Determination of Spawning Areas for King George Whiting in Southeastern Australia using Hydrodynamic Modelling

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1. Non-technical Summary

The spawning areas of King George whiting in Victoria are unknown. Lack of knowledge of spawning areas is a severe hindrance to the effective management of the fishery. For example, does each bay or inlet have it's own breeding population, or do these populations form part of a larger breeding stock?

It has long been suspected that the King George whiting caught in our bays and inlets did not breed in these places. No eggs and young larvae are caught in bays and inlets, however, small juveniles approximately 2 cm long, just transformed from the larval stage, are found in seagrass beds each spring. The ear bones (otoliths) of these juveniles have rings on them that are formed daily, and we recently determined that the juveniles arriving in seagrass beds were 3 - 4 months of age. We hypothesised that over this period larvae would be drifting offshore (Bass Strait), and because the prevailing winds over winter-spring are from the west, that spawning would occur well to the west of the bay or inlet where juveniles were collected.

In this project, we determined the age of newly-settled juveniles in seagrass beds based on rings on otoliths, and combined this with simulations of currents off the south-east Australian coast from a computer model, to predict spawning areas. Predictions were made for juveniles from Port Phillip Bay, Western Port and Corner Inlet. The model was run in 'reverse' to predict the origin of larvae.

Overall, the results showed that juveniles in all three bays had a similar origin, western Victoria and the southeastern coast of South Australia, suggesting that individuals from each bay were part of one population with a single spawning area. The length of larval life was progressively longer for juveniles in bays further to the

east, reflecting the longer distance travelled from the spawning area. We also compared predicted spawning areas for juveniles collected from Port Phillip Bay in three years; 1989, 1994 and 1995. The predicted spawning area for 1989 was similar to that described for 1995, however, in 1994, a year of particularly strong westerly winds, the predicted spawning area extended further west to approximately Kangaroo Island, one of the few sites where spawning of adult King George whiting has been recorded. Three dimensional modelling suggested that in the case of Corner Inlet, a small proportion of the juvenile fish could have come from spawning on the nearby coast. Larvae in this case would have been transported in a clockwise gyre around central Bass Strait.

We conclude that King George whiting in Victorian waters are probably part of a single, broad-ranging stock that spawns along the coast of western Victoria and southeastern South Australia. It is possible that at least some of the South Australian fishery is sourced from the same spawning area. Thus, populations of King George whiting in Victorian bays and inlets should, in general, be managed as a single stock, and it is possible that the stock is continuous between Victoria and South Australia and should be managed accordingly.

The results of this study will be used as a basis for sampling of eggs and larvae from the research vessel *Franklin* in 1998 to confirm King George whiting spawning areas. In the future, the results may also form the basis for sampling of adults for reproductive studies, necessary for the rational management of the species.

2. Background

Fundamental to the rational management of fish populations is an understanding of stock structure. The geographic extent of marine fish populations will be largely determined by the extent of larval dispersal in the species, a function of the duration of larval life and circulation patterns in the region, and also adult mobility. Although a small amount of cross seeding of populations will tend to make populations genetically homogeneous, from a fisheries management point of view, these populations should often be treated as separate stocks.

An example of the importance of understanding larval transport processes in elucidating stock structure is the abalone, where research, including modelling of circulation patterns, has indicated that many individual reefs are largely self-seeding and should be treated as individual stocks (Prince et al. 1987, McShane et al. 1988). Modelling of larval dispersal from scallop beds in Bass Strait suggests that stock decline may be due to management not accounting for a high degree of self-seeding of individual beds (Hammond et al. 1994). Other fish species are considered to consist of stocks ranging over wide areas due to adult mobility and wide larval dispersal. In this case it is not appropriate to subdivide the management of fisheries on the basis of State boundaries and management may be controlled by the Commonwealth, as in the case of the southeast trawl fishery.

The King George whiting is an important commercial species in southern Australia. There is limited evidence that sub-structuring of stocks occurs across the southern Australian coast (Sandars 1945, Dixon et al. 1987). Post-larvae of King George whiting appear in bays and inlets of Victoria from September to November each year at a size of approximately 15 to 20 mm (Robertson 1977, Jenkins & May 1994). The duration of the larval phase up to this point, determined from daily rings on otoliths, is approximately 100 to 150 d (Jenkins & May 1994) This extended larval phase allows for the potential for wide dispersal during this stage. Larval development occurs over the winter/spring period of strong westerly winds, suggesting that larvae would probably be transported from the west (Jenkins & Black 1994).

Spawning of King George whiting, as would be indicated by the presence of running-ripe adult fish or eggs and larvae, has not been identified in Victorian waters. Spawning in coastal rather than bay and inlet waters is supported by the presence of mainly sub-adults together with an absence of eggs and young larvae in bays and inlets (Jenkins 1986). In South Australia, young larvae are only found near the mouths of gulfs, whilst young juveniles are found deep within the gulfs (Bruce 1989). The only spawning aggregation identified to date in southern Australia was found near Kangaroo Island in South Australia. The long larval period and strong westerly current flow has led to the suggestion that post-larvae recruiting to Victorian inlets may be derived from spawning aggregations in South Australia (Jenkins & May 1994).

2.1 Numerical modelling

A numerical hydrodynamic model which accepts measured inputs and particular weather events, together with a coupled larval dispersal model, provides the means to back-calculate from settlement to spawning areas, given information on larval duration and prevailing weather conditions over the period. This study uses two distinctly different categories of model: the water flow (hydrodynamic) model and the dispersal (advection/diffusion) model. The relevant numerical hydrodynamic model at the Marine and Freshwater Resources Institute is the South-east Australian Model of Bass Strait (Black et al. 1990, Black 1992). This model was modified and extended for the present study.

The model is based on the hydrodynamic model code 3DD, a coupled 3-dimensional hydrodynamic and advection/diffusion numerical model (Black et al. 1993, Black, 1995). The code is general and has been applied to vertically-stratified and homogeneous ocean, continental shelf and shallow water environments. The hydrodynamic model is linked to a separate larval advection/dispersion model POL3DD (Black, 1996) which uses Lagrangian techniques to simulate larval transport.

The models are capable of simulating the effect of high frequency events such as rapid changes in wind direction. The actual daily weather conditions over the larval dispersal and recruitment period, including barometric pressure effects, coastal trapped waves and direct wind stress, rather than average weather conditions, are modelled. Our studies to date show that temporal and spatial distribution of late-stage King George whiting can be simulated accurately under the assumption that larvae act as passive particles (Jenkins & Black 1994, Jenkins et al. 1997). Larval mobility is apparently limited relative to the strength of currents in the planktonic environment of coastal Bass Strait.

3. Need

Spawning areas for King George whiting are unknown in Victoria, but the potential for wide dispersal has major implications for management. If juveniles in Victorian bays and inlets are derived from spawning in South Australian waters, then it is possible that the recruitment of whiting to the Victorian fishery may be independent of local catches, but strongly affected by catch rates in South Australia. If spawning is predicted to occur along the Victorian coast, then it is important to know whether recruits to different bays and inlets are derived from similar or different spawning areas. This knowledge would allow managers to determine whether bays and inlets should be managed as single stocks or whether populations along the coast can be treated as a single stock. Modelling will allow us to set realistic boundaries on the potential spawning areas for whiting recruiting in Victoria.

The identification of spawning areas is the necessary first step to obtaining important information for the management of fish populations such as spawning stock biomass, fecundity, and level of egg production. Identification of spawning areas may also allow sites under threat from pollution or degradation to be protected.

In the future, we propose to test the results of this study with a field study of spawning adults, and eggs and larvae. Model results will allow us to efficiently and cost-effectively target areas for sampling. The field program would consist of sampling for running-ripe adults together with plankton sampling for eggs and larvae in the identified areas. Eggs and larvae of this species have already been collected and identified in South Australia.

The value of the proposed approach extends beyond the identification of spawning areas. Whilst a number of methods can be used to delineate spawning areas, such as sampling of spawning aggregations and egg and larval surveys, these methods tell us nothing about the dispersal of larvae from the spawning areas, which is critical to understanding stock structure.

4. Objectives

To use spawning dates estimated from otoliths of post-larvae collected in bays and inlets of Victoria, and reverse modelling with the MAFRI Bass Strait Model based on the climatic conditions over the development period, to estimate spawning sites and larval advection pathways of King George whiting in south-eastern Australia.

5. Methods

5.1 Study sites

Sampling for newly-recruited King George whiting was conducted in Port Phillip Bay, Western Port and Corner Inlet, Victoria (Fig. 1). In Port Phillip Bay, post-larval King George whiting were collected by plankton net at two sites (BWS1, BWS11) immediately inside Port Phillip Heads from September to November (Fig. 1). In Western Port, post-larvae were collected from seagrass, *Heterozostera tasmanica* beds at Cribb Point, Rhyll and Corinella; whilst in Corner Inlet, post-larvae were collected from *H. tasmanica* beds at Welshpool, Toora and Yanakie (Fig. 1).

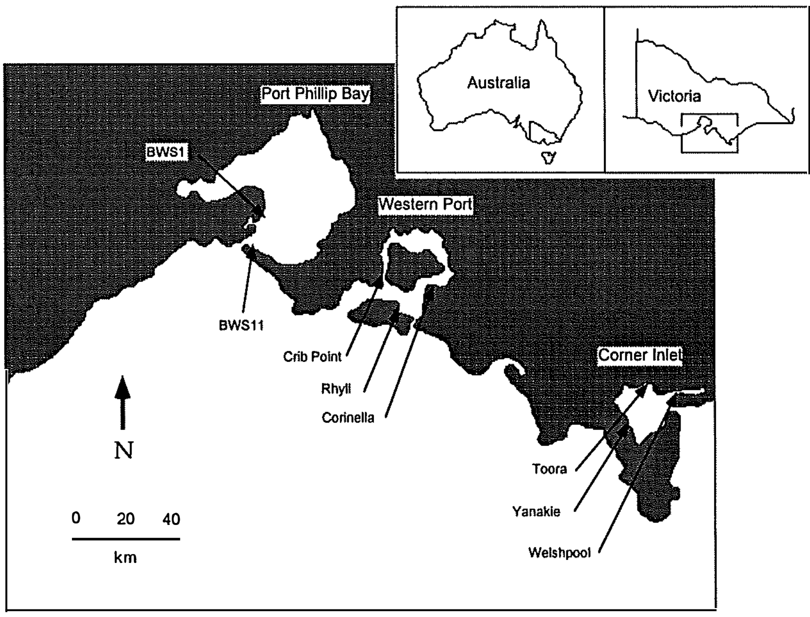

Figure 1 Sampling sites for post-larval King George whiting in Port Phillip Bay, Western Port and Corner Inlet. Insets: Position of the study area on the Victorian Coast, and location of the State of Victoria in Australia.

In addition to field collections in 1995, otoliths were also examined from post-larvae that had been previously collected by plankton net from BWS1 in Port Phillip Bay between September and November 1994. Additional otolith data for 1994 was obtained from specimens that were collected in the Edwards Point area in the study by Hamer (1995). Finally, otolith data for 1989 was obtained from post-settlement specimens collected from Swan Bay and described by Jenkins & May (1994).

5.2 Field sampling methods

Post-larval King George whiting in seagrass were sampled using a 10 m long, 2 m deep beach seine with a 1 mm^2 mesh. Two 10 m ropes were attached to each end of the net and the net was hauled over this distance. Two persons hauled the net into a plastic bin that was then transferred to shore or boat to sort the sample. Samples were placed in 95% ethanol to preserve otoliths. Replicate, non-overlapping hauls were conducted until an adequate sample size was obtained. Sampling was conducted approximately 2.5 h each side of low tide and each bay was sampled over a 2 - 3 d period. The depth of sampling was approximately 0.25 to 0.5 m below the mean-low-water-spring level.

Pre-settlement larvae were sampled with a 4 m long plankton net constructed of 1 mm^2 mesh attached to a 1m x 1m square frame. The towing cable was connected to a chain bridle attached to the top corners of the net frame. A 16 kg depressor weight was attached to a chain bridle on the bottom of the net. The towing speed was approximately 1 ms^{-1}, producing an angle of attack of the net of approximately 30^{o} and an effective mouth area of 0.9 m^2. Tow duration was 15 minutes. Again, samples were placed in 95% ethanol to preserve otoliths.

5.3 Laboratory methods

In the laboratory, otoliths were dissected from fish and examined under a compound microscope with attached video system using the techniques described by Jenkins and May (1994). Where necessary, grinding and polishing techniques were used to increase the resolution of larval-stage increments (Jenkins et al. 1993). Increment counts were done twice, the second reading blind with respect to the result of the first. If there was a discrepancy of more than five increments, a third reading was done. If all three readings differed as described, the otolith was rejected; if two of the counts were within the specified range, then the average of those two counts was used. In many recruits, otoliths contained a transition in microstructure, signified by a rapid increase in increment width, that occurs at approximately the time of entry to the bay or inlet (Jenkins & Black 1994, Jenkins & May 1994, Hamer & Jenkins 1996). The number of increments counted outside the transition was subtracted from the date of capture to give the approximate arrival date of an individual to a bay, thus providing an estimate of the period of larval drift from the spawning ground to the paticular bay. Five days, the approximate time from hatching to first feeding when the first increment is formed, was added to the increment count to give the total larval period (Jenkins & May 1994).

A total of 113 post-larvae from Port Phillip, 97 from Western Port and 83 from Corner Inlet had otoliths with increments sufficiently clear to interpret and analyse. In addition, otoliths from 55 post-larvae collected from Port Phillip Bay in 1994 and 51 collected from Swan Bay in 1989 were analysed. In some cases, otoliths from specimens from Western Port and Corner Inlet were ground and polished to increase the clarity of increments. Otoliths were mounted, proximate surface down, on microscope slides in epoxy resin and ground and polished on a lapping wheel, initially with 1000 grade wet and dry paper, and final polishing to the primordium with 6 μm diamond paste.

5.4 Numerical modelling

For the determination of spawning sites an earlier SE Australia - Bass Strait hydrodynamic model was extended, with additional bathymetry, so that the western boundary was placed near Ceduna, South Australia (Fig. 2). After extending the grid, the boundary condition techniques proved by Middleton & Black (1994) were adopted. This involved adding coastal trapped wave oscillations to the boundary sea levels using measured coastal water levels at Thevenard (Ceduna). Measured winds were taken from Ceduna, Cape Borda (Kangaroo Island), Portland, Cape Otway, Wilson's Promontory, Flinders Island, Low Head (Tasmania) and Gabo Island and interpolated using inverse distance weighting (Black 1995) onto each model cell. For model verification, predicted sea levels were compared with actual sea levels at Port Stanvac (Adelaide), Portland and Point Lonsdale.

The dispersal model accepted output from either a 2-dimensional or 3-dimensional hydrodynamic model. In the former case, the velocity profile is assumed to be logarithmic so that currents can be specified throughout the water column when calculating the larval advection. The three dimensional model provides a more accurate description of currents with depth. In both cases, the dispersal model is 3-dimensional with larval position specified by it's x,y,z coordinate.

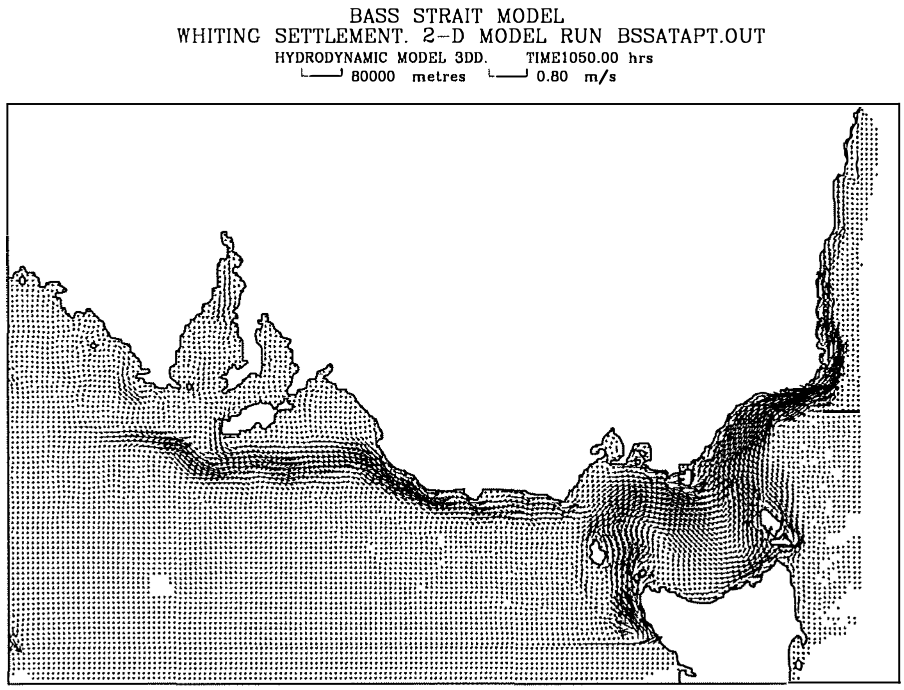

Figure 2 Model grid used for reverse modelling of King George whiting larval advection.

Two-dimensional hydrodynamic modelling was used for simulations of 1995, 1994 and 1989, whilst three-dimensional modelling with six depth strata was also applied to 1995 (Table 1). Selected empirical coefficients are presented in Table 1. The period simulated was from April 1 to November 30 of each year. Simulations in 1995 included all three bays together as well as individually. For 1994 and 1989, simulations were based on data from Port Phillip Bay only. Larvae were modelled as moving randomly throughout the depth range, which gave the broad limits of the spawning distribution and larval transport of the species.

Table 1 Specifications of 2- and 3- dimensional numerical models

Specification	2-dimensional	3-dimensional
Hydrodynamic models		
depth layers	logarithmic	0-5, 5-15, 15-35, 35-55, 55-75, 75-6000 m
cell size	10 x 10 km	10 x 10 km
number of model cells	178 x 116	178 x 91
Bed friction roughness length (m)	0.002	0.002
Horizontal eddy viscosity $m^2 s^{-1}$	40	40
Vertical eddy viscosity $m^2 s^{-1}$	-	mixing length formulation (parabolic distribution)
Dispersal models		
Horizontal eddy diffusivity $m^2 s^{-1}$	0.0015	0.0015
Vertical eddy diffusivity $m^2 s^{-1}$	0.001	0.001

All post-larvae from the three bays for which otolith analysis was successful were represented in the model in order to simulate the actual larval advection based on measured larval durations and arrival dates. To improve statistical reliability each larva was represented by 10 neutrally buoyant particles that were seeded at the mouth of a bay or inlet on their estimated day of arrival. Particles were then tracked for their estimated larval duration in a "reverse" simulation to the point of hatching. The advection pathway and final (hatching) position was plotted in space for all particles.

Hydrodynamic model calibration compared the predicted and observed residual sea level (low frequency sea level oscillations) at Point Lonsdale (Fig. 3) and Portland (Fig. 4) in Victoria, and Port Stanvac (Fig. 5) in South Australia. Low frequency sea levels indicate the mass water movements in and around Bass Strait which primarily govern larval dispersal over long time periods.

The model is skilful in predicting sea level at all three sites (Figs. 3 to 5), but was most accurate in the west, nearer to the western boundary. Overall, the model showed a high degree of accuracy in predicting sea level, supporting previous similar calibrations of sea levels and current speeds (Hammond et al. 1994, Middleton & Black 1994).

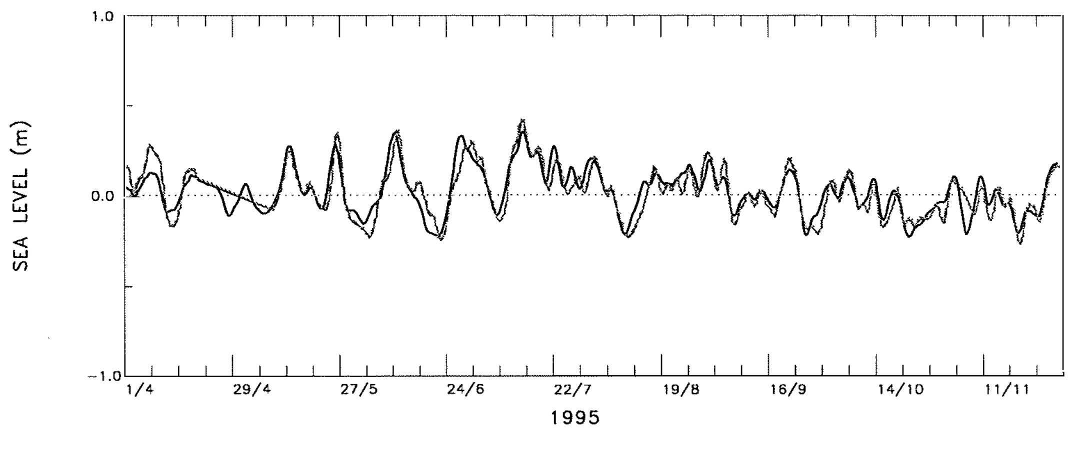

Figure 3 Correspondence between actual (grey) and predicted (black) residual sea levels at Point Lonsdale, Victoria for the period 1 April to 30 November, 1995.

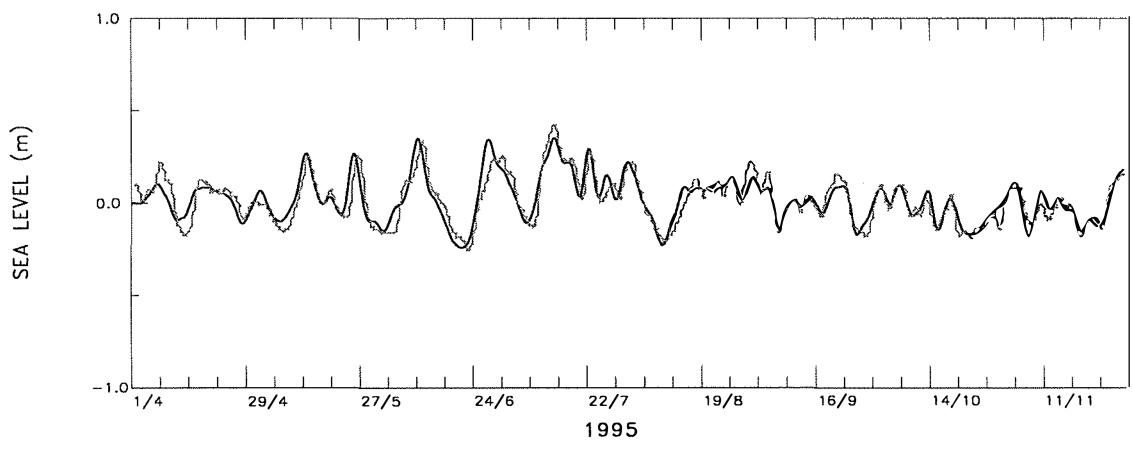

Figure 4 Correspondence between actual (grey) and predicted (black) residual sea levels at Portland, Victoria for the period 1 April to 30 November, 1995.

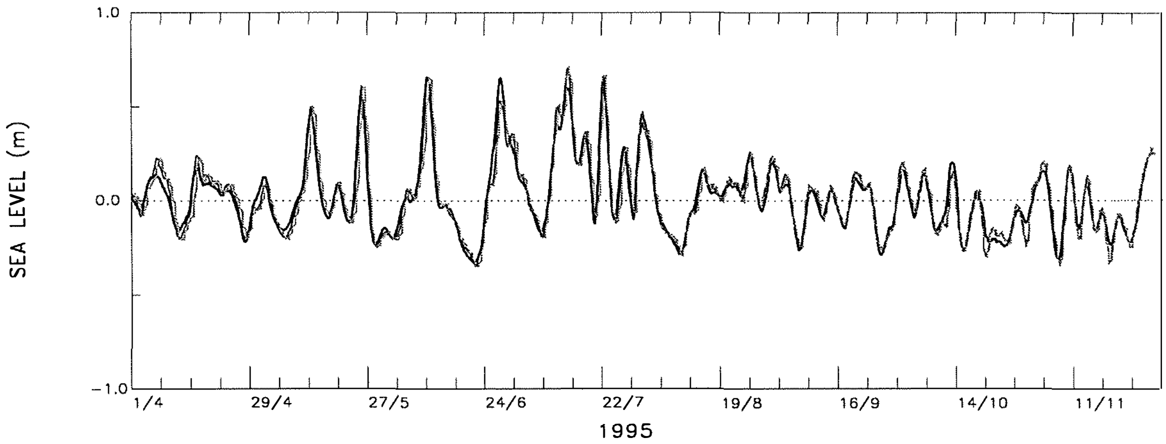

Figure 5 Correspondence between actual (grey) and predicted (black) residual sea levels at Port Stanvac, South Australia, for the period 1 April to 30 November, 1995.

The present model extends much further to the west than previous versions and includes the South Australian gulfs. The good results indicate that the model is satisfactorily simulating the propagation of continental shelf waves past the gulfs and into Bass Strait. These waves, together with local wind-driven currents, are primarily responsible for the larval advection excursions.

6. Results

The objective of this project has been fully achieved. Spawning dates were estimated from otoliths of post-larvae collected in bays and inlets of Victoria. In addition to estimates for post-larvae collected in 1995 as proposed originally, we have also used post-larvae from 1994 and 1989 so that a temporal as well as spatial comparison could be made. Reverse modelling in both two- and three- dimensions has been successfully used to estimate spawning sites and larval advection pathways of King George whiting in south-eastern Australia.

6.1 Comparison amongst bays

Larval durations estimated from otoliths varied significantly amongst bays (ANOVA df=2/290, F=62.07, P<0.001) in 1995, with a mean duration of 119 days for Port Phillip, 128 days for Western Port, and 138 days for Corner Inlet. Post-hoc testing indicated that all bays differed significantly from each other (Tukey's HSD, P<0.001). There was an apparent trend for increasing larval duration from west to east (Fig. 6).

Hatch date estimated from otoliths also varied significantly amongst bays (ANOVA df=2/290, F=34.14, P<0.001), with a mean date of June 8 for Port Phillip, May 30 for Western Port, and May 20 for Corner Inlet. Post-hoc testing indicated that all bays differed significantly from each other (Tukey's HSD, P<0.001). There was a trend for earlier spawning from west to east (Fig. 7).

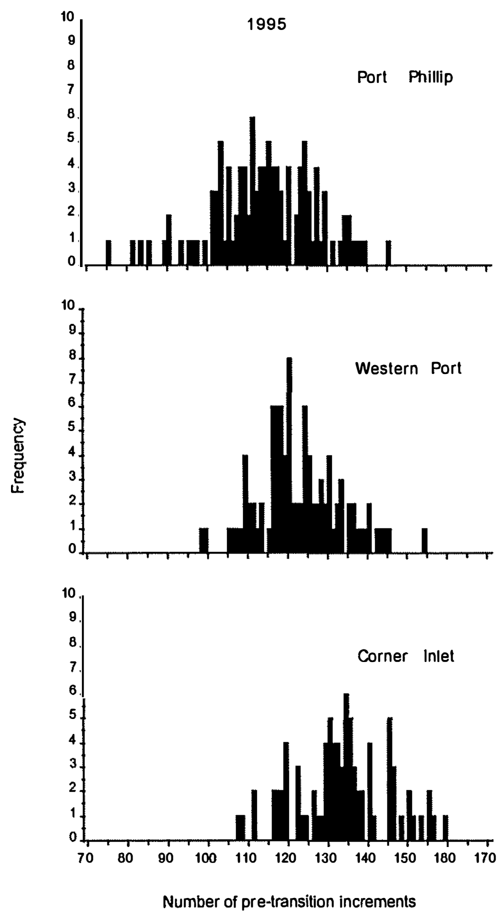

Figure 6 Larval durations estimated from otoliths for post-larval King George whiting from three bays in 1995.

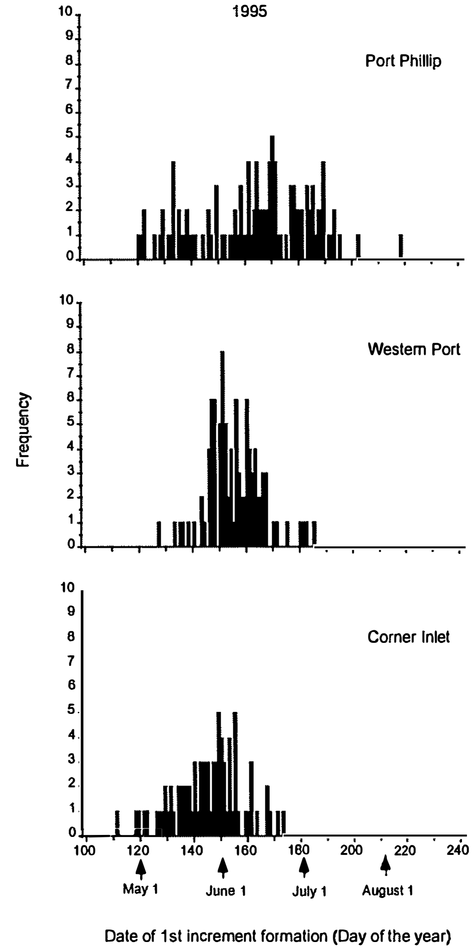

Figure 7 Date of first increment formation estimated from otoliths of post-larval King George whiting from three bays in 1995

The mean date of arrival at the bays was very similar, October 4 for Port Phillip Bay and October 5 for Western Port and Corner Inlet. The variability and spread of the distribution for Port Phillip was greater than for Western Port or Corner Inlet (Fig. 8).

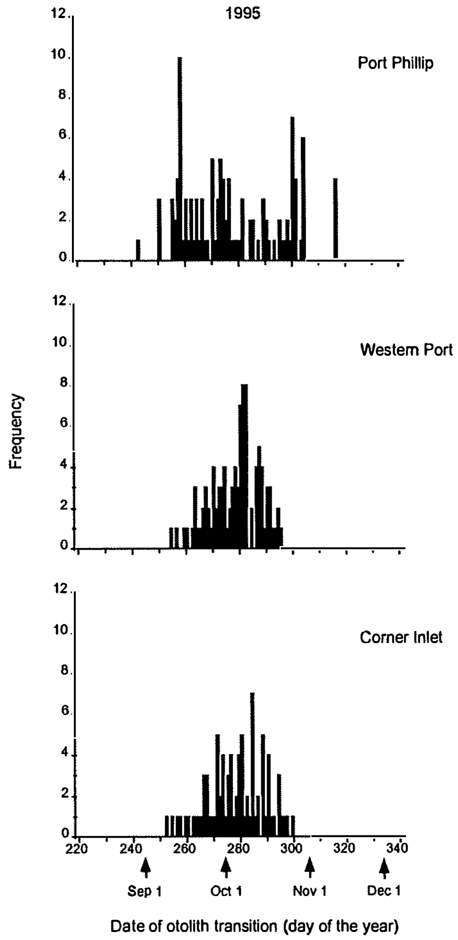

Figure 8 Date of otolith transition estimated from otoliths for post-larval King George whiting from three bays in 1995.

6.2 Comparison amongst years

Larval durations estimated from otoliths varied significantly amongst years for Port Phillip (ANOVA df=2/216, F=19.203, P<0.001), with a mean duration of 119 days for 1995, 121 days for 1994, and 132 days for 1989 (Fig. 9). Post-hoc testing indicated that larval duration for 1994 and 1995 was not significantly different, but 1989 was different from the later years (Tukey's HSD, P<0.001). Thus, larval durations in 1989 were longer than in the other two years (Fig. 9).

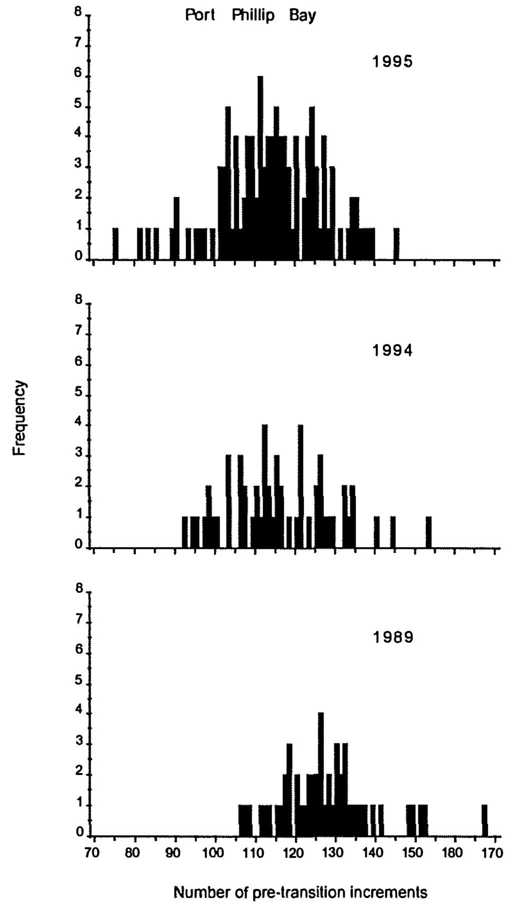

Figure 9 Larval durations estimated from otoliths of post-larval King George whiting from Port Phillip Bay for three years.

Hatch date estimated from otoliths also varied significantly amongst years for Port Phillip (ANOVA df=2/216, F=11.70, P<0.001), with a mean date of June 8 for both 1994 and 1995, and May 23 for 1989. Post-hoc testing indicated that mean hatching date for 1989 was different from the later years (Tukey's HSD, P<0.001). Thus, the mean hatch date in 1989 was earlier than in the other two years (Fig. 10).

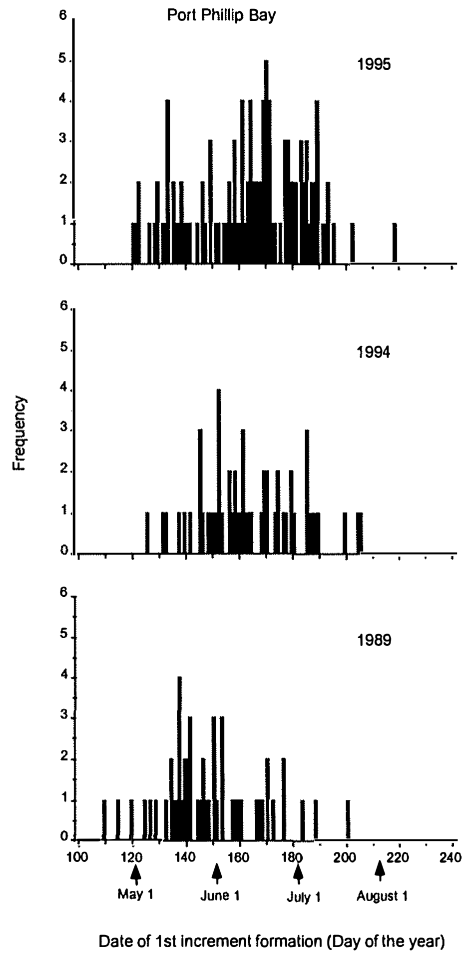

Figure 10 Date of first increment formation estimated from otoliths of post-larval King George whiting from Port Phillip Bay for three years.

The mean date of arrival at Port Phillip for the three years was very similar, October 4 for 1995, October 6 for 1994 and October 3 for 1989. The range of arrival dates was greater in 1994 and 1995 compared with 1989 (Fig. 11).

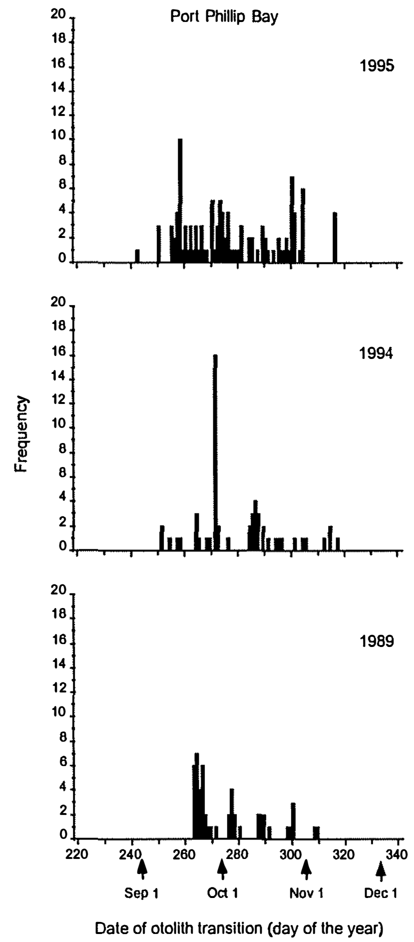

Figure 11 Date of otolith transition estimated from otoliths of post-larval King George whiting from Port Phillip Bay for three years.

6.3 Comparison within a year

A comparison was made of larval durations and hatching dates for post-larvae entering Port Phillip Bay in the early (September 12-17), mid (September 27 - October 3) and late (October 27 - 31) parts of the recruitment season in 1995.

Larval durations estimated from otoliths varied significantly within the 1995 recruitment season for Port Phillip (ANOVA df=2/62, F=7.696, P<0.001), with a mean duration of 120 days for early recruits, 109 days for mid recruits and 115 days for late recruits (Fig. 12). Post-hoc testing indicated that larval duration for early recruits was significantly longer than for mid recruits (Tukey's HSD, P<0.001), other comparisons were not significantly different.

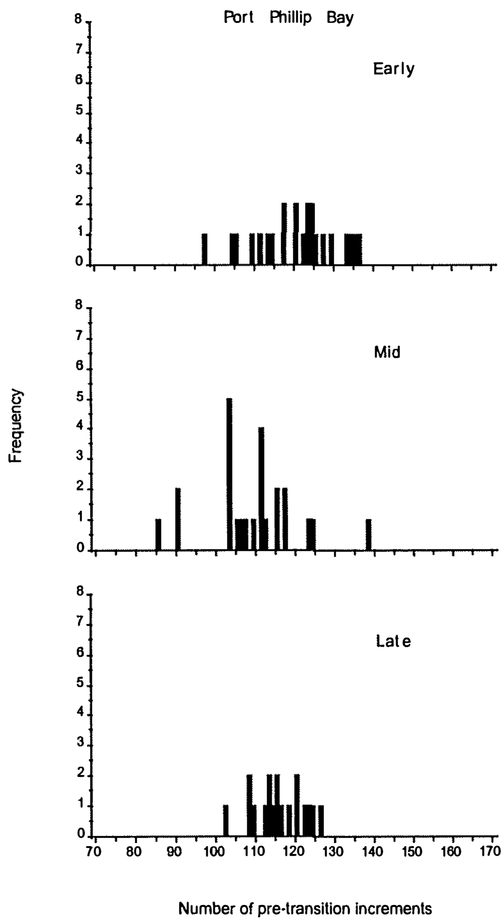

Figure 12 Larval durations estimated from otoliths of post-larval King George whiting from Port Phillip Bay in the early, mid and late parts of the recruitment season.

Hatching date estimated from otoliths also varied significantly within the 1995 recruitment season for Port Phillip (ANOVA df=2/62, F=113.63, P<0.001), with a mean date of May 17 for early recruits, June 13 for mid recruits, and July 5 for late recruits (Fig. 13). Post-hoc testing indicated that mean hatching dates for early, mid and late recruits were significantly different (Tukey's HSD, P<0.001).

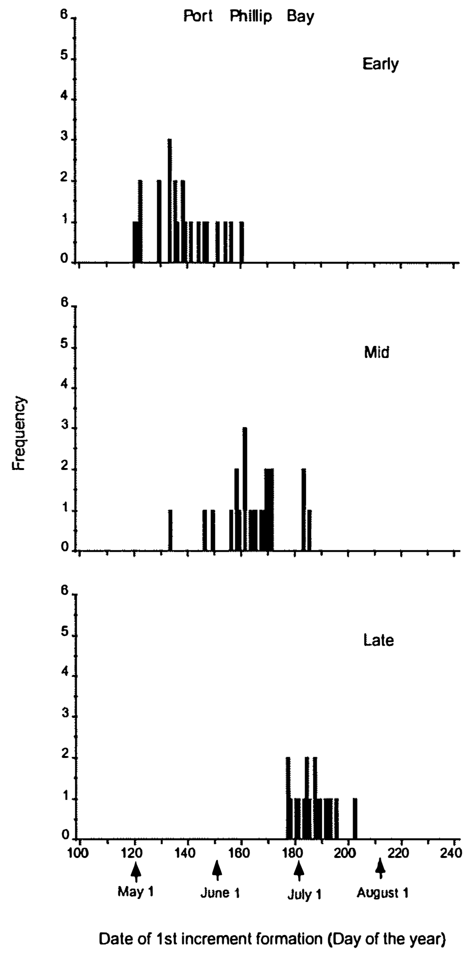

Figure 13 Date of first increment formation estimated from otoliths of post-larval King George whiting from Port Phillip Bay in the early, mid and late parts of the recruitment season.

6.4 Reverse Modelling

6.4.1 Two-dimensional modelling

6.4.1.1 Comparison of bays

When otolith data for all three bays were used in a combined simulation, the predicted total spawning area was located close to the coast of western Victoria and the south-east coast of South Australia, ranging from approximately Apollo Bay to the Coorong region (Fig. 14). The major concentration of spawning was from Portland to the Coorong (Fig. 14). When otolith data for the three bays was run in separate simulations, the predicted spawning for recruits to each bay was very similar, again ranging from approximately Cape Otway to the Coorong (Figs. 15-17). The most concentrated area of spawning shifted slightly from the west for Port Phillip Bay recruits to the east for Corner Inlet with an intermediate concentration of spawning for Western Port (Figs. 15-17).

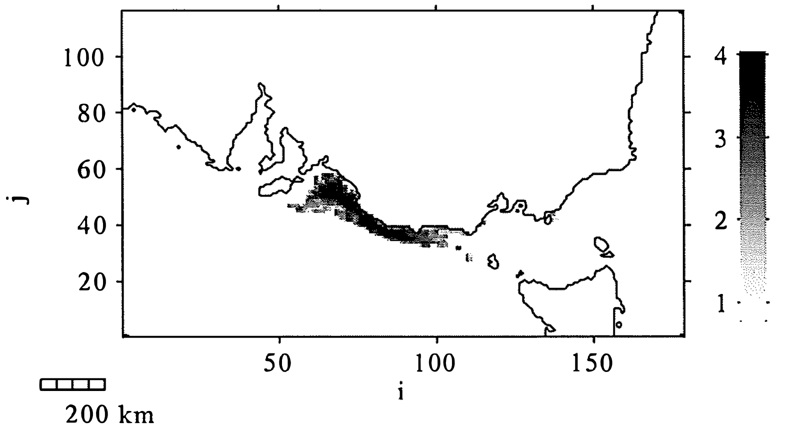

Figure 14 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay, Western Port and Corner Inlet in 1995 based on 2-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

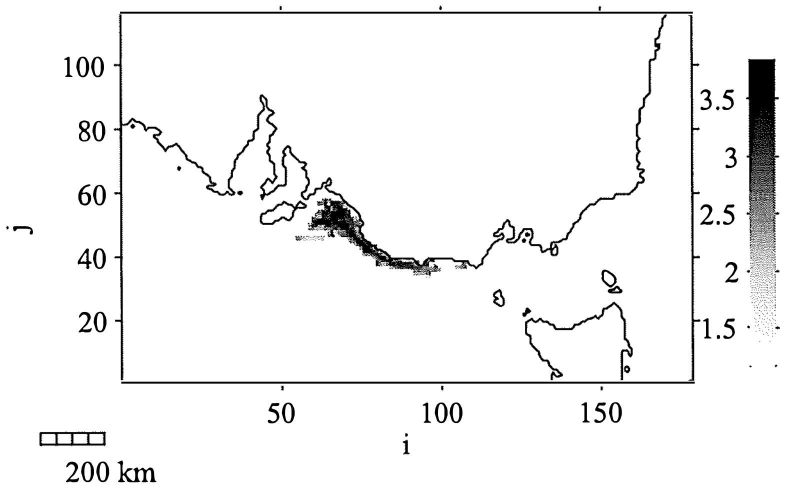

Figure 15 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay in 1995 based on 2-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

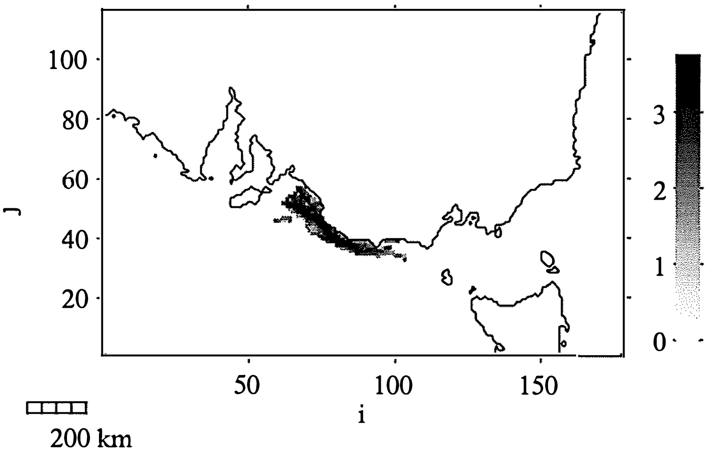

Figure 16 Predicted spawning area of King George whiting for post-larvae from Western Port in 1995 based on 2-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

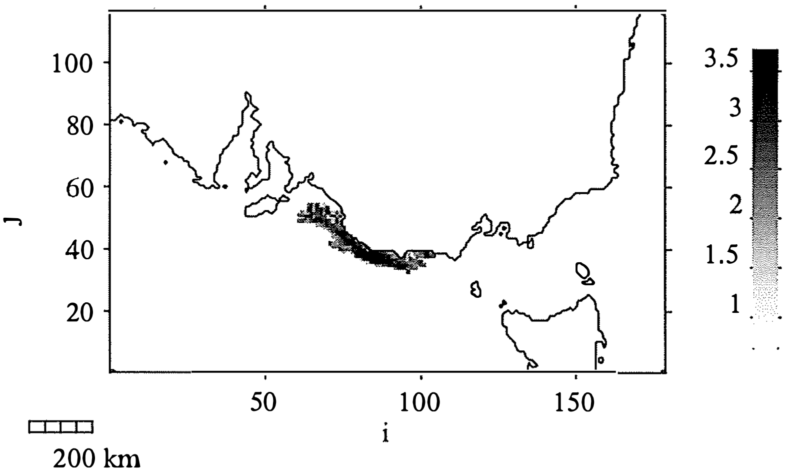

Figure 17 Predicted spawning area of King George whiting for post-larvae from Corner Inlet in 1995 based on 2-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

6.4.1.2 Comparison of years

Otolith data for Port Phillip Bay in 1995 (Fig. 15) and 1989 (Fig. 18) gave very similar spawning distributions, ranging from approximately Portland to the Coorong, although the most concentrated area of spawning was shifted slightly to the east in 1989. In contrast to the other years, the predicted spawning area in 1994 for recruits from Port Phillip Bay was extended much further to the west, reaching Kangaroo Island and the mouth of Gulf St Vincent (Fig 19).

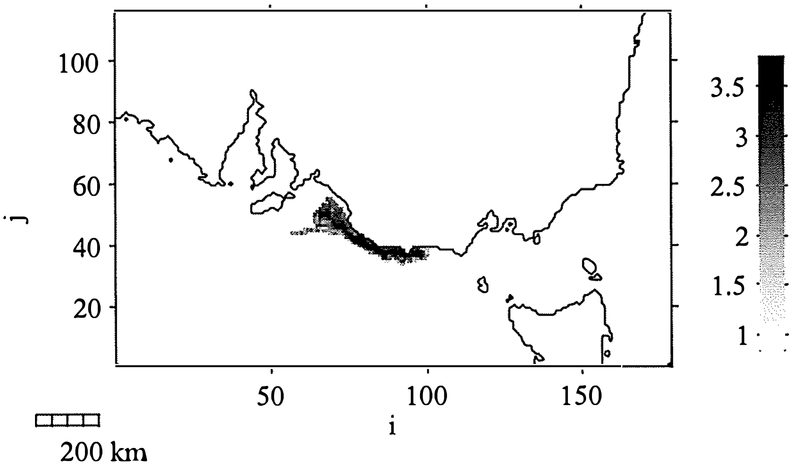

Figure 18 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay in 1989 based on 2-dimensional simulation. Scale refers to log particle density, ‘i’ = grid cell number from west to east, ‘j’ = grid cell number from south to north.

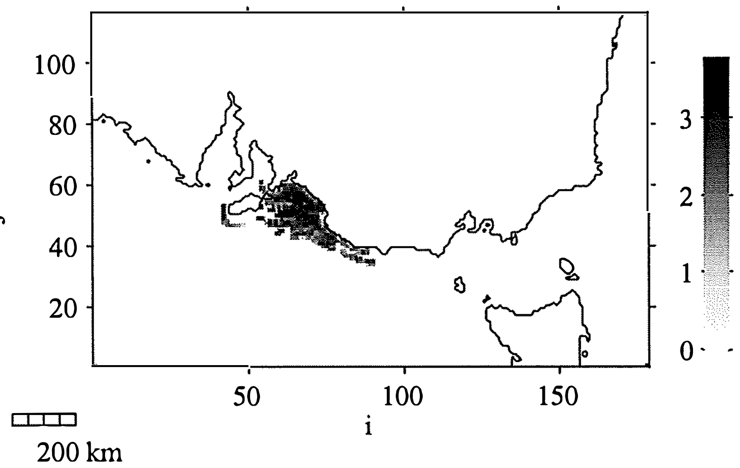

Figure 19 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay in 1994 based on 2-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

6.4.1.3 Comparison within a year

A comparison was made of predicted spawning areas in 1995 for post-larvae arriving at Port Phillip Bay in the early, middle and late stages of the recruitment period. Once again, the predicted spawning area was very similar for each stage of the recruitment period (Figs. 20-22).

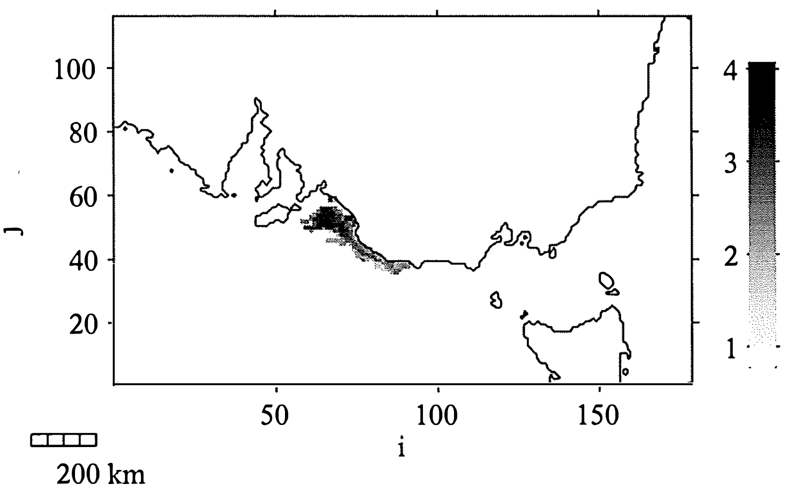

Figure 20 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay in the early part of the 1995 recruitment season based on 2-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

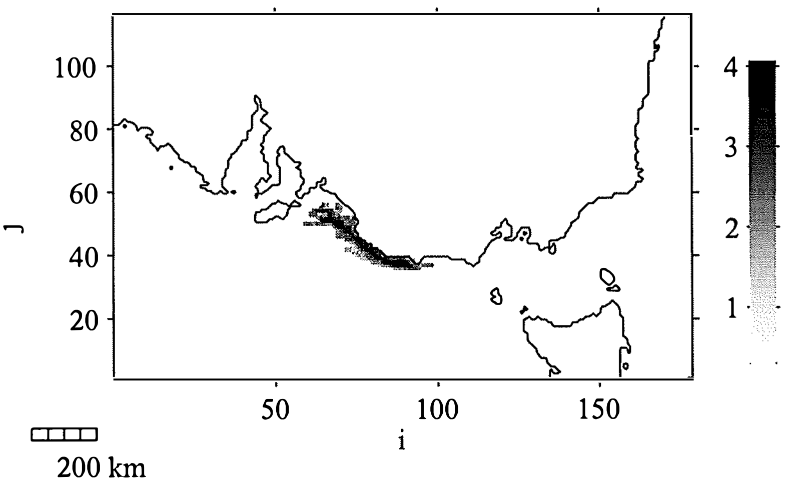

Figure 21 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay in the middle part of the 1995 recruitment season based on 2-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

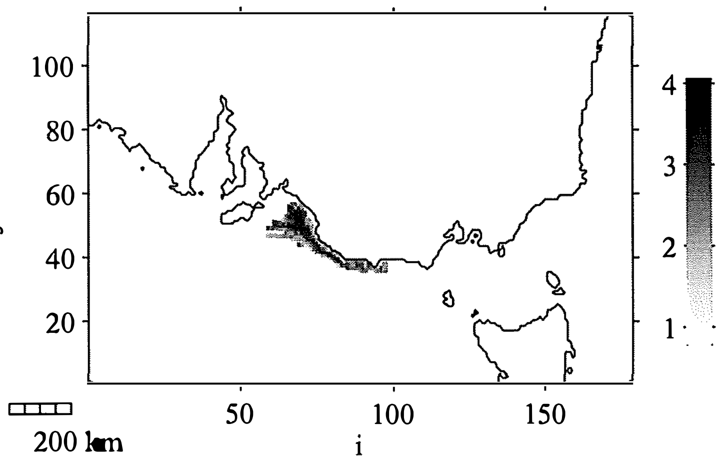

Figure 22 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay in the late part of the 1995 recruitment season based on 2-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

6.4.2 Three-dimensional modelling

Three dimensional modelling gave a different pattern to the 2-dimensional modelling. When otolith data for all bays in 1995 were combined we found potential spawning near the coast from approximately Cape Otway to the Coorong similar to the 2-D simulation (Fig. 23). However, spawning was also predicted to occur along the western boundary of Bass Strait, and also a low amount in the central Bass Strait region (Fig. 23). The area of predicted highest concentration of spawning was around Portland to the South Australian border (Fig. 23), slightly east of the area of maximum concentration predicted by the 2-D model (Fig. 14). The predicted spawning areas for recruits to the individual bays showed marked differences. The simulation for Port

Phillip Bay recruits showed the majority of the spawning to occur along the coast from Cape Otway to the Coorong, most concentrated around Cape Nelson, with a very low level of spawning predicted for the western boundary of Bass Strait (Fig. 24). The simulation for Western Port recruits showed a similar pattern to Port Phillip recruits with the exception that a greater level of spawning was predicted to occur along the western boundary of Bass Strait (Fig. 25). The simulation for Corner Inlet recruits gave a markedly different pattern, with predicted spawning not extending as far west along the coast, but showing high levels along the western boundary of Bass Strait and low levels in central and eastern Bass Strait (Fig. 26). The highest intensity of predicted spawning, however, was still located near Cape Nelson (Fig. 26).

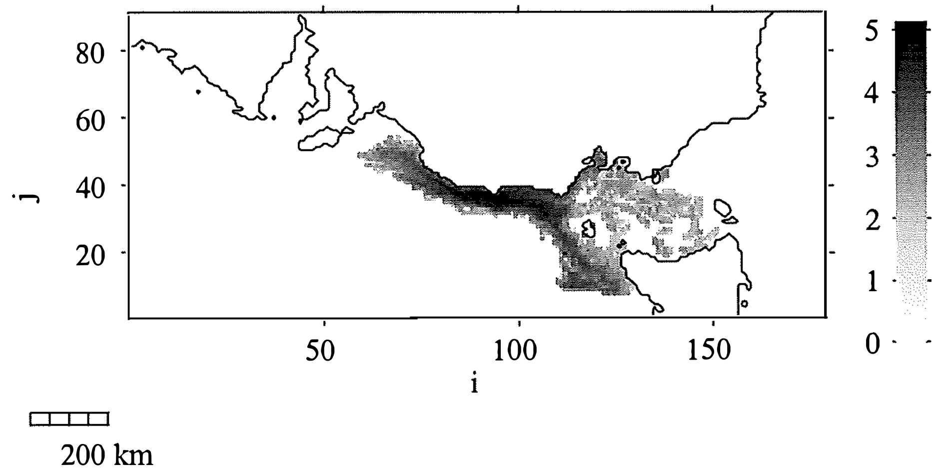

Figure 23 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay, Western Port and Corner Inlet in 1995 based on 3-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

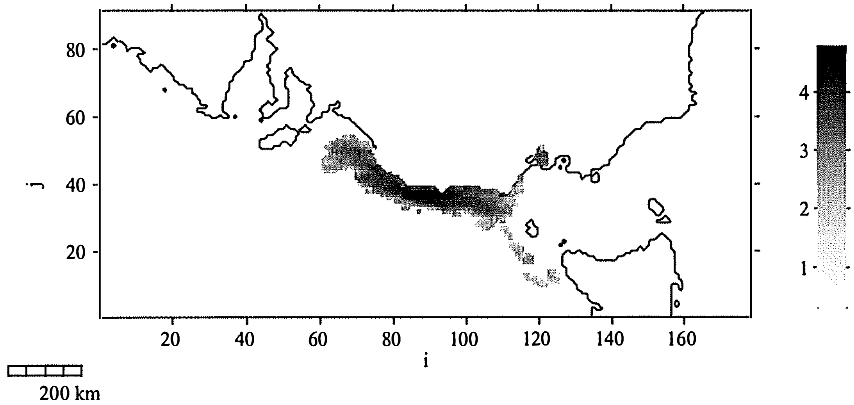

Figure 24 Predicted spawning area of King George whiting for post-larvae from Port Phillip Bay in 1995 based on 3-dimensional simulation. Scale refers to log particle density, ‘i’ = grid cell number from west to east, ‘j’ = grid cell number from south to north.

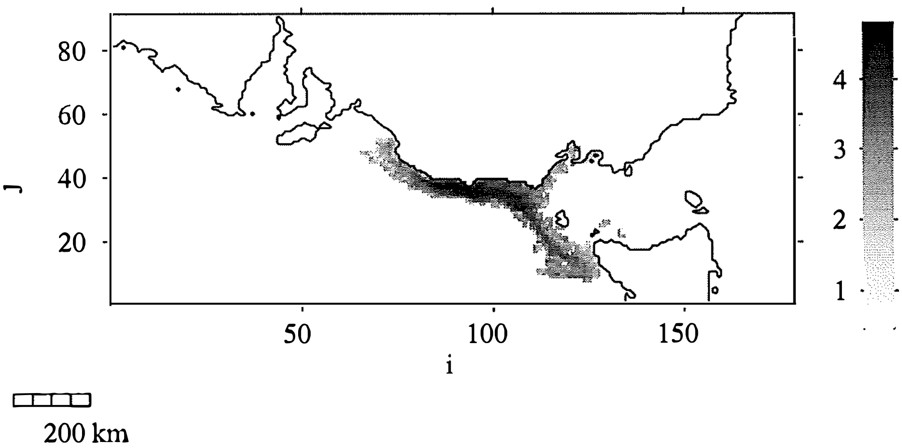

Figure 25 Predicted spawning area of King George whiting for post-larvae from Western Port in 1995 based on 3-dimensional simulation. Scale refers to log particle density, ‘i’ = grid cell number from west to east, ‘j’ = grid cell number from south to north.

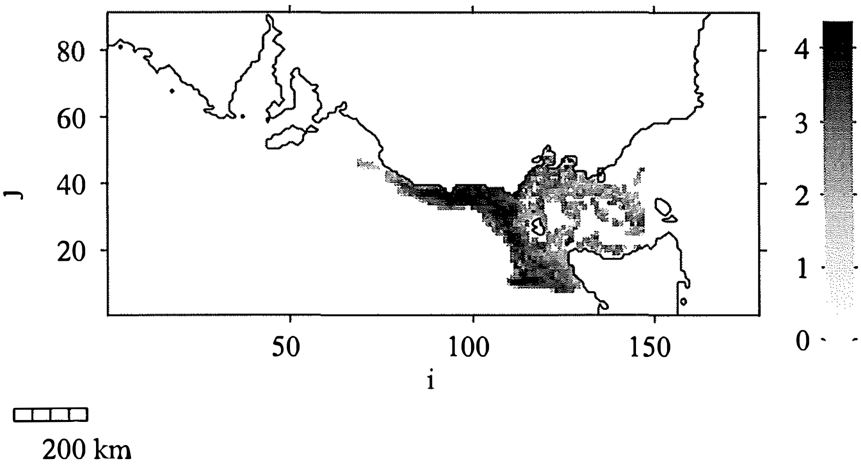

Figure 26 Predicted spawning area of King George whiting for post-larvae from Corner Inlet in 1995 based on 3-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

To investigate the larval advection pathways associated with the predicted spawning areas in the 3-D simulations, we also plotted the integrated numbers of particles throughout each simulation (the position of particles throughout the simulation is recorded and presented on a single graph). As would be expected, the Port Phillip Bay simulation showed a concentration of particles from Port Phillip Bay along the coast to the predicted spawning area (Fig. 27). The Western Port simulation showed a concentration of particles along the coast and also a bifurcation down the western boundary of Bass Strait to northwestern Tasmania (Fig. 28). The Corner Inlet simulation was similar to Western Port but also showed an advection pathway that looped around the western Boundary of Bass Strait and northern Tasmania to central Bass Strait (Fig. 29). This latter advection pathway suggests that recruits in Corner Inlet could be derived from spawning on the nearby coast, with larval advection in a clockwise gyre down to northern Tasmania, northwards along the western boundary of Bass Strait, and eastwards along the Victorian coast to Corner Inlet.

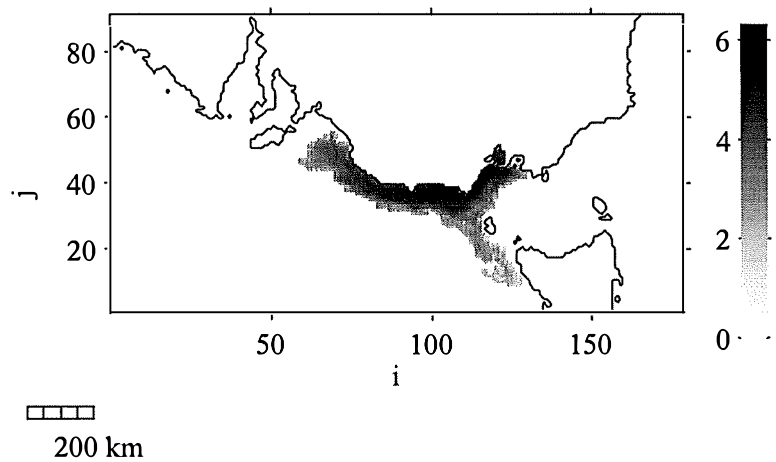

Figure 27 Predicted advection pathway for King George whiting post-larvae entering Port Phillip Bay in 1995 based on 3-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

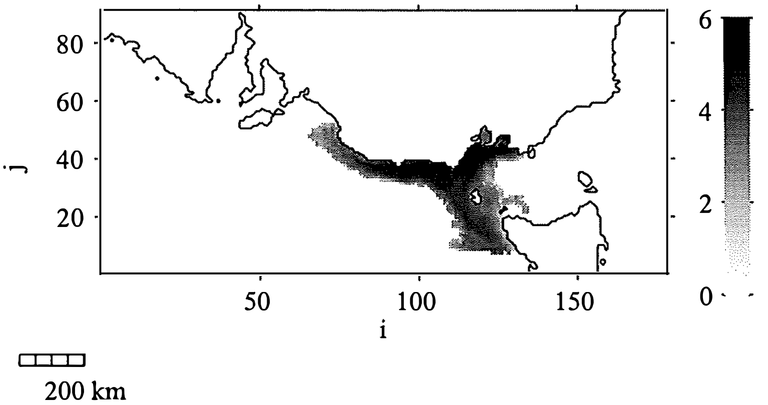

Figure 28 Predicted advection pathway for King George whiting post-larvae entering Western Port in 1995 based on 3-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

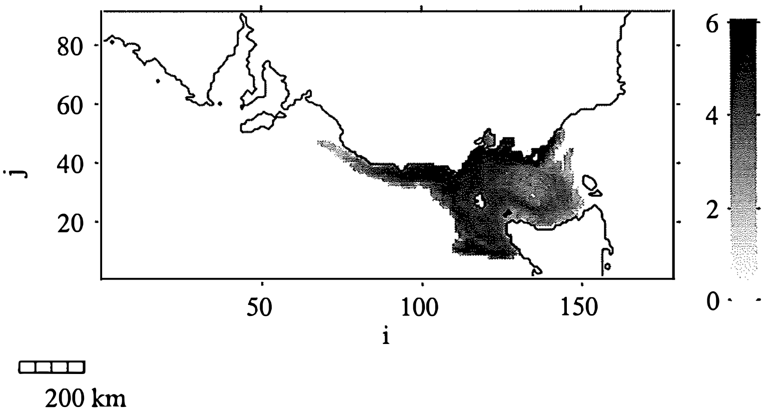

Figure 29 Predicted advection pathway for King George whiting post-larvae entering Corner Inlet in 1995 based on 3-dimensional simulation. Scale refers to log particle density, 'i' = grid cell number from west to east, 'j' = grid cell number from south to north.

7. Discussion

The major predicted spawning area for recruits from all bays and years, and based on both 2- and 3- dimensional modelling, was the western coast of Victoria and the far south-eastern coast of South Australia. This result is consistent even though larval durations and spawning times varied amongst bays and particularly amongst years. In contrast, arrival times of recruits at bays and amongst years were remarkably consistent. The comparison of bays in 1995 showed that when larvae were subjected to similar conditions of larval transport, larval duration increased and spawning time was correspondingly earlier for post-larvae recruiting to bays further to the east, reflecting the greater distance that would need to be travelled from a common spawning ground to more eastern recruitment sites. It is interesting that rather than spawning occurring at one time and recruits arriving progressively later to bays further to the east, recruits tended to arrive at bays at the same time, and the further to the east recruitment occurs, the earlier in the spawning season the recruits are derived from. This implies there is a 'window of opportunity' for recruitment before and after which recruitment cannot occur. Thus, rather than the recruitment period changing from year to year, the spawning period (or period within the spawning season) as well as the major source area (within the general spawning region) may vary from year to year dependent on transport processes.

When predicted spawning was compared amongst years for recruits to Port Phillip Bay the arrival times of recruits were consistent, but larval duration in 1989 was significantly longer and spawning was significantly earlier than in the other years, and the predicted area of spawning extended further west in 1994. These results probably reflect varying rates of larval transport amongst years, with a reduced rate of transport in 1989 resulting in longer larval duration, and an increased rate of transport in 1994 resulting not in shorter larval durations, but instead a westward extension of the predicted spawning area. This latter result may be due to the larvae having a minimum pre-competent phase before which settlement can occur (Jenkins and May 1994). The area of spawning predicted for 1994 encompasses the only area where spawning King George whiting have been recorded; Investigator Strait, South Australia.

Interannual differences in larval transport are most likely related to interannual variation in factors such as the strength of the westerly wind field, forced by factors such as the El Nino / Southern Oscillation. Such interannual variation in larval transport may have major implications for the fishery. For example, in 1994, when our results show that transport of larvae from the west was relatively strong, abundance of recruits in Port Phillip Bay was the highest in six years of monitoring (Jenkins, unpublished). This result appears to be translating into elevated commercial and recreational catches of three year old King George whiting in 1996/97.

Comparisons of larval transport within one recruitment period showed that post-larvae were derived from the same spawning area, but that early recruits were generally the result of early spawning and late recruits the result of late spawning. Larval durations were variable for the recruitment times but showed no trend, probably reflecting the particular oceanographic conditions that individual cohorts of larvae were exposed to over the larval period.

The 3- dimensional modelling suggested that spawning areas other than the coast of western Victoria and south-eastern South Australia were possible, particularly for recruits to Western Port and Corner Inlet. A caveat on the results is that the modelling will show all potential sites of spawning that could result in recruits arriving at a particular time and site, but in reality all such sites may not be spawning sites. Adult King George whiting are common on the rocky exposed coast of western Victoria and south-eastern South Australia, and they are also recorded on the northern Tasmanian coast and on the Victorian coast between Port Phillip Bay and Corner Inlet. In contrast, there is little evidence that adult King George whiting occur in deep water along the western boundary of Bass Strait. The results imply some possible segregation of stocks, particularly between Port Phillip Bay and Corner Inlet, because recruits to Port Phillip are derived from spawning in western Victoria, but recruits to Corner Inlet may be derived from central as well as western Victoria (and to a small extent Corner Inlet may be 'self seeding' if adults spawning on the central Victorian coast were derived from Corner Inlet). Our results are consistent with the fact that juvenile and adult King George whiting are rare to the east of Corner Inlet.

The results suggest that King George whiting are part of a broad ranging stock with spawning concentrated in western Victoria and southeastern South Australia. It is possible that the source spawning area also supplies recruits to the South Australian

Gulfs. For example, some recruits in 1994 may have been spawned in the Kangaroo Island area and it is possible that some larvae could have been advected northwward to the South Australian Gulfs. Thus, the stock appears to be widespread and straddles State boundaries, suggesting that management on an individual State basis may not be ideal. A minor contribution of self-seeding may be possible given the 3-D simulation results for Corner Inlet, but this likely to be overwhelmed by recruits from more distant sources.

A factor that might modify the results presented here is larval behaviour. We have demonstrated that late-larvae of King George whiting entering Port Phillip Bay show strong diurnal vertical migration, and also weak tidal vertical migration (Welsford 1996). Larvae are concentrated near the surface during daylight and tend to be randomly distributed through the water column at night. Such behaviour has implications for larval transport in that larvae near the surface are likely to be transported faster by wind driven currents than those deeper in the water column. This implies that diurnal vertical migration in younger larvae in Bass Strait could lead to more extensive dispersal than predicted in the passive model. For example, the influence of larval behaviour on predictions could lead to a shift of the predicted spawning area westward towards Kangaroo Island and the South Australian Gulfs. A caution on this interpretation, however, is that vertical migratory behaviour in fish larvae tends to be less well developed in younger stages (Neilson & Perry 1990, Heath et al. 1991, Champalbert & Koutsikopoulos 1995). Thus, larval behaviour may have less influence on the transport of younger stages. We are undertaking plankton sampling cruises on the R.V. *Franklin* in 1998 that will involve vertically stratified sampling and may provide information on the vertical migratory behaviour of younger larval stages of King George whiting.

8. Benefits

The benefit of the research is that it gives an understanding of the likely stock structure of King George whiting in Victoria and south-eastern South Australia. The results indicate that fisheries in bays and inlets of Victoria principally represent one stock with a common spawning area in western Victoria and southeastern South Australia. Thus, managers will be able to manage bay and inlet fisheries in Victoria as one stock with some confidence. The results also call into question the present separate management regimes between States, the fishery would probably benefit from cross-State management.

The results allow us to target our efforts in confirming the spawning areas and times for this species. For example, plankton sampling cruises on the R.V. *Franklin* in 1998 will now be planned on the basis of the predicted spawning areas and times. We are therefore planning cruises in May/June and July, with transects extending into southeastern South Australia. The South Australian Research and Development Institute (SARDI) will undertake simultaneous plankton sampling cruises on the R.V. *Ngerin* to extend transects further into south-eastern South Australia.

The present study will aid in the rational management and protection of the present King George whiting fishery. For example, the development of fishery management models such as is presently being undertaken by scientists in South Australia (FRDC project 95/008) requires information on stock structure so that modelling is conducted at the relevant spatial scales. This study suggests that such modelling should be conducted on a very broad, cross-State scale. Such models also require information on factors such as population age structure, fecundity and egg production, all dependent on the identification of spawning areas. These results provide initial predictions of spawning areas and times that will eventually be confirmed by plankton and adult sampling.

9. Further Development

The results of this study will be used as the basis for a plankton sampling survey on the R.V. *Franklin* and R.V. *Ngerin* in 1998 to confirm spawning areas and times of King George whiting in Victorian and south-east South Australian waters. The results could also be used as the basis for a study of adult reproductive condition, aimed at determining spawning areas and times, and reproductive parameters such as sex ratio, fecundity, and egg production.

10. Conclusion

The objective of this project was to use spawning dates estimated from otoliths of post-larval King George whiting collected in bays and inlets of Victoria, and reverse modelling with the MAFRI south-eastern Australian model based on climatic conditions over the larval development period, to estimate spawning sites and larval advection pathways. The objective was successfully achieved, spawning sites were predicted using two dimensional modelling for Port Phillip, Western Port and Corner Inlet in 1995, and for Port Phillip Bay in 1989 and 1994. Predictions were also made for the three bays in 1995 using three dimensional modelling.

The predicted spawning area for post-larvae collected in the three bays in 1995 using 2-dimensional modelling was along the coastline of western Victoria and south-eastern South Australia. A similar spawning area was predicted for post-larvae collected in Port Phillip Bay in 1989 but in 1994 the predicted spawning area extended west to approximately Kangaroo Island. Three-dimensional modelling for the three bays in 1995 again suggested that most post-larvae were derived from spawning in western Victoria and south-eastern South Australia, however, for post-larvae from Western Port, a small proportion may have been spawned on the western shelf of Bass Strait and north-western Tasmania, and for Corner inlet, a small proportion of the spawning may have occurred in the local area with larvae transported in a clockwise gyre around Bass Strait.

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12. Appendix 1: Intellectual Property

The major intellectual property is in application of the model to the study of King George whiting, particularly the utilisation of previously developed modelling techniques to extend the grid and focus on the specific problem at hand. New features of the model for King George whiting simulations have been developed and improved through the course of the project.

13. Appendix 2: Staff

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