Modelling Prawn Larvae Dispersion and Settlement in Spencer Gulf—Management Implications

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FISHERIES RESEARCH & DEVELOPMENT CORPORATION

Project 91/004

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ii Non-Technical Summary

The western king prawn (*Penaeus latisulcatus*) is a commercially trawled pelagic species in Spencer Gulf, South Australia. On a world-wide basis, this fishery is the major producer of western king prawns. It has been valued at approximately $AUD40 million per annum and approximately 90% of the catch is exported.

Trawlers manned by members of the Spencer Gulf and West Coast Prawn Fishermen's Association (SGWCPFA) operate on days of the year predetermined by fisheries management officers at the South Australian Research and Development Institute (SARDI) and are restricted in their efforts in terms of periods open to fishing, numbers of vessels trawling, haul sizes taken, ship and equipment types used, and individual prawn lengths allowed, etc. In order to set these restrictions so as to successfully manage such an economically significant resource, management needs an in-depth understanding of the factors which structure recruitment to nurseries and the fishery. Larval dispersion and the level of reproductive depletion of key spawning areas by fishing are considered by SARDI to be important factors which affect recruitment to the fishery.

At some point in each prawn's life expectancy, it will reach a maximum biovalue. The regime developed by SARDI of sampling and stock harvesting at key areas in Spencer Gulf and during key times of the year has aimed at achieving as close to this maximum as possible. The management of a fish resource becomes in this sense closer to crop or forest husbandry, whereby the producer waits for the best biological and economic conditions to reap the benefits. Strategies can be designed to target best market periods providing that an understanding of the fundamental processes which structure recruitment to the fishery are better understood. Significant economic benefits can thus accrue by allowing prawns to grow to a more valued size, but there is a need to develop harvesting strategies which have stronger biological basis.

The coupling of modelling studies of larval dispersion with empirical field testing will provide a better understanding of the importance of dispersion and other factors which structure recruitment to fisheries. In this Project, rather than attempt a near impossible statistical analysis of expensive field measurements to determine the spread of larvae from known sources to possible destinations, a deterministic mathematical modelling approach was preferred.

A tidal model solves the mathematical equations governing shallow sea motion, using highly specialised numerical techniques, to determine the tidal currents. The model predictions are at much greater spatial and temporal resolution than is economically feasible—and usually physically possible—by field measurement using moored current meters. This model was optimised for maximum performance on a CRAY Y-MP vector supercomputer, in order to determine currents in Spencer Gulf at a temporal and spatial resolution unprecedented in most coastal seas.

Wind-stress was found to have a significant effect on the current regime in the Spencer Gulf region, and thus the larval dispersion therein. With winds and currents accurately specified, it was determined that the choice of numerical technique used to approximate the dispersion process had an equally significant effect on the predictions of prawn larvae movements. The best numerical techniques with which to model larval dispersion were determined by considering a suite of candidate techniques and subjecting them to both mathematical and numerical analyses.

The larval dispersion model solves the mathematical equations governing larval dispersion based on transport in currents produced by tides and winds, diffusion due to small-scale eddy turbulence, and mortality due to predation, etc. It does this using highly specialised numerical techniques, to determine larval concentrations to a spatial and temporal scale chiefly limited only by the accuracy in specification of program inputs parameterising larval biological factors such as the initial patch of fertilised prawn eggs, and the capacities of the computer on which the model is executed.

The initial distribution of eggs fertilised by adults in the larval spawning grounds of the Gulf interior was found to measurably affect the final distribution of postlarvae in the juvenile nurseries along the Gulf coast. It was also determined that postlarval settlement was sensitive to the time interval of the larval dispersion period following spawning.

The results of this Project have shown that the mathematical/numerical modelling approach is qualitatively effective in determining larval dispersion in coastal waters. Results and conclusions were presented in graphical, written, numerical, and computer animated form to various interested parties including the perceived beneficiaries of this research: the fishing industry, fisheries management, and academic communities.

iii Background

There was no background provided in the original application. There were no changes which emerged during the research.

The Project proposal was conceived as an extension of the early works of I'Anson (1989), Wong (1990), and Noye et al. (1992)—all of which were undertaken in consultation with SARDI research officers.

iii.1 Numerical Tidal Modelling

A deterministic larval dispersion model requires information concerning the location and strength of larval "sources" (Gulf-interior spawning grounds) and, provided that the local currents are known to a required degree of accuracy and spatial and temporal resolution, can predict the location and strength of possible larval "sinks" (coastal nursery areas).

In order to determine these currents, either a battery of expensive meters must be placed to record currents at all time periods for which larval dispersion information is required, or the currents themselves can be mathematically modelled. It is the purpose of numerical tidal models, based on the fundamental principles of hydrodynamics, to do just that.

As input to these models the physical characteristics of the region of interest, such as the bathymetry of the sea–bed, the topography of the local coastlines and islands, the strength and direction of prevailing or time- and space-dependent winds, and the sea–surface elevation above mean sea level (MSL) at the boundaries of this region, must all be known to varying degrees of accuracy.

The tidal model then solves the mathematical equations governing shallow sea motion, using highly specialised numerical methods based on finite-difference techniques, to determine the tidal currents and sea–surface elevations to a spatial and temporal scale chiefly limited only by the capacities of the computer on which the model is executed. These variables are output for each computational element in the horizontal plane and, in the case of currents, at as many depth–levels as are required. In either case, the model predictions are at much greater spatial and temporal resolution than is economically feasible—and usually physically possible—by field measurement using tide gauges or current meters, respectively. Such tide–height and tidal current measurements—to any degree to which they are available—can, however, be used to both validate the model (to improve the accuracy of "hindcasts" of past events) as well as to calibrate the model (to also improve the accuracy of "forecasts" of future events). It should be noted that, as part of the solution process, the vertical component of tidal velocity—typically 1/5000 th that of the horizontal components in Spencer Gulf—is also determined.

iii.1.1 Sea Surface Elevation Observations

The tide–height observations are made at numerous ports and other coastal and island locations in the Spencer Gulf region, using tide gauges operating over periods ranging from weeks to years. The collected tidal signals are decomposed into constituent components using tidal harmonic methods (a form of Fourier analysis) to produce tables of amplitudes and phases for tidal constituents whose frequencies correspond to the interactions of sun, moon, and other periodic gravitational effects.

iii.1.2 Tidal Current Observations

Current meters are placed, usually in more open water locations, for similar time periods to the tide gauges discussed in Section iii.1.1. The speed and direction of the recorded current is broken down into north-south and east-west component signals. Each signal is then harmonically analysed separately, in an analogous manner as described in Section iii.1.1 for sea–surface elevations, thus providing measures of the tidally periodic current in the region of interest.

The tidal constituent phases and amplitudes for the two horizontal current components can then be combined to produce what are termed tidal ellipses. These are prescribed by the locus of the end points of a vector mapping out the current for a particular tidal constituent, over the complete tidal cycle pertaining to that constituent, at a particular computational element. The three main characteristics of the tidal constituent ellipse computed for an observational location and it's modelled counterpart—namely the semi-major and semi-minor axis lengths and the orientation of these relative to north/south—can be compared, as can the direction of rotation in time of the vector "around" the ellipse. It is usually these four measures that are used in comparisons, rather than the phases and amplitudes of the respective current components themselves, if only for ease of interpretation.

iv Need

The need, as defined in the original application, is summarised as follows. There were no changes which emerged during the research.

Little detail is known about the strictly larval and (assumed) pelagic phase of the penaeid life cycle as individuals develop from fertilised eggs in open-water (i.e. offshore) spawning grounds to juvenile prawns settling, hopefully, in suitable coastal-water (i.e. inshore) nurseries. Figure iv.1 depicts a

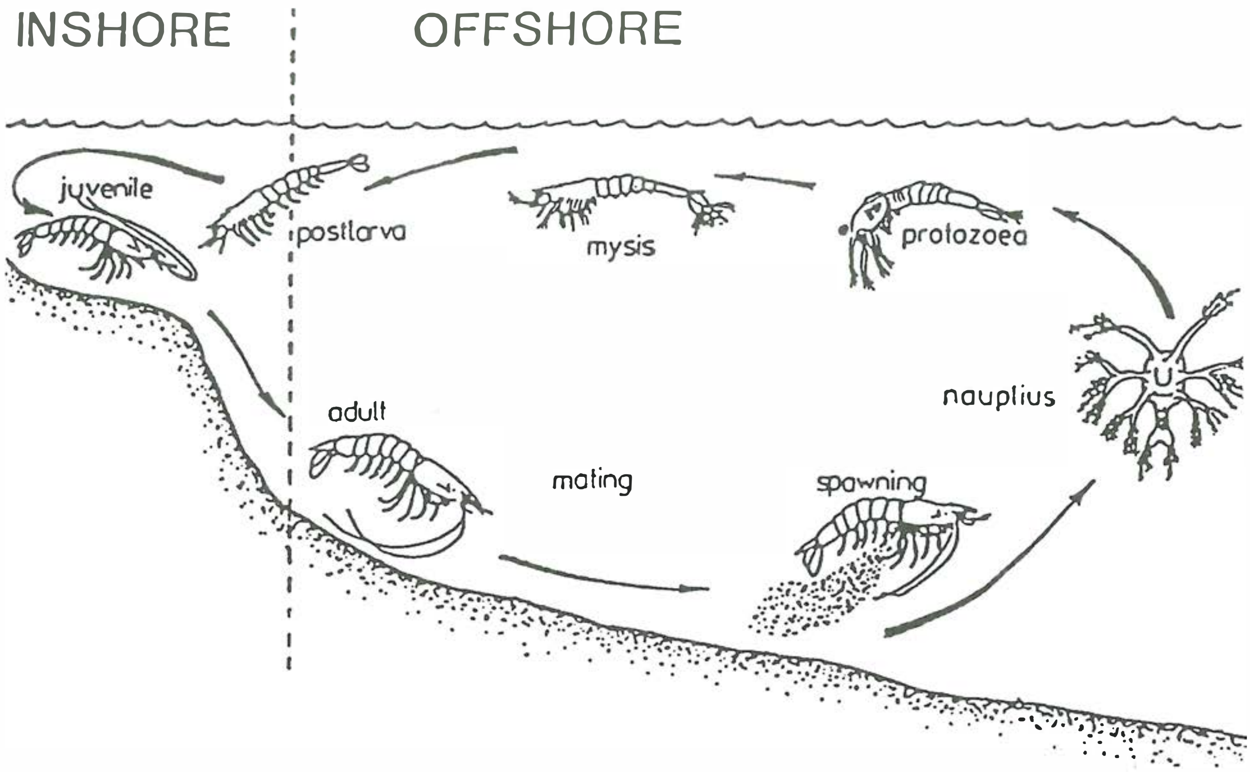
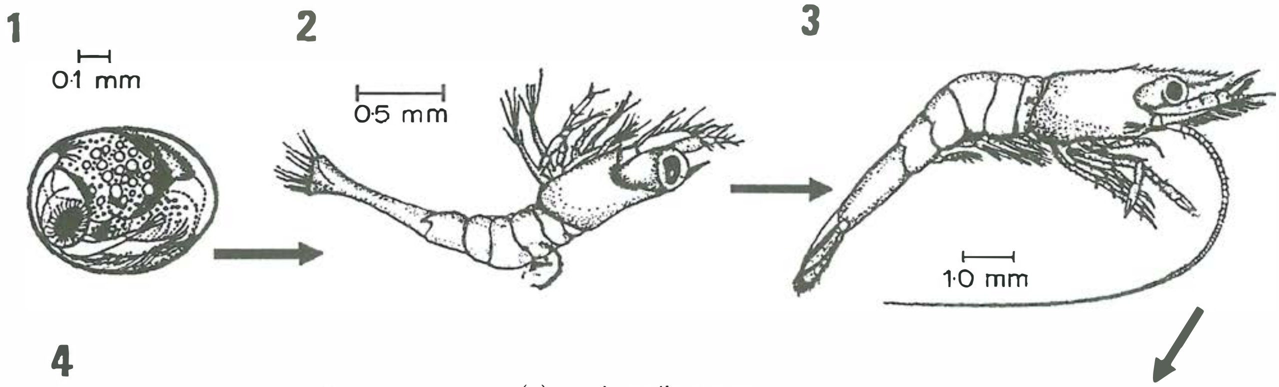


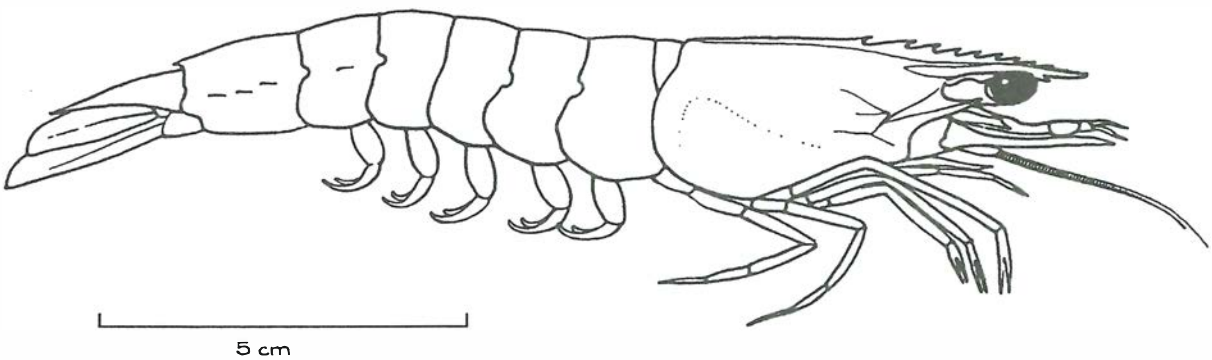
Figure iv.1: A typical penaeid prawn life cycle, showing three larval development stages: (1) nauplius, (2) protozoea, and (3) mysis (original source unknown). The dispersal period with which this Project was most concerned is depicted by the arrows between the spawning–larval, larval–postlarva, and postlarva–juvenile stages. Note that this schematic is not to scale.

typical penaeid prawn life cycle—not to scale.

During this 3–4 wk period of their life cycle the larvae are of such minute size and limited horizontal locomotive ability that they can essentially be considered buoyant passive particles subject to tidal currents, predators, and meteorological conditions. Figure iv.2 depicts typical prawn life stages—to scale. They are, however, of such large spatial distribution and low density that physical tracking or capture is usually difficult and often expensive. Thus, rather than attempt a statistical regression type analysis of field data to determine larval spread from spawning grounds to nurseries in a particular breeding season, a more general deterministic mathematical modelling approach is used here, in which the laws of physics are used to compute tidal currents and hence larval movement.



(a) pre-juvenile stages



(b) post-juvenile stage

Figure iv.2: A typical prawn life cycle. (a) Pre-juvenile: **1** egg; **2** larva; and **3** postlarva (from Wickins 1976, Figure 4, of a cridean prawn, *Macrobrachium* sp.), and (b) Post-juvenile: **4** adult (from King 1980, Frontispiece, of the western king prawn, *Penaeus latisulcatus*).

v Objectives

The objectives as they appeared in the original application were stated as:

> To determine the proportion of prawn larvae which successfully travel, via tidal currents, from off-shore spawning grounds to settle in near-shore nursery grounds, hindcast from a variety of meteorological and tidal scenarios, as represented by known periods in history.

and there were no changes to these original objectives.

The objectives were achieved to an extent commensurate with the quantity and quality of data available by which to make such an assessment.

vi Methods

The methods used in the research are described in the following. There were no changes made during the research from those described in the original application.

vi.1 Model Input Data Requirements

All known bottom bathymetric, coastal topographic, tidal elevation, tidal current, wind vector, and other data pertinent to the tidal model were obtained from sources including but not limited to the Australian Hydrographic Office, the National Tidal Facility (NTF), the Bureau of Meteorology (BoM), and the literature on the tidal dynamics of the Spencer Gulf region.

Figure vi.1 depicts the locations of tidal elevation and tidal current observations sites in the Spencer Gulf region. Figure vi.2 depicts the locations of wind observation stations in the Spencer Gulf region.

vi.1.1 Wind Input Data

A subset of the meteorological data obtained from the National Climate Centre (NCC) at the BoM is depicted in Figures vi.3–vi.4.

It was determined that changes in wind direction and magnitude at the times at which prawn larvae are closest to the sea–surface, and hence most susceptible to the influence of sea–surface wind–stress, were required to be well represented. The wind field input to the tidal model was therefore derived from upper wind data rather than surface wind data, due to the paucity of measurements recorded during non daylight hours in the latter with respect to the former. However, the surface wind data were used to verify the procedure by which surface wind–stress was determined from the upper wind data, both directly (see Figure vi.5 for an example) and using correlation methods (see Figure vi.6 for an example).

A literature review was also conducted of works constituting the available historical record of wind measurements in the Spencer Gulf region. Published observation summaries were related to the data supplied by the BoM as well as the winds derived from these data.

vi.2 The Numerical Tidal Model

The numerical tidal model solves the mathematical equations governing fluid flow in tide and wind driven systems, using highly specialised numerical methods based on finite-difference techniques, to determine the tidal currents and sea–surface elevations to a spatial and temporal resolution chiefly limited only by the capacities of the computer on which the model is executed.

Bills (1991) describes the mathematical/numerical tidal model in detail. This work available in the Public Domain.

vi.3 Tidal Model Calibration and Verification

The tidal model was established and calibrated against tidal elevation records in the Spencer Gulf region. Tidal currents were then validated.

Figure vi.7 depicts the fine grid Spencer Gulf model as used in this Project. Figure vi.8 depicts contours of the Spencer Gulf sea–bed bathymetry, in terms of depth below MSL, as input to the tidal model used in this Project.

Sea–surface elevations simulated by the model at specific computational elements are decomposed in the same manner as discussed in Section iii.1.1, and the amplitudes and phases thus computed are compared with those as supplied by the NTF from tide–height observation stations. From this analysis, a single measure combining the absolute error in sea–surface elevation above MSL (representing an amplification or retardation of the numerical tide with respect to the observed tide), as well as a

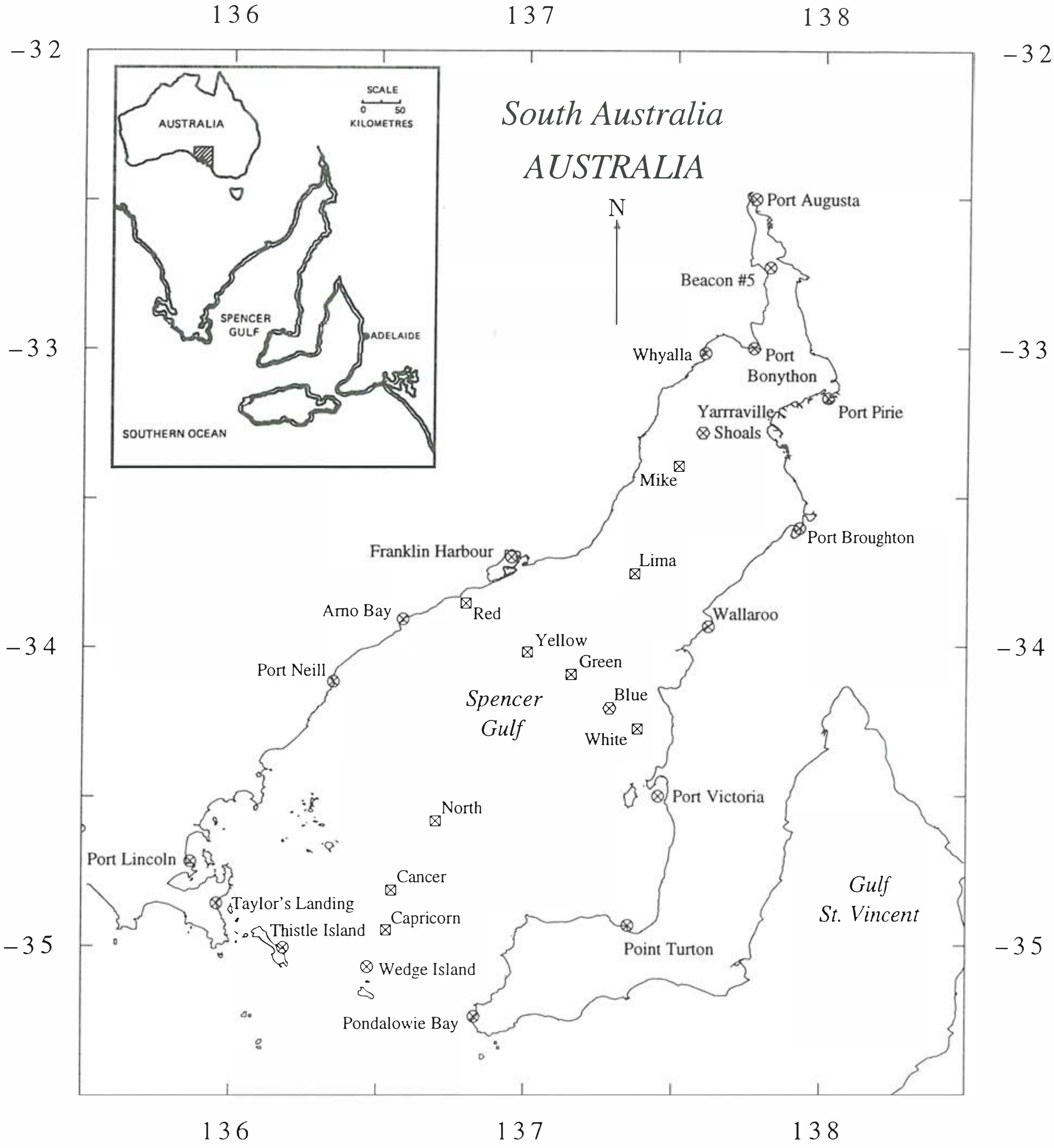


Figure vi.1: Observation stations for tide–height only (crossed circles), tidal current only (crossed squares), and both (crossed hexagons) in Spencer Gulf. Important geographical features (italics) are also shown. The x and y axes indicate longitude (°E) and latitude (°N), respectively.

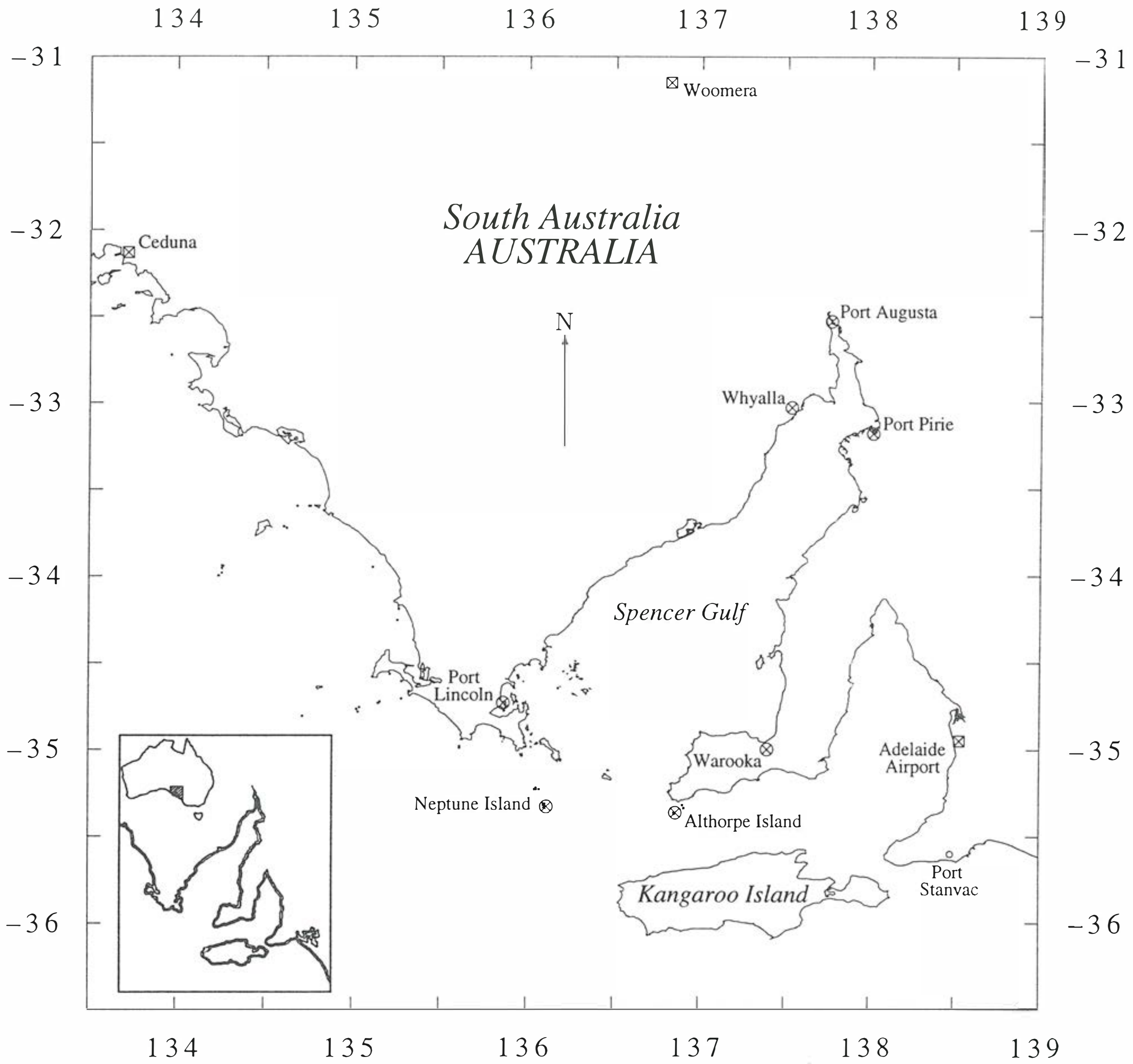


Figure vi.2: Meteorological observation stations for surface (crossed circles) and upper (crossed squares) wind in the Spencer Gulf region. Important geographical features (italics) and places of interest (roman) are shown. The x and y axes indicate longitude (°E) and latitude (°N), respectively.

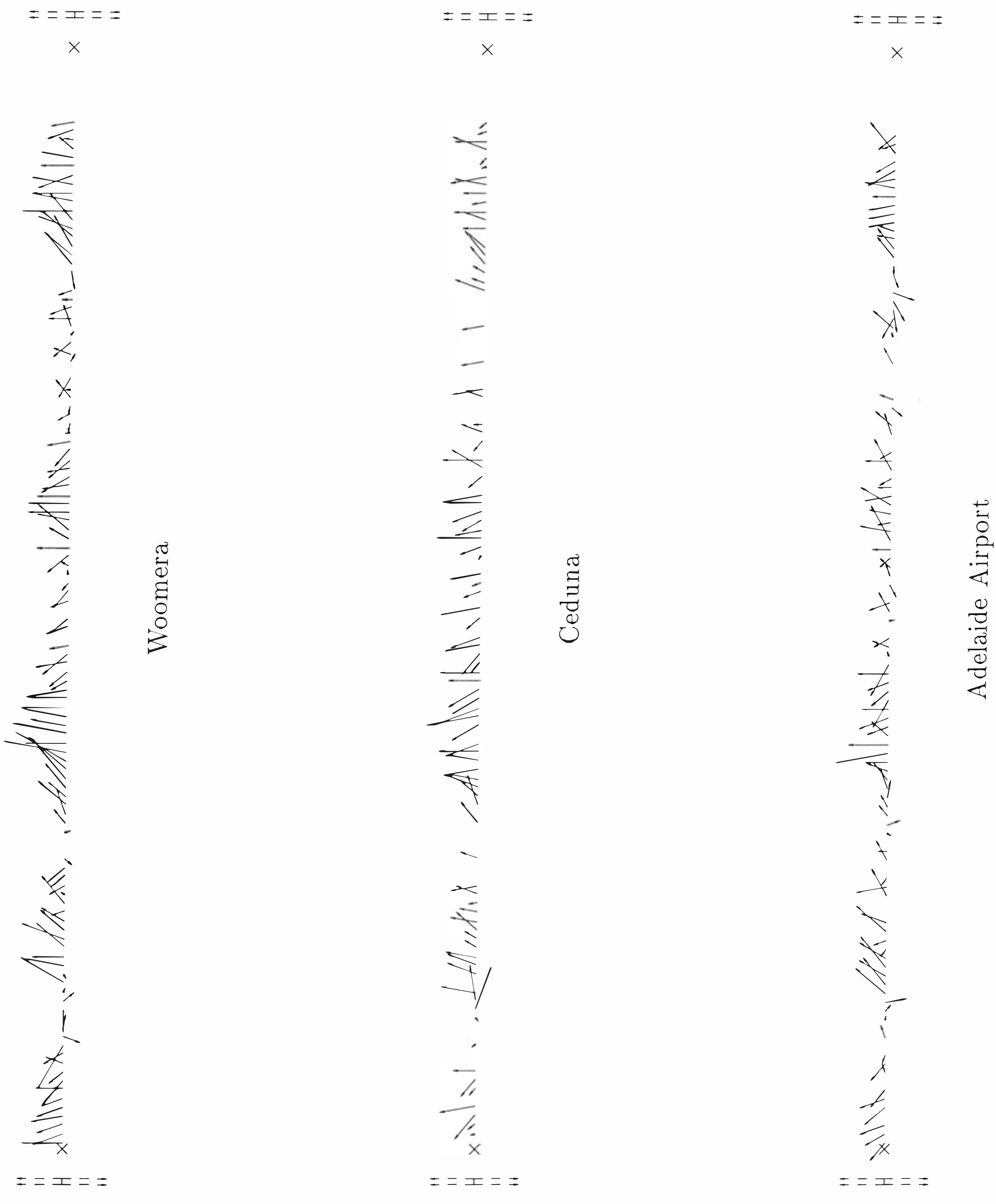


Figure vi.3: Vector time–series of winds measured by the BoM at upper wind stations Woomera, Ceduna, and Adelaide Airport during February 1988. The scale vectors at left and right represent wind speeds of 10 m s^{-1} at a time interval of 4 h directed towards the north (up) and the south (down). The crosses at left and right represent 00:00 hrs on the first of the month and 00:00 hrs 31 d later, respectively. Winds of zero amplitude have no directional arrows and thus appear as dots.

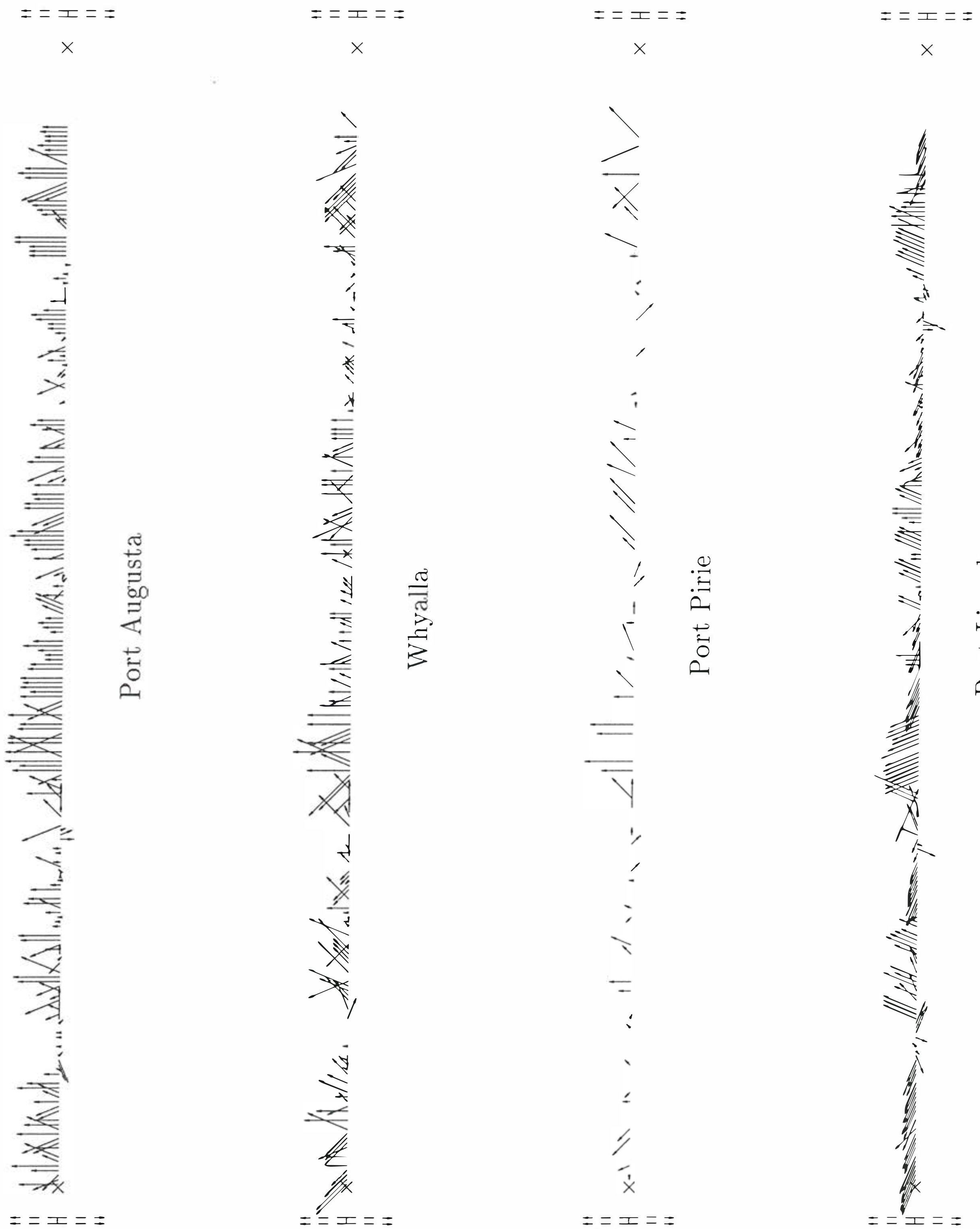


Figure vi.4: Vector time–series of winds measured by the BoM at surface wind stations Port Augusta, Whyalla, Port Pirie, and Port Lincoln during February 1988. The scale vectors at left and right represent wind speeds of $10\,\mathrm{m\,s^{-1}}$ at a time interval of 4 h directed towards the north (up) and the south (down). The crosses at left and right represent 00:00 hrs on the first of the month and 00:00 hrs 31 d later, respectively. Winds of zero amplitude have no directional arrows and thus appear as dots.

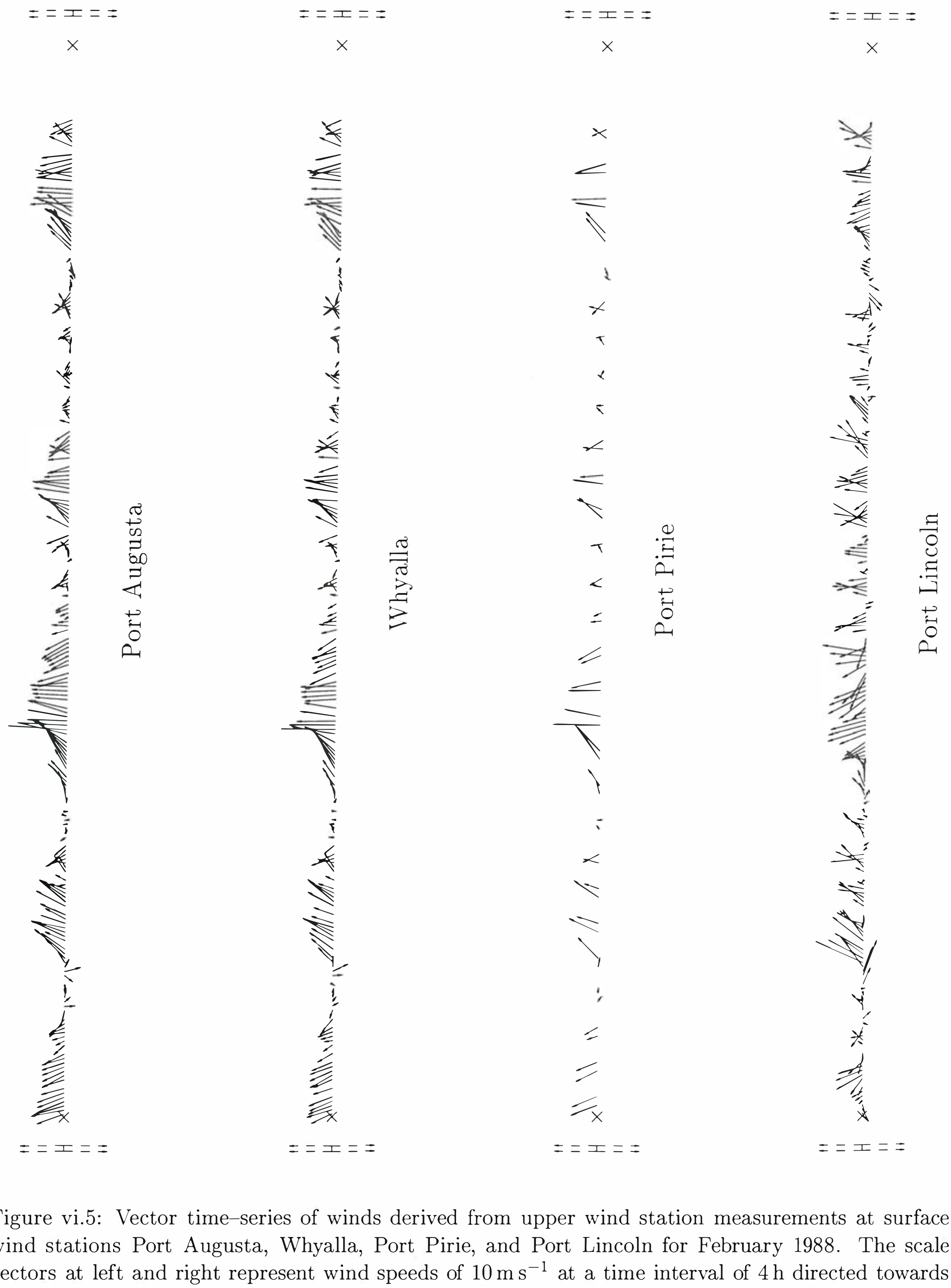


Figure vi.5: Vector time–series of winds derived from upper wind station measurements at surface wind stations Port Augusta, Whyalla, Port Pirie, and Port Lincoln for February 1988. The scale vectors at left and right represent wind speeds of $10\,\mathrm{m\,s^{-1}}$ at a time interval of 4 h directed towards the north (up) and the south (down). The crosses at left and right represent 00:00 hrs on the first of the month and 00:00 hrs 31 d later, respectively. Winds of zero amplitude have no directional arrows and thus appear as dots.

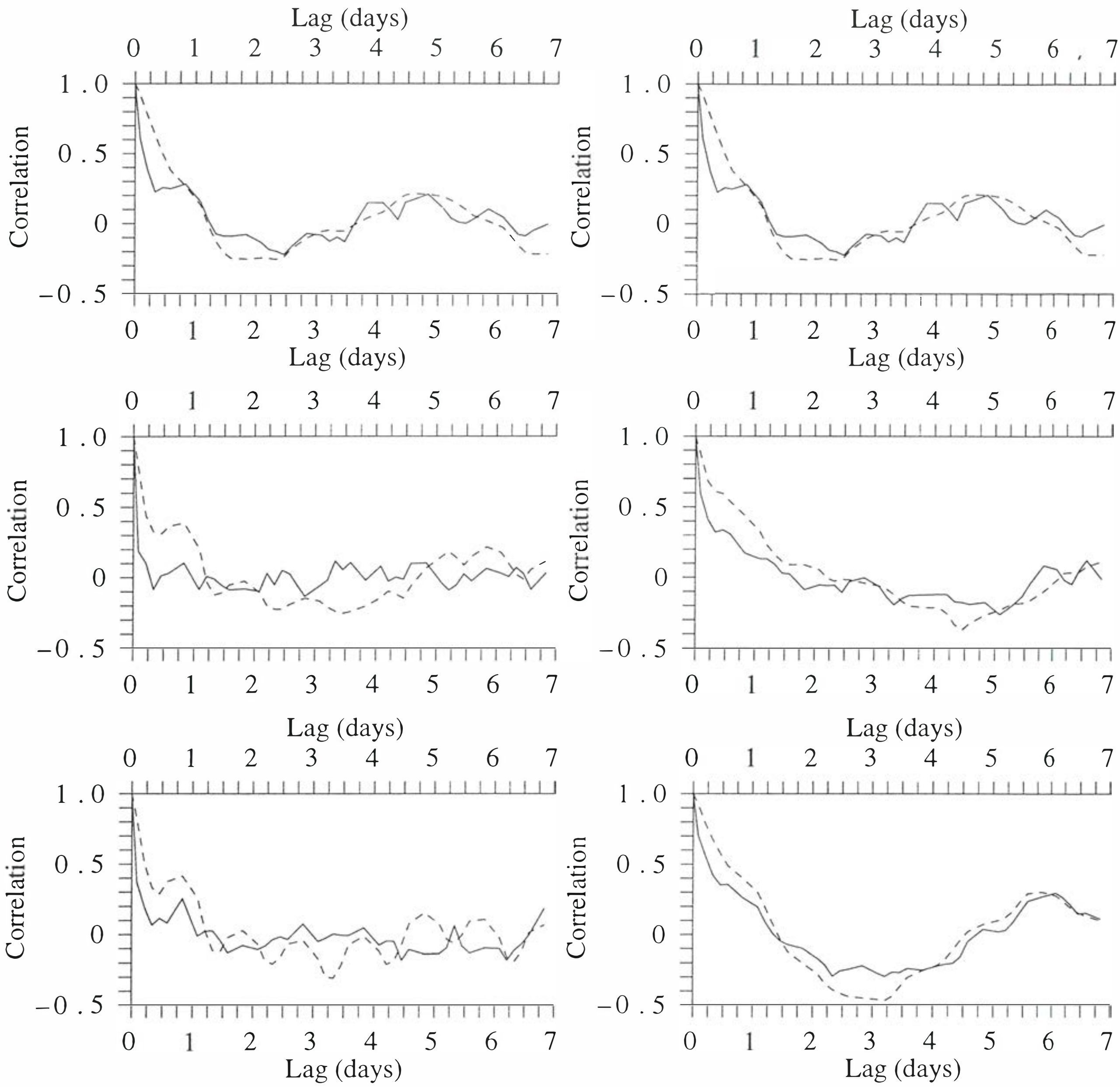


Figure vi.6: Lagged auto-correlations of the E-W (left) and N-S (right) wind velocity components at Whyalla as determined by the surface wind stations data (solid curves) and as derived from the upper wind stations data (dashed curves) for the months December 1987 (top), January 1988 (middle), and February 1988 (bottom).

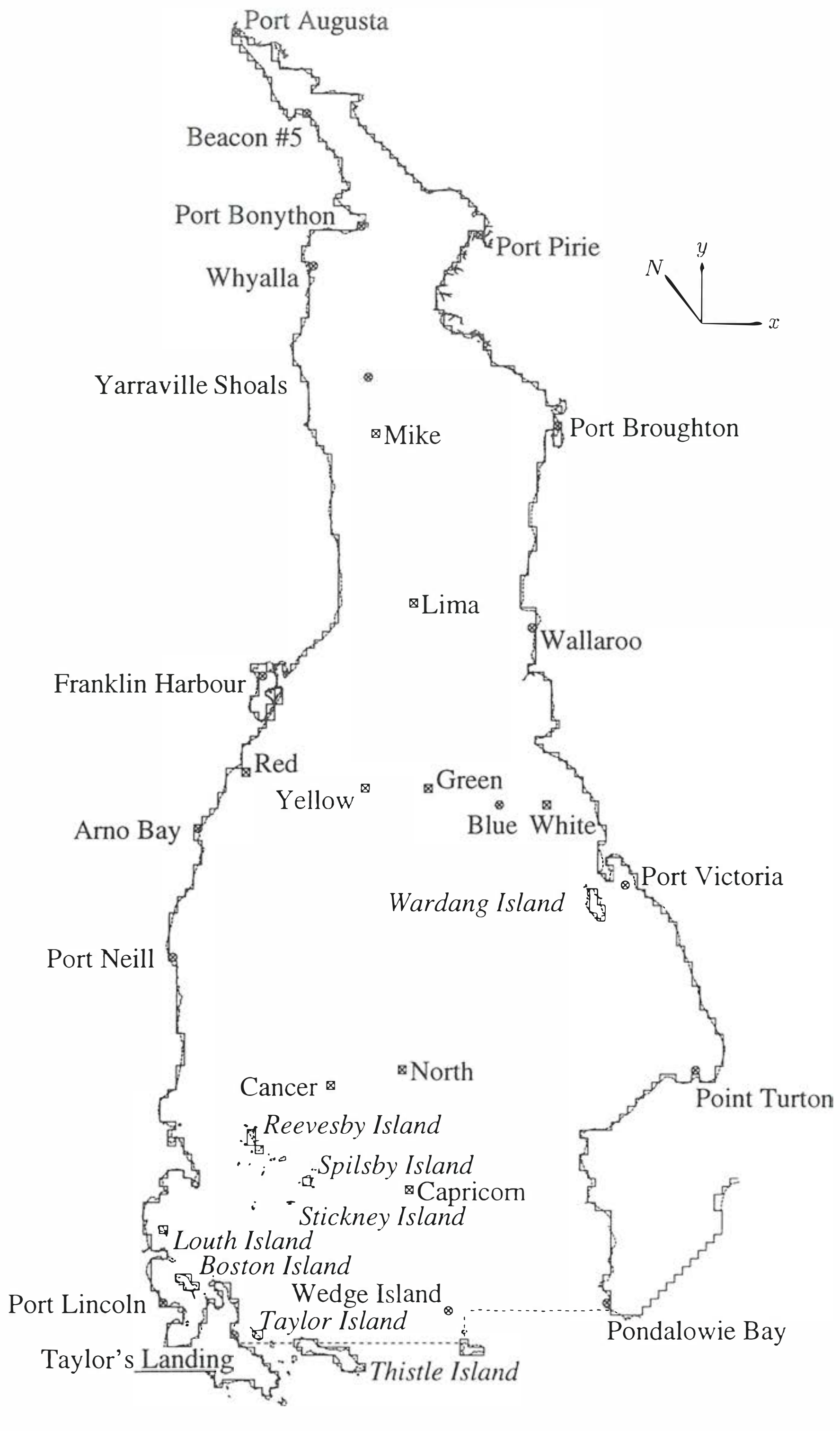


Figure vi.7: The fine grid Spencer Gulf model, indicating the location of the model coastal boundary (solid line) approximating the physical coastal boundary (dashed curve), the model open boundary (dashed line), and the model location of the tidal observation stations for tide–heights only (crossed circles), tidal currents only (crossed squares), and both (crossed hexagons). Stations (roman) and islands (italics) are named.

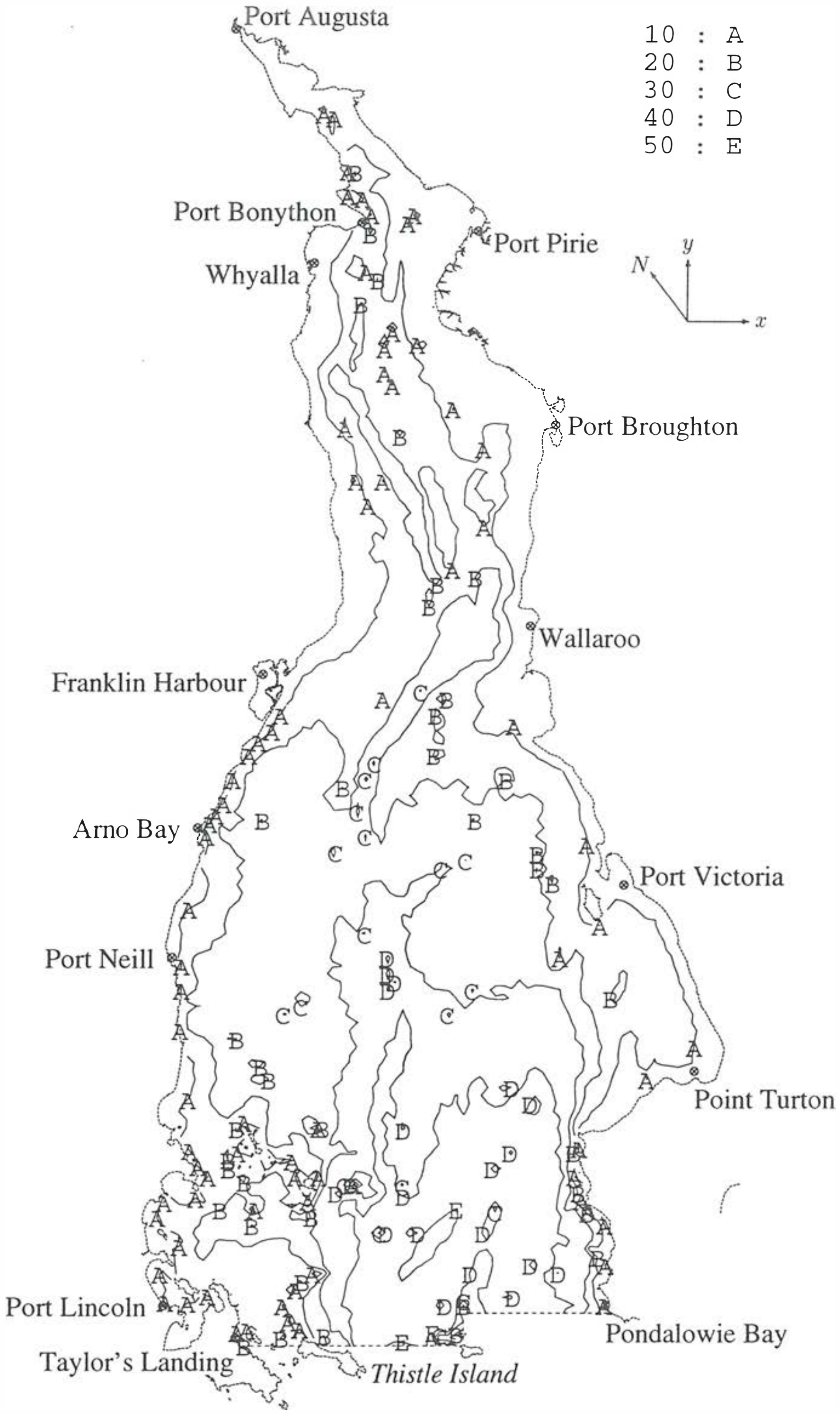


Figure vi.8: The mean sea level depth contours (m) for the fine grid Spencer Gulf model. Some stations (roman) and islands (italics) are named.

relative phase error (representing a time lag or lead of the numerical tide with respect to the observed tide) is deduced.

Similarly, modelled currents are analysed as described in Section iii.1.2 and ellipse characteristics at specific computational elements can be compared with those as supplied by the NTF from tidal current observation stations.

Models developed by the Investigators, including that of this Project, have resulted in predictions of tidal elevation that are in agreement with observations within 4 cm, or equivalently within a 1% margin of error, averaged over the total of approximately 15 tide–height observation stations in the Spencer Gulf region. Tidal currents have also been determined to within an approximate 5% margin of error at over 75% of current observation stations for which data are available in the Spencer Gulf region. These levels of accuracy far exceed expectations of tidal models routinely used worldwide NTF (1995).

vi.3.1 Tidal Current Residuals

Current component time–series are reconstituted from the computed current time–series after Fourier–decomposition into constituent signals with characteristic frequencies corresponding to those of the major tidal constituents used to force the tidal model. Table vi.1 lists these constituents and their

Spencer Gulf Major Tidal Constituents		
Constituent (symbol)	Frequency ($^\circ\,h^{-1}$)	Phase Correction ($^\circ$)
O_1	13.9430355980	356.138
K_1	15.0410686393	10.190
M_2	28.9841042373	6.328
S_2	30.0	0.0

Table vi.1: The major tidal constituents in Spencer Gulf. Listed for each is its Frequency ($^\circ\,h^{-1}$), and Phase Correction (a lag/lead relative to 00:00 hrs on 01/01/1900 at Greenwich Mean Time (GMT)).

characteristic frequencies. Differences between the originally computed components and those reconstituted are averaged over the simulation period and residual currents can then be plotted as vector additions of the two components at each computational grid–point. The residual vectors thus represent the nonlinear interactions of the constituents forcing the tidal model, averaged over the period of interest, and hence indicate bulk mean water movements which are non-periodic in relation to the tidal regime.

It should be noted that since other long period constituents are also accounted for in the tidal modelling by means of phase corrections, as listed in Table vi.1, to the specified amplitudes and phases along the open boundary of the modelled region, the residual circulation obtained is dependent on the time period being simulated. This circulation is also dependent on the inclusion or exclusion of wind–stress and, in turn, on the spatial and temporal variation in wind–stress in the latter case.

vi.4 The Larval Dispersion Model

The larval dispersion model solves the mathematical equations governing larval dispersion based on transport in currents produced by tides and winds, diffusion due to small–scale eddy turbulence, and mortality due to predation, etc. It does this using highly specialised numerical methods based on finite-difference techniques, to determine larval concentrations to a spatial and temporal resolution chiefly limited only by the accuracy in specification of program inputs parameterising larval biological factors such as the initial patch of fertilised prawn eggs, and the capacities of the computer on which the model is executed.

Nixon (1996) describes the mathematical/numerical dispersion model in detail. A copy of this thesis will be made available to the FRDC within three months of it being classified as Passed.

vi.4.1 Dispersion Model Input Data Requirements

Figures vi.9 and vi.10 depict the northern and southern Spencer Gulf spawning grounds, respectively, as determined by the resolution of the fine grid models constructed, and SARDI trawls for pregnant female adults to determine egg production estimates. Table vi.2 relates the numbered spawning

Spencer Gulf Major Spawning Grounds	
Region (number)	Ground (name)
?	Port Broughton
1	*unnamed*
2	Eastern Shoal–Lowly Channel
3	Musgrave Shoal
3	Teardrops
4	Stones
5, 6	Yarraville Basin
7	Middle Bank
8	Wallaroo
9, 13	Gutter
10–12	Cowell
14	Western Gutter
(11)–(12)	Southern Gutter

Table vi.2: The major *Penaeus latisulcatus* spawning grounds in Spencer Gulf, South Australia. Listed for each is its region number (see Figures vi.9–vi.10) and ground name (from Carrick 1982).

regions of these figures to significant spawning grounds as named by the Spencer Gulf fishery.

To formulate, from the available egg production data, initial conditions for the prawn larvae dispersion model, these discrete data were augmented by fitting a thin-plate smoothing spline to a set of control points and then interpolated/extrapolated by evaluating this functional representation on the model finite-difference grid. This was achieved using smoothing parameters chosen by a practical data-driven method for selecting them, known as generalised cross validation (GCV). The GCV procedure results in what is essentially a compromise between data smoothing and data fitting. It should be noted that the units of the SARDI-supplied egg production data input to the prawn larvae dispersion model—"millions per nautical mile" ($10^6\,\text{NM}^{-1}$), and those of the desired prawn larvae concentrations output by the model—"millions per square metre" ($10^6\,\text{m}^{-2}$) are considered in this Final Report to be equivalent.

vi.5 Model Computational Requirements

The physical boundaries required for both the tidal and dispersion models were defined, subject to the position of the known larval "sources" and possible larval "sinks", as determined by SARDI research officers. The model grid-length was thus determined by the desired spatial resolution of the results envisaged, and the computational limitations of the hardware available.

The fine grid Spencer Gulf models required approximately 6,000 computational elements in the horizontal plane and 10 depth-levels in the vertical direction. The horizontal plane was divided into a uniform grid of dimension approximately 2 km each side. The vertical extent was divided up into a non-uniform grid with more depth-levels near the sea-surface and the sea-bed, to better represent

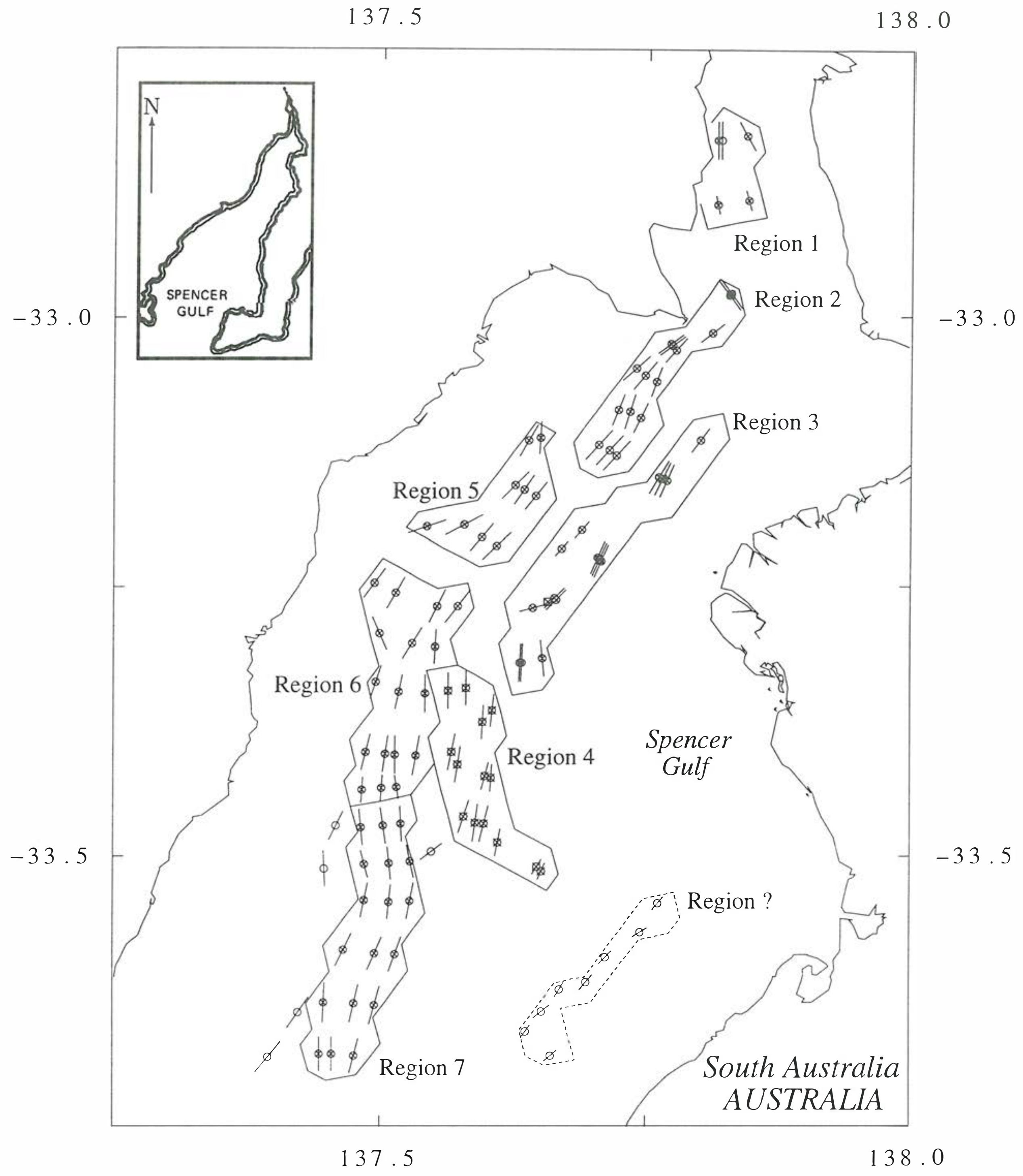


Figure vi.9: Spawning trawl locations in northern Spencer Gulf. Coordinates for locations at which spawning data were supplied, calculated as midpoints of associated endpoints (circles) and derived from midpoints of known locations (squares) are shown. Trawl locations for which data were supplied (crossed midpoints) and for which data were not supplied (hollow midpoints) are differentiated. Region boundaries determined by data availability and fine resolution Spencer Gulf model grid location are also shown. The x and y axes indicate longitude (°E) and latitude (°N), respectively.

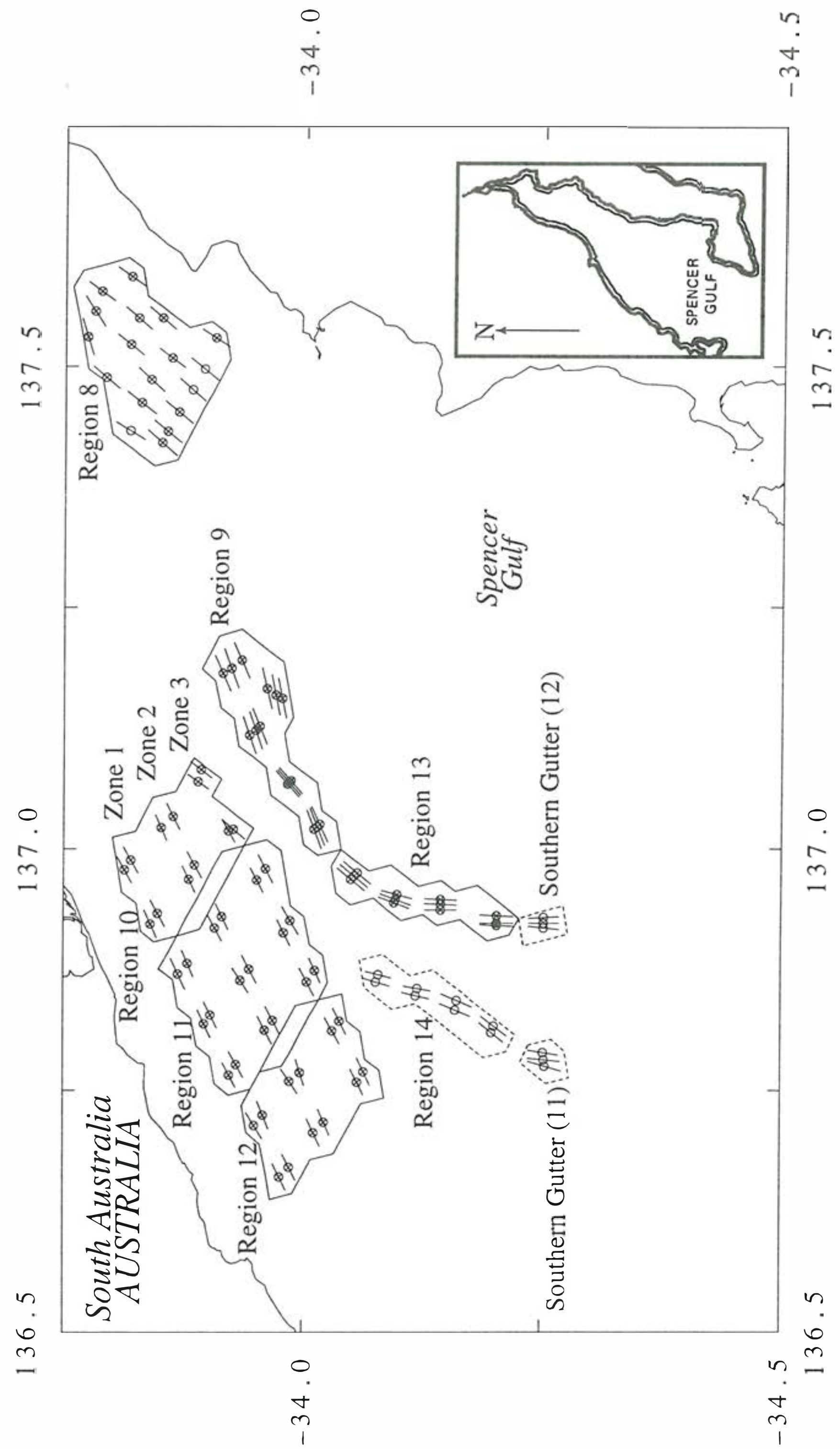


Figure vi.10: Spawning trawl locations in southern Spencer Gulf. Coordinates for locations at which spawning data were supplied, calculated as midpoints of associated endpoints (circles) and derived from midpoints of known locations (squares) are shown. Trawl locations for which data were supplied (crossed midpoints) and for which data were not supplied (hollow midpoints) are differentiated. Region boundaries determined by data availability and fine resolution Spencer Gulf model grid location are also shown. The x and y axes indicate longitude (°E) and latitude (°N), respectively.

the effects of surface wind–stress and bed friction, respectively. The vertical grid is based not on physical depths, but is a relative coordinate so that, independent of overall depth, each horizontal computational element has a fixed number of depth–levels, in this case 10.

This tidal model required approximately 10 central processor unit (CPU) hours to simulate approximately six months of tidal events on a CRAY Y-MP supercomputer.

The corresponding fine grid Spencer Gulf larval dispersion model required approximately 2 CPU hours on a Sun Microsystems SPARCstation workstation, in order to simulate approximately one month of larval activity.

vi.5.1 Computational Facilities Used

Hardware available to the Investigators in the Department of Applied Mathematics at The University of Adelaide consisted of a number of Sun Microsystems SPARCstation workstations (SPARC IPX) and one SPARCstation superstation (SPARC 10). These machines are all multi-user departmental machines and were not available specifically for the research purposes of this Project. Well over 200 CPU hours, worth nearly $1,000,000 were, however, executed on a CRAY Y-MP supercomputer in creating, modifying, testing, and calibrating the fine grid Spencer Gulf tidal model. Of the 10 six-month simulation periods requested by SARDI research officers, each requiring 10 CPU hours to simulate on the CRAY machine, a total of only 4 one-month simulations were found to be suitable for use in the prawn larvae dispersion modelling. Unfortunately, due to a combination of poor choices of simulation periods specified by SARDI research officers, and a paucity of egg production, larval spawning, and postlarval settlement data received for the remaining simulation periods, only 7% of the tidal simulations carried out were thus used in the prawn larvae dispersion simulation results reported.

vii Detailed Results

Detailed results of the research follow. No statistical analyses were undertaken during the research.

vii.1 Tidal Model Numerical Predictions

The tidal model as described in Sections vi.2 and vi.5 produced results to the degree of accuracy discussed in Section vi.3. The sea–surface elevations and depth-dependent currents simulated were thus at least as accurate as, yet at a much greater temporal and spatial resolution than, any previously computed for the entire Spencer Gulf region. The simulations carried out also approximated the tidal dynamics of this region for a much greater length of time (6 mo) than had previously been attempted (1 mo).

vii.2 Dispersion Model Numerical Techniques

The dispersion model as described in Sections vi.4 and vi.5 produced results to a degree of accuracy that has yet to be fully determined, as discussed in Sections vii.3 and x.

The Project determined the best numerical techniques with which to model larval dispersion, by considering a suite of candidate techniques and subjecting them to both analytical mathematical and numerical experimental analyses. These numerical solutions were rigorously compared with exact solutions to problems similar to the one at hand. Idealisations of some physical geometrical aspects were required for the existence of the exact mathematically analytical solutions themselves.

vii.3 Dispersion Model Calibration and Verification

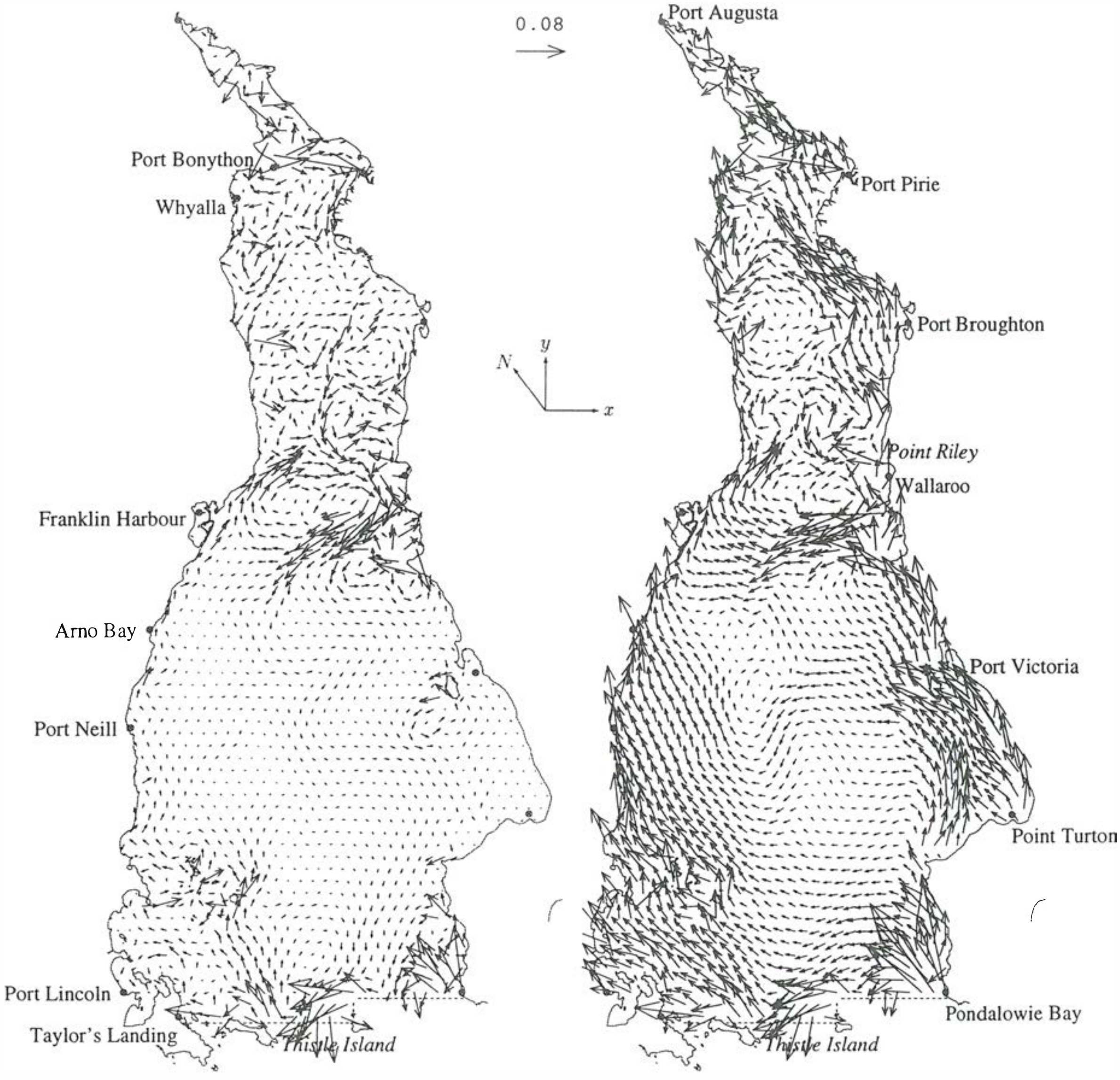
The mathematical and numerical techniques were derived in order to determine if the accurate simulation of larval dispersion was technically possible. It was found that, subject to the availability and accuracy of the initial data supplied (chiefly the temporal and spatial distribution of recently spawned populations), this was indeed the case. It was also found that, subject to the availability and accuracy of the secondary data supplied (chiefly the temporal and spatial distribution of recently settled populations), the model itself could be calibrated in order to improve the accuracy of simulation results.

This calibration process, wherein poorly known input parameters representing model assumptions are improved upon by comparing model predictions with field measurements, ensures that the prawn larvae dispersion model produces the best possible results, subject to the quantity and/or quality of the observational data available. Model variables such as vertical larval migration rates, spatially varying horizontal eddy diffusion coefficients, etc., can be tuned—to varying degrees—on comparison of simulation results with field measurements. Unfortunately data concerning larval dispersion and postlarval settlement were not available within the time-frame necessary for such data to be used for this purpose in this Project.

vii.4 Surface Wind–Stress Sensitivity

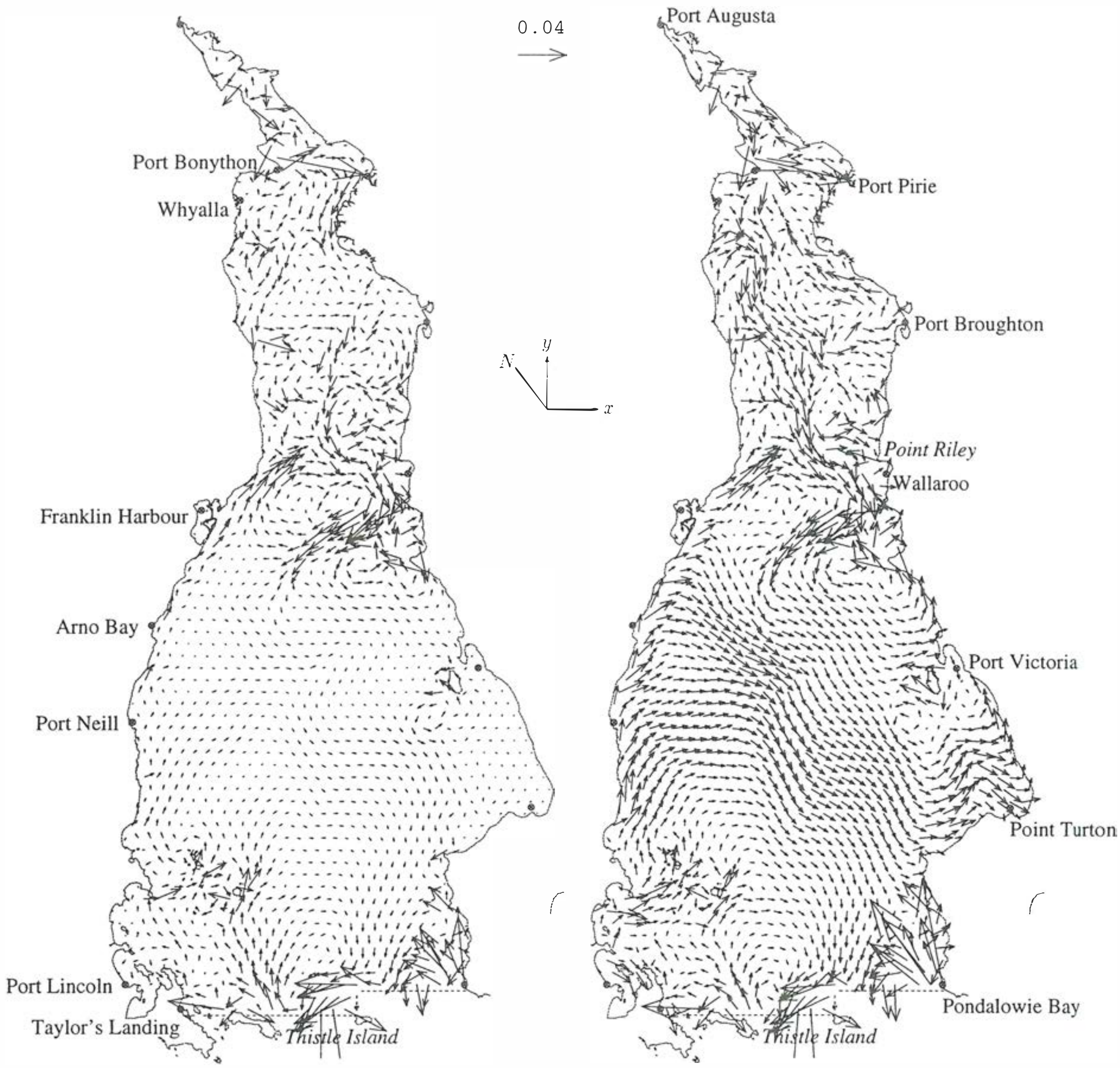
Wind–stress was found to have a significant effect on the current regime in the Spencer Gulf region, and thus the larval dispersion therein. Figures vii.1–vii.2 depict current residuals computed from a subset of the wind–stress scenarios simulated. Details of the mid-northern Spencer Gulf regions are depicted in Figures vii.3–vii.4. Figures vii.1(a)–vii.4(b) indicate graphically the differences in non-tidal currents as generated by the tidal model with zero constant wind–stress specified (i.e. zero wind–stress) and time and space varying wind–stress specified (i.e. non-zero wind–stress).

It was determined that tidal currents in Spencer Gulf are required to be computed taking into account sea–surface wind–stress to the full extent of the known data available for the winds during



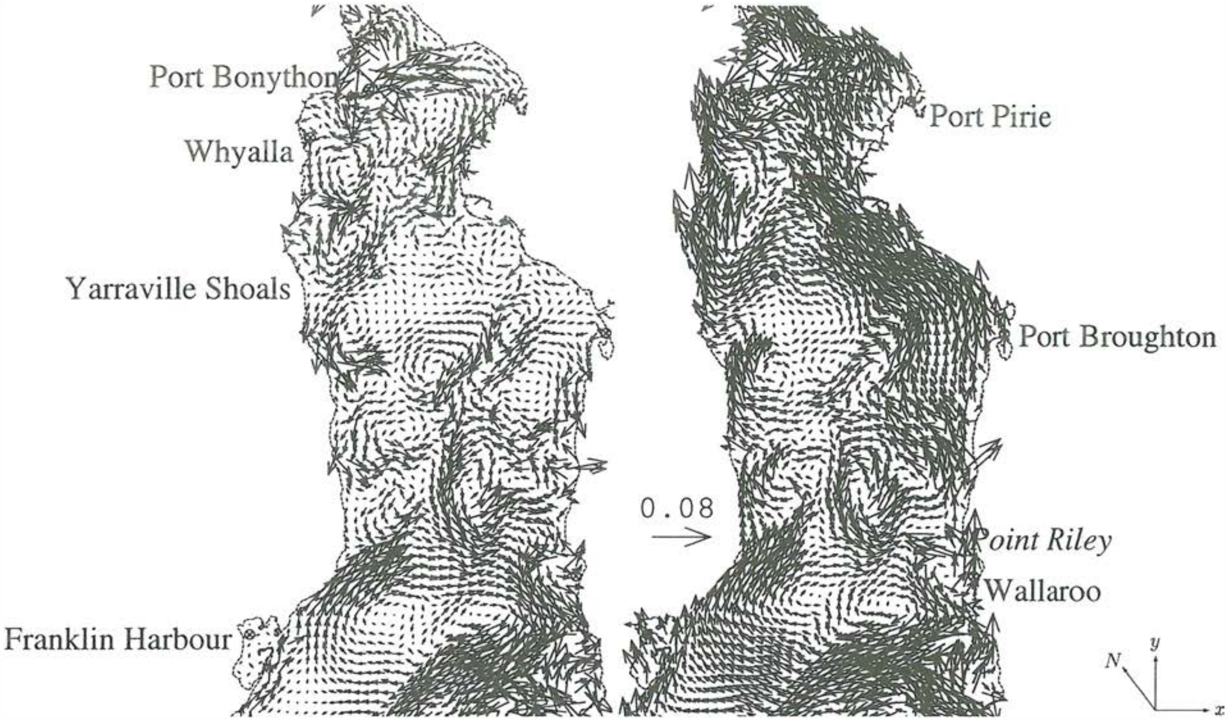
(a) zero wind–stress (b) non-zero wind–stress

Figure vii.1: Spencer Gulf near sea–surface depth–level tidal current residuals ($\mathrm{m\,s^{-1}}$) for the 29 d period from 21:30 February 1 1988. Vectors are plotted for every second computational element in both the x and y directions. Tidal stations (roman) and places (italics) are named.



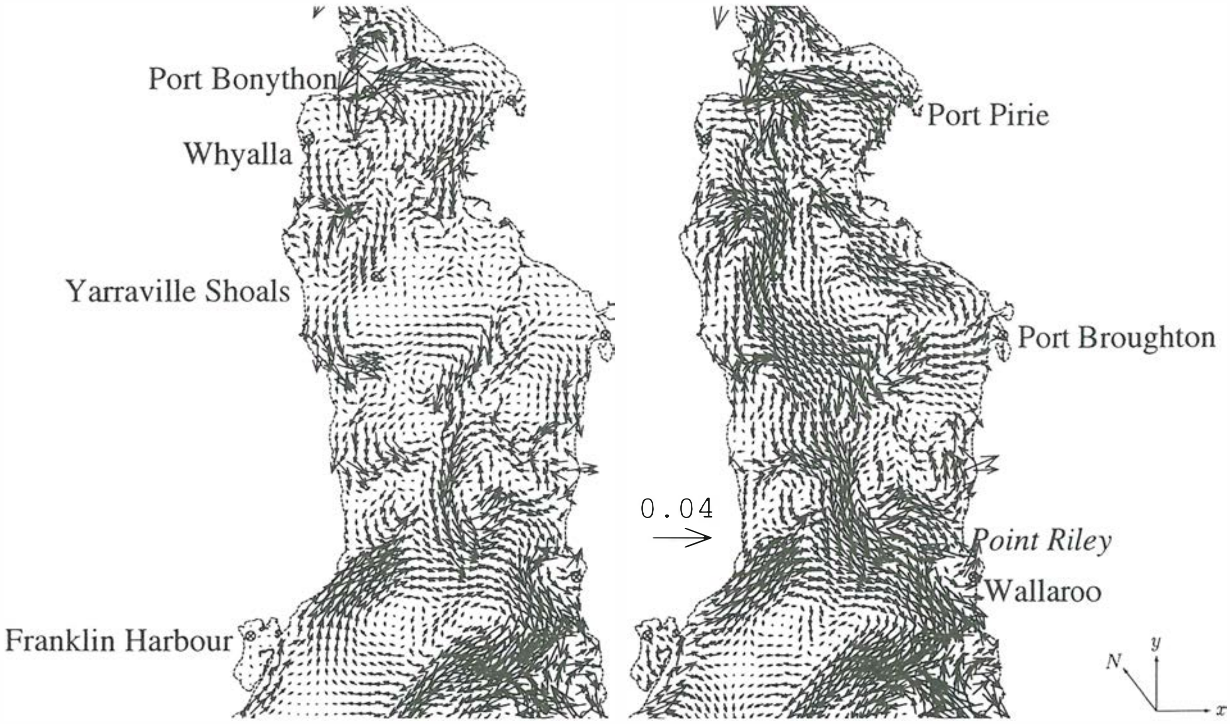
(a) zero wind–stress (b) non-zero wind–stress

Figure vii.2: Spencer Gulf near sea–bed depth–level tidal current residuals ($\mathrm{m\,s^{-1}}$) for the 29 d period from 21:30 February 1 1988. Vectors are plotted for every second computational element in both the x and y directions. Tidal stations (roman) and places (italics) are named.



(a) zero wind–stress (c) non-zero wind–stress

Figure vii.3: Mid-northern Spencer Gulf near sea–surface depth–level tidal current residuals ($\mathrm{m\,s^{-1}}$) for the 29 d period from 21:30 February 1 1988. Vectors are plotted for every computational element in both the x and y directions. Tidal stations (crossed circles) are shown.



(a) zero wind–stress (c) non-zero wind–stress

Figure vii.4: Mid-northern Spencer Gulf near sea–bed depth–level tidal current residuals ($\mathrm{m\,s^{-1}}$) for the 29 d period from 21:30 February 1 1988. Vectors are plotted for every computational element in both the x and y directions. Tidal stations (crossed circles) are shown.

the period of interest. For this reason it was deemed imperative that wind data be obtained, from the BoM or other sources, for the time period of prawn larvae dispersion which is required to be modelled.

Mechanisms relating the spatial form of the initial condition with that of the final concentrations simulated were proposed. These were based on the interaction between characteristics of the initial spawning concentration and the residual currents determined by analysis of the tidal model predictions, assuming a variety of wind specifications.

vii.5 Larval Spawning Sensitivity

It was determined that the results of the model were sensitive to the specification of the initial condition input to represent the larval spawning event occurring at the commencement of simulations. These initial conditions, derived from SARDI field measurements of egg production in the adult spawning grounds, were found to vary from year to year. A suite of simulations in which the initial condition was forced to be the only variable produced results in which measurable differences in postlarval settlement were noted. Mechanisms relating the spatial form of the initial condition for each year with that of the final concentrations simulated were proposed. These were based on the interaction between characteristics of the individual spawning events and the residual currents determined by analysis of the tidal model predictions.

Since field measurements of larval dispersion, postlarval settlement, or juvenile recruitment corresponding to any of these spawning events were not available, quantitative error measures could not be determined and were thus not reported.

An initial condition representing an "typical" spawning event was derived by calculating an "average" from those representing the individual spawning seasons sampled in SARDI field surveys. This "average" initial condition, illustrated in Figure vii.5, was derived by means of a region by region average of the 1988 and 1991–1994 initial conditions, constructed as described in Section vi.4.1.

In Figures vii.5 and vii.6 level curves representing larval concentration are marked by solid curves. The fine grid Spencer Gulf model open boundary is marked by a coarsely dashed curve. Grid orientation with respect to latitude and longitude is represented by the compass at bottom right. Horizontal transects—at bottom left—are along the line $y = constant$ through the grid–point of maximum concentration, with the x–axis corresponding to distance (m) from the left hand coastline and the y–axis corresponding to larval concentration ($10^6\,\mathrm{NM}^{-1}$ or $10^6\,\mathrm{m}^{-2}$). Vertical transects—at top right—are along the line $x = constant$ through the grid–point of maximum concentration, with the y–axis corresponding to distance (m) from the top edge coastline and the x–axis corresponding to larval concentration ($10^6\,\mathrm{NM}^{-1}$ or $10^6\,\mathrm{m}^{-2}$). The tidal observation stations of Figure vi.1 are indicated for positional reference. In Figure vii.5 the actual Spencer Gulf coastline is marked by a finely dashed curve, as are islands in the Gulf. In Figure vii.6 the modelled Spencer Gulf coastline is marked by a series of solid straight line segments, as are the islands represented in the modelled Gulf.

vii.6 Dispersion Period Sensitivity

Simulations determined that the results of the model were sensitive to the time interval specified to represent the larval dispersion period following the spawning event. Figure vii.6 depicts concentration contours representing postlarval distributions resulting from one such simulation.

A baseline dispersion period of 29 d was determined from the literature on larval biology and discussions with SARDI prawn biologists. Analyses of both larval concentration time–series over this entire period at individual locations, and larval concentration trends at individual time-points within this period at strategic groups of locations were carried out. The individual locations chosen corresponded to sample sites at which SARDI field measurements of larval concentrations have been made. The strategic groups chosen corresponded to combinations of both east-west (E-W) and north-south (N-S) transects as defined by SARDI from these individual sample site locations. Figure vii.7 depicts

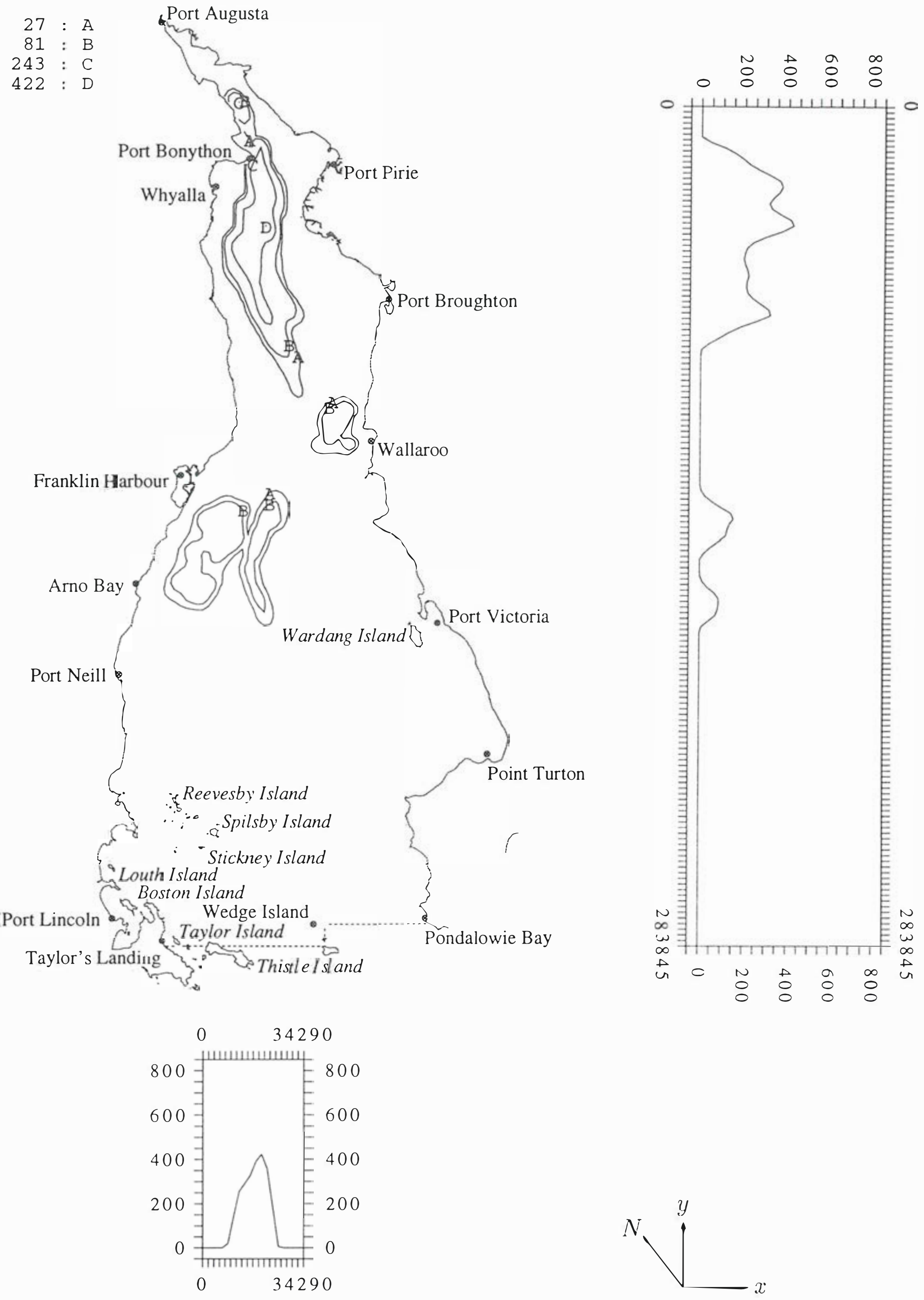


Figure vii.5: The "average" initial concentration (10^6 NM^{-1}) level curves (top left), and transects vertically (top right) and horizontally (bottom left) through D (south of Whyalla). Tidal stations (crossed circles), islands (italics), and closed (solid lines) and open (dashed lines) boundaries are also shown.

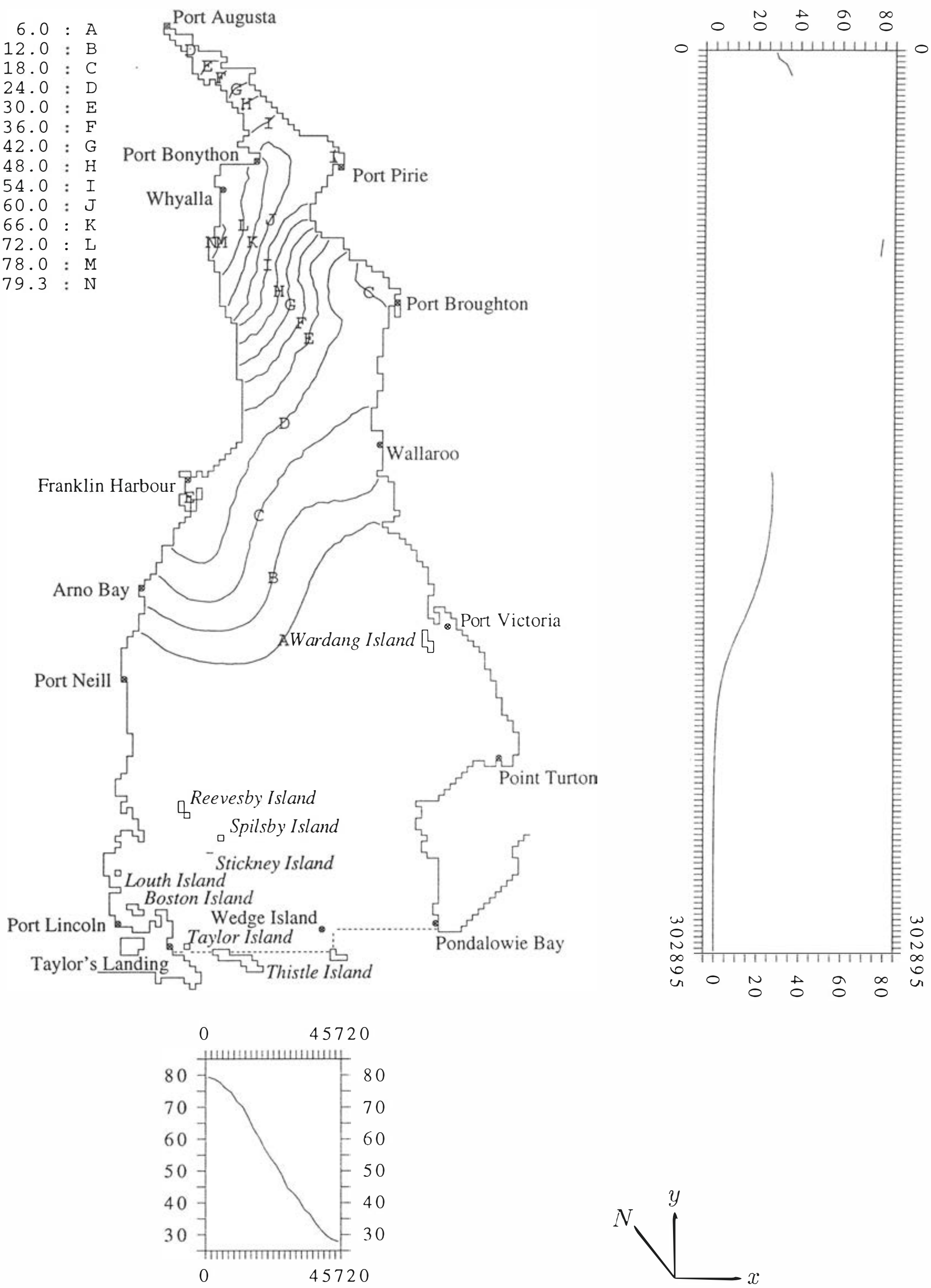
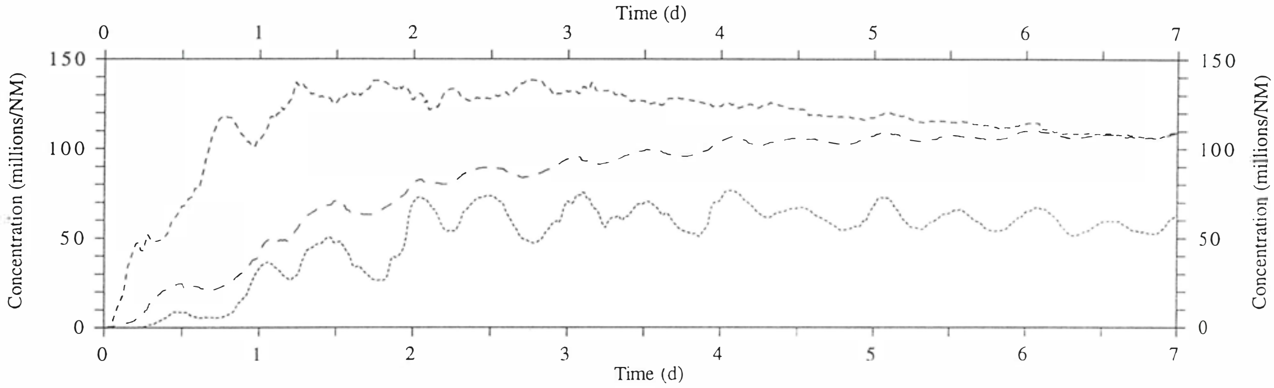


Figure vii.6: The 21:30 01/02/88–21:30 01/03/88 dispersion period simulation larval concentration ($10^6\,\mathrm{m}^{-2}$) level curves (top left), and transects vertically (top right) and horizontally (bottom left) through N (south-west of Whyalla). The "average" initial condition was used. Tidal currents calculated with wind–stress were used. Zero larval mortality was assumed. Tidal stations (crossed circles), islands (italics), and closed (solid lines) and open (dashed lines) boundaries are also shown.

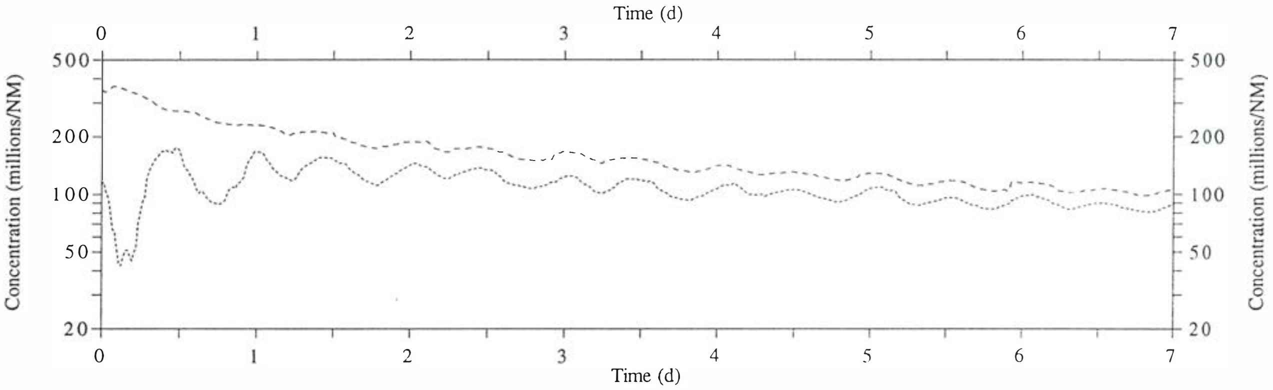
Figure vii.7: Prawn larvae observation stations (crossed squares) in Spencer Gulf, South Australia. Important geographical features (italics) and places of interest (roman) are also shown. The x and y axes indicate longitude (°E) and latitude (°N), respectively.

the locations of these sites and transects. The SARDI-defined transects run approximately east-west, and site numbering is of the form "*number = transect.station*".

Time–series analyses were carried out for two dispersion events with time intervals corresponding to both the earlier (i.e. mid-December) and later (i.e. January/February) of two peaks in spawning activity observed in Spencer Gulf during the summer season. Figure vii.8 depicts some week-long



(a) Station 1 (coarse dash), Station 2 (medium dash), Station 5 (fine dash)



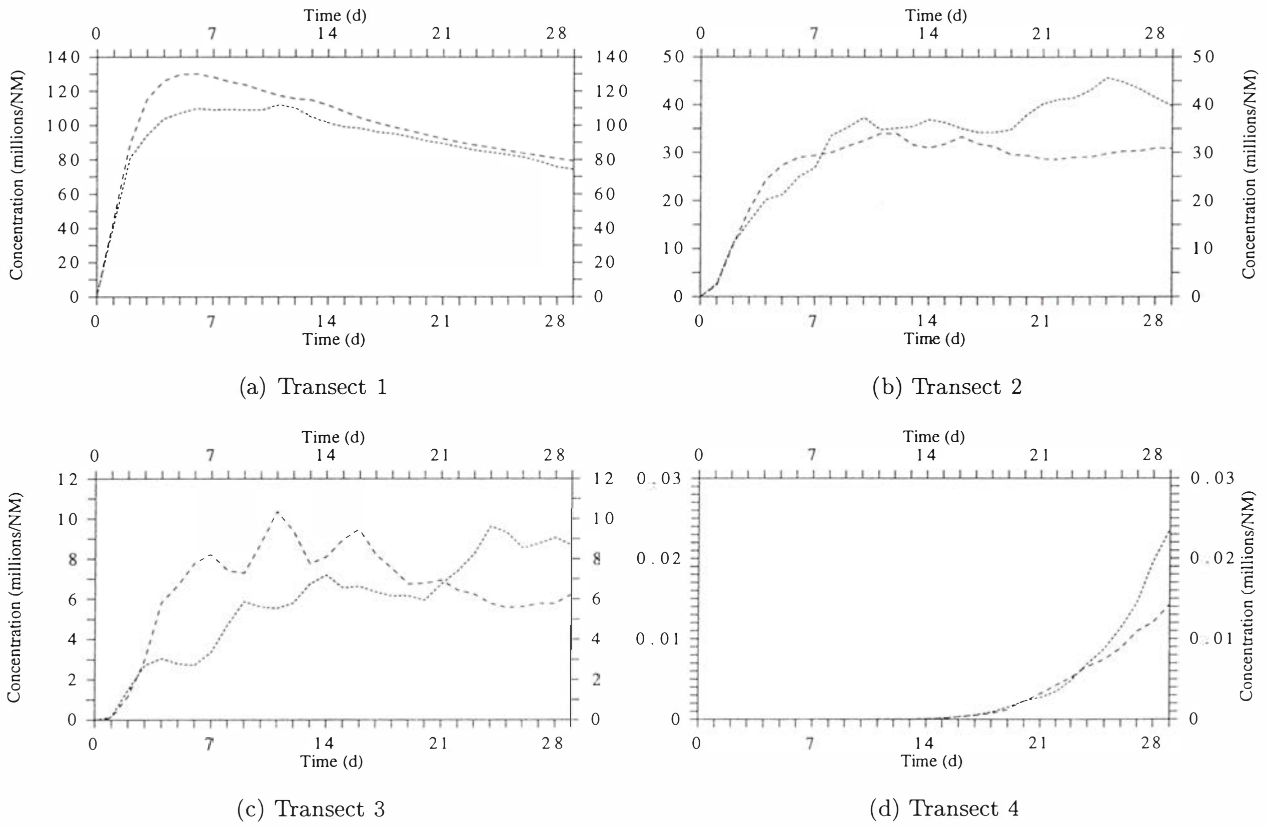
(b) Station 3 (coarser dash), Station 4 (finer dash)

Figure vii.8: Predicted concentration (10^6/nautical mile) time–series at SARDI larvae sample Transect 1 for the 7 d period of 21:30 01/02/88–21:30 08/03/88, with linear interpolation between each time–step (20 min).

time–series, with points plotted at every time–step of the larval dispersion model simulation output. Figure vii.9 depicts some month-long time–series, with points plotted at every 24 h of the larval dispersion model simulation.

Transect trend analyses were carried out for two dispersion events with time intervals corresponding to both the mid-December and January/February peaks in spawning activity. Figures vii.10 and vii.11 depict some transect trends for averages of the two spawning periods, indicating larval concentrations at the initial (i.e. after 0 d), intermediate (i.e. after 14.5 d), and final (i.e. after 29 d) stages of simulations. Figures vii.12 and vii.13 depict some transect trends for each of the two spawning periods, indicating postlarval concentrations at the cessation of simulations. Note that in some of the plots of Figures vii.10–vii.13 averages of simulation results from groups of stations, as specified in the subfigure captions, have also been taken.

Mechanisms were proposed relating the form of both the time–series and transect trends observed, to characteristics of the prevailing currents determined by the tidal model to be affecting larval dispersion during the relevant time periods.



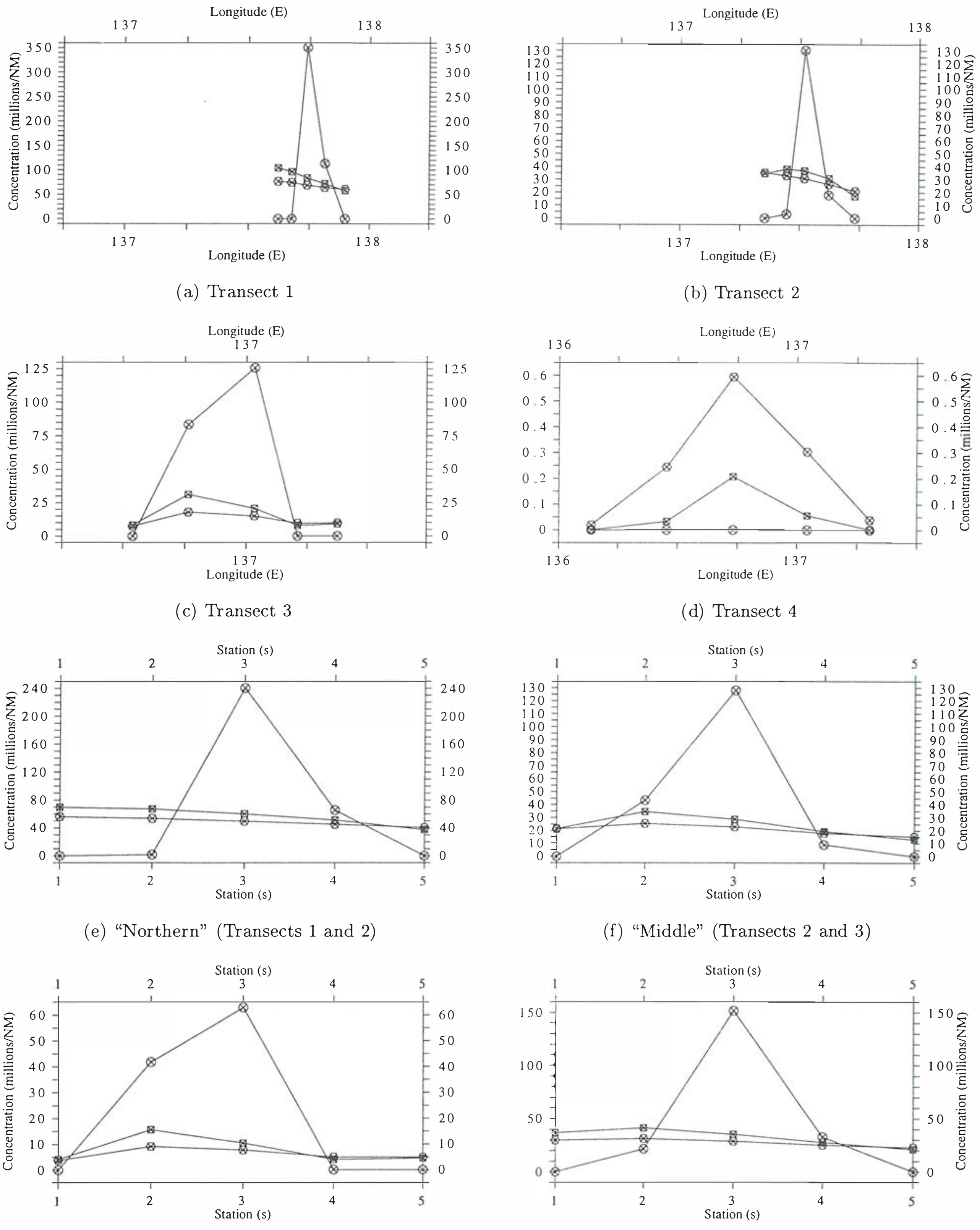
(a) Transect 1

(b) Transect 2

(c) Transect 3

(d) Transect 4

Figure vii.9: Predicted concentration (10^6/nautical mile) time–series at SARDI larvae sample Station 1 for the mid-December 1987 (coarser dash) and January/February 1988 (finer dash) simulations, with linear interpolation between each time–point (24 h).



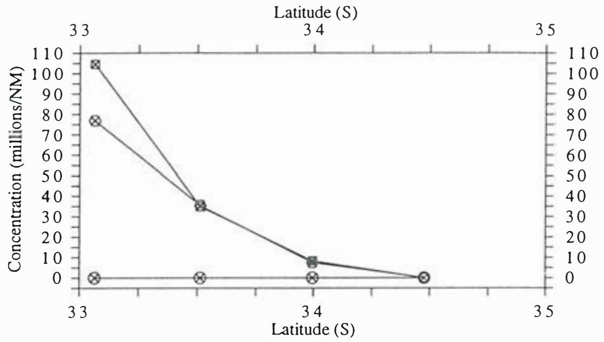
(a) Transect 1 (b) Transect 2

(c) Transect 3 (d) Transect 4

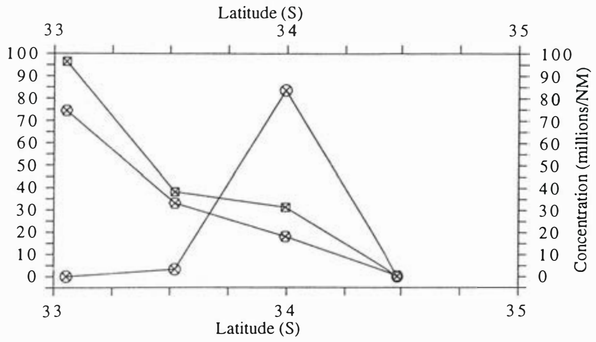
(e) "Northern" (Transects 1 and 2) (f) "Middle" (Transects 2 and 3)

(g) "Southern" (Transects 3 and 4) (h) "Average" (Transects 1–4)

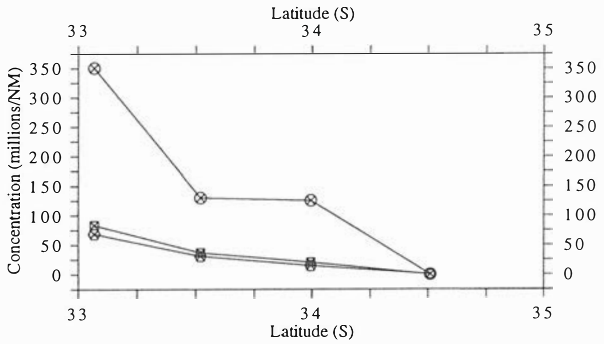
Figure vii.10: The east-west trends and trend means at SARDI prawn larvae sample station locations (Longitude, °E; Station, s) for the initial (circles), intermediate (squares), and final (hexagons) average of mid-December 1987 and January/February 1988 larval concentrations (10^6/nautical mile).



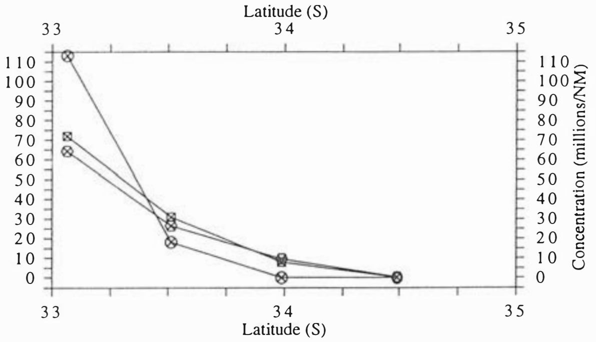
(a) Station 1



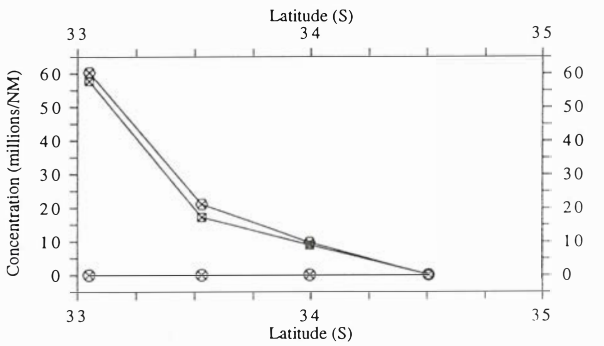
(b) Station 2



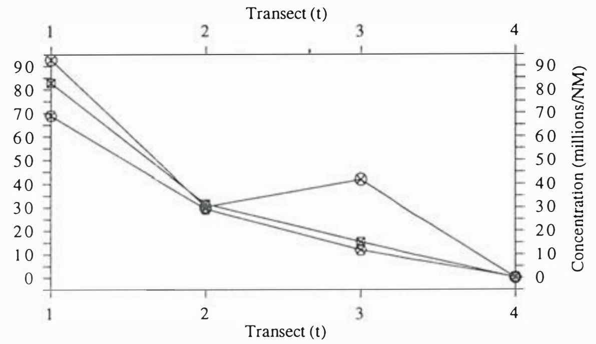
(c) Station 3



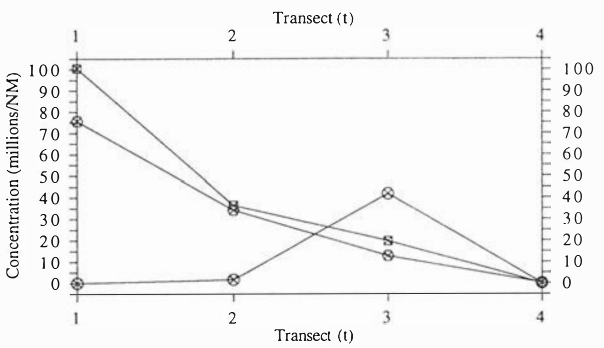
(d) Station 4



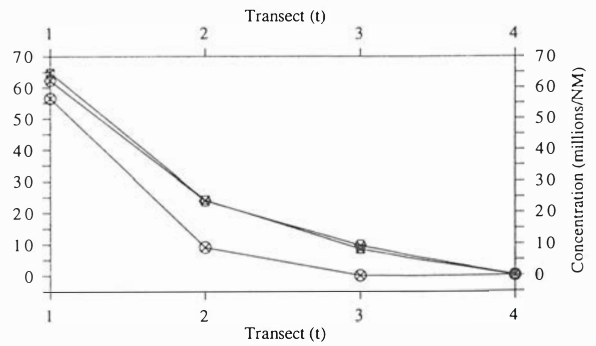
(e) Station 5



(f) "Average" (Stations 1–5)

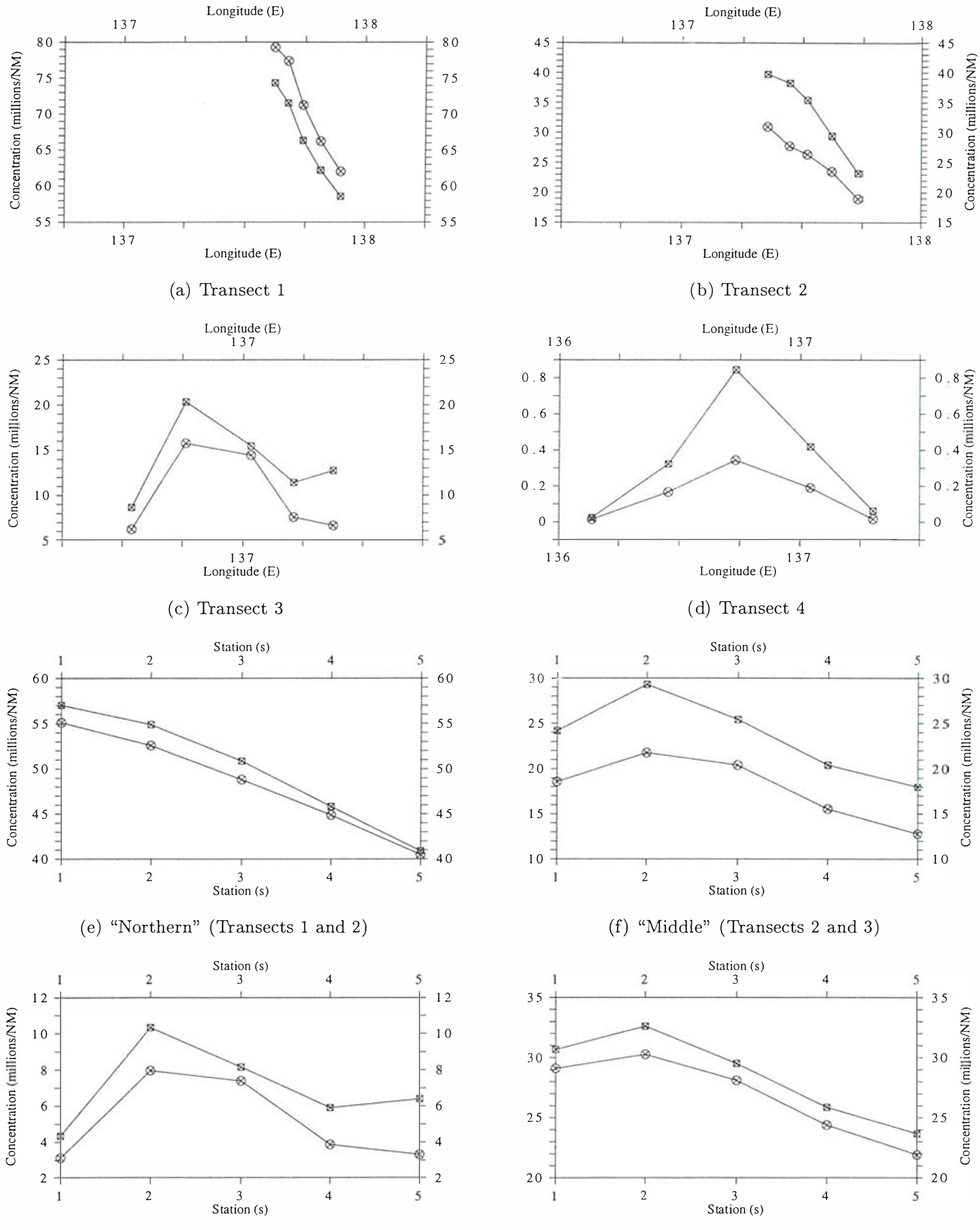


(g) "Western" (Stations 1 and 2)



(h) "Eastern" (Stations 4 and 5)

Figure vii.11: The north-south trends and trend means at SARDI prawn larvae sample station locations (Latitude, °S; Transect, t) for the initial (circles), intermediate (squares), and final (hexagons) average of mid-December 1987 and January/February 1988 larval concentrations (10^6/nautical mile).



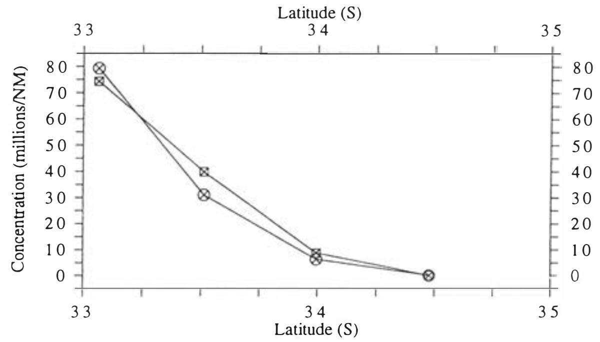
(a) Transect 1 (b) Transect 2

(c) Transect 3 (d) Transect 4

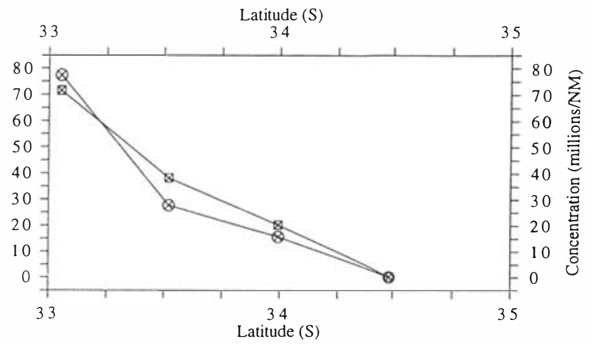
(e) "Northern" (Transects 1 and 2) (f) "Middle" (Transects 2 and 3)

(g) "Southern" (Transects 3 and 4) (h) "Average" (Transects 1–4)

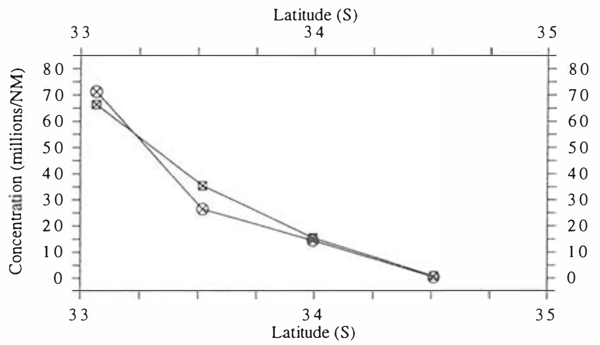
Figure vii.12: The east-west trends and trend means for final larval concentrations (10^6/nautical mile) at SARDI prawn larvae sample station locations (Longitude, °E; Station, s) for the mid-December 1987 (circles) and January/February 1988 (squares) larval dispersion periods.



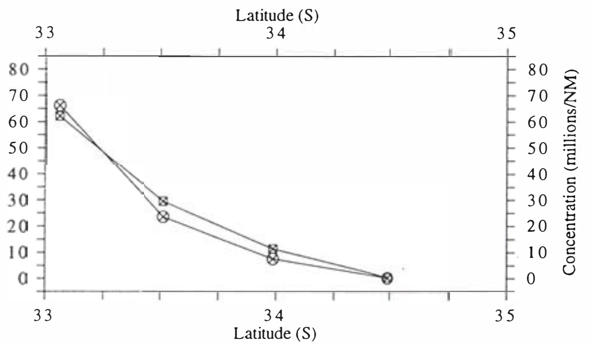
(a) Station 1



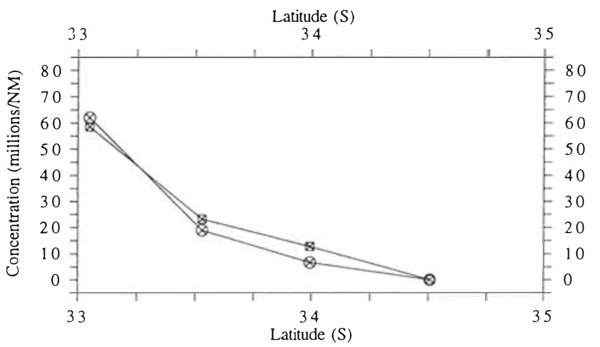
(b) Station 2



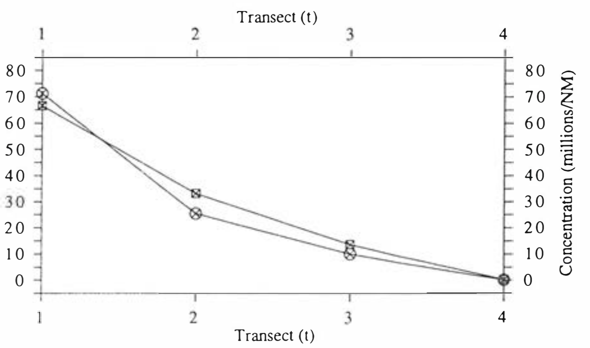
(c) Station 3



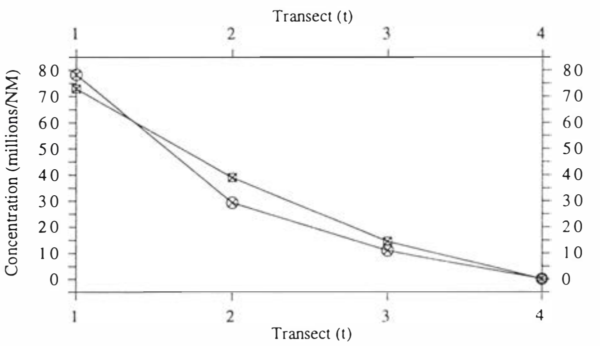
(d) Station 4



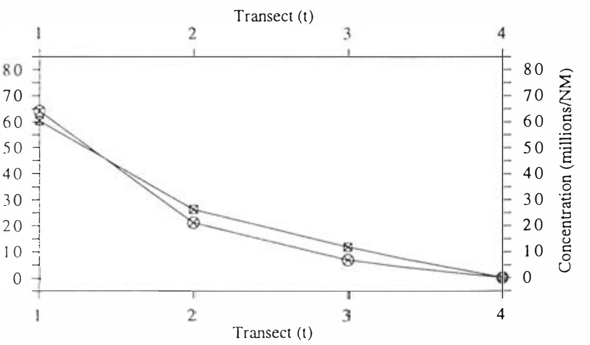
(e) Station 5



(f) "Average" (Stations 1–5)



(g) "Western" (Stations 1 and 2)



(h) "Eastern" (Stations 4 and 5)

Figure vii.13: The north-south trends and trend means for final larval concentrations (10^6/nautical mile) at SARDI prawn larvae sample station locations (Latitude, °S; Transect, t) for the mid-December 1987 (circles) and January/February 1988 (squares) larval dispersion periods.

Since field measurements of larval dispersion, postlarval settlement, or juvenile recruitment corresponding to any of these dispersion events were not available, quantitative error measures could not be determined and were thus not reported.

vii.7 Model Results Presentation

In order to reduce the enormous amounts of data generated by the numerical models—of both tidal currents as well as larval dispersion—to forms which could be readily digested and assessed by researchers and industry, both graphical and numerical representations and measures of simulation results were derived during the course of the Project. These were used to present preliminary, intermediary, and final simulation results in this study of prawn larvae dispersal in Spencer Gulf.

Results and conclusions were presented in graphical, written, numerical, and computer animated form to various interested parties including, but not limited to, the beneficiaries as well as industry, management, and academic communities.

viii Benefits

The Australian prawn fishing industry, particularly the Spencer Gulf fishery, will benefit directly from the research. Differences in terms of prices, costs, and/or catch that the adoption of the research results will make to fisheries management and industry profitability are to be quantified by fisheries officers at SARDI responsible for managing the fishery as a sustainable resource.

The benefits and beneficiaries are exactly those identified in the original application.

viii.1 Non-Market Benefits

Non-market benefits, defined by the results of the larval dispersion model, are quantified by the level of interest regarding the Project in the academic world. This is discussed in detail in Section ix.1.

viii.2 Presentations/Publications

Many conference, seminar, and colloquia talks were presented as a result of the Project, and many research papers were published. The more pertinent presentations and publications are described in Section ix.1. Copies of these presentations and/or publications were also forwarded to all interested parties soon after they were presented and/or published. In the Project's early stages, during which the basic mathematical and numerical techniques were developed, these publications appeared chiefly in mathematical journals and conference proceedings. However, it was anticipated that, as a result of the more applied nature of the work towards the Project's final stages, further publications would appear in fisheries and/or environmental modelling journals. Since it has been possible to come to very few "solid" conclusions concerning the results which have so far been produced, chiefly due to the lack of and/or late arrival of useful larval dispersal and postlarval settlement data from SARDI research officers, this has not eventuated.

Nixon (1996) is a detailed account—over 300 pages in length—of the research undertaken during the period of this Project. This work also discusses prawn larvae dispersion modelling research carried out prior to this Project, as well as that carried out in the eight months since FRDC funding ceased. A copy of this thesis will be made available to the FRDC within three months of it being classified as Passed.

ix Intellectual Property

Intellectual property arising from the research, defined by the results of the larval dispersion model, are quantified in the level of interest concerning the Project in the academic world. This can be determined by the number of research papers published, as detailed in Section ix.1.

All other intellectual property will be realised on the adoption of the research results by fisheries management officers at SARDI. Commercially significant developments are also to be quantified by fisheries officers at SARDI responsible for managing the fishery as a sustainable resource. Patents applied for or granted, and licences, etc. total zero.

ix.1 Presentations/Publications

The expected aims, methods, and preliminary results of the proposed Project were first presented publicly at the Australian Mathematical Society Division of Applied Mathematics, Applied Mathematics Conference '93 (AMC-29), as Noye and Nixon (1993).

Intricacies of the supercomputer model discussed in Section vi.5.1 were presented at the Computational Techniques and Applications Conference '91 (CTAC-91) and were published in the proceedings thereof, as Nixon (1992).

Aspects of the mathematical and numerical analyses discussed in Section vii.2 were presented at the Pacific Congress on Marine Science and Technology '94 conference (PACON-94) and were also published in the proceedings thereof, as Nixon and Noye (1995a).

Results concerning the model wind–stress sensitivity discussed in Section vii.4 were presented at the Computational Techniques and Applications Conference '95 (CTAC-95) and were published in the proceedings thereof, as Nixon and Noye (1996).

Presentations described in Section vii.7 were also made to industry bodies such as the Spencer Gulf and West Coast Prawn Fishermen's Association (SGWCPFA) at their 1993 Annual General Meeting by Nixon and Noye (1993) as well as to the general mathematical community such as staff and students of the Department of Applied Mathematics at The University of Adelaide (Nixon 1994b; Nixon 1994c). Presentations were also made to the public by Noye (1994, 1995) as part of Seaweek-94 and Seaweek-95. Aspects concerning result presentation were themselves presented at the Visualising the Atmosphere and Ocean '94 (VIS-94) conference by Nixon (1994a).

Some of the final results of the completed Project were presented at the Ocean and Atmosphere Pacific '95 conference (OAP-95) and have been submitted for publication in the proceedings thereof, as Nixon and Noye (1995b).

All papers published during the Project period, or submitted for publication during this period and under peer review at the present time, are as listed in the References section (pp. 44–45). Those published are thus in the Public Domain.

x Further Development

The calibration process discussed in Section vii.3 and the validation process discussed in Sections vii.5–vii.6 require comparison of simulation results with field measurements undertaken by SARDI fisheries research officers. Unfortunately data concerning larval dispersion and postlarval settlement were not supplied within the time–frame necessary for such data to be used for these purposes in this Project.

Partly due to the lack of consensus encountered in the literature concerning many biological phenomena associated with prawn species larvae in general—and lack of appropriately conclusive information from SARDI research officers pertaining to *Penaeus latisulcatus* larvae in Spencer Gulf in particular—calibration of model inputs parameterising such biologically based behaviour could not be carried out. Simulation results could not be validated by comparison with experimental data for the same reasons. It should be pointed out once again, however, that the underlying algorithms of the dispersion model were proven in this Project to be *theoretically* at least as accurate as those of the tidal model—the *practical* accuracy of which is well established.

x.1 Management Implications

The data situation frequently discussed in this Final Report deemed it necessary, in our view, for the Investigators associated with Project 91/004 to put forward to the FRDC a further proposal related to this Project (Nixon 1995). This proposal, which was in fact approved, was drafted in the hope that the original aims of the Project could possibly be met—some time in the future when the analyses of SARDI larval dispersion and/or postlarval settlement data were able to be completed. Only after comparison with SARDI larval dispersion and postlarval settlement data can an accurate assessment of the prawn larvae dispersion model results be made, from which management implications can then be inferred. It thus remains to be seen if the fisheries management objectives of the Project can be achieved.

xi Staff

The following staff have been employed on the project.

Staff Employed	
Project Supervisor:	B.J. Noye, Ph.D., B.Sc., A.U.A., Dip.Ed.(Sec)
(Principal Investigator)	Associate Professor of Applied Mathematics
Assistant Supervisor:	H.P. Possingham, D.Phil., B.Sc.(Hons.)
	Lecturer of Applied Mathematics
Tidal Modeller:	P.J. Bills, Ph.D., B.Sc.(Hons.)
	Lecturer of Applied Mathematics
Larval Dispersion Modeller:	J.B. Nixon, B.Sc.(Hons.)
	Post-graduate Student of Applied Mathematics
	Higher Educational Officer Level 5/6

Table xi.1: Staff employed.

xii Final Cost

The FRDC Statement of Receipts and Expenditure, and details of other contributions made to the Project, follow.

STATEMENT OF RECEIPTS AND EXPENDITURE
Fisheries Research and Development Corporation
Statement of Receipts and Expenditure for the period ending 30 June 1995

Name of Research Organisation	FRDC Project Number	Title of Project
The University of Adelaide	91/4	Modelling prawn larvae dispersion and settlement in Spencer Gulf - Management Implications

Budget Summary	1991-92	1992-93	1993-94	1994-95 (1)
Original Budget	40,965	41,863	42,761	-
Current Budget (2)	23,700	20,482	42,162	46,244

Summary Receipts and Expenditure for the Project since commencement

	1991-92	1992-93	1993-94	1994-95
B/F	N/A	22,112.62	(13,398.76)	(30,839.79)
FRDC Funds (Plus)	23,700.00	-	20,482.00	76,845.00
Expenditure (Minus)	1,587.38	35,511.38	37,923.03	46,005.21
Refunds (3)	N/A	N/A	N/A	NIL
Balance C/F	22,112.62	(13,398.76)	(30,839.79)	NIL

Details Financial Year to 30 June 1995

Funds Available			
	Balance brought forward from previous year		(30,839.79)
	Total funds received from FRDC during Financial Year 1994-95		76,845.00
	Funds Available for FY 1994-95 (4)		46,005.21
Allocation FY (5)	**Less Expenditure**		
$45,944.00			
$300.00	Salaries	44,992.74	
	Travel	1,012.47	
	Operating		
	Capital		
Total $46,244.00	**Balance as at 30 June 1995**		46,005.21
			NIL

Notes

(1) Use this column for the final year ONLY regardless of the length of the project.
(2) Total current budget shall not exceed Total original budget without approval, in writing, from the FRDC.
(3) Refunds should only be paid at completion of the project together with the final audited statement.
(4) ACTUAL EXPENDITURE (whether cash or accrual) ONLY. Commitments shall not be included.
(5) Show allocation for the current financial year. Transfers between budget heads allowed under 9(f) of the Project Agreement, or approved, in writing by the FRDC, shall be listed in the comments.

Comments:

Certified by: (Signature)

CH Gilmour
(Print Name)

xiii Distribution

Distribution lists of the Final Report follow.

xiii.1 Fisheries Research and Development Corporation

The Research Organisation herewith provides 10 copies of the Final Report to the FRDC.

- Mr Peter Dundas–Smith
  Executive Director
  Fisheries Research and Development Corporation
  PO Box 9025
  Deakin ACT 2600

One copy is unbound.

xiii.2 Beneficiaries

A copy of the Final report has been distributed to each of the following beneficiaries, as identified in B7 Flow of Benefits, Part B of the Project Description forming part of the original application.

- Dr John Keesing
  Chief Scientist
  South Australian Research and Development Institute
  South Australian Aquatic Sciences Centre
  PO Box 120
  Henley Beach SA 5022

- Mr Neil A Carrick
  Senior Prawn Biologist
  South Australian Research and Development Institute
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xiii.3 Additional Distribution

The Research Organisation has also distributed a copy of the Final Report to:

- Dr Peter Grimes
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  570 St Kilda Road
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- National Fishing Industry Council
  Unit 1, 6 Phipps Place
  Deakin ACT 2600

- National Fishing Industry Training Council
  GPO Box 2851AA
  Melbourne VIC 3001
- CSIRO Division of Fisheries
  GPO Box 1538
  Hobart TAS 7001
- CSIRO Division of Fisheries
  PO Box 12
  Cleveland QLD 4163

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