatanaka and Kosaka 1958). Length can be calculated from age using the pert distribution of K values. Thus, from the population model specified in equation (2), using the pert distributions for K and Z, the total reproductive output of a population (separated into appropriate age classes) can be calculated. Values of Z and K were bootstrapped 5000 times and mean and 95% confidence intervals calculated for the Derwent Estuary. Average total egg output was 3.75×10^{12}. Ling *et al.* (unpublished manuscript) estimated the total number of zygotes produced in the Derwent to be between 1×10^{10} and 9×10^{10}. Given that the expected fertilization rates are between 1-5% for the densities over much of the estuary, these two figures clearly closely correspond, despite their different methods of calculation.

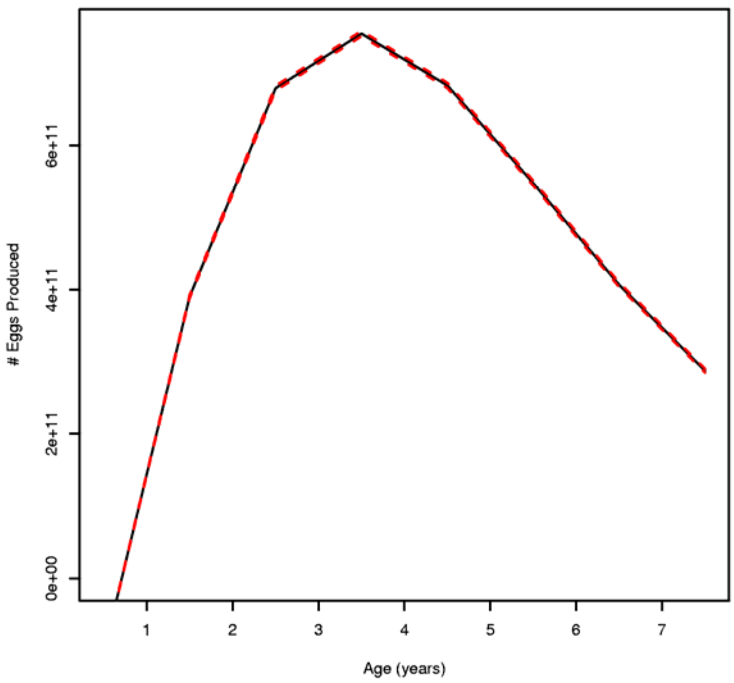

Figure 9 Number of eggs produced by age in the Derwent Estuary

These calculations can be used for other populations, including the existing population in Port Phillip Bay and any new populations that establish in the model.

The density of individuals is critical to determining fertilisation success. The fertilisation success of populations of starfish across different densities has been calculated using a 3-dimensional fertilisation model (Morris 2002 pp. 52). For large numbers of seastars the equation is Fertilisation rate = 0.165 * log(Adult Density) + 0.609.

The most accurate recent survey of densities of *A. amurensis* was reported in Ling *et al.* (unpublished manuscript). In this study, seastar densities were calculated for transects across a range of depths in the Derwent estuary. From these data, the proportion of a population at a particular density can be calculated. As no other comparable density data at such a low scale are available, the density proportions are applied across all estuaries and oceanic cells that contain adult *A. amurensis* populations.

Larval release in the model occurs between 1st July and 15th October each year, with the maximum release occurring on the 15th August. Given that the maximum observed larval period is 120 days, larvae will be present in the model from July to mid February the following year corresponding with predicted larval presence in the Derwent estuary (Bruce *et al.* 1993 and unpublished data).

Asteroid larvae were most common in the Derwent Estuary from June through to March with low densities in April and May (Figure 10). Major peaks in larval density (400-1800 larvae m^{-3}) occurred in early August to late September following the peaks in gonosomatic index reported for adult *A. amurensis* by Byrne *et al* (1997). Minor peaks in larval density (200-300 larvae m^{3}) occurred in November, January and February. Genetic typing confirmed that 97% of the asteroid larvae collected in August were *A. amurensis*. All larvae from September were *A. amurensis*. 54% of the larvae typed in November were *A. amurensis*. In January only 11% were *A. amurensis*. No larvae were typed in June and July, but based on the documented spawning period for Asterias (Byrne *et al* 1997) and our observations of ripe adults from May through to August it is likely that the majority of these larvae were also *A. amurensis*.

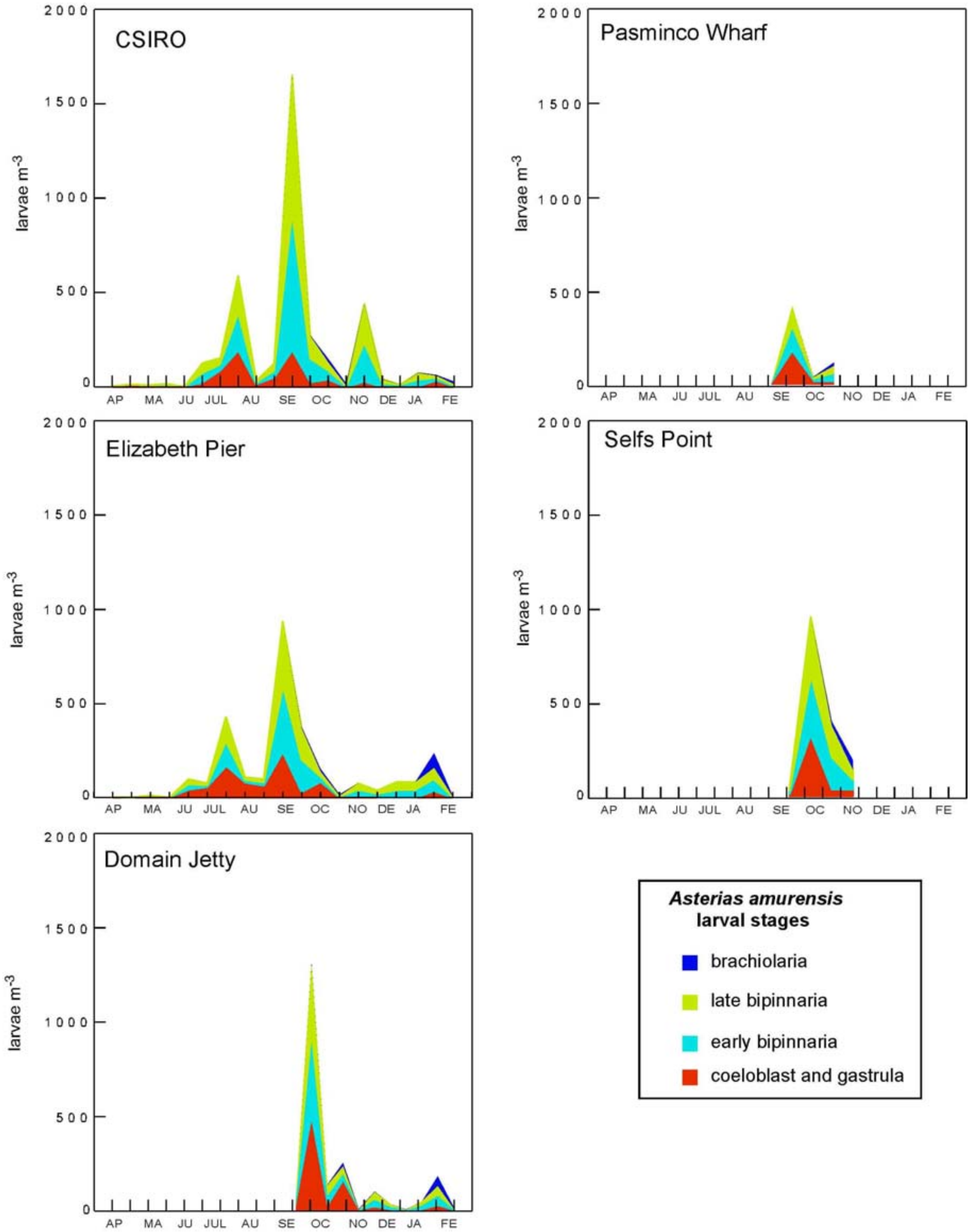

Figure 10 Seasonal distribution of asteroid larvae categorised in four developmental stages at five sites in the Port of Hobart from March 1995 to March 1996.

Larval availability through the season in Port Phillip Bay was determined in the Victorian DSE NHT project (Michaela Dommisse, DSE Victoria, *pers. comm.*)[8]. Vertical haul plankton samples were collected at 3 sites and analysed with the *Asterias* gene probe developed for the NHT/Victorian EPA Hastings Ballast Water Demonstration project. *Asterias* larvae were present in the water column from at least the end of May through the end of October. One of the three replicates from earliest sample from the breakwater at Gellibrand (May 2, 2002) and of the three from Anne Street on the same date tested positive.

Larval Duration

Larval duration in the laboratory was protracted and variable ranging from 95-119+ days at 10°C up to 112 days at 12°C (Table 3, Sutton and Green 1999).

Table 4 Larval duration of laboratory reared *Asterias amurensis* at 10 and 12°C

Developmental stage	**Age in days at 10°C**	**Age in days at 12°C** * Reared by Alice Morris
Eggs and gastrula	2	2
Early bipinnaria	2-15	4-14
Late bipinnaria	15-60	14-79
Brachiolaria	60 -119	79-112

The larval duration appears to be strongly associated with temperature. Bruce *et al.* (1995) examined a range of studies and determined that there was a significant relationship between temperature and larval duration. Larval duration in the *A. amurensis* model is determined as duration = exp(-0.11*Temperature + 5.58). Temperatures are updated with oceanic current in the model and the temperatures in estuaries taken from the temperatures in the adjacent oceanic cell.

2.2.3 Larval Survival And Settlement

The effect of larval mortality (Z_L) on the number of larvae in the model was simulated using the same functional relationship as for adult *Asterias* (eq 5), and was applied on a weekly basis. Once the larvae were competent to settle, settlement occurred in suitable habitat with a probability of S (uniformly distributed R=0,1).

Estimates of larval survival and settlement success are difficult to obtain. Laboratory studies have suggested mortality rates between 83-88% per week (Sutton and Bruce 1996), though extrapolation to natural circumstances is difficult. Likewise, settlement success appears to vary between 0 and 100% depending on the substrate type (Morris 2002) in laboratory studies, but without field validation extrapolation is difficult.

To better constrain the ranges of settlement success (S) and larval mortality (Z_L), a reduced physical model was run on the Derwent estuary and adjacent oceanic cell with a complete population model. The values for larval mortality and settlement success were varied across a range of possible values (0.1<=settlement success<=0.9; 0.001<=larval mortality<=0.2) to determine which combinations of S and Z_L generated a final population closest to the existing

[8] Project # 35601 – Controlling the Northern Pacific Seastar (*Asterias amurensis*) in Australia.

abundances in the Derwent estuary. Larvae were exchanged with the adjacent oceanic cell at the rate used in the full MSE model (retention = 15.43 days). The model runs of 30 years were repeated 50 times and the final populations averaged, for each combination of S and Z_L . The outputted abundances were compared with the existing population size in the Derwent estuary and appropriate values of S and Z_L were selected.

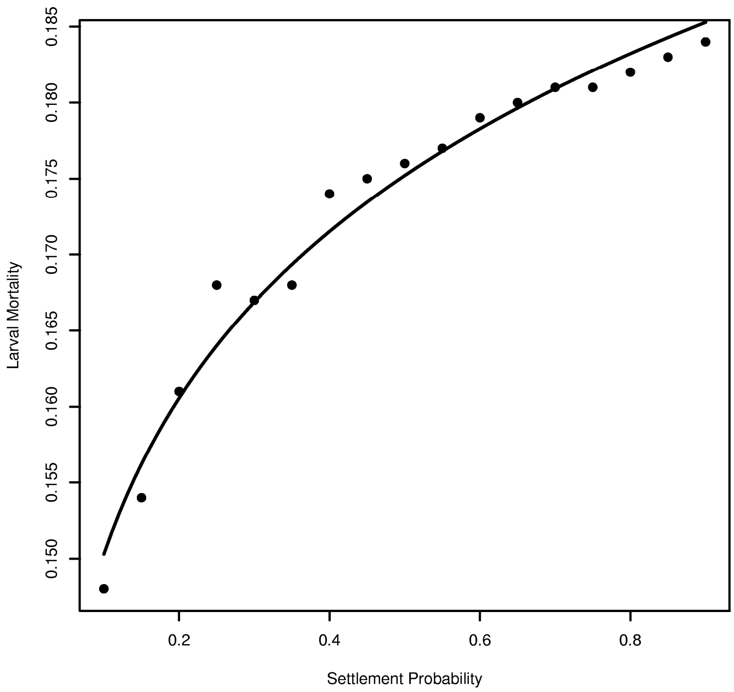

Figure 11 Predicted values of settlement success and larval mortality.

$$Z_L = 0.1872*S^{0.0952}$$

The Derwent population densities were persistent over a range of values of S and Z_L. Three possible combinations of Z_L and S were chosen to explore the effect on the dynamics of the MSE model (Table 5). The MSE model was run with each particular scenario set to explore the impacts that differing larval mortality and settlement has the outcomes of management options. It should be noted that the values of Z_L and S derived here are relative to the fine structure of the model, particularly the estuarine retention rates and may change as this information is updated.

Table 5 Mortality and settlement values used in MSE model

	Larval Mortality	Settlement Rate
Set 1	0.177	0.5
Set 2	0.148	0.1
Set 3	0.184	0.9