Modelling the possible effects of climate change on an Australian multi-fleet prawn fishery

M. C. Ives[A,C], *J. P. Scandol*[B], *S. S. Montgomery*[B] *and I. M. Suthers*[A]

[A]School of Biological, Earth and Environmental Sciences, The University of New South Wales,
 Sydney, NSW 2052, Australia.
[B]NSW Department of Primary Industries, PO Box 21, Cronulla, NSW 2230, Australia.
[C]Corresponding author. Email: matthew.ives@industry.nsw.gov.au

Abstract. The relationship between fisheries and climate has been given renewed emphasis owing to increasing concern regarding anthropogenically induced climate change. This relationship is particularly important for estuarine fisheries, where there are documented correlations between river discharge and productivity. The commercial catch of school prawns (*Metapenaeus macleayi*) has been shown to be positively correlated with the rates of river discharge in northern New South Wales, Australia. In the present study, a simulation model was developed to analyse the dynamics of the stock for 10 years under alternative river discharge scenarios, and the effectiveness of a series of management strategies under these scenarios was examined. A size-based metapopulation model was developed that incorporated the dynamics of school prawn populations in three habitats being harvested by three different fishing methods. The model indicated that both the growth and movement of prawns were affected by the rates of river discharge, and that higher rates of river discharge usually generated increased commercial catches, but this outcome was not certain. It was concluded that the population does not appear to be overexploited and that none of the three alternative management strategies performed better within the model than the current spatio-temporal closures, even under a wide range of river discharge scenarios.

Additional keywords: Bayesian modelling, climate variability, management strategy evaluation, stock assessment.

Introduction

The relationship between the productivity of commercial fisheries, rainfall and temperature has been given renewed emphasis with concerns regarding anthropogenically induced climate change (Murawski 1993; Klyashtorin 1998, 2001). One of the many concerns associated with climate change is the effect that climate change may have on river discharge and water resources (Oki and Kanae 2006). These impacts are likely to be compounded by increasing demands from human populations for fresh water (Vorosmarty *et al*. 2000).

Correlations have been found between river discharge and the productivity of several estuarine fisheries around the world (Growns and James 2005; Childs *et al*. 2008; Nicholson *et al*. 2008). Such correlations appear to be particularly important for penaeids, which inhabit subtropical regions (Vance *et al*. 2003; Robins *et al*. 2005; Díaz-Ochoa and Quiñones 2008). The association between river discharge and catch may be positive (e.g. *Penaeus fluviatilis* and *Penaeus aztecus* Gunter and Edwards 1969; *Penaeus merguiensis* Vance *et al*. 1985) or negative (e.g. *Penaeus merguiensis* Vance *et al*. 1998) and may not be consistent between regions for the same species (e.g. *P. merguiensis* Vance *et al*. 1985, 1998). One of the key commercial penaeids in Australia that has been identified as having a positive correlation between commercial catch and river discharge rates is the eastern school prawn (*Metapenaeus macleayi*) (Racek 1959; Ruello 1973*b*; Glaister 1978*b*).

The eastern school prawn is a valuable target species for commercial fisheries operating on the east coast of Australia. *Metapenaeus macleayi* also plays an important ecological role in estuarine ecosystems as a significant species in the food web that connects detritus and primary production to higher trophic levels (Ruello 1973*a*; Dall *et al*. 1990; Griffiths *et al*. 2007). The commercial and ecological importance of school prawns has encouraged several research studies into the species' life history, growth and movement (Ruello 1977; Glaister 1978*a*; Coles and Greenwood 1983); behaviour (Ruello 1973*a*); size selectivity in fishing gear (Broadhurst *et al*. 2004; Macbeth *et al*. 2005, 2006); and the extent of recreational harvest (Reid and Montgomery 2005).

The life cycle of the eastern school prawn occurs primarily in estuarine waters and, in general, only sexually mature prawns move out into ocean waters to spawn. However, as has been identified in almost every major study of the species, heavy rain events and subsequent large river discharges appear to promote the seaward movement of both mature and immature school prawns (Ruello 1973*a*; Glaister 1978*b*; Loneragan 1999).

A major fishery for school prawns exists in the Clarence River, in northern New South Wales (NSW), Australia. The Clarence River is the largest coastal river in south-eastern Australia, with a total water area of ∼103 km² and a catchment area that covers over 200 000 km² (McVerry 1995). The Clarence River region has a mostly subtropical climate with over 1400 mm of rain per

annum, most of which occurs in the months from December to April. Rainfall is highest in the upper regions of the catchment area, and periodic flooding of the lower catchment occurs after heavy rain events (although major flood mitigation works completed in the 1960s and 1970s have significantly reduced the volume of flooding) (McVerry 1995). The commercial prawn fisheries operating in the Clarence River region land approximately half of the total annual catch of school prawns in NSW (NSW DPI Catch statistics). During the past 5 years, the Estuary Prawn Trawl (EPT) fishery has landed, on average, over 70% of the school prawns caught in this Clarence region, with the Ocean Prawn Trawl (OPT) and stow-net fisheries landing ~15% and 9% respectively.

The research presented here had two objectives. The first objective was to develop a simulation model based on the association between river discharge and school prawn landings in the Clarence River, and to analyse the dynamics of the stock under various alternative river discharge scenarios. The second objective was to evaluate alternative management strategies for the three major commercial fisheries that harvest the stock, considering the uncertainty associated with future rainfall variability.

Materials and methods

Operating model

The model developed for the present study can be classified as a stage/size-structured metapopulation model (Caswell 1989). Explicitly modelling the spatial population structure using a metapopulation model was considered essential to capture the dynamics of the interactions between the prawn population and the three fisheries that target the species (Cadrin and Secor 2009). Together with the dynamics of the school prawn population, the model incorporated river discharge and temperature as drivers of school prawn movement and growth (and hence catchability/vulnerability), and a fisheries component encompassing the three major commercial fisheries that harvest the species. As each of these fisheries operates in a different area of the Clarence system, any environmental effects on prawn movement and growth can impact the fisheries in different ways. The model was used to analyse the impact of various simulated environmental scenarios on the three main fisheries in the Clarence River area, as well as on the state of the school prawn stock. A full description of the model used in this project is presented in an Accessory Publication, available on the web.

Spatial structure of the model

The model represented the Clarence River region and was defined by three broad compartments. The division of compartments was based primarily on the fisheries that exploit the population, but could be loosely represented as spatial zones (Fig. 1). The first compartment was the non-fishing zone (C1), which consisted of the areas of the Clarence River closed to commercial fishing and encompassed all areas upstream of Ulmarra (near Grafton). The second compartment was the estuary fishing zone (C2), which consisted of the areas of the Clarence River open to estuary prawn trawl and stow-net fishing. The third compartment was the ocean fishing zone (C3), which consisted of the

ocean waters surrounding the mouth of the Clarence River classified by NSW DPI as Zone 2 of the ocean prawn trawl grounds; this compartment lies between 29 and 30°S. This zone covered what is understood to be the extent of ocean movements of the school prawns that emigrate out of the Clarence River estuary to spawn (Glaister 1978a). Each of the compartment zones were chosen specifically so that the model would represent the entire Clarence River school prawn stock (Ruello 1977).

The three compartments shown in Fig. 1 can also be represented diagrammatically in the context of the model structure (Fig. 2). The top half of Fig. 2 shows each of the prawn stock metapopulations in each of the compartments, with reproduction and the movement of prawns between compartments shown with arrows. The bottom half of Fig. 2 presents the size stages used in the model, with the relative numbers of the three main life stages – larvae, juveniles and adults – represented by the polygons. As shown, the modelled larvae occurred in greatest numbers in the non-fishing zone, whereas juveniles occurred in all compartments but mostly in the estuary fishing zone. Adults were primarily present in the estuary and ocean fishing zones.

Stages of each model run

Each model simulation underwent three stages. A model run began with a population of 10^7 larval prawns and underwent a 10-year burn-in process with fishing effort based on the average monthly effort from the calibration data. Following this, the model moved into the 21-year calibration period (1985–2005) where observed fishing effort and river discharge data were applied (see the Accessory publication for data sources). Finally, the model moved into the 10-year simulation period from January 2006 to December 2015. In this stage, fishing effort was based on the average historical monthly effort from the past 10 years as well as catch per unit of effort levels (see Eqn 9 in the Accessory publication), and river discharges were generated using a probabilistic model based on the past 21 years of observed records.

Model calibration

The model was calibrated against existing catch data from the Clarence River fisheries. The output from the model was compared with 21 years of existing catch history from January 1985 to December 2005. However, it became evident in the calibration of the model to catch history that early life mortality and catchability were highly correlated. This resulted in several possible solutions from very different combinations of these parameters. This dilemma was resolved in part by also calibrating the size distributions of the harvested prawns produced by the model with empirical distributions presented in several publications (Broadhurst and Kennelly 1996; Broadhurst *et al.* 2003), including information on the change in size distribution after a major rain event (Ruello 1973b).

The model was then fitted to the observed catch data using a maximum likelihood function and the Bayesian Sampling Importance/Re-sampling (SIR) method (Brandon *et al.* 2007; Ives and Scandol 2007). Owing to computational limitations, Bayesian priors were only applied to a subset of parameters (see also Fay and Punt 2006). Choosing the most appropriate parameters for the Bayesian priors was a three-step process.
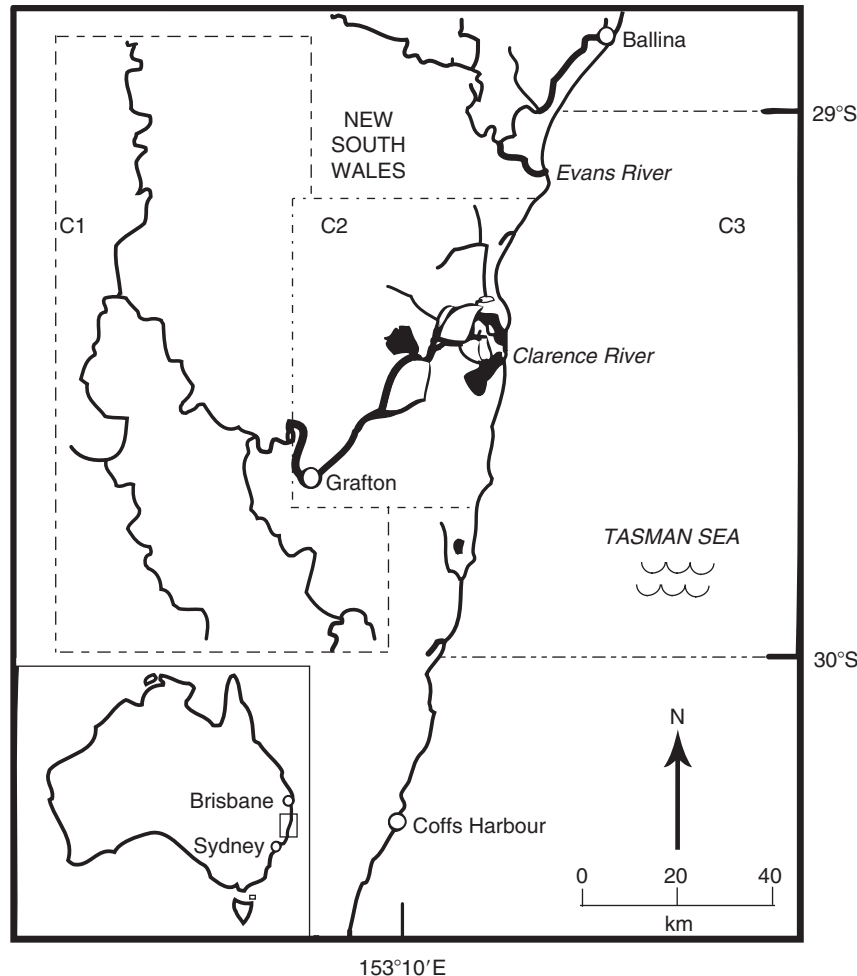
Fig. 1. A map of the Clarence River region showing the three model compartments. C1, the non-fishing zone; C2, the estuary fishing zone; C3, the ocean fishing zone.

First, the model was manually calibrated using a cost function. Second, a sensitivity analysis was conducted on the manually calibrated model to help determine the most appropriate parameters. Finally, the Bayesian SIR approach was applied to the manually calibrated model with Bayesian priors given to the five most suitable parameters. Each of these steps is explained in more detail in the Accessory Publication.

Climate variability scenarios

The present study examined the effect of nine different climate scenarios on the prawn stock and the estuary and ocean fisheries that harvest them. The nine scenarios were combinations of the different river discharge states created by increasing and decreasing future rates of mean river discharge and river discharge variability with respect to a scenario that maintained historic rates (i.e. those observed from January 1985 to December 2005; see Fig. 3a, b). The historic river discharge rates will hereafter be referred to as the L20D data (Late 20th Century Discharge data).

The scenarios were conducted by projecting into the future the joint posterior distribution of the model runs produced in the

Bayesian SIR step of the calibration process. Each of the model runs that made up the posterior was projected forward 10 years to produce posterior probability distributions of the management indicators. The re-sampled joint posterior distribution consisted of 4000 model runs, each with its own set of values for the five key parameters and each with its own unique stochasticity in river discharge levels, recruitment error and effort dynamics. The effort for each fishery in the future months was dependent on the average historical effort, but also on each future month's catch per unit effort levels (Eqn 9 in the Accessory publication). The log of the recruitment error was a normally distributed random variable (mean = 0, coefficient of variation (CV) = 0.2; Eqn 10 in the Accessory publication). The future maximum monthly river discharge rates were derived from a series of seasonal lognormal distributions (one distribution for each month), each with a separate mean and CV. This allowed for months that are historically wetter to have a higher mean and CV than drier months and thus an increased likelihood of a higher river discharge. The monthly mean and CV values were calculated by fitting the past 21 years of river discharge data to log-normal distributions. The mean and CV values of these distributions were then modelled with a sine curve (Fig. 3a, b). These two sine curves represented
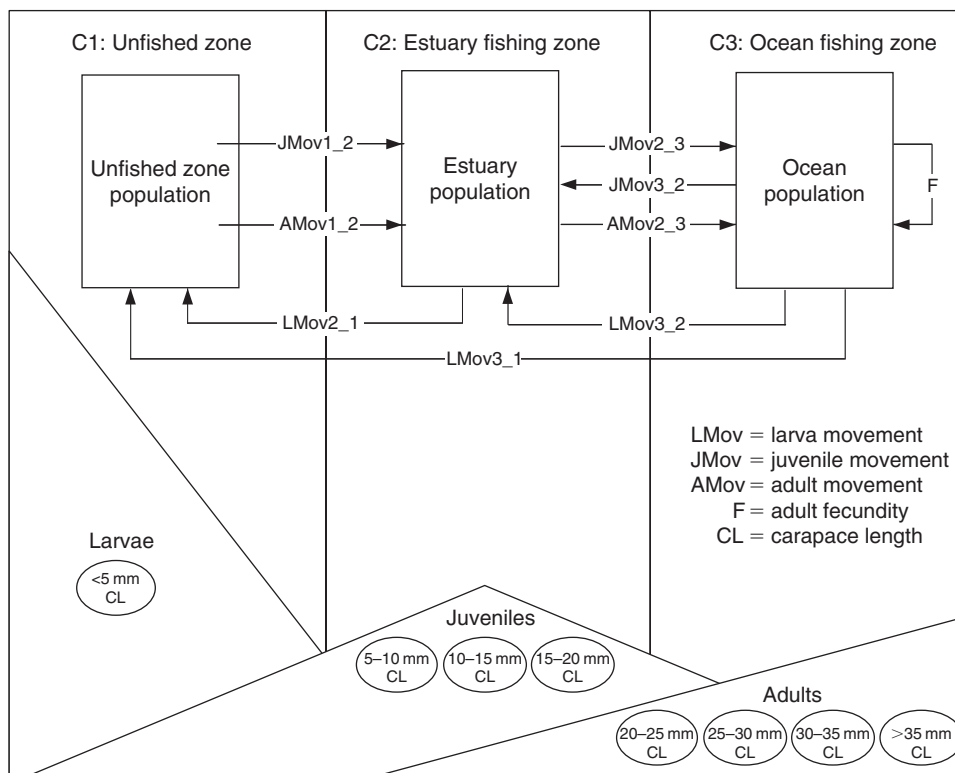
Fig. 2. The stage-size structured metapopulation model showing the three model compartments (C1–C3). The upper area displays the three metapopulation stocks within each compartment and shows the movement between the populations. The lower area displays the various life stages based on carapace lengths (CL) into which individuals are graded. The polygons provide a stylistic representation of the relative numbers of individuals of the three main life stages – larva, juvenile and adult – and in which compartment these life stages predominantly reside.

the L20D levels. As the log-normal distribution has a very long tail, a cap was placed on the maximum allowed river discharge of 15-fold the mean value. The lower and higher values involved a 50% decrease and increase, respectively, from the L20D levels. At the extremes, these scenarios translated into a 20% increase or decrease in the maximum river discharge over the 10-year projected period, which is consistent with the extremes of predicted changes in precipitation levels for the Clarence River basin as generated by the climate change model OzClim Version 2.0.1 Beta (CSIRO and IGCI 2007) (see the Accessory publication for further details).

Stochasticity was incorporated into the model through the log-normal distributions, from which the river discharge values were generated, as well as through the recruitment error in the stock–recruitment function (Eqn 10 in the Accessory publication). Each scenario was simulated with 100 replicates, producing a distribution of possible outcomes. Each of the nine climate scenarios was conducted under the 'current closures' management strategy explained below.

Alternative management strategies

The eastern school prawn fisheries in NSW are input controlled. The NSW Department of Primary Industries (NSW DPI) manages the activities of fishers through the number of commercial licences, through restrictions on fishing gear, boat size and engine power; and through temporal and spatial closures. The alternative management strategies examined in the present study were restricted to alternative temporal closures and included the following four strategies.

(1) Current closures (base case): in the current closures strategy, the ocean prawn trawl fishery does not have any closed season. However, the main channel of the Clarence River is closed to estuary prawn trawling for the months of June through to November, with Lake Wooloweyah (part of the Clarence estuary system) closed from June through to September. Finally, for the stow-net fishery, there is a closed season extending from June through to July, with some additional complexities that did not affect the present study.

(2) Add May EPT closures: this strategy includes all of the closures in the 'current closures' strategy plus the closure of the EPT fishery in May.

(3) Add Oct EPT closures: this strategy includes all of the closures in the 'current closures' strategy plus the closure of the EPT fishery in October.

(4) Sampled prawns per 1/2 kg closures: in this strategy, a sample is taken at the end of each month using a single standard estuary prawn trawl boat-day of effort (without error). If the
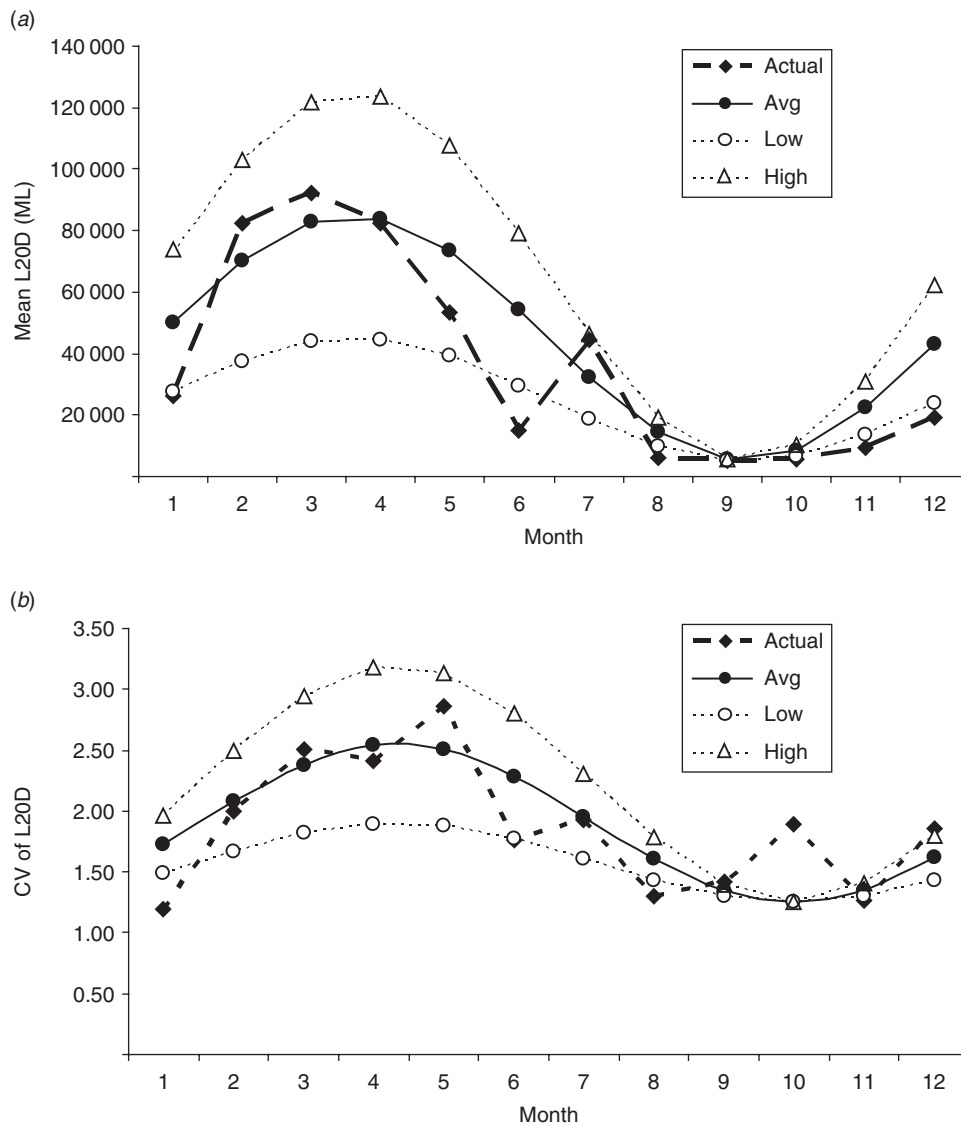
Fig. 3. Sine curves used to model seasonal variation in the (*a*) mean and (*b*) coefficient of variation (CV) of log-normal distributions fitted to historical maximum river discharge data. The Actual line shows the values from the historical record and the Low, Avg and High lines show the values used in their respective scenarios.

average number of sampled prawns per 1/2 kg lies above a set threshold (130 prawns per 1/2 kg) then the EPT fishery is closed the following month. The ocean prawn trawl and stow-net fishery closures remain the same as in the 'current closure' strategy.

The three alternative management strategies were chosen after consultation with fisheries managers and representatives of the Clarence River Fishermen's Co-operative. Each of these four management strategies were examined under three climate variability scenarios, namely scenarios S4, S5 and S6 (Table 1), which are the low, average and high L20D scenarios with average L20D variability. This enabled each strategy to be examined for its performance given the uncertainty associated with future river discharge levels.

Results

Model calibration

Step 1: manual calibration

After careful manual calibration, the model was found to have a 'good' fit to the observed catch records from 1985 to 2005 for each of the three fisheries (cost function values of 0.35 for EPT, 0.36 for OPT and 0.73 for stow net). Fig. 4*a*–*c* displays the observed and estimated catch values for the model run produced by the manual calibration process. This single replicate indicated that the model was capable of both a good qualitative and quantitative representation of the three commercial fisheries in the present study.

The observed ocean and estuary catches are considered to be reasonably accurate records, although there exists an issue with

Table 1. The nine climatic scenarios evaluated

Summary of the alternative combinations of low to high historic river discharge (L20D) rates and low to high discharge variance (represented by the coefficient of variation (CV)) that form the nine climatic scenarios

	Low L20D mean	Avg L20D mean	High L20D mean
Low L20D variability	S1: Low CV, low mean	S2: Low CV, avg mean	S3: Low CV, high mean
Avg L20D variability	S4: Avg CV, low mean	S5: Avg CV, avg mean	S6: Avg CV, high mean
High L20D variability	S7: High CV, low mean	S8: High CV, avg mean	S9: High CV, high mean

the logbooks before July 1997 where estuary catches from stow nets were uncertain (approximately 10% of estuary catches). Furthermore, there is some speculation as to the accuracy of the misclassification of juvenile eastern king prawns (*Melicertus plebejus*) as juvenile school prawns.

One possible explanation for why the modelled stow-net catches did not always track the peaks of the observed data is that stow nets are generally set adjacent to the banks of the river in the water column where it is believed that many of the larger prawns choose to move out to sea on the river flow-out currents. As the modelled stow-net fishers pulled their catch from the entire population in the estuary rather than a smaller subset of larger prawns, the modelled catches would be expected to be lower than the catches observed.

Finally, although gear selectivity and size frequency distributions produced in the field can differ greatly both temporally and spatially within the same river system (Broadhurst *et al.* 2004; Macbeth *et al.* 2005), the size frequency distributions produced by the model were found to lie within the range of published distributions from the Clarence River (Broadhurst and Kennelly 1996; Broadhurst *et al.* 2003).

Step 2: sensitivity analysis

In each of the stepwise regression analyses for the sensitivity analysis, the R^2 correlation co-efficient was above 50% (Table 2), indicating that the retained parameters could be associated with the key processes driving the changes to the management indicators. The R^2 for the Future Ocean Prawn Trawl Catch was 69% (Table 2), indicating a relatively good fit for this regression. The comparatively lower R^2 values for the depletion ratio (DR) and estuary catches (DR $R^2 = 50\%$, EPT $R^2 = 51\%$) suggest that the responses of these indicators could not be so easily represented as a simple combination of the parameters in the model.

The sensitivity analysis illustrated that the key drivers of the estuary and ocean catch levels and DR were catchability (q), larval mortality (LM), juvenile mortality (JM), the base unfished zone salinity levels (C1SalBas) and the base unfished zone and estuary food levels (C1FooBas and C2FooBas). The importance of catchability and larval and juvenile mortality is reasonable given their importance in stock dynamics. Thus, these three variables were obvious candidates for the Bayesian analysis, especially considering the lack of research regarding their true values (Appendix 1). Salinity levels are directly related to the impact of river discharge on migration into fishing zones and hence catch levels. Investigation of the impact of base unfished zone and estuary food levels (C1FooBas and C2FooBas) showed that these parameters had virtually the same effect on the model results as larval and juvenile mortality. Because these parameters

directly affected the rate of growth of prawns, changes in these parameters affected the amount of time prawns spent in each of the high-mortality early life stages.

The significance of some of the temperature-related parameters indicates the importance of the model assumptions regarding the effect of seasonal patterns on prawn growth and migration. The phase and frequency parameters (e.g. C1TempCp and C1TempCf) are of less concern than the amplitude and base parameters (e.g. C1TempCa and C2TempCb). The phase and frequency are dictated by the more rigid annual seasonal pattern of the Earth's rotation around the sun, whereas the base and amplitude of seasonal temperature cycles may have changed in recent history, with a portion of these changes likely to be attributable to anthropogenic impacts (Hennessy *et al.* 2004).

Several notable parameters did not show up in any of the regression results. The fact that only three migration parameters were found to be significant (LMov3_1, JMov2_1 and AMov2_3) suggests that the initial migration parameter values did not greatly impact the results. This is noteworthy as these parameters were selected to initiate the model and could only be speculated on based on published trends (detailed in the section on movement in the Accessory publication). In addition, the parameter for the initial number of larval prawns (InitN), which was used to start each model run, was found to be non-significant for all of the management indicators except ocean trawl catch. This suggests that the burn-in process that generated a steady-state prawn population before the calibration stage was working satisfactorily. The von Bertalanffy growth parameters would most likely be significant in a sensitivity analysis, but they were not included in the analysis as the uncertainty in these parameters was contained within the growth rate distributions applied to the population (see the section on individual growth in the Accessory publication).

Step 3: Bayesian SIR calibration

The quality of the joint posterior pdf was found to be adequate (in particular maximum importance ratio (MIR) < 0.005 and maximum single density (MSD) < 1%; Ives and Scandol 2007) only when raw (i.e. not log-transformed) catch values were used in the likelihood function (Eqn 24 in the Accessory publication). This required the reasonable assumption that the residuals between the observed and predicted catches were normally distributed.

Scenarios

Moving from smaller to larger river discharges resulted in an increase in mean ocean catches (a 20% increase in mean catch with a 20% increase in mean discharge) and a small decrease
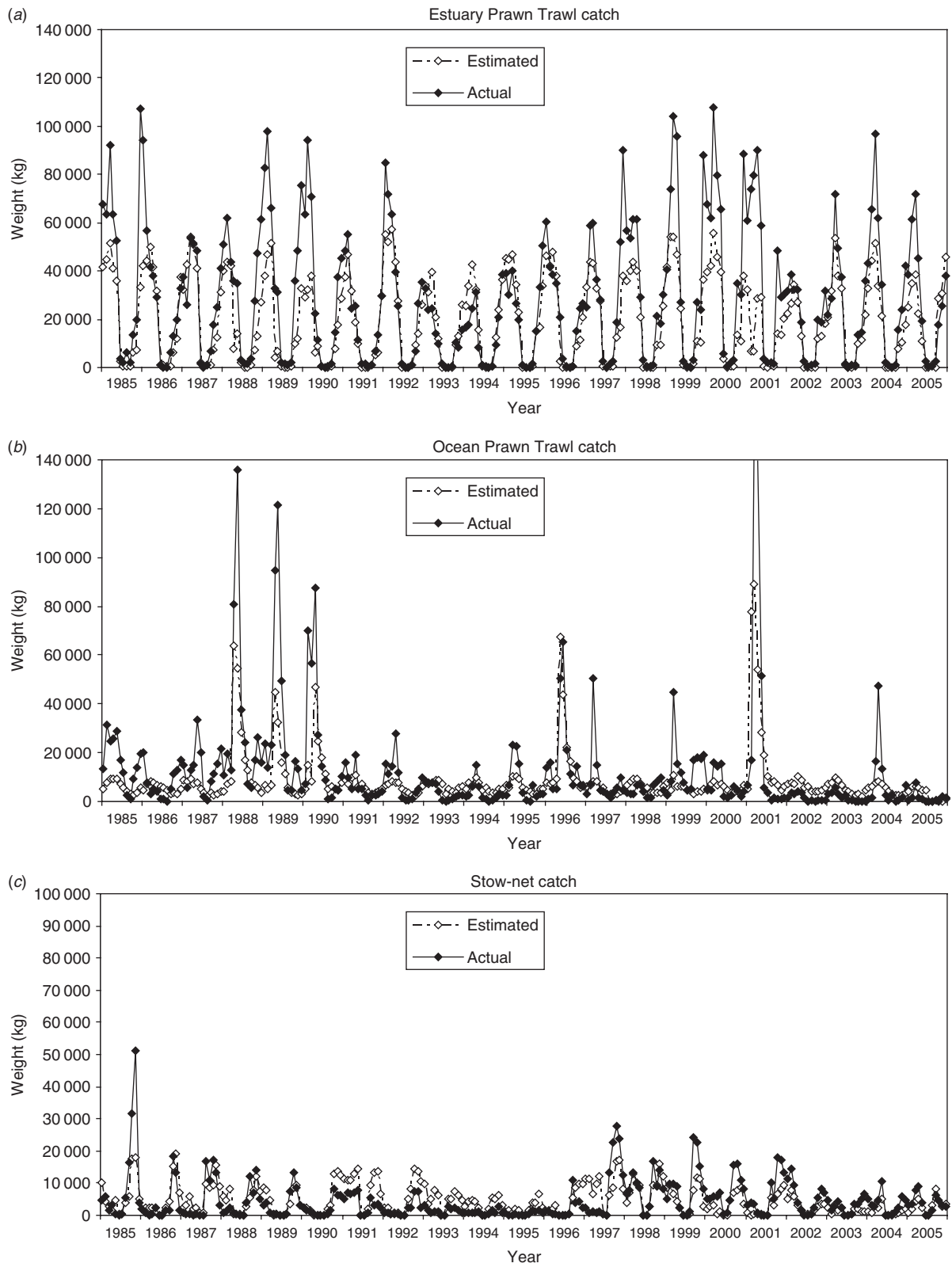
Fig. 4. Modelled and actual (observed) catches from the three fishing methods considered in the present study from the Clarence River and Ocean Zone 2 (29 and 30°S) from January 1985 to December 2005. (*a*) Estuary Prawn Trawl; (*b*) Ocean Prawn Trawl; (*c*) stow netting.

Table 2. Results of the stepwise regression best-fit to model parameters for the three management indicators

The management indicators are Future Ocean Prawn Trawl Catch (OPT), Future Estuary Prawn Trawl Catch (EPT) and the Depletion Ratio Biomass 2005/Biomass 1985 (DR). The percentage values indicate the average movement in the management indicator (columns) attributed to a 20% absolute deviation in each parameter (row) over that parameter's estimated range of possible values. The final row shows the R^2 value for each regression equation

Parameter	Description	OPT (%)	EPT (%)	DR (%)
AM	Adult natural mortality	3	2	3
JM	Juvenile natural mortality	7	4	
LM	Larva natural mortality	17	13	
q	Catchability/fleet efficiency	29	31	36
Rv	Virgin recruitment levels	4	3	
z	Steepness of the stock-recruit relationship	1	1	
InitN	Initial population number of prawn larvae	3		
F8	Fecundity of female prawns >35 mm carapace length	1		
LMov3_1	Larva migration from ocean to unfished zone	1		
JMov2_1	Juvenile migration from estuary to unfished zone			1
AMov2_3	Adult migration from estuary to ocean	4	2	1
C1TempCa	Unfished zone temperature cycle amplitude	1	1	2
C1TempCb	Unfished zone temperature cycle base level	2	2	5
C1TempCp	Unfished zone temperature cycle phase			10
C1TempCf	Unfished zone temperature cycle phase			1
C2TempCa	Estuary temperature cycle frequency	1	1	1
C2TempCb	Estuary temperature cycle base level	2	2	4
C2TempCf	Estuary temperature cycle frequency		1	1
C2TempCp	Estuary temperature cycle phase		4	3
C3TempCp	Ocean temperature cycle phase			1
C1SalBas	Unfished zone salinity base level		15	17
C1FooBas	Unfished zone food base level	7	5	3
C2SalBas	Estuary salinity base level	2	4	4
C2FooBas	Estuary food base level	7	7	7
MDCVb	L20D variance cycle base level	1		
TMRD	Total future maximum river discharge	3		
RE	Months since last major rain event	2		
EPT_BasE	Estuary Prawn Trawl base monthly effort level		2	
OPT_BasE	Ocean Prawn Trawl base monthly effort level	1		
OPT_MaxE	Ocean Prawn Trawl maximum monthly effort level	1		
Mult. R^2	Multiple R^2	0.50	0.69	0.51

in estuary catches (a 4% decrease in mean catch with a 20% increase in mean discharge) (Table 3). This is unsurprising given the effect that river discharge has on the ocean migration of prawns. The DR also increased, but not to any significant extent. The lack of change in the DR was likely to be the result of the effect of rain events on increased growth away from early-life mortality being tempered by the higher overall catches. That is, the feedback loops in the model, in particular the density dependence built into the stock recruitment function and the fisher effort dynamics, helped to maintain a fairly stable biomass.

The variance of each indicator also increased with increasing river discharge levels. That is, the low extremes for the high L20D scenarios were similar to the low extremes of the low L20D scenarios. This can be interpreted as indicating that higher discharge levels do not guarantee higher catches.

Alternative management strategies

Very little separated the results from the four alternative management strategies (Table 4), with none of the alternative management strategies showing a significantly different effect on the management indicators than the current strategy (i.e. the 90% confidence intervals of the modelled outcomes overlapped). That said, the current closure and high prawns kg^{-1} strategies provided the highest combined catch weights. However, the May closure and October closure strategies produced a slightly lower variance in the catch. Lower variance in catches can also be an important management goal as it provides a steadier flow of income to fishers (Grafton *et al.* 2004). Thus, if we were to judge the alternative strategies using a range of criteria even these small differences between the alternative strategies may disappear.

Discussion

One of the key findings from the present modelling study was the possible impact on the Clarence River school prawn fisheries of future droughts, or reduced river discharge from increasing human water extractions. If, as suggested by recent research (Hennessy *et al.* 2004), climate change results in lower future river discharge levels and increased variability for the Clarence River, the various school prawn fisheries could be significantly

Table 3. Results from the nine climatic scenarios showing median values (the 25th and 75th percentiles are in parentheses) for each of the three management indicators

	Low L20D mean	Avg L20D mean	High L20D mean
Future Average Annual OPT Catch (tonnes)			
Low L20D variability	S1: 67 (63, 74)	S2: 84 (72, 100)	S3: 105 (85, 121)
Avg L20D variability	S4: 67 (63, 75)	S5: 82 (67, 99)	S6: 102 (80, 120)
High L20D variability	S7: 65 (63, 73)	S8: 74 (66, 91)	S9: 87 (73, 107)
Future Average Annual EPT Catch (tonnes)			
Low L20D variability	S1: 225 (217, 234)	S2: 213 (204, 222)	S3: 208 (198, 216)
Avg L20D variability	S4: 226 (219, 237)	S5: 219 (207, 226)	S6: 212 (204, 220)
High L20D variability	S7: 229 (221, 238)	S8: 223 (212, 231)	S9: 218 (207, 227)
Future Depletion Ratio (Estimated Biomass 2015/Estimated Biomass 1985)			
Low L20D variability	S1: 1.08 (1.04, 1.13)	S2: 1.09 (1.04, 1.15)	S3: 1.08 (1.04, 1.16)
Avg L20D variability	S4: 1.08 (1.04, 1.14)	S5: 1.08 (1.04, 1.15)	S6: 1.08 (1.04, 1.16)
High L20D variability	S7: 1.08 (1.04, 1.14)	S8: 1.08 (1.04, 1.14)	S9: 1.08 (1.04, 1.15)

Table 4. Results from the four alternative management strategies against the three climatic scenarios showing median values (5th and 95th percentiles in parentheses) for each of the four management indicators

	Low L20D mean	Avg L20D mean	High L20D mean
Future Average Annual OPT Catch (tonnes)			
Current closures	67 (63, 75)	82 (67, 99)	102 (80, 120)
Add May closure	68 (63, 75)	82 (68, 99)	103 (80, 120)
Add October closure	68 (63, 75)	82 (68, 99)	103 (80, 120)
High prawns kg^{-1}	68 (63, 75)	82 (67, 99)	102 (80, 120)
Future Average Annual EPT Catch (tonnes)			
Current closures	226 (219, 237)	219 (207, 226)	212 (204, 220)
Add May closure	206 (202, 216)	200 (190, 208)	193 (186, 201)
Add October closure	218 (211, 227)	211 (200, 218)	204 (195, 212)
High prawns kg^{-1}	226 (219, 236)	220 (208, 226)	213 (204, 220)
Future Depletion Ratio (Estimated Biomass 2015/Estimated Biomass 1985)			
Current closures	1.08 (1.04, 1.13)	1.09 (1.04, 1.15)	1.08 (1.04, 1.16)
Add May closure	1.09 (1.04, 1.15)	1.10 (1.05, 1.15)	1.09 (1.05, 1.16)
Add October closure	1.08 (1.04, 1.14)	1.09 (1.05, 1.15)	1.08 (1.05, 1.16)
High prawns kg^{-1}	1.08 (1.03, 1.14)	1.08 (1.04, 1.15)	1.08 (1.04, 1.15)

affected. However, some reassurance can be found from the present modelling study in that none of the alternative discharge scenarios showed a significant depletion in the school prawn stock if the current fisheries were maintained. Given the role that *M. macleayi* plays in the Clarence River food web, this is an important finding for the long-term condition of the estuarine ecosystem, which could be susceptible to the ability of key species to cope with drought (Martin and Michael 2000).

The sensitivity analysis showed that one of the most important drivers of each of the management indicators was the total future river discharge rate. Higher discharge levels resulted in an increased probability of higher catches and a higher stock biomass, but they did not guarantee them (as illustrated in the spread of the management indicators).

The sensitivity analysis also showed some clear insights into the main drivers of the population dynamics. In particular, the catchability of the prawns was shown to have a significant impact on all three of the management indicators. Given that these populations are known to school, this process may well be more complex than that represented, yet little research was available to understand this important process for school prawns (but see Zhou *et al*. 2007). Also significant in the sensitivity analysis were parameters associated with larval and juvenile mortality and the stock-recruitment process. Unfortunately, these are also areas in which little research was available to parameterise the model. The sensitivity of the results to these parameters suggests that research into recruitment and early-life survival of prawns could significantly improve the understanding of such stocks (Werner *et al*. 1983). Research on issues such as the role played by non-fishing zones (Sheaves *et al*. 2007) and the impact of pollutants on early survival could prove fruitful (McVerry 1995). Another research area of potential value is the artificial stocking of juvenile prawns to help alleviate problems associated with seasonal fluctuations in recruitment (Loneragan *et al*. 1998; Rothlisberg *et al*. 2001). Finally, the fact that the recreational catch of school prawns was included in 'natural mortality'

could be a significant oversimplification of this process, particularly as recreational catch is most likely to have increased over time with increases in coastal populations.

Although an increase in river discharge generally resulted in an increase in the variability in both estuary and ocean catches, the effect of such large catches on the biomass was mixed. Large river discharge levels sometimes increased the catch so much that they actually resulted in an overall reduction in future recruitment in several model runs. This result suggests that alternative management strategies, such as the closure of different fisheries at different times, could reduce the variability in catch levels. In any case, there was no significant reduction in catch variability between the four management strategies tested.

The results of the alternative management strategies suggested that there was little reason to change from the current spatio-temporal closures, and this would be the case even under a wide range of river discharge scenarios. First, the current strategy produced one of the highest overall future average annual catches in all scenarios. Second, although the mean DR was slightly lower for the current strategy, the difference between the strategies was not significant and in all cases the DR was greater than one, suggesting that the stock was not at serious risk of recruitment overfishing, regardless of the management strategy used. Finally, significant industry and transition costs could be involved in moving to a new strategy, particularly to a strategy based on sampled prawn counts. Although this latter closure strategy fared reasonably well in this analysis, it would be difficult for fishers to manage because it would create an inconsistency in their income streams and make the payment of large costs and loans more difficult. Furthermore, it would make it harder for the fishers to retain skilled workers as they would not be able to offer defined periods of work. Such considerations are rarely included in models, so they should not be the only source of information used to base management decisions (Schnute and Richards 2001).

One weakness with the analysis presented here is that it does not include economic components such as the market price of the prawns and the costs of inputs such as fuel. It is the profitability of fishing rather than the total catch that drives the long-term behaviour of fishers. Finally, each of the three fishing methods presented in the present study – stow netting, estuary prawn trawling and ocean prawn trawling – harvest multiple species. In particular, the trawling methods also catch eastern king prawns, which are another highly valued prawn species in NSW. These additional dimensions of these fisheries are avenues for future research that could generate contrasting results to those presented here.

The SIR algorithm used in the present study is a relatively simple and versatile Monte Carlo method for use in fisheries assessment. However, the models used in the present study uncovered some of the limits of the SIR algorithm, as evidenced by our difficulty in finding an acceptable joint posterior pdf for more than a handful of parameters. Furthermore, although the assumption that the residuals between the observed and predicted catches were normally distributed was reasonable, we were forced into this option by the limitations of the SIR method. When log-transformed catches were used, the joint posterior pdf was excessively dominated by the simulation that generated the maximum likelihood. This problem can only be resolved in SIR by running an order of magnitude more iterations (which was beyond our current computational limits) or by using a more directed importance function, which would have its own inherent biases (McAllister and Ianelli 1997).

Bayesian methods have a proven track record in these types of population modelling studies (Peterman 2004; Zeller *et al.* 2008; Zhou *et al.* 2008), even in the somewhat limited capacity used here (Fay and Punt 2006), but they clearly enable a better representation of the uncertainties associated with such stock assessments. The net result of including more uncertainty in this assessment is that the differences between the management scenarios were reduced. That is, when the alternative management strategies were compared using only the manually calibrated model, there was more separating the effects of the alternative strategies on the various indicators (with the current closure strategy proving the best option). This suggests that the more we incorporate uncertainty into modelling studies, the less conclusive the results may be. Intuitively this makes sense because the increased uncertainty would widen the distribution of possible outcomes from each alternative strategy, creating greater possibility for overlap.

Bayesian methods can provide modellers with the ability to more fully represent the uncertainty in their models (Punt and Hilborn 1997), but at the possible expense of a reduction in the clarity of outcomes (especially if model structure uncertainty is also included (Ives and Scandol 2007; Jiao *et al.* 2009)). This, however, is only because the models are more encompassing of our uncertain knowledge. Such a finding implies that the fisheries management community should be cautious when interpreting the results of complex models if their additional complexity came at the expense of more thorough representations of uncertainty (Longhurst 2006).

The impact of climate change on harvested marine resources is an issue of increasing international interest (Perry *et al.* 2005; Brander 2007; Allison *et al.* 2009). The impact of changes to river discharge levels is of particular importance for several species, both in terms of the sustainability of the species and the fisheries that exploit them (Esmaeili and Omar 2003; Fernández-Delgado *et al.* 2007). Fortunately, improvements in both technology and assessment techniques have given scientists greater capacity to evaluate the possible impacts of such changes. There are many obvious benefits to being able to evaluate alternative management strategies without incurring costs and frustrations to industry. The challenge for resource managers is to focus research into key areas of uncertainty and to develop and apply management strategies that are more robust to uncertainty, particularly scenarios associated with increasing climate variability.

Acknowledgements

References

Allison, E. H., Perry, A. L., Badjeck, M.-C., Adger, W. N., Brown, K., *et al.* (2009). Vulnerability of national economies to the impacts of climate

change on fisheries. *Fish and Fisheries* **10**, 173–196. doi:10.1111/J.1467-2979.2008.00310.X

Brander, K. M. (2007). Global fish production and climate change. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 19 709–19 714. doi:10.1073/PNAS.0702059104

Brandon, J. R., Breiwick, J. M., Punt, A. E., and Wade, P. R. (2007). Constructing a coherent joint prior while respecting biological realism: application to marine mammal stock assessments. *ICES Journal of Marine Science* **64**, 1085–1100.

Broadhurst, M. K., and Kennelly, S. J. (1996). Rigid and flexible separator panels in trawls that reduce the by-catch of small fish in the Clarence River prawn-trawl fishery, Australia. *Marine and Freshwater Research* **47**, 991–998. doi:10.1071/MF9960991

Broadhurst, M. K., Young, D. J., and Damiano, C. (2003). Effects of Nordmøre-grid angles, profiles and other industry-developed modifications on catches in an Australian penaeid-trawl fishery. *Ciencias Marinas* **30**, 155–168.

Broadhurst, M. K., Millar, R. B., Young, D. J., Wooden, M. E. L., and Rowland, S. (2004). Atypical size selection of captive school prawns, *Metapenaeus macleayi*, by three recreational fishing gears in southeastern Australia. *New Zealand Journal of Marine and Freshwater Research* **38**, 755–766.

Cadrin, S. X., and Secor, D. H. (2009). Accounting for spatial population structure in stock assessment: past, present, and future. In 'The Future of Fisheries Science in North America'. (Eds R. J. Beamish and B. J. Rothschild.) pp. 405–426. (Springer: New York.)

Caswell, H. (1989). 'Matrix Population Models. Construction, Analysis, and Interpretation.' (Sinauer Associates: Sunderland, MA.)

Childs, A. R., Cowley, P. D., Næsje, T. F., Booth, A. J., Potts, W. M., *et al.* (2008). Do environmental factors influence the movement of estuarine fish? A case study using acoustic telemetry. *Estuarine, Coastal and Shelf Science* **78**, 227–236. doi:10.1016/J.ECSS.2007.12.003

Coles, R. G., and Greenwood, J. G. (1983). Seasonal movement and size distribution of three commercially important Australian prawn species (Crustacea : Penaeidae) within an estuarine system. *Australian Journal of Marine and Freshwater Research* **34**, 727–743. doi:10.1071/MF9830727

CSIRO and IGCI (2007). OzClim. (International Global Change Institute, University of Waikato and CSIRO Atmospheric Research: Hobart.)

Dall, W., Hill, B. J., Rothlisberg, P. C., and Sharples, D. J. (1990). 'The Biology of the Penaeidae.' (Academic Press: London.)

Díaz-Ochoa, J. A., and Quiñones, R. A. (2008). Relationship of precipitation, freshwater input, and sea level height with the abundance of the white shrimp (*Litopenaeus occidentalis*; Street, 1871) off Buenaventura, eastern tropical Pacific. *Fisheries Research* **92**, 148–161. doi:10.1016/J.FISHRES.2008.01.002

Esmaeili, A., and Omar, I. (2003). Influence of rainfall on optimal spawner catch for the shrimp fishery in Iran. *North American Journal of Fisheries Management* **23**, 385–391. doi:10.1577/1548-8675(2003)023<0385:IOROOS>2.0.CO;2

Fay, G., and Punt, A. E. (2006). Modeling spatial dynamics of Steller sea lions (*Eumetopias jubatus*) using maximum likelihood and Bayesian methods: evaluating causes for population decline. In 'Sea Lions of the World'. (Eds A. W. Trites, S. K. Atkinson, D. P. DeMaster, L. W. Fritz, T. S. Gelatt, L. D. Rea and K. M. Wynne.) (Alaska Sea Grant College Program, University of Alaska: Fairbanks.)

Fernández-Delgado, C., Baldó, F., Vilas, C., García-González, D., Cuesta, J., *et al.* (2007). Effects of the river discharge management on the nursery function of the Guadalquivir river estuary (SW Spain). *Hydrobiologia* **587**, 125–136. doi:10.1007/S10750-007-0691-9

Glaister, J. P. (1978*a*). Movement and growth of tagged school prawns, *Metapenaeus macleayi* (Haswell) (Crustacea : Penaeidae), in the Clarence River region of northern New South Wales. *Australian Journal of Marine and Freshwater Research* **29**, 645–657. doi:10.1071/MF9780645

Glaister, J. P. (1978*b*). Impact of river discharge on distribution and production of the school prawn *Metapenaeus macleayi* (Haswell) (Crustacea : Penaeidae) in the Clarence River region, northern New South Wales. *Australian Journal of Marine and Freshwater Research* **38**, 225–241. doi:10.1071/MF9870225

Grafton, R. Q., Adamowicz, W., Dupont, D., Nelson, H., Hill, R. J., *et al.* (2004). 'The Economics of the Environment and Natural Resources.' (Blackwell Publishing: Cornwall.)

Griffiths, S. P., Fry, G. C., Manson, F. J., and Pillans, R. D. (2007). Feeding dynamics, consumption rates and daily ration of longtail tuna (*Thunnus tonggol*) in Australian waters, with emphasis on the consumption of commercially important prawns. *Marine and Freshwater Research* **58**, 376–397. doi:10.1071/MF06197

Growns, I., and James, M. (2005). Relationships between river flows and recreational catches of Australian bass. *Journal of Fish Biology* **66**, 404–416. doi:10.1111/J.0022-1112.2005.00605.X

Gunter, G., and Edwards, J. C. (1969). The relation of rainfall and freshwater drainage to the production of penaeid shrimps (*Penaeus fluviatilis* Say and *Penaeus aztecus* Ives) in Texas and Louisiana waters. *FAO Fisheries Report* **57**, 875–892.

Hennessy, K., McInnes, K., Abbs, D., Jones, R., Bathols, J., *et al.* (2004). Climate Change in New South Wales. Part 2: Projected changes in climate extremes. CSIRO Atmospheric Research and the National Climate Centre of the Australian Government Bureau of Meteorology, Canberra.

Ives, M. C., and Scandol, J. P. (2007). A Bayesian analysis of NSW eastern king prawn stocks (*Melicertus plebejus*) using multiple model structures. *Fisheries Research* **84**, 314–327. doi:10.1016/J.FISHRES.2006.11.006

Jiao, Y., Reid, K., and Smith, E. (2009). Model selection uncertainty and Bayesian model averaging in fisheries recruitment modeling. In 'The Future of Fisheries Science in North America'. (Eds R. J. Beamish and B. J. Rothschild.) pp. 49–76. (Springer: New York.)

Klyashtorin, L. B. (1998). Long-term climate change and main commercial fish production in the Atlantic and Pacific. *Fisheries Research* **37**, 115–125. doi:10.1016/S0165-7836(98)00131-3

Klyashtorin, L. B. (2001). Climate change and long-term fluctuations of commercial catches: the possibility of forecasting. FAO Fisheries Technical Paper No. 410, Rome.

Loneragan, N. R. (1999). River flows and estuarine ecosystems: implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. *Austral Ecology* **24**, 431–440. doi:10.1046/J.1442-9993.1999.00975.X

Loneragan, N., Die, D. J., Kailis, G. M., Watson, R., and Preston, N. (1998). Developing and assessing techniques for enhancing tropical Australian prawn fisheries and the feasibility of enhancing the brown tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf. Fisheries Research and Development Corporation, Canberra.

Longhurst, A. (2006). The sustainability myth. *Fisheries Research* **81**, 107–112. doi:10.1016/J.FISHRES.2006.06.022

Macbeth, W. G., Broadhurst, M. K., and Millar, R. B. (2005). Improving selectivity in an Australian penaeid stow-net fishery. *Bulletin of Marine Science* **76**, 647–660.

Macbeth, W. G., Broadhurst, M. K., Paterson, B. D., and Wooden, M. E. L. (2006). Reducing the short-term mortality of juvenile school prawns (*Metapenaeus macleayi*) discarded during trawling. *Journal of Marine Science* **63**, 831–839. doi:10.1016/J.ICESJMS.2006.03.008

Martin, J. A., and Michael, P. (2000). Effects on invertebrate populations of drought-induced changes in estuarine water quality. *Marine Ecology Progress Series* **203**, 133–143.

McAllister, M. K., and Ianelli, J. N. (1997). Bayesian stock assessment using catch–age data and the sampling importance resampling algorithm. *Canadian Journal of Fisheries and Aquatic Sciences* **54**, 284–300. doi:10.1139/CJFAS-54-2-284

McVerry, S. (1995). A socio-economic evaluation of the Clarence River commercial fishery. BEc (Hons) Thesis, Southern Cross University.

Murawski, S. A. (1993). Climate change and marine fish distributions: forecasting from historical analogy. *Transactions of the American Fisheries Society* **122**, 647–658. doi:10.1577/1548-8659(1993)122 <0647:CCAMFD>2.3.CO;2

Nicholson, G., Jenkins, G. P., Sherwood, J., and Longmore, A. (2008). Physical environmental conditions, spawning and early-life stages of an estuarine fish: climate change implications for recruitment in intermittently open estuaries. *Marine and Freshwater Research* **59**, 735–749. doi:10.1071/MF07197

Oki, T., and Kanae, S. (2006). Global hydrological cycles and world water resources. *Science* **313**, 1068–1072. doi:10.1126/SCIENCE.1128845

Perry, A. L., Low, P. J., Ellis, J. R., and Reynolds, J. D. (2005). Climate change and distribution shifts in marine fishes. *Science* **308**, 1912–1915. doi:10.1126/SCIENCE.1111322

Peterman, R. M. (2004). Possible solutions to some challenges facing fisheries scientists and managers. *Journal of Marine Science* **61**, 1331–1343.

Punt, A. E., and Hilborn, R. (1997). Fisheries stock assessment and decision analysis: the Bayesian approach. *Reviews in Fish Biology and Fisheries* **7**, 35–63. doi:10.1023/A:1018419207494

Racek, A. A. (1959). Prawn investigations in eastern Australia. *Research Bulletin of the New South Wales Fisheries Station* **6**, 1–57.

Reid, D. D., and Montgomery, S. S. (2005). Creel survey based estimation of recreational harvest of penaeid prawns in four southeastern Australian estuaries and comparison with commercial catches. *Fisheries Research* **74**, 169–185. doi:10.1016/J.FISHRES.2005.03.007

Robins, J. B., Halliday, I. A., Staunton-Smith, J., Mayer, D. G., and Sellin, M. J. (2005). Freshwater-flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. *Marine and Freshwater Research* **56**, 343–360. doi:10.1071/MF04087

Rothlisberg, P. C., Preston, N., Loneragan, N. R., Die, D. J., and Poiner, I. R. (2001). Approaches to reseeding penaeid prawns. In 'Stock Enhancement and Sea Ranching'. (Eds B. R. Howell, E. Moksness and T. Svåsand.) pp. 365–378. (Fishing News Books: Oxford.)

Ruello, N. V. (1973*a*). Burrowing, feeding, and spatial distribution of the school prawn *Metapenaeus macleayi* (Haswell) in the Hunter River region, Australia. *Journal of Experimental Marine Biology and Ecology* **13**, 189–206. doi:10.1016/0022-0981(73)90066-X

Ruello, N. V. (1973*b*). Influence of rainfall on the distribution and abundance of the school prawn *Metapenaeus macleayi* (Haswell) in the Hunter River region, Australia. *Marine Biology* **23**, 221–228. doi:10.1007/BF00389488

Ruello, N. V. (1977). Migration and stock studies on the Australian school prawn *Metapenaeus macleayi*. *Marine Biology* **41**, 185–190. doi:10.1007/BF00394025

Schnute, J. T., and Richards, L. J. (2001). Use and abuse of fishery models. *Canadian Journal of Fisheries and Aquatic Sciences* **58**, 10–17. doi:10.1139/CJFAS-58-1-10

Sheaves, M., Abrantes, K., and Johnston, R. (2007). Nursery ground value of an endangered wetland to juvenile shrimps. *Wetlands Ecology and Management* **15**, 311–327. doi:10.1007/S11273-006-9031-5

Vance, D. J., Staple, D. J., and Kerr, J. D. (1985). Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguiensis*) in the Gulf of Carpentaria, Australia. *Journal du Conseil International pour l'Exploration de la Mer* **42**, 89–97.

Vance, D. J., Haywood, M. D. E., Heales, D. S., Kenyon, R. A., and Loneragan, N. R. (1998). Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguiensis*) and environmental variation in two estuaries in tropical northeastern Australia: a six-year study. *Marine Ecology Progress Series* **163**, 21–36. doi:10.3354/MEPS163021

Vance, D. J., Bishop, J., Dichmont, C. M., Hall, N., McInnes, K., *et al.* (2003). 'Management of Common Banana Prawn Stocks of the Gulf of Carpentaria: Separating the Effects of Fishing From Those of the Environment.' (CSIRO, AFMA: Canberra.)

Vorosmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *Science* **289**, 284–288. doi:10.1126/SCIENCE.289.5477.284

Werner, E. E., Gilliam, J. F., Hall, D. J., and Mittelbach, G. G. (1983). An experimental test of the effects of predation risk on habitat use in fish. *Ecology* **64**, 1540–1548. doi:10.2307/1937508

Zeller, D., Darcy, M., Booth, S., Lowe, M. K., and Martell, S. (2008). What about recreational catch? Potential impact on stock assessment for Hawaii's bottomfish fisheries. *Fisheries Research* **91**, 88–97. doi:10.1016/J.FISHRES.2007.11.010

Zhou, S., Dichmont, C., Burridge, C. Y., Venables, W. N., Toscas, P. J., *et al.* (2007). Is catchability density-dependent for schooling prawns? *Fisheries Research* **85**, 23–36. doi:10.1016/J.FISHRES.2006.11.034

Zhou, S., Vance, D. J., Dichmont, C. M., Burridge, C. Y., and Toscas, P. J. (2008). Estimating prawn abundance and catchability from catch-effort data: comparison of fixed and random effects models using maximum likelihood and hierarchical Bayesian methods. *Marine and Freshwater Research* **59**, 1–9. doi:10.1071/MF07090