Australian Society for Fish Biology
Workshop Proceedings

Fish Movement and Migration

Bendigo, Victoria 28–29 September 1999

Donald A. Hancock, David C. Smith
and John D. Koehn (editors)

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FISHERIES RESEARCH & DEVELOPMENT CORPORATION

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Foreword

Pat Dixon

President
Australian Society for Fish Biology

This Workshop entitled *Fish Movement and Migration* continues the series, commenced in 1985 by the Australian Society for Fish Biology. The major objective of the workshops has been to focus national expertise on an issue that has regional or national significance. The proceedings are now widely regarded as the benchmark of current knowledge on the subject area.

Most fish and other exploited aquatic species exhibit movement and/or migrations during some part of their life cycle. In recent years the importance of these migrations to fish and fisheries management has been increasingly realised. Changed fish behaviour due to varying environmental conditions has significant impacts on species availability/catchability and hence the interpretation of abundance indices. In freshwater, improved fish passage is seen as one of the major areas for river rehabilitation to be conducted over the next decade. Spatial models that take into account, explicitly or implicitly, fish movements are now widely used. Recent technological developments allow for greatly improved analysis of the patterns of fish movement and migration.

This Australian Society for Fish Biology Workshop was the first time that fish migration and movement has been considered in a national forum. In 1988, ASFB and the then Bureau of Rural Resources convened a workshop on tagging, 'Tagging - Solution or Problem', which focussed on all aspects of tagging. Tags as a means of measuring movement and migrations in fish were considered as part of the current workshop but the emphasis was on new approaches and technologies. It is clear there have been major technical advances over the last 10 years. The workshop also covered environmental aspects of fish movement including the impacts of barriers and human interference. There was a focus on developments in analysis and the adoption of spatial models, and the management implications of fish movement and migration.

The Society would like to acknowledge the contribution made by Dr Geoff Arnold and Dr John Eiler to the workshop. They demonstrated the role that new technologies have played in improving our understanding of fish migrations, providing a valuable international perspective.

The proceedings follow the established format of recent years with papers delivered by invited speakers followed by rapporteurs' reports of the ensuing discussion. As expected these were thought-provoking and lively.

As always many people contributed to the success of the workshop. David Smith and John Koehn, the workshop convenors, obtained funding and put the workshop together. They were well assisted by the other members of the organising committee: Martin Gomon, Rob Day, Sandy Morison, Kylie Hall, Tarmo Raadik, Brenton Zampati, Victor Gomelyuk, Tim O'Brien, Simon Nicol and Dianne Bray.

The Society gratefully acknowledges the support of the Fisheries Research and Development Corporation which provided funds for this Workshop and have generously supported ASFB workshops since 1988. The Murray-Darling Basin Commission, Fisheries Victoria and Parks Flora and Fauna of the Department of Natural Resources and Environment, Melbourne Water, Hallprint Tags, the Floy Tag Co. and Lotek Marine Technologies, were also significant contributors.

Finally, these proceedings could not have been produced without the effort of the editors, Don Hancock, David Smith and John Koehn, and the text editor Diane Mahon.

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Welcome and Introduction

David Smith

Workshop Co-Convenor and
Director, Marine and Freshwater Resources Institute
PO Box 114, Queenscliff VIC 3225

Welcome everyone, to Bendigo and the 13th Australian Society for Fish Biology (ASFB) Workshop: "Fish Movement and Migration".

The importance of fish movement and migration to fish conservation and management has been increasingly realised. In freshwater, improved fish passage has long been an issue for fish biologists and it is seen as one of the major areas for river rehabilitation over the next decade. Spatial models that take into account, explicitly or implicitly, fish movements are now widely used and/or being developed for stock assessment purposes. Changed fish movement due to varying environmental conditions may have significant impacts on species availability/catchability, and the understanding of these relationships is crucial to the interpretation of abundance indices. In addition, there are major implications for the management of migratory fish species, particularly those that span jurisdictional boundaries.

In recent years, there have been significant technological developments that have greatly improved our understanding of the patterns of fish movement and migration. Such methods are providing surprising insights. Often the results show that fish movements are more complex and quite different from what were assumed or expected. The Overview Papers by our invited speakers, Dr Geoff Arnold and Dr John Eiler, provide striking examples of this.

The Workshop addresses issues concerning movement and migration during four sessions:

- Techniques for measuring
- Environmental determinants, barriers and human interference
- Analysis, interpretation and spatial models
- Management implications.

There are a number of panellists in each session who will give brief presentations on particular aspects of the session theme. Considerable time has been allocated for discussion during each session. These discussions will be an important component of the workshop publication.

I would like to thank my co-convenor, John Koehn who is also a Session Chair, and the other Session Chairs, John Gunn, André Punt and Nick Rayns for their help with the programme, and also members of the ASFB Conference Organising Committee for ensuring that all will run smoothly.

Funding for this Workshop was generously provided by our principal sponsor the Fisheries Research and Development Corporation (FRDC), the Murray-Darling Basin Commission, and Fisheries Victoria and Parks Flora and Fauna of the Department of Natural Resources and Environment. Melbourne Water, Hallprint Tags, the Floy Tag Co. and Lotek Marine Technologies are also thanked for their support.

I would now like to call on Alex Wells, who is Projects Manager with FRDC, to give some opening remarks on behalf of the Corporation.

Opening remarks from FRDC

Alex Wells

Fisheries Research and Development Corporation
PO Box 222, Deakin West ACT 2600

First of all I'd like to thank Dr David Smith and the organising committee for inviting me to say a few words on behalf the Fisheries Research and Development Corporation at this year's Australian Society for Fish Biology workshop and conference. I'll be very brief because I don't want to take up too much of your time and I know everyone's pretty keen to get things under way.

It really is a great pleasure to be here today, and I want to reinforce the point that the FRDC is very happy to be supporting the ASFB for yet another year. The partnership between the ASFB and the FRDC has been a longstanding one and also a very important one for both organisations. It's been important for a number of reasons, but the role that ASFB plays in developing fisheries science in Australia would have to be regarded as one of its main achievements and in this context, a relationship with the FRDC is central to the FRDC achieving its corporate objectives.

The particular corporate objective I'm referring to is what we call People Development. Developing the expertise of the people who apply their minds to fisheries science, such as yourselves, is not only a key issue for our R&D portfolio planning but believe it or not, supporting the scientific community is actually written into legislation. It's L.A.W.-LAW - and unlike that well-known circumstance a number of years ago where LAW ended up delivering nothing, this object of our legislation, which is called the Pierd Act, assists the FRDC to deliver direct financial support to Australian fisheries science and the continual improvement of that science.

So developing scientific expertise has been important to us in the past, there's no doubt about that, but the good news is that it will be even more prominent from now on. Skills development is listed as a separate R&D programme, in the draft of the new R&D Plan, which will take effect from July 2000. So the fact that the development of scientific skills will probably be constituted as a programme in itself, I think you'll agree is good news for the fisheries science community.

FRDC support for ASFB is just one of the ways that we as a corporation pursue our people development objective and we will continue to fund many activities that have, as one of their objectives, some component of skills enhancement.

Some of the recent examples of this type of funding support are international conferences like World Aquaculture '99, and the upcoming Fishrights '99 in Perth, and workshops such as the stock assessment review in Queensland and the South East Fishery workshop to be held in November. We support Management Advisory Committee courses at the Australian Maritime College and also the quantitative training unit at Sydney University. There's also the Australian Rural Leadership Program which we've been supporting for a number of years and next week a conference called Seafood Directions '99 is being held in Adelaide.

Seafood Directions '99 would probably be best described as the fishing industry equivalent of the ASFB Conference and we're supporting it for exactly the same reason as we support the ASFB, and that is to enhance the exchange of ideas and to get people thinking outside their normal worldview.

I think everyone here would agree that the ASFB Conference is one of the key events on the national fisheries calendar, and even though it is hard to accurately quantify the value of these events, the role it plays in facilitating communication within the scientific community cannot be overstated, just as the value of peer review to the advancement of fisheries science cannot be overstated. The need for communication among fishing industry operators and their representatives is just as crucial for them as it is for fisheries biologists, and furthermore, just as it is imperative to encourage the fishing industry to think outside of its normal parameters, which have in the past been pretty narrow, so too is it important for fisheries biologists to keep in mind that research related to fisheries is no longer restricted to just counting fish.

In an article about 12 months ago, Bob Carline, the President of the American Fisheries Society, raised the question of whether fisheries professionals are thinking broadly enough and chose the issue of human population growth as an example of one of the major threats facing many fisheries in the United States. He suggested fisheries biologists must start engaging in public policy discussions on the implications of continuing population growth and the effect that will have on access to both recreational and commercial fisheries, not to mention habitat and biodiversity impacts.

This is just one of a range of complex issues facing our fisheries and I know most of you are all well aware of these. The point is that awareness alone won't solve our fisheries problems and we particularly won't solve the problems if the people who make their living out of harvesting fisheries are not engaged in all aspects of fisheries discussions and that includes involvement in forums like this.

Perhaps in future, the FRDC won't have to sponsor conferences that are *completely* separate in space and time depending on whether it's a fisheries biologists' or a fishing industry conference. The potential for a bit of co-learning between fisheries biologists, managers and industry operators is something that shouldn't be underestimated.

You know history is full of examples of situations where people who *really* know what they're doing, put their heads together to come up with an achievement that benefits everyone. The "think tank" approach has stood the test of time - and it works. The FRDC has used this approach on numerous occasions in order to develop key research planning documents. These documents are the tools we use to determine the status of current knowledge in a given research area and to ascertain what sort of research is required to avoid duplication and to move away from funding research on an *ad hoc* basis.

Finally, on behalf of FRDC I wish you all a very successful workshop.

Overview Address

Unravelling mechanisms of fish migration: a 30-year perspective

Geoff Arnold

Unravelling mechanisms of fish migration: a 30-year perspective

Geoff Arnold

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Abstract

Most of the several hundred species that sustain the world's major commercial fisheries follow extensive migration circuits, which they undertake annually for feeding and reproduction. Eggs and early larvae are carried passively by residual currents and in many species the adults home to well-defined spawning areas sited upstream of nursery grounds used by the juvenile fish. Adult spawning migrations compensate for the drift of eggs and larvae and stocks of migratory fish tend therefore to be contained within oceanic gyres. As yet, however, there are too few direct observations of the behaviour of oceanic fish to know whether they routinely follow gyres during their migration circuits, or can navigate and only take advantage of currents when these save the fish energy. Recent observations on the European continental shelf, however, suggest that adult fish can make use of transporting currents when this is energetically advantageous, but adopt other mechanisms of migration when it is not. In areas of fast tidal streams adult demersal fish (plaice, cod and a number of other species) make selective use of the tidal streams to transport them to and fro between spawning and feeding grounds and save energy by also swimming downstream in the same direction as the tidal current. In areas of slower and less-directional tidal streams, however, adult fish (plaice) do not exhibit the regular vertical movements diagnostic of tidal stream transport. Instead, they migrate close to the bottom and may swim in a different direction to the current. Circumstantial evidence from other species suggests that facultative use of environmental transport may be a general phenomenon.

Introduction

Until the early 1970s, fisheries scientists had to rely on indirect information, such as catch rates and seasonal changes in distribution of fisheries to deduce patterns of migration. Useful data could also be obtained from conventional tags, such as buttons, discs and streamers, although return data were heavily biased by the distribution of fishing effort, which was often poorly described. Knowledge of mechanisms of migration and underlying sensory systems was also seriously limited by the inability of conventional tags to provide any information about the actual track of the fish between release and recapture. As a result, we have learnt more about fish migration over the last 30 years, since the development of the acoustic tag (e.g. Yuen 1970), than in the preceding 75 years, following the invention of the Petersen disc (e.g. McFarlane *et al.* 1990). The rate of progress continues to accelerate. Acoustic tags allow us to track free-ranging, individually-identified fish over several days and describe their patterns of vertical and horizontal movement in some detail. Archival tags allow us to do the same over several years and replicate observations with large numbers of fish, without incurring the high costs of a research vessel. Pop-up tags, which float to the surface after a pre-set time and communicate with satellites (Block *et al.* 1998; Lutcavage *et al.* 1999), should allow us to recover large amounts of data independently of the fisheries. The aim of this overview, which concentrates on migrations of marine fish, is to assess the scientific advances made with these new tools and suggest possible avenues for future research. I begin by summarising what we know about the linkages between production cycles, water circulation and fish life-histories and then describe how our views about mechanisms of migration have changed as a result of research reported over the last 30 years. I attempt to synthesise work done in the open ocean, as well as on the continental shelves, and to indicate what the new observations reveal about orientation and navigation.

Ecology of fish migration

Unlike entomologists, who use migration and emigration as synonyms, fisheries ecologists usually follow Heape (1931) and distinguish between the two terms. Heape defines migration as 'a class of movement which impels migrants to return to the region from which they have migrated', and contrasts this with emigration - 'movements which entail change of environments, but which do not involve return to the original area of habitat'. The distinction is a useful one for the several hundred species of fish that form the basis for the world's major commercial fisheries and undertake extensive annual migration circuits, which they can repeat for several decades, if not subjected to overexploitation.

Functions

Heape (1931) recognised three types of migration: *alimental* migration, in search of food and water; *climatic* migration, in search of more suitable environmental conditions; and *gametic* migration, for reproduction. The most spectacular migrations are those for feeding and reproduction, during which the adults regularly cover distances of several hundred to several thousand kilometres, depending on whether they live on the continental shelves or in the open ocean. For some large oceanic species annual migration circuits extend to as much as 10 000 km.

Production, circulation and containment

Most teleosts produce large numbers of pelagic eggs, which are carried passively by the prevailing current until they hatch as yolk-sac larvae. The yolk sac provides an initial reserve of food, but the larvae must find a sufficient density of planktonic food, if they are to survive once the yolk is exhausted. In tropical latitudes, where standing stocks are low and production continuous, there is probably always enough food to ensure survival of moderate broods of larval fish, and spawning can occur more or less continuously. In temperate and polar latitudes, however, production is discontinuous and, although much larger and capable of sustaining very large populations of fish, standing stocks are also much shorter-lived. In these regions, spawning is most successful when the larvae hatch at times of high food abundance. Eggs and early larvae are carried passively by the current, so reproduction is also most successful when spawning takes place upstream of a suitable nursery ground (Harden Jones 1968, 1980). There is therefore strong selection pressure on adult fish to spawn in the right place at the right time and return regularly to the same spawning grounds.

In many species spawning areas are well-defined and persist for many decades, possibly many centuries. After recruiting to the adult stock, fish generally home to the spawning area – in some species to the same ground - even though this may not be where they themselves were spawned. Many fish follow regular migration routes, which take them between their feeding and overwintering grounds and back to their spawning grounds (Harden Jones 1968, 1980). In some species (e.g. cod and herring), new recruits probably learn the route by accompanying older fish (e.g. Rose 1993; McQuinn 1997). Homing ensures that adult fish return to a location from which it is probable that larvae will be carried to favourable nursery grounds at the start of each new generation.

Spawning migrations compensate for the drift of eggs and larvae, and migratory fish stocks tend therefore to be contained within oceanic gyres. Fish that stray outside the gyre are generally lost to the stock (Harden Jones 1968). In tidal seas it has been suggested that stocks may be contained within the boundaries of the tidal streams (Harden Jones *et al.* 1978; Arnold 1981). The key features of fish migration can be summed up as stability, regularity, seasonality, containment and homing.

Mechanisms of migration

Water currents can provide a transport system and possibly also directional clues for migrating fish (Arnold 1981). Transport can occur by passive drift, if the fish is pelagic and has no external reference points, or by modulated drift (Arnold 1974), if it makes vertical movements in the water column. Orientated movements may occur if the fish can detect the speed and direction of the current. Fish use visual or tactile clues to detect the current when they are close to a solid boundary (Arnold 1974); in mid-water they may be able to detect electric potentials generated by the flow of water through the earth's magnetic field (Royce *et al.* 1968; Kalmijn 1971).

Most small fish larvae drift passively with the current because of their limited powers of locomotion. But swimming capabilities increase rapidly with growth, and larger larvae, juveniles and adult fish can all achieve a degree of control over their distribution, if they move vertically to take advantage of currents flowing in different directions at different depths in the water column (Arnold 1974). Larger fish - especially adults of large pelagic species – may, of course, become completely independent of the water circulation, if their swimming speed exceeds that of the water by an appropriate margin and the direction of the current diverges significantly from that of the migration. Theoretically, though, because water is dense, short in oxygen and much more resistant to movement than air, there is good reason to suppose that, regardless of size, most fish will take advantage of currents whenever there is an energetic advantage and ignore them only if there is no corresponding penalty.

In trying to resolve how fish migrate, therefore, one fundamental question to be asked is: what are the movements of the fish relative to those of the water at the depth at which the fish is swimming (Harden Jones 1968, 1984; Arnold 1981)? As the result of the last 30 years' work with electronic tags, there are now a substantial number of relevant data for shelf seas and these will be reviewed in a later section. For logistic reasons to do with cost and weather, however, there are, as yet, few direct observations of the tracks of migrating fish in the open ocean and even fewer with any data on the speed and direction of the water. The work described by Brill *et al.* (1993) is a rare exception. In considering oceanic migrations, therefore, it is generally necessary to fall back on descriptions of life histories, from which there is a *prima facie* case that the migration circuits of many fish follow the oceanic gyres (Harden Jones 1968; Arnold 1981). Some of the evidence is reviewed in the next section.

Environmental transport – evidence from life histories

Many species, which spend their entire lives in the ocean, make spectacular migrations on the scale of whole ocean basins. The albacore tuna (*Thunnus alalunga*), for example, ranges over the entire North Pacific during its life, spawning between the Hawaiian Islands and the Philippines (Figure 1). Albacore move from Japan to North America, apparently following the clockwise movements of the Kuroshio, California and North Equatorial Currents that comprise the North Pacific subtropical gyre (Harden Jones 1980). Northern bluefin tuna (*Thunnus thynnus*) may make similar use of the subtropical gyre in the North Atlantic, although the full extent of their movements and the degree of overlap between fish of American and European origin is not yet fully understood (Block *et al.* 1998; Lutcavage *et al.* 1999). Southern bluefin tuna (*T. maccoyii*), which occur in both Pacific and Indian Oceans, may range even more widely, following the West Wind Drift and possibly making circumpolar migrations, in a clockwise direction (Harden Jones 1984).

Some *anadromous* and *catadromous* species that migrate between fresh and saltwater and use the sea for feeding and spawning, respectively, also make large-scale oceanic migrations. Pacific salmon (*Oncorhynchus* spp.) from North America, for example, migrate north to Alaska and then westwards along the Aleutian Chain before moving out into the open ocean, where they mix with fish from Asia.

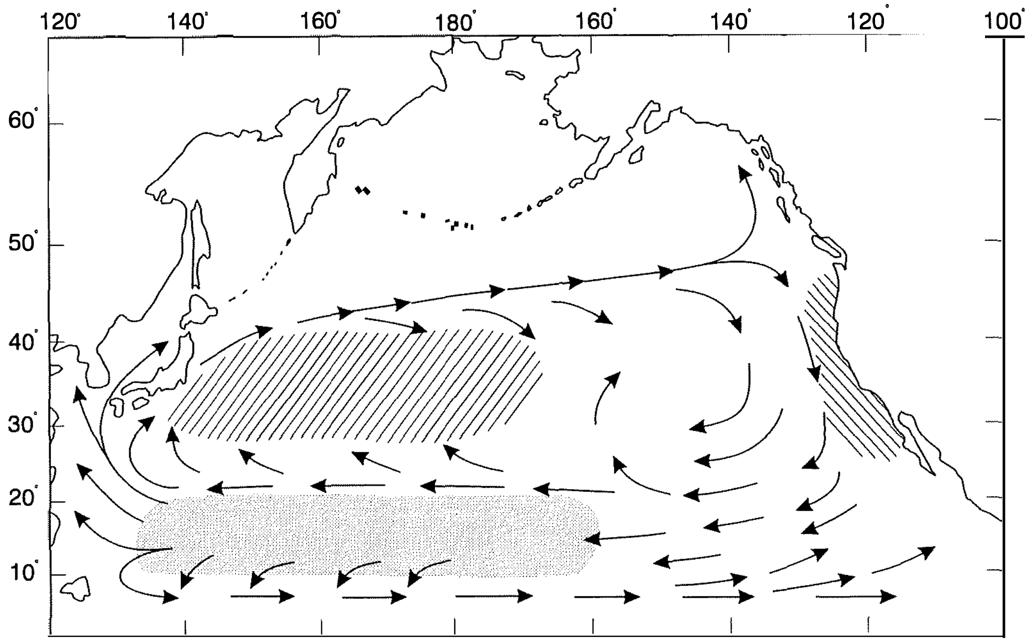

Figure 1. Distribution of albacore (*Thunnus alalunga*) in the North Pacific (Harden Jones 1980). The areas of the American fishery on young albacore and the Japanese fishery on older albacore are crosshatched; the area in which the adults are believed to spawn is stippled. Arrows show the main features of the subtropical gyre (Kuroshio, California and North Equatorial Currents) and the North Equatorial Counter Current.

Fish from some North American stocks feed in the Gulf of Alaska for several years (5-6 in the case of chinook salmon, *O. tshawytscha*), before returning to spawn in US or Canadian rivers. During this period they make several anti-clockwise circuits of the Gulf, apparently swimming downstream in the direction of the Alaskan Gyre (Royce *et al.* 1968). The route that sockeye (*O. nerka*) salmon take in returning to the Fraser river is also affected by the Sitka Eddy, which determines whether the fish pass north or south of Vancouver Island (Hamilton and Mysak 1986). European eels (*Anguilla anguilla*) return to the Sargasso Sea, after spending up to 20 years feeding in freshwater (Harden Jones 1968). Their migration route is unknown but they are able to find their way to the Subtropical Convergence Zone, where they spawn. The Gulf Stream and the North Atlantic Current system carry the larvae (leptocephali) back to Europe (McCleave 1993; McCleave *et al.* 1998), where they metamorphose into glass eels and then elvers before entering freshwater.

The classic contranatant theory of fish migration

The terms *denatant* and *contranatant*, which mean, respectively, drifting, swimming or migrating with the current, and swimming, or migrating against the current, were introduced by Meek (1915) to describe the movements of fish in relation to water currents. Meek's purpose (Harden Jones 1968) was to draw attention to the biological relationship between the downstream drift of eggs and larvae and the subsequent movements of the adult fish when returning to the spawning grounds. Used descriptively, the terms are helpful in recognising that adult fish compensate for the geographical displacement that occurs early in the life history. In the intended sense, therefore, adult migrations can usefully be said to be contranatant.

Unfortunately, however, Meek's terms came to be used in an explanatory sense long before it was possible to describe how fish actually react to water currents. Bowman (1933) suggested that lemon soles (*Microstomus kitt*) migrated around the Shetland Islands in the opposite direction to that of the prevailing bottom currents and the concept subsequently became enshrined in the classic 'contranatant' theory of fish migration (Russell 1937). This infers that pre-spawning migrations are active movements against the prevailing current, whilst post-spawning migrations of spent fish are passive denatant movements with the prevailing current. The theory was quite widely quoted (e.g. Tait 1952; Hasler 1956; Beverton and Holt 1957), even though Bowman's (1933) deductions about the clockwise migration of lemon soles at Shetland, which were based on conventional tag returns, were flawed (Harden Jones 1968).

The 'contranatant' theory could not be put to the test until it became possible to follow the movements of fish in the open sea from the early 1970s onward. Some of the tracking work undertaken in the North Sea by the Lowestoft Laboratory over the last 30 years is discussed in the remaining sections. Most of this work has involved plaice (Greer Walker *et al.* 1978; Metcalfe and Arnold 1999), although a substantial amount of work has also been done with cod (*Gadus morhua*), eels (*A. anguilla*) and several other species, including Atlantic salmon (*Salmo salar*) (Arnold 1981; Arnold and Greer Walker 1992; Arnold *et al.* 1994; McCleave and Arnold 1999). Plaice are economically valuable and particularly easy to work with, because they lack a swimbladder.

Southern North Sea plaice populations

The plaice (*Pleuronectes platessa*), a typical flatfish, is found on the sandy parts of the European and Scandinavian continental shelves from the Mediterranean to the Barents Sea. It is also found at Iceland and may sometimes migrate long distances across the deep water between one continental shelf and another (Sigurðsson 1982). Plaice populations are, however, usually relatively limited in geographical extent and there are often several different stocks within a single basin. In the North Sea, for example, there are four main stocks, which spawn off the Scottish east coast, Flamborough Head and in the Southern and German Bights, respectively. There is an intermediate spawning area between the centres of spawning off Flamborough and in the German Bight, and also an extensive spawning in the eastern English Channel (Harding *et al.* 1978). Conventional tagging experiments with Petersen disc tags show that, in summer, the Southern Bight, German Bight and Flamborough spawners occupy different feeding areas, with only a limited overlap south of the Dogger Bank (Harden Jones 1968, Figure 52). There is also some evidence that repeat spawners return to the same spawning ground in successive years (Harden Jones 1968, Figure 53).

Adult migrations in the Southern Bight

Conventional tagging experiments (summarised by Harden Jones 1968) have shown that in November and December maturing fish move some 200-300 km south into the Southern Bight and eastern English Channel from more-northerly feeding areas mostly situated to the south of the Dogger Bank. Spent fish migrate back to the north in January, February and March. A large number (>60%) of the plaice that spawn in the eastern English Channel originate in the North Sea (Houghton and Harding 1976) and there is a steady exchange of pre-spawning and post-spawning fish through the Straits of Dover during the winter months (Arnold and Metcalfe 1996).

Movements of eggs, larvae and juvenile fish in the Southern Bight

Plaice spawn in the Southern Bight and eastern English Channel in winter, with peak egg production in mid-January. The pelagic eggs and larvae drift to the north-east at a rate of about 3 km d^{-1} with the residual current entering the North Sea through the Straits of Dover. After 5-8 weeks the larvae metamorphose and drop to the seabed. Many young plaice enter the Dutch Wadden Sea, although the estuaries of the rivers Maas and Scheldt and the sandy beaches of the open coast are also important nursery areas. Plaice move into

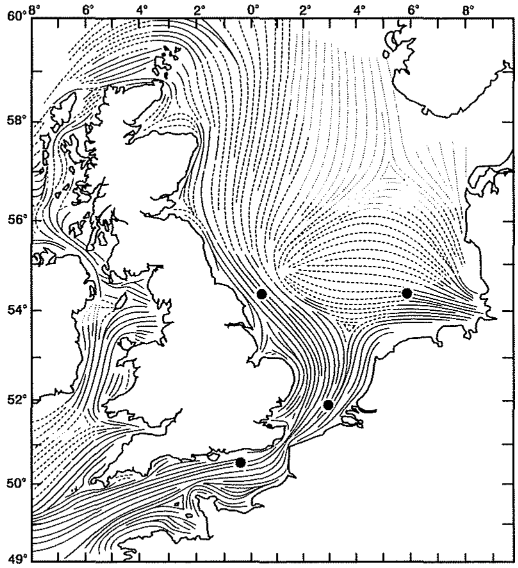

Figure 2. A tidal streampath chart for the North Sea and adjacent areas (Arnold 1981; Arnold and Holford 1995). The centres of spawning off Flamborough and in the German and Southern Bights and eastern English Channel are indicated by black circles.

deeper water from their second year of life and some of the larger fish, mostly males, reach first maturity in their third year, joining mature fish of earlier year-classes on the spawning grounds towards the end of the season. After spawning the majority of both first-time and repeat spawners move back north up the western side of the Southern Bight (Harden Jones 1968; Arnold 1981).

Mechanisms of plaice migration in the Southern Bight and adjacent areas

Prior to metamorphosis, the planktonic eggs and larvae of the plaice are carried to and fro by the fast, directional tidal streams that dominate much of the continental shelf surrounding the United Kingdom (Figure 2). As explained above, though, their progression is determined by the residual current flowing east through the Straits of Dover and, without a visual reference point, the larval fish are probably unable to detect the regularly reversing flow of the tidal stream (Arnold 1974). After they have descended to the seabed at metamorphosis, however, juvenile and adult fish can both detect currents of the order of 1 cm s^{-1}, or less (Arnold 1969 a and b) and tidal currents become a major feature in their ecology. Average tidal stream speeds exceed 40-50 cm s^{-1} in many areas of the North Sea and English Channel, and theoretical calculations (Weihs 1978; Metcalfe *et al.* 1990) show that adult plaice can save significant amounts of energy by using the tidal streams to assist their migrations. The same calculations show that juvenile fish cannot progress without making use of the tidal streams, indicating that there must be strong selection pressure acting on the patterns of behaviour of flatfish migrating in tidal seas.

Selective tidal stream transport

Tracking (Greer Walker *et al.* 1978) and mid-water trawling experiments (Harden Jones *et al.* 1979; Rijnsdorp *et al.* 1985; Arnold and Metcalfe 1996) have both shown that, from metamorphosis onwards, plaice in the southern North Sea migrate by *selective tidal stream transport*. The pattern of behaviour is deceptively simple. The fish leaves the bottom at one slack water and spends about six hours off the bottom, usually swimming in the upper half of the water column and often near the surface (Figure 3). It returns to the seabed around the time of the next local slack water and spends the ensuing tide on the bottom, making no significant movement in any direction (Figure 4). Vertical movements are usually well synchronised with times of local slack water, although occasionally the fish remains in mid-water over the turn of tide and is carried back some distance in the opposite direction. Plaice and other flatfish, such as soles (*Solea solea*) usually bury in the sand when not in mid-water. Roundfish, such as cod (*G. morhua*) and silver eels (*A. anguilla*), which exhibit similar migratory behaviour (Arnold *et al.* 1994; McCleave and Arnold 1999), hold station by swimming against the adverse current, or taking refuge from the flow behind a sand ridge or other topographical feature.

Fish using selective tidal stream transport progress rapidly in a consistent direction determined by the

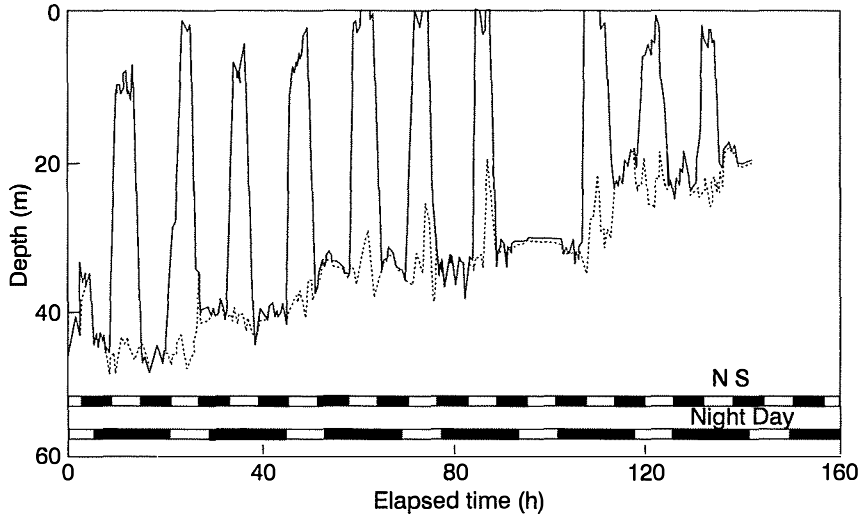

Figure 3. Vertical movements of a 44-cm maturing female plaice tracked in the southern North Sea in January 1991 (Arnold and Holford 1995). The dotted line indicates the depth of the seabed. The upper black and white bar indicates the direction (north and south) of the tidal stream. The lower bar indicates times of day and night.

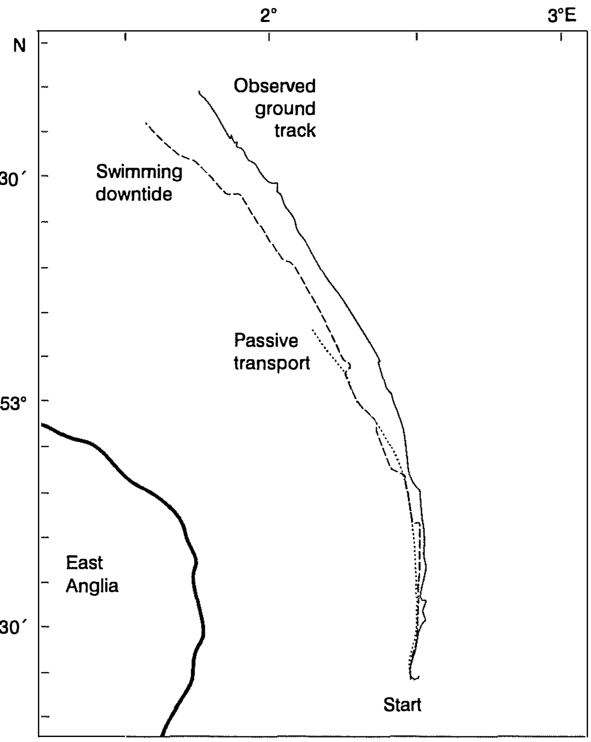

Figure 4. Geographical track of a 44-cm plaice female plaice tracked in the southern North Sea in January 1991 (Figure 3). Also shown are computer simulations of how far the fish would have moved if it had been transported passively with the tide or had swum downtide at a speed of one fish length per second. The fish moved 152 km to the north in six days by selective tidal stream transport (Arnold and Holford 1995).

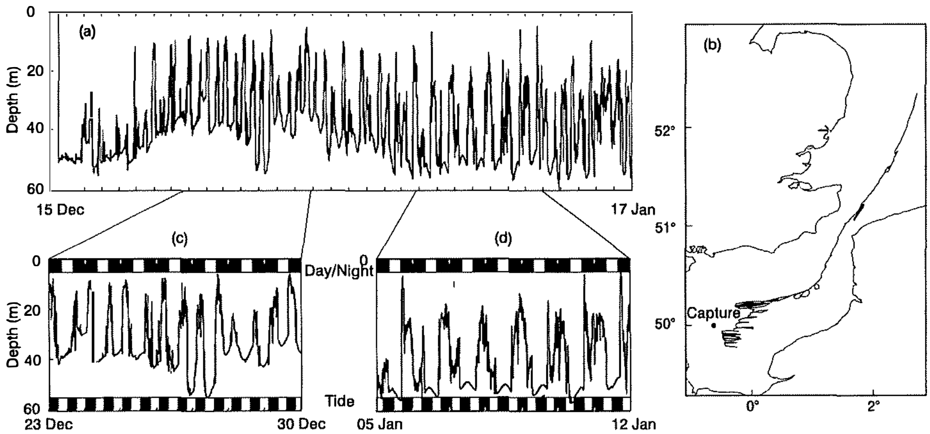

Figure 5. The reconstructed track of a 48-cm maturing female plaice fitted with a data storage tag, which recorded depth (pressure) at 10-min and water temperature at 24-h intervals. The track (b) was reconstructed from the vertical movements of the fish (a) and a computer simulation model of the tidal streams (Figure 7). During the first seven days the fish showed selective tidal stream transport (c) and moved rapidly from the Southern Bight into the English Channel. During the remainder of the track the fish showed a diel pattern of vertical migration (d) and swam in mid-water at night. It remained within the plaice spawning area in the eastern English Channel, where it was caught by a French trawler.

choice of transporting tide. Pre-spawning and post-spawning fish move in opposite directions, and in the Dover Strait maturing and spent plaice can be caught in mid-water on opposing tides in January (Arnold and Metcalfe 1996). Migration speed is determined by a number of factors, including the average speed of the tidal stream (commonly between 1-2 m s^{-1}), the size of the fish and whether it uses all available tides. At various times, some fish use the transporting tide at night only; at other times the same fish uses the transporting tide during the day as well and makes more rapid progress (Arnold and Holford 1995).

Recent tracking studies using predicted (Metcalfe *et al.* 1990) and measured tidal stream speeds (Buckley and Arnold in press) show that tidally-transporting plaice save energy by heading downtide within ± 60° of the tidal stream axis. They swim through the water at a speed of approximately 0.6 fish lengths s^{-1} and cover significantly more ground than the tidal stream (Figure 4). For a 35-cm female plaice the saving on a typical annual migration circuit of 560 km is equivalent to 30% of the energy content of the eggs she spawns each year (Metcalfe *et al.* 1993).

Once plaice reach a spawning ground, geographical movement ceases abruptly (Figure 5). The tidal pattern of vertical movement disappears and is replaced by a diel one, in which the fish spends most of the night in mid-water. This behaviour also occurs in a few fish during the summer, and may provide a mechanism for moving locally in search of food; it may similarly serve to locate a spawning partner in winter (Arnold 1981; Arnold and Holford 1995). Switching between tidal and diel patterns of vertical movement is rapid and, if reversed, can lead to the fish leaving one spawning ground after only a few days and migrating to another (Metcalfe and Arnold 1997).

Mechanisms of plaice migration in the German Bight

My colleagues and I are currently attempting to resolve whether plaice use selective tidal stream transport throughout the European continental shelf, or only in areas where they can achieve an energetic advantage. Funded by the European Union (Project PL96-2079), and in conjunction with a number of other laboratories in the UK, Netherlands, Belgium and Denmark, we

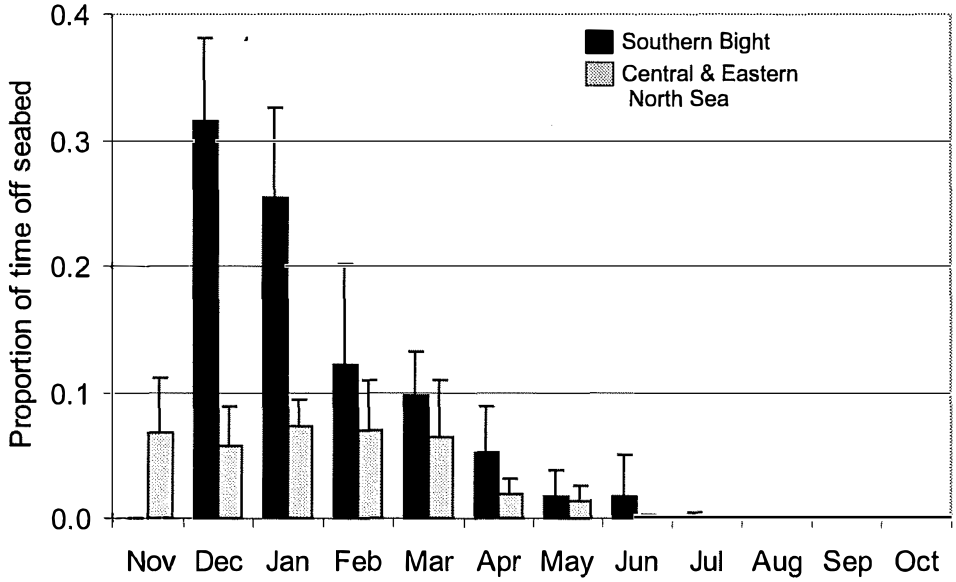

Figure 6. Release positions for groups of plaice tagged with data storage tags in the Southern and German Bights. The fish released in the German Bight were tagged with cylindrical (60 x 18 mm) tags (Lotek model LTD-100), which weighed 2.5 g in seawater. Those tagged in the Southern Bight off Lowestoft were tagged with larger hemispherical tags (46 dia. x 22-mm max height), which weighed 23 g in seawater (Metcalfe and Arnold 1997). The contours indicate average tidal stream speeds in cm s^{-1}.

have been releasing fish marked with data storage tags at a number of positions in the central North Sea (Figure 6). At these locations, the tidal streams flow along an east-west, rather than a north-south axis, and are generally much slower than in the Southern Bight and English Channel.

Results to date suggest that vertical movement is much less common than in the Southern Bight and that plaice in this more northerly area rarely leave the seabed, even during migration (Figure 7). Fish moving east, however, change their behaviour and start exhibiting a tidal pattern of vertical migration once they reach the narrow band of fast tidal streams extending along the coast of Germany and the Netherlands. The track of one such plaice is reconstructed in Figure 8. The fish showed little vertical movement either in the German Bight, or subsequently when it arrived in the Straits of Dover, and in these areas its track had to be reconstructed from times of high water and tidal range recorded by the data storage tag (Metcalfe and Arnold 1997). In the intervening period, when the fish was moving south along the Dutch coast, it was possible to reconstruct its movements with our selective tidal stream model (Arnold and Holford 1995). These results suggest that selective tidal stream transport is a facultative rather than an obligate pattern of migratory behaviour and that the boundaries between different tidal stream systems may be less of a barrier to movement than originally suggested (Harden Jones *et al.* 1978; Arnold 1981).

Discussion and synthesis

Russell's (1937) 'contranatant' theory of fish migration suffered from a number of flaws. It was formulated before it had been realised that migration circuits generally follow oceanic gyres and it failed to recognise that in shelf seas fish cannot detect a residual, oceanic current in the presence of strong tidal currents. As a result the theory has not been substantiated by observations of fish behaviour in the

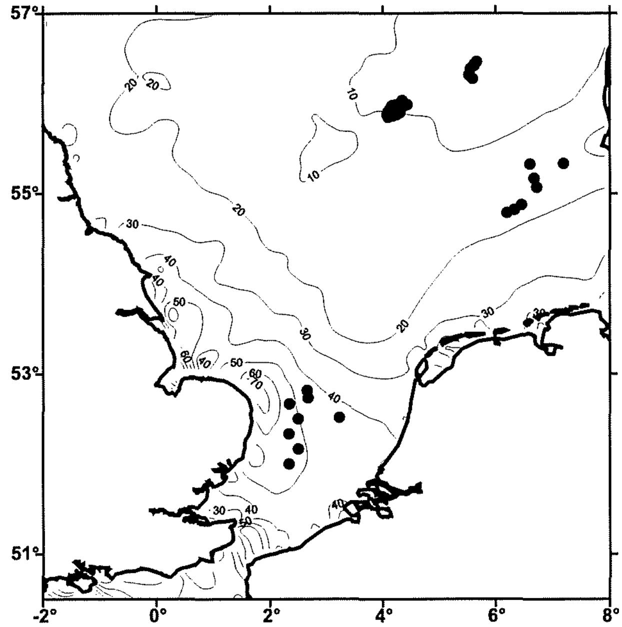

Figure 7. The proportion of time spent off the seabed by plaice tagged with data storage tags (Figure 6) in the German and Southern Bights. Few of the German Bight fish exhibited selective tidal stream transport, whereas most of the Southern Bight fish did, even though the tag was much heavier.

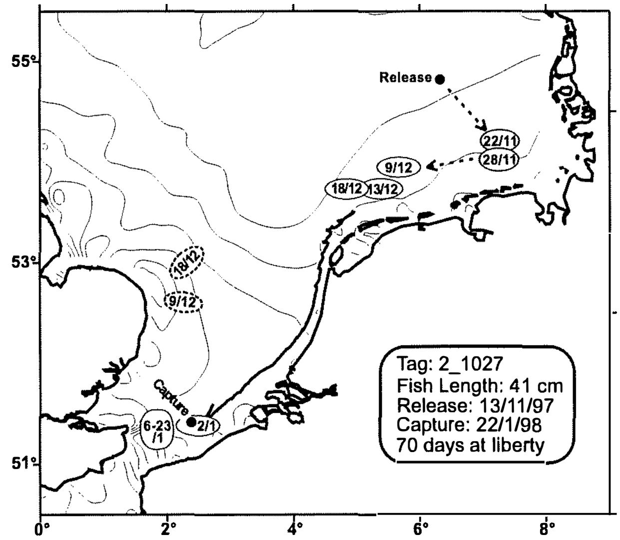

Figure 8. Reconstructed track of a 41-cm female plaice fitted with a cylindrical data storage tag (Figure 6). The fish, which was released in the German Bight on 13 November 1997, was at liberty for 70 days. The geographical positions of the fish between release and 18 December have been estimated from pressure measurements made when the fish was on the seabed (Metcalfe and Arnold 1997). Between 18 December and 2 January the track was reconstructed from its vertical movements and a simulation model of the tidal streams (Arnold and Holford 1995). The contours indicate average tidal stream speeds in cm s^{-1} (see Figure 6 for values).

open sea that were made possible by the development of electronic tags. The observations of the last 30 years do, however, support the idea that water currents provide an essential transport system for the young stages of all migratory species. They also suggest that the system can be used facultatively by older fish, if it saves them energy. There is growing evidence for the 'facultative' hypothesis from fish tracking work in strongly energetic tidal environments. As yet, however, there are too few direct observations of the movements of oceanic fish to know whether they routinely follow oceanic gyres during their migration circuits, or only take advantage of the currents when there is an energetic gain. Circumstantial evidence, however, suggests that the hypothesis could well have general applicability. For example two northern bluefin tuna (*T. thynnus*), which were tagged off the Bahamas in 1961 and recaptured near Bergen in Norway 118 and 119 days later, almost certainly received substantial assistance from the Gulf Stream and North Atlantic Drift. The fish migrated at least 4832 km with a minimum average speed of about 0.5 m s^{-1} (Mather 1962). The Gulf Stream flows at speeds of between 0.5 and 2.5 m s^{-1} in places in the upper 200 m (Stommel 1965); the North Atlantic Drift is rather slower.

Even if it is eventually shown that ocean currents can provide a transport system for the adults of some highly migratory species, it is unlikely that this will prove to be the whole story. There are already sufficient data to know that fish in mid-water, or near the surface, can maintain a consistent direction for quite long periods in the apparent absence of any obvious reference points (e.g. Metcalfe *et al.* 1993). There are also various lines of behavioural and physiological evidence that implicate a magnetic compass sense (Walker *et al.* 1997), which may explain how fish in tidal seas can detect the direction of the transporting tide. Magnetic orientation may also provide the basis for all long-distance oceanic migration, although it is not yet known if fish can compensate for lateral displacement by the current and thus navigate in the true sense of the term. Using satellite telemetry to track post-spawning migrations from Ascension Island to Brazil, Luschi *et al.* (1998) have, however, recently demonstrated this ability in green sea turtles (*Chelonia mydas*). Similar observations are now needed with migratory fish, once the technology has been fully adapted for use with species that, unlike turtles, do not conveniently spend large amounts of time on the sea surface.

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Session 1

Techniques for measuring

Chair:	John Gunn
Speakers:	John Koehn Ivor Stuart Julian Pepperell Geoff Arnold John Gunn David Mills John Stevens Naomi Clear (Presented by John Gunn)
Rapporteur:	Barry Bruce

Chair's Introduction

John Gunn

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In 1988, at the last ASFB workshop on tagging (Hancock 1989), presentations and discussions covered a very broad range of topics; from the assumptions on which tag and recapture experiments are based, to case studies on a wide range of fishes and invertebrates, and the strengths and weaknesses of analyses on tagging data. With very few exceptions the papers presented in 1988 focussed on the use of "conventional tags" – simple, individually-numbered plastic dart or metal markers. Ten years ago alternative methods and technologies were either in the early stages of development, or had not been invented. Kearney (1989) briefly discussed the potential for studying migration using indirect means (e.g. otolith chemistry, otolith marking, radio-isotopes, etc.), Keenan and MacDonald (1989) introduced the concept of genetic tagging, and Jernakoff (1989) described an innovative study using electromagnetic tags on rock lobsters.

Today, a decade later, an impressive array of new electronic technology is available to study fish migration, behaviour and responses to environmental factors. There has also been considerable research into the use of alternative approaches - otolith chemistry, genetic tags, etc.

The speakers in this session will provide brief descriptions of both conventional and new methods and technology used in movement and migration studies. In many applications, Australian fisheries scientists are leading international research efforts in this field, so much of what is presented will be at the cutting edge. The objective is to show what is available and, where either the literature or personal experience allows, to provide an assessment of the strengths and weaknesses of the various approaches.

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Why use radio tags to study freshwater fish?

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Abstract

A wide range of techniques and methods is available for marking and tagging fish. Selecting the most appropriate tagging method depends both on the purpose for which tagging is required and the species on which it is to be used. Which method will best help answer the questions being asked? Tagging and marking can be divided into two categories: those which provide a batch mark and those which can identify individual fish. This paper provides a brief review of available tagging techniques considering the benefits and constraints of each. Sonic and radio tags have the added advantage of allowing individual fish to be tracked on a continuous basis and 'observations' and measurements made of 'natural' behaviour. The differences between the use of sonic and radio tags are discussed for the study of freshwater fish. Options for different radio frequencies, tag configurations, tracking devices, data loggers, remote stations, costs and attachment techniques are explored. The benefits of the development and use of radio tags in Australia for the study of Murray cod and other species are discussed.

Introduction

A wide range of tags, techniques and methods is available for both marking and tagging fish (see CATAG website; Hancock 1989; Kearney 1989) for use in studying fish migrations (e.g. Harden-Jones 1968). Selecting the most appropriate method depends both on the purpose for which the marking or tagging is required and the species on which it is to be used. Identifying the correct questions to be asked must still be undertaken together with the appropriate experimental design (see Majkowski 1989) before the method which will best help to answer those questions can be selected.

Radio tracking has been widely used in a range of studies of terrestrial fauna in Australia (e.g. O'Connor and Pyke 1987; Newell 1999), but until recently had not been used on fish (Koehn 1996,1997). Both radio and ultrasonic tagging have however, been used widely in overseas fish studies (see Priede 1980; International Society on Biotelemetry 1999). A wide range of telemetry techniques, equipment and study examples is provided in Amlaner and MacDonald (1980).

This paper provides a brief review of different tag types: the benefits and constraints of each; a comparison of the attributes of sonic and radio tags; choices of frequency; tag attachment techniques; and a review of uses for radio tracking.

Tag options

Tag or mark selection always depends on the question which is to be answered, but other key considerations include: the size and species of the fish, their habitat, cost per fish, ease of application, the number of fish which need to be tagged and the duration of the study and likely recapture rates. Characteristics of different mark/tag types are given in Table 1.

Table 1. Characteristics of different types of tags and marks for use on fish. ($=cheap (<$5 per fish), $$=moderate ($5-$20 per fish), $$$= expensive (>$20 fish). * These methods have substantial set-up costs. ** PIT tags can be detected and read at close range (<30cm), while coded wire tags can be detected at close range but the fish need to be captured and sacrificed so that the individual tag can be identified.

	Characteristic							
Tag/ mark type	**Individual/ Batch mark**	**Cost per fish**	**Ease of use**	**Marine/ freshwater**	**Need recapture?**	**Continuous monitoring**	**Limitations**	**Comments/ references**
Tattoo, brand, fin clips, O-rings, dyes, polymer	Batch, Individual	$	Easy	Both	Yes	No	Not lasting	Kearney (1989), Hancock (1989)
Antibiotic, radio isotope marks	Batch	$	Moderate	Both	Yes	No	Sometimes kill fish to retrieve	Hancock (1989)
Genetic tags	Individual	$	Difficult	Both	Yes	No	Expertise	Keenan and MacDonald (1989)
Passive Integrated Transponder (PIT)	Individual	$$	Easy	Both	Yes/No*	No		Can monitor at close range
Dart, T-bar, streamer, disc	Individual	$	Easy	Both	Yes	No		CATAG website
Coded wire	Individual	$*	Moderate	Both	Yes/No**	No	Equipment, kill fish to retrieve	NMT website; Ingram (1989)
Satellite	Individual	$$$*	Difficult	Both	No	Yes	Cost	e.g. ARGOS (see Roche 1999; Priede 1980)
Electro-magnetic	Individual	$$$*	Difficult	Both	No	Yes		Jemakoff (1989)
Archival	Individual	$$$*	Difficult	Both	Yes	Yes	Size, recapture, cost	Gunn and Young (2000)
Radio	Individual	$$$*	Difficult	Freshwater	No	Yes	Fish size, numbers, attachment, tracking time, limited by battery life	e.g. ATS website, Lotek website, can monitor from a distance
Ultrasonic	Individual	$$$*	Difficult	Both	No	Yes	Fish size, numbers, attachment, tracking time, limited by battery life	e.g. Lotek website, Vemco website, can monitor from a distance

As fish generally cannot be observed in freshwater situations, most tag types rely on fish recapture to obtain data. This poses a problem for data collection, with low percentages of tagged fish being recaptured and consequently the potential for capture bias. Sonic and radio tags however, have the advantage of allowing individual fish to be tracked, potentially on a continuous basis, with 'observations' and measurements made of 'natural' behaviour for a large percentage of the tagged fish.

Ultrasonic and radio tags

Ultrasonic tags use acoustic soundwaves generally around 50 KHz, whereas radio tags use signals in the 30-150 MHz range. Both ultrasonic and radio tags consist of three essential components: circuitry, a transmitting aerial and a battery. These components are encased in an epoxy resin. As these tags rely on battery power, they have a limited life determined by the battery, making tag longevity a consideration. There are currently new options which can assist in power saving such as microcontrollers, that allow tags to only be active for certain periods rather than in

Table 2. A comparison of the performance of sonic and radio tags under different study conditions.

Characteristic	Ultrasonic	Radio
Salt water	Excellent	No
High conductivity	Excellent	Poor
Low conductivity	Excellent	Excellent
Deep water	Excellent	Limited
Turbulent water	No	Excellent
Fast animals	Poor	Excellent
Long migrations	Poor	Excellent
Dense aquatic vegetation	Poor	Very good
In water obstructions	Poor	Very good
Turbid water	Poor	Very good
Algae	Poor	Excellent
Thermocline/Temperature gradient	Fair	Good
Ice	Poor	Good
Number of animals	Same	Same
Tracking options	Hydrophone (in water)	Many options: land, boat, air, remote (out of water)
Power usage	Poor	Good

continuous use. In general, radio tags make more efficient use of power, providing a longer life for comparable size transmitter. There is, however, always a chance of tag failure.

Ultrasonic and radio tags offer the option of individual tags which can allow information to be collected in a harmless manner without the need for fish recapture. Both of these tagging methods do, however, have some disadvantages over other tagging methods. These include: higher cost, the need for greater expertise, limitations on fish size and a limitation on the number of fish which can realistically be tagged. This limitation is somewhat overcome by the high level of 'recaptures' although most studies are forced to rely to some degree on repeat measurements from the same individuals. Manual tracking can also become very labour-intensive.

Another key limitation for radio tracking is water conductivity. Use of radio tags is essentially limited to 'freshwater' environments and difficulties can arise in areas such as estuaries and lowland rivers where high salinity levels may occur. Areas with 'intermittent' high salinities such as those which change throughout the year or areas which have saline pools or haloclines may pose particular problems. Testing of the 48-49 MHz wavelength has indicated an effective limit to tracking at conductivity levels greater than about 600 EC. To overcome these difficulties combination ultrasonic/radio tags are now available from some suppliers (e.g. see Lotek, Vemco).

A comparison of the performance of ultrasonic and radio tags under different circumstances is given in Table 2.

Kenward (1987) asked the following questions in relation to whether radio tracking was an appropriate study method for terrestrial research:

- Do I have the time?
- Can I catch enough animals?
- Can they be tagged?
- Can I afford it?

Table 3. Relative performances of low (<50 MHZ) and higher (>50MHz) radio frequencies for a range of characteristics.

Characteristic	<50 MHz	>50 MHz
Attenuation	Less (better signal)	Greater
Depth	Greater transmission	Less
High conductivity (>600EC)	Greater transmission	Less
Land vegetation	Less blockage	More
Signal efficiency	Less	More
Transmitter efficiency	Less	More
Antennae	Bulky	Smaller

- Can I collect appropriate data?

These questions are equally appropriate for the study of fish.

Choice of radio frequency

Generally the frequency options for radio tags are in the ranges of 30-32 MHz, 48-49 MHz and 150-151 MHz. Most terrestrial radio tracking has been conducted using 150 MHz equipment, which can also be utilised for aquatic research, but there are some advantages with lower frequencies (Table 3). Lower frequencies provide better reception and range through water and therefore have advantages in deep or more saline waters. As the size of a conventional (yagi) antenna is based on the inverse of the wavelength, low frequency antennae can be large and unwieldy. This can be overcome by the use of smaller whip or loop antennae, but these are less directional for tracking.

Transmitter attachment techniques

Transmitters can be attached to fish either externally or internally. Externally-attached tags can be wired through the flesh or bony structures such as spines or operculae. Such attachments have the potential for entanglement in natural environments, especially if the species utilises habitats such as woody debris or vegetation. Internal tags can either be inserted into the stomach or implanted into the body cavity. These procedures are much more difficult and are likely to require some veterinary training, but encapsulate the tag within the fish. Such operations can however be stressful to the fish and there is the chance of infection of the wound or rejection of the transmitter. Using the generally accepted rule of a transmitter weight being less than 2% of fish body weight (Knights and Lasee 1996), this avoids balance and entanglement problems. Care must also be taken to ensure that the size and shape of the transmitter is appropriate for the body cavity of the fish to avoid contact with vital organs. This may be particularly difficult if female fish are in spawning condition.

Tags inserted into the stomach provide a relatively quick and easy form of attachment but have the potential to be ejected or interfere with feeding patterns. This type of attachment has proven ideal for use on large numbers of spawning salmon in North America as these fish no longer feed (Eiler 2000).

Attachment techniques must also give consideration to the type of aerial which the tag uses to transmit its signal. Aerials which are incorporated within the tag are convenient, but seriously compromise transmission power (see ATS). Most transmitters use a stainless steel, trailing aerial which can be kept inside the body of the fish or, more commonly exited from the body either through the implant sutures or *via* a separate incision (Koehn 1997). Externally-attached transmitters do not have this problem and those inserted into the stomach can allow the aerial to protrude from either the mouth or be folded back

Table 4. Characteristics of different types of transmitter attachments for freshwater fish.

	Attachment type		
Characteristic	**External**	**Stomach**	**Implant**
Installation time	Moderate	Quick	Slow
Difficulty	Moderate	Low	Highest
Recovery time	Moderate	Quick	Longest
Balance problems	Greatest	Least	Least
Transmitter size	Smallest	Moderate	Largest
Entanglement	Greatest	Low	Low
Infection	Moderate	Low	Highest

through the operculum (Brown and Eiler 1999). The performance of externally-attached and oesophageal tags in salmonids have been assessed by Brown and Eiler (1999). Rejection of internally-implanted tags is a possibility and the survival, growth, health and healing of surgically-implanted transmitters in bluegills has been assessed by Knights and Lasee (1996).

Discussion

Fish are not readily visible in their natural environment and knowledge of their biology and movements has usually been assembled from many isolated and discontinuous observations (Priede 1980). Both radio and ultrasonic tagging allow better information to be obtained through the ability to follow individuals. In reference to marine studies, Arnold (2000) concluded that 'we have learnt more about fish migration over the last 30 years, since the introduction of acoustic tag, than in the preceding 75 years, following the invention of the Petersen disc.' Radio tracking has the ability to have the same effect on the studies of freshwater fish.

Many applications of fish radio tracking have concentrated on small-scale studies which detailed aspects such as movements and habitat use (Coeck and Colazzo 1999). Advances in technology, however, are providing new tools for collecting detailed information (Eiler 2000). Radio telemetry studies are now under way on larger scales, in which large numbers of fish are tagged. Adams *et al.* (1999) report behavioural data from over 4 000 juvenile salmon, while Eiler (2000) and Bjorn *et al.* (1999) report telemetry studies where in excess of 3 000 individual fish have been tagged per year. Such large scale tagging now allows radio tracking to provide information previously obtained by more traditional tagging methods including abundance (Hasbrouck *et al.* 1999), population estimates (e.g. English *et al.* 1999), survival rates (English *et al.* 1999) and stock assessment (Fish 1999). Behavioural studies on fish have included schooling (Johnsen 1980a), the effects of heated effluent (Johnsen 1980b; Langford *et al.* 1980), homing and spawning activity in salmonids (Hawkins *et al.* 1980; Weatherly *et al.* 1996) and tracking around and through fishways (Adams *et al.* 1999).

Other options for radio tags now include activity, mortality and depth sensors (ATS; Beeman *et al.* 1998), temperature sensors (Venditti and Rondorf 1999), movement sensors, temperature probes, heart rate/metabolism monitors (Hinch *et al.* 1996) and other physiological and environmental monitoring (e.g. Miller *et al.* 1980).

Tracking can be undertaken manually by land, boat or aircraft or by remote stations using data loggers. Tracking by air can provide considerable advantages, especially along river systems (Holder and Eiler 1999), although it can be weather limited, provide staff hardships and be difficult when tracking large numbers of fish. It is now possible to incorporate GPS (Olexa *et al.* 1999), GIS (Hooge *et al.* 1999) and satellite up links (Eiler and Masters 1999) as part of remote monitoring systems (Bridger *et al.* 1999). Options used by acoustic tags such as those for swimming speeds on marine fish (Webber *et al.* 1999) can easily be added as options to radio tags for use in freshwater. Microcontroller tags which can be pre-set to determine when tags are operational, and provide considerable savings on battery power, hence extending tag life. Similarly, trade offs can be made with power outputs and pulse times to reduce power consumption.

The benefits of the relatively recent development and use of radio tags in Australia for the study of Murray cod (Koehn 1996, 1997) and other species (Koehn and Nicol 1998) can be given as examples where significant new biological information on movement patterns, homing, and habitat preferences has been collected which could not have been possible without radio tracking as a technique.

Conclusion

The use of radio tags to study freshwater fish has the ability to transform the way freshwater fish are studied in Australia. Radio tags have considerable advantages over ultrasonic tags in relation to tracking methods and power usage. They are, however, limited by water conductivities. Radio tracking can allow data to be collected on difficult-to-capture species in a cost-effective manner to answer questions on basic biological parameters such as movement and habitat preference. More advanced utilisation of this methodology, together with technical advances, mean that more detailed and extensive studies can be undertaken. The use of radio tracking will prove to be a quantum leap in the study of freshwater fish.

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Fishways as tools for monitoring movement patterns of large fish populations

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Abstract

The recent advent of effective fishways has presented researchers with an important opportunity to not only monitor large-scale fish movements, but to also quantify other more subtle behavioural habits exhibited by native fish. Traditional count data are useful to determine the effectiveness of a fishway and assess long-term changes in the abundance and species composition of migratory fish populations. However, several emerging technologies will potentially further develop this research. For example, the entrance of a fishway is a very useful site for remote scanning of fish previously tagged with active or passive external/internal tags. Such technology is now commonly used and is advantageous because there is no requirement for continued handling of migrating fish. Hence, long-term data, such as fish home range and timing of spawning movements, can be reliably collected. Several case studies will be presented outlining the current technologies and methods used for monitoring of large migratory fish communities in fishways, their advantages and possible limitations.

Introduction

This century about 150 fishways have been constructed on many of the coastal and inland rivers of eastern Australia. Over 50% of these have been built in the last 10-15 years, including approximately 18 rock ramp, 22 vertical slot and 4 lock-type fishways. Many others are planned. Towards the latter part of the century the impetus for new fishway research and construction has largely been a decline in the distribution and abundance of native fish species (Cadwallader 1978). Hence, most fishways built since the late 1980s incorporate standard design criteria which aid successful passage of a wide size range of native fish (Mallen-Cooper 1999). Indeed, fishways are likely to have an important role in maintaining and restoring biodiversity of whole fish communities (Stuart and Mallen-Cooper 1999). However, although most river regulation agencies support multi-million dollar fishway programmes, few of these new facilities have been subject to intensive monitoring. Consequently, there have been limited opportunities to provide effective design feedback to engineers and no cost/benefit analyses have been available to the licensee or general public. This paucity of monitoring, particularly of new "generic" facilities, also exacerbates the lack of clearly specified performance and operating objectives presented to the fishway operators. Unless monitoring programmes continue there is a risk that serious individual design flaws will be undetected, or at least remain unrectified and the current momentum to provide for fish passage may be diminished (Jackson 1997).

A shared and somewhat surprising finding among almost all of the more recent fishway monitoring projects has been the high diversity and abundance of fish captured migrating. In sub-tropical river systems, 34 fish species have been captured entering a single fishway and, during peak periods of movement, up to 4 500 fish per day (Stuart and Berghuis 1999). Large-scale fish migrations are not only restricted to northern rivers. They have been documented in several temperate rivers of south-eastern Australia (O'Brien 1997; Mallen-Cooper 1999). Monitoring these movements within fishways has traditionally consisted of trapping and counting fish at several points, usually at the top and bottom. However, most fishways have been built with little understanding of fish attraction. For example, there are few data on how fish approach barriers, their ability to quickly detect a fishway entrance particularly during high flows, the consequent extent of temporal delays and their behaviour immediately before entering the facility. Collection of these data may be essential to optimise fish passage. To this end the use of other monitoring techniques such as underwater video surveillance of fishway entrances and radio telemetry devices is also discussed. The specific aims of this review are to outline the current techniques for monitoring large migratory fish populations and briefly discuss some future research directions using existing technology.

Methods of evaluating fishways

Evaluation of fishways is almost always dependent on an accurate assessment of the number of fish successfully utilising the facility. This has usually been carried out by sampling migrating fish at fixed points within the facility. The top of the fishway has been used in many studies to trap fish and this has revealed information on the movement habits and general effectiveness of the fishway (Kowarsky and Ross 1981; Russell 1991). However, the arrangement of the fishway entrance, hydraulic conditions within the pools and the differing swimming ability of fish species and size classes can confound such data. Consequently, other projects have sought to provide a more robust measure of effectiveness by sampling at several locations, usually at the top and bottom (Mallen-Cooper *et al.* 1995). These independent data can yield considerable information on population size, life stages migrating and passage efficiency; other experiments can also be employed to monitor fish behaviour and physiological abilities. Nevertheless, these methods require handling of all target and non-target fish and collection of as much data as possible, over a wide range of flows and seasons. Occasionally, monitoring may be limited by small sample sizes and conversely during peak periods of movement very large numbers of fish may enter the fishway, thus placing an additional strain on field workers and on the safe release of fragile fish species. In addition, some studies have included sampling in the river below a barrier to determine population size and whether there are accumulations of fish (Marsden *et al.* 1997). These methods may also be used to infer fish migration through changes in abundance before and after fishway installation (Mallen-Cooper 1999) together with mark-recapture techniques (Gwartney 1969). However, the requirement for large numbers of fish and appropriate choice of the sample sites may limit the success of these experiments.

Several new technologies have been developed for fisheries ecological research, which may be adapted to minimise these problems. For example, time-lapse video and visual observation were used to record salmon passage at a fishway in North America (Hatch *et al.* 1994). The authors concluded that the system was accurate and cost-effective, but possible limitations to the technique are a need for relatively clear water and a considerable amount of image processing time (Hatch *et al.* 1998). Irvine *et al.* (1991) used image recognition software to automate fish counts and in Australia the development of another automatic system was also recently reported (Owen and Harris 1998). The latter study found that the underwater camera and imaging software system were highly accurate using simulated data, but that problems relating to turbidity and tracking of large fish numbers were likely to arise during a field study. Furthermore, video technology is usually dependent on strong lighting, which can alter fish behaviour and diel movement patterns (Hadderingh *et al.* 1999).

Radio telemetry has been successfully used for tracking the movements of several temperate and sub-tropical native fish species (Koehn and Nicol 1998; Kind and Brooks 1999), but this technology has not been specifically employed to evaluate fishways. Conversely, in North America researchers have used radio tags to study the movements of migrating fish as they attempt to locate fishway entrances (Barry and Kynard 1986; Vogel *et al.* 1990) and their behaviour within (Theiss and Kynard 1997). These individual radio signals can provide important information on how fish approach weirs, possible distraction to spillways during high flow, their success at quickly detecting a fishway entrance and their behaviour once inside the facility. To date similar data have not been collected in Australia. Interestingly, automatic datalogging receivers coupled to a satellite uplink have allowed remote collection, processing and transfer of riverine fish movement data (Eiler 1995). The disadvantages of these methods are the initial cost of the equipment, consequent limitation to the number of tagged fish, restriction of tagging to larger size classes and post-handling behavioural changes.

In the mid 1980s passive integrated transponder (PIT) tags were developed which have several advantages over radio tags. These include relatively low cost (A$ 7-8), unlimited life expectancy, and the ability to be used in both small and large fish (Prentice *et al.* 1990). PIT tags have been used to monitor the movements of fish in experimental fishways (Castro-Santos *et al.* 1996), where high detection efficiencies have been reported. Antennae can be built into the fishway (e.g. around a vertical slot) and automatic reading and logging of tagged fish, their location, passage efficiency and time of arrival recorded. However, the range of detection of the tags is limited to approximately 60 cm, hence antennae arrays must be carefully positioned or specially made reader tunnels employed. The system seems only to be otherwise deficient if large numbers of tagged fish enter the detection zone simultaneously (Castro-Santos *et al.* 1996). A combination of the methods outlined above is likely to be important in further elucidating the behavioural patterns of migrating fish and of their ability to find a fishway entrance during high flow events.

Conclusion

Ongoing performance monitoring should complement the increased interest in fishway construction. A lack of objective monitoring may result in a real risk of site-specific design or operation flaws and consequent delays to migrating fish. More importantly, without monitoring the lessons gained from each site cannot be integrated into future constructions (Cada and Sale 1993). Clearly, quantification of the number of fish approaching the facility, their ability to detect the fishway entrance and length of delays is important for fishway design, particularly at sites where the river channel is wide or hydraulic conditions during overtopping events prevent or distract fish from finding the fishway entrance. Radio telemetry and PIT tag technology will be integral in answering these questions and may provide important evidence of the need for a fishway on both river banks. Additional benefits of fishway evaluations include long-term population monitoring and positive promotion of results toward public support for other river restoration projects (Bennett 1997). Proving the success of fishways should not be the sole province of government agencies, but also of the water authorities and design agencies. Only then can clear and measurable fishway performance goals be achieved.

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Is there a role for 'uncontrolled' tagging in 'real' fisheries science?

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Abstract

The demand by fishery participants to tag fish has sometimes resulted in the information of large-scale, long-term tagging programmes. The best known examples of these are so-called cooperative tagging programmes through which recreational anglers tag and release fish as part of a broad-scale tagging undertaking. There are many such programmes in operation around the world, some of which have been in operation for many years. Periodic reviews of long-term programmes allow assessment of their progress, utility and application to research goals. The main differences between user-based and scientific tagging operations tend to lie in the areas of planning and quality control. Scientifically-tagged fish may be caught by more 'fish friendly' methods, be more carefully handled and be more accurately measured. It is also likely that scientifically-based tagging operations result in better quality data overall since data on all fish released are retained. These differences appear to be intuitively obvious, but may not necessarily be real. Despite their shortcomings, recreationally-based tagging programmes do provide important and useful data which would otherwise be difficult, if not impossible, to obtain.

Introduction

Tagging of fish by fishery participants is popular. It gives the fisher a sense of participation in a scientific activity which will add to knowledge about the target species. The best-known examples of this activity are so-called cooperative tagging programmes through which recreational anglers tag and release fish as part of a broad-scale undertaking. There are many such programmes around the world, some of which have been in operation for several decades.

The main perceived differences between user-based and scientific tagging operations are in the areas of planning and quality control. Scientifically-tagged fish may be caught by more 'fish friendly' methods, be more carefully handled and be more accurately measured. It is also likely that scientifically-based tagging operations result in better overall data quality due to greater control over all aspects of the study. These differences appear to be intuitively obvious, but may not always be real. The assumptions that scientifically-based tagging programmes are always well structured, and usually achieve their goals are obviously not always met. And in practice, how poorly structured are user-based programmes?

This paper focusses on two large-scale, Australian cooperative tagging programmes, the Australian Gamefish Tagging Program, operated by New South Wales Fisheries, and AUSTAG, operated by the Australian National Sportfishing Association in conjunction with the Fisheries Branch of the Queensland Department of Primary Industry.

Brief history of recreational tagging

Tagging of large fish by recreational anglers was made possible by the development of nylon and steel-headed

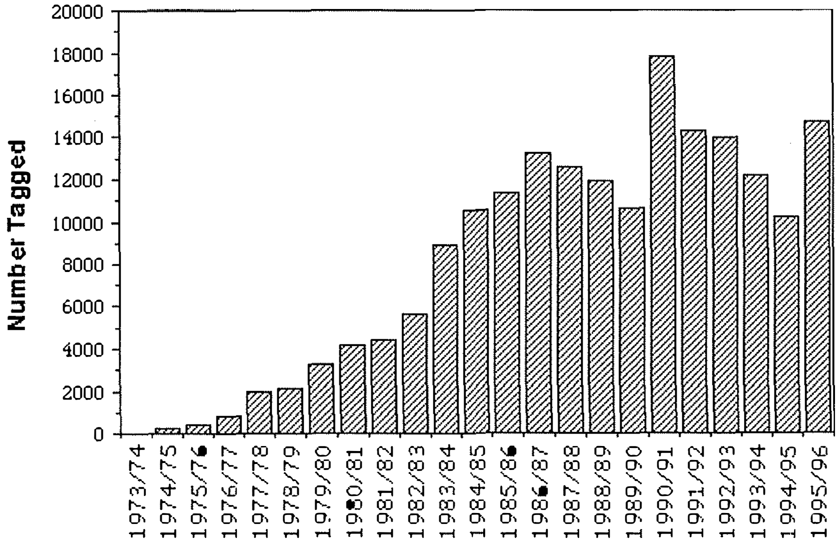

Figure 1. Numbers of fish tagged on the Australian Gamefish Tagging Program.

plastic dart tags that could be placed into the dorsal musculature of fish without removing them from the water. The system was developed in the early 1950s by Frank Mather III of the Woods Hole Oceanographic Institute, and tags were made available to anglers on a trial basis in the early 1960s. By 1980, the programme had recorded 11 200 white marlin tagged, 194 of which had been recaptured, and 21 000 sailfish tagged for 213 recaptures. Perhaps one of the most important findings that Mather had recorded by that time, was the fact that recreational-based tagging was indeed a useful scientific exercise. This was shown by the recapture rate of recreationally-tagged bluefin tuna. Mather noted that the overall tag return rate from over 3 200 releases by sport was 20 percent (21.4 to 48.5 percent in the years 1963 - 1972) demonstrating the ability of school tuna to survive being captured on rod and reel, then tagged and released.

The Mather method has since been adopted by many programmes, including all of the gamefish tagging programmes operated by the US National Marine Fisheries Service (NMFS), the South African tagging programme, operated by the Oceanographic Research Institute in Durban, Canadian shark tagging programmes operated by Fisheries and Oceans, Canada, and the Australian Gamefish Tagging Program, operated by NSW Fisheries.

Tagging smaller recreationally important fish, such as bream, flathead, barramundi etc., makes use of tagging equipment used on standard fisheries research programmes. The main tool which has made mass tagging of smaller fish by recreational anglers possible is the 'tagging gun', a modified clothing tag applicator which applies cartridge banks of anchor tags possessing a 'T' shaped head. This method is used by AUSTAG.

In Australia, angler-based tagging programmes are generally confined to these two large, centralised operations. This is in contrast to the US, where numerous tagging programmes have evolved at both governmental and private levels.

Summary results of both Australian programmes are published in annual reports, and are widely distributed to participants and all interested parties. Briefly, the statistics on both programmes may be summarised as follows:

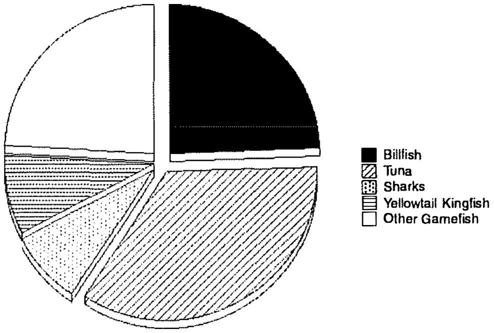

Figure 2. Species composition of Gamefish Tagging Program.

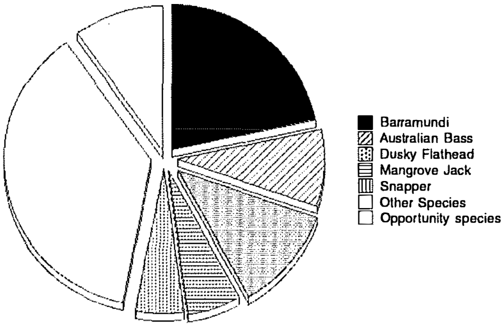

Figure 3. Numbers of fish tagged on the Australian Sportfish Tagging Program. (AUSTAG).

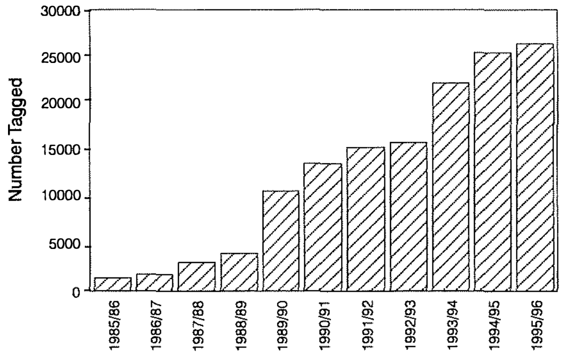

Figure 4. Species composition of Australian Sportfish Tagging Program.

Gamefish Tagging Program

This programme was commenced in 1974, and has operated nationally (and in some overseas countries) ever since. All recognised species of marine gamefish are eligible for tagging, including all billfish and tuna, pelagic sharks and other species such as yellowtail kingfish, dolphin fish, mackerel and wahoo. The growth of the programme is illustrated in Figure 1, showing that there was a steady increase in numbers of fish tagged until the late 1980s, followed by a slight decline, a peak in 1990/91 and an average of about 12 000 fish tagged per year since. The broad species composition for the programme is shown in Figure 2. The results of this programme have been used widely for many purposes, including stock delineation, movement rates, variation in year-class strength and growth studies. Many published papers have resulted from, or have used data from this programme.

Sportfish Tagging Program

The AUSTAG Programe began in 1985, and has grown ever since (Figure 3). Eligible species are generally those termed 'sportfish' by the Australian National Sportfishing Association, the main targeted species for the programme being barramundi, dusky flathead, Australian bass, mangrove jack and snapper (Figure 4). The programme has concentrated on specific scientific studies, such as movement and stock structure of dusky flathead and school mackerel in southeast Queensland, and of snapper in Victoria. AUSTAG operates in all Australian States except New South Wales.

Benefits of recreational tagging

There are two main areas of benefit which derive from recreational tagging programmes. The first is new scientific knowledge, which is discussed below, and the second area of benefit is that of angler and community perception and attitudes. If anglers feel that they are contributing to a worthwhile endeavour, they will be more likely to develop, and promote, ethical attitudes towards fishing, and the fish they target. This leads to a strong conservation ethic in participating anglers which has a range of additional benefits. For example, participating individual anglers, and angler organisations, tend to be very supportive of research programmes in general, and will readily participate and assist in programmes other than tagging. Awareness of tagging programmes, and willingness to assist by anglers, ensures that recaptured tagged fish from any programme are more likely to be reported to the tagging agency.

Recreational tagging programmes are popular with the media, not only angler-oriented, but also mainstream electronic and print outlets. The more 'spectacular' tag recaptures (long distance, long time-at-liberty) capture the public imagination, leading to support for research in general. Pubic awareness and education may also demonstrate conservation aspects of recreational fishing which would not otherwise be known.

Scientific gains and uses

Do recreational tagging programmes achieve scientifically useful or meaningful results? It is clear from an inspection of the uses to which recreational tagging data have been put that the answer to this question is in the affirmative. The main uses of such data are:

Stock delineation

One of the important issues in fisheries management is the determination of the extent, or boundaries, of stocks which may exist within the range of an exploited species. For the large, pelagic species such as tuna, billfish and sharks, which have trans-oceanic ranges, and are often fished by many nations, delineation of stocks is a critical question. Genetic studies of such species have often (but not always) proven to be inconclusive in determining stock structure. Tagging is then the only tool available for giving some indications of stock structure.

Because billfish and tuna have extensive trans-oceanic ranges, and because tagged individuals of some species of tuna and billfish sometimes show long distance movements, billfish and tuna are often called "Highly Migratory Species", a term which has international legal connotations. However, it is also known that some species of billfish and tuna are much less 'migratory' than others, and that many of them aggregate seasonally in localised areas. A good example of this is the annual aggregation of adult black marlin off the Great Barrier Reef, the basis for the famous charter fishery off Cairns. It is also known that aggregations may be separated by great distances. Therefore, the rate of exchange of individual fish between such aggregations is a critical factor in assessing the effects of fishing on a given aggregation. This rate of exchange of individual billfish and tuna throughout their ranges is often termed a "mixing rate", and can be likened to the viscosity of a fluid. If a fluid is highly viscous, like molasses, then mixing will be very slow. Similarly, if the mixing rate of a given species of tuna or billfish is very slow, then it may take a long time to recover from depletion of the stock in a localised part of its range, even though this depletion may be of a temporary nature. Tagging has been used to determine such mixing rates of pelagic fishes, notably the tagging programmes on skipjack and yellowfin tunas operated by the Secretariat of the Pacific Community (SPC). Similar information has been derived from tagging of Istiophorid billfish (marlin, sailfish) by recreational anglers. In fact, virtually all of the data on rates and extent of movements have been derived from recreational tagging programmes operating in the US and Australia.

Interaction and sector allocation

Reporting of recaptured fish by different sectors of a fishery is often a good indicator of interaction between sectors. Recreationally-tagged tuna have been reported by both commercial and recreational fishers, while tagged billfish have been reported by recreational, artisanal and commercial fisheries using a range of gear types, including trolling, longline and purse seine. If tags are returned by all fishery sectors, either in total, or in proportion to the relative catches of each, then return rates will provide a measure of proportional catch of each sector. Of course, in practice, this is virtually never the case, but nevertheless tag returns by sector will still provide some indication of fishery interaction.

Growth

Even though it is often argued that, because of unreliability of initial release measurements or estimates, recreationally-based tagging data are of no use in determining growth rates, important information on growth rates can be derived from recreational programmes. The AUSTAG Sportfish Tagging Program relies on well-trained taggers who accurately measure all released fish with standardised equipment. Growth data derived from that programme are therefore of good quality (provided, of course, that reliable measurements are made at recapture – a caveat of all tagging programmes). Similarly, smaller gamefish are sometimes accurately measured at release on the Gamefish Tagging Programme, although it is more common to estimate the size of tagged fish. For larger fish which are tagged while still in the water, the weight of the fish is estimated, and while such estimates are prone to error, under some circumstances, good growth information has been able to be derived. For example, when most fish being released are of similar size, as is the case for juvenile (0+) black marlin which are tagged off Townsville each year, estimates of size-at-release have very narrow ranges. If any of these fish is recaptured years later, and if an accurate measurement of weight or length is obtained, then good long-term growth estimates may be obtained. This has indeed been the case for a number of species, including black marlin, albacore, yellowfin and southern bluefin tuna.

Survival

The condition of fish at release is usually recorded for recreationally-tagged fish. Many cases have been recorded of fish with apparently serious injuries at release being recaptured in healthy condition much later, demonstrating, at least for some individual fish, recovery and healing after hooking injuries.

Catch information

One of the little-realised benefits of recreational tagging programmes is the information derived from release data. Catches of recreational fisheries are rarely monitored due to cost and logistic constraints, and while records of released fish usually do not include effort data, they nevertheless may form a long-term record of the availability of fish through time and space. Examples of this would include examination of tagging data bases to reveal changes in species composition of sharks, tuna and billfish off the New South Wales coast over the last 40 years. Such changes need to be considered in relation to changes in targeting practices, but can be indicative of real changes in availability.

Criticisms of recreational tagging

As mentioned above, recreational tagging is sometimes criticised on a number of grounds. The main criticisms of recreational tagging might be summarised as follows, together with brief comments:

It is unscientific

The apparent lack of quality control over recreational tagging operations is sometimes cited as a reason for non-acceptance of results from such programmes. As discussed, lack of total quality control does not negate the utility of some forms of data which derive from such programmes. Also, it is possible to direct and train participants in tagging projects to achieve excellent data quality.

It causes unacceptable mortality

In some cases, tagging may lead to additional mortality of fish. This argument has always seemed redundant. A tagged fish has a far greater chance of survival than a landed fish, and in any case, any slight increase in mortality caused by the physical act of tagging would be more than compensated by the information which tagging could provide.

It may damage sensitive populations of fish

This argument suggests that availability of tags may encourage fishing where, in the absence of tag and release, it would not take place. This would appear to be a purely hypothetical objection, since anglers will still seek out fishing opportunities, and if they wish, still catch and release fish with or without tags. Anglers who take part in tagging programmes tend to be highly-motivated supporters of ethical and careful fishing practices.

It is expensive

Cooperative tagging programmes often cost a lot to run, but is value for money achieved? The decision on cost-benefits of any programme rests with the managers of those programmes. In determining costs and benefits of recreational tagging programmes, all benefits must be considered. Reviews of the utility of the data generated by such programmes should be regularly undertaken, and goals and targets modified accordingly. The social benefits of such programmes should not be underestimated. Finally, the popularity of these programmes readily allows opportunities for external, private-sector based sponsorship.

Conclusions

Angler-based tagging programmes can and do produce very useful information which would otherwise not be possible, or be prohibitively expensive, to achieve. Stock delineation and determination of movement and mixing rates are two areas in which recreational tagging programmes have been particularly helpful. The value of goodwill generated by such programmes, both within the angling community and the community at large, should not be underestimated.

Acoustic tracking

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Abstract

Acoustic tags are used to track marine fish because, unlike radio waves, sound propagates well in salt water. Simple 'pingers' transmit at regular pre-set intervals; transponders transmit on receipt of an external signal. Both types of tag can be used to telemeter physical or physiological data. The diameter of the tag and detection range both vary inversely with operating frequency, which ranges from 30 to 300 kHz. Tags can be attached externally, surgically inserted in the peritoneum, or ingested voluntarily. Fish tagged with acoustic tags can be tracked with a fixed hydrophone array or a series of moored buoys, from which data can be recovered by radio or satellite. High-resolution systems can be used to track the small scale of movements of fish in the vicinity of dams or barrages. Mobile tracking systems range from small boats fitted with rotatable, directional hydrophones to large research vessels towing a hydrophone array, or fitted with a sector scanning sonar. These tracking systems are labour intensive and development is increasingly towards automated listening stations or data storage tags, which record information at equivalent rates but avoid the need to follow the fish continuously for long periods, and remote data retrieval by satellite.

Introduction

Acoustic tags (30-300 kHz) are used to track marine fish because sound propagates well in salt water, whereas radio waves are rapidly absorbed (e.g. Niezgoda *et al.* 1998). Acoustic tags can also be used in freshwater, if there is no aeration. In this paper acoustic tags and tracking systems are described first, followed by discussions on tracking fish in the open sea and in estuarine and coastal waters.

Acoustic tags and tracking systems

Types of tag

Simple 'pingers' transmit regularly and continuously, whilst transponders transmit on receipt of an external signal. Both can be used to telemeter environmental data, such as pressure, temperature, and light intensity, or physiological data, such as heart rate, respiration rate and body temperature (e.g. Priede 1992). Tags can be individually coded by modulating frequency or pulse repetition rate and this permits groups of fish to be followed at the same time. Coding with pseudo random (PN) numbers, a recent development, allows large numbers of fish to be tracked simultaneously (Cote *et al.* 1998; Voegeli *et al.* 1998).

Operating frequencies

Acoustic tags emit ultrasonic frequencies, which are usually produced by driving an annular ceramic transducer at its resonant frequency. Tag size is governed by the size of the transducer, whose diameter is inversely proportional to frequency (Priede 1986). Range also varies inversely with frequency, so that, whilst a large diameter 32 kHz tag may have a range of as much as 2.5 km (Klimley *et al.* 1998), a small 300 kHz tag usually has a range of less than 400 m. Frequencies of 30-50 kHz are used for tracking large pelagic fish in the open ocean; frequencies of 60-80

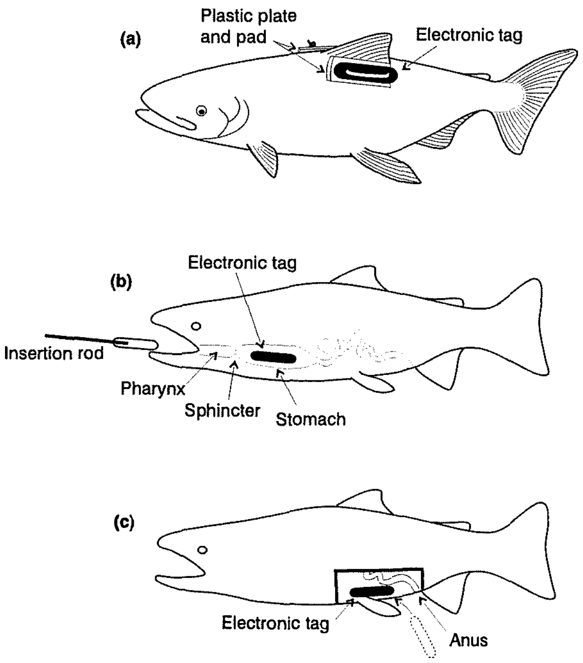

Figure 1. Methods of attaching acoustic tags to salmonid fish: (a) external; (b) stomach; and (c) peritoneum (redrawn from Mellas and Haynes 1985). Similar techniques are used for other types of fish (see e.g. Anon 2000).

kHz are commonest in coastal and estuarine waters (Priede 1992). A frequency of 75 kHz, with a typical working range of one km, is popular for use with coastal and freshwater fish. Higher frequencies of 150-300 kHz are used where a small tag is required (Priede 1992), or where specialised high-frequency imaging sonars are available (Arnold *et al.* 1990). Physical constraints on acoustic signal propagation and detection are discussed by Priede (1992) and Voegeli and Pincock (1996).

Tag attachment

Acoustic tags are attached to fish in a variety of ways, either internally or externally (Figure 1). External tags are commonly attached at the base of the dorsal fin with non-corrosive wires or threads inserted through the dorsal muscles. A compressible pad is often used to protect the skin of the fish. Internally tags may be put inside the stomach or inserted into the peritoneum after surgery. Voluntary ingestion in bait is another common approach (e.g. Løkkeborg 1998).

Tracking systems

The simplest tracking system, which consists of a directional hydrophone, a receiver and headphones, allows the operator to follow the tagged fish and obtain an approximate estimate of its position relative to the boat (e.g. Holland *et al.* 1985). Accurate location, however, requires a hydrophone array, or active sonar. Mobility to equal that of a free-ranging fish is achieved with a research vessel (e.g. Arnold *et al.* 1990). Weather permitting, a large research vessel can track an individual fish until the tag batteries are exhausted, usually after 10-15 days at most. With a small boat, track duration is primarily limited by human endurance (Nelson 1978), although autonomous vehicles may perhaps overcome this limitation in future (Goudey *et al.* 1998).

Tracking fish in the open sea

There have been many fish tracking studies in the sea since Yuen (1970) first followed a skipjack tuna in Hawaiian waters. These have recently been reviewed by the CATAG working group in Europe (Anon 2000) and further information can be found at http:// www.hafro.is/catag.

Ship-mounted and towed hydrophone systems

Most marine fish tracking has been carried out with small boats using a directional hydrophone (e.g. Lawson and Carey 1972) attached to a long retractable pole. The hydrophone is deployed at a depth of 1.5 to 3 m below the surface and is usually contained in a streamlined housing, which permits acoustic tags to be detected at speeds up to 7 knots (e.g. Stasko and Polar 1973; Holland *et al.* 1985). The retractable pole can be fitted to a block clamped to the gunwale (Nelson 1978) or mounted in a special bracket attached to the side of the boat (Holland *et al.* 1985, 1992). Another option is to use a fared shaft on the bow (Stasko and Polar 1973; Carey and Robison 1981), although bow-mounted hydrophones are more susceptible to movement than those on the side of the boat (Jolley and Irbey 1979).

The hydrophone can be fixed facing forwards and the tag located by turning the boat (Jolley and Irby 1979; Holland *et al.* 1985). Alternatively, the hydrophone may be rotated by hand to locate the tag and detect the direction of maximum signal strength (Lawson and Carey 1972; Carey and Lawson 1973; Holland *et al.* 1992). Rotating hydrophones have also been used on larger research vessels (~25-50 m), either attached to the side of the vessel (Ogura and Ishida 1992) or mounted under the hull (Tesch 1974; Block *et al.* 1992).

After release, the tracking boat follows the tagged fish, keeping the acoustic tag within audible range. Because it is not possible to measure the range of the tag with a single hydrophone, it is assumed that the track of the fish is the same as that of the boat, whose position is plotted from visual landmarks, a radio navigation system (e.g. Loran or Decca), or GPS. More accurate fish tracks can be obtained with a towed hydrophone system, such as the VR28 Tracking System (Vemco Ltd, Nova Scotia, Canada), which can measure the range and bearing of the acoustic tag with a micro-controller receiver and four independent acoustic receivers (aligned ahead, astern, port and starboard). Block *et al.* (1997) report detection ranges of 0.8 to 1 nautical mile when using this system to track yellowfin tuna in the eastern Pacific with 34 and 50 kHz transmitters.

Sector scanning sonar and transponding acoustic tags

The Lowestoft Laboratory uses high-frequency, high-resolution sector scanning sonar (Voglis and Cook 1966; Mitson and Cook 1971) and transponding acoustic tags (Mitson and Storeton West 1971) to track fish at sea. The sonar, which produces acoustic pictures of the seabed and other underwater targets such as trawl gear (Cushing and Harden Jones 1966), insonifies a 30° x 10° beam (Figure 2) with a 2 ms pulse of sound at rates of 2 or 4 pulses s^{-1}. The beam is scanned electronically at 10 000 Hz. Range and bearing resolution are 20 cm and 0.33°, respectively, although during tracking the position of the fish is estimated only to the nearest 5 m and 1°. The sonar transducer is hydraulically stabilised against roll, pitch and yaw and can be steered in azimuth to observe all round the ship. Tilt angle can be varied continuously from vertical to horizontal. The sonar can be quickly switched from horizontal (Figure 2a) to vertical mode (Figure 2b) to estimate the depth of the target (Greer Walker *et al.* 1978). Depth estimates are quite good (± 0.5 m) at close range but increase significantly at longer distances (Arnold and Greer Walker 1992).

Transponding acoustic tags, which transmit a 3 ms pulse of sound when insonified by the sonar (Mitson and Storeton West 1971), can be detected out to ranges of about 600 m under ideal conditions. Fish are, however, normally tracked at ranges between 120 and 250 m (Arnold *et al.* 1994). The fish track is plotted electronically, using the range and bearing of the fish estimated from the sonar display, and the position of the ship determined by GPS. The original acoustic tag, whose dimensions were 50 x 10 mm, had negligible drag (Arnold and Holford 1978) but an

Figure 2a

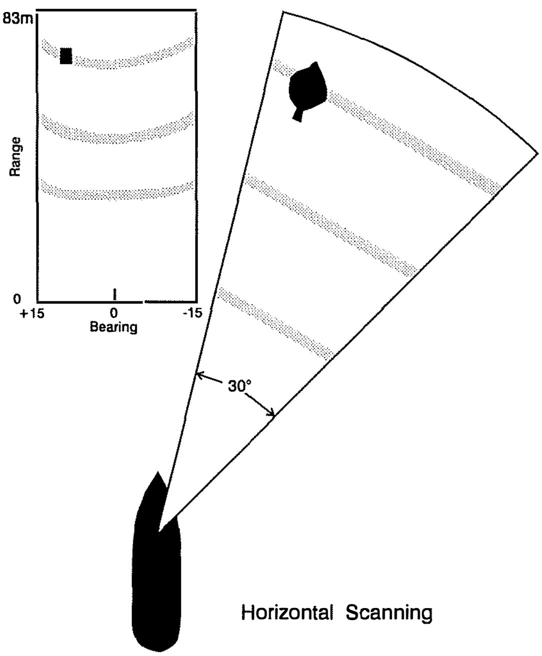

Figure 2b

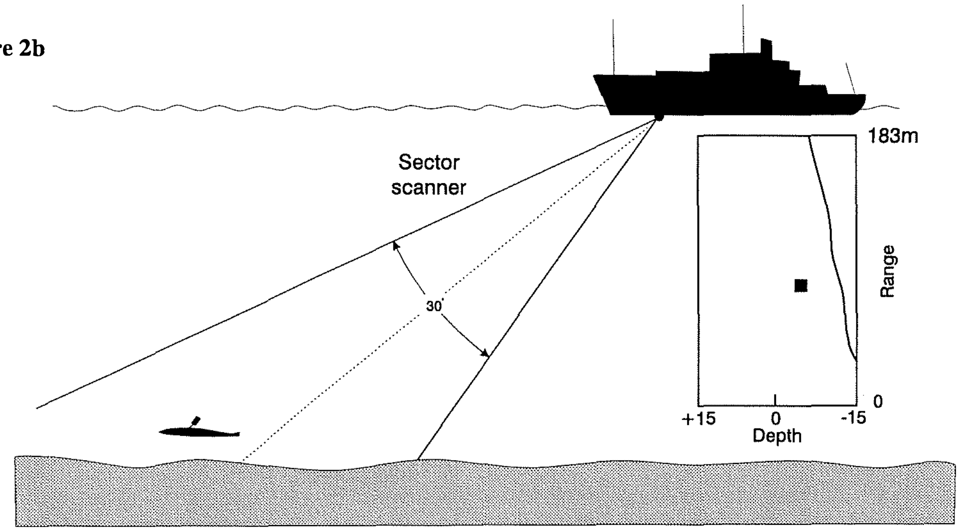

Figure 2. Tracking fish in the open sea using transponding acoustic tags and 300 kHz sector scanning sonar in (a) horizontal and (b) vertical mode. The range and bearing of the fish are measured in horizontal mode. Depths are estimated in vertical mode from slant range and the tilt angle of the transducer when first the tag signal and then the bottom signal are brought on to the centre line of the B-scan display (see insert). For further details see Greer Walker *et al.* (1978) and Arnold and Greer Walker (1992).

operating life of only about 2-3 days. The tag we currently use is larger (60 x 15 mm), has bigger batteries and a life of about 10 days, which can be increased by transmitting alternate pulses of sound with the sonar.

Automated listening stations

Simple listening stations have been developed to investigate the seaward movements of wild Atlantic salmon smolts in coastal waters of eastern Canada (Voegeli *et al.* 1998). Smolts marked with small (single-chip) acoustic pingers and released in freshwater are detected by chains of self-contained underwater receivers moored in the passages between Passamaquoddy Bay and the Bay of Fundy. Tidal currents are strong in these passages and water depth ranges from 50-150 m, creating a hostile environment for fish tracking. The system uses single channel receivers and miniature transmitters, which contain a micro-controller and transmit a complex six-pulse code capable of identifying 4 096 different fish on the same frequency.

Several groups of fish, including sharks and tunas, regularly return to the same location (e.g. Klimley and Holloway 1999) and this behaviour raises the prospect of setting up long-term listening stations with fully automated acoustic systems capable of downloading data and re-programming tags attached to returning fish. Preliminary trials with tiger sharks (Klimley *et al.* 1998) suggest that such systems could be practical in certain conditions.

Sonar buoys with radio transmission of data

Fixed hydrophone arrays connected by cables to an onshore listening station have been used successfully in confined coastal waters (e.g. Glass *et al.* 1992) but are not practical in open waters. The concept has, however, been extended to the open sea with the use of sonar buoys, which can convert acoustic signals to radio signals and transmit them to a ship, or shore-based listening station (e.g. Engås *et al.* 1996; Løkkeborg 1998). At least three buoys are required, moored 400-600 m apart in a triangular configuration; four buoys can provide three-dimensional information on the position of the fish (Voegeli and McKinnon 1996). Commercial sonar buoy systems are manufactured by Vemco Ltd (Shad Bay, Nova Scotia, Canada) (e.g. O'Dor *et al.* 1998) and Lotek Engineering Inc. (Newmarket, Ontario, Canada) (e.g. Cote *et al.* 1998).

Deep-sea tracking systems

Scientists at Aberdeen University in Scotland have developed an autonomous free-fall acoustic tracking vehicle capable of following the movements of abyssal scavengers, such as grenadiers (*Coryphaenoides* spp.), in the deep ocean (e.g. Armstrong *et al.* 1992). In its latest version, the AUDOS (Aberdeen University Deep Ocean Submersible) vehicle, which is capable of operating at depths down to 6 000 m, carries a scanning directional sonar, as well as a camera, flash unit, electromagnetic current meter, compass, micro-controller and batteries (Bagley and Priede 1996). Fish are tagged with ingestible code-activated transponding (CAT) tags, operating at 77 kHz (Bagley 1992). The tags (65 x 12.5 mm), which transmit a single return pulse on receipt of an individually recognised pulse code, can be detected out to a range of 500 m with a precision of 0.5 m.

Tracking fish in estuarine and coastal waters

Research vessels are often too large for confined waters, where tracking is better carried out with small boats, or moored sonar buoys, which convert acoustic signals to radio signals and transmit them to automatic listening stations (ALS).

Tracking salmonids between the sea and freshwater

CART (combined acoustic and radio) tags, which can switch from acoustic to radio transmission after a pre-set time interval (Solomon and Potter 1988), or in direct response to a change in salinity (Dearey *et al.* 1998; Niezgoda *et al.* 1998) are used to track adult fish through estuaries. CEFAS CART tags, which

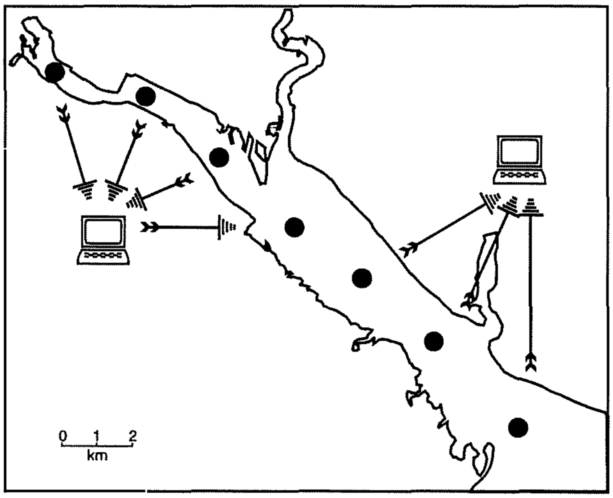

Figure 3. Chart of Southampton Water indicating the positions of acoustic sonar buoys (●) and automatic listening and data logging stations (🖳) (Moore *et al.* 1998).

incorporate a 76 kHz acoustic transmitter and a 173.7-174.0 MHz radio transmitter, are 70 mm long by 16.5 mm in diameter and weigh 4.5 g in water. The tags are individually identified by radio frequency and pulse rate, and switch from acoustic to radio transmission at a pre-set time. They can be detected at ranges up to 300 m, depending on water conditions.

It became possible to study the downstream movements of juvenile Atlantic salmon (*Salmo salar*) and sea trout (*S. trutta*) in the early 1990s, with the development of an acoustic pinger small enough to be attached to wild smolts (Moore *et al.* 1990a). This miniature tag (17 mm long, 8 mm dia.), which operates at a frequency of 300 kHz and has a life of about 35 days, weighs 1.3 g in air and 0.35 g in water. Pulse repetition rate, which is used to identify individual fish, can be set between 40-120 pulses per minute. The acoustic source level of the tag is 148 dB re 1 μPa at 1 m ± 3 dB. The maximum range of detection varies with the acoustic properties of the water. In a fast-flowing estuary with a high sediment load, for example, the range may be only about 75 m; in the open sea ranges of up to 230 m are achievable (A. Moore, pers. comm.). Miniature pingers are surgically implanted in the peritoneal cavity of wild smolts trapped in freshwater during downstream migration. Smolt survival is not adversely affected by this method of tag attachment and a twelve month laboratory study (Moore *et al.* 1990b) indicated no significant effect on behaviour or physiology.

CART tags and miniature pingers are both used in conjunction with a chain of sonar buoys anchored at key positions along the estuary (Solomon and Potter 1988) and monitored with one or more automatic listening stations (Figure 3). Each ALS can monitor signals from up to five sonar buoys. Environmental data, such as temperature, salinity and water quality are monitored at stations close to the sonar buoys. The data logger on the ALS provides a record of the date and time at which each tag signal was detected, the identity of the buoy that detected it and an audio recording of the pulse rate of the tag, which allows the identity of the fish to be established.

Tracking juvenile salmonids in coastal waters

It has recently become possible to study the behaviour of smolts in near-shore coastal waters after emigration from the estuary (Moore 1996). Individual fish are tracked manually using a directional hydrophone on a small (~30 m) research launch, whose geographical position is fixed every 2 min using GPS. Smolts are tagged in freshwater and followed down the estuary with a chain of sonar buoys, as described above. The launch is anchored alongside the most seaward sonar buoy until the tag signal is detected by the hydrophone on the buoy. The launch then recovers its anchor and follows the fish, keeping the tag signal within detectable range (100-150 m). The hydrophone can be operated in vertical mode to give an indication of whether the smolt is swimming close to the surface or close to the bottom.

Tracking salmonids in relation to estuarine barrages

There is considerable concern in the UK about possible adverse effects of barrages on estuarine fish ecology. These barrages, which have been constructed for amenity value or power generation, modify the tidal regime and have the potential to disrupt the migrations of diadromous species, which migrate between sea and freshwater at different stages of their life histories. Fine-scale movements of migrating salmonids can be observed with the CEFAS HiRes system (Russell *et al.* 1990; Kell *et al.* 1994), which depends on the detection of a signal from a 76, or 300 kHz acoustic tag by at least three hydrophones placed at known co-ordinates in the study area. A timer gate interface linked to a PC is used to measure the interval between the time of arrival of the tag signal at each buoy of a pair. The position of the tag is estimated by a non-linear least squares technique. The system can be used with miniature 300 kHz acoustic pingers to record the behaviour of salmonid smolts migrating downstream past the barrage or with 76 kHZ CART tags to follow upstream passage of adult fish (Russell *et al.* 1998).

Discussion

The application of acoustic tracking technology to fisheries research has resulted in some important advances in our understanding of how fish react to their environment and how behaviour affects the efficiency of fishing gear. It has also led to new discoveries about mechanisms of migration and patterns of movement that are leading to a better understanding of stock structure and distribution. Short tag life and the inability to follow more than one fish at a time have, however, both been major limitations. Although tracking will still be needed for some years yet to make detailed observations, or address specific physical or physiological questions, the general trend of future development is likely to be increasingly toward systems that allow observations to be replicated with many fish at the same time. These systems are likely to involve archival (data storage) tags, pop-up tags that release from the fish at pre-set times and transmit data to the laboratory by radio or satellite, and coded acoustic tags that can be used in conjunction with automatic listening stations. Improved systems of acoustic telemetry may also allow data to be recovered in some circumstances, without the need to recapture the fish and remove the tag. It should also become feasible to build smaller acoustic tags as electronic components get smaller or custom-built integrated circuits become affordable. Tags may, however, not necessarily get much smaller in the foreseeable future. The size of batteries is likely to remain a limiting factor for some years and it may be desirable to utilise some of the space saved by incorporating several different sensors. Physiological telemetry is, as yet, in its infancy and major developments in this field are to be expected in the next few decades, along with further advances in understanding of fish behaviour.

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From plastic darts to pop-up satellite tags

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Abstract

The development of electronic tagging technology over the last decade has provided today's fisheries researchers with many new options for studying the movement and migration of marine fishes. Conventional tags (dart, disc, internal, etc.) have provided us with only points of release and recapture, and often these reflect the distribution of fishing effort rather than the true movements of fish.

Acoustic tags provide a means of examining movement patterns in very fine detail. When they include environmental (water temperature) or physiological (EMG) sensors they also allow us to study the interaction of the animal with its environment However, the duration of most tracks is limited by the technology (in particular battery power), cost (tracking vessel charter, etc.) and human endurance (tracking is a very labour intensive activity). There is also a question of whether a tagged animal behaves "normally" in the first 24-48 hrs tagging when it is being followed by a vessel.

Since their development in the early 1990s, archival tags have been used extensively in tunas (Australia and the US) and groundfish (UK/Europe). These tags are miniature data loggers incorporating environmental sensors (light, temperature, depth). They can record data every few minutes for years, allowing researchers to study the daily/weekly/ seasonal/inter-annual variation in movement, migration, behaviour and physiology of their study animals. They are relatively expensive ($2 000) and can only be used where the expected recapture rate warrants the cost of tags. The data from these tags have provided researchers with a quantum leap in the understanding of their animals, and in many cases have shown that models of movement and migration developed from conventional tagging have been seriously flawed. Although the studies conducted to date have focussed on large animals (tags currently available are 50-70 mm in length and weigh 25 g in air) archival tag manufacturers are currently designing and testing tags that will be suitable for use in fish as small as 500 g.

Pop-Up satellite transmitting archival tags currently being developed and tested in the US, Europe and Australia promise to provide all the data-logging functionality of archival tags without the need to recapture the fish. These tags are a hybrid of an archival tag and a satellite transmitter, allowing researchers to program data collection over a specified period and a predetermined release date. On that date, a corrosive link within the tag is activated, allowing the tag to release from the fish, float to the surface and start transmitting a summary of the data collected to a NOAA satellite carrying an ARGOS receiver. Only a small fraction of the data collected can be transmitted to the satellite due to low transfer rates. This presents significant problems in transmission of position estimates as these often involve considerable data manipulation. At present manufacturers are testing on-board geolocation estimation software.

Introduction

As Everhart *et al.* (1975) note in their text "Principles of Fisheries Science", "Fisheries scientists have been searching for the ideal mark since 1873 when Atlantic salmon, tagged in the Penobscot River, Maine, were recovered in fair numbers".

Over the last 120 years, hundreds of tag designs have been developed in attempts to optimise tag retention, visibility, reporting, etc. The "conventional" tags used since 1873 allow fisheries scientists to mark and release a fish (group of fish) at a one location, and then recapture the fish(es) at another location(s) after a period at liberty. With large-enough sample sizes at release and recapture, a picture of the movement and migration can be developed, for a species, populations, individual age classes, etc. For almost 100 years conventional tag technology represented the only direct method of studying movement of individuals.

When acoustic tags were developed in the 1960s, fisheries biologists had a tool that allowed them to follow fish for periods of days to weeks. These tags provided very detailed data on short-term movement and behaviour that conventional tags could not provide. They also allowed the simultaneous collection of environmental data from which links between movement and habitat parameters could be determined.

Over the last decade the development of microchip technology, particularly miniaturised, low-power memory chips and micro-controllers, has resulted in a revolution in tagging technology. Fisheries scientists now have at their disposal an exciting range of specialised electronics with which to keep tabs on fish and study their behaviour. Five years ago archival tags (also known as data storage tags) were first deployed on plaice and tunas. Archival tags are basically miniature computers complete with a range of environmental sensors that collect data on the behaviour, migration, and physiology of a fish over periods of months to years (Gunn *et al.* 1994; Metcalfe and Arnold 1997). At much the same time as archival tags were being pioneered, the first acoustic listening stations – data-logging hydrophone arrays tuned to receive signals from fish fitted with ultrasonic pingers – were developed to map the movement of fish around Fish Aggregating Devices (Klimley and Holloway 1999). In the last 18 months archival tags have been hybridised with satellite transmitters to produce the first pop-up satellite transmitting archival tags (Block *et al.* 1998; Lutcavage *et al.* 1998). These tags are able to collect data for a specified period (up to a few years), summarise these data on the tag's micro-controller and then, at a user-defined time, release from a fish, pop up to the surface and transmit data summaries to an ARGOS satellite.

The quantum leaps in technology over the last decade provide new and exciting options for studying movement and migration. There is certainly a great attraction in using the "gee whiz" technologies, particularly where conventional tagging has been unsuccessful. However, before investing large amounts of money in microchip tags, there is a very clear need to define the questions one seeks to answer, and to assess whether these questions can be addressed in a meaningful way by the various new technologies. In this brief review I've addressed what I see as some of the strengths and weaknesses of three levels of tagging technology: conventional, archival, and pop-up tags.

Conventional tags

Data from experiments using conventional tags have provided most of what we know about the movement and migration of fishes and a number of invertebrate species, and a huge literature has developed over this century from which the strengths and weaknesses of this simplest form of tagging technology can be determined.

Strengths of conventional tags

1. They provide accurate data on the point of release and recapture.
2. Data on growth, fishing mortality and natural mortality.

3. If used in conjunction with injection of chemicals such as strontium chloride or tetracycline, results can be used to validate annual formation of growth bands on hard parts.
4. A wide range of conventional tag designs is available to suit a range of species and attachment methods.
5. Tags are relatively cheap, although costs of deployment and recovery are often significant.
6. Low unit costs mean sample sizes can be large, and studies can be conducted on scales allowing results to be representative of population.

Weaknesses of conventional tags

1. Data are heavily fishery dependent. Non-reporting, inaccurate data on recapture location and size-at-recapture significantly compromise conventional tagging experiments. As it is often difficult to estimate non-reporting rates, caution must be taken when interpreting patterns of movement in cases where non-reporting is suspected.
2. For the data to be useful, it must be assumed that tagged fish behave in the same way as untagged fish. However, objective assessment of whether this assumption is met is very difficult.
3. The pattern of releases and recaptures is most often determined by the operations of commercial fisheries. Thus, tagging data often show the movement between one fishery and another, but provide no data on movement into/from unfished areas.
4. No information is collected on the movement of fish while at liberty. Thus, if an animal is recaptured close to its release location, one can either assume little movement, or some kind of cyclical movement. It is very difficult to distinguish between these two assumptions using conventional tagging data alone.
5. There are significant problems in interpreting low recapture rates. Do they mean low reporting rates, high tag shedding rates, poor tagging method, or simply a very large population?

Archival tags

The development of archival tags was driven by the requirement in many studies to bridge the information gap between the basic, but often biased, data on movement and migration collected by conventional tags and the highly detailed, but short-term information provided by ultrasonic or acoustic tracking. The tags are designed to collect data every few minutes, from which the daily position and behaviour of an animal can be determined. Archival tags have been used over the last five years to study movement and migration of demersal fish such as plaice and cod (Metcalfe and Arnold 1997), and tunas (Gunn *et al.* 1994). In the five years since the deployment of the first generations of archival tags the technology has improved significantly. However, there remain significant challenges to tag manufacturers in four areas:

- Improvements need to be made in tag reliability under the full range of environmental stresses imposed by the large oceanic pelagic species – dives to 1000+ metres, temperature ranges from 2-35°C.
- The performance of sensors must be better specified under a range of conditions, and improvements made in the consistency of performance of sensors, in particular the light sensors.
- The size of tags must be reduced significantly to allow application to a wider range of species.
- The price of tags must be reduced if they are ever to become a routine tool for studying fish movement and behaviour.

As the technology is in the early stages of application it is perhaps premature to conclude too much about its strengths and weaknesses. However, the following are offered as a personal assessment after using them for five years:

Strengths of archival tags

1. Highly detailed data are collected over periods of months to years, allowing researchers to examine variation in position, behaviour and physiology over seasonal, lunar, and inter-annual time scales.
2. Data produced are largely fishery independent. Although one still relies on fishermen to report/ return the tags, the data from tags returned provide an unbiased picture of where a fish has travelled while at liberty. In the case of tuna, this often involves migrations to areas where no fisheries operate.
3. In fish recaptured close to the location of release, it is possible to distinguish between the no-movement and cyclical movement hypotheses.
4. As the tags collect data on the physical environment of the fish, it is possible with regular position estimates to examine the links between movement, behaviour and oceanographic conditions.

Weaknesses of archival tags

1. Cost: the two major manufacturers of archival tags currently charge around US $1 200-1 400 per tag. To promote returns, substantial rewards are also required. At such a cost it is very expensive to mount large tagging studies unless the expected recapture rates are high.
2. Require cooperation of fishermen to return tags.
3. There are significant overheads in the time and expertise required to analyse archival tag data. Calculating geoposition from archival tag light, depth and water temperature data is not straightforward, and there is often a requirement for a) customising analytical software, and b) access to satellite sea surface temperature archives.
4. The relatively large size of current generations of archival tags restricts their application in smaller fishes.
5. Tag attachment is a significant issue for many species.
6. Estimates of geolocation based on daily variation in light levels are prone to significant and varied sources of error. Currently, even for species that live principally in the upper 50-100 m, errors in longitude estimate are in the order of 1°, while latitude errors can be much greater, and are dependent on the time of the year and factors such as weather and depth at which a fish is swimming.

Pop-up satellite transmitting archival tags

The successful application of archival tags in the early 1990s encouraged fisheries scientists and electronics engineers to design and develop a tag that could be used in species where return rates were significantly lower than the 15-20% experienced in the bluefin tunas studied with archival tags. These tags, now known as Pop-Ups, were first conceived by Hunter *et al.* (1986), as a way of being truly independent of fisheries in the collection of movement data. The pop-up concept was a tag that could trail behind a fish, collecting and storing data for a user-defined period and then, after detaching from the fish, float to the surface to transmit these data to a satellite.

Data loggers linked to satellite transmitters had been used successfully for some time on large marine mammals and penguins. However, as these animals either spend significant periods on the surface or on land, the tags designed for them did not need to pop-up/off to allow for transmission. Also, the large size of most of these animals meant that the tags could be large, and include enough batteries for high-powered and numerous transmission.

As very few species of fish spend enough time out of the water to allow data transmission, engineers designing the pop-up tags were faced with the following challenges:

- packing all of the electronics to control tag function, store and transmit data, plus batteries to power transmission over a long-enough period to allow a significant amount of data to be transferred, into a housing small enough that a fish could tow it around for months to years;

- making the package hydrodynamically efficient, positively buoyant and stable in the floating position;
- developing smart software to summarise data collected by the tag, and undertake a series of simple calculations on board; and
- developing a release mechanism that could be controlled by the tag to allow for user-defined release times.

The first prototype tags were tested in 1997 and two pilot studies conducted later that year (Block *et al.* 1998; Lutcavage *et al.* 1998). These tests used simple pop-up tags that provided only a series of temperature records and a location at which the tag popped-up.

The second generations of tags, featuring more sensors, greatly enlarged memory, smart software and on-board processing, are currently being tested. Given successful performance it is likely that the first large-scale experiments with fully functional pop-up satellite transmitting archival tags will be conducted early in 2000.

On the basis of limited use the following appear to be the primary strengths and weaknesses of pop-up tags:

Strengths of pop-up tags

1. With no requirement for tag recapture, pop-ups are completely fishery independent.
2. Promise to be very useful in species where low recapture rates and solitary behaviour make conventional tagging impractical.
3. User-friendly and flexible data acquisition schedules.

Weaknesses of pop-up tags

1. Cost: pop-up tags currently sell for US $3 500-$4 000 per tag.
2. Size: current generations can only be used on fish >75 kg.
3. Slow transmission rates to the ARGOS satellite mean that only limited amounts of data can be transmitted. This required significant data reduction and loss of information on behaviour and movement. It also places limitations on the number of days for which a position estimate can be transmitted.
4. Attachment of a large external tag remains a problem in some species.
5. On-board geolocation estimation remains unproven and a significant challenge.
6. Pop-up may be unsuccessful if fish is at great depths when the tag releases.

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Acoustic tracking of small-scale movement in juvenile southern rock lobster *(Jasus edwardsii)*

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Abstract

Acoustic tracking was used successfully to monitor short-term movement and behaviour of lobsters released to the wild after on-growing in captivity for one year. Tagged on-grown and wild-caught (control) lobsters were released on an area of patch reef. Each tag emitted a unique frequency to allow individual identification of lobsters in close proximity. The combination of a sensitive, narrow-band boat-mounted receiver, and a diver-held receiver enabled tagged lobsters to be located regularly by divers. There were no detectable differences in behaviour or habitat usage between treatments. Lobsters were recaptured at the completion of the field trial to assess feeding success, and change in condition during liberty. While this approach to tracking was labour-intensive, data quality was high, and the ability to recapture animals invaluable.

Introduction

There is considerable interest in starting a southern rock lobster aquaculture industry in Tasmania. While research into closing the life cycle is gaining momentum, commercial culture from the egg to market size is still a long way off. It is possible, however, to capture large numbers of the late larval stage, called puerulus, from the wild (e.g. Mills *et al.* in press). An industry could commence based on the on-growing of wild-caught puerulus to a marketable size. However, there is a high-value wild fishery for this species, and there is concern that the harvest of puerulus would increase exploitation of the stock.

Two mechanisms have been proposed to compensate for puerulus removal: commercial quota purchase; or reseeding of one-year-old juveniles. Commercial quota purchase involves a reduction in catch of adult animals, achieved by reduction in fishing effort through quota purchase. However, the implementation of this method has proved contentious, and details of the number of puerulus to be harvested per quota unit removed could not be resolved. Additional problems were the effect of this method on egg production of undersize females and the concentration of effort (on both puerulus and adults) in sheltered regions. The alternative method of reseeding of one-year-old juveniles is based on the discrepancy between post-settlement survival in the wild and in captivity. Mortality associated with settlement and first year post-settlement in the wild for various lobster species has been estimated at between 75% and 97%. First year mortality of *J. edwardsii* puerulus removed from the wild into culture is between 1.1% and 7% (Crear *et al.* 1998).

If, after a year of on-growing, 25% of captured lobsters are released to the areas of capture, this should compensate for the puerulus removed, and may represent a level of fishery enhancement. The remaining 75% of lobsters are available for culture.

The success of this method depends entirely on the ability of animals on-grown for a year to survive when released. To estimate relative survival, it was proposed to release similar numbers of on-grown and wild-caught lobsters onto an area of patch reef which was divided up in a searchable grid. All animals would be marked with a diver-visible tag to allow individual identification. The numbers and position of on-grown and control animals could be scored by divers on regular occasions. Movement between grid squares on the reef could be used to estimate emigration from the grid, and accordingly loss of lobsters due to emigration could be separated from loss due to mortality.

Juvenile lobsters are difficult to capture by traditional trapping methods, as they are not attracted to bait and will not readily enter pots. As a result, little is known about the behaviour and movement of this life history stage. If parameters such as distance moved and habitat usage vary detectably between on-grown and control lobsters, the methods described would not be appropriate. Movement information is also required to calculate a biologically relevant size for the search grid. A method of tracking which allows regular sighting of tagged animals was seen as the best way to obtain these data.

Methods

Acoustic tracking was seen as the most appropriate method for tracking lobsters. Radio tracking is not an option, as radio frequencies do not transmit well in the high conductivity marine environment. While electromagnetic tracking has been used successfully on small lobsters (e.g. Jernakoff and Phillips 1986), appropriate systems are not commercially available, and specialist knowledge is required.

Acoustic tags can be individually identified by two methods; frequency and 'ping codes'. Tags on the same frequency can be separated by 'ping codes'. For example, the signal transmitted may be broken down into three pulses, followed by two pulses, followed by four pulses, with a short silence between ('ping code' is 3-2-4). While the search process is simplified by having all tags on one frequency, this method of separation is not appropriate if animals are likely to remain close to each other. If two tags can be heard at once with similar intensity, it is difficult to separate the ping codes. Given the gregarious nature of lobsters, and little information about how far they were likely to move, tags separated by frequency were chosen.

To minimise the possibility of tag loss due to moulting, all lobsters were moult-staged prior to tag attachment, and only intermoult lobsters were used. Tags (Sonotronics IBT-96-1) measured 8 mm by 20 mm and weighed approximately 1.5 g. Tag frequencies were from 70 to 80 KHz , were separated by 1 KHz and had an operational life of 21 days. Tags were glued to the lobster carapace using 5 minute Araldite epoxy glue.

Two receivers were used to locate tagged lobsters; a narrow-band boat-mounted unit (Sonotronics USR-96) with directional hydrophone (Sonotronics DH-4), and a diver-held unit (Vemco VUR-96).

Nine lobsters were tagged: three on-grown, three wild 'controls' caught at the experimental site, and three wild 'controls' caught away from the experimental site. Lobsters were released by divers into good lobster habitat at randomised locations within the study site. Lobsters were tracked with the boat-mounted unit every three hours for 12 hours post-release, every six hours for the following 48 hours, then daily and eventually every second day for a total of 12 days. The diver-held unit was used to re-sight animals daily initially, then every second day.

Once located, lobster positions were marked with a surface buoy attached to a weight. Distances and bearings between subsequent positions were measured with a tape measure and hand-held compass by two people in the water.

Results

The range at which tags could be detected by both receivers varied greatly depending on water conditions. High turbidity, and the presence of a distinct halocline could reduce the effective range of the boat-mounted receiver from a maximum of 150 m to approximately 20 m. The maximum detection range

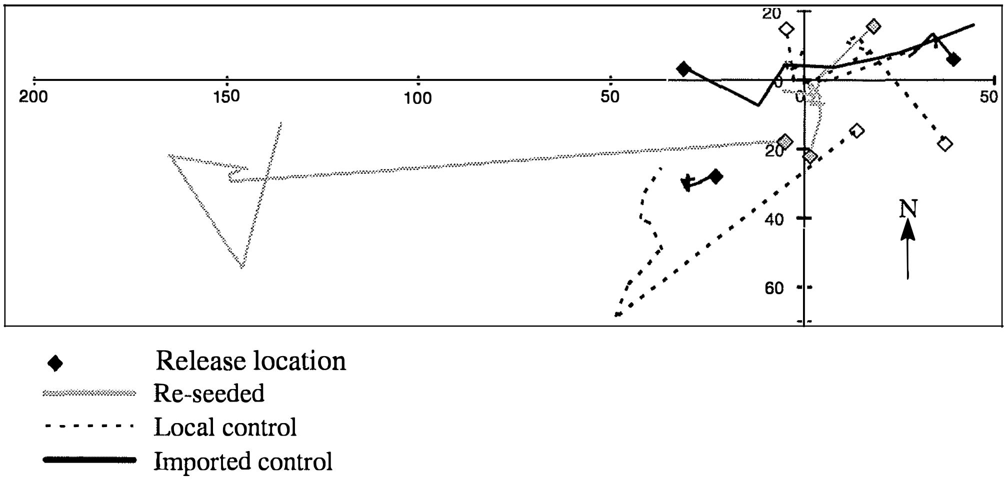

Figure 1. Movement of nine lobsters from three treatments over a period of 12 days. Axes in metres.

of the diver-held unit was about 20 m, but reduced to 5 m in poor conditions. The range of both receivers was considerably greater when tested in open water away from reef.

The position of lobsters could be repeatedly pinpointed with the boat unit to a circle of uncertainty of approximately 5 m radius. In all but the worst conditions, this allowed easy detection by the diver-held unit. It was found to be advantageous for the diver to swim on the surface until a signal was received, before descending.

All tagged lobsters were tracked successfully throughout the 12 day release trial (Figure 1). Lobsters were found to move at night, and remain stationary during the day. The greatest movement was observed within the first two days post-release, with the single longest daily movement being 145 m. This distance was recorded from an on-grown lobster, and included movement of at least 50 m over unstructured sand. No consistent differences were observed between treatment groups.

No differences were observed in habitat selection between treatments. Lobsters from all treatments were found singly in small hides, and with other wild lobsters in larger dens. On-grown lobsters appeared to respond appropriately to the presence of large 'predators' (a diver) by withdrawing into dens.

All tagged, and nine untagged, lobsters were captured by divers at the end of the trial. Stomachs were removed and gut fullness estimated (Figure 2). All lobsters had been successfully feeding during the trial, and the presence of acoustic tags did not appear to impede feeding.

To calculate the optimal size of the search grid for the survival trial, lobster movement was re-plotted with all release points at the origin (release in the survival trial was to be from a single central point). A graph of number of lobster location points included in increasing size of search grid (Figure 3) shows that maximum search efficiency is gained in a grid of 32 m side length (1024 square metres). By increasing the grid length to 56 m (effectively tripling the search area), only a further 8% of points would be included.

Discussion

Tracking cryptic animals in a high-relief environment such as rocky reef is problematic. Acoustic transmission can become directional if a lobster is situated deep within a den, and acoustic waves can propagate off adjacent rocks, leading to displacement

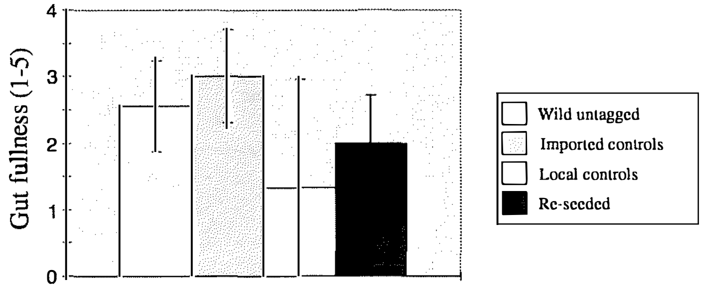

Figure 2. Gut fullness index of three experimental treatments and untagged wild lobsters at time of recapture.

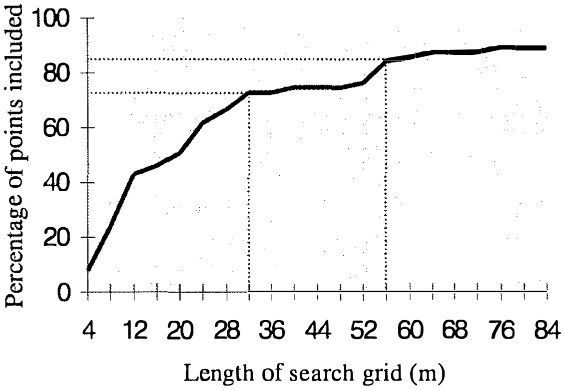

Figure 3. Percentage of recorded lobster locations contained within a search grid of increasing size (size given as length of one side of search grid).

of the apparent signal source. Such problems make the use of the emerging technique of acoustic real-time 3-dimensional tracking difficult, the biggest problem being the fixed positions of the receiver array. Van der Meeren (1997) used such a system to track four lobsters over a period of 21 days. Only 72 reliable position fixes were made during the trial, and there were often periods of several days when no reliable fixes could be recorded.

While labour-intensive, manual tracking proved ideal for our application. The detectable range of tags was of similar magnitude to maximum movement of lobsters. The diver-held receiver enabled lobsters to be re-sighted regularly, and high quality information on habitat usage was collected.

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Shark tagging: a brief history of methods

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Abstract

The first large-scale shark tagging programmes were initiated during the 1940s using Petersen disc tags (or similar variants) wired through the relatively rigid first dorsal fin. During the same period in Australia, school sharks were tagged with internal Nesbit tags inserted into the body cavity. These tags, developed because of concerns over high shedding rates of early fin tags, still hold the record for the greatest time at liberty of any tagged fish, with some recaptures made 40 years after tagging. The 1960s saw the trialing and use of plastic cattle ear tags (rototags), applied to the first dorsal fin, that had much better retention qualities than the earlier fin tags. The same era saw the initiation of large-scale cooperative game fish tagging programmes, particularly in the US, and the development of dart tags that could be applied without removing the shark from the water. More recently, shark tagging has taken advantage of electronic technology to overcome some of the limitations of standard tagging methods. A number of species have been tracked with acoustic tags. Satellite tags have been used on blue and whale sharks and archival tags have produced exciting results on school sharks.

Conventional Tags

One of the main advantages in tagging sharks compared to similar-sized teleost species is that sharks have relatively rigid fins which offer a good attachment site for tags. The first large-scale tagging programmes on sharks were initiated in the 1940s (Foerster 1942; Bonham *et al.* 1949) and used Petersen disc tags wired through the first dorsal fin. A hole was made with an awl and two circular plastic discs wired through the fin. Titanium wire was used to avoid corrosion. In the 1940s in southern Australia, Olsen (1953) started a large tagging programme on school sharks (*Galeorhinus galeus*). Olsen used a combination of Petersen disc and internal Nesbit tags. Internal tags were used because of concerns over high shedding rates of the Petersen discs, which were well above 50% per year, especially when applied to smaller sharks (Xiao *et al.* 1999). Internal tags were inserted into the coelomic cavity through a small incision made with a scalpel. One of these internally-tagged sharks was recaptured 42 years after tagging and holds the record for the longest time at liberty of any tagged fish (Anon 1991). Internal tags have very high retention rates but, unless accompanied by an external tag, are prone to low reporting rates as they can only be found during gutting and processing.

In the 1960s, plastic cattle ear tags (Rototags and Jumbo Rototags) were trialed and used on shark fins (Davies and Joubert 1967; Kato and Carvallo 1967). These had much better retention qualities than the earlier fin tags, especially when applied to the first dorsal fin. They are normally applied through a pre-punched hole, made with a leatherpunch, just in from the leading edge, and towards the base, of the fin. The tag is then punched together through the hole using special applicator pliers. Jumbo Rototags have been returned from sharks at liberty for up to 28 years (Kohler *et al.* 1998). Shedding rates have been estimated at 6-8% per year when these tags are correctly applied (Xiao *et al.* 1999). Tags applied towards the thinner trailing edge of the fin are prone to tear out. When applied too close to the base, particularly on fast-growing species or size classes, the tags tend to dig in as the fin thickens and the tag can eventually work its way through the fin and be shed (Stevens *et al.* unpublished data). The fin tags on recaptured sharks are sometimes abraded and it is likely that the tags have irritated the fin and the shark has tried to rub them on the seabed.

The 1960s also saw the instigation of large-scale cooperative game-fish tagging programmes. The largest of these, run by the National Marine Fisheries Service in the North-west Atlantic, has seen some 106 000 sharks of 33 species tagged in its 30-year history (Kohler *et al.* 1998). The requirement for tagging sharks without taking them into the boat led to development of the 'M' type stainless steel-headed dart tag. This is applied using a tagging needle mounted on a pole, which is jabbed into the dorsal musculature of the shark below the first dorsal fin. Dart tags do not have as good retention qualities as the best fin tags but have the advantage that the shark is less likely to be damaged during removal from the water, which is particularly important for large individuals. Other types of dart tags have nylon heads. These have high shedding rates which can be in excess of 50% per year when inserted in the musculature, but are somewhat better when locked into fin-ray cartilages at the base of the dorsal fin (Xiao *et al.* 1999).

Other passive tags, or marking techniques, used on sharks have included rubber or metal collars slipped over the caudal peduncle, fin clipping and freeze-branding. However, these are only suitable for short-term studies.

Electronic Tags

The advent of electronic tags opened up new possibilities for fish tagging, and was particularly suitable for sharks as tag size was less of a problem (some of the early tags were relatively bulky). Since the first tracking of a transmitter-equipped shark in 1965, at least 26 species of shark have been tracked. These include demersal, pelagic, reef and deep-sea species and range up in size to white sharks (*Carcharodon carcharias*), whale sharks (*Rhincodon typus*) and megamouth (*Megachasma pelagios*) (Nelson 1990; Nelson *et al.* 1997; Gunn *et al.* in press). Most of these studies have provided basic information on diel patterns of movement and space utilisation. Trackings have also used sensor-equipped transmitters to provide data on depth behaviour, body temperature, swimming speeds and other physiological parameters. Acoustic tags are usually tracked manually but can also employ automated fixed listening stations (Nelson 1990). Acoustic tags can be applied externally or internally. External attachment methods which have been used successfully include darting a stainless steel arrow-head (linked to the tag) into the musculature, either from a boat or underwater, attachment to a fin or fin-spine, or attachment *via* a body harness (Yano and Tanaka 1986; Nelson 1990). Alternatively, the tag can be placed internally either by feeding the tag hidden in a bait to a free-swimming shark, force-feeding to a captured shark, or surgically implanting the tag in the body cavity (Nelson 1990). The various advantages or disadvantages of these attachment methods include the degree of trauma caused by capture and any subsequent procedures, signal loss on internally placed tags, and the risk of tag loss through shedding or regurgitation. One of the challenges of attaching transmitters is that the sharks are often large and can pose a potential hazard to the tagger. However, one technique used on sharks is to put them into a state of tonic immobility. This has been done successfully with large tiger sharks (*Galeocerdo cuvier*) by inverting them in the water (Holland *et al.* 1999).

More recently, satellite and archival tags have been used on a few species of sharks. Satellite tags were attached to the dorsal fins of three blue sharks (*Prionace glauca*) in 1994, two of which provided positional data *via* the ARGOS system for one month. Basking (*Cetorhinus maximus*) and whale sharks have been tracked by embedding the tag in a float which is towed by the shark *via* a tether (Priede 1984; Stevens *et al.* unpublished data). Assuming you have an animal you know will visit the surface (radio waves do not pass effectively through sea water), the main challenge, particularly with the towed system, is the attachment methodology. We have used archival tags successfully on school sharks (West and Stevens unpublished data). Some of these have been attached externally to the first dorsal fin, and some have been surgically implanted in the body cavity. A dummy tagging experiment showed that both attachment methods produced high return rates.

A final problem common to both conventional external and electronic tags, especially in coastal waters, is weed growth. In some cases this can be suppressed by antifouling, or in the case of tags which rely on re-sighting without recapture, by using large identification tags with cut-out letters.

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Application of otolith chemistry to studies of fish movement and migration

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Abstract

In the past decade, research has confirmed that otoliths contain a chemical record that can be interpreted in relation to the past life of individual fish. The extent to which this chemical record can be considered an undistorted log of past environments and, concomitantly, movements experienced by a fish, is still open to debate. Furthermore, the complexity of this debate has increased dramatically in recent years. Otolith chemistry has progressed from measurement of major trace elements in whole otoliths by solution-based atomic absorption spectrophotometry, to the quantification of individual isotopes at ultra-trace levels with quadrapole mass spectrometers linked to laser ablation systems. This advance represents the jump from identifying changes in the gross chemical composition of individual otoliths, to the determination of the age at which an individual fish moved into a particular estuary. The instrumental escalation associated with otolith chemistry studies is the result of three key factors: 1) development and increased availability of new analytical instrumentation; 2) a greater appreciation, by fish biologists, of aquatic chemistry and its possible influence on the composition of fish; and 3) increased collaboration with those involved in geochemistry and related disciplines. Although analysis of an individual otolith may have reached new heights in terms of cost and complexity, the detailed information that can now be extracted is unlikely to be attainable by any other method. Furthermore, these data are realised without manipulation of the fish prior to its death, ensuring a virtually unlimited supply of samples.

Background

Recent research has confirmed that otoliths contain a chemical record that can be interpreted in relation to the past life of an individual fish. Patterns of fish growth, movement and stock separation have been revealed through analysis of the structure and chemistry of otoliths. This record is evident due to the incorporation of particular elements and isotopes into the otolith from the surrounding water in concentrations that reflect the physical and chemical aspects of the ambient environment and the physiology of the fish (Kalish 1990; Fowler *et al.* 1995; Secor *et al.* 1995). Two assumptions are commonly made in studies of otolith chemistry:

- otoliths grow throughout the life of the fish; and,
- otolith material is not resorbed or altered after deposition.

These assumptions are well-supported by a range of otolith studies, and the notion that otoliths contain a permanent record of a fish's environment, tempered in varying degrees by physiology, is established in the otolith literature.

Otoliths, the crystalline 'ear-stones' found in the bony auditory capsules at the back of the cranium, are part of the 'labyrinth', the auditory-equilibrium organ of teleost fishes (Platt and Popper 1981). There are three pairs of otoliths in the inner ear: the sagitta, lapillus and asteriscus. In most fishes, the sagitta is the largest of the three otoliths and is used most often in studies of otolith chemistry.

The major components of otoliths are calcium carbonate, as aragonite, and several otolith proteins including a protein called otolin (Degens *et al.* 1969). While the major component of otoliths is calcium carbonate (approximately 99%), the organic component (< 1%) plays an important role in the deposition of $CaCO_3$ and incorporation of other elements from the endolymph into the otolith structure.

Little research has been concentrated on the process of mineralisation in otoliths. What is known, however, is that despite being only a small proportion of the otolith, the organic components can affect the variability of metal ions: the organic material is largely anionic protein and hence has a high affinity for cations. Dove *et al.* (1996) found that the ratio of protein to inorganic material varies throughout the otolith and that there are chronological differences in trace elements. Although there are several studies of otolith proteins, the relative affinities that ions have for the organic and inorganic constituents of otoliths have not been determined.

The extent to which the chemical record can be considered an undistorted log of past environments and, concomitantly, movements experienced by a fish, is still open to debate. If otolith composition reflects the water mass in which the fish lives, then the elemental 'fingerprint' could provide a history of fish movements (Kalish 1989). However, many things affect the elemental composition of otoliths including environmental factors, such as temperature and salinity, as well as the physiology of the fish, further influenced by factors such as ontogeny and stress.

The incorporation of elements into the otolith structure may not occur in a simple way (Kalish 1989; Fowler *et al.* 1995) and the various factors that affect deposition may confound interpretation of results of otolith microchemistry studies. Otoliths grow through the regular deposition of both mineral-rich and organic-rich zones (Campana and Neilson 1985; Mugiya 1987). Nevertheless, there can be large variations in elemental concentrations around the margins of otoliths (Kalish 1989), which indicates that a simple 'onion' model with concentric shells of mineral-rich and organic-rich material may not be adequate to describe otolith growth. This has particular implications for chronological studies that measure otolith chemistry, assumed to be deposited at particular times during the life of a fish (Gunn *et al.* 1992; Dove *et al.* 1996; Kalish *et al.* 1996b).

To fully understand the significance of surrounding water masses in otolith composition and hence to be able to reconstruct the movement and migration patterns of fish from the otolith elemental concentrations, the effects of multiple factors should be considered. In one such study of the anadromous striped bass *Morone saxatilis*, Secor *et al.* (1995) conducted aquarium experiments in which temperature and salinity were manipulated. By measuring elemental concentrations along otolith sections through the transverse plane they were able to determine the extent to which temperature and growth rate affected strontium deposition and quantified the relationship between salinity in the surrounding water and otolith Sr/Ca ratios.

Techniques

Otolith chemistry has progressed from measurement of major trace elements in whole otoliths by solution-based atomic absorption spectrophotometry, to the quantification of individual isotopes at ultra-trace levels with quadrapole mass spectrometers linked to laser ablation systems. This advance has facilitated more complex analyses: from identifying changes in the gross chemical composition of otoliths, to the determination of the age at which an individual fish moved into a particular estuary.

Table 1. Commonly used methods in otolith chemistry research.

Instrument/method	Otolith constituents measured	Method
Stable isotope mass spectrometry (SIMS)	carbon and oxygen isotope ratios	whole otolith
Atomic absorption spectrophotometry (AAS)	micro elements	whole otolith
Energy-dispersive electron microprobe (ED-EM)	macro elements	point analysis of sectioned and polished otoliths
Wave dispersive electron microprobe (WD-EM)	micro elements	point analysis of sectioned and polished otoliths
Proton-induced X-ray emission (PIXE)	trace elements	point analysis of sectioned and polished otoliths
Solution-based inductively coupled plasma-atomic emission spectroscopy (ICP-AES)	trace elements	whole or isolated portion of otolith
Isotope dilution inductively coupled plasma-mass spectrometry (ID-ICP-MS)	trace elements/isotopes	whole otolith
Solution-based inductively coupled plasma-mass spectrometry (ICP-MS)	trace elements/isotopes	whole or isolated portion of otolith
Laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS)	trace elements/isotopes	point analysis of sectioned and polished otoliths
Accelerator mass spectrometry (AMS)	ultra-trace isotopes	whole or isolated portion of otolith

The instrumental escalation associated with otolith chemistry studies is the result of three key factors:

- development and increased availability of new analytical instrumentation;
- a greater appreciation, by fish biologists, of aquatic chemistry and its possible influence on the composition of fish otoliths; and,
- increased collaboration with those involved in geochemistry and related disciplines.

The cost of otolith chemistry research can be high and techniques may produce varied results so a thorough review of methodological considerations should be carried out before choosing the most appropriate method for the required analysis. Which instrument and method are chosen for otolith chemistry analyses depends on the type and concentration of elements being studied (Table 1). In general, the concentration of elements in otoliths can be described as 'macro', >10% by weight, such as Ca, C and O; 'micro', 100-5 000 ppm, including Na, Sr, K, S and Cl; and 'trace', less than 50-100 ppm, including Zn, Br, Se, Ni and Pb. In addition, otolith research on movement and migration has included analyses of stable isotopes of carbon and oxygen, which are potential indicators of environmental temperature (Kalish 1991; Radtke *et al.* 1996, Edmonds and Fletcher 1997; Edmonds *et al.*1999; Thorrold *et al.* 1997).

A recent study (Campana *et al.* 1997) provided an inter-laboratory calibration of trace element analyses based on the more popular techniques used in otolith chemistry research. They compared the accuracy, precision and sensitivity of the energy-dispersive electron microprobe (ED-EM), wave dispersive electron microprobe (WD-EM), proton-induced X-ray emission (PIXE) and laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). Independent researchers at eight laboratories conducted assays for ten elements of 'blind-labelled' real and artificial otolith samples.

No individual instrument was found to be the most effective for measurement of all elements. However, the authors did reach several conclusions:

- electron microprobe measured 'abundant' elements such as sodium and potassium most accurately;
- trace elements required PIXE or LA-ICPMS; and,
- strontium could be measured accurately and precisely by WD-EM, PIXE and LA-ICPMS.

The authors also make a cautionary note that comparisons between published studies should only be made the *proviso* that adequate calibrations were used, as significant differences were found between the results from different laboratories.

Contamination/effects of handling

The introduction of contaminants into chemical analyses has always been of concern, but the increasing sensitivity of analytical techniques makes avoiding contamination even more pertinent. Recent research (Milton and Chenery 1998; Proctor and Thresher 1998) has been focussed on possible changes in otolith chemistry due to procedures used to collect and prepare otoliths for chemical analysis. These include:

- storage and preservation of fish before extracting otoliths;
- delay in extracting otoliths;
- preservation of otoliths;
- cleaning; and,
- preparation for analysis.

By exposing otolith pairs to different treatments before WD electron probe analysis, Proctor and Thresher (1998) showed that the six elements tested were sensitive to the treatments; calcium and strontium were least affected by collection and preparation procedures whereas; sodium, potassium, sulphur and chlorine showed significant variation. Post-capture storage has also been found to affect results of LA-ICPMS analyses. Milton and Chenery (1998) compared concentrations of elements at the primordium and otolith edge and found that, for four of the seven elements tested, method of storage had measurable effects on the concentrations.

Applications of techniques relevant to movement and migration

Applications of recent developments in otolith chemistry analysis have been effective in studies of anadromous and non-anadromous fish (Kalish 1990 using WD-EM; Radtke *et al.* 1996 using WD-EM; Babuluk *et al.* 1997 using PIXE), the results of which have important implications for the management of fish populations in river and lake systems.

In studies of species that display facultative anadromy, such as Arctic charr *Salvelinus alpinus* and rainbow trout *Oncorhynchus mykiss*, otolith composition can differentiate groups of anadromous and non-anadromous fish. Distinct patterns of strontium distribution associated with two life histories are revealed when comparing otolith strontium levels measured along transects between the primordium (earliest-formed) and outside edge (latest-formed). This knowledge can be applied to investigations of groups whose life histories are 'unknown', providing evidence that the fish are either anadromous or non-anadromous and even at what point in their lives they entered particular estuaries.

The otolith chemistry of the material deposited during the earliest part of life can reveal information about fish population structure: the natal area and coastal migrations. As trace elements are incorporated into otoliths as the fish grows, different otolith elemental composition can reflect environments or water masses that have different physical and chemical characteristics.

Site-specific otolith chemistry has been detected in some species. It has been shown to exist in yellowfin tuna *Thunnus albacares*, and can be detected using WD-EM and PIXE (Gunn and Ward 1994). Young-of-the-year were sampled at spawning sites throughout the western Pacific and analysed for otolith chemical variation. Seven of the 15 elements found in the otoliths exhibited significant variation among sites. Interestingly, the samples from the two semi-tropical sites, Coral Sea and Hawaii, were most similar. This suggests that the elemental variation measured in otoliths from fish collected at different sites may be associated with factors other than ambient water chemistry, such as growth rate (Kalish 1989; Sadovy and Severin 1992; Fowler *et al.* 1995).

Understanding the origins of individuals within a fishery is a question asked commonly by fishery managers. The 'elemental fingerprint' has been used to identify the origins of sub-groups within fishery stocks and to determine the extent of mixing of different populations (Edmonds *et al.* 1989, 1991; Campana *et al.* 1994). Campana *et al.* (1995) used ID-ICPMS to identify Atlantic cod *Gadus morhua* that originated from the Gulf of St Lawrence within the fishery off the coast of eastern Canada. Elemental fingerprints, however, are not always effective for the identification of unique stocks (Thresher *et al.* 1994; Kalish *et al.* 1996a). In most cases the basis for the measured differences in otolith composition among putative stocks is not understood despite its usefulness in stock discrimination, and further research is essential to provide a stronger foundation for these investigations.

Variation in otolith composition can be useful for understanding the migration of fish from their spawning area. Using LA-ICPMS analysis, Milton *et al.* (1997) investigated the otolith microchemistry of the tropical shad, terubok *Tenualosa toli*, thought to originate from only two spawning estuaries. They compared the composition of otolith nuclei of fish collected at eight coastal sites and the two known spawning areas. Evidence of one or more additional spawning areas was revealed the otolith chemistry of fish from two of the eight sites was significantly different from the otolith chemistry of the fish collected in the estuaries.

Conclusions

Although analysis of an individual otolith may have reached new heights in terms of cost and complexity, the detailed information that can now be extracted is unlikely to be attainable by any other method. The development of ICPMS techniques during the last decade has been a major advance in detection of trace elements in otolith chemistry studies. Over the next few years, modifications to the instrument should bring improvements in sensitivity and a reduction in interferences for many elements. A further development to magnetic-sector and multiple-collector ICPMS will allow precise isotopic ratios to be determined for stable isotopes and elements such as strontium (Halliday *et al.* 1998).

The recent investigations of possible changes in otolith chemistry due to handling and preparation should lead to an awareness of possible post-mortem artefacts and their effect on levels of trace metal concentrations. These results challenge the assumption that otoliths are inert and permanently retain a true record of the otolith chemistry deposited during the life of a fish. A further, related challenge is to improve the understanding of otolith structure, the differential deposition of trace elements into the protein matrix and aragonitic crystalline structure, and the labile nature of particular elements.

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Discussion of Session 1

Chaired by John Gunn

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Chair John Gunn invited discussion after each presentation. These are recorded in sequence here. This concluded the morning session. Further discussion relevant to this session occurred during the closing "General Discussion" at the end of day 2.

The first comment after *John Koehn's* presentation was that it is vital, in studies of movement patterns, to have very specific questions in mind and then to determine what was the best method and hardware (including type and number of tags) to use. Sometimes a combination of conventional tags and radio tracking tags could be useful as the two techniques provide very different but often complementary information. However, without specific questions, using radio tags can waste a lot of time and money. John Koehn agreed that radio tags were just another tool and that the most important thing to consider was what question was being asked.

Tony Fowler (SARDI) asked what type of metabolic or physiological data could be collected with radio tags. John Koehn answered that heart rate had been monitored in a number of studies (internationally) and that the technology to monitor other metabolic parameters was expanding rapidly. There were several medical developments that were currently being applied to terrestrial studies (e.g. measuring hibernation) and these offered considerable promise for technology transfer to aquatic studies.

Malcolm Haddon (TAFI University of Tasmania) pointed out that differentiating between electronic tag types was becoming increasingly arbitrary with the appearance of hybrid tags (e.g. combination of radio and acoustic technologies) and that there was not yet a good nomenclature for these advanced tags. However, the primary issue was not so much how tags were labelled but what researchers did with them – how they defined specific questions and then applied resources to solving them. John Koehn again restated his agreement regarding the importance of clearly specifying the objectives of any tracking study. He also noted that hybrid electronic tags were getting over some of the limitations of the mono-tag type, e.g. radio waves do not penetrate seawater so a fish must come to the surface before such a tag in the marine environment will transmit, but combining this with acoustics – which allow free transmission through seawater – allows tracking for and transmission of data. Some hybrid tags still suffered from limited battery duration. However, advances in power-saving measures (e.g. programmable tags that cycled on and off, or that could switch to a low power mode) were extending the life of such tags and thus reducing the need for extra batteries – the heaviest components of such tags. This was particularly useful for the study of small fish where tag size and weight were critical.

John Gunn, from the chair, commented that there was a wealth of expertise in the electronics engineering field and that it was really up to researchers to identify a specific question or identify the type of technological requirement rather than necessarily wait for something to be developed. Electronics engineers (particularly within universities) are relatively untapped resources by fish biologists in Australia. There is a growing tendency in the US and Europe for biologists to liaise more and more with electronics engineers to develop new technology.

Following *Ivor Stuart's* presentation, Richard Tilzey (BRS) asked if the extent of downstream movement through fishways was known. Ivor Stuart replied that such studies primarily concentrated on upstream movement. He noted that while some studies had attempted to look at downstream movement by trapping (largely with sea mullet and yellowfin bream), this area still needs a great deal more research in Australia.

Mark Kennard (CCISR) asked if there were any attempts to link fish movement or the use of fishways with environmental parameters such as river discharge. Ivor Stuart replied that their studies had addressed movements associated with discharge, noting that some species turned up in samples on high flows that were completely absent on low flows (and vice-versa), but that it is far more difficult to establish relationships with other parameters such as water temperature, salinity or conductivity. This is because it is hard to isolate these particular components in the field and design manipulative experiments to test them.

Andrew Sanger (NSW Fisheries) asked if Ivor Stuart could elaborate on the downstream migration problems associated with catadromous species. Ivor Stuart replied that this had been largely ignored in many studies and that several catadromous fish are now locally extinct above many barriers, so getting them back upstream is probably the first issue. Fish returning downstream will be a large problem in the future in Australia. He went on to report that researchers in North America are currently grappling with how to keep adult and juvenile fish from going back downstream through turbines and over spillways by developing bypass technology and screens. Australia has not progressed to that stage yet. It is unknown what are the effects on survival for juvenile and adult Australian fishes of going over weirs or going through turbines or even the extent to which species can successfully find fishway entrances so they can get back downstream. This is an enormous problem that should receive research attention. NRE is starting programmes to look at this issue.

Martin Mallen-Cooper (Fishway Consulting Services) emphasised that fishways can also be incredibly useful tools for looking at the movements of particularly small fish that would otherwise be hard to monitor. Paul Close (NRE) asked if there were studies that identified what proportion of fish were moving upstream and how selective were the fishways? Is sampling a fishway going to give a representative sample? Ivor Stuart replied that fishway assessments first had to establish the success of the facility by making an accurate count of how many fish made it to the top. Second, was to establish how many fish were out in the river and whether they were actively migrating, resident or doing their own thing. Ivor Stuart referred to work conducted by Martin Mallen-Cooper which had attempted to quantify these parameters by netting a river before and after a fishway was constructed. By examining changes in abundance, this study had concluded that a large proportion of fish was actively migrating upstream. These types of studies would benefit from using both PIT-tag and radio tracking technology.

Following *Julian Pepperell's* presentation, Malcolm Haddon commented that while game-fish tag-release was useful because fish were released rather than killed, he believed that data derived from such studies would only be useful for looking at gross movement patterns. Estimates of size were too inaccurate to look at growth. Julian Pepperell did not agree. He pointed to a number of scientific publications that had come from such data sets and noted that utilising game and sports fishers as " unpaid field assistants" had many benefits. He did, however, note that to maximise the benefits of such studies, it is important to co-ordinate game and sports fishing groups to collect specific data or target specific species.

André Punt (CSIRO Marine Research) asked if anyone had looked quantitatively at whether there were greater reporting errors in estimates of movement rates and if there was a greater incidence of tag shedding in "non-scientifically" tagged fish compared to those tagged in conventional research programmes. Julian Pepperell replied that there had been a fair amount of double tagging of billfish in the Atlantic using two different tag types and that results were comparable to scientifically-tagged fish. He believed that estimates of movement rates should not differ between the two types of programmes. Yellowfin tuna tagging was a good example. This species had been extensively tagged by both researchers and game/sports fishers in the same areas and estimates of movement rates were not significantly different.

A further point was made from the floor that although there were at times, limitations to the data, one should not overlook the cooperative value of sports-fish tagging, particularly when the species concerned was targeted by both commercial and recreational fishing operations. Julian Pepperell agreed that involving recreational fishers often had benefits far in excess of the data collected.

John Gunn commented that CSIRO tag many of the species used in Julian Pepperell's cooperative tagging programmes and that he regarded the recreational data as semi-quantitative or qualitative, depending on the species. Nevertheless, recreational fishers are often able to tag fish in areas where the commercial fishers do not operate or which research programmes are unable to cover. One benefit of involving recreational fishers in tagging is thus the combined ability to tag over far broader areas.

Following *Geoff Arnold's* presentation, John Gunn asked whether the advances in "off the shelf" tracking technology had now approached the capabilities of the system that Lowestoft had been using. Geoff Arnold commented that the hydraulic stabilisation package that Lowestoft was using cost £250 000 in 1970. Nowadays there are much more affordable units available that can generate very good data as evidenced by the increasing number of publications dealing with such work.

Malcolm Haddon commented on the expense of both the systems used by Lowestoft and the ship-time required for the study of movements of a relatively small number of fish. He then asked if there were any problems with the ship influencing the behaviour of the fish during tracking. Geoff Arnold noted that work in the open sea is an expensive exercise at the best of times. He noted that there were also some things like obtaining concurrent ADCP data for the measurement of current patterns and orientation that you cannot get without using large vessels in these areas. What is needed are good, robust measures of the average speed and orientation of moving fish to put into models. With respect to the ship influencing the behaviour of the tracked fish, Geoff Arnold replied that they had looked at that by steaming around fish during tracking to see if they changed direction or behaviour. In all cases they had been unsuccessful in eliciting any activity that could be construed as influencing the fish. Tracking usually occurred at a very slow speed (1-2 knots) and the current ship was extremely quiet at that speed. Even in other vessels that were much noisier, there was no apparent influence on the fish during tracking. The behaviour of acoustically-tracked and archival-tagged fish was similar.

John Gunn commented that one of the interesting data series to come from his group's archival tag work with tuna was that the fish behaved very differently for the first 2-4 days compared to the rest of the time at liberty. With so much work put into tagging and tracking, this raised the question of whether much of the short-term data collected reflects abnormal (capture stress) or normal swimming behaviour. Because his group surgically implant their tags rather than attaching them externally, as was the case in many studies, this procedure may create more handling 'stress. Geoff Arnold replied that they do see a recovery period in their archival tag data of up to 1-2 days. With acoustic tagging, they have always inserted the attachment wire through the fish well ahead of time and then only attached the acoustic tag just before release. They had not seen evidence of a recovery period using this technique. On the other hand, monitoring a recovery period can be turned to your advantage. For example, their work with cod allowed them to look at swim bladder inflation over the first 2-4 days as the released fish adjusted their depth to neutral buoyancy. They were able to measure rates of increase of depth and deduce that the fish was not neutrally buoyant all through its depth range (which was the classical idea). The fish were neutrally buoyant at some specific depths.

John Gunn asked Geoff Arnold if they generally kept their fish in a tank for a while before releasing them. Geoff Arnold replied that they did so to be able to select the fish that were not heavily bruised during collection *via* trawling. It would be better if they did not have to hold them but this procedure had produced the best results.

Following *John Gunn's* presentation, André Punt commented that the extent to which tagging information was used seemed inversely proportional to the cost of the technology. He asked if we are yet ready to take the output from archival tags and use it to form management advice. How close are we realistically, to using such data to change the way we manage a resource? John Gunn replied that there is a very real and large potential for interactions between tuna fisheries that needs to be factored into management decisions. Using conventional tagging has given us a very biased perspective on the interactions between, say, the domestic southern bluefin tuna (SBT) surface fishery and the fishery in the central Indian Ocean. We have never had a conventional tag back from the central Indian Ocean and have previously assumed that there was little interaction between the domestic and this Taiwanese-based fishery. Archival tags have indicated that this assumption was flawed and this instigated a new research initiative that identified an enormous amount of SBT being taken in the Taiwanese fishery that was not being recorded. These catches are now being included in the stock assessments. Although this is not a direct use of archival tag data, it did provide the initial step towards including this catch component in assessments.

Will Zacharin (PIRSA) asked what level of under-reporting there was with archival tags and whether the information gained from the tags has been used by fishers to alter their fishing behaviour. John Gunn believed that there was a considerable level of under-reporting by the Japanese fishery. He also noted that Japanese researchers had concurrently been buying archival tag readers so that they could down-load the data themselves. He suspected that the fishers had benefited from this. John Gunn further indicated that the archival tag data were now encrypted so that this was becoming less of an issue.

Malcolm Haddon noted that there was a distinction between what populations do and what individuals do. Archival tags may be useful to help interpret what populations might do but this needs to be married with other information to make it more useful to managers. John Gunn suggested that this aspect would be covered in André Punt's session about spatial dynamics models. The integration of conventional tagging, catch data and archival tag data *via* spatial models was an active area within John Gunn's group.

Following *David Mills'* presentation, Rob Day (University of Melbourne) said that he had done something similar in California with seeding reared abalone onto reefs. They were able to show that doing so resulted in a decrease in the total number of wild juvenile abalone. This was not only a competition effect, but seeding apparently attracted predators into the area, which consequently reduced the natural abundance. David Mills replied that he was very interested in pursuing the predator issue and planned to do so by gillnetting around the site at the time of release.

Malcolm Haddon noted that some restocking attempts with *Homarus* lobsters in Norway had led to massive predatory loss of released juveniles. In this case juveniles were released from the surface. David Mills replied that they released their animals, using divers, directly into dens to give them the maximum chance of survival. They had not looked at large-scale reseeding methods at this point. As part of future work they intend to look at how to release large numbers effectively. For example, they may put them down in hides from which they can move out when ready, or have a tube from the vessel to the seafloor from which they could be released directly to the bottom. Geoff Arnold noted that reared *Homarus* had been successfully released from work in the Lowestoft laboratories. These were put into holes at night with very good survival rates, and had then been traced into the commercial fishery. So it can work if it is done properly.

Karina Hall (SARDI) asked if David Mills had thought of using moored hydrophone arrays to get a continuous picture of where lobsters are going. David Mills answered that den orientation and habitat complexity limited the ability to detect tag signals and this made it hard to use the more automated listening arrays. The chances of getting a signal out to at least three hydrophone stations at any one time was very low. The manual option they were currently using appeared to be the best solution.

Following *John Stevens's* presentation, Julian Pepperell (Pepperell Research) noted that fouling is something that they see a lot of on tags put on billfish. Tag fouling is the suspected reason why pop-off tags have not worked very well with marlin as compared to the success of such technology with bluefin tuna. Fouling may reduce the buoyancy of the tag so that it no longer floats when released from the fish. John Stevens noted that antifouling tags can help but that there were limitations to using such paints.

The session concluded directly after *John Kalish's* (given by John Gunn) presentation and the chair thanked all speakers and the floor for their presentations and the ensuing discussion.

Overview Address

Fish Movements - The Missing Piece

John Eiler

Fish movements – the missing piece

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Abstract

Movement patterns are an important component in the life-history strategies of fish species, constituting the mechanism used to access the resources necessary for survival. Fish adapt their movements to accommodate for restrictive local conditions. Although often oversimplified due to the difficulty in collecting data, or considered ancillary to other types of information, an understanding of movement patterns can provide significant insight into the management of fish populations. Advances in technology are providing new tools for collecting detailed information on movements. Findings from three radio telemetry studies on three salmonid species in Alaska, U.S.A., are discussed in relation to survival strategies and management considerations.

Introduction

Movement patterns are an important component in the life-history strategies of fish species, constituting the mechanism used to bring individuals into contact with the resources needed to survive and reproduce. Competition and limited resources often make it necessary to adapt movement patterns to accommodate for restrictive local conditions. However, from an energetics standpoint, there can be a substantial cost associated with movement, so there has to be a tangible benefit to make it worthwhile.

Management decisions related to fish populations often give less consideration to movement patterns than other aspects of their life history, primarily because collecting movement information is difficult and often relatively expensive. Because of dwindling budgets, agencies have to be selective in order to obtain the best data with the funds available. Management decisions are often based on "logical" assumptions to fill in the missing pieces of information. The problem inherent with this approach is that our perspective is often limited, and seemingly logical assumptions, particularly in relation to the natural pressures affecting wild populations, are not always valid.

New technologies are providing powerful tools to address information needs. Since the 1960s, radio telemetry has been used to collect information on a variety of aquatic species (Winter 1983). Initially, most studies were limited to small numbers of tagged individuals, usually fewer than 40, and relatively small areas. Advances in telemetry have made it possible to track large numbers of wide-ranging individuals (Burger *et al.* 1985; Block *et al.* 1998), making it feasible to collect detailed movement information on a variety of fish species.

This paper presents findings from radio telemetry studies on three salmonid species in Alaska, U.S.A., that illustrate the potential significance of movement data. Local conditions undoubtedly influence the life-history strategies exhibited by fish populations. Alaska, located in northwestern North America, is a diverse ecosystem, consisting of an extensive coastline and vast interior. Habitat types range from temperate rain forest to tundra. In addition to the marine

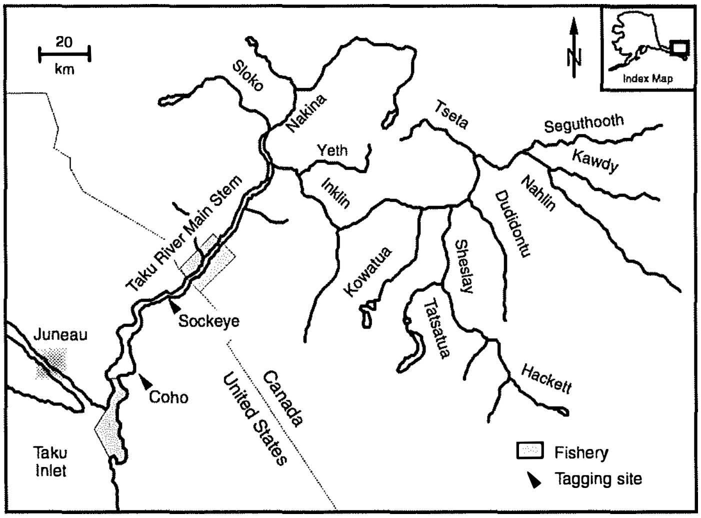

Figure 1. Map of the Taku River drainage showing the location of US and Canadian commercial fisheries.

environment, large river systems and small coastal streams occur throughout the area and support important fish populations. Winter conditions, particularly in the interior, can be extremely harsh, with temperatures ranging to below -30°C (National Oceanic and Atmospheric Administration 1997). The information presented shows that movement patterns and the underlying forces related to them are not always straightforward, and can provide important insight into the management of fish populations.

Taku River sockeye salmon

Sockeye salmon *(Oncorhynchus nerka)*, an important commercial species in the North Pacific Ocean, spawn in many rivers along the western coast of North America and the eastern coast of Asia. Exhibiting an anadromous life cycle, the juvenile salmon leave fresh water and spend several years in the marine environment before returning to their natal streams to spawn. Returning adults typically migrate to areas associated with lake systems, and spawn along lakeshores and in nearby inlet streams (Foerster 1968). The Taku River (Figure 1), a large, glacial river flowing through Alaska, U.S.A., and British Columbia, Canada, drains a watershed of over 16 000 km^2. This river is an important producer of sockeye salmon with an average run of over 233 000 fish (Pacific Salmon Commission 2000). Returns of Taku River sockeye salmon support commercial and subsistence fisheries in both countries and have been the focus of numerous disputes over harvest allocation. However, the large size, remote nature, and turbidity of the drainage make it difficult to collect information needed to manage the returning salmon.

In 1984 and 1986, radio telemetry was used to follow the movements of adult sockeye salmon returning to the Taku River to spawn. The fish were captured with fish wheels (Meehan 1961) near the river mouth and placed in a tagging cradle submerged in a trough of fresh water. Radio transmitters, 6.5 cm long and 2.0 cm in diameter, were inserted through the mouth and into the stomach of the fish. Salmon do not feed extensively during this period of their spawning migration. Compared to attaching the tag externally, this approach also minimises any adverse effect on the hydrodynamic shape of the fish, particularly when it is swimming upstream against strong current. A total of 375 fish were tagged during the study. Radio-tagged fish moving upriver were located weekly from fixed-wing aircraft until they reached their final destination. Helicopters were used to pinpoint the fish in localised areas and to access these sites for collecting samples (Eiler *et al.* 1992).

Before this study, relatively little was known about sockeye salmon returns to the Taku River other than general information on run timing, the location of certain spawning areas, and harvests from the commercial fishery. Because sockeye salmon is typically a lake-dependent species, it was assumed that most spawners travelled to lake systems in the upper drainage (D. J. Ingledue, Alaska Department of Fish and Game, Douglas, Alaska, U.S.A., unpublished report), and management decisions were based on escapement estimates from these areas. Surprisingly, only 37% of the radio-tagged fish travelled to areas associated with lakes; the remaining 63% were tracked to riverine areas – sections of the drainage without lakes (Eiler *et al.* 1992). Spawning in these riverine areas by tagged and untagged fish was verified during aerial surveys in 1986, when normally turbid side channels and sloughs cleared as a result of several weeks without precipitation and unusually low water levels. Spawners in riverine areas used a variety of habitat types, including main-river channels, side channels, and upland sloughs - spawning areas previously considered unsuitable for this species. The fish were not considered strays, because large numbers of untagged fish were also observed, and sockeye salmon typically home with great precision to their natal streams (Quinn *et al.* 1987). Genetic information collected from the Taku River also indicated that sockeye salmon from riverine areas were genetically distinct from fish returning to the major lake systems (Guthrie *et al.* 1994).

The primary reason riverine areas were considered unsuitable for spawning sockeye salmon is the perceived lack of juvenile rearing habitat. After emerging from redds, juvenile sockeye salmon typically rear in lakes for one or more years before migrating to sea (Foerster 1968). However, sockeye salmon in some river systems have adopted alternative strategies that compensate for the lack of typical rearing areas. About half of the fish sampled in riverine areas of the Taku River migrated to sea as juveniles before their first winter. Similar observations have been reported in other major river systems (Bugaev 1984; Wood *et al.* 1987).

Adult sockeye salmon also use lakes as holding areas where they can complete the physiological maturation process associated with spawning. This habitat component is seemingly absent in riverine areas. However, intensive tracking of radio-tagged fish suggests that sockeye salmon were staging in river channels in the vicinity of spawning areas before pulsing into the side channels and slough to spawn.

Little information is available on the productivity of riverine sockeye salmon compared to those that spawn in areas associated with lakes. In riverine areas, the lack of lacustrine rearing habitat, extreme changes in main-channel and side-channel water levels (making these areas susceptible to freezing or desiccation), and heavy silt loads may result in low or highly-variable production by riverine spawners. However, the large returns of riverine spawners to the Taku River suggest that these are not always limiting factors. The ability of sockeye salmon in some drainages to spawn and rear in riverine areas, as well as in the vicinity of lakes, provides the flexibility to adapt to changes in local conditions and colonise new areas. Before this study, harvest levels for Taku River sockeye salmon were based on abundance estimates from lakes in the upper drainage. Movement information from this study provided a better understanding of run characteristics and a basis for improved management.

Taku River coho salmon

Coho salmon *(O. kisutch)*, another commercially important salmon species, also spawns in the Taku River. Compared to other salmonids, less is known about coho spawning runs, due to poor weather conditions during the fall when the fish return to spawn and the extensive use of cover by this species. Telemetry studies, similar to those described for sockeye salmon, were conducted on Taku River coho salmon. Returning adults were captured near the river mouth with small-mesh gill nets (Figure 1), and 444 fish were tagged with radio transmitters. Radio-tagged salmon moving upriver were tracked with remote tracking stations (Figure 2). Tracking stations, located at 15 sites in the drainage, detected the radio-tagged

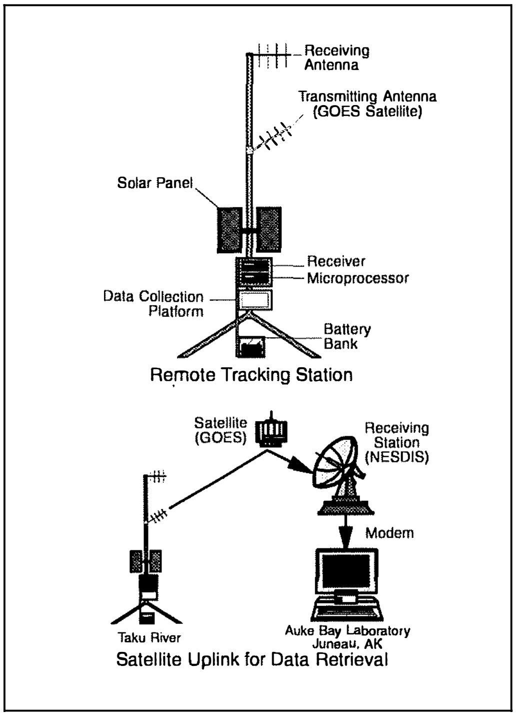

Figure 2. Remote tracking system used to record the movements of radio-tagged fish in large, isolated rivers.

fish, and recorded the date and time they were at the site (Eiler 1995). A satellite uplink was used to retrieve the data, because access to the stations was severely limited. Helicopter surveys were conducted when weather permitted during October and November to locate radio-tagged fish in spawning areas and access these sites to verify the presence of untagged fish.

Although coho salmon were tracked to areas throughout the drainage, temporal differences in distribution were observed. Fish tagged during August travelled primarily to upper reaches, whereas fish arriving during September and October used spawning areas in lower sections of the drainage. Spawning habitat ranged from main-stem side channels to upland sloughs associated with beaver ponds.

The movement patterns observed for coho and sockeye salmon differed substantially. Sockeye salmon exhibited relatively continual upriver movement while migrating to spawning areas; the fish would then hold in nearby staging areas for several weeks before moving into spawning areas. Coho salmon movement patterns were much more varied. Rather than holding in one particular area, the fish would often move extensively between areas, sometimes travelling over 20 km between holding sites. Both upriver and downriver movements were observed. In one extreme case, a coho salmon was tracked to a known spawning area over 200 km upriver. After remaining in the area for eight days, the fish moved back downriver, and within 48 hours had left the drainage, possibly destined for another river.

Aerial surveys are conducted on clear-water areas of the Taku River during the fall in order to count coho salmon spawners. The counts are used as an abundance index for the drainage, and assume that sources of bias such as observability and annual variation are minimal or can be accounted for, both debatable points. However, telemetry data from this study also suggest that fish holding in areas before

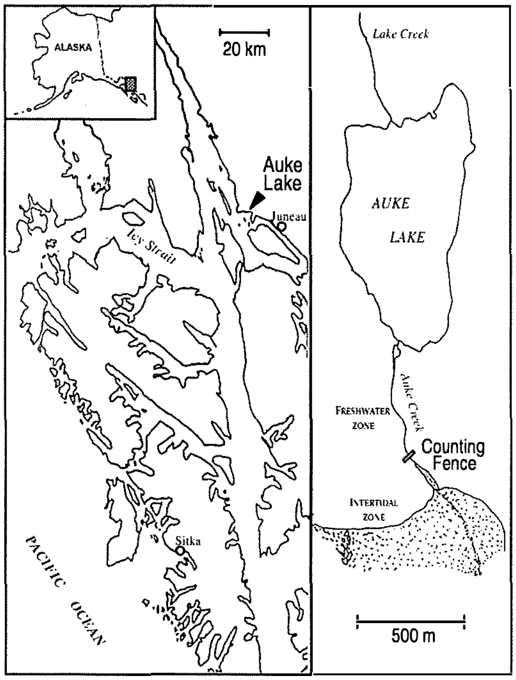

Figure 3. Map showing the location of Auke Lake near Juneau, Alaska U.S.A.

spawning may move extensively between sites. This pattern of movement, combined with the timing of the surveys, may have a significant impact on the survey counts.

Cutthroat trout in southeastern Alaska

Coastal cutthroat trout (*Oncorhynchus clarki*), a prized sport fish species, occur along the western coast of North America from northern California to Prince William Sound in Alaska (Scott and Crossman 1973). Cutthroat trout in southeastern Alaska spawn in the spring, with the peak of spawning in early to mid-May. Cutthroat populations exhibit two life-history strategies in southeastern Alaska - resident and sea-run. Resident cutthroat trout rear in small rivers and streams for several years before migrating into lakes, where they spend the remainder of their lives. Sea-run cutthroat leave their natal rivers and streams and migrate to small coastal lakes. In the spring they leave these lakes and migrate back through saltwater to spawning streams. After spawning, they return to the rich marine environment to feed until late summer and fall, when they re-enter lakes to overwinter (Jones 1976). However, little information is available on the composition and migration pattern of these sea-run populations.

Cutthroat populations are typically small and vulnerable to overfishing and habitat loss. Since the late 1970s, cutthroat numbers and harvests in southeastern Alaska have declined (Schmidt 1997). In 1994, the Alaska Department of Fish and Game and the National Marine Fisheries Service conducted a radio telemetry study to document the movements and spawning distribution of adult sea-run cutthroat emigrating from Auke Lake - a small, coastal lake near Juneau, Alaska.

In the spring, emigrating sea-run cutthroat trout were caught at a counting fence located at the outlet of Auke Creek (Figure 3). Thirty-one adults were placed in a tagging cradle submerged in a trough of fresh water, and tagged with radio transmitters 2.8 cm long and

1.0 cm in diameter. The tags were inserted through the mouth and into the stomach. After tagging, the fish were released to continue their ocean migration. Aerial tracking surveys were flown weekly to locate radio-tagged fish in local creeks and rivers. Because radio transmitters cannot be detected in saltwater, the surveys were timed to coincide with low tides to increase the opportunity of locating radio-tagged fish in stream mouths (i.e. areas inundated by seawater at higher tide stages). A remote tracking station was also placed near the mouth of the Mendenhall River (8 km down the coast from Auke Creek) to record the passage of radio-tagged fish moving upriver; resident cutthroat trout spawn in several tributaries of this drainage. Ground surveys were also conducted in the rivers and streams where radio transmitters were detected to obtain a more precise location and identify potential spawning areas.

Cutthroat trout from Auke Lake were tracked to 10 streams throughout the Juneau area (Jones and Seifert 1997), indicating that the overwintering fish represented an aggregate population. The fish travelled to spawning areas up to 50 km from Auke Lake, appearing to closely follow the shoreline; movements to streams across deep, open stretches of water were not observed even though in some cases the distances involved would have been substantially less. Some fish were recorded in more than one stream during their spawning migration.

Several populations of resident cutthroat trout use river systems in the Juneau area. Before this study, it was assumed that sea-run cutthroat trout were a component of these local populations and would migrate to the same spawning areas. Instead, the fish travelled to small coastal streams incapable of supporting year-round resident populations due to the lack of suitable winter habitat. Several radio-tagged fish were tracked to headwater areas where stream width was no greater than 8 cm! Rearing juveniles were observed in these headwater areas, indicating that successful spawning was occurring. Sea-run fish travelling to more traditional spawning areas would have to compete with fish from existing resident populations. The movement pattern documented during this study – using spawning streams devoid of winter habitat and, therefore, not suitable for resident fish – reflects an adaptive response by sea-run fish that avoids competition. By leaving these areas in the fall and returning to small lakes to overwinter, sea-run cutthroat trout utilise an otherwise unexploited niche.

The findings from this study have several management implications. Cutthroat trout congregate in small lakes to overwinter, and occur in sufficient numbers to constitute a harvestable population. However, movement data indicate that these fish are actually an aggregate of many small, distinct populations, essentially a mixed stock, which may be more vulnerable to overexploitation than a discrete resident population – a consideration important in managing local fisheries.

Findings from this study were also important in identifying previously unrecognised spawning habitat. Southeastern Alaska is heavily forested, and many areas are logged for timber. Buffer strips are mandated for spawning streams to protect critical habitat. Many streams used by sea-run cutthroat trout were not recognised as spawning habitat due to their small size and, therefore, were not protected. Efforts are being made to reflect the importance of these areas when classifying critical habitat.

Summary

Fishery management is typically a mixture of science, budget considerations, and politics. Managers often face the dilemma of having to manage wild populations with limited information. Seldom are sufficient funds available to collect all the information needed, making it necessary to prioritise research programmes to address the most critical areas. Which programmes are most necessary is often subject to debate. Although a key element in the life-history strategies of fish species, information on movement is often considered secondary to other research needs, especially because movement studies can be difficult and relatively expensive. Conventional wisdom or logical assumptions are often used to fill in the missing information. However, the patterns of movement exhibited by fish populations are often much more complex than generally perceived.

The common theme in the studies discussed is that the movement patterns observed were significantly different from what was expected. Although the established pattern for sockeye salmon is to spawn in the vicinity of lakes, a major portion of the Taku River return travelled to sections of the drainage without lakes, and used areas previously considered unsuitable for spawning. Subsequent review of the literature and unpublished data suggests that this life-history strategy may be more common than originally thought (Eiler *et al.* 1992). Salmon are generally thought to return directly to natal streams to spawn. However, coho salmon in the Taku River exhibited wide-ranging movements after arriving at established spawning areas. Sea-run cutthroat trout overwintering in small coastal lakes, initially thought to be a component of local resident populations, were instead comprised of an aggregate of many, small populations and travelled to extremely small stream systems where spawning had not been documented.

Wild populations often adapt their behaviour to reflect limitations in resources and competition. Movement patterns are simply a reflection of these underlying forces and, not surprisingly, are not always straightforward. Although often oversimplified due to the difficulty in collecting data, or considered ancillary to other types of information, an understanding of movement patterns can provide significant insight into the understanding and management of fish populations.

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Session 2

Environmental determinants, barriers and human interference

Chair:	John Koehn
Speakers:	Martin Mallen-Cooper Richard Tilzey John Gunn Tim O'Brien Tim Marsden Anthony Fowler Lachlan McKinnon
Rapporteur:	Pam Clunie

Chair's introduction and overview: Environmental determinants, barriers and human interference to the movements of fish

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Abstract

The purpose of this paper is to provide an overview and to stimulate discussion for this workshop session. Types of fish movement include: large-scale, local, migratory, seasonal, daily, active, passive, diurnal, upstream, downstream and vertical. Some of these movements have well-understood, definite purposes, whilst others are not understood at all. Such movements can be stimulated by a range of environmental variables, which can act either alone or in combination with other variables. Many of these variables have been altered by human interference. Barriers to fish movements are often common, particularly in river systems. Barriers can be either a physical structure or a non-physical impedance such as an interruption to suitable water quality, quantity or velocity. Captures of fish are often aided by or rely on their movement. Whilst this forms a major example of human interference, such interference also takes many other forms. The effects of environmental determinants and human interference to fish movements are illustrated through examples using individual species.

Introduction

The patterns of movement and migratory behaviour in fish cannot be understood without consideration of their evolution and benefits to the life history of the species (Dodson 1997). Such traits co-evolve to form adaptive strategies which provide selective advantage to a specific set of environmental conditions (Hutchings and Morris 1985). The energetic costs of migration and the efficiency of such migrations must be incorporated into any such strategies with the costs of the movement being outweighed by the evolutionary advantage. This will be determined by the length of migration, conditions faced, body size and shape, efficiency of movement, fecundity, reproductive uncertainty and egg and larval survival rates (Dodson 1997). Movement patterns are an important component in life history strategies as they provide the mechanism for accessing and utilising the resources necessary for survival (Eiler 2000).

The purpose of this paper is to provide an overview which will stimulate discussion for this workshop session.

Types of movement

Movements can take many forms; some movements have well-understood, definite purposes, whilst others are not understood at all. Examples of some movement types are given in Table 1.

Social behaviour and interactions of the species such as territoriality, aggression and schooling can all be

Table 1. Types of movements and examples of why they may occur.

Movement type	Examples of movements
Large-scale	movements between spawning, feeding and nursery habitats
Local	feeding, habitat preference, territoriality, home range
Migratory	generally larger-scale, for spawning, recolonisation
Seasonal	Spawning, temperature/condition-related
Daily	local, diurnal
Regular	related to regular cues such as light
Opportunistic	feeding-related/prey abundance, flooding
Obligate	innate spawning mechanisms
Preferential	habitat selection
Active	upstream movements, unassisted
Passive	using currents or streamflows for assistance or drift
Diurnal	activity-based, predator avoidance related to light levels
Upstream	active, often spawning or recolonising
Downstream	may be passive or active, post-spawning
Vertical	may be following prey/avoiding predators, advantages to placement in the water column e.g. temperature, light
Lateral	On or off the floodplain or in and out of anabranches

major influences on movement types. Movements can avoid competition or prevent or enhance predation. Within rivers, fish can also move opportunistically into anabranches (Koehn 1997) or onto the floodplain, although Australian evidence for the latter is limited to date (Humphries *et al.* 1999). Fish movements from lakes into inflowing rivers to spawn have also been documented (Koehn 1996; Tilzey 2000).

Northcote (1978) defined migration as those movements which occur with a regular periodicity and involve a large proportion of the population. Such movements involve losing any site attachment the species has, can incur considerable energy costs and may have increased predation risks by travelling through unfamiliar localities. The benefits of these movements accrue as the habitats they move to are more suitable than the habitats they have left. Such migrations are typically for feeding or reproduction (Wootton 1992). Migrations for many species can involve diadromous movements between freshwater and marine environments (McDowall 1988). Gross (1987) suggested that the patterns of diadromy exhibited by the world's fishes reflect the relative productivity of fresh and sea waters at the different locations. Such movements take advantage of optimal reproductive and feeding conditions for adults or larvae and can involve movements which compensate for larval drift.

Vertical movements both for following prey items and potentially obtaining preferred temperatures to maximise energetics have been outlined for southern bluefin tuna (Gunn and Young 2000).

Environmental determinants

Movements can be stimulated by a range of environmental variables, which can act either alone or in combination with other variables as outlined in Table 2.

Often these environmental variables have secondary influences which can also influence movements. For

Table 2. Environmental determinants for movement and examples of species to which they may apply.

Determinant	Example
Moon phase	Glass eels (McKinnon *et al.* 2000)
Light	Southern bluefin tuna (Gunn and Young 2000)
Streamflows	Murray cod (Koehn and Nicol 1998)
Currents	Plaice (Arnold 1981), southern bluefin tuna (Gunn and Young 2000)
Tides	Glass eels (McKinnon *et al.* 2000)
Water temperatures	Southern bluefin tuna (Gunn and Young 2000), carp (Mallen-Cooper *et al.* 1995), brown trout (Tilzey 2000)
Season	Murray cod, trout cod (Koehn and Nicol 1998), silver perch, carp (Mallen-Cooper *et al.* 1995; McKinnon 1997)

example, light levels caused by moon phase can illuminate prey, or flooding can cause an influx of prey. Many environmental variables have been altered by human interference, especially in river systems (Koehn and O'Connor 1990) but their effects on movement have usually not been quantified.

Barriers

One of the issues of human interference to fish movements that is specific to river systems is barriers. Physical barriers and solutions to them have been reviewed by O'Brien (2000) and include both large (e.g. dam walls) and small (e.g. culverts) structures. There are over 3 600 barriers to fish movement in the Murray-Darling Basin alone (Murray-Darling Basin Commission in prep). Harris (1984a, 1984b) calculated from a study in south-eastern Australia that about half the potential fish habitat in coastal rivers was not available to migratory species due to blockages by barriers. In general, about seventy percent of fish species in these rivers require migrations to complete their natural life cycles (Koehn and O'Connor 1990), so barriers can affect the majority of the fish fauna, particularly in coastal rivers. Barriers have also been recognised as a major threat to totally freshwater species (Koehn and O'Connor 1990).

Whilst most attention to movement barriers has been for fish passage to allow upstream movements, downstream movements are also important. Examples of downstream movements of adult fish have now been provided for species such as Australian bass (Harris 1986), common galaxias (Frankenberg 1966), Murray cod (Koehn 1997), golden perch (Koehn and Nicol 1998; McKinnon 1997) and carp (Koehn and Nicol 1998), the latter three species being restricted wholly to freshwater environments.

Barriers to movement which are harder to detect are those of a non-physical nature. Such barriers can be created by: thermal, saline or other water quality changes; interruption to continuous habitats; high or unsuitable water velocities; and shallow water. These barriers, as with some physical barriers, may not be total in their nature but may affect only a portion of the population or may act for only a certain period.

The impact of movement barriers on population fragmentation of, and the restrictions to, genetic mixing have not been quantified for river populations.

Human interference

Many captures of fish are aided by or rely on their movements and migratory habits, making these migratory species particularly vulnerable to capture. Many of the world's most important commercial species are migratory fishes. In 1978, 24 of the 25 marine species which gave the highest yields were migratory species (Harden Jones 1981). Targeting migratory stocks often means targeting spawning migrations, which means not only reducing the existing numbers but also preventing potential recruitment.

Fowler (2000) has recommended management policies to protect King George whiting populations to allow escapement through a 'gauntlet' fishery of both commercial and recreational fishers in South Australia. Several States have closed seasons for Murray cod to protect them from capture during spawning season movements.

Conclusion

We need to understand the movements of fish species in order to apply adequate management regimes. The movements of fish need to be considered in relation to their purpose in the lifecycle of the species and their evolutionary benefit. The benefits of movements need to be considered to understand the dynamics of fish populations. The swimming speeds and ability to migrate are not known for most species, nor are the cues to movements. Understanding the reasons and cues for movement is the first step in providing management which can allow those movements to continue (e.g. providing flooding). Understanding swimming abilities can assist in the design of more efficient fishways to alleviate the problems caused by barriers. The protection of many migratory species is essential for regulating their capture by both commercial and recreational fishers.

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Taking the mystery out of migration

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Abstract

In south-eastern Australia the migration of freshwater fish is a widespread phenomenon and many of the general patterns of migration are well known. However, the terminology that is generally used to describe these fish tends to underestimate the significance of migrations that appear to be facultative, and oversimplify the ecology of these fish communities.

The major cues for migration of these fish are season, streamflow, and water temperature, which are sometimes overlaid by diel period. Large rises in river level often stimulate large fish to migrate, but small rises and low flows are very significant cues for the movement of smaller immature fish, and these can be severely affected by river regulation.

In streams of south-eastern Australia the most common barriers to migration are low-level weirs which are submerged during floods. These barriers are changing the structure of freshwater fish communities in the streams of this region, favouring migratory strategies that are facultative or can be completed at high flows. Those species or life stages that have obligate or large-scale migrations at low or moderate flows (when weirs are barriers) are declining most rapidly. This highlights the need to design fishways for these flows, and to provide environmental flows for the fishways to function and to stimulate migration. These specific needs of upstream migration also need to be part of a broader vision of managing migratory fish populations that incorporates downstream passage requirements, protection of habitat and inter-weir distances, with goals of distribution and abundance of these fish within catchments.

Introduction

The fact that many freshwater fish in Australia migrate is well known. In some cases the role of these migrations in the life history of the fish is also well understood. However, there is still considerable mystery in this area of fish biology in Australian streams. Many of the migrations appear to be facultative or opportunistic, and even at a quite fundamental level, we are still adding to the list of Australian freshwater fish that migrate.

In this paper I would like to look at three different areas:

1. The different types of fish migration in eastern Australia, and how the terminology that is commonly used may oversimplify the ecology of these fish.
2. The environmental cues for movement in two species, where we do know something about their migrations, and then examine a model of migration in one species to show what we don't know!
3. The management implications, specifically how river regulation may be changing the freshwater fish community, and some suggestions for applying existing knowledge for better management.

Terminology

To start at the broadest level, there are two major types of freshwater fish migration and these are well-represented in Australia. There are those fish that migrate between the sea and freshwater, called *diadromous* fishes, and those species that migrate wholly within freshwater, called *potamodromous* fishes.

Diadromous fishes

Within *diadromous*, there are a further three subdivisions:

- Catadromous - these fish migrate downstream to the sea to spawn. This is a common strategy in south-eastern Australia and includes fishes like Australian bass (*Macquaria novemaculeata*), freshwater mullet (*Myxus petardi*) and freshwater herring (*Potamalosa richmondia*).
- Anadromous - these fish migrate upstream to spawn. Although the most studied type of migration because of salmon, it is a rare strategy in Australia - the only confirmed examples in Australia are the lampreys.
- Amphidromous - these fish migrate between the sea and freshwater but not for breeding.

These terms were clarified by Myers (1949) and were applied to Australian fishes by Harris (1984). The categories would seem clear cut, and there are certainly some species in Australia, such as eels and some galaxiids, that do fall very neatly into them. However, there are other species that can't obviously be classified. This is partly because these terms have developed from species that have obligate migrations that must be completed within one generation. There are some species in Australian coastal streams, for example, that are a common component of the freshwater fish community, but their migration into freshwater appears not to be essential for the completion of their life cycle. So their use of freshwater habitat could be considered facultative.

Barramundi (*Lates calcarifer*) is a good example of where the definitions are unclear. Barramundi can complete their life cycle below tidal barriers, so a freshwater phase would not seem obligatory. However, immature fish actively migrate into freshwater. Is this then a facultative catadromous species, where the migration into freshwater is not essential for the completion of the life cycle, and how then would this differ from amphidromy?

The trap in using terms like *facultative* is that to some people it might suggest it is not a necessary function and it could then be ignored in the management of these species. Whatever category barramundi is in and to whatever degree their migrations are facultative or obligate, there is no doubt about the impact that migration barriers, especially tidal barriers, have had on this species. There has been a massive reduction in the distribution of this species in freshwater with a major overall decline in abundance. That is the impact at a species level. At a fish community level, there is also a major change because a large predator has been taken out of the freshwater ecosystem. So the migration of barramundi into freshwater might be considered *facultative* for the completion of its life history, but it is *obligate* in:

- maintaining the natural distribution of the species,
- contributing to its abundance, and
- maintaining the structure of the freshwater fish community.

Another example of where the migratory definitions are unclear is their application to striped mullet (*Mugil cephalus*) (also called sea mullet and bully mullet). Striped mullet is interesting because it can be a common component of the freshwater fish community of coastal streams, it can complete its life cycle within marine/estuarine waters, and it appears the degree to which it migrates into freshwater increases with decreasing latitude.

In the southern part of its range, in Victoria, a few juveniles occasionally enter freshwater (Tarmo Raadik, Victorian Department of Natural Resources and Environment, pers. comm.) and the species could be considered to be a '*marine wanderer*' (McDowall 1992). Heading north to New South Wales, sea mullet commonly enters freshwater, and there is a significant migration of juveniles, and adult fish that have returned from spawning. In NSW it is referred to as *amphidromous* (Harris 1984). In Queensland, in the sub-tropics, it enters freshwater in high numbers and it is often referred to there as *catadromous,* although it can still complete its life cycle in estuarine/marine waters. All three categories might be correct within the range of this species. Like barramundi, striped mullet is affected by migration barriers, and the migration into freshwater could be considered obligate for the same reasons as given above for barramundi.

Differences in migratory strategies with latitude have been described elsewhere for American shad (*Alosa sapiddissima*) (Glebe and Leggett 1981). This is an anadromous species where in the south of its range it dies after spawning (semelparous), and in the north of its range many fish survive after spawning (iteroparous).

Hence, it is important to keep in perspective that the terms used to describe migration in fish are often not clear-cut. This is probably particularly so in the sub-tropical and tropical rivers in northern Australia, and trying to fit fish into the standard migration categories runs the risk of oversimplifying the ecology of those river systems.

Potamodromous fishes

Within the term *potamodromous* there are no sub-categories. Rather than reflecting the lack of different migrations, I suggest this reflects the history of research on migration. This has focussed on *diadromous* fishes, like salmon, because they have supported such valuable commercial fisheries. In Australia, there are many species migrating wholly within freshwater for a range of reasons, but they are all grouped into this one category.

For example, in the Murray-Darling river system there are many observations of migrating fish, including a range of species and life stages (Table 1), which can be considered to be potamodromous migrations. The reasons for these migrations, and the obligatory/facultative nature of these migrations are unclear. In Table 2, are listed some suggestions for different types of upstream potamodromous migrations in the Murray-Darling river system.

Spawning migrations have been divided into two possible categories, the first being *habitat and site specific* (i.e. there is high site fidelity), and the second *habitat specific*, where the site may vary but the habitat conditions remain the same, e.g. peak of a flood or recently inundated ground. The conditions for the latter might be specific or flexible – there is still considerable research needed to confirm these for native fish.

'Dispersal' is often used to describe migrations, and it is sometimes used where the reasons for the migrations are not fully understood. The term 'dispersal' suggests movement from a concentration of individuals to a more widely-distributed state. This may occur if juveniles are moving from an adult spawning zone. However, other reasons for migrating upstream, such as countering active or passive displacement downstream, could easily be categorised as 'dispersal', thereby diluting the ecological meaning of some migrations.

'Dispersal' may also not involve a large fraction of the population (and hence might not strictly be classified as migration (Northcote 1997), but may still be very significant ecologically. In discussing potamodromous salmonids, Northcote (1997) suggested that 'straying' might be an important 'mechanism for recolonisation in the wake of local population exterminations'. In a semi-arid river system, such as the Murray-Darling, severe droughts can cause local exterminations as pools dry up. In Reynolds' (1983) landmark study of fish migration in the Murray-Darling river system, the 0.3% of adult golden perch (*Macquaria ambigua*) that migrated upstream over 1 000 km could fall into this category of straying or 'dispersal'.

'Dispersal' in small mammals is accepted as having a major ecological role, most obviously in maximising distribution and gene flow (Stenseth and Lidicker 1992). It is possible that the difficulties of studying this type of movement in fish, which often represents the 'outliers' in tagging data, has led to this area receiving little attention.

Table 1. Fish species recorded moving upstream in the Murray-Darling river system (? indicates unconfirmed).

Sources of information

1. Reynolds (1983) 2. Mallen-Cooper (1999) 3. McDowall (1996)

4. J. Koehn pers. comm. (Vic. Department of Natural Resources and Environment)

5. D. Moffat pers. comm. (Qld. Department of Natural Resources)

		Migratory			Sources of
Common name	Species name	adults	sub-adults	juveniles	information
Native species					
golden perch	*Macquaria ambigua*	●	●		1
silver perch	*Bidyanus bidyanus*	●	●		1
bony herring	*Nematalosa erebi*	●	●	●	2
spangled perch	*Leiopotheropon unicolor*	●		●	3
Murray cod	*Maccullochella peelii peelii*	●	●		4
Macquarie perch	*Macquaria australasica*	●			3
catfish	*Tandanus tandanus*		●	●	5
Hyrtl's tandan	*Neosiluris hyrtlii*	●	?		5
Australian smelt	*Retropinna semoni*	?	?	●	2
flyspecked hardyhead	*Craterocephalus stercusmuscarum fulvus*	?			5
olive perchlet	*Ambassis agassizii*	?			5
Non-native species					
carp	*Cyprinus carpio*	●	●	●	2
goldfish	*Carassius auratus*	?			5
brown trout	*Salmo trutta*	●			3
rainbow trout	*Oncorhynchus mykiss*	●			3

Table 2. Suggested reasons for upstream potamodromous migrations in the Murray-Darling river system.

Spawning	*habitat and site specific* (obligate) [e.g. Macquarie perch] *habitat specific* (obligate, facultative or just flexible?) [e.g. golden perch]
'Dispersal'	to maintain maximum distribution and gene flow; significant for colonisation (e.g. following droughts)
Counter *active* downstream migration	as larvae, or possibly an *environmental* migration (refuge-seeking, during onset of droughts or unfavourable water temperatures)
Counter *passive* downstream movement	fish could be displaced downstream during floods

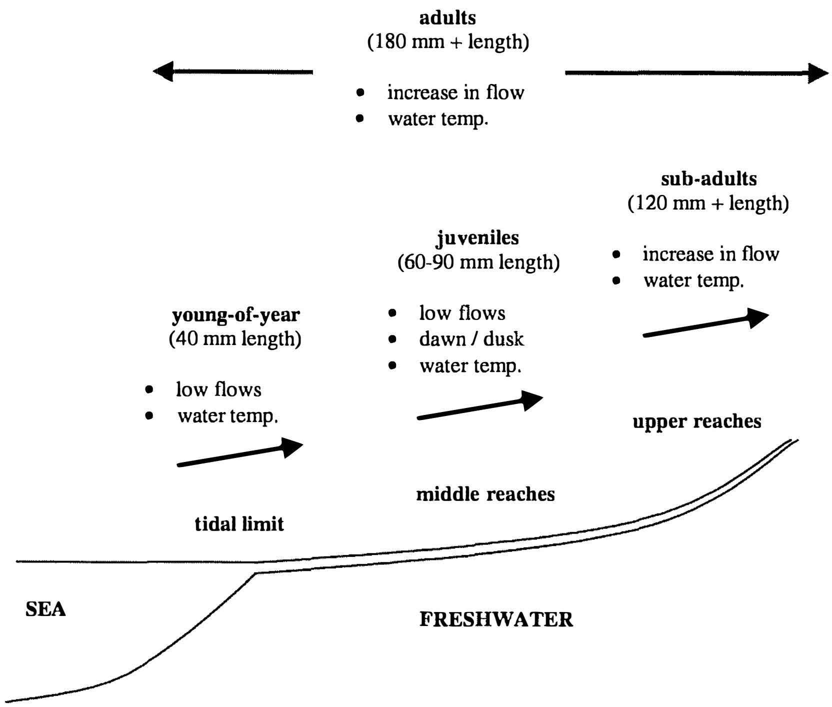

Figure 1. Migration in Australian bass - life stage, length and cues for movement.

Cues for movement

Australian bass

Australian bass have a catadromous life history with the adults migrating downstream to the estuary to breed during winter floods, followed by a migration back upstream. The juveniles then migrate into freshwater in spring. At the tidal limit the juveniles are about 40 mm in length and they are migrating at low flows (Figure 1). From the few observations of diel movement there does not appear to be a particular diel pattern - they just seem to be keen to get out of the estuary and away from the predators!

The important aspect of this migration is that it is occurring at low flows. This means that small weirs, which may be submerged at high flows and not be a barrier to migration in those conditions, are a major barrier for young Australian bass. Tidal weirs, therefore, have a devastating effect on the recruitment of those young fish into freshwater.

This situation, with young-of-the-year migrating in low flows, seems to occur with a number of catadromous species. For management, there are two immediate priorities - firstly, fishways need to be designed to function at low flows, and environmental flows need to be allocated to those fishways.

As young Australian bass migrate into the middle reaches of the river they are still migrating at low flows, but there is a strong diel pattern. If those fish have to pass a shallow riffle or causeway they will mainly attempt it at dawn and dusk (Harris 1983). Water temperature appears to be an important stimulus for migration at all life stages.

In the upper reaches of the river the stimulus to migrate changes. The sub-adults move upstream when there are rises in river level and this appears to override any diel pattern. At this stage in the river system, the gradient has increased and there are natural migration barriers at low flows. The implications for management here are that rises in river flow need to be incorporated into environmental flow plans, and fishways in this section of the river need to function at these higher flows.

Adult Australian bass move downstream in autumn and upstream in late-winter and spring. In both cases the migration appears stimulated by rises in river flow. Little is known about diel movement of adult fish. Their migration at higher flows means they can migrate over small weirs, when they are submerged. So at the tidal limit, adult fish can negotiate a low-level weir, where the juveniles cannot. In this situation the result can be a remnant population with a small number of adult fish surviving above the tidal barrier.

Hence, it is important in managing migratory species to know, not only that they are migratory, but also what is stimulating migration at each life stage. This helps identify priorities for river management.

Golden perch

Golden perch is a well-known migratory species of the Murray-Darling river system. It provides an example of a potamodromous species, not only to examine what stimulates migration, but also to build a model of migraiton in this species which shows how potentially complex potamodromous migrations in Australia might be.

The main cues for movement in golden perch are, as in Australian bass and many freshwater fish (Northcote 1984), flow and water temperature. In discussions of water temperature, however, it is important to keep in mind that in most field studies of migration it is often difficult to separate water temperature from day length, which can also be a cue for migration.

In golden perch, sub-adult and adult fish respond to different ranges in flows and temperatures. The sub-adult fish are stimulated to migrate upstream over a much wider range of flow and temperature. In fact sub-adult golden perch respond instantly to very small increases in flow (e.g. a 15 cm rise in a 4 m deep river), and they move upstream in large over-bank floods. The migration season seems to be from spring to mid-autumn. The adult fish appear to move upstream mainly on larger river rises, and mainly in spring and summer.

Interestingly, the sub-adult fish stop migrating immediately the river level falls, and they appear not to move back downstream. Their upstream migration, therefore, appears to occur in stages - just moving when there is an increase in flow. This also leads to congregations of fish remaining below weirs for some time after a river rise has passed and, significantly, these fish are then susceptible to predation from birds (and fishers who keep small fish!). A good example of this is the almost permanent cormorant colony below Euston Weir on the Murray River.

The many observations of this species responding to river rises, and the seasonality of movement which strongly suggests that water temperature is important, have practical implications for river management. The small river rises in which sub-adult fish are migrating are variations in flow that could occur within present irrigation releases. Regulated flow could be released to enhance fish migration simply by introducing variation in flow delivery but keeping the same total volume released per week.

The importance of water temperature in freshwater fish migration raises the issue of thermal pollution from the low-level offtakes of dams and high weirs. The restoration of migratory pathways for fish in the Murray-Darling Basin will almost certainly be linked to providing appropriate water temperature, as well as providing appropriate flows, and access past barriers through the use of fishways. Ignoring one of these three aspects will severely compromise reforms and rehabilitation in the other two.

As this discussion of fish migration leads to river rehabilitation, it is timely to put this paper briefly into a broader perspective. The important point here is that only one aspect (migration) of the life history of

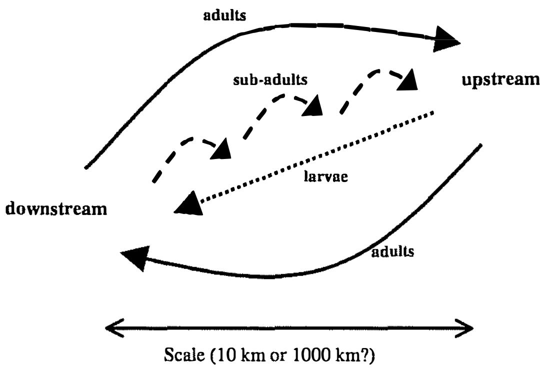

Figure 2. A model of migration in golden perch ('central stock').

one group of fishes (migratory) is so far being discussed. The sometimes visible nature of the fish migration has popularised this aspect of the life history of fish, but it is still only one component of a sustainable fish community. This point will be examined further at the end of the paper.

A model of migration in golden perch

Golden perch is one of the most studied fish species in the Murray-Darling river system and there is much data to use in constructing a migration model that also incorporates life history. Initially the model appears easy to construct and also to be robust, explaining much of the primary field data. However, it is the absence of a couple of key steps in the model, and the observed variation in some others that make migration in this species potentially much more complex than previously thought.

This discussion of golden perch refers here to the 'central stock' in the Murray-Darling and Murrumbidgee Rivers that Watts *et al.* (1994) identified as genetically distinct from other golden perch populations. The data that contribute to a model of the life history of this particular stock are:

Adult fish

- Recorded moving upstream as running ripe fish in the nets of commercial fishers.
- Tagged fish recorded moving hundreds and, in a few individual cases, thousands of kilometres upstream (Llewellyn 1968; Reynolds 1983). These studies were in the lower Murray River.
- Tagged fish moving similar distances downstream (McKinnon 1997). This study was in the middle reaches of the Murray River at Barmah Forest.
- Migration on high flows during spring and summer.
- Induced to spawn in ponds when the water temperature and water level rises (Lake 1967).

Sub-adult fish

- Sub-adult fish, greater than one-year-old, recorded moving upstream (Mallen-Cooper 1999).
- Migration during high and low river rises from spring to mid-autumn; migration stops when river falls. These fish appear to move upstream in stages.

Larvae

- Larvae recorded drifting downstream (J. Koehn pers. comm., Department of Natural Resources and Environment).

These observations fit into a simple model in which adult fish migrate upstream to spawn during large river rises, the larvae drift downstream, and the immature fish migrate upstream in stages to compensate for the downstream drift as larvae (Figure 2). Most of this has been hypothesised for some time and it looks like a robust model, with observations to support each component. However, even with these observations there are still big gaps in the model.

Firstly, the scale of the migration is unclear. There are spectacular tag returns of fish going upstream over 1 000 km and downstream almost 900 km, and the possibility that these may be dispersal migrations was discussed earlier. But importantly, the majority of tagged fish (over 60%) in Fred Reynolds' (1983) work and Lachlan McKinnon's (1997) work moved less than 60 km, and 20% of tagged fish in both studies hardly moved at all, staying close to the tagging site. Are there then migratory and non-migratory components of the population, as has been described for a number of freshwater fish such as *Barbus barbus* (Hunt and Jones 1974), smelt *Retropinna retropinna* (Northcote and Ward 1985), threespine stickleback *Gasterosteus aculeatus* (Snyder 1991), and brown trout *Salmo trutta* (Näslund 1992)? If so, there would be significant management implications. Only further research will clarify this aspect of migration in golden perch.

The other major aspect of the model open to interpretation is the original work of John Lake in the mid-1960s, where he had golden perch in 30 m square earthen ponds, and he inundated a small artificial floodplain. These fish spawned without migrating anywhere! This then suggests the question of 'how obligate are the migrations of adult fish in the wild?' They may not be obligate for spawning, but if they are a flood-spawner, they may be important for optimising larval survival.

Golden perch may be more flexible and opportunistic than previously thought, spawning during small and large river rises, possibly migrating a small distance in a small flood or a long distance in large flood. And very likely getting quite variable larval survival. But in a semi-arid river where a big flood might not occur for a decade or two, it is a more robust strategy to have some larval survival on the small floods as well.

One thing is certain - for a well-studied species there are still plenty of questions.

Changes in the structure of migratory fish communities in eastern Australia

Golden perch is one migratory species that, although its numbers have declined, is still relatively common and widespread. Some other migratory species have declined severely, like silver perch in the Murray-Darling Basin or barramundi in coastal streams of Queensland. However, other native species that migrate have possibly increased, or at least maintained, their abundance. Notable examples are bony herring in the Murray-Darling Basin, blue catfish in coastal streams of Queensland, and Australian smelt in south-eastern Australia.

The degree to which these species have declined probably reflects variations in migratory strategies, and the characteristics of river regulation in eastern Australia. The geography of this region, with generally low relief on the coastal plains and for much of the Murray-Darling Basin, has meant that the most common barriers to migration are low-level weirs that are submerged during floods. The migratory species that appear to be adapting most effectively to these changes are characterised by:

- facultative migrations, or
- small-scale migrations that can be completed between barriers, or
- migrating at high flows when the low-level weirs are submerged, or
- migrating on a wide range of flows, including high flows.

Those species or life stages which have obligate or large-scale migrations at low or moderate flows (when weirs are barriers) appear to be declining more rapidly. Hence river regulation, and specifically the high frequency of low-level weirs, is likely to be contributing to major changes in the structure of freshwater fish communities in eastern Australia.

Avoiding migration management mediocrity

To conclude with some comments on management, consideration of the following might help in avoiding migration management mediocrity:

- *Environmental flows*

Seems obvious, but still frequently forgotten or ignored. A particular issue here is providing flows for tidal fishways to function.

- *Temperature regime*

Flow and temperature are the main cues for migration. The provision of environmental flows and effective fishways are unlikely to restore fish populations below major dams without addressing thermal pollution.

- *Fishways design to suit the flows on which migration is occurring*

Migration occurs over a wide range of flows, but it also occurs at different flows in different parts of the river system. One of the most common compromises in fishway design is reducing the range of flows over which the fishway operates. Biologists and engineers need to work together so that if a compromise is needed, it has an ecological basis.

- *Holistic view of management (species and fish community, habitat)*

The focus on managing migratory fish has often been on commercially or recreationally important species, and the main mechanism of management has been providing fish passage, usually through the construction of fishways. A broader perspective is needed to manage fish populations sustainably, recognising that:

- migratory fish are an integral part of the wider fish community
- all freshwater fish species need to move freely within a river system
- once the fish get upstream (or downstream) there needs to be high quality habitat!

- *Importance of downstream passage*

Upstream migration and providing fish passage for these fish has been the focus of much of the research and management on migratory fishes in Australia. Recent observations of adult golden perch migrating downstream and getting trapped on the trash racks of the Yarrawonga Weir Power Station have highlighted the need for research on downstream passage. Supporting this need are the observations of larval drift downstream (J. Koehn, Department of Natural Resources and Environment, pers. comm.; C. Schiller, NSW Fisheries, pers. comm.).

- *Inter-weir distances*

There is a common view when a new weir is proposed that installing an effective fishway and therefore maintaining a migratory pathway will address all the impacts on the fish populations. Apart from the change to streamflow and the change from a lotic to a lentic habitat, the inter-weir distances are frequently overlooked as an issue. These distances may be critical in maintaining some fish populations. One of best silver perch populations in the Murray-Darling Basin is between Torrumbarry and Euston Weirs which is one of the longest inter-weir distances in the Basin. Whether this is the reason for the existence of this population or a coincidence is unknown.

- *The need for a vision*

In designing fishways with engineers and water resource managers it is often clear that they have a vision for the river system, which includes the maximum sustainable harvest of water and all potential dam and weir sites identified.

The position of biologists in this situation is often a reactive one, whereas it would be more productive to start with a very specific vision of fish populations in the river system. This vision needs to be as quantitative and measurable as possible. It should include potential distribution maps of each fish species, inter-weir distances that should not be fragmented, habitat that needs special protection, and if fishways are required then performance standards for passage of fish need to be included.

Temperature regimes below existing and proposed dams and weirs should be specified. Environmental flows are a complex issue but without specifically recommended flows, weirs are presently being built without the capacity to release significant environmental flows – they are still being designed to release the maximum regulated flow. Hence, the vision needs to include a specification for dams and weirs (existing or proposed) that states a minimum capacity for flow releases (e.g. 'any weir needs the capacity to release the 50th percentile of a monthly flow duration curve'). This criterion would need to have an ecological basis to ensure the potential to implement a future environmental flow regime.

The vision also needs to be realistic with achievable goals. That is, aiming for pre-1788 fish abundance might not be achievable! However, financial constraints should not be imposed on the vision – that will almost certainly come later!

Conclusion

Fish migration in freshwater has been high on the agenda for a decade, as can be seen with the construction of fishways in eastern Australia and the subsequent research (Berghuis *et al.* 1997; Mallen-Cooper 1999; Stuart and Mallen-Cooper 1999). However, we are still a long way from understanding the ecology of freshwater fish migrations in Australia, especially in semi-arid and sub-tropical/tropical streams. As further work reveals not only the cues for movement, but also the role these movements have in population and community dynamics, our management of these ecosystems will vastly improve.

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Environmental cues in the reproductive migrations of brown trout (*Salmo trutta*) in Lake Eucumbene, New South Wales

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Abstract

During studies into the dynamics of Lake Eucumbene brown trout populations, the winter spawning 'runs' in a major inlet stream were monitored via *a fish trap from 1968 to 1970. Also, mark/recapture experiments were conducted, and reproductive homing behaviour resulted in tagged spawners being recaptured in successive years. The composition of the Eucumbene brown trout spawning population is similar to that of Great Lake, Tasmania, but spawning occurs about two months later. Changes in annual percentage maturation during the study period caused corresponding shifts in sex ratio and age structure in the spawning run. The major upstream migration cue appeared to be stream flow, with most fish moving during or immediately after rises in stream level. No correlation was found between fish movement and water temperature or moon phase. Comparisons between the temporal patterns of spawning runs in successive years and the capture/recapture dates of marked brown trout indicated an inherent timing mechanism, probably associated with day length, largely over-rode local environmental migration cues for this species.*

Introduction

Spawning migrations of salmonids are generally thought to be stimulated by a combination of stream flow, water temperature and day length (McKeown 1984). This study examines factors influencing the spawning migrations of brown trout (*Salmo trutta*) in Lake Eucumbene, New South Wales. Brown trout were first introduced to Australia *via* Tasmania in 1864 and were subsequently released into NSW waters in 1888 (Roughley 1951; Clements 1988). Populations were established in the Snowy River catchment by the late 1890s. Following the Snowy Mountains Hydro-electric Scheme during the 1950s and 1960s, lotic trout populations rapidly expanded to occupy the lentic waters of the newly created reservoirs. Although these reservoirs received stockings of rainbow trout (*Oncorhynchus mykiss*), their brown trout populations stemmed solely from wild fish within their catchments. Lake Eucumbene is the largest such impoundment, having a surface area of 145 km^2 and a volume of 4.8 km^3 at full supply level.

Whereas brown trout have been established in Australia for well over a century, published Australian studies on their spawning behaviour are few. Davies and Sloane (1987) described the characteristics of brown trout spawning migrations in Great Lake Tasmania. Tilzey (1977) described repeat-homing by spawning brown trout in Lake Eucumbene, with this study being part of wider investigations of Eucumbene's trout populations during the period 1967-79. Data from these investigations are used in the current study to examine factors influencing the timing and periodicity of brown trout spawning migrations and to compare these findings with those of Davies and Sloane (1987).

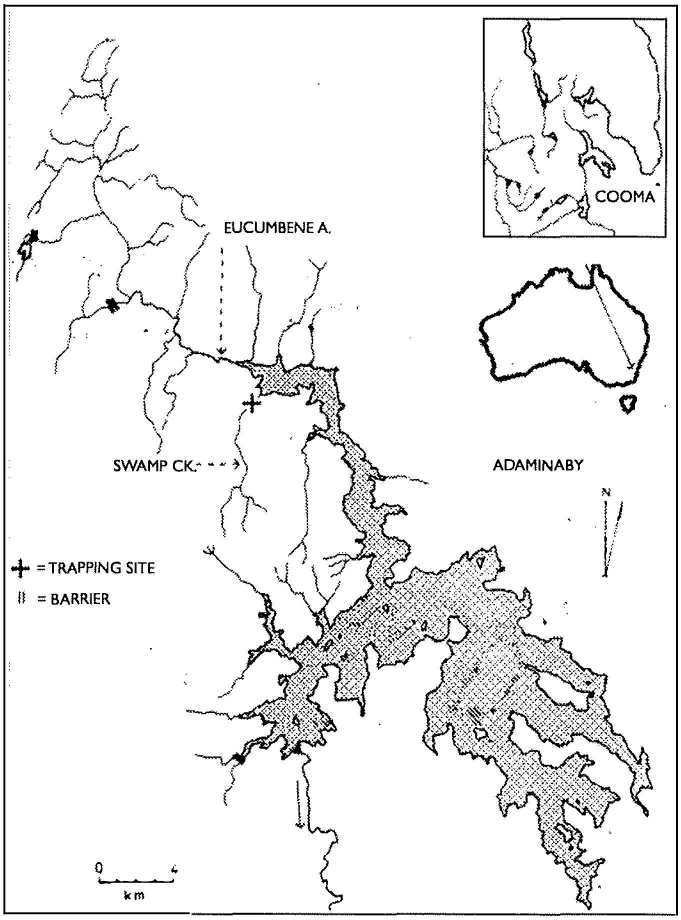


Figure 1. Lake Eucumbene at full supply level and its feeder streams.

Methods

This study centred on Swamp Creek, a major (10.5 km in length) stream entering the northern arm of the lake (Figure 1). In 1968, 1969 and 1970, trout spawners ascending this stream were caught in a fixed upstream trap and examined for species, sex, weight, fork length, and the presence of tags or tag-loss scars. The trap was serviced daily except where stated otherwise. Many fish were also aged by scale analysis and tagged or re-tagged. Tilzey (1977) described the tagging procedures and numbers of fish marked. The tagged fish referred to in the current study were originally tagged and released between 1 June and 2 August 1968. In 1968, trapping was primarily aimed at tagging fish, did not commence until 1 June and finished on 15 October 1968. Respective trapping dates for 1969 were 2 May and 17 October. In 1969, all fish were placed above the trap and allowed to spawn, with downstream migrants also being monitored *via* an adjacent downstream trap. Equivalent trapping dates for 1970 were 3 May and 10 October except that, from 26 July onwards, the trap was used principally to obtain fertilised rainbow trout ova for the Gaden Hatchery near Jindabyne, NSW and was serviced at irregular intervals (1-3 days). The repeat-homing of tagged brown trout facilitated comparison between their respective annual capture and recapture dates. Stream depth was recorded *via* a metric rule at a fixed site throughout the spawning

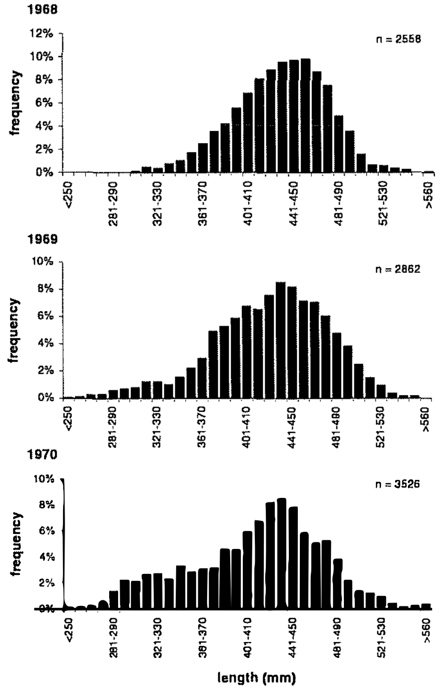


Figure 2. Size composition (LCF, mm) of brown trout in the 1968, 1969 and 1970 spawning runs.

season, but it should be noted that the 1968 site was in a deeper section of the creek than that used for 1969 and 1970. No attempt was made to measure flow volume, but because one of the stream banks at the trapping site had a sloping profile, an increase in depth saw a disproportionately greater increase in flow volume. Water temperatures were recorded from a submerged maximum/minimum thermometer, to provide median daily temperature. Water temperature was not recorded in 1968. Daily maximum/minimum air temperatures and rainfall records were recorded from a Snowy Mountains Authority weather-station raft approximately 15 km south of the trap site. Barometric pressure readings recorded in Cooma showed pressure declines to largely accompany rainfall. Consequently, barometric pressure could not be isolated as an environmental variable and was not considered further in this study. From 1968 to 1970, monthly samples of trout were gillnetted from lentic waters and percentage maturation values were derived from staging gonad development in fish caught over the period December-April, inclusive.

Results

Composition of spawning runs

The numbers of brown trout trapped in 1968, 1969 and 1970 totalled 2 558, 2 862 and 3 526, respectively. Females outnumbered males in every year, with the female:male ratios in 1968, 1969 and 1970 being 2.2:1, 2.0:1 and 1.5:1, respectively, an overall ratio of 1.8:1. The sex composition of runs changed with time, as more males ran earlier than females. For example, during May the female:male ratio was 0.6:1 in 1969 and 0.5:1 in 1970. Thus, the mean female:male ratio for 1968 would have been inflated because no trapping occurred in May. The female and male size ranges (LCF, mm) were (1968) 305-641 and 300-556, (1969) 253-560 and 251-556, and (1970) 265-575 and 215-730, respectively. Combined length frequencies are shown in Figure 2. In each year the most abundant age-class was 4 year-olds, with the second most abundant being 5 year-olds in 1968 and 1969 and 3 year-olds in 1970.

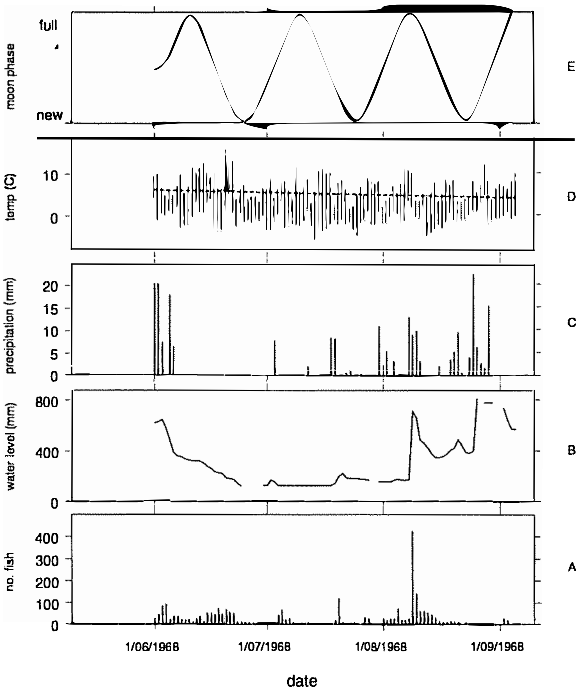


Figure 3. Summaries of daily (A) fish number, (B) stream depth, (C) rainfall, (D) max/min air temperatures (with a 5°C'benchmark'), and (E) moon phase during the 1968 spawning season.

Duration of migrations

In 1968 the start of the run was not recorded. The run peaked in August (Figure 3A) and the last 'ripe' brown trout entered the trap on 20 September, although a further 13 'spent' fish were recorded up to 4 October. In 1969, the run began on 14 May, with five peaks between then and late July (Figure 4A). The last ripe fish was recorded on 13 September, with spent fish (three) persisting until 20 September. In 1970, the run again began on 14 May with four peaks between then and early July (Figure 5A). The last fish was recorded on 5 September, but it was not noted if it was a ripe or spent fish.

Intra-annual periodicity of migrations

Spawning migrations showed considerable variation in the timing of major 'runs' during the three years studied (Figures 3A, 4A & 5A). In 1968, a large proportion of the run occurred in the first half of August, with comparatively few fish passing through the trap in July (Figure 3A). In 1969, the run was almost over by the start of August, with most fish passing through the trap in June and July (Figure 4A). In 1970, the run was almost over by 12 July, with only five days with >10 fish being recorded thereafter (Figure 5A).

Rainfall and stream flow

These were most variable environmental parameters. Despite the 15 km distance between the rainfall gauge and the trapping site, there was a good correlation between stream depth (i.e. stream flow) (Figures 3B, 4B and 5B) and rainfall (Figures 3C, 4C and 5C). The Swamp Creek catchment was to the south of the trapping site and thus closer to the gauge. Monthly rainfall totals for the period May to August are summarised in Table 1. In all years there was typically a strong positive correlation between stream flow and the number of fish entering the trap, although fish would sometimes run after water levels peaked and started to fall.

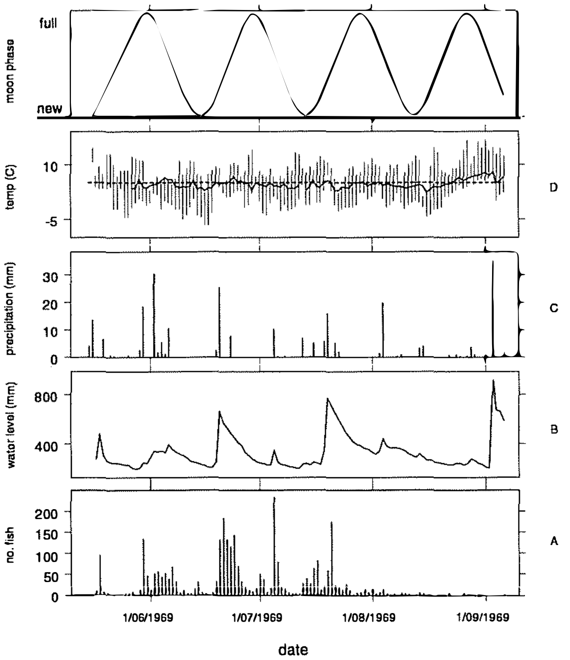


Figure 4. Summaries of daily (A) fish number, (B) stream depth, (C) rainfall, (D) max/min air temperatures and median water temperature (with a 5°C'benchmark'), and (E) moon phase during the 1969 spawning season.

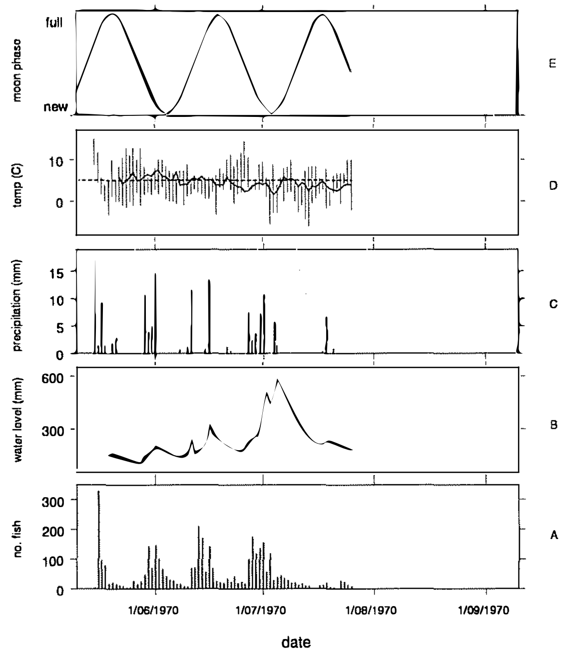


Figure 5. Summaries of daily (A) fish number, (B) stream depth, (C) rainfall, (D) max/min air temperatures and median water temperature (with a 5°C'benchmark'), and (E) moon phase during the 1970 spawning season.

Table 1. Monthly rainfall totals (mm).

	MAY	JUNE	JULY	AUGUST
1968	103.9	52.6	38.1	116.3
1969	50.6	79.2	51.1	35.1
1970	57.9	56.1	32.3	170.4

In 1968, trapping commenced at a comparatively high water level (622 mm) and daily fish number peaked at 94 on 4 June, a day after levels peaked at 648 mm (Figures 3A and 3B). Water level then slowly declined, but fish continued to run, with another pulse of fish >40 per day occurring between 14 and 22 June. A prolonged period of low flow from 24 June to 8 August then saw very few fish entering, except when a small water level rise occurred. A small rise (41 mm) during 2-3 July was followed by 152 fish during 4 to 7 July and a moderate rise (53 mm) on 20 July was accompanied by 120 fish. A sharp increase (539 mm) in level from 8 to 9 August saw a simultaneous run of 427 fish, followed by 140 fish on 10 August and >40 fish per day during 11-14 August. By the time the next major flow event occurred (a rise of 803 mm on 26 August), the spawning season was virtually over.

In 1969, a water level rise of 204 mm on 15 May was accompanied by 95 fish, but then <10 fish per day were recorded until a moderate rise of 46 mm on 30 May saw 134 fish trapped (Figures 4A and 4B). Following this, a period of moderate but irregular rises saw between 31 and 67 per day being recorded during 2-8 June. A major rise of 414 mm on 20 June saw >100 fish per day from 20-24 June. A moderate rise (119 mm) on 5 July saw 233 fish recorded, with a further 78 being trapped on 6 July, and a small rise (25 mm) on 16 July saw 63 fish, followed by 81 fish on 17 July. Another major rise of 432 mm on 20 July was accompanied by 58 fish and followed by 175 fish on 21 July. Again, by the time the next major flow event occurred (a rise of 711 mm on 3 September), the spawning season was virtually over.

In 1970, a depth of 155 mm was recorded on 14 May when three fish entered the trap. Following a 17.2 mm rainfall (Figure 5C), a significant rise in stream level then occurred, but unfortunately depth was not measured on 15 May when 327 fish were recorded. On 16 May, 95 fish were recorded and the depth had fallen to 267 mm. A slow rise of 101 mm over 28 May to 1 June saw >40 fish per day recorded during 29 May to 4 June, with a peak of 145 fish on 1 June (Figures 5A and 5B). Two moderate rises (98 mm on 11 June, 130 mm on 16 June) occurred during a seven day period of >50 fish per day. Daily fish number peaked at 208 on 13 June, fell to 54 on 15 June, then rose to 141 on 16 June. Rainfall during 27 June to 1 July caused creek depth to increase by 317 mm from 26 June to 2 July. Over the period 27 June to 3 July, 853 fish were trapped, with a peak of 174 on 28 June. The flood reached a second peak of 581 mm depth (73 mm higher than 2 July) on 5 July, but daily fish number declined to <40 after 3 July.

Air and water temperature

In general, mean daily water temperatures lay within the range of the maximum and minimum air temperatures recorded in 1969 and 1970 (Figures 4D and 5D) and to some extent matched the trends therein. However, there were a few days (13 overall) when water temperature was either higher than the maximum air temperature (e.g. 1 June '69 - water 3.4°C, air 2.8°C), or lower than the minimum air temperature (e.g. 26 June '70 – water 2.3°C, air 5.6°C). Nevertheless, because overall air temperatures in 1968 were lower than in 1969 and 1970 (Figures 3D, 4D and 5D), it can safely be assumed that 1968 water temperatures rarely exceeded 6°C during the spawning season. In 1969, June maximum/minimum water temperatures ranged from 1.2 to 6.7°C with a mean daily mean of 4.6 °C. Respective values for July 1969 were 1.7 to 7.7 and 4.7°C. In 1970, respective June and July values were 1.4 to 5.8 and 4.2°C, and 1.6 to 5.8 and 3.8°C. No correlation was found between fish movement and water temperature. In June and July 1969, there were 10 days with temperatures down and fish up, 16 days with both temperatures and fish down, 16 days with both temperatures and fish up, and 18 days with temperatures up and fish down. Respective values for 1 June to 26 July '70 were 7, 18, 13 and 14, with no temperature difference between days occurring on four occasions. Most migration occurred in water temperatures <6°C, with the bulk of fish moving in temperatures of 4-6°C. In 1969, only one major (>100 fish per day) run occurred on a day when water temperature exceeded 6° C. 1970 was the warmest of the three winters in the current study, but major runs only occurred on three days when water temperature exceeded 6°C. The lowest temperature accompanying a major run was 3.1°C, but fish numbers ranging from 2 to 98 per day were recorded for temperatures between 2 and 3°C.

Moon phase

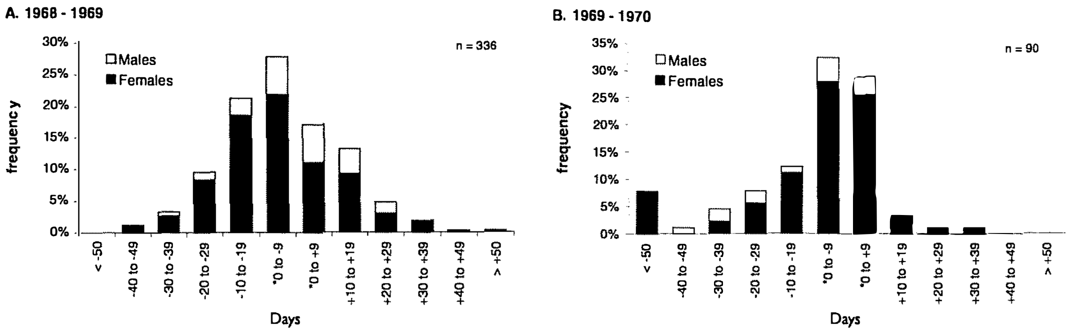
No correlation was found between moon phase and the timing of fish movement.

Inter-annual periodicity of migrations

There was a marked difference in the overall timing of migrations between each year, despite the spawning run commencing on the same date in 1969 and 1970. In 1968, the monthly numbers of fish migrating in June, July and August comprised 25.6%, 16.4% and 44.3%, respectively, of the total recorded run. These values would have been inflated by there not being any trapping in May 1968. Nevertheless, respective totals for 1969 were 46.5%, 38.2% and 3.5%, and for 1970, 55.9%, 19.4% and 0.2%. A greater proportion of spawners migrated at an earlier time than the preceding year(s). On top of this overall timing shift, there were also marked differences in the respective monthly stream flow regimes and the timing of major (>100 fish) runs. However, comparison between the respective dates of capture and recapture of marked fish from 1968 to 1969 and 1969 to 1970 found 44.7% and 61.1%, respectively, to return within nine days of the original capture date (Figure 6). Whereas there were mean shifts in capture/recapture dates of - 4.5 days from 1968 to 1969 and – 11.1 days from 1969 to 1970, the high occurrence of fish returning on similar dates indicated that the timing of migration by many fish was independent of environmental stimuli.

Discussion

The sex ratios and fish size ranges were similar to those reported for brown trout spawners from Great Lake, Tasmania (Davies and Sloane 1987). The temporal changes in sex ratio during the spawning season were also similar, with a greater proportion of male fish running earlier than females. The predominance of females in spawning population has also been observed in European brown trout (Munro and Balmain 1956), New Zealand brown trout (Hobbs 1937) and New Zealand (Dedual and Jowett 1999) and North American rainbow trout (Biette *et al.* 1981; Hartman *et al.* 1962). Several authors (e.g. Munro and Balmain 1956; Davies and Sloane 1987) have speculated that such female predominance could be attributable to a higher mortality in males. However, in the current study, comparison between the respective percentage maturation rates for each sex found that in 1967-68 and 1968-69 female maturation was much higher than that for males (Table 2). In Eucumbene, this was the major cause of female predominance in the spawning population. It is unclear why proportionately fewer males matured in each year. Downstream trap recoveries of marked fish in 1969 found males to remain in the spawning stream for a much greater time (up to 46 days) than females (up to 25 days) and it is probable that males required a longer period to regain spawning condition. Also, Tilzey (1977) observed a high incidence of repeat spawning by females. Whereas Stuart (1953) conducted intermittent surveys of spawning brown trout in Scottish loch inlets and found males to predominate, it is possible that a longer period of stream residence by males inflated his observed male:female ratio (1.4:1). However, although cautioning against



* *Fish that returned on the same day were shared equally between the + and – 0-9 groups.*

Figure 6. Differences (days) in dates of capture/recapture for individual marked fish between (A) 1968-1969 and (B) 1969-1970.

Table 2. Annual brown trout percentage maturation per year-class, 1967/68 to 1969/70.

		1967-68		**1968-69**		**1969-70**	
Age*	**Sex**	**No.**	**% Mat'n**	**No.**	**% Mat'n**	**No.**	**% Mat'n**
3	**M**	132	12.8	86	16.3	180	30.0
	F	139	10.1	66	18.2	172	31.4
4	**M**	87	27.6	64	34.4	62	74.2
	F	94	71.3	90	83.3	86	95.4
5	**M**	46	43.5	78	46.2	42	71.4
	F	47	87.3	76	94.4	62	90.3
>5	**M**	43	34.9	48	37.5	26	69.2
	F	41	65.8	46	69.6	21	90.5
Total All	**M**	308	24.7	276	32.6	310	47.7
	F	321	46.4	278	68.7	341	61.9
Total >3	**M**	176	33.5	196	38.8	130	72.3
	F	182	74.2	212	84.4	169	92.9

* *Age (years) at spawning.*

possible sampling bias, Stuart (1953) also observed that a greater proportion of female (49%) than male (33%) fish in lentic angling catches were immature fish.

Percentage maturation was also linked to lake level and consequent food availability. In 1967-68, the lake was at a low level (67.3 m depth at dam wall on 1 May '68) following a prolonged drought. In 1968-69, the lake began to rise (81.3 m on 1 May '69) and in 1969-70 surpassed its previous highest level and inundated new ground, reaching 87.4 m on 1 May '70. Thus food availability improved over the study period, particularly in 1969-70 when drowned terrestial invertebrates were a major dietary component. Mean fish condition (K) rose over this period (Tilzey – unpublished data), as did percentage maturation values (Table 2). It is clear that annual percentage maturation in brown trout can vary markedly between years, depending on environmental conditions. In 1969-70, the proportionate increase in male percentage maturation was greater than that for females (Table 2) and the female:male ratio during the 1970 spawning run (1.5:1) was the lowest observed. Because of the diluting effect of 2+ year-old (3 at spawning) fish in overall percentage maturation values, comparisons between years are best made between fish aged >3 years (Table 2).

Unlike Great Lake, Tasmania, where brown trout aged 5 years or more were the dominant spawning age group (Davies and Sloane 1987), 4 year-old fish constituted the most abundant spawning age-class in Eucumbene, followed by 5 year-olds in 1968 and 1969. The high lake levels during 1969-70 also resulted in increased lentic survival by the 1967 year-class (Tilzey – unpublished data) and 3 year-olds outnumbered 5 year-olds in the 1970 spawning run. Also, a small number of 2 year-old males occurred for the first time in 1970. The total number of fish in the 1970 spawning run was 23% greater than in 1969.

Although being geographically isolated for over a century, both Eucumbene and Great Lake brown trout are thought to stem from a common genetic stock. However, the mid-May to mid-August timing of Eucumbene brown trout spawning runs was much later than the March to June observed in Great Lake (Davies and Sloane 1987). There was also no temporal isolation between brown and rainbow trout spawning runs in Eucumbene, with an overlap occurring during mid-July to mid-August. This difference in the overall timing of brown trout spawning is probably associated with day length as Great Lake (42°S) lies about 660 km south of Eucumbene (36°S). Both lakes are at similar altitudes (GL – 1033 m, E – 1164 m above sea level) and experience similar climatic regimes. The overall timing of brown trout spawning runs in another Snowy Mountains impoundment, Lake Jindabyne, is similar to that for Eucumbene.

During the 3 year study period there was an overall shift towards earlier spawning by brown trout. Again, this was probably associated with rising lake levels and the consequent increase in trout growth and condition. When the Lake Jindabyne basin was first being inundated during 1967-69, the high availability of terrestial food items led to very rapid growth by trout therein (Tilzey – unpublished data). In 1968 and 1969, many maturing brown trout were observed to enter the major spawning stream, the Thredbo River, well in advance (February onwards) of the normal spawning season. Anecdotal evidence from anglers who fished Eucumbene during its initial inundation phase indicates that "summer-runs" also occurred during this time. With both the Great Lake (Davies and Sloane 1987) and Eucumbene spawning runs, the mean size and condition of brown trout declined as the spawning season progressed. Comparatively well-conditioned fish tended to run earlier than those in poorer condition. Stuart (1953) noted that the 1951 spawning runs of brown trout from the lochs under his observation were later than the preceding year following a severe winter and the consequent poor condition of fish in spring.

Temperature is considered to be an important stimulus for salmonid spawning migrations (McKeown 1984), although Munro and Balmain (1956) found no association between water temperature and brown trout spawning migrations in Loch Leven. Davies and Sloane (1987) found brown trout spawners in Great Lake to prefer migrating within a defined water temperature range (6-10°C) and consequently flagged temperature as a major migration stimulus. However, no relationship between water temperature and fish movement was observed for Eucumbene fish. Moreover, most brown trout migrated when water temperatures were <6°C. The higher water temperatures recorded during the Great Lake spawning run were largely attributable to the earlier spawning season. Although the seasonal water temperature regimes for Great Lake and Eucumbene are similar, the later Eucumbene spawning season saw brown trout migrating at lower water temperatures than those prevailing for Great Lake spawners. The similarity between the respective seasonal temperature regimes and the difference between spawning times indicates that temperature does not influence the timing of the maturation cycle, which is probably governed by day length.

Davies and Sloane (1987) found no relationship between stream flow and brown trout movement in Great Lake. However, in Eucumbene there was a strong positive correlation between fish movement and stream flow (Figures 3, 4 and 6) and increases in stream flow, or some change in water quality associated with increased flow, appeared to be the major migration stimulus. Both Stuart (1953) and Munro and Balmain (1956) found positive correlations between stream flow and brown trout spawning migrations in Scottish lakes, as did Alabaster (1970) for sea trout migrations. Because Davies and Sloane's (1987) study stream was a canal draining a regulated reservoir, the flows therein were generally high, subject to little variation, and only loosely associated with rainfall events. This was probably the reason why there was little correlation between stream flow and brown trout movement in Great Lake. Dedual and Jowett (1999) studied the movements of radio-tagged rainbow trout spawners in another regulated stream, the Tongariro River in New Zealand, and found that, although there was considerable variation in movement between fish, mean upstream movement decreased with flow. They noted that, in larger rivers like the Tongariro, the ability of fish to migrate upstream is not dependent upon flow and the relationship between flow and movement may be less defined than in smaller streams.

There was an overall shift to earlier spawning by Eucumbene brown trout over the period 1968 to 1970 and intra-annual temporal differences in migration events in the study stream. However, the similarity between the majority of repeat-spawning dates of marked fish in 1969 and 1970 (Figure 6) indicated that an underlying, innate mechanism influenced migration timing. It has been demonstrated that the time of spawning in salmonids is highly heritable (Leider *et al.* 1984; Stefanik and Sandheinrich 1999). In Eucumbene brown trout, an inherent migration cue appeared to largely over-ride local environmental migration stimuli. Tilzey (1977) demonstrated a high degree of reproductive homing by brown trout in Swamp Creek and hypothesised that this could be leading to partial reproductive isolation. Stefanik and Sandheinrich (1999) found stocked and wild brown trout in Wisconsin streams to exhibit different spawning times. The occurrence of distinct spring, summer and autumn spawning runs within common genetic stocks of Pacific and Atlantic salmon species has been documented by many authors (e.g. Teel *et al.* 2000). With salmonid species, the most important environmental cue influencing the timing of reproductive migrations is probably day length. For example, fish hatcheries commonly manipulate salmonid reproductive cycles by using artificial photoperiod methodology.

Although there are strong similarities between the compositions of brown trout spawning runs in Great Lake and Eucumbene, this study demonstrates that there are differences in the timing of spawning migrations between Tasmania and the Australian mainland. Whereas some local environmental factors undoubtedly influence migration periodicity in each of the populations studied, the major factor is probably an inherent response to day length.

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Environmental determinants of the movement and migration of juvenile southern bluefin tuna

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Abstract

Southern bluefin tuna (SBT) are among the most highly migratory of teleosts. Adults are thought to make spawning migrations each year from feeding grounds in the southern Atlantic, Indian and Southern Oceans to spawning grounds south of Java in the tropical Indian Ocean. From the spawning grounds juvenile SBT are thought to migrate south along the Leeuwin current reaching the south west coast of Western Australia within a year. At this point the majority head into the Great Australian Bight (GAB), where they spend their summers for the next 3-4 years. Through a large-scale archival tagging experiment we have been studying the movement, behaviour and physiology of 2-5 year old SBT, in the GAB, and during their winter migrations to oceanic waters in the Indian Ocean and the Tasman Sea. The data collected by the 75+ tags returned to date have provided new insights into cues for migration, short-term and seasonal changes in behaviour, and the links between behaviour, movement and key environmental factors.

Introduction

As one of the most highly migratory of all teleosts, southern bluefin tuna (*Thunnus maccoyii*) (SBT) are well adapted to moving quickly both on small and large scales. Their capacity for rapid and sustained swimming, combined with an ability to thermo-regulate (and thus operate efficiently over a wide range of water temperatures), allows them to dive from the surface to depths in excess of 1000 m in a matter of a few minutes and at the same time range broadly within areas in which they are feeding.

Thus, when one begins to examine the data on movement and patterns of abundance of SBT for clues as to the environmental determinants of movement and migration, it is immediately apparent that on the one hand they are plastic in their tolerance of different environments, but at the same time they are able to actively respond to environmental dynamics, i.e. they can make the most of a chosen habitat, but can also quickly move out of it if it is not suitable and search widely for new habitats.

Despite the value of the SBT fishery, and considerable research on the species over three decades, we have only recently begun to understand the environmental preferences and feeding ecology of SBT, and the physiological and biological constraints on movement. Our understanding comes through two areas of research. First, we have begun to examine the relationships between SBT abundance and physical and biological oceanography, on both large and fine scales (Young *et al.* 1996a; Lyne *et al.* 1997). Second, we have used archival tags (Gunn *et al.* 1994) to examine the movement, behaviour and physiology of 2-6 year old juvenile SBT. These complementary areas of research have provided the first insights into the links between feeding/trophic ecology, behaviour, fish abundance and large scale physical processes.

In this paper we discuss three examples of the links between movement and environmental variables, on localised to inter-ocean spatial scales, using archival tag and ship-based ocean monitoring.

1. Ontogenetic shifts in the distribution of SBT and their relationship to physiological constraints

The ability of SBT to maintain core temperatures significantly above ambient (Wotherspoon and Gunn submitted) is thought to be an adaptation that increases muscle efficiency, particularly at low temperatures (Carey *et al.* 1971; Graham 1975), and reduces the time taken to digest food. In performance terms, it means that SBT are able to operate effectively over a wide range of temperatures; make sustained deep dives into cold water; and digest meals quickly to provide maximum benefit when food resources are plentiful. The thermoregulation is provided by a *rete mirabile* – a system of inter-digitated veins and arteries that operate as a counter current heat exchanger (Wotherspoon and Gunn submitted). As the ability to conserve (and hence regulate) heat is related to the ratio of volume: surface area of the skin and gill surfaces, larger fish are able to operate efficiently in much colder temperatures than small fish. Thus, the relative ability to cope with cold water has a major influence on the distribution and movement of SBT as they go through their development.

As in most of the *Thunnus* species, SBT spawn in the tropics. Thus, over the first three months or so of life, SBT are "tropical" in their distribution, and live within the mixed layer in water temperatures of 25-30°C. Between three months (approx. 300g) and one year of age (3-4 kg) they move with the flow of the Leeuwin current down the west coast of Western Australia. With the southward migration, their environment becomes progressively more sub-tropical. However, as a rule, SBT of less than one year of age are rarely found in water temperatures of less than 18°C.

Between ages one and six they grow from 3 to 30 kg, and with increasing size comes an ability to withstand colder temperatures. From archival tag data we know that after spending summer in the warm (17-21°C) waters of the Great Australian Bight, 3-6 year-olds make large-scale winter migrations into the Indian Ocean and Tasman Sea. These migrations are generally at latitudes between 30 and 40°S, in surface water temperatures of 12-18°C. With increasing size fish also have the capacity to dive to greater depths (and colder temperatures). Four-year-old SBT spend up to 12 hours a day at depths in excess of 300 m and water temperatures of 7-8°C.

SBT of 6-40 years of age (30-220 kg) are widely distributed at latitudes 35-50°S throughout the southern Indian, Atlantic, west Pacific and Southern Oceans. With a low surface area: volume ratio, larger fish are capable of living at much lower temperatures than the 1-6 year-olds and, for the bulk of the non-spawning season, they are most abundant where sea surface temperatures are 8-12°C. In these areas, when diving to depths of 300-500m, these fish will experience temperatures of less than 4°C. Quite remarkably, the mature fish that spend most of their year in these temperate/sub-Antarctic waters also make large-scale migrations back to the spawning grounds south of Java in the NE Indian Ocean, where they will experience surface water temperatures in excess of 30°C. It seems likely that at these temperatures the adults would need to "dump" heat that in cold waters would be used to warm the body/brain and viscera. They would do this by opening up the *rete* and allowing as much blood to flow across the gills as possible. Although we have no data to indicate that it is happening, it also seems likely that these large fish may use deep dives to minimise heat build up, in the same way bigeye tuna do in the tropics (Holland *et al.* 1992).

2. Thermal fronts: barriers to SBT movement or aggregation foci?

In the Tasman Sea, off the east coast of NSW and Tasmania, both juvenile and adult SBT aggregate close to defined thermal fronts, where sub-Antarctic water meets sub-tropical water transported south by the East Australian Current (EAC). In these areas fishermen can set longlines across a front to catch yellowfin tuna on the warm side and SBT on the cold side. Lyne *et*

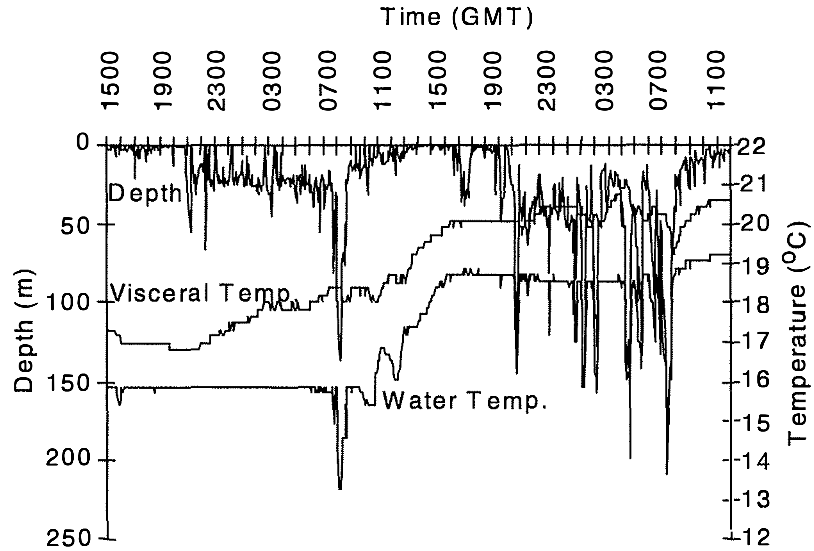

Figure 1. Archival tag data from a 100 cm LCF southern bluefin tuna swimming in the vicinity of a warm-core eddy on the east coast of NSW during May 1996.

al. (1997), on the basis of catch data from Japanese longliners that have operated off south-eastern Australia since the 1970s, showed that SBT appear to have a defined thermal preference in this area of 15.2-16.4°C, whereas yellowfin prefer waters > 17.5°C (Block *et al.* 1997). Bigeye tuna are also known to have thermal and oxygen preferenda (Holland *et al.* 1992).

Since 1994, archival tag data from juvenile SBT have provided a wealth of information on the behaviour of fish when they are associated with thermal fronts. From these data it is clear that SBT move freely across fronts. Figure 1 shows a 44 hour time series of diving, water temperature and visceral temperature in a 100 cm LCF fish that swam in and around a very pronounced frontal system off the southern NSW coast, in May 1995. These data indicate that the fish began digesting a small meal at approximately 2130 h GMT on the first day (0730 h local time – dawn), while in cold water. The feeding is indicated by the steady increase in visceral temperature beginning at 2130. At approximately 0930 GMT on the second day (1930 local time), the fish began to cross a significant front; by 1530 GMT (0130 local time) it had reached the warm core of the eddy. The fish's diving behaviour changed significantly as it moved from the "cold" to the "warm" side of the front. For the first 16 hours of this period, the fish swam in the upper 50 m of the mixed layer on the cold side of the front, in water temperatures of 15.8-16.0°C. At around 0700 GMT (1700 Local Time), the fish made a spike dive to approximately 130 m. Spike dives are very common at first and last light, irrespective of habitat, water temperature or location. Returning to the surface after the spike dive, the fish stayed in the upper 30 m for six hours while traversing a 16-19°C front. For the next twelve hours the fish made regular dives to depths up to 220 m in the warm pool of water. Despite the significantly deeper dives on the warm side of the front, the fish rarely experienced temperatures of less than 16°C. Thus, by moving into the warmer waters the fish appears to have increased its foraging depth range.

Behavioural thermoregulation has also been reported for bigeye tuna (Holland *et al.* 1992; Holland and Sibert 1994), which have a far more primitive and less efficient *rete mirabile* than SBT. Bigeye undertake diel migrations to depths over 500 m, following the diurnal migrations of squid and the deep scattering layer. During the day they routinely spend extended periods in water temperatures of 10-13°C, while the surface temperature may be as high as 30°C. Holland *et al.* (1992) found that the migration into cold water results in a slow but significant decrease in the temperature of the muscle. When the muscle temperature reaches 16-17°C, bigeye swim back up into warm waters of the mixed layer to warm up. By switching the operation of the *rete*, bigeye are able to conserve heat while swimming in cold water, allowing them to stay in their foraging zone for extended periods, and then heat up quickly in the warm waters, allowing them to quickly return to the foraging zone. It is our hypothesis that when they are in the frontal systems in the Tasman Sea, SBT are using the warm core eddies and sub-tropical sides of fronts as a thermal refuge, allowing them to feed in the colder, more productive sub-Antarctic waters while minimising the energetic costs of keeping warm.

3. Trophic dynamics and movements from oceanic to shelf habitats

Not only do southern bluefin tuna respond to differences in water mass structure in oceanic waters but there is evidence of movements between inshore and offshore waters where a combination of good feeding grounds and a thermal refuge present themselves in close proximity. Off eastern Tasmania, a predominantly northward-flowing current of cool subantarctic origin water along the continental shelf, and shelf break upwelling, in autumn provides a source of highly productive water (Harris *et al.* 1987). This source supplies the foundation for a "classic" food chain generally considered necessary to attract larger predators such as tuna (Cushing 1989). Massive concentrations of the euphausiid *Nyctiphanes australis*, particularly in autumn, provide a ready source of feed for jack mackerel *Trachurus declivis*, one of the main prey of southern bluefin tuna in these waters (Young *et al.* 1993). Offshore, the southern extremity of the EAC, itself derived from oligotrophic Coral Sea water, can be as much as 8°C warmer than inshore waters but has relatively little in the way of potential feed when compared to inshore shelf waters (Young *et al.* 1996a, b). A comparison of the diet of southern bluefin tuna caught on the shelf with those caught offshore showed those on the shelf to be full of jack mackerel, redbait (*Emmelichthys nitidus*) and juvenile squid (*Nototodarus gouldii*). In contrast, those caught offshore had relatively little food, and different prey species (e.g. the pelagic amphipod *Phronima sedentaria*), in their stomachs. Further, the daily rations of the inshore-caught tuna were three times higher than those caught offshore suggesting that the shelf is an important destination for tuna on their eastward migration (Young *et al.* 1997). The indication was that the tuna were travelling between these two areas fulfilling the dual needs of a plentiful food supply and a thermal refuge. During the period of these studies, a southern bluefin tuna, which had been tagged with an archival tag (Gunn *et al.* 1994) the previous year in the Great Australian Bight, and had spent a number of months off eastern Tasmania, was recaptured. The recapture and subsequent analysis of the data recorded on that tag gave us the opportunity to test whether the tag data supported the perception that SBT moved between inshore and offshore waters off eastern Tasmania.

During May 1994 the thermal structure of the waters off eastern Tasmania showed a mixed layer of ~13°C water to approx. 100 m on the shelf, a shelf-break front of 1°C with the warm (~15 – 16°C) EAC filament to the east (Figure 2). A thermocline was present offshore at ~ 180 m. We compared this cross section with temperature/depth profiles of the fish at different times during the same month when we knew the fish was in the same area. Data from two different days during the month show the main differences. The first, on 11 May 1994, shows the fish swimming in waters mainly between 15 and 16°C with occasional forays to a depth of 180 m (Figure 3a). The second, on 26 May 1994, shows the fish swimming in waters between 13 and 14°C to a maximum depth of 120 m (Figure 3b). These profiles are consistent with the fish spending time firstly in the EAC filament (11 May) and occasionally descending below the thermocline into colder <13°C waters. The second profile (26 May) shows that the fish spent the whole day over or just off the continental shelf. The combination of these data reinforce the original hypothesis that these fish are moving between the East Australian Current and the cooler, more productive inshore waters, presumably to feed.

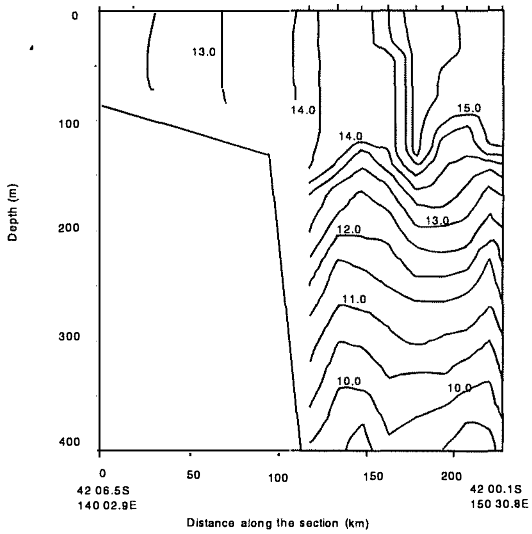

Figure 2. Vertical cross section along 42 degrees South from the continental shelf off eastern Tasmania to 100 kilometres offshore.

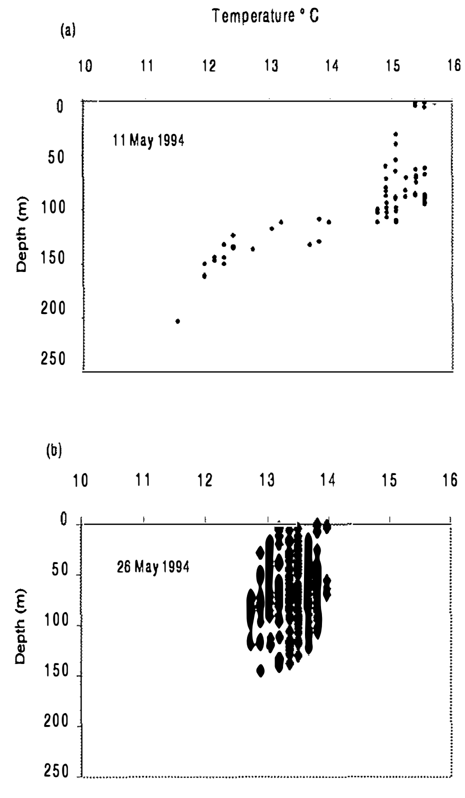

Figure 3. Temperature depth plots for a southern bluefin tuna tagged with an archival tag off eastern Tasmania on (a) 11 May 1994 and (b) 26 May 1994.

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Overcoming physical barriers to fish migration

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Abstract

Recent inventories have identified more than 7 000 dams and weirs along the east coast of Australia, all of which are potential barriers to fish movement. In addition, not generally recorded were the large numbers of relatively minor instream structures such as culverts and fords.

Most native fish are unable to leap, many migrate as juveniles with relatively poor swimming capabilities, and some species are reluctant to enter dark areas such as pipes. Almost any area with a vertical spill of water, high water velocities, shallow depth or lacking in light can prevent or delay fish movement. This may lead to increased predation, loss of breeding opportunities and in some cases the local extinction of fish species.

For dams and weirs a number of fishway designs, including rock-ramp, vertical slot, denil, bypass channel, and fishlifts have been installed with varying degrees of success. Further refinement of existing designs along with design guidelines to provide for fish passage at small structures such as stream gauging stations and culverts are required.

It is critical to the success of any fishway works programme that, in addition to the hydraulic, engineering and financial constraints of any works, all designs take account of the biological requirements of the species present. At present much of this information is lacking, and further research is required into the biology and behaviour of fish, particularly with respect to the use of existing fishways and their behaviour at other barriers. It is essential that engineers and biologists work together to formulate appropriate designs.

Introduction

All Australian native fish need to move along the streams they inhabit. Instream structures can form barriers that restrict this movement. The most obvious and dramatic impact is the exclusion of migratory fish moving to or from habitat essential for completion of their life cycle, such as spawning grounds in estuaries or headwaters. Barriers also reduce the diversity and abundance of accessible freshwater habitat, and change community composition by excluding migratory species and reducing recolonisation opportunities following events such as drought and floods. Instream barriers may also lead to increased risk of disease and predation by birds, other fish species and anglers along with genetic isolation of populations. Fish moving downstream may also be affected. For example, larvae washed into dams can become disorientated and end up in unsuitable habitat, or just not reach their downstream destination. Fish can be injured on spillways or concrete and rock sills, and on passing through turbines.

Most native fish are unable to leap, many migrate as juveniles with relatively poor swimming capabilities and some species are reluctant to enter darkened areas such as pipes. Any vertical or steep spill of water, area of high water velocity, shallow or dark area such as within a culvert, can prevent or delay fish movement. The growth of agriculture and other developments has resulted in the construction of various instream structures which have the potential to impede essential fish movements.

Extent of the problem

Recent studies (Jackson 1997; Leader and Smit 1997; Pethebridge *et al.* 1998; Department of Natural Resources and Environment 1999) have identified over 7 000 instream structures in New South Wales, Victoria and the Queensland reaches of the Darling River, all of which are potential barriers to fish movement and migration. These include dams and weirs, flood and erosion-control structures and tidal barriers. Not generally recorded were the large numbers of relatively minor instream structures such as culverts and fords. In addition to these, a further 150 instream structures are being constructed annually on Victorian streams alone (Bennett 1997).

In south-eastern Australia, from the Mary River in Queensland to the Gippsland Lakes system in Victoria, an average of 35% of the total smoothed valley length was upstream of physical barriers to fish migration. In some cases up to 95% of the system was upstream of a barrier (Marsden *et al.* 1997).

Given this prevalence of artificial barriers combined with the need for many fish species to migrate, it is understandable why instream barriers are often identified as a significant factor in fish population declines.

Consequences of restricted fish movement

The effect of a particular structure on fish populations is dependent on factors including the species present, their swimming abilities, the height and design of the structure and the frequency and timing of floods that may inundate the structure and hence permit fish movement. Some structures may be passable by fish that are adept swimmers or able to climb, yet completely restrict other species. Any impacts will be further compounded by factors such as reduced water quality, water temperature differentials (thermal barrier), de-snagging and altered flow regimes (O'Brien *et al.* 1999).

In Victoria, 60% of the coastal, and at least 17% of the Murray-Darling Basin, species of native freshwater fish, including a number of threatened species (Conservation and Natural Resources 1995) are considered migratory (White and O'Brien 1999). The loss of diadromous species above many dams in both coastal and inland waters has been cited (Harris 1986; Koehn 1986; Scientific Advisory Commitee 1993) as examples of local extinctions due to impeded fish movement, while free access along streams of the Murray-Darling river system is considered important to help ensure the long-term survival of the 14 migratory species present in this region (Mallen-Cooper 1989). In summary, for south-eastern Australia, over 40% of freshwater fish species 'make large scale movements or migrations that are essential for the completion of their life histories' (Mallen-Cooper and Harris 1990).

Options for providing for fish movement

It is preferable to design and build instream structures in a manner that inherently provides for fish passage. Where existing structures are to be modified however, or where it is not practical to modify the design of new structures to provide for fish movement, it will be more appropriate to install some type of dedicated fishway. The decision as to how best to provide for fish passage will be based on a number of site-specific factors such as the fish species present, site topography, flow characteristics and cost effectiveness (Lewis *et al.* 1999).

Large dams and weirs require a fully-engineered device such as a fish lift or a vertical-slot fishway to facilitate fish movement. The cost involved in constructing such fully-engineered fishways can be hundreds of thousands of dollars each, and when the number of potential barriers is considered, it is unrealistic to expect that a very high proportion of the existing barriers could be addressed immediately. The need exists for low cost-effective design to be made available. Some potential solutions for reducing the impact of instream barriers to fish movements through lower cost designs are discussed here, with particular emphasis on the rock-ramp fishway and bypass channels.

Culverts

Culverts can impede fish passage due to any of the following reasons:

- Occurrence of high water velocity due to the relatively smooth surface of the culvert surface, the constriction it imposes on the channel section or the culvert gradient;
- the lack of resting areas upstream or downstream of the culvert. These allow the fish to both conserve energy before upstream passage and to rest upon completion of passage;
- there being insufficient water depth for fish to swim in the culvert. The minimum depth required for swimming varies with the fish species;
- the culvert is too long and provides no respite from the relatively high velocities in the culvert. Depending on the swimming abilities of thspecies in relation to water velocities and distance, the length of culvert can become critical;
- the outlet of a culvert is at or above the streambed elevation (perching), or scour has lowered the streambed downstream of the culvert outfall creating an artificial barrier to fish; and,
- darkness as some species appear reluctant to move into dark areas (Mallen-Cooper 1989).

Guidelines exist for the design of culverts that will provide for fish passage in most situations (O'Brien 1996; Cotterell 1998; NSW Fisheries 1999). The recommended design modifications will often increase the cost of culvert construction, potentially to a level that would make the installation of a bridge (preferred from a fish perspective) viable.

Rock-ramp fishway and fish bypass design

A number of designs for rock-ramp fishways have recently been trialled in Victoria and NSW at gradients from 4.0-6.6%. A relatively steep (gradient 6.6%) fish bypass design first used on a low (<0.7 m) tidal barrage on the Barwon River in Victoria (O'Brien 1997) has been highly successful at passing small migratory coastal species of fish. Further installations, generally at a lower gradient than the Barwon site, along with several partial and full-width rock-ramp fishways have since being installed on Victorian coastal streams. Due to their irregular nature, rock-ramp fishways and bypass channels provide a range of alternative water velocities and depths to cater for differing behaviour of fish negotiating a barrier (Newbury and Gaboury 1993; O'Brien 1995). These designs are not considered appropriate where larger fish are expected to require upstream access but are more generally appropriate for coastal and upland streams. Where adequate flows prevail, there is potential to modify these designs for use in inland systems for use by larger fish species.

A modified, more formal design of rock-ramp such as proposed by Newbury and Gaboury (1989) has been trialled in NSW at a gradient of 5%. Survey results from various sites indicate that these fishways were able to pass small (generally <180 mm)-sized fish, however larger fish found below these structures did not appear to move upstream (Thorncraft and Harris 1997). The authors proposed that the reason for this was that larger fish may not have the intense migratory drive of juvenile and sub-adult native fish and that larger fish may pass during periods of high flow (Thorncraft and Harris 1997). Bypass channels are likely to be suitable for use by larger species as water depth, turbulence and velocity conditions are likely to be more favourable than would occur in a rock-ramp fishway.

Bypass channels, as used in several European sites to circumvent obstructions with near-natural stream channels, are characteristically of gradients less than 5% (Gebler 1998). Some channels described had gradients as low as 0.8% (Steiner 1998). However Parasiewicz *et al.* (1998) propose that gradients as low as 0.05% may be appropriate for some lowland river reaches. Costs for channels even at a gradient of 0.8% (i.e. 125 m long for every metre of weir head) may be prohibitive in all but sites having appropriate topography and access.

Further investigation and perhaps design refinements such as the less formal rock layout and provision for riparian transition zones as outlined by Gebler (1998) may lead to the ability to confidently design and construct cost-effective fishways for larger inland native species.

Alternatives to fishway construction

In some instances modifying the operating procedures at regulating structures can provide for or enhance the frequency of fish passage. This is achieved by opening gates more frequently and for longer durations, especially when this is timed to coincide with periods of fish movements. Flow regulation and controlled releases from upstream storages can also be designed to inundate low-level weirs to allow fish passage. The use of several small structures which are passable by fish, rather than a single large weir or regulating structure may reduce the net impact on fish passage while still achieving the original purpose of the works (Newbury and Gaboury 1993; O'Brien *et al.* 1999).

Biological and behavioural considerations

It is critical to the success of any fishway works programme that in addition to the hydraulic, engineering and financial constraints of any works, all designs take account of the biological requirements of the species present. At present much of this information is lacking, and further research is required into the biology and behaviour of many fish species to determine burst and sustained swimming capabilities, direction and periods of movement on both a seasonal and diurnal basis, the use of existing fishways, behaviour at other barriers or within weir pools and the influence of factors such as flow regime and the operation of irrigation/regulation schemes on movement and passage past instream structures. It is essential that engineers and biologists work together to formulate appropriate designs.

Conclusions

Provision of fish passage is an important aspect of stream rehabilitation. Installing fishways onto existing structures is often necessary to re-create migratory pathways, and new structures on streams should be built either to inherently provide for fish passage or be installed with a fishway. Ensuring that migratory pathways for native fish are uninterrupted should be a key component of any stream rehabilitation initiative, and obtaining more basic information on fish swimming abilities and behaviour should be a priority for stream rehabilitation research. Fishway designs must be appropriate for the species present, and have the entrance location and operating range optimised for critical upstream migration periods. To achieve this, it is critical that fishways be designed through collaboration between a fishway biologist and the project engineer. The engineer will need to assess a number of site-specific factors including the impact of a fishway upon the structure's main purpose, discharge required to effectively operate the fishway, erosion prevention and site geology and topography.

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Sampling to detect the impact of barriers on fish movement

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Abstract

With the recognition of the detrimental impacts of dams and weirs on native fish populations and the increased interest in fishways in Australia, there has been growing impetus to ensure river regulation agencies are responsible for mitigating the effects of their structures. Before committing considerable sums of money towards the construction of a fishway these agencies often require scientific evidence that the structure is having a measurable impact on migratory fish communities. To date there have been few studies in Australia which have scientifically demonstrated the impacts of construction of instream barriers on migratory fish communities. Most impacts have been identified from anecdotal evidence provided by ad hoc *surveys or angler reports. However, recent studies have refined these earlier efforts using better sampling technology and methodology to show the impacts that weirs and dams are having on the fish communities of the target river systems. Utilising backpack and boat-mounted electro-fishers to effectively sample the whole fish community above and below impacting structures has enabled us to show convincingly to the operator that there is a requirement for some form of mitigating fish passage device. An outline of the sampling design, techniques and results from studies on the Shoalhaven (NSW), Pioneer and Burdekin Rivers (QLD) indicates the success of this type of study to identify the impacts of dams and weirs.*

Speaker did not submit a full manuscript.

Characteristics of movement of adult King George whiting *(Percoidei: Sillaginidae)* in South Australian waters

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Abstract

In South Australia there are numerous historical tag/recapture databases of movement information for King George whiting (Sillaginodes punctata). *These indicate that patterns of movement varied between locations. Fish from Gulf St. Vincent moved southwards up to several hundred kilometres, but those from the south moved shorter distances, and showed no systematic directional displacement. Consequently, population size and age structures varied systematically throughout the fishery area. Fish moved from shallow areas dominated by seagrass meadows to deep offshore reefs and shoals, where spawning occurred. Consequently, adult movement is an obligate process in the life history, which ultimately sustains the populations in these spawning localities. The human activity most likely to impact on this process is fishing. As fish move southwards they must run the intensive fishing 'gauntlet' targeted at their capture. Estimates of fishing mortality on the small, young adult fish are very high. Consequently, management must focus on ensuring sufficient escapement from the northern localities to sustain the populations on the spawning grounds.*

Introduction

The adults of many species of marine fish are capable of substantial movement, which constitutes a significant obligate step in their life history (Wise 1963; Miller *et al*. 1984; Hilborn 1990). Such movement may represent seasonal or annual migrations, where fish spend part of the year in some places, associated, for example, with feeding, and then move to spawning grounds (Miller *et al.* 1984; Shimada and Kimura 1994). There is also movement associated with ontogenetic development where, as fish develop, they move to different places presenting habitats more appropriate to the requirements of that life-history stage (Wise 1963; Hyndes *et al.* 1998). In both cases completion of the life history and replenishment of the population through reproduction depends on successful fish movement.

Fishery managers and biologists need to understand the particular patterns of movement of adult fish:

1. because movement constitutes a significant process in the life history of the species which influences the spatial scale over which the life history works, thereby relating to issues of stock structure;
2. to assess the interaction between fisheries in different locations; and
3. to define the discreteness of stocks (Hilborn 1990).

The King George whiting (*Sillaginodes punctata*) constitutes a significant fishery resource of southern Australia (Kailola *et al.* 1993). It is endemic to Australia where it is found throughout the inshore, coastal areas of the southern temperate regions. Fisheries exist in Western Australia, Victoria and South Australia of which the latter is the most significant producing on average approximately five times the

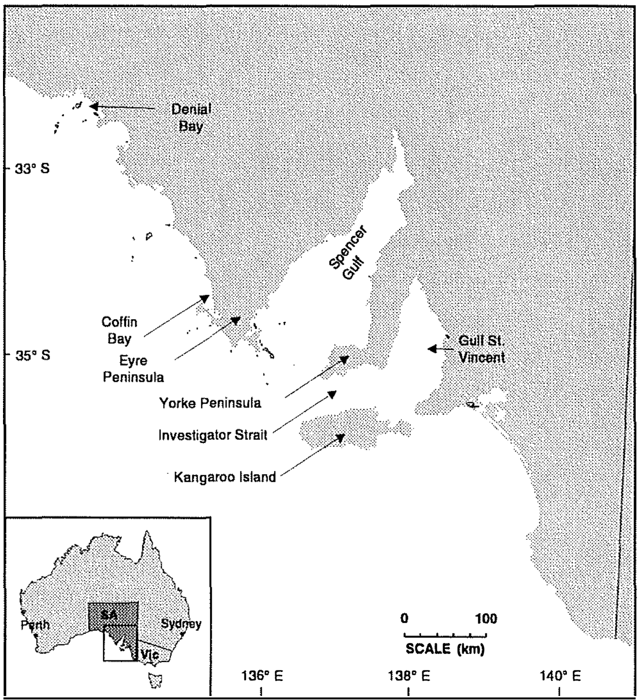


Figure 1. Map of part of South Australia showing the three fishery regions: Gulf St. Vincent, Spencer Gulf and the west coast of Eyre Peninsula, and other places referred to in text. Inset shows its position on the map of Australia.

biomass of the Victorian fishery and 20 times that of the Western Australian fishery. The productivity of this fishery may relate to the extensive fishable area between Gulf St. Vincent and Denial Bay (Figure 1). Throughout this area, the populations of King George whiting from different localities display different size and age distributions, which suggests that adult movement may be significant for this species (Fowler *et al.* in press). Also, in Western Australia post-larvae and juveniles occur in estuaries, whilst adults are associated with offshore limestone reefs at 6 – 50 m in depth, which suggests an association between offshore movement and ontogenetic development (Hyndes *et al.* 1998).

The most tractable method for determining movement patterns of adult fish is through tag/recapture programmes. For King George whiting in South Australia there is a considerable history of tagging studies which date back to the 1930s. Since the 1960s approximately 26 000 fish have been tagged from which there have been >2 500 recaptures (Table 1). In this paper the movement patterns of King George whiting, determined from these data, were assessed in the context of the Session theme of "Environmental determinants, barriers, and human interference". Consequently the specific objectives addressed were to:

1. describe patterns of movement of King George whiting;

2. present information on population structure and to relate this to the characteristics of habitat for the places from which and to which the adult King George whiting move; and

3. consider possible natural and anthropogenic impediments to fish movement.

Table 1. Summary of tag/recapture studies on King George whiting in South Australia since 1960.

Region	Period	No. tagged	No. recaptured	Useful recaptures
Gulf St.Vincent	1960s-80s	10 043	890	492
Kangaroo Island	1960s-80s	3 009	137	109
North Spencer Gulf	1960s-80s	>2 523	356	236
South Spencer Gulf	1970s-80s	3 263	129	99
Coffin Bay	1970s-80s	2 426	330	248
Mid-west coast	1960s	1 700	336	219
Denial Bay	1960s-80s	2 944	376	158
Total		>25 908	2 554	1 561

Materials and Methods

Of the >2 500 recaptures of King George whiting a total of 1 561 provided useful data for the analysis of movement patterns because these fish were at large for >30 days, and both the tag and recapture locations were sufficiently well identified to assign a latitude and longitude. The tag/recapture information for these 1 561 fish was entered into several ACCESS databases from raw datasheets or from historical LOTUS spreadsheets. The data were then imported into the MAPINFO GIS system. MAPINFO was used to calculate the displacement of each fish, i.e. the minimum net distance (around the coastline) between the tag and recapture locations. MAPINFO was also used to generate maps as visual representations of these displacements. Estimates of distances moved were then related to fish size and age, to determine which fish move, when, how far and where they move to.

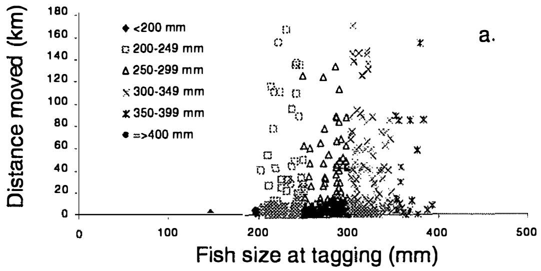
Results

Patterns of Movement in Gulf St. Vincent and Kangaroo Island

Although data on fish movement were available for several regions in South Australia, the dataset for only one geographic region is presented here as it incorporates the general patterns manifested at other places. In Gulf St. Vincent a total of 10 043 fish were tagged from which there were 492 useful recaptures (Table 1). For most, the distance between the tag and recapture sites was <20 km, although the remaining fish moved distances of up to 170 km (Figure 2a). There was little relationship between distance moved and size-at-tagging, indicating that fish tagged at the larger sizes (i.e. > 350 mm TL) moved similar distances to those tagged at smaller sizes (Figure 2a). However, there was an interactive influence of fish size and time-at-liberty on distance moved, i.e. those tagged in the size range of 200-249 mm TL were not caught more than 30 km from the tag site until several hundred days after initial capture (Figure 2b), by which time they would have grown much larger. Alternatively, some fish that were tagged when >300 mm TL were recaptured >160 km from the tag site, within only a few weeks of being tagged.

The net displacement of fish tagged in Gulf St. Vincent and that were at liberty for periods of 12 - 24 months are shown in Figure 3a. Clearly, fish moved considerable distances, and there was a systematic movement towards the south. Some fish left the Gulf, moved across Investigator Strait and were recaptured along the north coast of Kangaroo Island.

At Kangaroo Island, 3 009 fish were tagged in the north-eastern inshore bays. From these there were 137 recaptures, 109 of which provided useful data on



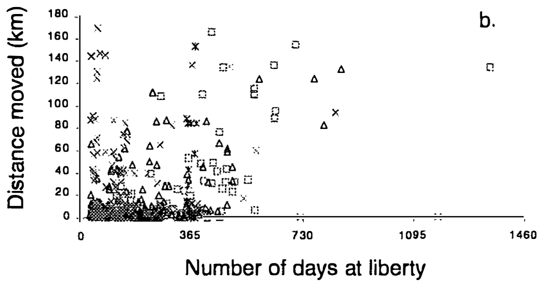
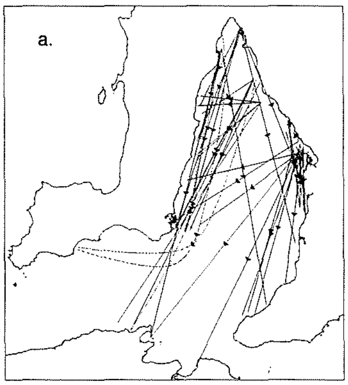


Figure 2. Characteristics of movement of fish tagged in Gulf St. Vincent. a. Relationship between distance moved and size at tagging. b. Relationship between distance moved and time at liberty - interpretation is based on the different size categories of fish at tagging, according to the legend.



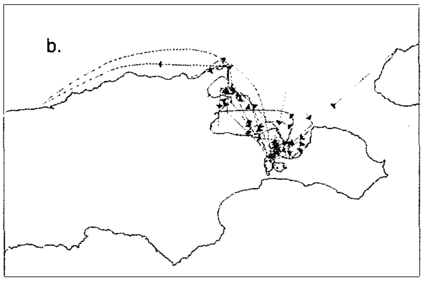


Figure 3. Maps showing the path of minimum net distance between the place where each fish was tagged and recaptured; arrowheads show the directions of movement. a. fish tagged in Gulf St. Vincent and at liberty for 12 - 24 months. b. fish tagged in the north-eastern bays of Kangaroo Island.

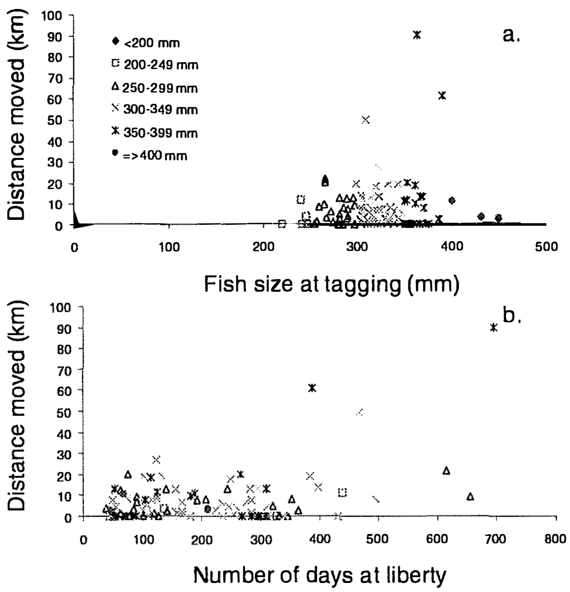


Figure 4. Characteristics of movement of fish tagged in the north-eastern bays of Kangaroo Island. Conventions as in Figure 2.

movement (Table 1). Despite many fish being at large for over one year, only three moved >30 km (Figure 4a). Of those that moved less than this, there was little relationship between distance moved and size at initial capture. Fish tagged at sizes greater than 350 mm TL were recaptured similar distances from tag sites to those tagged at smaller sizes (Figure 4a). Those greater than 250mm TL moved distances of up to 20 km within only a few months of initial capture. The three fish that moved the greatest distances were recaptured more than one year after tagging (Figure 4b).

All fish were initially tagged in the shallow north-eastern bays of the island, and most movement was restricted to within this relatively small area (Figure 3b). Of the three fish that moved farthest, two moved to the north-western coast of the island, whilst the third crossed back to the mainland. The movement of fish tagged at Kangaroo Island did not display the same systematic directional characteristics as those from Gulf St. Vincent.

Population structure and environmental correlates

There were substantial differences in size and age distributions between Gulf St. Vincent and Kangaroo Island. At the former locality, the fished population generally had a modal size of 32 - 34 cm TL, and >90% were in the 3+ age class (Figure 5). Alternatively, along the north coast of Kangaroo Island, fish ranged up to 50 cm in length, had a modal size of 38 - 42 cm TL and the age distribution included fish that were 3 - 15 years old. The contracted age structure from Gulf St. Vincent is consistent with fish moving out of this area, whilst the population structure at Kangaroo Island is consistent with the immigration and subsequent retention of fish.

The differential movement patterns also resulted in significant ontogenetic shifts in habitat use. The small, young adult fish taken from Gulf St. Vincent were generally associated with habitats that were shallow, relatively protected and supported extensive beds of *Posidonia* spp. and *Amphibolis antarctica*, where the fish are found in the patchy mosaic of seagrass and

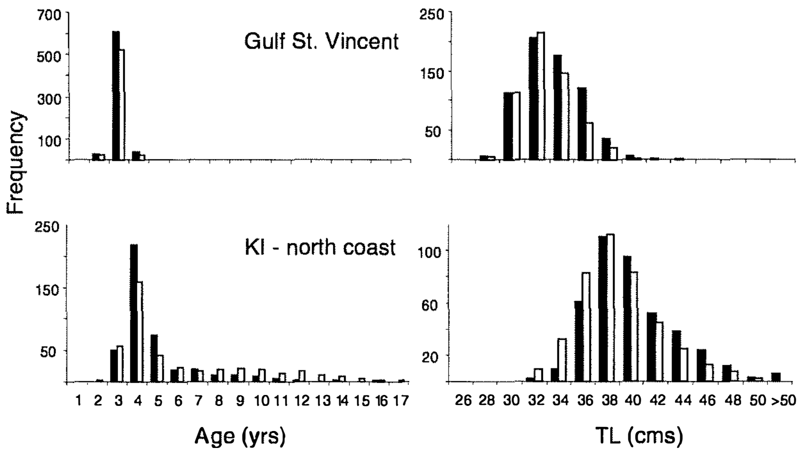


Figure 5. Age structures and size frequency distributions of King George whiting sampled from Gulf St. Vincent and along the north coast of Kangaroo Island (shaded bars, females; light bars, males).

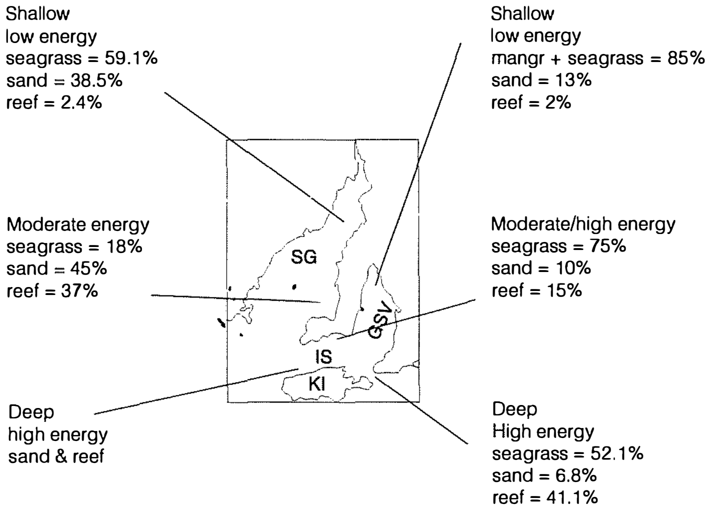


Figure 6. Habitat characteristics at several localities in Gulf St. Vincent, Spencer Gulf and Investigator Strait from Edyvane (1998). (KI – Kangaroo Island).

sand (Figure 6). However, the adult populations were associated with offshore reefs, shoals or large mounds, that occur in relatively deep water in exposed locations that experience medium/ high wave energy. There is also a significant interaction between population structure, reproductive maturation and habitat, since the few places where spawning occurs are those towards which the small, young fish move (Fowler and McGarvey 1997).

Natural and anthropogenic impediments to movement

The main fishing area in South Australia is divisible into three regions: Gulf St. Vincent, Spencer Gulf and the west coast, which are separated by the substantial land masses of Eyre and Yorke Peninsulas (Figure 1). Analysis of the tag/recapture information demonstrated little evidence of east/west movement between these three regions. Of the 1 561 recaptures

Table 2. Summary of F estimates obtained as 1/(mean time-at-liberty) for various tagging studies of King George whiting (from Fowler and McGarvey 1997).

Coastal Region	Years of tagging study	Recapture sample size	F
Ceduna	1966-68	160	2.3
Baird Bay	1966-68	121	2.1
Venus Bay	1966-68	132	1.8
North Spencer Gulf	1968-69	233	1.2
Ceduna	1979-85	53	2.0
Coffin Bay	1977-80	315	3.0
North Spencer Gulf	1977-86	80	2.3
South Spencer Gulf	1978-86	111	1.7
Gulf St Vincent	1978-84	120	2.5
Kangaroo Island	1977-85	131	1.9

from across the three regions, only five fish moved far enough in an east/west direction to move between regions: one fish moved from Gulf St. Vincent to the west coast; two moved from Spencer Gulf to the west coast; and two moved from Coffin Bay on the west coast to Spencer Gulf. Consequently, the two peninsulas may represent significant barriers to fish movement and thereby effectively divide the juvenile / adult populations into several discrete sub-population units.

The human activity most likely to disrupt the natural patterns of fish movement is fishing. Small fish first become vulnerable to fishing when they leave the nursery areas (shallow protected embayments), and move out into Gulf waters. Eventually, when these fish reach the size of 28 - 30 cm TL, they are capable of making substantial movements southwards. As they do so they must negotiate a substantial 'gauntlet' of commercial fishing nets and lines, as well as recreational lines in the nearshore coastal waters. Estimates of fishing mortality (F), calculated as 1/mean time-at-liberty, from tag/recapture information in all regions are high (Table 2). The fish that survive the fishing gauntlet in the Gulfs as they move southwards, ultimately replenish the populations of older, larger fish which occur in the southern, deeper, offshore places where spawning occurs.

Discussion

The analysis of historical tag/recapture databases from thousands of fish tagged in South Australia has provided a comprehensive understanding of the variation in movement patterns of King George whiting amongst different locations. Fish from the northern Gulf St. Vincent demonstrated systematic southward movement over distances approaching 200 kms. Alternatively, fish from more southern localities did not move far nor demonstrate the same systematic, directional displacement.

Such differential movement patterns had a significant effect on population structures. The fisheries in the localities from which fish moved were almost entirely single year-class fisheries, with the catch dominated by the 3+ age class. Locations to which fish moved, supported multi year-class populations. Such patterns of population structure are consistent with the emigration of fish from the former, and the immigration to and subsequent retention of fish by the latter locations.

The movement patterns also resulted in significant changes in habitat use. Movement was most evident for those fish approximately 28 - 30 cm TL, which primarily included the 3 - 4 year age classes (Fowler and McGarvey submitted). Their movement resulted in a substantial change in habitat use, moving from shallow, inshore areas that were dominated by seagrass meadows to deeper, offshore places that supported higher cover of reef habitat.

Most substantial movement by King George whiting in South Australia was primarily from north to south. There was little evidence of movement between any two of the three geographic regions of Gulf St. Vincent, Spencer Gulf and west coast, suggesting that Yorke and Eyre Peninsulas may present significant barriers to fish movement. Perhaps, also the southern parts of each Gulf present the appropriate habitat requirements for adult fish, and once they move into such areas have no need for subsequent movement.

The fishing pressure on the young immature fish in the northern parts of these Gulfs is substantial, as such fish are heavily targeted by both commercial and recreational fishers. Movement of such fish from these areas sustains the adult populations in the relatively small areas where spawning occurs. Consequently, management policies need to be put into place which allow enough escapement through this fishing 'gauntlet' from the northern areas to sustain such populations. Furthermore, since the spawning aggregations are still open to fishing, it is necessary to ensure that they are not overfished.

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Migration and assessment of glass eels (*Anguilla australis*) in the Snowy River System, South-Eastern Australia

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Abstract

Juvenile anguillid eels, known as glass eels, form the basis of important commercial fisheries in many parts of the world. The majority of glass eels are used as seedstock for aquaculture because the artificial propagation of anguillid eels is not yet technologically possible. Several environmental cues are thought to influence both the invasion of anguillid glass eels into estuaries from the sea, as well as their migration patterns within estuaries. An understanding of these environmental correlates may help to determine optimal fishing times to target peak glass eel invasion and migrations.

In the present study, the invasion of Australian shortfinned glass eels (Anguilla australis) *into south-eastern Australian estuaries was investigated for the purpose of characterising the primary environmental cues associated with such invasions and migrations. Glass eel assessment surveys were conducted in the Snowy River, south-eastern Australia, as part of a national glass eel assessment programme during the winter and spring of 1997 and 1998. Catch per unit effort (CPUE) was used to estimate relative abundance of glass eels. Several variables were examined for possible correlations with glass eel abundance including water temperature, salinity, stream discharge and tidal and lunar phases.*

CPUE of glass eels was highly variable between years. However, the results suggest that the migration of A. australis *glass eels occurs during discrete seasonal periods in the Snowy River, and that optimum fishing times can be identified using a range of environmental criteria including tidal and lunar phase, water temperature, stream discharge and salinity.*

Introduction

A commercial premium is currently being placed on the development of intensive eel culture technology throughout the world due to declining world fishery production of anguillid eels. The world aquaculture production of anguillid eels, mainly *Anguilla anguilla* and *A. japonica*, currently exceeds an estimated 130 000 tonnes per annum, worth approximately $US1.3 billion (Gooley *et al.* 1999). Most farmed eel production occurs in Asia, with annual production in China, Japan and Taiwan of 50 000, 35 000 and 34 000 tonnes respectively, and a smaller amount (approximately 10 000 tonnes) is produced annually in Europe (Gooley *et al.* 1999). Glass eels are preferred over other life stages as seedstock for aquaculture and, as the artificial reproduction of anguillid eels is not yet possible, glass eels must be obtained from the wild. Production from the glass eel fishery worldwide is highly variable but is currently in the order of 350-500 tonnes per annum in Europe (Moriarty 1996) and 100-150 tonnes in Asia (Gooley *et al.* 1999). Intensive eel aquaculture in Australia has recently received significant interest and investment, with a number of European-designed intensive eel culture systems being commissioned (O'Sullivan 1999).

Assessment of the glass eel resource in Australia is currently being undertaken to determine whether:

1. commercially significant and accessible shortfinned (*A. australis*) and longfinned (*A. reinhardtii*) glass eel resources exist; and
2. glass eels can be harvested sustainably.

This work forms part of a larger project which is examining the potential for eel aquaculture, based partly on the assessment of glass eel resources in eastern Australia.

The assessment component of the project is being conducted over three years in Victoria, Tasmania, Queensland and New South Wales, in collaboration with the respective State agencies, and aims to:

- Assess glass eel resources using catch per unit effort (CPUE) as a measure of abundance;
- Identify environmental criteria associated with glass eel invasion and migration;
- Establish a glass eel resource database; and
- Develop a preliminary model for defining the mechanisms of glass eel invasion and migration.

Glass eel invasion and migration

The spawning ground(s) of the Australian and New Zealand anguillid eels are not precisely known but spawning is thought to take place in the Coral Sea, up to 2 000 km from their freshwater habitats along the eastern and south-eastern coast of Australia and in New Zealand (Jellyman 1987). The East Australian Current is the proposed means of transport for leptocephali, a larval eel phase, from the Coral Sea to the Australian continent. In the vicinity of the continental shelf, leptocephali commence metamorphosis into the post-larval glass eel phase during which they temporarily cease feeding (Tesch 1977). The final invasion by glass eels into estuaries and their subsequent upstream migration into freshwater habitats is facilitated by tidal movement, using flood tides, generally at night (Jellyman 1977; Beumer and Harrington 1980).

A number of environmental cues are thought to influence these movement patterns, including salinity, temperature, lunar and tidal phase, rainfall and river discharge (Jellyman 1979; Tongiorgi *et al.* 1986; Tosi *et al.* 1990; Domingos 1992; Chen *et al.* 1994). Preliminary studies of the migration of *A. australis* glass eels have found that salinity, water temperature and tidal height showed significant correlation with glass eel abundance (McKinnon and Gooley 1998).

Materials and Methods

The main study site was the Snowy River in East Gippsland, Victoria. Experimental fishing for glass eels in the Snowy River was undertaken approximately 5 km upstream from the river mouth during nocturnal flood tides using Japanese glass eel or "Hell" nets, immediately following the new and full moon each month during winter and spring, nominally June to September. The nets have a mesh size of 2 mm, codend of approximately 2 m in length, wing depth of 4.4 m and wing span when set of 10-12 m. Nets are fixed using at least one plough-type anchor per wing and catch is cleared each hour. Up to three nets can be set, checked and retrieved by a two-member crew operating out of a 5 m aluminium vessel. Environmental data recorded during each survey include water temperature, salinity, tidal range and flow, river discharge and lunar phase at the time of fishing.

Results and Discussion

Abundance of glass eels in the Snowy River is highly variable between migration seasons, with CPUE ranging between 2 000 - 10 000 pieces/net/night in 1997, and 5 000 - 40 000 pieces/net/night in 1998 (Figure 1). This equates to approximately 0.3 - 2.0 kg and 1.0 - 8.0 kg/net/night respectively. Quantities in the upper ends of these ranges may be considered to be commercially viable in terms of harvesting glass eels for aquaculture purposes. The peak period of invasion of glass eels in the Snowy River was between mid-July and mid-August in both years, although considerable quantities (up to 1kg/net/night) were collected before and after these periods. The major

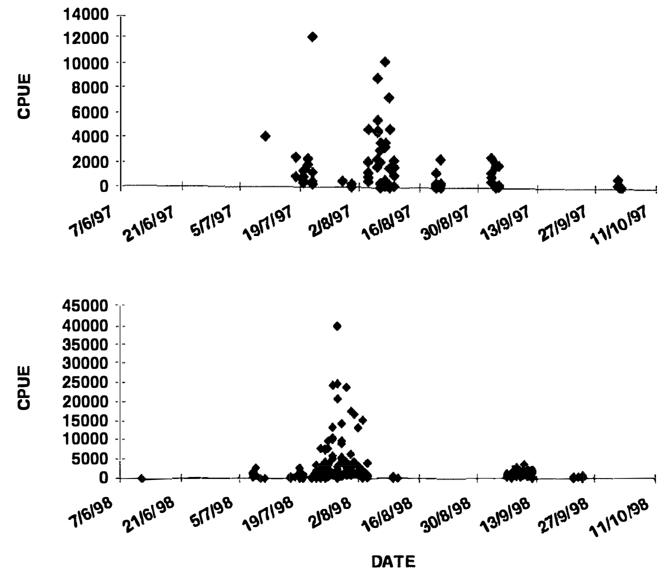

Figure 1. Catch per unit effort of glass eels in 1997 and 1998 (pieces/net/night).

period of glass eel migration in both years was associated with a seasonal rise in water temperature, and when salinity at the sampling site tended to be high (>20 000 mScm^{-1}). High glass eel catches were also associated with low stream discharge at the time of sampling. This association is expected to be due to increased tidal bore, or tidal penetration upstream, as a result of low river flow. The high salinity reflects the degree of tidal bore and associated influx of seawater into the estuary on the flood tide. Opportunities for glass eels to enter and migrate upstream in the estuary are maximised in these conditions. However, high river discharge following rainfall in the catchment is also believed to provide migration cues to glass eels and may direct their migration toward the estuary mouth (Creutzberg 1961; Chen *et al.* 1994).

Peak glass eel migration is also associated with lunar phase, with major migrations occurring immediately following the new and full moon. In addition, higher catches were made during flood tides which commenced after sunset than catches during flood tides which commenced before sunset. That is, peak catches of glass eels occur following the new and full moons when low slack water at the collection site occurs after sunset.

Management implications

Indications to date from this study are that quantities of glass eels suitable for small-scale commercial aquaculture may be available from the Snowy River, and optimal times for accessing these stocks can be partly determined by water temperature, time of year, lunar-tidal phase and stream discharge. High river discharge can prevent fishing activities, and can retard or prevent upstream tidal bore and associated glass eel recruitment. However, fishing effort may be concentrated following such events to target peak glass eel migration into estuaries, particularly when other environmental criteria are met which appear to favour migration.

Acknowledgements

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Discussion of Session 2

Chaired by John Koehn

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Recorded by Pam Clunie

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The discussion following each panel presentation is reported here.

Paul Humphries (MDFRC) asked *Martin Mallen-Cooper* why golden perch undertake upstream movements on only small rises in water level. Martin Mallen-Cooper emphasised that it was immature fish that were moving and whilst indicating that these movements were not well understood, he suggested some possible reasons. Golden perch are a widely-distributed species in the Basin occurring in lowland areas as well as the slopes, and in lowland areas golden perch may hang around until they are about one-year-old. While the fish have this migratory instinct, he saw little to no advantage of such behaviour in lowland areas, but it may be more helpful for the fish as they move up the catchment. He commented that Australian bass, which is in the same genus, exhibits the same behaviour; as it moves farther up catchment it moves on river rises and, where it can, often negotiates natural migration barriers.

Following *Richard Tilzey's* presentation, Andrew Sanger (NSW Fisheries) noted that if only a certain percentage of the population is maturing, and presumably these were the individuals moving, then what were the others doing and what was the advantage of a percentage not maturing? Richard Tilzey observed that at Lake Eucumbene when the water level was down, the overall fish condition declined and the percentage maturation per age cohort also declined. Obviously at times when food availability was high there was an increase in percentage maturation. He noted that in the following winter of 1970 he recorded 138 of these fish again and believed it would be interesting to compare their time of return to see if they came back at exactly the same time two years in a row. Males spent up to six weeks in the spawning creek whereas most females were up and back in 6-10 days depending on how ripe they were. The tagging trials provided some interesting results. In 1968, 1 500 fish were tagged using opercular strap tags: of these 1 000 fish had double tags and 500 had single tags. Fish that lost tags had distinctive scars. He found that the percentage loss of double tags was almost twice that of single tags. Therefore the assumption of independence of tag loss, on which most of the double-tagging theory is based, didn't hold true in this instance. He warned people not to assume that tag loss is independent and also that the results of loss from single and double tags should not be applied to each other.

Julian Pepperell (Pepperell Research) asked *John Gunn* about his observation that southern bluefin tuna put on most growth in a certain area. John Gunn responded that their work had shown that over 80% of growth was put on over three months during their time in the Great Australian Bight. Tuna would have a high maintenance cost, having to keep their bodies warm and swimming at relatively high speeds all the time. Even juveniles would have a high maintenance cost without having the reproductive costs. He felt that tuna are living on the edge a lot of the time, with mortality rates for one- and two-year-olds of about 40%, and believes this demonstrates how the fish have to keep moving and keep up with resources to maintain themselves.

Richard Tilzey (Bureau of Rural Sciences) asked what the tuna were feeding on. John Gunn replied that they predominantly eat pilchards and ruby fish and a range of pelagic and semi-pelagic species, but will switch to amphipods if there is a swarm. The tuna are top-level predators that will feed on anything encountered.

Malcolm Haddon (TAFI University of Tasmania) noted that John Gunn had some very interesting data for individual fish and wondered whether he was able to summarise the information into generalities. John Gunn noted that the basis of their work is to develop some energetics models and to use them for developing spatial dynamics models. He believes it will be a big job to combine all sources of data to create something meaningful. The energetics model will provide a major input into understanding why fish move when they do.

Geoff Arnold (CEFAS) asked about the water temperature for spawning off Java, to which John Gunn replied that the temperature on the sea surface in spawning grounds down to about 40 m, which is well mixed, is 28-32°C. From an energetics point of view it is interesting to note that adults are adapted to living in water temperatures of between 8 and 12°C, and so in these higher temperatures they are presumably dumping heat as fast as possible having a counter current heat exchange. He wondered whether adults swim at great depths up to the spawning grounds and only make excursions up to the surface to spawn.

Geoff Arnold wanted to know whether the tuna undertake circumpolar migrations. John Gunn indicated that they have started pop-up tagging of adults that will provide information about diving and migrations. Archival tagging is useful for juveniles since they get high return rates. However, given the level of cooperation of their Japanese counterparts, very low recovery rates for adults would be expected. He did not believe it is worth carrying out archival tagging of adults.

Terry Walker (MAFRI) asked what was the advantage to the tuna of diving. John Gunn observed that the tuna do not appear to be feeding at night on the surface; they are coming up at night because this is the warmest place for them to be and following squid as they move down. He did not know why these would be feeding on squid when they are undergoing migrations as he has seen no evidence of them feeding when they are at the surface.

Phillip Gibbs (NSW Fisheries) questioned *Tim O'Brien* about the importance of light at barriers. He has observed bream, mullet and silver biddies moving through 700 m of enclosed pipe in New South Wales. Tim O'Brien noted that the light issue is probably quite species-specific. Martin Mallen-Cooper agreed, observing that at Torrumbarry, placing covers over the fishway affected different species. Silver perch and bony herring would not go through, while golden perch were unaffected. He has also observed mullet and bream to move through in total darkness. Phillip Gibbs asked what differences there may be between freshwater and estuarine species. Martin Mallen-Cooper cautioned against making any assumptions; behaviour could vary greatly between species, although often behaviour within a family can be similar. Tim O'Brien questioned whether ambient light conditions might influence behaviour. He has observed numerous galaxiids accumulating at a pipe with no velocity barrier under tidal influence, and as the tide came up, or a wave came up, the fish sat there and didn't move. He wondered whether they would have moved up once it got dark when there wasn't such a strong contrast between daylight and the darkness of the pipe. Martin Mallen-Cooper advised that in America they have problems with herrings going through tunnels.

Richard Allibone (NIWA NZ) asked Tim O'Brien whether he had addressed the issue of movement of exotic species through fishways. Tim O'Brien indicated that the presence of exotic species is one of the selection criteria addressed when considering the implications of establishing a fishway. There have been examples where surveys have been carried out to check whether species such as carp are present. On the other hand, there have been cases where barriers have actually been put in place to prevent the movement of exotic species into areas with populations of native species.

Following *Tim Marsden's* presentation, Kevin Rowling (NSW Fisheries) asked what the cost of the Tallowa fishway is estimated to be. Tim Marsden indicated it would cost between a half- to two-million dollars. While he noted that fishways are expensive, he believed it is worthwhile putting this into context - if a one hundred million dollar dam is built, then the fishway would cost about one million dollars which is only 1% of the overall cost of the project. Unfortunately fishways are very expensive to retrofit and John Koehn (DNRE) emphasised that the key is to get them fitted when the dam is being built. Julian Pepperell asked what the current feeling was on stocking of bass, bearing in mind the genetic issues associated with translocations. Tim Marsden noted that bass are unfortunately already being restocked in the dam. There was also a large flood last year and most bass disappeared out of the dam and the anglers want it to be restocked. There is a good population of bass downstream of the dam, and once the fishway is established the species will probably build up in both areas. There may be an initial depletion downstream as fish spread out. In a broader context, he emphasised that a change in approach is needed, from only considering the management of a few species to managing all species. However, this change in approach is going to be very difficult. There is still some debate about how significant the genetic issue is for bass, with some feeling that it is not as much of a concern as initially thought. There are big problems with the genetics of other species such as barramundi in Queensland. Building fishways is a good method of avoiding genetic problems, by facilitating movement of fish that are natural to an area. Andrew Sanger indicated that Tallowa Dam is not being stocked with bass anymore. The Department is trying to be responsible about genetic issues associated with stockings but emphasised that there is a strong demand for them. Tim Marsden noted that it is not difficult to get broodstock out of the dam and then breed them up.

Richard Tilzey asked *Tony Fowler* whether he had looked at the population structure of the King George whiting in South Australia in terms of whether it is one distinct population. Tony Fowler replied that they had investigated mitochondrial DNA and microsatellites and that there was a homogeneous gene pool in that area. He also noted that in terms of the life history of the fish, with a larval duration of 80 to 120 days, the potential for larval movement is even substantially greater than the potential for adult movement. Bryan Macdonald (SARDI) indicated that one of the things that has perplexed SARDI in the past is that there is obviously quite a large population of whiting on the Eyre Peninsula but no one has identified any spawning grounds. He asked whether any migration routes to supply those recruitments had been identified. Tony Fowler believed that the most likely spawning grounds are somewhere out west but they have not been identified as yet. The water currents are from west to east so the transport of larvae must follow this pattern.

James Scandol (University of Sydney) asked whether anything was being done to restructure the fishery. He noted that the experience in New South Wales was that the number of participants and gear was being reduced but the problem they are experiencing is a re-allocation to the recreational sector. It can be a difficult issue when you have a key species that is heavily targeted by both the recreational and commercial sector. Tony Fowler noted that their stock assessment report includes recommendations about closing spawning aggregation sites at particular times of year to fishing. It is fortunate that, at least in the Investigator Strait area, fishing pressure is relatively low compared to the pressure on immature stocks in the Gulf. This maybe the current salvation of the fishery in South Australia.

Following *Lachlan McKinnon's* presentation, John Koehn commented that Australia has some of the most variable rivers in the world in terms of flow, which makes it very difficult to try to correlate environmental variables with things such as movement, particularly over short periods of time. Richard Allibone asked whether what was happening out in the ocean resulted in getting good populations in certain years. Lachlan McKinnon noted that what is happening in the ocean at any stage from the migration of adults to sea would have an impact on what ends up in the estuaries. They are trying to determine indicators which may establish the best combination of events for targeting these migrations.

Ivor Stuart (DNRE) asked for an opinion on the long-term sustainability of catching glass and adult eels. Lachlan McKinnon responded that commercial fishers are concerned that if the life cycle can be completed in captivity then there will not be a glass eel fishery and it may in turn affect the adult fishery. He also believed that in the short- to medium-term there will still be a market for wild-caught eels of a kilogram or more that probably would not be cost-effective to produce in an aquaculture situation. Richard Tilzey urged caution and indicated his concern that the eel industry had been hammered hard at both ends. He indicated there are also concerns in New Zealand about its fishery.

Rob Day (University of Melbourne) made the comment that the CPUE data look more like a logarithmic variable, and so a log transformation may be more appropriate. Lachlan McKinnon acknowledged this and emphasised that they are in the early stages of analysis. John McGuckin (Streamline Research) asked what would happen if flows in the Snowy River were increased. Lachlan McKinnon responded that large volumes flowing down river may have an attractant effect on glass eels out at sea. Some overseas work has suggested there is a correlation between freshwater flow events and glass eel migrations in particular rivers. Thus an increased flow in the Snowy River may increase recruitment of glass eels to river in the long run.

Mark Kennard (Griffith University) made a general observation about environmental flow management. While there is an apparent relationship between increased discharge as a cue for fish movement, the mechanisms behind this are not well understood. He questioned whether we really know whether it is the magnitude of the flow event, or the duration of flood event, or is it the associated changes in the hydrologic condition in terms of depth, velocity or water chemistry. Mark Kennard suggested that research projects need to try and identify these associated factors rather than only indicating that there is a relationship with increases in discharge.

Paul Brown (MAFRI) asked whether Lachlan McKinnon had undertaken any ageing of the eels but he had not. Bruce Pease (NSW Fisheries) noted there has been some ageing of *Anguilla reinhardtii* in Tasmania with fish aged between 20 and 40 years. Also, *Anguilla dieffenbachii* in the high alpine lakes in New Zealand have been aged up to about 100 years.

General Discussion

Simon Nicol (DNRE) made the comment that we usually work with very short-term data sets, where we have to try and determine patterns. We would be in a better position if we had more substantial data sets. As an example, Murray cod in the Murray River were monitored over four years. Three of these years experienced flooding while there was a drought in the fourth year. Murray cod were found to have moved upstream in all four years. This sort of information can only be obtained over time, allowing observations over different environmental conditions. Simon Nicol commented that if there had been five years of spring flooding, the assumption could have been made that this was what stimulated Murray cod to move. John Koehn noted that the collection of long-term data sets is generally not funded. Richard Tilzey agreed that there are only three- to four-year funding cycles and management bodies often perceive their key function as undertaking monitoring. There is a need to talk funding bodies into setting up trust funds for the development of long-term data sets. This is particularly true for inland areas which go from deluge to drought over ten-year cycles - if data sets do not span such a period of time, then the wrong assumptions could easily be made. At last year's ASFB conference Roly Griffin compared a three-to four-year data set for barramundi with a much longer data set. The short-term data set could have provided the erroneous conclusion that barramundi recruitment was dependent on rainfall. The long-term data set indicated that this variable was not relevant.

Mark Kennard spoke of the apparent reluctance to undertake experimental flow releases. Richard Tilzey indicated that there has been some work done, such as in the Campaspe River, a study that will hopefully continue for several more years. Our knowledge of larval drift of native fish is limited, and we seem to know more about upstream movement and far less about downstream movement. Andrew Sanger noted that fishways are being designed to consider upstream movement and sought opinions on the long-term impact of these fishways on species such as Murray cod. John Koehn advised that DNRE in Victoria has commenced a project looking at downstream migration. While aggregations have occurred previously due to the inability of fish to move upstream over barriers, the opposite may occur in the future; fish may be able to move upstream but not survive when they move back downstream. The impact of barriers on downstream movement was of concern to Martin Mallen-Cooper and could be a key issue for some fish species. He compared the behaviour of silver perch and golden perch. Silver perch tend to spawn on small rises in water level, and many of the low level weirs in the Murray-Darling Basin could represent barriers, and larvae which drift downstream over the weirs may be killed. On the other hand, golden perch tend to spawn during bigger flood events where weirs would not represent a barrier: this may be one of the reasons why this species is still abundant. Martin Mallen-Cooper noted that we could be in a similar position to North America about 30 years ago, where after focussing on upstream movement issues, fisheries managers then realised that the death of smolts going through turbines was the most significant issue. Large amounts of money were subsequently spent addressing downstream passage.

Brian Lawrence (MDBC) acknowledged that downstream movement problems are being experienced currently at sites such as Yarrawonga. It has been observed that fish coming out of the exit channel on the fish lift on Yarrawonga weir are being forced into the turbines by a cross flow. Mortalities of golden perch and Murray cod have been recorded as well as unknown quantities of smaller fish. The Yarrawonga fish lift has now been closed and fish have been transported manually above the weir, which is not a preferred technique. Fishers have observed that fish mortalities are continuing to occur, so solutions to this problem are needed. John Koehn indicated that similar problems have been experienced in North America.

Malcolm Haddon considered that there needs to be a distinction between things of scientific interest and those with management value. There are things which would be really interesting to know about, but what could we do about them? For example, it is unlikely that the Yarrawonga weir will be removed. You can reasonably expect funding agencies to fund projects which will provide useful management options. Martin Mallen-Cooper believed that it would be worth investigating the Yarrawonga weir problem. One useful management option would be to avoid such a situation again. There may or may not be options to fix this particular problem, but finance is a real problem and certainly will be in the future. In this particular case, the problem is caused by a low-level power station working on a four- to ten-metre head of water. Such stations are a popular way to produce small amounts of electricity throughout the world and will become more common in Australia. John Koehn noted that they may not be particularly cost-effective.

John Gunn agreed that there needs to be a reality check every once in a while, but he has often heard the comment that research can't be done unless it has a specific management bent. However he believed it is too easy to be an economic rationalist and lose the benefit of pure research. John Koehn could think of a number of key questions in the freshwater field where we clearly need long-term data sets but he was not aware of any agency willing to fund this work. For example, in investigating a one- in ten-year flood event, it is not possible to solve the question of whether this is a key component to the ecology of a river if a project is only funded for three years. André Punt (CSIRO) commented that people tend to emphasise long-term data sets as the answer to addressing mechanism questions but he believes this is a major fallacy. He used the glass eel data as an example of where the data look like a log-normal distribution. What this means in reality is that if you have four mechanisms and assuming that one is actually true, even to detect which one is true you would probably need to sample for a thousand years. People need to show that they will be able to answer a question, otherwise he would be reluctant to fund projects which involved collecting long-term data sets.

Paul Brown pointed out that we need to put some of these issues into context. For example, if you have instances of fish mortalities such as at the Yarrawonga weir or during electro-fishing surveys, how do you determine whether this is a problem when you place it in the context of natural mortalities? John Koehn indicated you need to ask the right questions and see if you can answer them. In the case of the Yarrawonga fish lift it may be appropriate to monitor the fish moving upstream in the first place but this is not being done at the moment.

Rob Day agreed that in trying to answer a specific question you can't just use long-term data sets to expect to get the answer. It is also clear that to get funding there needs to be some kind of management outcome. However, both of these comments miss the point that you need to do more than just answer questions about the system: you also need to think about what questions to ask. This is where long-term monitoring is absolutely essential. It is more useful as a hypothesis-generating procedure than as a hypothesis- answering procedure. It is arrogant to assume that we know what kinds of things could be happening and that we have a framework that is complete enough to say that we should only fund research where we can see a direct answer to some question. That is a very narrow view and we need to broaden our perspective and realise that there may be new questions for which we need to have the biological background expanded so that we can actually frame new questions we need to answer. John Koehn agreed and suggested that changes in funding arrangements are needed to achieve some of these things. For example, funding can currently be obtained for a three-year project, but would it be possible to develop a fifteen-year project using the same amount of money? The funding could be spread over this longer period, by working on the project for a few months of each year; for example to undertake monitoring of spawning or larvae or doing annual surveys. Such an approach could provide data over a longer period to answer specific questions.

John Gunn made the observation that in the freshwater field, many seem to be working on an issue such as fishways and are struggling with funding. He recognised that this involved different systems and different species. However, he wondered if funding is the real issue or whether mechanisms and general principles are needed to guide people in a range of systems. Can funding be pooled to work on unified projects? Aquaculturalists have recently found that they have been working on too many species in too many places and have spread their knowledge too thinly. In the case of fishway research a unified focus could be a good way to obtain maximum value from available money. Tim Marsden agreed that there is a need for a more co-ordinated approach, particularly in the fish passage area. For example, there is a lot of work being done in Victoria on flume tests on fishways, and it would be valuable for him to know of this information before he repeats the work in Queensland. He indicated that while there have been some attempts to co-ordinate this work, there still needs to be more co-ordination and sharing of information. Tim O'Brien (DNRE) commented that this was one of recommendations from the last fishway workshop. He referred to Alex McNee who has been compiling information on the progress each State is making with fishways. His report is due to be released soon. While this is one step towards achieving a co-ordinated approach, more information sharing is needed. Martin Mallen-Cooper believed there are two elements to discuss. One is the fish passage issue where there can be considerable sharing of technical data in terms of fish behaviour and fishway design. The other is about fish migration and environmental determinants, which are very different systems that work very differently; for example, subtropical, semi-arid and coastal systems. He believed it would be hard to develop a project to encompass all those systems, for example in working out fish migration and what stimulates fish to move. John Koehn asked Brian Lawrence whether Alex McNee's work was addressing this issue throughout the Murray-Darling Basin. Brian Lawrence responded that Alex McNee is preparing an overview paper of the status of the fish passage issue within the Basin. This includes details of the priorities identified by each State and aims to co-ordinate activities in terms of investigations and onground works. Claire Peterken (Queensland DPI) commented that in terms of fishways work she believes there is quite a good exchange of information in Australia. People attending the Workshop might get the impression that there are many people working on this issue, but this is not the case. Most, if not all, people working on the issue just happen to be at the Workshop.

Paul Humphries observed that several people had raised an important issue during the day: that of how representative are the observations we make about some fish of an entire population. Is the movement we see general, is it obligatory or facultative? In terms of freshwater habitats how far do fish move? While we now know that golden perch can move 1 000 km it becomes entrenched in the literature and provides the impression that all golden perch move such a distance. He sought people's views on how to consolidate the information provided by radio tracking of individuals into what happens in an entire population. He also questioned how we determine how far fish go and how important is it to deal with the issue of barriers to movement. John Gunn commented that in terms of tuna, the number of tagged fish could be important. 75 fish returned with tags exhibited a suite of behavioural types. Results indicated that different fish behaved in exactly the same way at the same time and in the same areas. He believed this provided an indication of a typical behaviour of a particular size class in a particular area. However, this was a complex issue, and he questioned how to tum this information into something predictive. In a modelling sense you would need to move from a statistical model into an individual-based model which could then be used to predict population movement; this would be very challenging. David Crooks (MDFWRC) reported from his work in a freshwater environment, that there were lots of individual differences between fish and that it would be hard to generalise. He believed John Koehn obtained similar results with his radio tracking of Murray cod, the situation being quite complex with the fish not exhibiting only a few types of behaviour. Richard Tilzey indicated that in the case of southern bluefin tuna, you are dealing with a homogenous situation from a habitat and stock point of view. Inland situations are likely to be much more complex. For example, there may be resident populations of golden perch and migratory populations of golden perch. He believed it is hard to tease out such levels of complexity and would be surprised if we could generalise about migratory behaviour of any but a few species. John Gunn emphasised that southern bluefin tuna were not simple in their behaviour, and in fact exhibited complex behaviour. However, having hundreds of days of data enabled behaviours to be looked at in a longtime series compared to just looking at a day. He believed that by looking at the bigger and broader picture, common behaviours could be identified and that these were the ones we need to look at when searching for cues of why fish migrate or do particular things. He was unsure in a freshwater situation what time-spans of radio tracking data would need to be looked at to provide similar information. Martin Mallen-Cooper referred to his work on golden perch. 20% of the tagged fish didn't move, although this assumed that the fish had not moved away and then returned to the same spot. He asked whether a proportion of the tuna did not move. John Gunn's experience was that none of the tagged fish exhibited this behaviour. One of the complexities was that when they left the Bight they either moved left or right; however all did seem to leave. A management issue that needed to be considered was whether there is anything predictable about which way they would move. Martin Mallen-Cooper emphasised that an important issue is what advantage there is in different fish exhibiting different behaviours.

Session 3

Analysis, interpretation and spatial models

Chair:	André Punt
Speakers:	Terence Walker Simon Nicol André Punt Charles Todd Rob Kenyon James Scandol Norman Hall
Rapporteur:	Robin Thompson

Chair's Introduction

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Movement and migration can have important implications for management and understanding of the nature of the species concerned. However, most of the techniques used to estimate rates of movement and migration lead to vast quantities of data, which require model-based methods for interpretation, in addition to a well-designed experimental programme. For example, the results from tagging studies can only be interpreted meaningfully once they have been analysed in conjunction with information on the probability of a tagged animal being recaptured (which may depend on whether it has grown and where it has moved to).

The methods of fisheries science have always included approaches to estimating movement and migration (e.g. Ricker 1954). However, even the application of simple methods can be computationally prohibitive and this has limited detailed analysis and modelling of data on movement. Recently, however, the availability of computing resources of sufficient power has meant that some more realistic spatial models can now be considered. These, combined with the more rigorous statistical treatment of the data (using, for example, maximum likelihood or Bayesian approaches), means that management advice based on models that explicitly recognise and handle movement and migration may be close at hand (or here already).

The papers in this session reflect the broad range of techniques being applied in this rapidly developing area of fisheries science. The particular analysis approach applied will differ if the objective of the work is to produce a model primarily for management purposes or primarily to be used to generate hypotheses for further investigation. The papers in the session also reflect different choices for the scales (both spatial and temporal) at which data are analysed and the processes included in the model (which need to be selected carefully to avoid throat cutting using Occam's razor). A particular challenge associated with spatial modelling is that the models are extremely complicated and considerable effort needs to be taken to make the assumptions and model output transparent to stakeholders, managers and other scientists.

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Modelling school shark (*Galeorhinus galeus*) movement in the Southern Shark Fishery

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Abstract

Tag studies during 1947-99 show widespread movement of school shark. Some individuals of this long-lived species (>50 years) undertake migrations exceeding 2 000 km across the range of the fishery in southern Australia and the Tasman Sea. Annual movement by a major component of the large animals occurs between the eastern and western regions of the fishery, with a minor component of the population moving north and south on the New South Wales coast. Movement patterns on and off the continental shelf and diurnal vertical movement are only now beginning to be understood. A variety of quantitative models have been developed as part of the Australian Fisheries Management Authority's assessment process to mimic the movement dynamics of school shark. The results from a fine-scale model of shark movement dynamics based primarily on subjective judgements are included in fully age- and spatially-structured fishery assessment models for school shark. These models variously take account of the peculiarities of shark biology and the highly length-selective characteristics of the gill-nets of several mesh sizes and the hooks used throughout the fishery. The results from these assessment models are notably more precise than those from previous assessment models, highlighting the value of explicitly including tagging data in assessments within a spatially-disaggregated framework.

Introduction

School shark (*Galeorhinus galeus*) exhibit complex stock-structuring and migratory behaviour. Ignoring these characteristics in the past has contributed to high uncertainty in the results of stock assessments. Recently, uncertainty in school shark stock assessment has been markedly reduced through the development of complex spatially-structured models, which account for the demographic characteristics of sharks and the highly length-selective characteristics of gill-nets of various mesh sizes deployed in the fishery. These models explicitly include movement of the sharks and are fitted to tag data and spatially-disaggregated fishery monitoring data.

Earlier approaches to analysis of the tagging data assisted understanding of movement patterns but quantified broad movement rates were not incorporated explicitly into the assessments. For example between its inception in 1993 and its 1999 assessment of school shark (Punt *et al.* in press-a), all of the assessments conducted by the Southern Shark Fishery Assessment Group (SharkFAG) were based on spatially-aggregated assessment models that ignored the tagging data and their implications. This occurred even though potential stock structuring had been explored earlier by considering separate stocks in several regions (Prince 1991).

Despite attempts to account for regional effects by incorporation of region into the standardisation of catch-per-unit-effort (CPUE) when producing abundance indices by generalised linear modelling (Xiao 1995a; Punt *et al.* in press-b), estimates of stock depletion based on spatially-aggregated models were highly uncertain. Three types of assessment method were applied between 1993 and 1998. The first of these was based on a general biomass dynamics model (Schaefer 1957; Xiao 1995b). The second type was based on a delay–difference model (Deriso 1980; Schnute 1985; Schnute 1987) adapted to include stochastic recruitment for risk analysis (Walker 1995b). The third type was based on an age-structured model, which included shark growth, reproduction and gear selectivity (gill-nets of various mesh size and longlines with various hook sizes) parameters and assumed levels of inter-annual variation in pup survival (Punt and Walker 1998).

Three separate school shark tagging studies have been carried out in southern Australia. These studies were during the 1940s and 1950s (Olsen 1953; Olsen 1954; Stanley 1988), 1970s (Walker 1989) and 1990s (Stevens and West 1997; Walker *et al.* 1997). Of 9 800 school sharks tagged, 1216 (12%) had been recaptured and reported by April 1999. Data from the studies have been used in various methods to assess movement dynamics. These methods include simply plotting release and recapture positions on a map, vector analysis, application of models for determining rates of movement between broad regions, and building highly complex spatial models that incorporate multiple stocks, and movement dynamics of sharks of each age group.

This paper briefly describes various tag data analyses undertaken and how interpretation of the results from these analyses, in conjunction with fishery monitoring data and biological studies, led to alternative hypotheses of school shark stock structuring and movement. Finally, it describes how fitting tag release-recapture and other data to the spatially-structured model adopted as part of the 1999 assessment markedly reduced uncertainty in estimates of stock depletion.

Tag data analyses

Basic analyses

It is common in the scientific literature to summarise movement dynamics from tag release-recapture studies by plotting information for only the recaptured animals and ignoring the uncaptured animals. This was the earliest and simplest method adopted for school shark. The approach considers the start and finish positions and time at liberty of each animal plotted on a map to provide a visual representation of the magnitude of displacements and rate at which displacement occurs (i.e. velocity) by individual animals (Olsen 1954; Walker *et al.* 1997).

Of 301 reported tag recaptures from 2 505 releases during 1990–96, 65% of the displacements were >500 km for large females (>140 cm total length—TL); 20 recaptures of male and female sharks had displacements >1000 km. The mean distance between release and recapture positions was 415 km (Walker *et al.* 1997). The longest recorded displacement was 3 016 km for a female (156 cm TL at release) released in the Great Australian Bight and recaptured at a position near the south east coast of New Zealand South Island after 1033 days.

Vector analysis

Vector analysis of the school shark tag recapture data has been undertaken for each of the three separate tagging studies using data available to the end of 1996 (Walker *et al.* 1997). An update of the analysis of recaptured tagged school sharks of >140 cm TL to include data to April 1999 is presented in Table 1. Here separate analyses are presented for male and female sharks and the data are separated on the basis of the position at release into the Western and Eastern Regions (demarcated by longitude of the South Australia–Victoria border). This analysis indicates that females move longer distances than males, and that larger animals move longer distances than smaller animals (not presented).

Table 1. Vector analysis for recaptured sharks (TL >140 cm) tagged during 1990–99.

Mean value (with s.e.) of selected quantities for sharks recaptured by April 1999.

Variable	Units	Male		Female	
		Western region	Eastern region	Western region	Eastern region
Recapture no.		15	41	26	28
Time free	Days	500 (75)	391 (32)	351 (52)	416 (48)
Dispersion	km^2/day	1 163 (273)	1 749 (482)	3 147 (781)	3 465 (779)
Distance	km	643 (103)	515 (88)	752 (139)	841 (114)
Direction	°N	127	312	123	309
North vector	km	–296 (86)	230 (57)	–347 (95)	489 (83)
East vector	km	399 (125)	–257 (92)	529 (139)	–610 (103)
Displacement	km	497	345	633	782
Velocity	m/day	993	882	1 802	1 881

Vector analysis can provide a basis for comparing populations between separate areas for a species or between species on the basis of quantities such as mean displacement, distance, velocity and speed, but such analyses provide information only on the shortest distance between release and recapture positions rather than on the full distance moved between these positions. A major disadvantage of vector analysis (and simply plotting the data) is that no account is taken of the spatial distribution of fishing effort.

An initial modelling approach

A maximum likelihood model was adopted for estimating rates of movement between separate regions, where the rate of movement is the proportion (also probability) of animals leaving one region to move to another region within a specified time-step (one year in this case). The model treats the contribution of each tag independently and makes use of information from both the recaptured and non-captured tagged sharks. Data inputs to the model included total fishing effort within discrete time intervals for each type of fishing gear, the gear selectivity function of each fishing gear deployed in the fishery, and region and shark length and date at the time of release and the time of recapture (Dow 1989). The model allows the sharks to grow while at liberty using reparameterised von Bertalanffy parameters (Francis 1988) as previously determined (Moulton *et al.* 1992). This model is similar to one developed to provide an experimental design for tagging school and gummy sharks (*Mustelus antarcticus*) during 1993–96 (Xiao 1996).

This model is applied to determine the rates of movement between the Western Region and Eastern Region for each of male and female sharks for those of TL <120 cm and those ≥120 cm separately. The analysis indicates that for male school sharks of the smaller size group, the movement rate from east to west (0.15 yr^{-1}) is higher than the rate from west to east (0.08 yr^{-1}), whereas for the larger-sized group, the movement rate from west to east (0.39) is higher than the rate from east to west (0.08 yr^{-1}). For female school sharks, the results give a similar pattern for the smaller-sized group (0.21 yr^{-1} from east to west and 0.08 from west to east) but the pattern is much different for the larger-sized group where the movement rate is much higher from east to west (0.68 yr^{-1}) than from west to east (0.11 yr^{-1}).

Stock structure hypotheses

Harvested stocks of school shark occur off southern Australia, New Zealand, South Africa, the east coast of South America, the west coast of North America and in the North Atlantic (Walker 1999) and these stocks appear to be genetically distinct from the evidence of allozyme and mitochondrial DNA studies (Ward and Gardner 1997). In southern Australia, tagging studies show mixing across all regions of its range and a number of trans-Tasman tag recaptures show there is also mixing between Australia and New Zealand (Coutin *et al.* 1992; McGregor 1994; Walker *et al.* 1997; Hurst *et al.* 1999). The genetic and tag data, together, suggest mixing of the Australian and New Zealand populations on common feeding grounds, but not inter-breeding.

Initial stock-structure hypotheses

Neonate and small juveniles aggregate in particular inshore bays and estuaries (referred to as nursery areas) of Victoria and Tasmania (Olsen 1954) and occur at lower density in certain coastal ocean waters. Larger juveniles are most abundant in Bass Strait and the proportion of mature fish is higher in Western Australia (Walker 1995a), South Australia (Walker *et al.* 1989a; Walker 1995a; Walker and Hudson 1995) and Tasmania (Walker 1995a) than in Bass Strait (Olsen 1954; Walker *et al.* 1989a). Concentrations of mature females have been scientifically observed in South Australian waters during June–October and in Victoria and Tasmania during November–January while schools of adult males have been observed during June–August on the west coast of Tasmania.

Consistent with these observations, an early theory of movement and distribution was developed from recapture of the sharks tagged and released during 1947–56, and from anecdotal information received from fishers, whereby pregnant sharks move into the nursery areas of Tasmania and Victoria to give birth. The adults tend to move inshore in summer and offshore at the start of winter, while others move to warmer waters in New South Wales and South Australia before returning south in late spring. After parturition they move to deep waters. The young remain in the nursery areas until the late summer months, when they gradually move seaward to deeper coastal waters where they remain during winter. During the following spring the majority return to their former nursery areas. Juveniles of age two years or more remain outside and move to eastern Bass Strait where the bulk of the immature population is centred (Olsen 1954; Olsen 1962).

Developments in the fishery and additional data collected more recently generally support this theory. One exception is the absence of significant catches of school shark from the east coast longline fishery which suggests only a small component of the stock currently occurs off New South Wales (Walker *et al.* 1998). There is stronger evidence for the movement of pregnant sharks to waters off South Australia, particularly to the Great Australian Bight, where they remain during much of the period of gestation, before returning to eastern Bass Strait and Tasmania to give birth. Scientific observations indicate that pregnant sharks with mid-term embryos before October are rare in Bass Strait and off eastern Tasmania and eastern South Australia but common in the Great Australian Bight (Walker *et al.* 1989b). Length-frequency samples of sharks show that the school sharks caught off Western Australia and western South Australia are much larger than those caught off eastern South Australia and in Bass Strait (Walker 1995a). Tagging during the 1990s in nursery areas (Stevens and West 1997) confirms the observations of juvenile movement. Anecdotal information indicates that many of the school sharks caught off Western Australia are pregnant or in a pre-ovulatory condition. Sharks 0–1 years of age have not been detected off South Australia by scientific survey.

A scientific survey undertaken during 1986–87 using four experimental gill-nets of 5, 6, 7 and 8-inch mesh size to catch sharks which were subsequently aged demonstrate a marked absence of young school sharks from South Australia compared with Bass Strait. Only 32% of the school sharks caught in waters off South Australia were under 5 years of age whereas 81% of those caught in Bass Strait were under 5 years of the age (Moulton *et al.* 1992); 19% of female school sharks caught in waters off South Australia were mature whereas only 6% of those caught in Bass Strait were mature (Walker *et al.* 1989b).

Although archival tags offer the potential to provide information for determining total distance travelled and spatial movement patterns, the present use of photo-period for estimating longitude and latitude precludes resolving position to sufficient accuracy for analytical methods. Nevertheless, making use of depth data from recording bathometric pressure, archival tags have provided valuable insights into onshore-offshore and vertical diurnal movement patterns of school sharks (West and Stevens in press).

SharkFAG's movement hypotheses

SharkFAG initially considered two alternative movement hypotheses for conceptual purposes but eventually found that available data fit its spatially-structured stock assessment model best when it adopted a mix of the two hypotheses. The two alternative conceptual hypotheses can be stated simply:

1. Single panmictic population with components of the stock at different life history stages occupying different localities within the range of its distribution.
2. Discrete separate sub-populations with no or very limited interbreeding.

The first hypothesis—the single stock hypothesis—is consistent with the breeding patterns and large-scale movements described for this species (Olsen 1954; Olsen 1962) and with most data collected subsequently. The second hypothesis—the multiple sub-stock hypothesis—was assumed when the stocks were assessed as separate stocks in eight separate regions as part of an earlier assessment (Prince 1991).

The hypothesis adopted by SharkFAG for its 1999 school shark assessment requires there to be separate breeding sub-populations but there is mixing at other life history stages (Punt *et al.* in press-a). This might be referred to as a 'mixing multiple sub-stock hypothesis'. One way of explaining mixing sub-stocks for school shark is to invoke the concept of philopatry ('home loving') effected through 'natal homing' whereby pregnant female sharks return to their birth place (Hueter 1998). However, natal homing has not been demonstrated and genetic differences in neonates or young juveniles between nursery areas have not been detected for school sharks; these uncertainties need to be investigated. There is also the question of whether mating occurs between animals of different sub-populations. A supporting argument for separate sub-stocks is the occurrence of 'localised stock depletion', a concept first described for shark species taken in bathing beach meshing programmes designed to reduce risk to humans from shark attack (Holden 1977). This appears to have occurred on a broader scale in southern Australia as once-productive fishing areas became unproductive (notably in eastern regions) while other areas have remained productive (notably in western regions). In addition, the almost complete loss of a nursery area in the Geelong Arm in Port Phillip Bay, Victoria, is consistent with the loss of a sub-population, although habitat degradation cannot be ruled out as a possible cause for the loss (Walker 1996; Walker 1998).

SharkFAG's spatially-structured stock assessment model

During 1999, SharkFAG adopted a stock assessment model that makes the spatial structure of the fishery explicit. The fishery has been divided into eight regions based on the size and age structure of the population and the history of its catch and CPUE. In addition, the model allows for multiple stocks to accommodate consideration of a range of alternative hypotheses for stock structure and movement. The model includes demographic parameters to represent the growth of sharks and the pupping and recruitment processes and includes multiple gears (gill-nets of various mesh size and various hook sizes) with their selectivity parameters (Punt *et al.* in press-a).

For the purpose of its assessment, SharkFAG defined 'stock' as 'a group of animals that have the same pupping grounds and movement patterns'. The SharkFAG model is fitted simultaneously to data disaggregated in the eight regions, and the assessment is based on the assumption that two stocks of school shark occur off southern Australia. A two-stock model was found to fit the data better than a single-stock model that allows for movement, but the data cannot support estimation of parameters for models based on more than two stocks. Movement patterns differ between the two sub-stocks. The probability of moving between regions is assumed to depend on month and age to better capture the relatively complex movement patterns observed from tagging data. Parturition is assumed to occur only in the eastern region of the fishery.

School sharks tagged in New Zealand have been recaptured in Australia (Hurst *et al.* 1999) and school sharks tagged in Australia have been recaptured in New Zealand (Walker *et al.* 1997). The SharkFAG model allows school sharks from New Zealand to move to Australia where they can be caught. Only animals aged 6–12 years (evidenced by tag returns) are assumed to move from New Zealand to Australia and it is assumed that there is a 50% probability each year that a New Zealand school shark in Australia returns to New Zealand. The impact of fishing in Australia or New Zealand is assumed to have negligible impact on the population in New Zealand because the level of fishing mortality in New Zealand is much lower than that in Australia. For this reason, movement of Australian school sharks to New Zealand is ignored. A range 0–15% is examined for the percentage of the number of school sharks in Australia (in a pristine state) that originated in New Zealand.

Movement is modelled as the probability of a shark of a given age and stock moving from one region to another region in monthly steps. The matrix of movement probabilities is selected to represent a mix of large-scale pupping migrations, feeding migrations and random movement (Punt *et al.* in press-a). The values for the parameters that determine movement in the SharkFAG assessment model are obtained using a two-step process. First, alternative movement hypotheses are presented using a special 'movement simulation model'. This model operates on a daily time-step and considers movement of individuals within each age-class in a particular stock or sub-stock between contiguous cells of 1° latitude by 1° longitude. The movement is displayed on a map of southern Australia by a computer program where alternative hypotheses can be simulated by specifying values for a small number of behaviour-related parameters (e.g. the probability of randomly leaving a cell). Net movement in one direction is achieved by setting the probability of moving in one direction greater than in the opposite direction (Taylor 1997). The results from the 'movement simulation model' are aggregated to monthly and regional resolution and used as initial estimates for the movement rates in the fully age- and spatially-structured fishery stock assessment model. As part of the actual assessment, the initial guesses for the movement rates are modified based on 36 parameters to better mimic the available tagging and catch rate data (Punt *et al.* in press-a).

The spatially-structured assessment is much less uncertain than earlier assessments. For example, by allowing for spatial- and stock-structure and using tagging data for estimation purposes, the mature biomass at the start of 1997 is estimated to be 12–18% of the 1927 level. This is a markedly narrower range than that obtained by Punt and Walker (1998) who, using a spatially-aggregated model and ignoring the tagging data, estimated the 1994 mature biomass to be 15–46% of the 1927 level.

Conclusions

School shark has particularly low productivity, and CPUE data used as abundance indices are uninformative. Despite standardisation for regional effects on these indices and incorporation of all essential demographic and gear selectivity parameters for school shark, when the resource is considered as one stock in a single-region model, the estimates of mature biomass and stock depletion are highly uncertain. Only through incorporation of tag data directly into the assessment, using spatially-structured models to embrace specific stock-structuring and movement hypotheses, have highly uncertain assessments been turned into assessments in which there is confidence. Incorporation of tag data into spatially-structured models is the key to successful assessment of school shark.

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Do Bayesian concepts assist the ability to interpret migration and movement patterns of freshwater fish?

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Abstract

Obtaining the necessary statistical power to identify fish movement in relation to environmental triggers and comprehend their meaning is often problematic. Classical statistics often requires complex experimental designs to separate confounding effects and large replication to provide the required statistical power. Bayesian statistics however provides an alternative method for analysing and interpreting movement of fish species. A case study is presented using Murray cod in the Ovens River as an example. In the case study, the trigger for movement is tested against the hypothesis of spring flooding to stimulate the upstream migration of Murray cod over a four-year period. The case study explores the outcomes provided by both the Bayesian and classical approaches.

Introduction

Movements and migrations of freshwater fish in Australian freshwater streams are important ecologically for re-colonisation within the river system and for the completion of various parts of the fish's life-cycle such as spawning, successful recruitment and habitat shifts (Reynolds 1983; Koehn and O'Connor 1990; Mallen-Cooper *et al.* 1997). Aspects of a river's natural flow regime often provide important stimuli for this movement. For example, adult Australian bass require seasonal high flows to migrate downstream to estuarine spawning grounds (Koehn and O'Connor 1990); small river rises in spring to mid-autumn are required for movements upstream by silver perch and golden perch to spawning habitats (Mallen-Cooper *et al.* 1997); and late winter/early spring flooding coincides with an upstream spawning migration of Murray cod (Koehn 1997). The large and unpredictable variability in flow experienced by Australian rivers has resulted in a high degree of regulation and water abstraction in many rivers to provide security of water supply for domestic, agricultural and industrial users. This demand and regulation of water for users other than the environment has seen natural flow regimes substantially altered and important movement stimuli lost. For example, the seasonal flow regime immediately below Lake Hume in the Murray River to Lake Mulwala has been reversed with high flows now in summer/autumn rather than winter/spring to provide water for irrigation (MDBC 1995). This has reduced the frequency of over-bank flows during the period of Murray cod spawning and subsequently the stimuli for spawning migration. The implementation of operating rules that minimise the impact of these changes to the natural flow regime and provide for the needs of other users (irrigation) is a key target of many management actions (e.g. the transparent dam rules for Lake Hume recommended in Thoms *et al.* in press.).

The allocation of water, like many natural resource management issues (e.g. timber harvesting in public forests) has political and social impacts that often fuel heated and confrontational debate between the stakeholders (e.g. proposed increased flow allocations for the Snowy River). Often, there is little flexibility in the determination of water allocations to the environment unless allocations for other users are reduced. As a result, revised operating rules offer the only flexibility to environmental flows. Where the relationship between species, their environments and their responses to change is known, the determination of the environment's water requirements may be a relatively straightforward process. In most scenarios however, there is uncertainty about these relationships, and determining water allocations to the environment is often difficult. Expert judgement (Thoms *et al.* in press) or techniques that preserve a minimum flow regime, such as the Cascading Seasonal Flow Method (Tim Doeg pers. comm.) are often used as interim measures. The assumption of these methods is that although it is not known what flow-related stimulants are required by fish species, by prescribing a flow which attempts to mimic the natural timing of flow events, then most stimulants should be conserved.

One approach to evaluating decisions regarding flow timing and magnitude is to do so in a framework of probability and risk. When data are examined using probabilistic methods, the experimental design and analytical procedures used are critical to the validation of the data. The prominence of frequentist statistical methods (e.g. Analysis of Variance) in environmental sciences sees many investigations and experiments designed and analysed using these approaches, almost as a matter of habit, even though other methods may be available for the particular question. This paper examines the application of a Bayesian model rather than a frequentist model for determining fish movement and how uncertainty surrounding stimuli for movement can be incorporated into the evaluation of flow management actions. A data set (Koehn 1997) that describes the movement of Murray cod (*Maccullochella peelii peelii*) in the Ovens River in south-eastern Australia will be used as a basis for the discussion of this Bayesian approach.

Bayesian statistical theory provides an approach to the analysis of data for resource management that allows straightforward probability statements to be made about specific cases (Crome *et al.* 1996). Bayesian analysis is explicitly a process for updating beliefs in hypotheses where probability is defined as an expression of an observer's confidence or degree of belief in the hypothesis (Anderson 1998; Hayes 1998). The analysis asks a different question of the hypothesis: "given an observer's previous belief, how should they revise the probability assigned to the hypothesis in the light of the new data?" (Anderson 1998). In a Bayesian analysis the data are fixed and the parameters are random. The analysis is therefore a statement about how well the hypothesised relationship between the parameters fits the data. This means that the interpretation of the analysis can be described with simple statements like "the probability that upstream movement of Murray cod is stimulated by spring flooding is greater than 0.95". This has often been reported as a significant advantage in resource management where communication of results to stakeholders is important to defuse tensions (Crome *et al.* 1996).

The method involves generating a function (prior distribution) that reflects the degree of confidence in the hypothesis before any new data are examined. The new data are then combined with the prior through a likelihood function to generate a posterior distribution for the parameter of interest. This distribution can then be used to communicate the current evidence on the relative likelihood of different values of the parameter. This has direct application to decision analysis where the likelihood of a number of scenarios (differing values of the parameter) can be evaluated (Anderson 1998).

Murray cod in the Ovens River

Until 1992 little was known regarding the ecology of Murray cod, the largest freshwater fish in the Murray-Darling Basin. Between 1992 and 1995, a study was undertaken on the Ovens River in the lower Murray-Darling Basin to investigate the habitat and movement patterns of this species (Koehn 1997). Radio transmitters were surgically implanted into Murray cod, and their locations in the river regularly monitored. The use of radio tracking is the only practical method for sampling the movement of species such as Murray cod, since the recapture rates of Murray cod by other methods are extremely low (less than 1%) (J. Koehn pers. comm). The purpose of this study was largely to ascertain movement times, rates and distances, rather than a specific experiment to determine the movement-flow relationship of Murray cod, from the movement data collected.

Radio tracking was used to sample movement by repeated regular census of individuals. The amount of movement undertaken was inferred from the difference between river locations after consecutive census periods. When to census was determined after monitoring individuals on a daily, weekly, fortnightly and monthly basis. A monthly census was implemented for summer, autumn and early winter and fortnightly for late winter and spring. A census at intervals more regular than these, sampled local rather than large-scale movements. The number of individuals being tracked at any time was restricted to generally no more than 20.

The occurrence of particular flow rates between the census periods was used as measures of flow change. Direct inference between movement and flow was therefore not possible, meaning the design could not identify whether fish moved on an increase in flow, but states that there was an increase in flow during the period that the fish moved.

Koehn (1997) reported the observed pattern of movement to be seasonal. During summer, autumn and early winter, Murray cod were relatively sedentary, moving only locally. This behaviour changed in late winter/early spring when large upstream movements began and these continued until late spring. The onset of these movements generally coincided with over-bank flows in late winter and early spring. In 1994 over-bank flows were absent. However, an upstream movement was still observed (albeit smaller than in previous years and from a substantially reduced sample size), questioning the importance of over-bank flows to stimulate movement. In all years, the observed upstream migration was followed by a relatively rapid downstream migration, with almost all fish returning to exactly the same area they had occupied before their upstream movement.

As with most biological data, the variability of individual Murray cod movements at any specific census within the spawning season was high, with some individuals moving downstream, others not moving at all, and a proportion moving upstream. For this paper the data have been reviewed to examine the importance of particular flows to upstream movement. Since it was not always possible to locate every fish at every census (resulting in poor balance in the data collected) the data have been organised to account for these absences. The movement distance is the total distance that the fish moved in a particular direction. This may be a single movement or the sum of a number of consecutive movements in an upstream direction or in a downstream direction. Flow is the median value of the flow over the period between movements. The data are summarised into three movement categories: (i) greater than 5 km downstream; (ii) local movement (within 5 km upstream or downstream); and (iii) movements greater than 5 km upstream. Four flow categories were used: (i) flow less than 5 000 megalitres per day (M/L); (ii) between 5 000-10 000M/L; (iii) between 10 000-15 000M/L; and (iv) greater than 15 000M/L. The number of movements that fall into these categories are presented in Table 1.

Bayesian Analysis

Koehn (1997) showed that Murray cod undergo an upstream movement (>5 km) over the entire spawning period. What was unclear was the function of the stimulus to move and whether it may be demonstrated that there is an increasing probability that Murray cod would move greater than 5 km upstream with increasing flow. The mean flow pattern from 1992-

Table 1. Number of movements recorded in each category for the Ovens River movement data during the Murray cod spawning season (start of July to end of November) (Koehn unpubl. data).

	Median flow (M/L)			
	<5 000	5 000-10 000	10 000-15 000	>15 000
1992/1993 movement				
>5 km downstream	0	1	1	1
< 5 km	1	20	6	21
>5 km upstream	0	0	2	3
1993/1994 movement				
>5 km downstream	7	8	2	4
< 5 km	0	15	11	22
>5 km upstream	2	7	6	14
1994/1995 movement				
>5 km downstream	6	0	0	0
< 5 km	15	0	0	0
>5 km upstream	10	0	0	0
1995/1996 movement				
>5 km downstream	7	3	5	1
< 5 km	9	9	6	3
>5 km upstream	10	4	3	3

1996 in the Ovens River during the spawning period shows that flows tend to build up over time. The increase in flow rate is sequential with the <5 000 M/L flow category preceding the 5 000-10 000 M/L category and so forth. Our expectation, if movement >5 km upstream and flow are positively related, was that changes in the general upstream migration rate should mimic the flow pattern. Since the flow categories were sequential, we were therefore interested in how the probability of a movement >5 km changed with each increasing flow category. This probability is conditioned on the probability of upstream movement in the previous category (i.e. given the number of movements >5 km upstream when flows are in the <5 000 M/L category, was there an increase in the probability of this movement in the 5 000-10 000 M/L category?). The data collection limitations in this study have provided difficulties in analysing these data with conventional statistics such as Analysis of Variance. If we were to use Analysis of Variance, substantial problems would occur with how to treat the poor balance and lack of replication (there is only one Ovens river). The Bayesian approach provides a method where we can quantify the relationship by using an iterative approach that updates the prior with the data from the previous category. This provides quantification of how the probability of an event changes given the conditions before the change. i.e. given the current flow regime and the number of large movements observed, what is the probability of increased movements if flows are increased?

The data have been analysed using First Bayes (www.shef.ac.uk/~stl ao/1b.html). Unfortunately, the current version of First Bayes does not allow full specification of the prior distribution. This limitation may be overcome by initialising the computations using a weak (uninformative) prior (p(mu, sigma^2) proportioned to sigma^{-2} and then calculating a posterior. This can then be used to update the weak prior before the next iteration. A N(mu, sigma^2) likelihood function was chosen to calculate the posterior since the data were normally distributed.

The posterior distribution for <5 000M/L was calculated, first using an uninformative prior for the probability of movements >5 km. The prior was then updated with this posterior and the posterior distribution for the 5 000 - 10 000M/L data computed.

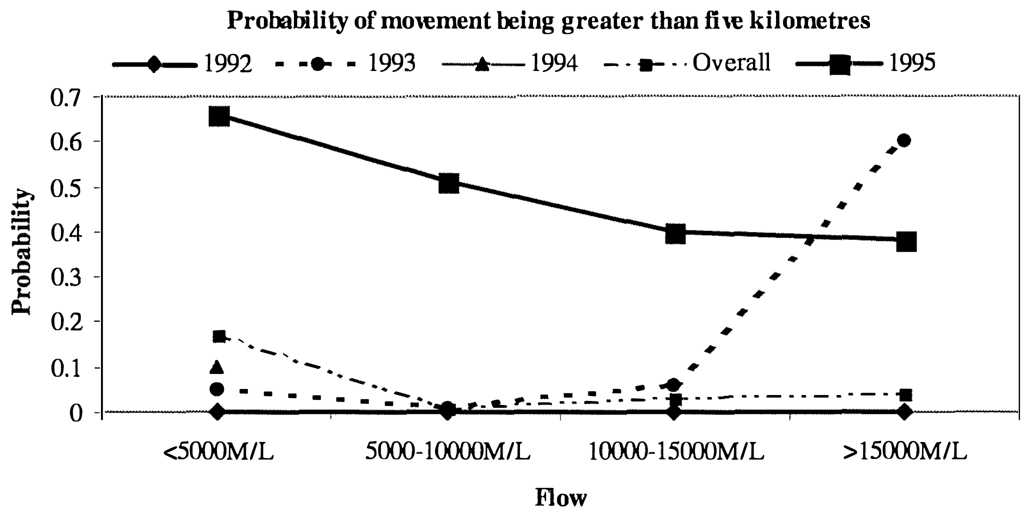

Figure 1. Probability of movement being greater than 5 kilometres with increasing flow for each year of the study.

The probability of movement >5km was recorded, the prior updated and the process repeated for the 10 000-15 000M/L and >15 000M/L flow categories. The process was then repeated for each year. Analysing the data this way allows us to examine whether the probability of movement >5 km increases with each flow increment, given how likely it was during prior flow conditions. The data in each flow category were then combined across years, and the analysis performed to examine the overall pattern of movement with flows (Figure 1).

The analysis shows that 1993 was the only year that the probability of movement >5 km increased as flow increased. In all other years there was no increasing probability of large movements upstream with increasing flow, indicating that flow itself does not appear to be an important stimulus for upstream movement in the spawning period. There are several possible explanations for these conclusions. An extremely large flood coincided with the spawning season in 1993 where flows were elevated for longer periods than in other years. The relationship between movement and flow observed may be an artifact of this flood. In 1994, flows did not occur above 5 000M/L restricting the analysis in that year. In 1992 the probability of large movements was zero at any flow and in 1995 the probability of large movements decreased. The absence of large movements in 1992 was most likely due to the study being commenced during the early part of the spawning season and the number of fish radio tagged was small. The combined data suggest that in isolation, flow is most probably not that important for stimulating large movements.

Design considerations for Bayesian analysis

The use and generation of the prior appears to be the most controversial aspect of using Bayesian methods in the scientific literature (Walters and Ludwig 1994; Crome *et al.* 1996; Dennis 1996; Ellison 1996 and Chen and Fournier 1999). Three methods for calculating the prior probability distribution are commonly used:

1. a uniform prior over some specified range of parameter values;
2. an informative prior based on the empirical distribution from previous or similar studies; and
3. an informative prior based on basic biology combined with scientific intuition (Walters and Ludwig 1994).

If a uniform prior is chosen, then the limits of the range need to be carefully chosen. If the prior is considered zero outside of a particular range (i.e. zero probability that the parameter is outside of this range) then the posterior will be "suspect" for values outside this range (Walters and Ludwig 1994; Adkison and Petermen 1996). Using an informative prior based on an empirical distribution or on scientific judgement needs also to be carefully considered. The transferability of an empirical distribution needs to be examined: are the scales, location and species that the data describe relevant to the current situation (Walters and Ludwig 1994)? Walters and Ludwig (1994) argue strongly against the use of scientific judgement for two reasons. Firstly, the track record of scientists making intuitive prediction is poor and estimates generally represents statements of "over-confidence" about what is known. Secondly, it is very easy for past experience with the current data to bias the estimation.

The outcomes of a Bayesian analysis, as with a frequentist analysis, are impacted upon the distribution of the data (Chen and Fournier 1999). The analysis conducted by Chen and Fournier (1999) simulated a data set that included outliers in order to evaluate sensitivity of the posterior distribution to their presence. The posterior distributions were severely biased in the presence of outliers when Bayesian analysis assuming normally-distributed error terms was performed. This sensitivity is most likely a result of the small tails associated with normal distributions where the probability of occurrence drops off quickly a few standard deviations from the mean. Chen and Fournier (1999) offer a method to minimise the influence of any outliers by using a mixture distribution that increases the size of the tails so that the severity of this "drop off" is reduced. Alternatively, the data may need transformation (as in frequentist methods) to minimise the impact of the outliers (Crome *et al.* 1996).

Once the assumptions of the analysis are met, the data are generally combined with the prior distribution to calculate the posterior through a likelihood function, which provides a joint posterior (i.e. a summary of all the parameters). The joint posterior is integrated over all parameters to obtain the marginal posterior distribution for the parameter of interest (Crome *et al.* 1996). Typically, the data are considered random samples from a normal distribution as the assumptions from a normal distribution provide the most computationally simple procedures (Walters and Ludwig 1994). More complex functions can be used however, provided it is clear how to estimate the marginal posterior distributions (Walters and Ludwig 1994).

Bayesian analysis, as with any analysis, requires an experimental design that structures the data so that the probability for the research question can be estimated (Anderson 1998). The benefit of a Bayesian approach is that it is an iterative process. The results of the analysis, together with the shortcomings of the data can be taken into account, and future analyses benefit through the quantitative education of the prior. I encourage any reader to further explore the possibilities of Bayesian methods and recommend the papers by Anderson (1998) and Crome *et al.* (1999) as examples of the possibilities of Bayesian methods.

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Including spatial structure when conducting yield-per-recruit analysis

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Abstract

Yield-per-recruit analysis is one of the most commonly applied techniques in fisheries stock assessment. However, most applications of this technique assume that length is related deterministically to age and ignore any spatial structure in the population. A variant of yield-per-recruit analysis that allows for variability in growth rate and asymptotic length among individuals, and models the spatial structure of the population by means of a Markov transition process, is outlined. This variant is applied to data for tiger flathead, Neoplatycephalus richardsoni, *off south eastern Australia. The parameters related to growth and depth distribution are obtained through a generalised 'catch curve' analysis.*

Introduction

Yield-per-recruit analysis (Beverton and Holt 1957) is one of the commonly applied approaches for providing management advice for fish populations. The popularity of this approach can be ascribed to its relative simplicity and the fact that the model inputs (natural mortality, selectivity-at-age, and mass-at-age) are readily available for most species, or reasonable guesses can be obtained by inference with similar species. However, yield-per-recruit analysis is not without its weaknesses. Prime amongst these are the assumptions that population is in steady state and that recruitment is independent of the size of the spawning stock. The last of these assumptions is only needed if the results of the analysis are used to make inferences about likely yields (rather than levels of yield-per-recruit). Recent analyses of stock and recruitment data sets for many species (e.g. Myers *et al.* 1994; Myers and Barrowman 1996) reveal that the assumption that recruitment is independent of spawning-stock size is probably invalid for many, if not most, stocks.

Other weaknesses of the yield-per-recruit approach as it is usually applied are that it completely ignores the dynamics of movement and migration and assumes that length is related deterministically to age. This paper outlines an extension to yield-per-recruit theory that is not subject to these weaknesses and applies it to data for tiger flathead (*Neoplatycephalus richardsoni*) off south eastern Australia. Readers interested in how yield-per-recruit theory can be extended to handle (deterministic) stock-recruitment effects should consult Sissenwine and Shepherd (1987) and Hilborn (1989). Fournier and Archibald (1982) and Methot (1989, 1990) describe extensions to yield-per-recruit theory that allow for stochastic recruitment and violations of the assumption that the system is in steady state.

Methods

The basic yield-per-recruit model

The model divides the population into several growth groups to represent individual variability in growth. All animals in a growth group grow according to the same growth curve but the growth curve differs among growth groups. This approach to modelling individual variability in growth was chosen because it is simpler than attempting to develop a size-structured (e.g. Bergh and Johnston 1992) or an age- and size-structured (e.g. Deriso and Parma 1988) population dynamics model. The extended yield-per-recruit model considers the dynamics of the population by age within each of n spatial cells:

$$N_a^{A,l} = \begin{cases} \tilde{N}_0^{A,l} & \text{if } a=0 \\ \sum_{A'} X_{L_a^l}^{A',A} N_{a-1}^{A',l} e^{-Z_{a-1}^{A',l}} & \text{if } 1 \le a < x \\ \sum_{A'} X_{L_x^l}^{A',A} \left\{ N_{x-1}^{A',l} e^{-Z_{x-1}^{A',l}} + N_x^{A',l} e^{-Z_x^{A',l}} \right\} & \text{if } a = x \end{cases} \quad (1)$$

where

$N_a^{A,l}$ is the number of animals of age a in growth group l and cell A,

$Z_a^{A,l}$ is the total mortality on animals of age a in growth group l and cell A:

$$Z_a^{A,l} = M + S_{L_{a+0.5}^l} F^A \quad (2)$$

F^A is the (fully-selected) fishing mortality in area A,

S_L is the selectivity on fish of length L,

L_a^l is the length of an animal of age a in growth group l,

$X_L^{A',A}$ is the probability that an animal of length L moves from cell A' to cell A at the end of the year (given that it survived the year), and

$\tilde{N}_0^{A,l}$ is the distribution of the 0-year-olds among growth groups and cells.

The catch in mass is given by:

$$C = \sum_l \sum_a \sum_A \frac{w_{L_{a+0.5}^l} S_{L_{a+0.5}^l} F^A}{Z_a^{A,l}} N_a^{A,l} (1 - e^{-Z_a^{A,l}}) \quad (3)$$

where w_L is the mass of a fish of length L.

The spawner biomass-per-recruit is given by:

$$SB = \sum_l \sum_a \sum_A w_{L_a^l} N_a^{A,l} \quad (4)$$

where the summations are restricted to the combinations of age and growth group for which L_a^l is greater than (or equal to) the length-at-maturity.

The standard form of yield-per-recruit analysis is obtained if only a single cell is modelled and there is only one growth group.

Application to tiger flathead

Simplifying assumptions

It is necessary to make the following simplifying assumptions to apply the above model to tiger flathead:

a) Weight is related to length according to a power relationship:

$$w_L = e_1 L^{e_2} \quad (5)$$

b) Selectivity is related to length according to a logistic curve:

$$S_L = (1 + \exp(-\ell n 19 (L - L_{50}) / (L_{95} - L_{50})))^{-1} \quad (6)$$

where L_{50} and L_{95} are respectively the lengths at which selectivity is 50% and 95%.

c) Length is related to age by means of a von Bertalanffy growth equation. The parameters ℓ_∞ and κ differ among growth groups but t_0 is the independent of growth group, i.e.:

$$L_a^l = \ell_\infty^l (1 - e^{-\kappa^l (a - t_0)}) \quad (7)$$

d) The spatial cells are aligned linearly, movement occurs to adjacent cells only, and the rate of movement is a function of length:

$$X_L^{A',A} = \begin{cases} P_1^{A'} + (P_2^{A'} - P_1^{A'}) L / \bar{\ell}_\infty & \text{if } A' = A+1 \\ Q_1^{A'} + (Q_2^{A'} - Q_1^{A'}) L / \bar{\ell}_\infty & \text{if } A' = A-1 \\ 1 - X_L^{A',A'-1} - X_L^{A',A'+1} & \text{if } A' = A \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

Table 1. The free parameters of the model.

Description	Number of parameters
Growth parameters, $\bar{\ell}_\infty$, σ_{ℓ_∞}, $\bar{\kappa}$, σ_κ, t_0	5
Selectivity for 40 mm mesh, L_{50}, L_{95}	2
Growth parameters, P_1^A, P_2^A, Q_1^A, Q_2^A	12
Average fishing mortality	1
Total	20

where $P_1^{A'}$ and $P_2^{A'}$ determine the rate of movement to nearest 'shallower' cell and $Q_1^{A'}$ and $Q_2^{A'}$ determine the rate of movement to nearest 'deeper' cell. $\bar{\ell}_\infty$ is the geometric mean of the values of ℓ_∞ for the various growth groups. Equation (8) is modified as necessary to handle situations in which a cell is located on a boundary (e.g. if cell A' is the shallowest cell there is no 'nearest shallower cell').

e) 0-year-olds are found in the shallowest spatial cell only:

$$\tilde{N}_0^{A,l} = \begin{cases} 1/n_L & \text{if } A \text{ is the shallowest cell} \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

where n_L is the number of growth groups.

Assumptions (a) and (b) are standard assumptions when conducting yield-per-recruit analysis while assumption (c) is a generalisation of the common assumption that length is related to age according to a von Bertalanffy growth equation. Equation (8) makes the assumption that the spatial cells are large enough that annual movement is restricted to being between adjacent cells and that the rate of movement changes linearly with length. These assumptions cannot be tested directly because of paucity of data. However, alternative parameterisations for movement can be compared based on fits to available length-frequency data. Assumption e) is motivated by the absence of 0-year-olds from the more offshore survey length frequencies. This assumption is, however, inconsequential for the purposes of this study because the fishing gear poorly selects young fish so errors in modelling their behaviour are unlikely to impact the final outcomes noticeably.

Parameterisation

Some of the parameters of the above model are pre-specified rather than being estimated. The values for the parameters of the length-weight relationship (Equation 5) were derived independently of the model (I. Knuckey, MAFRI, pers. comm.), the rate of natural mortality, M, is assumed to be 0.15yr^{-1}, the lengths at 50% and 95% selectivity are taken to be 35 and 40 cm respectively, the length-at-maturity is taken to be 30 cm, the plus-group is taken to be age 20, and 16 growth groups are modelled. The number of potential growth parameters is reduced to five by assuming that ℓ_∞ and κ are log-normally distributed. This reduces the number of parameters related to growth from 33 (16 values for each of ℓ_∞ and κ and a single value for t_0) to five ($\bar{\ell}_\infty$, σ_{ℓ_∞}, $\bar{\kappa}$, σ_κ and t_0). Four spatial cells are considered in the analysis (defined by depth zones off New South Wales of 25-50m, 50-150m, 150-250m and 250-600m). The specific choices for the depth zones are based on data availability.

The values for the parameters not fixed from auxiliary information (Table 1) are determined by fitting the above model to ageing, relative abundance and length-frequency data. The basic data are the mean lengths-at-age from the ageing data collected by the Central Ageing Facility, the relative abundance of flathead by depth zone from surveys conducted by R. V. Kapala and CSIRO, and the length-frequency distributions by depth from these surveys. Account is taken in the fitting procedure that the surveys were conducted using a variety of trawl mesh sizes (40, 44, and 90 mm). The standard errors for the various data sources were obtained through bootstrapping.

The estimation involves minimising the following objective function:

$$SS = \lambda SS_1 + SS_2 + SS_3 \quad (10)$$

$$SS_1 = \sum_f \sum_g \sum_A \frac{1}{2(\sigma^I_{f,g,A})^2}(I_{f,g,A} - \hat{I}_{f,g,A})^2$$

$$SS_2 = \sum_f \sum_g \sum_A \sum_L \frac{1}{2(\sigma^p_{f,g,A,L})^2}(p_{f,g,A,L} - \hat{p}_{g,A,L})^2$$

$$SS_3 = \sum_a \frac{1}{2(\sigma^L_a)^2}(L_a - \hat{L}_a)^2$$

where:

$I_{f,g,A}$ is the catch-rate index for cell A based on survey type f (CSIRO or Kapala) fishing with gear size g

$\hat{I}_{f,g,A}$ is the model-estimate of the catch-rate index for cell A based on survey type f fishing with gear type g:

$$\hat{I}_{f,g,A} = q_f \sum_l \sum_a S^g_{L^l_{a+0.5}} N^{l,A}_a e^{-Z^{l,A}_a/2} \quad (11)$$

$\sigma^I_{f,g,A}$ is the standard deviation of $I_{f,g,A}$

λ is the pre-specified weight assigned to the catch-rate data (set equal to 100 for the purposes of this study)

$p_{f,g,A,L}$ is the proportion of the catch in cell A from fishing by survey type f using gear type g that is in (25mm) length-class L

$\hat{p}_{g,A,L}$ is the model-estimate of the proportion of the catch in cell A from fishing using gear type g that is in length-class L:

$$\hat{p}_{g,A,L} = \tilde{S}^g_L \tilde{N}^A_L / \sum_{L'} \tilde{S}^g_{L'} \tilde{N}^A_{L'} \quad (12)$$

$\sigma^p_{f,g,A,L}$ is the standard deviation of $p_{f,g,A,L}$

$\hat{L}_a$ is the model-estimate of the mean length of a fish of age a in the catch:

$$\hat{L}_a = \sum_A \sum_l L^l_{a+0.5} S_{L^l_{a+0.5}} N^{l,A}_a e^{-Z^{l,A}_a/2} / \sum_{A'} \sum_{l'} S_{L^{l'}_{a+0.5}} N^{l',A'}_a e^{-Z^{l',A}_a/2} \quad (13)$$

L_a is observed mean length of a fish of age a based on ageing data

σ^L_a is the standard deviation of L_a

$\tilde{N}^A_L$ is the number of animals in length-class L that are in cell A in the middle of the year:

$$\tilde{N}^A_L = \sum_a \sum_l N^{l,A}_a e^{-Z^{l,A}_a} \quad (14)$$

where the summations over age and growth group are restricted so that L^l_a lies in length-class L

q_f is the catchability coefficient for survey type f (assumed to be independent of gear type)

S_L is (commercial) selectivity as a function of length (see Equation 6), and

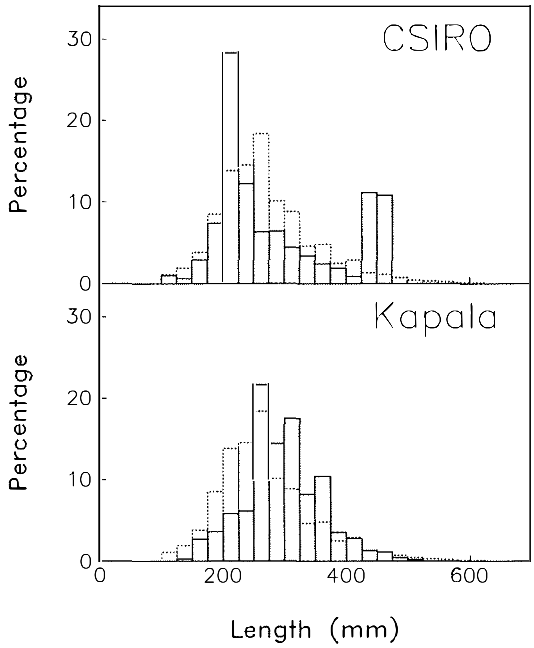

Figure 1. Observed (solid bars) and model-predicted (dotted bars) length-frequencies by cruise-type (CSIRO / Kapala) for the 25-50m depth zone. For ease of presentation, the length frequencies have all been scaled to 100.

$\tilde{S}_L^g$ is the selectivity on fish of length L by gear type g.

The selectivity pattern for 90 mm mesh is assumed to be same as that for the commercial fishery while the selectivity pattern for 40 mm mesh (assumed to be the same as that for 44 mm mesh) is estimated. This estimation approach is a generalisation of the traditional 'catch curve' approach to estimating fishing mortality (e.g. Ricker 1975).

Results and discussion

Figure 1 shows the fit of the model to the length-frequency data for the shallowest (25-50m) depth zone. Results are shown separately for data collected by CSIRO and by R. V. Kapala. The model captures the overall pattern quite well. However, it is unable to mimic the peak between 410 and 430 mm in the CSIRO length frequency, which is not apparent in the Kapala data. The peak in the CSIRO length-frequency data is either a reflection of sampling error or, more likely, the impact of variable movement / recruitment (features that the model does not incorporate). The fits to data for other depth zones (not shown here) suggest that the model is able to mimic the data well. Figure 2 shows the observed and model-predicted mean lengths at age. The model is again able to capture the underlying structure of the data, although it fails to predict well for old fish. This is perhaps not surprising as large fish comprise only a small fraction of the population.

Figure 3 plots yield-per-recruit against spawner-biomass-per-recruit for three different choices for the distribution of fishing mortality by depth. The "deep" fishing mortality profile increases fishing mortality linearly from 0 in the 25-50m depth zone to a maximum value in the 250-600m depth zone while the "shallow" fishing mortality profile decreases fishing mortality from a maximum value in the 25-50m depth zone to zero in the 250-600m depth zone. The "flat" fishing mortality profile sets fishing mortality to the same value in all depth zones. Fishing

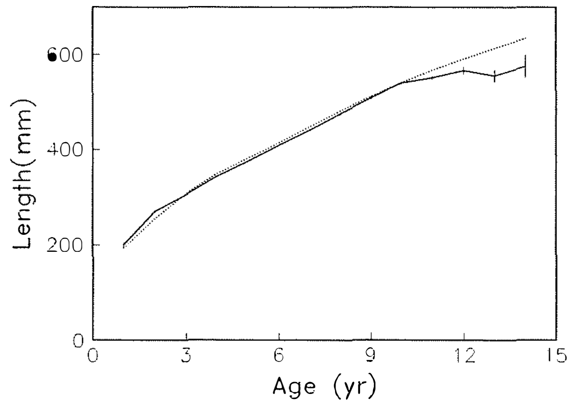

Figure 2. Observed (solid lines) and model-predicted (dotted lines) mean lengths at age. The vertical lines denote one standard error.

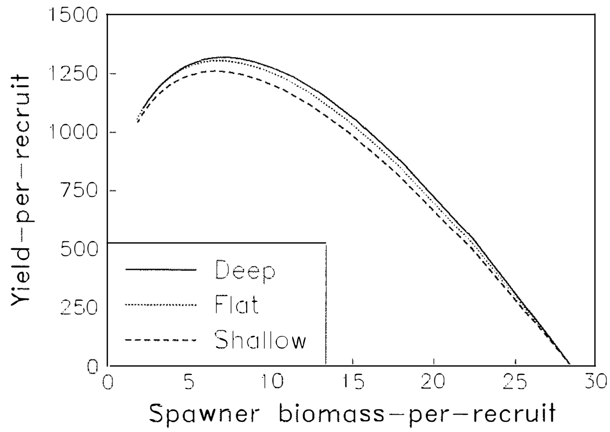

Figure 3. Yield-per-recruit as a function of spawner-biomass-per-recruit for three alternative distributions of fishing effort.

according to the "deep" fishing mortality profile leads to higher yields for all levels of reduction in spawner biomass indicating that it is clearly the superior fishing strategy. However, the extent of difference between the three profiles is not particularly large. For example, the maximum yield-per-recruit for the "deep" profile is only 4.6% larger than that for the "shallow" profile.

The yield-per-recruit model outlined in this paper can be extended to allow for a stock-recruitment relationship and temporal as well as spatial dynamics. Such extensions will lead to models similar to those used by Punt *et al.* (submitted) and Deriso *et al.* (1991). Other extensions could be to output the age- / size-structure of the catch, to reduce the time-step of the model, and to allow for multiple fleets / gear-types.

The specific approach to modelling movement considered in this paper (Equation 8) was tailored to the situation for flathead off south eastern Australia. As such, it would not be appropriate for species for which the hypothesis is invalid that movement is between adjacent spatial cells on an annual basis or for which annual migrations occur (e.g. school shark). However, the basic formulation (Equations 1 – 4) provides a general theory within which the implications of spatial differences in fishing mortality can be considered within a yield-per-recruit framework.

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Directing experiments in freshwater ecology using spatial population models developed for freshwater fish

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Abstract

The process for undertaking most ecological experiments is to use a set of observations, develop an explanation for the observations, formulate and test the null hypothesis, interpret the results and change or update any of the preceding steps as need be. When the habitat and dynamics of fish populations are complex then an explanation of a set of observations may also be complex. Conceptual models may be developed to explain these observations; however it may be difficult to develop testable hypotheses due to complex interactions, including movement between populations. Population models can be developed that provide the required synthesis of information from which predictions are readily made. Stochastic population models typically include mechanisms for demographic variation and environmental variation and may also include spatial structure. These models can be used to develop testable hypotheses for freshwater fish and help direct research efforts to improve our understanding of the ecology of freshwater fish.

Introduction

Underwood (1990, 1997) describes a method for experimental investigation of biological processes and patterns. Underwood states the method to include: the use of a sequence of observations in space and time or some anomaly in such a sequence; explanations of the biological processes that led to the observations (Underwood defines this to be the development of a model; here it is defined to be the development of a conceptual model); derive predictions from the conceptual model; construct the logical null hypothesis; test the logical null hypothesis by experiment and either reject the null or accept it; and finally, the process should be repeated. If the null is rejected then the process should be repeated using a conceptual model that is more general or specific, as the case may be, together with more stringent testing criteria. However, if the null is accepted then a new conceptual model needs to be developed.

It is often difficult to observe fish in their natural environment and to relate their occurrence to their ecology, particularly Australian freshwater fish due to the difficulties of undertaking life history studies in turbid and variable Australian rivers. However, with improved observation techniques, such as the ability to implant radio transmitters into some of the larger freshwater fish species, simple patterns have begun to be developed about these species. For example, in the same period each year some Murray cod migrate from Lake Mulwala up the Ovens River and then return; subsequently larval drift from the river into the lake has been observed as well as larval drift from the lake to the irrigation outlet channel. It generally takes approximately one to two days for a water mass to move through the Ovens River from Wangaratta to Lake Mulwala depending upon the flow. However,

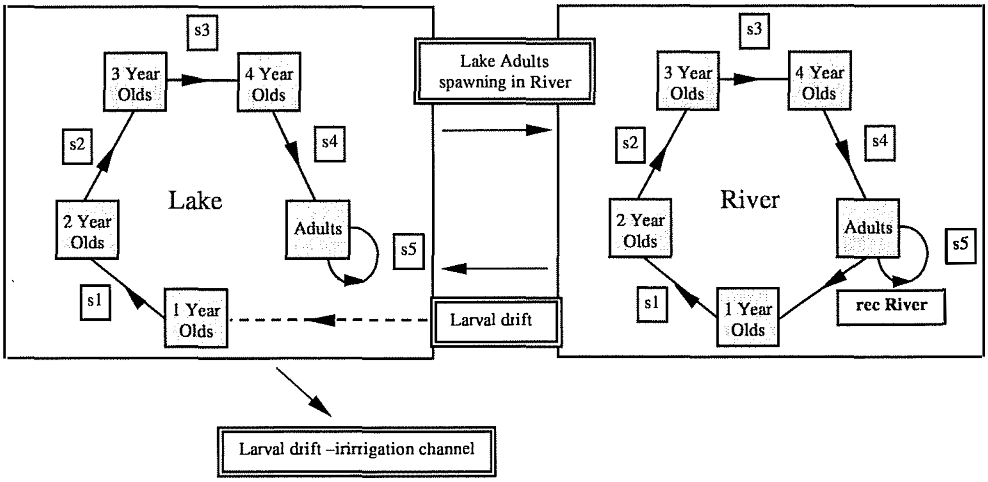


Figure 1. Population structure for the Murray cod metapopulation model. s1 – proportion of one-year-old fish surviving to become two-year-old fish (annual survival rate); similarly s2, s3 and s4; and s5 – annual survival rate for adult fish. Recruitment of one-year-old fish occurs at two levels: rec River – recruitment into the river population from both river adult fish and lake adult fish on a spawning run; and larval drift – from the river population into the lake.

during over-the- bank flows water velocities drop to zero in some areas on the flood plain. Through sampling the Murray cod populations in the lake and the river for a number of years it appears that these populations are relatively stable. Given this variation in the environment, the occurrence, timing and size of flows and the relationship with fish spawning is clearly of interest in exploring fish population dynamics.

The conceptual model presented in this paper is developed from the set of observations of fish and larval movement. Subsequently, predictions can be made and hypotheses tested. However, with an apparent lack of useful information it would seem that the possibilities are infinite and certainly there are many. On the other hand, a general understanding of the Murray cod's ecology is more comprehensive than this set of observations and some method of combining the observations with this knowledge base is required. A population model may offer the structure within which our knowledge base may be combined with observations to develop a formal statement of understanding. A population model requires a rigorous statement of relationships from which it is possible to form simple testable hypotheses. The set of observations about the lake and river Murray cod populations include movement of fish and larvae from one habitat type to another, that is a riverine habitat and a lake habitat. Population models that differentiate between habitats, and that have some interactive terms between habitats (movement), are spatially explicit (exhibit spatial structure) and as a class of models are generally called metapopulation models (see Caswell 1989; Hanski 1991;Hanski and Gilpin 1991; Burgman *et al.* 1993; Possingham and Davies 1995; Akçakaya *et al.* 1997 and references therein).

Metapopulation models

Metapopulation models exhibit a full range of possibilities with regard to modelling more than one population. Models may be constructed that may be either continuous or discrete, deterministic or stochastic, concern whole populations or individuals, regions or patches. The approach adopted will depend upon the information available, the size of the populations to be modelled, the questions asked and

Table 1. Testable assumptions for the Ovens River/Lake Mulwala Murray cod metapopulation.

Assumed process	Scenario	Support	Negation
Larval drift	High: within–bank flows Low: over–the–bank flows	Measured difference between high-low flows. Significant numbers of larvae on floodplain	No perceived change between high/low flows. Larvae not significantly present on the floodplain
Adult fish movement	Spawning run	Significant numbers of adult fish moving at one time of the year	Only small numbers observed; fish move all year round
No other movement between populations	Spawning run and larval drift only movement processes	Current understanding	Juvenile fish found to be moving between populations
No lake recruitment	No spawning in lake	Not observed to occur	Fish found breeding in the lake

the types of outcomes desired. The construction adopted for the Murray cod Ovens River/Lake Mulwala metapopulation is an age/stage model with yearly age classes for juveniles and once five years of age is reached the fish is considered to be an adult thereafter (see Figure 1). The matrix structure required to model the system presented in Figure 1 is a multi-regional design (for detail see Caswell 1989 and Burgman *et al.* 1993). Recruitment to the first age class (one-year-olds) is the proportion of eggs laid that develop and survive to be one-year-olds, which includes the hatching of eggs into larvae, larvae developing into fingerlings and fingerlings attaining the age class of one-year-old. The model represents only female populations at each location where it is assumed that there are enough males to carry out the necessary fertilisation of eggs.

The same life history parameters are specified for each population with the exception of larval to fingerling survival. The only interactive movements considered between the two populations are adult spawning movement and larval drift (see Figure 1). Discounting the effects of eddies, anabranches etc., flow rates suggest that a water mass may pass through the river and lake populations in two to three days. It generally takes larvae about seven days after hatching to develop into a mobile form able to manipulate their position in the water column. Consequently, some mechanism must be occurring to promote the stability of both the river and lake populations given larval drift. The model constructed does not propose to account for all the reasons why the population might be stable other than to develop testable hypotheses to expand our understanding.

A number of assumptions may be made about larval drift from the river to the lake: larval drift is constantly low; larval drift is constantly high; larval drift is moderate; larval drift alternates from high to low; larval drift is high but disperses in the lake; and many other possibilities. A scenario that has readily testable predictions is that larval drift swings between high and low (Table 1) depending upon the flow. The biological process that this scenario represents is the over-the-bank flow (flood) where fish lay eggs in the main river channel but larvae are dispersed over the flood plain. Provided the flow remains over-the-bank long enough, the eggs have hatched and the larvae develop into fingerlings before the process of drift impacts upon the larvae by carrying them into the lake and possibly down the irrigation channel. This process describes the low larval drift component. Expanding upon this scenario it is possible to achieve all types of larval drift from low to high depending on the flow. Large flows (floods) result in low larval drift, smaller flows (no rise in river levels at spawning time) result in high larval drift due to the restriction of larval movement to downstream only. Observations over a number of years revealed that most fish with radio transmitters moved into the river in the same period that the fish are known to spawn each year. Some of these fish moved quite large distances. It was assumed that a large proportion of fish moved from the lake upstream into the river to spawn. If this is the case, then there is a small proportion of fish that are left in the lake and are assumed not to be breeding in the lake, as this has not been observed. The consequence of this assumption is that larval drift is the only form of recruitment into the lake.

The assumptions about larval movement are clearly very important to the conceptual model and consequently critical to the population model. Equally important are the assumptions regarding larval survival. These assumptions are set out as follows. Of the larvae that survive in a high flow an average of 70% remain in the river with a coefficient of variation (CV) of 20%. Of the remainder an average of 25% drift and settle out in the lake with a CV of 20%, and 75% of this remainder either perish or drift into the irrigation channel. Of the larvae that survive in a low flow an average of 7% remain in the river. Of the remainder, as in the case of high flows, an average of 25% drift and settle out in the lake with a CV of 20%, and 75% of this remainder either perish or drift into the irrigation channel. For example, of the 400 larvae that hatch in a high flow an average of 280 survive and remain in the river. The remaining 120 either perish or survive in the lake. Applying the above rule, an average of 25% survive in the lake, that is 30 larvae, leaving 90 larvae that perish in this process. In a low flow, for the same 400 larvae, an average of 28 survive and remain in the river. An average of 93 ([400 – 28] x 0.25) survive in the lake and the remainder perish. Larvae that drift from the lake cannot contribute to the metapopulation. The proportions specified above are averages; the survivorships used in the model are drawn from normal distributions with characteristics specified and restricted to the unit interval.

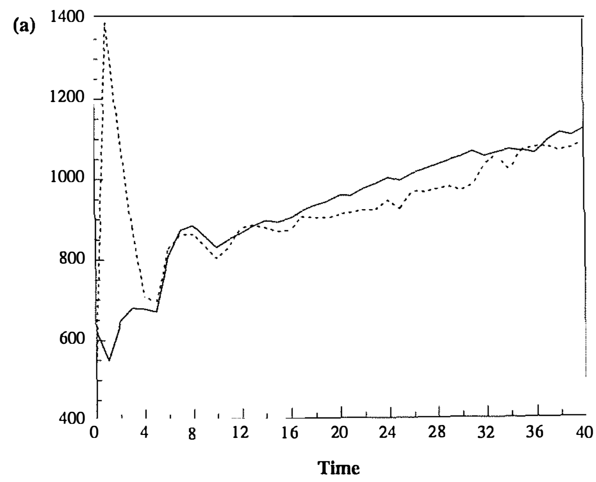
The proportion of female adults from the lake moving into the river to spawn was set at 50%. These females are presumed to be able to find suitable spawning sites in the same manner as the river population. This proportion is fixed, and assumed not to vary. Over-the-bank flows occur irregularly; however, it has been assumed that over-the-bank flows occur on average every five years. This is not an assumption to test, rather a parameter that requires statistical verification and to be adjusted as needed.

Results

All parameters vary according to their specified mean and standard deviation with the exception of the proportion of female adults moving from the lake into the river for a spawning event and the cycle of high flows-low flows. The model is replicated 2 000 times over a period of forty years. The model begins two years after a high flow with a one-in-five chance of a high flow occurring annually thereafter. The initial population size is set at the stable age distribution for this occurrence.

A forty-year forecast period is used to allow the population trajectories to escape the influence of the initial conditions, so that any stability in the simulated populations is a result of the model parameters and assumptions, and not a consequence of initial conditions. Figure 2 shows the mean trajectories of the river and lake populations of both adult and one-year-old fish. The predicted means establish a clear trend once the trajectories escape the influence of the initial conditions around year ten. However, the mean trajectories do not provide any insight into the expected population structure at any given point in time, only average numbers of age/stage classes present.

Individual trajectories may be utilised to examine population structure. Figure 3 provides an example of a single trajectory over the forty-year period



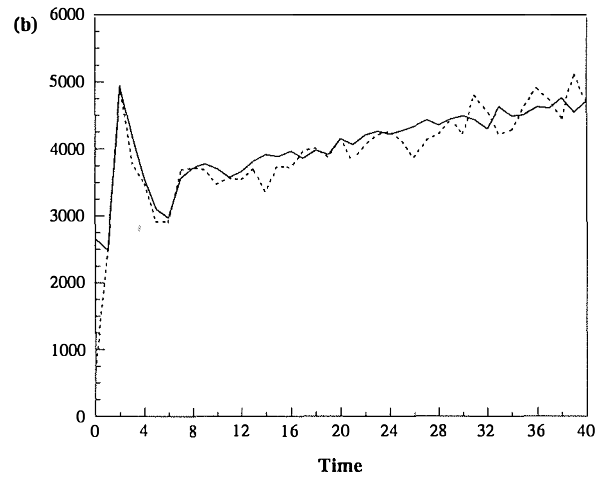


Figure 2. Mean population trajectory for both the Lake Mulwala population (solid line) and the Ovens River population (dashed line); (a) adult, and (b) one-year-old, fish.

considered. Examination of the one-year-old trajectories indicates that recruitment events (equivalent to a high flow the previous year) occur irregularly but consistently throughout the forecast period. Also, in the years of low flows, recruitment to the lake population is generally higher than when there are high flows. Further, it is possible to follow some recruitment events through the various age/stage classes. For example, a flood occurred in year nine that influenced one-year-old recruitment in the river population in year ten. This in turn can be followed through the two-, three- and four- year-olds to the adults in year fourteen. Another point of interest is that between high recruitment events to particular age classes in the river population the number of fish in each age class may be quite low. Recruitment to the lake population is higher in low flows, as expected, and given the number of low flows recruitment is more consistent. The result from this is that generally the lake population is predicted to have a larger representation of juvenile fish particularly in comparison with the river population. These dynamical patterns should be testable and provide either support or opposition to the current understanding. While the numbers are not thought to be representative of what may be observed in reality,

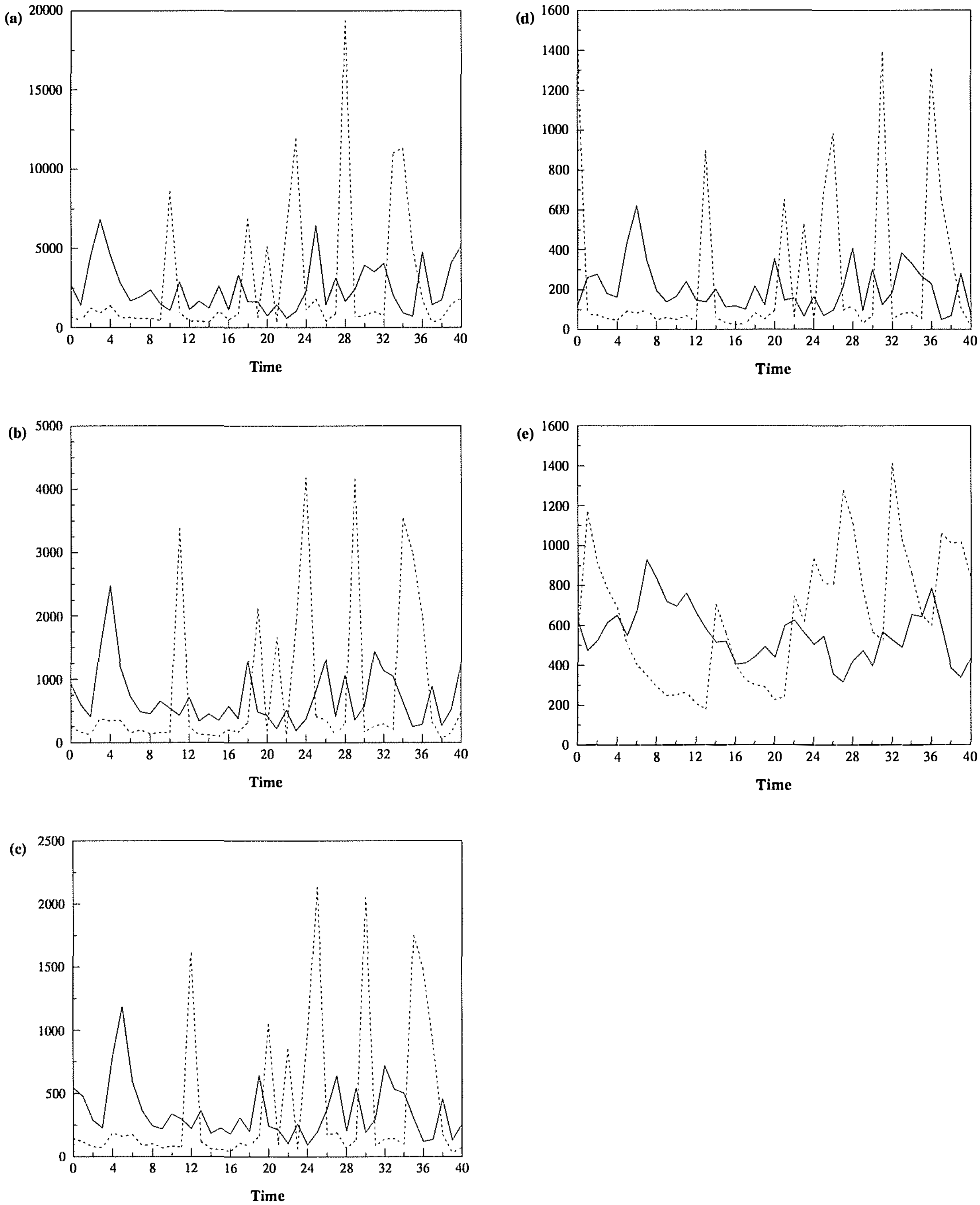


Figure 3. A particular realisation of one replication of the model (a single population trajectory) for all age/stage classes of the Lake Mulwala population (solid line) and the Ovens River population (dashed line); (a) one-year-old, (b) two-year-old, (c) three-year-old, (d) four-year-old, and (e) adult, fish.

the patterns are expected to be similar to those that may be observed and therefore provide support for the hypothesis of interaction expressed in the model. There are many other facets about the model predictions that provide direction in our search for further information. For example Figure 3 between years ten and eighteen illustrates a substantial increase in the number of one-year-old fish in the river the year following a high flow, followed by a substantial decline to continual low levels of recruitment until the year after another high flow. Hence the model provides readily testable patterns on both a short-term and long-term scale.

The hypothesis developed from the construction of the metapopulation model is that larval drift effects the spatial and temporal distribution of age classes in the Ovens River/Lake Mulwala metapopulation. This hypothesis can be tested in a number of ways as already indicated. If the null hypothesis is rejected then it does not necessarily follow that the population model should be accepted, but rather strengthens the argument that the relationships that are postulated are at least plausible and possibly representative of the system. Rejecting the null hypothesis is not an affirmation for the population model itself and should not be taken as one.

Conclusions

The method of experimental investigation proposed by Underwood (1990, 1997) has many similarities with another method that uses predictions from stochastic population models. Population viability analysis (PVA, Boyce1992) is a process that includes combining available information on a species and developing population models that return estimates of the expected time to extinction, or interval quasi-extinction. The viability of a population is the probability that it will persist at some location over some time (generally fixed) period. It is usual as part of the PVA process to develop population models that represent a synthesis of available information, knowledge and intuition regarding the dynamics of a population or species (Ralls *et al.* 1992; McCarthy 1994). The PVA process shares many similarities with the framework that Underwood advocates (see Akçakaya *et al.* 1997 p. 200 and compare with Underwood 1997 p. 9). The population model constructed for analysis in this study is of the type usually associated with PVA, that is explicitly accounting for random events that impact on the life history of the species. While the model is not being used as part of a PVA process, it may well form the basis for such a process and is therefore constructed with equal rigour where the purpose (as in this case) is to develop testable hypotheses. The results from the complete stochastic implementation of the model provide predictions of the mean trajectory over time, which provide some indication of the stability of the modelled populations. However, single trajectories provide the basis for some of the relationships that can be tested.

In the conceptual model presented in this study, movement was modelled in two ways. Firstly, the spawning run of adult fish, where adult fish moved upstream from the lake into the river for the purposes of spawning; and secondly, larval drift from the river to the lake and implicitly from the lake to the irrigation channel (barren habitat). There is scant knowledge on the movement of freshwater fish; however, there are sufficient data to suggest that some Murray cod move upstream to spawn. There is little evidence to show that fish spawn far from the main channel. However, larvae of native fish have been found on the flood plain during an over-the-bank flow. It is thought that larval drift plays an important role particularly when rivers have barriers that prevent larvae from settling out into habitable reaches of the river by forcing them into irrigation channels with little chance of survival.

The model is a representation of the system as it is understood to be, in which case it is expected that certain ecological processes within the two populations can be predicted by the model. Many of the assumptions underlying the model are likely to be false. However, the model has been constructed with a combination of knowledge, available information, and intuition regarding the species and the particular circumstances of the Ovens River/Lake Mulwala metapopulation. The relationships specified within a population are thought to be biologically sensible and therefore plausible. If the processes predicted by the model are proved to be incorrect by empirical observation then we have to question our understanding of the processes involved and develop new hypotheses and new tests, expanding our understanding in the process. The inclusion of movement into the conceptual model helps us to look at more complex scenarios and develop more complex questions regarding threatened aquatic fauna.

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Preliminary analyses of migration and movement of adult, red-legged banana prawns in Joseph Bonaparte Gulf, Northern Australia

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Abstract

Red-legged banana prawns (Penaeus indicus) *are fished commercially in waters between 50 and 100 m in the north-west region of Joseph Bonaparte Gulf, as part of the Northern Prawn Fishery. A spatial closure, south of 13° 57' S, is in place during the first half of the fishing season (April to June) to protect small recruits to the fishery. Fishers however, consider that the closure may stop them fishing large prawns that have returned inshore. The second half of the season opens in August and closes in November.*

In 1997, 8 473 red-legged banana prawns were tagged and released, primarily for a study of mortality and growth. In 1998, a further 9 540 prawns were released. The location of recaptures was documented for 916 tagged prawns in 1997 and 512 tagged prawns in 1998. Tag recapture and commercial fishery logbook information was used to test whether red-legged banana prawns moved continuously to deeper waters or whether they moved first to deep water but then returned to shallower waters. The net vectors of prawn movement were determined and categorical models of recaptures per unit of fishing effort were used to test whether the recaptures were proportional to fishing effort.

Recapture probabilities for any given 12 nautical mile grid for each fishing period were not proportional to the fishing effort in that period. As well, the recapture probability for any given grid varied and was affected by the amount of effort and the fishing period. There is no evidence of a return migration to shallower waters during the fishing season. In the first half of the season tagged P. indicus *were recaptured mainly to the north-east of their release points; and more north to north-west in the second half of the season. The lack of a return migration by the prawn stocks suggests that the current spatial seasonal closure that prevents fishers from fishing the shallow-water stock (recent recruits to the fishery) during April to June is not reducing their access to large prawns that are already resident in the fishery.*

Introduction

Penaeus indicus (the red-legged banana prawn) is a tropical penaeid prawn that is widely distributed in the Indian and western Pacific Oceans (Jayawickrema and Jayakody 1992; Primavera 1996, 1998; Fennessy and Groeneveld 1997). In Australia, this species is found in Joseph Bonaparte Gulf (JBG) and in the Melville Island/Port Essington area on the Northern Territory coast (Grey *et. al.* 1983; Somers 1994). Red-legged banana pawns form about 10% of the catch of the Northern Prawn Fishery (NPF) and they have been fished regularly since the early 1980s with fishing effort and catch increasing markedly (Robins and Somers 1994). Currently, the catch fluctuates between about 200 and 1 000 tonnes per year. During this time, overall effort has increased from <20 boat days prior to 1980 to about 1 000 to 1 500 boat days since 1993 (Taylor and Die 1999). Since fishing closures have been imposed in the NPF, the pattern of fishing effort in JBG has shifted from September to December

(1981-1984), through June to September in 1985 and 1986, to effort being highest in May-June and October-November since 1988 (Robins and Somers 1994; Loneragan *et. al.* 1997).

Presently, fishing in the NPF extends over two parts of the year - the first season begins in April and ends in mid-June; the second season begins in early-August and ends in November. During the first season, a fishing closure is in place in JBG, south of 13° 57' S, to prevent fishing on recent recruits to the offshore region. Due to the large tidal range in JBG (up to 7 m), *P. indicus* are fished on the neap tides, when tidal currents are least. Thus, over a tidal cycle, fishing effort is high on the late spring-neap, neap and early neap-spring tides, and low to non-existent at other times when the fleet moves to fishing grounds north of Melville Island and Port Essington, outside the JBG. The extra steaming time that this fishing pattern generates, together with the remoteness of the JBG and the lower price of *P. indicus* in comparison to other species of prawns, makes the JBG a less attractive area to fish than other parts of the NPF. As a result, the annual fishing effort in the JBG fishery is dependent on the catch levels elsewhere in the NPF; if catches are good elsewhere, effort in JBG is low. Lately however, as catch levels elsewhere have declined due to overfishing (Wang and Die 1996), the JBG fishery has become one of the main fisheries in the NPF and there is increasing concern about the status of *P. indicus* stocks.

In 1997 and 1998, a tag-release-recapture experiment was undertaken in Joseph Bonaparte Gulf to evaluate the status of the *P. indicus* population by determining the natural and fishing mortality, as well as determining growth and movement of *P. indicus* in the Gulf. Similar tagging studies have been undertaken for other NPF prawn species (Somers and Kirkwood 1984; Somers 1987); and other species elsewhere (Glaister *et al.* 1987; Derbyshire *et al.* 1990; Montgomery *et al.* 1995). This paper uses the tag-return data to determine the movement of tagged *P. indicus* in JBG, and to assess whether there is any evidence of an inshore movement of large prawns to areas south of the seasonal closure line in JBG, where they cannot be fished until August.

Materials and methods

Field tagging and release

Live prawns were caught, tagged and released using two vessels; the RV "Gwendoline May", in 1997; and the Austfish Pty Ltd-owned commercial trawler "Libertine", in 1998. Prawns were tagged during two cruises in each year: March and April/May in 1997; and February and March in 1998. Short trawls (about 10 min duration) were made with otter trawls to reduce damage on the prawns, before the catch was winched on board and sorted. Immediately, all live prawns were placed into buckets with fresh seawater, before being transferred to flow-through seawater tanks. The prawns were allowed to acclimatise for about an hour, before they were tagged through the 2[nd] abdominal segment (see section on tags). The tagged prawns were transferred to holding baskets in flow-through tanks and allowed to acclimatise before being transferred to the release cage, and released overboard. The water temperature of the holding tanks was about 28-30°C and the flow rate of the circulating seawater was in excess of 50 l min^{-1}.

Prawns were released on the bottom of JBG in 45-65 m of water. A release cage was used to transfer prawns from the surface to the bottom. It consisted of a rectangular aluminium cage with one complete side in the form of a flap, which opened when activated by a heavy stainless-steel "sender" on the rope which lowered and retrieved the cage.

Tags

Polyethylene streamer tags (Hallprint streamer tags, numbers 5 and 7; 77 mm by 3 mm and 57 mm by 3 mm, respectively) were inserted using an attached needle which was daubed in aureomycin antibiotic ointment. Tag were individually numbered to identify each prawn.

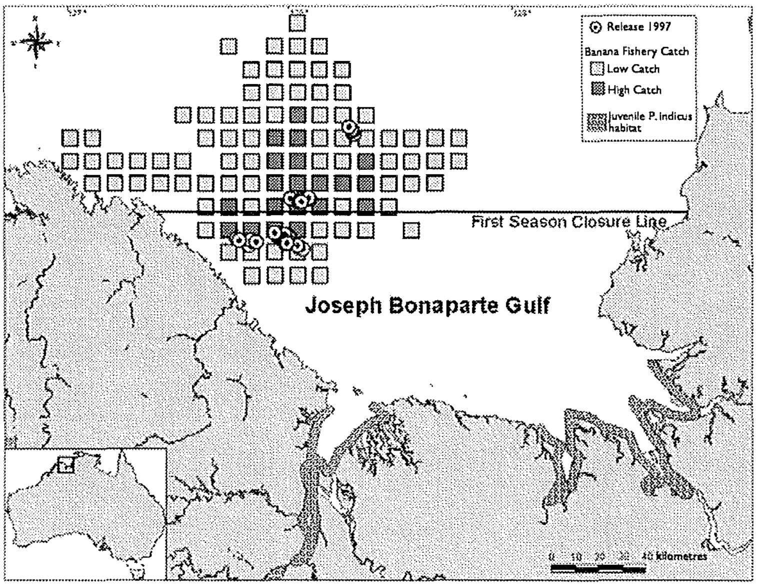

Figure 1. Map of the Joseph Bonaparte Gulf, north-western Australia showing the location of the release sites for tagged prawns (*Penaeus indicus*) in 1997 and the distribution of fishing catches over 10 years from 1988 to 1998. The stippled area on the coast shows the location of mangrove-lined creeks and rivers that are the juvenile habitat for *Penaeus indicus*. (The catch distribution is from grids where at least five vessels fished for at least ten vessel-days over the 10 years, to protect the anonymity of fishing vessels).

Release sites

In 1997, the majority of tagged prawns was released in an area towards the southern extent of the fishing grounds, as defined by the area where catch is relatively high (Figure 1). The release sites were chosen on the basis of the mortality estimation experiment, to ensure good mixing of the tagged prawns and the non-tagged population. Thus, the releases were made in two main localities within a relatively small area. One group of releases in this locality was just south of the first-season closure line. Another group of releases was made just north of the first-season closure line (Figure 1). Most of these latter releases were made during April/May, when prawns were caught farther north than in March.

In contrast, 735 tagged prawns (8.7 % of all releases) were released in the northern portion of the fishing grounds (Figure 1). These release sites were about 50 km north-east from the major release sites.

In 1998, tagged prawns were released in the southern portion of the fishing grounds, similar to the majority of releases in 1997 (Figure 2). No prawns were released in northern sections of the fishing grounds. All prawns were released south of the first-season closure line, except one batch that were released on the line (Figure 2).

Tagged prawns

In 1997, 8 473 live tagged *P. indicus* were released, and in 1998, 9 540 tagged prawns were released. In 1997, the tagged prawns that were released had a mean carapace length of 27.9± 0.1 mm (range 20.8 mm to 35.8 mm, n = 8 473) at release, and a mean carapace length of 31.9± 0.1 mm (range 24.3 mm to 45.2 mm, n = 760) at recapture. In 1998, the tagged prawns that were released and recaptured were larger; mean carapace length at release = 31.1±0.1 mm (range 24.8 mm to 38.4 mm, n = 9 540); mean carapace length at recapture = 34.6± 0.2 mm (range 28.0 mm to 46.3 mm, n = 493).

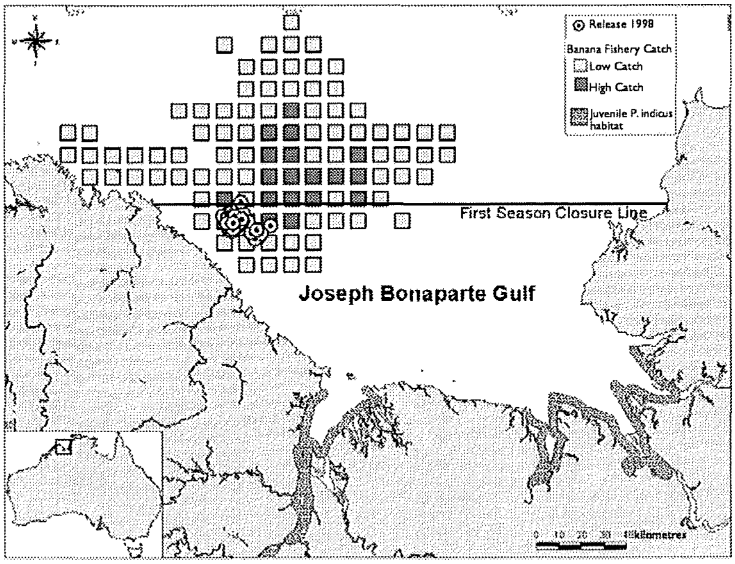

Figure 2. Map of the Joseph Bonaparte Gulf, north-western Australia showing the location of the release sites for tagged prawns (*Penaeus indicus*) in 1998 and the distribution of fishing catches over 10 years from 1988 to 1998. The stippled area on the coast shows the location of mangrove-lined creeks and rivers that are the juvenile habitat for *Penaeus indicus*. (The catch distribution is from grids where at least five vessels fished for at least ten vessel-days over the 10 years, to protect the anonymity of fishing vessels).

Return of tagged prawns

A novel tag-reward scheme was put in place as inducement for the return of tagged prawns and to promote awareness of the tag-release-recapture experiment among the fishing fleet. An information programme was conducted by Brian Taylor of CSIRO Marine Research to ensure that fishers were aware of the experiment and the reward scheme. Fishers were asked to provide details of the location, depth, date and time of the recapture. Recaptured prawns were collected from Darwin, Cairns, Karumba and Perth, at the end of each half-season, in June and November each year. Rewards consisted of a $3 scratch-it lottery ticket for each prawn returned, accompanied by a $50 cash reward for each tag that ended in the number "9". Checks were also made of onshore processing plants to look for recaptured prawns that may have been missed by vessel crews.

Analysis of prawn movement

To accommodate the nature of fishing operations, as driven by tidal cycles, the fishing season (the possible time span over which tagged prawns could be recaptured) was divided into fishing periods (Table 1). Fishing periods were referenced to the neap tides, including the week before and the week after the neap when most fishing occurred. Fewer boats fished in JBG during 1998 and they caught fewer tagged prawns, so only the first half of the fishing season was divided into fishing periods. Changes in the movement of prawns during the year were analysed using these reference fishing periods.

Tagging did not provide information on the short-term movements of the prawns during their time at liberty; only a record of the net vector of movement by a prawn from release to recapture. To describe movement, the net vectors were classified within 16 classes corresponding to the arcs of a circle, each class representing 22.5 (Table 2). The arcs were centred on prominent compass points, e.g. north-north-east, south-east or west-south-west. The total number of prawns that moved within each arc was calculated for each fishing period.

Table 1. Fishing periods used in the analysis of movements of tagged prawns.

Fishing period	1997	1998
1	01 April to 16 April	27 April to 10 May
2	17 April to 27 April	11 May to 27 May
3	28 April to 10 May	28 May to 15 June
4	11 May to 24 May	16 June to 31 October
5	25 May to 08 June	
6	09 June to 21 June	
	Seasonal Closure	
9	22 July to 06 August	
10	07 August to 22 August	
11	23 August to 05 September	
12	06 September to 18 September	
13	19 September to 02 October	
14	03 October to 17 October	

ANOVA analysis

A two-way ANOVA was used to compare the mean direction of movement by tagged prawns between fishing periods and months of tagging (1997 and 1998 were analysed separately). Only those fishing periods with adequate numbers of recaptures (>50) were included in the analyses. Thus, for 1997, fishing periods 2, 3, 4, 5 and 9 were analysed. For 1998, fishing periods 1, 2, and 3 were analysed. In 1997, only those prawns released in the southern section of the fishing grounds were included in the analysis as their movement was not consistent with those released in the north-east.

Differences in the direction of movement of tagged prawns were analysed by standardising the direction of prawn movements around the mean direction of movement (X_o). The mean direction of prawn movement was calculated following the method of Mardia (1972). Once the mean direction was calculated, all movement was standardised relative to this mean direction. All the directions travelled by prawns were made to be within the range of -180 to +180 degrees from the mean direction. This process sets a normal distribution around zero degrees for the analysis.

The formula below was used to calculate the standardised direction (X_t') from the observed direction (X_t):-

i.e. if $X_t < X_o$, then $X_t' = -(X_o - X_t)$;

if $X_t < (X_o + 180)$, then $X_t' = (X_t - X_o)$; and

if $X_t > (X_o + 180)$, then $X_t' = (X_t - 360 - X_o)$.

Table 2. The 16 arcs of a circle, based on compass points, used to interpret the direction of movement of tagged prawns.

	Centre point (degrees)	Least angle (degrees)	Greatest angle (degrees)
North	0	348.75	11.25
North-north-east	22.5	11.25	33.75
North-east	45.0	33.75	56.25
East-north-east	67.5	56.25	78.75
East	90.0	78.75	101.25
East-south-east	112.5	101.25	123.75
South-east	135.0	123.75	146.25
South-south-east	157.5	146.25	168.75
South	180.0	168.75	191.25
South-south-west	202.5	191.25	213.75
South-west	225.0	213.75	236.25
West-south-west	247.5	236.25	258.75
West	270.0	258.75	281.25
West-north-west	292.5	281.25	303.75
North-west	0	303.75	326.25
North-north-west	337.5	326.25	348.75

Categorical Models

Log-linear categorical analysis models were also used to investigate the relationship between fishing effort and the catch of tagged prawns within the fishing grounds. Recaptures and effort were grouped into 12 x 12 minute fishing grids (144 square nautical miles), and by the fishing period defined in Table 2.

The following hypotheses were then tested:

(1) **That there is complete mixing of tagged prawns within the fishery:** the hypothesis is that recapture probabilities for any given grid for each fishing period are proportional to the fishing effort in that fishing period.

The predicted number of recaptured prawns R_{ij} in fishing period i and grid j is:

$$R_{ij} = \frac{f_{ij}}{\sum_i f_{ij}} \sum_i r_{ij} \qquad (1)$$

where f_{ij} is the fishing effort and r_{ij} is the observed number of recaptured prawns.

(2) **That the probability of recapture is independent of the fishery**: the hypothesis is that recapture probability for any given grid is constant, independent of fishing effort and fishing period. Under this hypothesis, the predicted number of recaptured prawns R_{ij} in fishing period i and grid j is:

$$R_{ij} = \frac{\sum_i r_{ij} \sum_j r_{ij}}{\sum_j f_{ij} \sum_i r_{ij}} \qquad (2)$$

where f_{ij} is the fishing effort and r_{ij} is the observed number of recaptured prawns.

Results

Prawn movement by compass points

1997

During the first two fishing periods, all recaptured prawns had moved in a north-north-westerly to east-north-easterly direction from their release point. During all of the fishing periods before the mid-season closure (1 to 5), only two prawns out of the total of 601 recaptures had moved in a direction with any southerly component. However, during fishing periods 3 to 5, prawns were caught in a wider arc (180°), from due west, through due north, to due east.

This result is confounded by the fact that during April, May and June, no recaptures could occur south of many of the release points due to the fishing closure south of 13° 57' S. Prawns that may have moved south would not have been detected. Thus, few prawns being recaptured south of their release points was to be expected. Even those prawns that were released a short distance north of the closure line had little chance of recapture to the south of their release point.

However, during the second half of the fishing season (after the lifting of the seasonal closure), most tagged prawns still were caught to the north of their release point, although quite a few had moved west, north-west and east. Only nine prawns out of 148 (6 %) had moved in a direction with any southerly component; for example some had moved south and south-west.

In contrast to prawns released in the south, those prawns released in the northern section of the fishing ground did move in directions with a southerly component. Throughout the fishing season, 47 prawns (63 % of recaptures) moved in the 135° arc from west-south-west to east-south-east. Some had also moved due west, west-north-west and north-west. Also in contrast to those that were released in the southern section of the fishing ground, none had moved in the 90° arc from due north to due east.

1998

In 1998, during the first half of the fishing season (fishing periods 1 to 3), the majority of recaptures (94 %) had moved north in a 90° arc from due north to due east. Six percent moved in the arc from north-north-west to due west. However, as all of the prawns were released south of the first-season closure line, no recaptures could occur south of the line, as no fishing occurred south of the closure line during the first half of the season. Thus, prawn movement to the south could not be detected.

Only 16 recaptures in total were made in the second half of the fishing season, after the lifting of the seasonal closure. However, of those 16 prawns, 63% had moved in an arc from north-north-west to due west, compared to 6% (one prawn) that had moved in a 90° arc from due north to due east. Thirty one percent had moved in a direction with some southerly component.

Statistical analysis of directional prawn movement

During 1997, the mean direction of movement of tagged prawns recaptured during the second fishing period was north (10.2°), which included 9.4° for those released during March, and 18.7° for those released during April/May (Table 3). This direction of movement differed significantly from those during all other fishing periods (Tables 3 and 5). During fishing periods 3, 4, 5 and 9, tagged prawns moved in a north-north-westerly direction (-14.2° to –20.7°) and their mean direction of movement did not differ significantly between each of the fishing periods (Table 3).

The mean direction of prawn movement differed significantly between the two months of tagging. Tagged prawns released during March moved in a northerly direction (0.6°), while those released during April/May moved in a north-north-westerly direction (-29.8°, Table 3).

During 1998, the mean direction of prawn movement differed significantly for the recaptures from each

Table 3. The direction (degrees from -180 to +180 , with 0 being north) and distance (nautical mile) of movement of tagged prawns released and recaptured in Joseph Bonaparte Gulf in 1997. Numbers in parentheses are the recaptures in each fishing period.

	March		**April/May**		**Total**	
	Direction (degrees)	Distance (km)	Direction (degrees)	Distance (km)	Direction (degrees)	Distance (km)
Period 2 (134)	9.4° ± 1.67	44.8 ± 1.39	18.7° ± 7.39	12.2 ± 0.35	10.2° ± 1.66	41.9 ± 1.50
Period 3 (334)	-2.0° ± 2.20	42.8 ± 1.28	-30.2° ± 3.53	16.9 ± 1.06	-15.3° ± 2.17	30.6 ± 1.09
Period 4 (61)	-9.4° ± 4.00	40.2 ± 2.59	-43.7° ± 13.2	27.1 ± 2.87	-20.7° ± 5.43	35.9 ± 2.11
Period 5 (60)	1.3° ± 5.03	32.2 ± 1.56	-33.3° ± 8.24	13.7 ± 1.96	-14.2° ± 5.10	23.9 ± 1.70
Period 6 (80)	-5.0° ± 4.48	33.4 ± 1.46	-33.2° ± 7.62	22.2 ± 1.76	-19.1° ± 4.67	27.8 ± 1.30
Total (669)	0.6° ± 1.31	40.4 ± 0.74	-29.8° ± 2.90	19.1 ± 0.76		

fishing period (Tables 4 and 5). Those recaptures taken during fishing period 1 had moved in a north-north-easterly direction (21.6°), while those taken during fishing period 2 moved north (4°, Table 4). Prawns caught during fishing period 3 had also moved north (10°); however, their mean direction of movement was sufficiently different to those taken in fishing period 2 to be significant ($p<0.05$).

In 1998, the mean direction of prawn movement differed significantly between the two tagging cruises. Tagged prawns released during February moved in a northerly direction (7.7°), while those released during March moved in a north-north-easterly direction (19.8°) (Table 4).

The mean distance that tagged prawns moved was about 40 km, except those released during April/May in 1997. The prawns released during April/May were released farther north than others and they moved an average of about 20 km.

Mixing of tagged prawns and independence of recapture

The analyses using categorical models shows that the recapture probabilities for any given grid for each fishing period were not proportional to the fishing effort in that fishing period (χ^2_{80} = 10 849, $p<0.001$). As well, they showed that the recapture probability for any given grid was not constant and therefore, that it was affected by fishing period (χ^2_{30} = 5 761, $p<0.001$).

Discussion

Direction of movement of adult *P. indicus*

In 1997 and 1998, the number of tagged prawns that were recaptured differed markedly because fewer boats fished in JBG during 1998 and these boats started fishing much later in the year. As a result, the fishing periods used in these analyses are not strictly comparable from one year to the next. However, a consistent trend in prawn movement is evident in both years. During both years, 100 % and 94%, respectively, of the tagged prawns that were recaptured during the first weeks of fishing (fishing periods 1 and 2 in 1997, April 1 - 27; and fishing period 1 in 1998, April 27 - May 10) had moved in an arc from east-north-east to north. During the remainder of the fishing seasons of both years, significant numbers of prawns had moved more north, through to the north-west. In 1997, their westward movement was more pronounced.

In the second half of the fishing season, after the fishing closure was lifted and recaptures south of the line were possible, only six percent of tagged prawns were recaptured in a position to the south of their

Table 4. The direction (degrees from -180 to +180, with 0 being north) and distance (nautical mile) of movement of tagged prawns released and recaptured in Joseph Bonaparte Gulf in 1998. Numbers in parentheses are the recaptures in each fishing period.

	February		March		Total	
	Direction (degrees)	Distance (km)	Direction (degrees)	Distance (km)	Direction (degrees)	Distance (km)
Period 1 (201)	13.5° ± 2.50	31.7 ± 1.13	34.8° ± 2.95	29.8 ± 1.28	21.6° ± 2.04	30.9 ± 0.85
Period 2 (124)	-1.0° ± 2.77	44.7 ± 1.06	8.3° ± 2.66	42.8 ± 1.15	4.0° ± 1.96	43.7 ± 0.80
Period 3 (123)	2.6° ± 2.81	43.0 ± 2.67	14.9° ± 2.84	38.2 ± 1.15	10.1° ± 2.11	40.0 ± 1.26
Total (448)	7.7° ± 1.68	36.7 ± 0.93	19.8° ± 1.80	35.4 ± 0.80		

Table 5. Mean square and significance levels for an ANOVA analysis of the direction of movement of tagged prawns released during two tagging-cruises in each of 1997 and 1998, in Joseph Bonaparte Gulf. The analysis for 1997 only included fishing periods 3,4,5 and 9. When period 2 was included, the treatment "fishing period" became significant, but the ANOVA was unbalanced.

	1997		1998	
	Mean square	(d.f)	Mean square	(d.f)
Tagging cruise	112 381 ***	(1)	16 536 ***	(1)
Fishing period	805	(4)	12 808 ***	(2)
Interaction	1 195	(4)	5 948 ***	(2)
Error	1 202	(659)	600	(442)

release position. Thus, the prawns that were released in the southern portion of the fishing grounds largely moved north and their movement suggests that *P. indicus* continue to migrate north to deeper offshore waters (70-80 m), usually less than about 60 km, and that they don't return inshore. However, some individuals moved farther afield towards Lesueur Island (13° 49.2' S, 127° 16.2' E) and Cape Londonderry (13° 44.4' S, 126° 57.6' E).

Juvenile *P. indicus* are found in extensive inshore mangrove habitats of Cambridge Gulf and the eastern Joseph Bonaparte Gulf (CSIRO Marine Research, unpublished data), south of 14° 45' S, 128° 15' E and 14° 34.8' S, 129° 19.8' E, respectively (Figures 1 and 2). Emigrating juveniles and sub-adults must move from these inshore habitats 200-300 km to the north and north-west to the offshore fishing grounds. They seem to move rapidly across shallower (30-40 m), sandy substrates to the south and east of the area where prawns were tagged in 1997 and 1998. This conclusion is inferred from two sources – little fishing effort occurs in this region during the period when the areas are open to fishing (Figures 1 and 2), and – regular trawling of these areas during the tagging cruises in an attempt to find prawns to tag resulted in no catches of *P. indicus* (R. Kenyon, personal observation). The prawns move beyond the 45 m depth contour into the region where they were found in sufficient numbers to tag for this study.

As no fishing occurred south of the closure line from April to June each year, it is possible that many prawns movedsouthward. They would not have been detected until during the second half of the fishing season. However, southward movement seems unlikely as:-

- large numbers of tagged prawns were not caught south of the closure line during the second half of the fishing season,
- of those tagged prawns caught after the seasonal closure was lifted, most had moved in a northerly direction, and
- during fishing periods 1 and 2, over 90% of tagged prawns had moved in a relatively restricted arc from east-north-east to north. Few had moved eastward or westward.

A difference in habitat to the south of the areas where prawns were tagged and released may also support the contention that *P. indicus* does not return inshore. South of the release area, water depth decreases from 45-50 m to about 30-40 m and the substrates change from mud to sandy substrates.

By contrast, a significant percentage of those prawns released in the northern portion of the fishing grounds moved south and west. This result suggests that initially *P. indicus* move north into the "fishing ground", but don't necessarily continue to move in a northern direction. The release sites in the northern portion of the fishing grounds were about 50 km north-east of the main area of releases. By chance, 50 km is similar to the average distance that tagged prawns moved northward during this study. Thus, it would seem that those tagged prawns released in the north were released towards the "natural" northern extent of their range, which matches the northern boundary of high commercial catches (Figures 1 and 2). Consequently, most of the prawns that were released to the north of the fishing ground did not move farther north; they moved in a more random way. Although some of these prawns moved in west-north-westerly to north-north-westerly directions, none moved in the 90° arc from due north to due east, despite an easterly component of movement being common for tagged prawns released in the southern portion of the fishing ground. Of course, some tagged prawns moved greater distances than average and ranged farther north, east and west. Their distribution matches the distribution of low commercial catches (Figures 1 and 2). Less fishing effort in areas of lower catch may confound estimates of movement, and the incidence of recaptures in relation to effort is currently being investigated further.

The predominant northward movement of tagged prawns does not support the existence of a strong inshore migration of *P. indicus* to shallower waters during the fishing season. However, *P. indicus* probably move toward the western portion of the fishing grounds later in the year, as shown by tagged prawn recaptures being made to the north-west of release points in the latter fishing periods (after a longer period at liberty), compared to recaptures made to the north-east early on. The lack of a return migration suggests that the current spatial seasonal closure, which prevents fishers from accessing the shallow water prawn stocks during April to June, is not reducing their access to the adult population that is already resident in the offshore fishery. The shallow-water stock is made up of a high proportion of recent recruits to the fishery.

Prawn mixing and independence of recapture

In both 1997 and 1998 the tagged prawns from the two months of tagging moved in different directions and were not recaptured in the same area at the same time. This result implies that the prawns released during the two cruises each year may have had different migration patterns, or that the time delay between tagging cruises resulted in incomplete mixing of the prawns that were tagged on each cruise, and a staggered pattern of movement between the two cruises. The prawns were released on the two occasions to facilitate the estimation of natural and fishing mortality; however, their movement in different directions confounds the issue.

Recapture locations are not just a result of fishing effort. At some locations the number of tagged prawns recaptured was greater than would have been expected from the distribution of fishing effort. In other locations, the number of tagged prawns that were recaptured was smaller than would have been expected from the distribution of fishing effort. This result implies that tagged prawns were not fully mixed with the rest of the fished population. The distribution of tagged prawns was more localised than the distribution of the prawn population that was fished by the fleet. Prawns probably recruit to the fishery over a broader front than the area in which prawns were tagged and released. Thus, as the tagged prawns initially moved north-north-east, they probably mixed with the wild population to the north, but not to the west or east. More detailed analyses of recaptures in relation to fishing effort and time at liberty will provide a full account of prawn movement.

Despite the tagged-prawn release sites being chosen for a study of natural and fishing mortality, and despite the restricted range of prawn movements that can be monitored from limited release areas, the information gained on the movement of the recaptured prawns has provided an insight into the effectiveness of the seasonal spatial closure in JBG. Small adult prawns are found south of the closure line, and there is no evidence of a strong inshore migration by large individuals during the first half of the fishing season, and thus the closure does not prevent access to prawn stocks.

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Computer visualisation of spatial models for communication and management

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Abstract

The purpose of numerical analysis is insight not numbers. Many fisheries modellers have suggested that the insights generated by their models could be communicated more effectively with appropriately designed visualisation software. The wide availability of graphical user interfaces for personal computers and elaborate graphical development environments has encouraged this view. This article gives an abridged review of some visual models (AbaSim, SharkSim, CotSim, NerkaSim and the Geographical Fisheries System) that have been developed by Australian fisheries modellers. It appears that no rigorous evaluations have been completed to determine the impact of computer visualisation strategies within Australian fisheries science and management. Although much has been published about the benefits of visualisation for fisheries models there have been few comments on the costs. Such as: numerical inefficiency; platform dependence; loss of batch-processing capability; code ownership concerns; and opportunity costs. It is recommended that future proposals for visual models (spatial or otherwise) in Australian fisheries science and management include an explicit articulation of proposed objectives and defendable methods for evaluating the actual outcomes.

Introduction

Advanced computer technology has enabled the development of sophisticated computational procedures in fisheries science. Not only have the underlying calculations become more ambitious but the interface between the underlying numbers and user have become much more elaborate. This so-called "visualisation" has become big business with expensive software designed and marketed specifically for this purpose (e.g. SAS JMP Statistical Discovery Software - SAS 1999). Computer scientists have studied visualisation and have established an active field of research (Thalmann 1990). Nielson (1991) defines computer visualisation as the process of using computer technology and the "human vision system" to accelerate the process of model formulation, model evaluation and model reformulation.

This article outlines some of the issues associated with computer visualisation in fisheries management and fisheries science, with particular reference to the author's own experiences. Two types of computer visualisation are identified: (1) Data visualisation: where the objective is to display patterns in data using two- or three-dimensional computer graphics and animation, and (2) Gaming visualisation: where a visual interface is used to encourage a user to explore the dynamics of the underlying computer model. Both types of visualisation effectively accelerate the process of model formulation but there are two distinct objectives. Data visualisation is usually employed to entice an expert into the formal analysis of data, whilst gaming visualisation is usually designed to encourage a non-expert to complete an informal analysis of an underlying model. When the term visual model is used in this article it implies that the software had either data or gaming visualisation as a design objective.

Walters (1986) originally suggested that allowing scientists and managers to "game" with a computer model would give them an appreciation of the dynamics of the system and inferred that this supported the management of a fishery. These ideas were more formally discussed and evaluated in Walters (1994). In this later article Walters used gaming visualisation to attempt to understand the responses of resource managers to simulated assessment advice. This advice was generated during the evaluation of simulated harvesting or stocking strategies. These strategies were adapted from earlier work completed at the University of British Columbia by Holling (1978) in the seminal work on adaptive environmental impact and assessment (AEAM). Construction and analysis of a computer simulation model of an environmental issue was an important component of this strategy. Graphics were noted as being a good way to communicate output. Holling (1978) suggested that key stakeholders play a role in actually defining the models within the AEAM workshop process. Gilmour *et al.* (1999) reviewed three catchment management projects with extensive stakeholder input. These projects received mixed comments about the utility of the associated simulation model.

Some examples of computer visualisation in marine resource management

The following models provide an overview of the visual software to which the author has had ready access to review. Many other programs have been written but these are not mentioned here. For example, CSIRO is currently preparing a visual model for management of line fishing in the Great Barrier Reef. This is a failure of this article which should be addressed within a proper review. Any readers of this short article who support this conclusion could please email the author (jscandol@bio.usyd.edu.au), with information (anecdotal or otherwise) on the development, location, analysis and evaluation of visual fishery models in Australia. Most of this information is in the grey literature (or worse) and will be time-consuming to obtain.

SharkSim and AbaSim

Fisheries scientists in Australia were inspired by the approach that Walters (1986) had identified. Philip Sluczanowski co-ordinated the preparation of SharkSim (Sluczanowski *et al.* 1993) and AbaSim (Tonkin *et al.* 1991) for the South Australian Department of Fisheries. The simplicity of the interfaces for these models was compelling, with use of keyboard up and down arrow keys to simulate the management of fishing effort or catch quota. Sluczanowski was quite explicit that these models were for "playing with" and exploring the response of the system to catch and effort decisions (gaming visualisation). Figure 1 shows the main window of AbaSim. This Figure illustrates a time-series of effort, catch-per-unit-effort (CPUE) and underlying biomass. A histogram indicates the age-structure of the catch. This model had the rare ability to illustrate to a casual user some of the issues associated with stock management.

One undeniable benefit of these models was their ability to demonstrate the near uselessness of incremental management actions in preventing overfishing once it had become evident. Incrementalism (Lindblom 1959) or "muddling through" is often the default strategy used by resource managers. Incrementalism involves taking small decisions to ameliorate issues rather than accepting the need for, and initiating, major shifts in management strategy. Incrementalism is often the only feasible decision-making strategy: any employee from a large institution could recognise incrementalism immediately. Within natural resource management it can be disastrous. Once the rate of decline of the

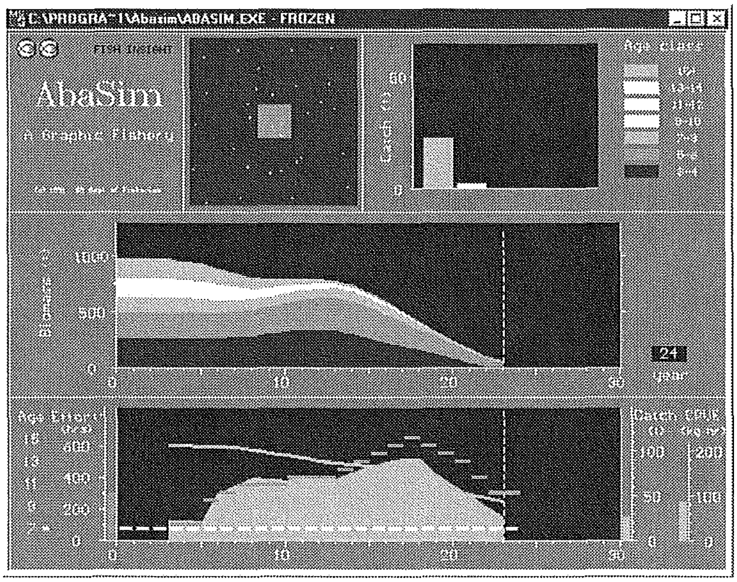

Figure 1. The graphical interface of AbaSim. Lower pane: the filled polygon illustrates the catch history, the horizontal bars indicate the fishing effort (specified by the user) and the catch-per-unit-effort is represented by the solid line. Middle pane: time-series of the underlying age-structured biomass. Upper right pane: histogram representing the age-structure of the current catch. Upper middle pane: a simple graphic illustrating the density of the population.

biological resource exceeds the rate of incremental decision making, resource collapse is inevitable. The author has used AbaSim to illustrate this point on many occasions.

SharkSim created substantial impact in the early 1990s but was not without controversy (Terry Walker pers. comm.). Some scientists considered the model to be overly simplistic and there was debate over the parameter values and CPUE series used, for both gummy shark and school shark. Walker commented that the model was good for communication and education, but these values of SharkSim were compromised once the model was seen as being used for formal stock assessments. Neither AbaSim nor SharkSim included spatial or stochastic components. The untimely death of Dr Sluczanowski was a loss for Australian fisheries science as his approaches were unique, powerful in their simplicity and very transparent. This section does not give justice to SharkSim and AbaSim but introduces their intent.

CotSim

The author was attracted to the approach used by Sluczanowski because it created interest in, and criticism of, simulation modelling. After spending two years developing large-scale spatial population models of crown-of-thorns starfish (*Acanthaster planci*) on the Great Barrier Reef it became evident that the values of simulation models were not easy to communicate. Data and gaming visualisation appeared to be effective strategies to publicise this research and generate greater feedback from managers and scientists. Although these models did not "predict" starfish outbreaks they did capture important qualitative biophysical features of management interest. In particular, this model made it evident that large-scale control programmes could not stop an outbreak event. Such a result should have been available to a wider audience. CotSim 1.0 was written to fill this role (Scandol 1994). The software was distributed to research and management institutions with a questionnaire requesting feedback on the

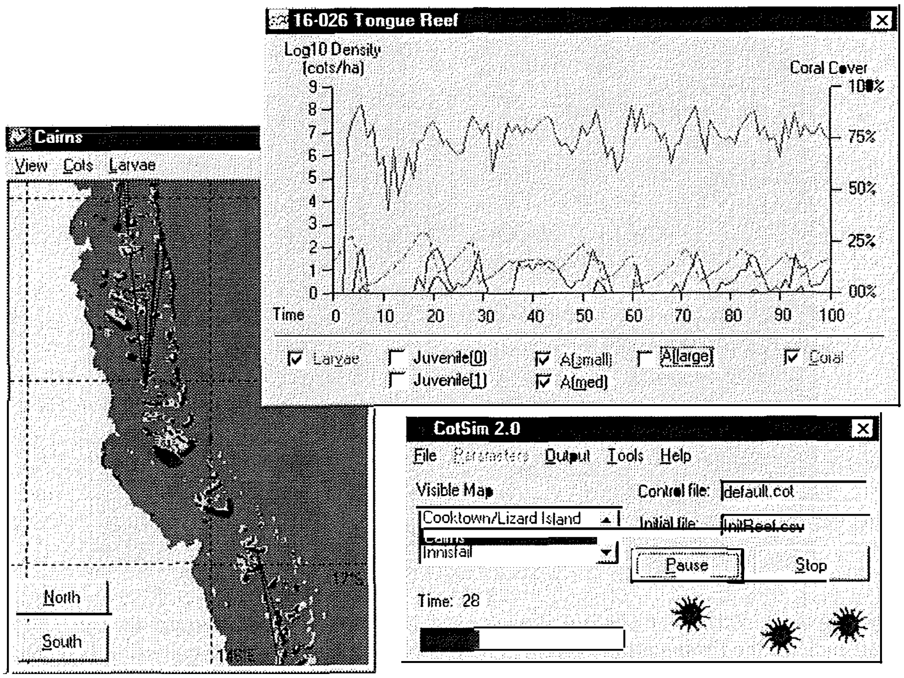

Figure 2. Windows from CotSim. Lower right hand pane: the control panel, enables users to switch maps, start and pause a simulation and manage other program services. Upper right hand pane: a time-series plot of the size/age-structured population of crown-of-thorns starfish and the percentage coral cover on Tongue Reef. Lower left pane: map of the Cairns sector of the Great Barrier Reef. The black lines illustrate simulated dispersal events of crown-of-thorns starfish.

approach. For all intents and purposes, the software and the questionnaire were completely ignored. The software was revised and published (Scandol in press). Figure 2 presents the control screen of CotSim. This model was driven by a strategy of data visualisation but did include some game-like components. Ross Claytor made the most pertinent comment about CotSim (when a doctoral student at The University of British Columbia):

"The user-friendly models will be most useful and efficient if the interfaces are divided between the two principle functions of the programme. There could be an interface for education, the synthesis and communicating aspects [data visualisation], and a second interface for exploring management options [gaming visualisation]. These tasks are just too different to be accommodated in one interface."

NerkaSim

In 1995 the author was appointed to a post at the University of British Columbia in Vancouver, Canada to develop spatially-explicit visualisation software for sockeye salmon. This project was not directed at managers explicitly, but the funding application implied that the product would have beneficial management outcomes. The resulting product, NerkaSim 1.1 (Scandol *et al.* 1997) was completed in 1997 and is available for downloading at (http://www.eos.ubc.ca/salmon/nerkasim/). Motivation and objectives for the project were presented in Rand *et al.* (1997). The extensive help for the program includes the initial comments:

"NerkaSim is a tool for:

- exploring hypotheses about sockeye migration and bioenergetics in the ocean;

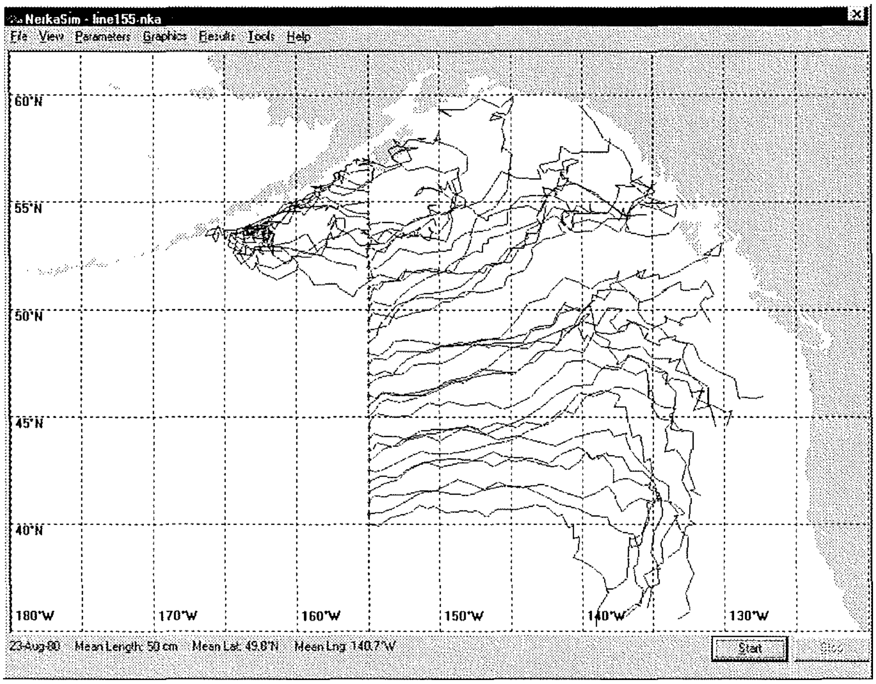

Figure 3. The main window from NerkaSim illustrating the simulated trajectories of sockeye salmon being advected and actively migrating from the meridian at 155° W in the north-east Pacific.

- displaying characteristics of the biophysical environment in the Northeast Pacific Ocean, including: surface currents, sea surface temperatures, and zooplankton biomass.

While NerkaSim is an excellent tool for exploring hypotheses, it cannot be viewed as a predictive model."

There has been no formal evaluation system put in place to gauge the consequences and outcomes of NerkaSim. The authors maintain a database of the 160 people who have downloaded the software to date. Figure 3 illustrates the geographic range of NerkaSim and shows the trajectories of simulated salmon migrating from a line of longitude (155°W). NerkaSim was primarily an application for data visualisation.

Geographical Fisheries System (GFS)

The Northern Fisheries Centre (Queensland Department of Primary Industries) developed a spatial model of prawn migration within the Great Barrier Reef (Derbyshire *et al.* 1995). The program was developed "as an animated, interactive model for displaying the data collected" during a Fisheries Research and Development Corporation project on small prawn habitat and recruitment. GFS enabled users to display data collected from tagging projects. The interface was very well designed and included "wizards" for importing data and a detailed map of the northern Great Barrier Reef. Users had to have some understanding of the role of GFS because for an interested casual observer some of the output and analyses are somewhat cryptic. The system clearly intended to have the role of data visualisation, but the dynamic aspects suggest that the authors also had gaming visualisation objectives for the software.

The GFS was distributed with a small piece of educational software called PrawnEd. This program displayed life history patterns, distributional information, example logbook data and meteorological data and catch responses for commercial prawn species for the Turtle Group of reefs. The manual suggested the software was written primarily for decision makers. This small educational application is interesting and gives an overview of important processes for the northern prawn fisheries.

Discussion: models, muddles and management

Comments about outcomes

Within the fisheries science and management community there is a spectrum of rewards offered for individual efforts. For example, writing quality research publications will reward a scientist, facilitating an effective decision process might reward a manager, and writing slick fisheries models will reward a computer programmer. It would be unwise to suggest that there exists a single framework of desirable outcomes that will suit every individual involved in fisheries research and management in Australia. Nevertheless, scientists employed by management agencies will be constantly reminded that the purpose of their research is to support the achievement of the objectives of appropriate fisheries management legislation. There are many ways that good science can be done to achieve this. This prompts the question about how to prioritise research options. In particular, where do models for data and gaming visualisation fit into this prioritisation scheme for research in Australia?

The articulated purpose of most models that have been designed for gaming visualisation or data visualisation has been to help communicate science to managers and other stakeholders. This is a very worthwhile objective and could be evaluated. Within the evaluation process we need to consider questions of the type:

- Has the strategy of building visual models resulted in the outcomes that were originally proposed?
- What are measures of "communication of science"?
- What sorts of interface designs work best for achieving these outcomes?
- What sorts of interfaces don't work well for achieving these outcomes?

There is a middle ground between being such a devoted empiricist that if something cannot be precisely quantified it is not worth considering, and refusing to acknowledge that there is a traceable path of logic between an objective and an outcome for any concept. Proposals for visual models need to explore this middle ground. An evaluation strategy should be included with proposals to build visual models. A lot of fisheries modellers (and indeed a lot of scientists) oversell the impact their work will have on actual outcomes. This reflects the personal and intellectual investment made by individuals in their area of expertise. Gaming and data visualisation models (with or without spatial representation) do have a role in fisheries science and management, but more effort needs to be directed at exploring exactly what this role is.

Costs of visual models

There is a lot of optimism regarding the benefits of visual fisheries models so it is worthwhile occasionally being pessimistic about the costs. The primary cost is numerical efficiency: visual programs run more slowly on equivalent hardware. This will often result in a less thorough analysis of variability (lower number of replicate simulations computed compared to a stochastic model) and a less complete exploration of the parameter space. Some visual programs may run so slowly that certain sorts of analysis are not possible at all. These might include complex non-linear parameter optimisation procedures.

A more obvious problem for many users of visual programs is that they are slow, awkward or impossible to use for anything but their original application (which may or may not have been well thought out). Sensitivity analyses involve running a model over a range of parameter values and comparing outputs. If each time the parameter needs to be changed, the user has to type numbers in fields, push buttons, rename output files and all that sort of palaver, even the most patient user will tire of the repetition. Modellers usually avoid these issues by including a batch processing capability in their models. This feature is almost always excluded from visual software. Scandol *et al.* (1997) was an exception.

Another type of cost is reduced portability. Models written in C or Fortran can be edited and compiled on virtually any type of computer: from a handheld device to a supercomputer. In contrast, most visual models have been prepared with platform-dependent software like Visual Basic (Microsoft 1997). Visual Basic is a tremendous application but the code cannot be easily ported to faster machines. This is a cost of visual models that must be recognised. Strategies such as building dynamic link libraries that isolate platform-independent model code from the platform-dependent interface code are usually more trouble than they are worth. What is perhaps even more important is that often these programming tasks are so complex that specialist software developers are hired to complete them. Code development thus becomes very expensive and there will be hesitation from the sponsoring institution to distribute the source code. This reduces the ability to critique the calculations actually performed.

Opportunity costs are the most difficult costs to quantify. Opportunity costs are the work that *could* have been completed if the visual model had not been prepared. Visual models often absorb the intellectual resources of a small number of modellers that could have been employed gainfully elsewhere. Often the problems being solved are somewhat trivial programming tasks such as interface control management issues. Ironically these interface problems are fun to solve because they often have elegant yet easily recognisable solutions. What could the modellers or sponsoring agencies have achieved if their efforts were directed elsewhere? In most cases we will never know.

Visual models have costs. The people who propose and build visual models need to justify these in light of the proposed benefits. Actual success in achieving these proposed benefits needs to be critically evaluated and reported upon.

Confusing information, attitude and behaviour

There are some unfortunate assumptions that many scientists make about human psychology. The first assumption is that when people are presented with "objective information" that is contrary to their initial beliefs they will change their minds. The second assumption is that if people have a particular attitude to an issue then they will behave in a manner that is consistent with this attitude. The belief that a computer interface is an effective mechanism for delivering this "objective information" to change people attitudes and behaviour is the presupposition of most, if not all, visual models in fisheries. There are many reasons why these assumptions are often flawed: two are briefly discussed.

The first reason arises because "objective information" (as illustrated by the quotation marks) is not context dependent. If an individual has an antagonistic history with the institution that has provided the "objective information" he or she is unlikely to be much influenced by it no matter what the delivery mechanism. The second reason is a consequence of the so-called tragedy of the commons (Hardin 1985). Individuals may understand it is in the best interests of the resource and all the users of the resource to reduce exploitation rates, but it may not be in the best interests of any particular individual.

Exactly what causes people to change their minds and behaviour regarding environmental issues is a complex subject. Large amounts of research are (for example Bazerman *et al.* 1997) devoted to understanding this issue. If fisheries scientists want to use visual computer models to communicate their ideas to a greater audience and have this audience absorb and act on this information then they should: (1) be increasing their collaboration with computer scientists specialising in interface design; (2) be running research projects in collaboration with psychologists to identify how the information is actually being interpreted; and (3) be prepared to trial and evaluate different strategies of visual modelling to determine which tactics achieve what outcomes within fisheries science and management.

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A spatial representation of the tiger prawn (*Penaeus esculentus*) fishery in Shark Bay, Western Australia

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Abstract

The fishery for brown tiger prawns, Penaeus esculentus, *in Shark Bay, Western Australia, experienced reduced recruitment in the early 1980s. It is considered that this decline resulted from recruitment overfishing. The measures subsequently implemented to reduce fishing effort on the tiger prawns were constrained by the objective of maintaining the harvest of western king prawns,* P. latisulcatus, *which was the dominant species in the catch. A series of spatial closures was applied to different regions within the fishery in an attempt to reduce effort on brown tiger prawns, yet maintain catches of western king prawns. The closures were intended to take advantage of the spatial structure of the fishery and the migration that occurs between fishing grounds. Until now, a subjective approach has been used, in consultation with the fishing industry, in determining the appropriate closures. A compartmental delay-difference model has been developed to represent the spatial structure of the brown tiger prawn fishery and to describe the distribution of the prawns through consecutive months of the fishing season. In the absence of explicit information on the rates of migration between fishing grounds, the model represents the migration rates as parameters, and estimates these, together with catchability and recruitment parameters, from the observed monthly catch rates within the fishing grounds. Using this model, a more accurate time series of annual recruitment indices has been calculated for the Shark Bay tiger prawn stock.*

Introduction

Commercial exploitation of prawns in Shark Bay (Figure 1) commenced in 1962. The two species that dominate the prawn catch in this fishery are western king prawns, *Penaeus latisulcatus*, and brown tiger prawns, *Penaeus esculentus*. Endeavour prawns, *Metapenaeus endeavouri*, and other smaller prawns are also caught as bycatch. Limited entry was introduced in 1963 and the fishing fleet was restricted to 25 trawlers (Penn *et al.* 1989). By 1975, the fleet had increased to 35 vessels (Penn *et al.* 1989), remaining at this level until 1990 when a buy-back programme reduced the number of vessels to 27.

Postlarval and early juvenile tiger prawns are found in *Posidonia* seagrass beds along the eastern and southern shorelines of Shark Bay (Penn and Stalker 1979). Larger juveniles (to 25 mm carapace length) are located along the seaward edges of the seagrass beds in water depths of 12-15 m, with nursery areas extending along both the eastern and southern shorelines (Penn 1988). Recruitment of juveniles to the trawl grounds begins in February-March of each year (Penn 1988). The Quobba, Western Ground, Elbow Shoals and Peron regions (Figure 1) were considered by Penn (1988) to have been equally important as recruitment areas. The average size of the tiger prawns in survey data increases to the west and north (Penn and Stalker 1979). While Slack-Smith (1969) suggested that tiger prawns moved northward, Penn (1988) noted that peak catches for regions other than Peron tended to occur in the same month of each year, and considered that the prawns at Peron were being fished earlier in their life cycle.

Initial assessments of the tiger prawn stock in Shark Bay were based on surplus production models (Hancock 1975; Bowen and Hancock 1984; Penn *et al.* 1989). These models were fitted to the total annual catch and effective effort for the stock, treating the fishery as a single spatial unit. Effective effort for each fishing season was calculated by dividing the annual catch by the average catch rate over fishing grounds and over months, using the method described by Hall and Penn (1979). Later assessments of the tiger prawn stock (Penn *et al.* 1989) have indicated that current levels of fishing effort are in excess of those that are associated with the peak of the stock production curve. Penn *et al.* (1989) expressed the view that surplus production models were no longer able to provide the advice required by managers of the Shark Bay prawn fishery, citing the lack of responsiveness of these models to recruitment overfishing and the need for information on the relationship between yield (or yield-per-recruit), fishing mortality and size-at-first-capture.

The decline in catches of tiger prawns in Shark Bay in the 1980s has been attributed to growth and recruitment overfishing (Penn *et al.* 1989). Although there was a need to rebuild the stock of tiger prawns, fisheries managers have been obliged to consider the potential impact of proposed rebuilding strategies on the catches of western king prawns, as this is the major species in the Shark Bay prawn fishery. The strategy that has been adopted to rebuild the tiger prawn stock has been to define areas where fishing is permitted. Fishing has been allowed in regions where king prawns are caught but catches of tiger prawns are reduced, while regions where exploitation of tiger prawns might be greater have been closed to fishing.

Early estimates of a recruitment index for Shark Bay tiger prawns were based on catch rates from the Western Ground (Figure 1) during March-May (Penn 1988). Later recruitment indices were derived using a simple cohort analysis. This assumed equivalence between growth and mortality. Recruitment was estimated from the weights of those catches recorded in fishing regions in which the new recruits were believed to be located (Penn *et al.* 1995).

Analysis of the fishery data for the prawn fisheries in Shark Bay has been complicated by the spatial structure of the fishery and the changing distribution of prawns and of fishing effort throughout the fishing season. The need existed for a spatial representation that provided a description of the fishery at monthly time steps. Walters (Prof. C. J. Walters, University of British Columbia, Canada, pers. comm.) developed a prototype age-structured spatial model of one of the prawn fisheries in Western Australia, which demonstrated that potentially such a model could be used for these fisheries.

The objective of this study was to develop a spatial model of the brown tiger prawn fishery of Shark Bay, in order to (1) describe the fishery at a spatial resolution consistent with current management strategies, (2) produce an improved time series of annual recruitment indices for the tiger prawn stock, and (3) estimate the proportions of prawns migrating between fishing regions.

Methods

Data used in the analysis

The data used for this study were the monthly records of catch (tonnes) and standardised fishing effort (thousand standard hours of trawling) within each of the fishing grounds in Shark Bay (Figure 1) for the annual fishing seasons from 1969 to 1980 and from 1982 to 1998.

Catch and nominal fishing effort data from the fishery have been collected through a comprehensive logbook programme which was initiated in the early 1960s

(Penn *et al.* 1989) and has subsequently operated in all years except 1981. An alternative data collection method was adopted for 1981, resulting in a break in the time series for that year. The logbook data have provided almost 100% coverage of catches from the fishery.

Information recorded within the logbooks consists of the fishers' estimates of the catch (kg) of each species obtained during each individual trawl, the duration (minutes) of trawling and the location of fishing. The location of fishing was originally recorded in the logbooks with reference to a 10' x 10' grid, based on latitude and longitude (Penn *et al.* 1989), but the logbook data recorded in this form have been reallocated to the fishing grounds that are now used to describe the fishery (Figure 1).

Accurate records of the landings by each vessel are obtained from the shore-based factories (Penn *et al.* 1989), or directly from those vessels that process their catches at sea. These have been used to adjust the logbook estimates of catch for errors of estimation, and to calculate values of any missing catch and effort data.

The vessels that now operate within the fishery have considerably greater fishing power than those that fished in earlier years (Penn *et al.* 1989). An estimate of the fishing power is calculated for each vessel, and such estimates are used to standardise the recorded fishing effort for each vessel within and between years (Hall and Penn 1979). The resulting estimates of standardised fishing effort represent the equivalent amount of fishing effort by a vessel with the average efficiency that existed in 1970.

Model

Time steps, t ($1 \le t \le 348$), used in the model were monthly, where $t = 1$ represented January 1969. The year, y ($1969 \le y \le 1980$ or $1982 \le y \le 1998$), was calculated from the time step using the equation:

$$y = \begin{cases} 1969 + \text{int}\{(t-1)/12\} & \text{for } 1 \le t \le 144 \\ 1970 + \text{int}\{(t-1)/12\} & \text{for } 145 \le t \le 348 \end{cases} \qquad (1)$$

while the calendar month, m ($1 \le m \le 12$), was calculated as

$$m = 1 + \{(t-1) \bmod 12\} \qquad (2)$$

The function, int(x), returns the integer portion of the real number, x, truncating the decimal fraction. The function, j mod k, returns the remainder after the number j is divided by k.

The system state was represented in the model as a vector containing the number (thousands) of prawns, N_t^g, within each fishing ground, g ($1 \le g \le G$ where $G = 6$), at the beginning of the time-step, t, and a vector containing the biomass of prawns (tonnes) within each ground, B_t^g. The model does not differentiate between sexes of prawns. Codes used for the fishing grounds (Figure 1) were 1 = Quobba (Q), 2 = Koks Island (KI), 3 = Western Ground (WG), 4 = Elbow Shoals (ES), 5 = Peron (P) and 6 = West Peron (WP).

The model structure used to represent the fishery was based on the delay-difference model derived by Deriso (1980), which was subsequently extended by Schnute (1985, 1987), and described by Hilborn and Walters (1992). The equations representing the dynamics of the tiger prawn fishery were:

$$B_{t+1}^g = \sum_{j=1}^{G} \left\{ \left[\alpha N_t^j + \rho B_t^j \right] \left[1 - H_t^j \right] X_{j,g} \exp(-M) \right\} + W_R R_{t+1}^g \qquad (3)$$

and

$$N_{t+1}^g = \sum_{j=1}^{G} \left\{ N_t^j \left[1 - H_t^j \right] X_{j,g} \exp(-M) \right\} + R_{t+1}^g \qquad (4)$$

M is the instantaneous coefficient of natural mortality (month^{-1}). Growth was represented by the Brody growth equation, where the body weight (kg) of a prawn at time step t+1, w_{t+1}, was related to the weight at the previous monthly time step, w_t, by the equation

$$w_{t+1} = \alpha + \rho w_t \tag{5}$$

W_R is the body weight (kg) of a prawn at the age of recruitment to the exploited stock. The harvest rate (proportion caught) within fishing ground, g, at time step, t, is H_t^g. The proportion of prawns migrating from fishing ground j to fishing ground g at the end of the time step is $X_{j,g}$. The number (thousands) of prawns recruiting to fishing ground g at time step t is R_t^g.

Logbook data were not available for the Shark Bay fishery in 1981. It was assumed that the abundances (number and biomass) in the different fishing grounds at the commencement of 1982 were identical to those at the beginning of 1981.

No estimate was available for the instantaneous rate of natural mortality (M) for brown tiger prawns. Somers and Wang (1997) assumed $M = 0.18$ month^{-1}, and considered values ranging from 0.12 to 0.26 month^{-1} when assessing the sensitivity of their model for tiger prawns in Australia's northern prawn fishery. After reviewing estimates reported in the scientific literature, Garcia (1985) recorded that the reported level of M for adults of *Penaeus* species was around 0.2 month^{-1}. This latter value was applied for Shark Bay tiger prawns.

The weight (kg)-carapace length (mm) relationship (Penn and Hall 1974) for brown tiger prawns has been estimated as:

$$W = \begin{cases} 0.000002078L^{2.764} & \text{for males} \\ 0.000003739L^{2.574} & \text{for females} \end{cases} \tag{6}$$

It was assumed that male and female prawns recruit to the fishery at 20 mm carapace length, or a weight of approximately 0.0083 kg.

To reduce the number of parameters that were required to be estimated when fitting the model, estimates of the growth parameters were determined from the weight-length relationship (equation 6) and from parameters of the von Bertalanffy growth equations for *P. esculentus* reported in other studies (Kirkwood and Somers 1984; Wang and Somers 1996; Wang 1998). Approximate values of α and ρ were estimated as 0.0082 kg and 0.844 respectively.

The model was conditioned on catch (Punt 1988). The monthly harvest rate applied at each time step was calculated from the weight (tonnes) of the recorded catch, C_t^g, within the fishing ground for the time step, using the equation:

$$H_t^g = \frac{C_t^g}{B_t^g} \tag{7}$$

Using this estimate of harvest rate, an estimate of the number of prawns (thousands) caught within fishing ground g during time step t was calculated as $H_t^g N_t^g$. These estimates of catch in numbers were accumulated over all fishing grounds and months within the calendar year to obtain an estimate of the total annual catch in numbers, A_y.

The monthly harvest rate for a region was set to 1 when the weight of the recorded catch exceeded the estimated biomass that was available. A penalty function, λ_1, was applied when fitting to ensure that the harvest rate ranged between 0 and 1, where

$$\lambda_{t,1}^g = \begin{cases} 0 & \text{if } C_t^g \le B_t^g \\ 1000\left(C_t^g - B_t^g\right)^2 & \text{if } C_t^g > B_t^g \end{cases} \tag{8}$$

and

$$\lambda_1 = \sum_{t=1}^{348} \sum_{g=1}^{6} \lambda_{t,1}^g \tag{9}$$

The factor 1000 in equation (8) was chosen arbitrarily, but appeared adequate to ensure that parameter estimates resulted in an estimate of the biomass for each fishing region and time step that was sufficient to produce the recorded monthly catch.

The observed catch rate (kg/hour of trawling) was determined from the observed catch and standardised fishing effort, E_t^g, as

$$U_t^g = \frac{C_t^g}{E_t^g} \tag{10}$$

while the expected catch rate, $\hat{U}_t^g$, was estimated as

$$\hat{U}_t^g = q^g B_t^g \tag{11}$$

It was assumed that the catchability, q^g, within each fishing ground, g, remained constant over time (month and year).

The annual recruitment (thousands of prawns) to the whole fishery in calendar year, y, was denoted by R_y. It was assumed that the distribution of the relative recruitment within the calendar months of the year remained constant through time, where the proportion of the annual recruitment that recruited to the exploited stock in month m was denoted by p_m. Because of the limited catch and effort data available for November and December, it was assumed that $p_{11} = 0$ and $p_{12} = 0$, hence $p_{10} = 1 - \sum_{m=1}^{9} p_m$. It was also assumed that the relative distribution of recruitment to the different fishing grounds remained constant over time (month and year). The proportion of the recruitment for each month that recruits to fishing ground g was denoted by p^g, where $p^6 = 1 - \sum_{g=1}^{5} p^g$

The number of prawns, R_t^g, recruiting to the exploited stock within the fishing ground g at time step t was calculated from the annual recruitment, the proportion recruiting within the month and the proportion recruiting to the fishing ground:

$$R_t^g = p^g p_m R_y \tag{12}$$

An alternative more complex model was also fitted, where the proportion recruiting to each fishing ground was constant within each year, but varied between years. For this model, the annual recruitment to each fishing ground, R_y^g, was regarded as a parameter to be estimated, and

$$R_t^g = p_m R_y^g \tag{13}$$

To avoid the possibility of the optimisation procedure converging to extremely large estimates of population size and improbably low estimates of exploitation rate, an additional penalty function, λ_2, was calculated:

$$\lambda_2 = \sum_{y=1969}^{y=1998} \lambda_{y,2} \tag{14}$$

where

$$\lambda_{y,2} = \begin{cases} 0 & \text{if } y = 1981 \text{ or } \dfrac{A_y}{R_y} \geq h \\ 1000\left(h - \dfrac{A_y}{R_y}\right)^2 & \text{otherwise} \end{cases} \tag{15}$$

The fraction, h, was termed the minimum annual harvest fraction. The factor 1000 was chosen arbitrarily, but appeared adequate to ensure that estimates of annual recruitment levels and levels of exploitation were reasonable, given the exploitation status of the fishery.

Garcia (1985) reviewed the available studies for penaeid stocks and concluded that F_{MSY} for these studies was around 1.6 ± 0.3 year^{-1}, compared with the mean value of M in the same papers, which was 2.4 ± 0.3 year^{-1}. The Shark Bay tiger prawn stock has been fully exploited since the early 1970s, and experienced recruitment overfishing in the early 1980s. Based on this, the minimum annual harvest fraction, h, for the Shark Bay tiger prawn stock was set at 0.2. To test whether this constraint acted as an informative prior which played a significant role in determining the final parameter estimates, the model was also fitted with $h = 0.1$, and the results were compared.

The proportion of the prawns, $X_{g',g}$, migrating from fishing ground g' to fishing ground g at the end of each time step was assumed to remain constant through time. Slack-Smith (1969) had suggested a northward movement of tiger prawns. Thus, it was assumed that prawns only move northward between adjacent regions. The only monthly flows, $X_{g',g}$, considered in this study were $X_{6,5}$ $X_{5,4}$ $X_{4,3}$ $X_{3,2}$ and $X_{2,1}$ (Figure 1). With such flow of prawns from a fishing ground to only one adjacent fishing ground, the proportion remaining within the fishing ground from which the prawns emigrated was calculated as

$$X_{g',g'} = 1 - X_{g',g} \tag{16}$$

The system was assumed to be at an unexploited equilibrium at the beginning of the first time-step, with annual recruitment, R^*, where

$$R^* = R_{1969} \tag{17}$$

To determine the abundance (number and biomass) within each fishing ground at the commencement of each simulation run, the number and biomass within each region was set to zero, and the model run (without fishing mortality) through each month for 30 calendar years. The resulting set of numbers and biomasses was taken as the initial state of the fishery at the beginning of January 1969.

Parameters estimated for the less complex model were q^g (for $1 \le g \le 6$), $X_{2,1}$ $X_{3,2}$ $X_{4,3}$ $X_{5,4}$ $X_{6,5}$, p_m (for $1 \le m \le 9$), p^g (for $1 \le g \le 5$), and R_y (for $1969 \le y \le 1980$ or $1982 \le y \le 1998$). A total of 54 parameters were estimated for this model. The parameters was estimated for the more complex model were q^g (for $1 \le g \le 6$), $X_{2,1}$ $X_{3,2}$ $X_{4,3}$ $X_{5,4}$ $X_{6,5}$, p_m (for $1 \le m \le 9$), and R_y^g (for $1 \le g \le 6$ and $1969 \le y \le 1980$ or $1982 \le y \le 1998$). A total of 194 parameters were estimated for the more complex model.

The objective function used in fitting the model was

$$SS_1 = \sum_{t=1}^{348} \sum_{g=1}^{g} \left[\log\left(U_t^g + 1\right) - \log\left(\hat{U}_t^g + 1\right)\right]^2 \tag{18}$$

Catch rates were unavailable when regions were not fished within the month, thus reducing the number of observations included in calculation of SS_1. The model was implemented in AD Model Builder (Fournier 1994), which provided estimates of the parameters and the associated variance-covariance matrix of parameter estimates. Other versions were implemented in Microsoft Visual Basic and Microsoft EXCEL, to verify model implementation.

A phased approach was adopted when fitting the model. For the simpler 54 parameter model, it was assumed in the initial phase of model fitting that relative recruitment to each region and the relative recruitment to each month (January to October) were equal (for regions or months, respectively), the annual recruitment was constant through time, migration rates were equal and approximate values for catchabilities might be calculated as

$$\hat{q}^g = \frac{1}{n} \sum_t \log\left(\frac{U_t^g + 1}{B_t^g + 1}\right) \tag{19}$$

where n is the number of observations.

The initial estimates of the proportions migrating were set to 0.5, and the initial estimate of annual recruitment was set to 500 million prawns. The model was then fitted to the tiger prawn data to estimate proportions migrating and annual recruitment. Using these resulting parameter estimates as the new starting values, the constraints were progressively removed and the model fitted at each new phase to obtain the next set of starting values. Constraints were relaxed by first estimating the relative regional recruitment, and then, in order, the relative monthly recruitment, annual levels of recruitment, regional migration rates, and finally the approximation used to estimate catchabilities was dropped, allowing AD Model Builder to estimate these parameters. An iterative fitting procedure was then applied, alternating between fixing the catchabilities and fixing the levels of annual recruitment. The catchabilities are nuisance parameters, and are highly correlated with the levels of annual recruitment.

A similar approach was applied for the more complex 194 parameter model.

Selection of the more appropriate of the two models, the simpler 54 parameter model and the more complex 194 parameter model, was determined after calculation and consideration of two criteria. Akaike's information criterion (Akaike 1969) was calculated for each model using the formula:

$$AIC = n\log\left(\frac{SS}{n}\right) + 2p \quad (20)$$

where p is the number of parameters and n is the number of observations. The Bayesian Information Criterion (Schwarz 1978) was also calculated, as

$$BIC = n\log\left(\frac{SS}{n}\right) + p\log(n) \quad (21)$$

These criteria may be used to determine the optimum model complexity, by ensuring that each criterion is not increased when incorporating additional parameters. However, the Akaike Information Criterion tends to accept the more complex model when n is large (Raftery 1986 as cited by Zabel 1996), and the Bayesian Information Criterion is considered more appropriate in such situations, when conclusions based on the two criteria differ.

After selecting the more appropriate of the two models, the selected model's performance was tested by using it to generate 10 sets of synthetic data using a set of known parameters. Catch rates were calculated as $\hat{U}_t^g \exp(0.6\varepsilon_t^g)$, where ε_t^g were assumed to be standard normal variates. If the resulting catch rate was negative, it was reset to zero. The monthly harvest rate was calculated as

$$H_t^g = \left(\frac{0.2(y-1960)}{5+(y-1960)}\right)\left(\frac{(U_t^g)^5}{2.5^5 + (U_t^g)^5}\right) \quad (22)$$

This arbitrary function increases with year, while responding to changes in catch rate within each fishing season.

The model was fitted to each set of synthetic data. Model estimates were compared with the actual parameter values used to generate the synthetic data.

When presenting results, approximate confidence limits were generated for each parameter by adding and subtracting twice the estimated standard deviation to and from the parameter estimate. The standard deviations were estimated from the Hessian matrix by AD Model Builder (Fournier 1994). When the resulting values fell outside the range valid for that variable, the value was reset to the appropriate upper or lower limit of the range.

Results

Selection of model complexity

The simpler form of the model, with 54 parameters, 1504 observations and minimum annual harvest fraction $h = 0.2$, resulted in an AIC of −1604 and a BIC of -1317 ($SS_1 = 482$), while the more complex model, with 194 parameters, 1504 observations and minimum annual harvest fraction $h = 0.2$, produced an AIC of −1873 and a BIC of −1239 ($SS_1 = 334$). With 1504 observations, the conclusion drawn from the BIC is preferred. Thus the simpler model was considered the more appropriate representation of the Shark Bay tiger prawn data, and was used in subsequent analysis.

Model results

The model was fitted under the assumption that the minimum annual harvest fraction was 0.2. The resulting parameter estimates for the 54 parameter model are presented in Tables 1 to 5.

The estimated percentage migrating between West Peron and Peron was 28.9%, while larger emigration rates of 100% were estimated from the Western Ground to Koks Island and Koks Island to Quobba (Table 1; Figure 2). The magnitude of the estimated rate increased from the south to the north.

The fishery received 22.6% of the total annual recruitment in January, with the estimates increasing to 30.4% in February and peaking at 31.6% in March before declining to 10.4% in April (Table 2; Figure 3). The estimated percentage recruitment in the period from May to September was 0%, but increased to 5.0% in October.

A plot of the proportion recruiting to each region is presented in Figure 4. The Western Ground received the lowest recruitment (2.9%), while Peron received the highest (31.8%) (Table 3). West Peron (15.8%) received greater recruitment than Quobba (11.8%), but slightly less than Koks Island (17.3%).

West Peron produced the highest estimate of catchability, i.e. 0.094 (1000 standard trawl hours)$^{-1}$ (Table 3; Figure 5). This is likely to reflect the size of the fishing ground over which the fleet operates (Figure 1). However, the Western Ground produced an estimate for catchability of 0.085 (1000 standard trawl hours)$^{-1}$, only slightly lower than that of West Peron. The lowest estimate of 0.008 (1000 standard trawl hours)$^{-1}$ was recorded for Quobba.

The marked decline in annual recruitment in the early 1980s is evident in the recruitment estimates presented in Figure 6 (also Tables 4 and 5). From 1985, estimates of annual recruitment increased, reaching a peak of 190 million in 1995 before declining to 105 million by 1998.

Sensitivity associated with minimum annual harvest fraction

Fitting the simpler form of model, with 54 parameters, 1504 observations and minimum annual harvest fraction $h = 0.1$ (rather than $h = 0.2$) reduced the sum of squares to $SS_1 = 446$ (from $SS_1 = 482$).

Comparison of the parameter estimates for $h = 0.1$ and $h = 0.2$ (Tables 1 to 5) suggested that, as the minimum annual harvest rate was relaxed, catchability estimates decreased and estimates of annual recruitment increased by about 80%. The pattern of annual recruitment remained similar (correlation coefficient = 0.976). However, the catchability showed a greater decrease in the northern than southern regions, while the catchability at Elbow Shoals remained relatively unchanged.

The percentage of annual recruitment received at Quobba increased from 11.8 to 22.5%, while Elbow Shoals recruitment decreased from 20.3 to 10.1% as the constraint on minimum annual harvest rate was relaxed. There was little change in the monthly distribution of recruitment. A general increase in migration rates resulted from the change from $h = 0.2$ to $h = 0.1$.

Analysis of synthetic data

Results of the analysis of the synthetic data sets are presented in Tables 6 to 9. In general, there was close agreement between the average of the parameter estimates and the actual parameter used in generating the data. However, the percentage of the annual recruitment received at Quobba was overestimated on average (16.7% compared with 11.7%), while at Peron it was underestimated (24.0% compared with 31.9%) (Table 7). Estimates of these parameters were imprecise (coefficient of variation of 0.59 for Quobba and 0.28 for Peron). Catchabilities at Peron and West Peron were overestimated by 56 and 25%, respectively (Table 7). The imprecision of the estimates of catchability increased with location of the regions from north to south.

Discussion

For over a decade, management of the tiger prawn fishery in Shark Bay has been based on advice derived from models that have treated the fishery as a single spatial entity. The advice related to the impact of alternative regional closures was subjective. While the implementation of such closures affected the distribution of fishing and the catch rates achieved, the resulting change to catchability was ignored in these models. The new model provides a description of the spatial structure of the fishery that, for the first time, permits exploration of the impact of the controls that are actually used in the fishery, i.e. the use of regional closures to control exploitation of the brown tiger prawns. Further, the study has provided information on both the regional and temporal distribution of recruitment of brown tiger prawns to the fishery and provided estimates of the annual recruitment to the fishery. The recruitment indices that had been used in earlier studies of the stock-recruitment relationship for tiger prawns in Shark Bay were derived from a simple cohort analysis. The new recruitment indices are considered more accurate as they are based on more appropriate assumptions.

Estimates of the proportions of annual recruitment received in the regions were consistent with the view of Penn (1988) that Quobba, Elbow Shoals and the Peron regions (Figure 1) were important as recruitment areas. However, the model also suggested that the West Peron region was of equal importance to the Quobba and Koks Island regions, and that the Western Ground received relatively little recruitment. The latter region had been considered a relatively important recruitment area (Penn 1988), and catch rates from this region had been the basis of the recruitment indices used in early stock-recruitment studies (Penn *et al.* 1995).

Lack of catch and effort data in November and December prevented the proportions of tiger prawns recruiting in these months from being estimated. It must be recognised that estimates of the proportions recruiting in the months from January to October were conditional on the assumption that there was zero recruitment in November and December. The small recruitment (5%) in October and relatively large recruitment estimated for January (22.6%) suggest that the assumption of zero recruitment for November and December may be inappropriate.

A number of zero values of observed catch rate were recorded, for which the model estimates were non-zero (due to the structure of the model); the number of such points appeared insufficient to justify change in model structure to accommodate such data. However future studies should address this issue.

The absence of logbook data for 1981 complicated the analysis. It was assumed that the numbers and biomass of prawns present within each region at the commencement of 1982 were equal to the numbers and biomass of prawns within that region at the beginning of 1981. This assumption ignores the level of recruitment in 1981 and the catches that occurred in 1981. However, total catch data are available for 1981, and alternative assumptions might be considered in future analyses that could be more appropriate. For example, the monthly catches and monthly harvest rates within each region applying in 1980 and 1982 might be averaged and used within the model to improve the estimate of the system state at the commencement of 1982. Exclusion of the observations for 1982 when calculating the objective function, SS_1, might also be considered, as this would reduce the possible sensitivity of parameter estimates to the assumptions associated with the 1981 fishing season.

It should be noted that considerable residual variation exists after fitting the tiger prawn model. A detailed examination of residuals may suggest other opportunities for model improvement. Further model simplification appears possible, as recruitment between May and September appears negligible, and the small level of recruitment in October is likely to have little impact on the objective function. Considerable model simplification also appears possible through replacement of the estimates of the annual recruitment by values determined from a stock-recruitment relationship.

While analysis of the synthetic data sets suggests that the model is likely to recover the actual parameter estimates used when generating the data, this conclusion must be qualified by noting that the synthetic data were produced by the same model. All assumptions regarding model structure were therefore satisfied. When applying the model to the actual fishery data, sensitivity to failure of model assumptions and to lack of contrast in the data must be considered.

For the Shark Bay tiger prawn fishery, the catch and effort data appear inadequate to allow the absolute magnitude of recruitment to be accurately estimated. This is reflected in the improved fit and marked change in parameter estimates obtained when the minimum annual harvest fraction was reduced from $h = 0.2$ to $h = 0.1$. Further improvement in the sum of squares was obtained by removing this constraint entirely, with estimates of exceptionally high recruitment levels and low exploitation resulting from the fitting procedure. It appears that the model compensates for higher recruitment by a decrease in catchability (particularly in the northern regions), and an increase in migration rates, moving the prawns to the less frequently fished Quobba region (fewer observations). For the model with $h = 0.2$, it is possible that the low value estimated for the catchability at Quobba compared with the catchability estimates for other regions, coupled with the high migration rates estimated for the more northerly regions, may reflect an overestimate of recruitment levels and underestimate of the level of exploitation.

Knowledge of the distribution of prawns (that is, relative levels of catchability for the fishing regions) or migration rates may assist in improving parameter estimation. Additional constraints imposed on catchability, based on the area swept and the area of the fishing grounds, may also assist. Until such further studies are undertaken, estimates of annual recruitment may be considered only to be indices of recruitment strength rather than absolute estimates of abundance. The high correlation between the recruitment levels estimated for $h = 0.2$ and $h = 0.1$ supports the view that the estimates are likely to be relatively accurate indices of the levels of annual recruitment.

As with estimates of the absolute levels of annual recruitment, estimates of migration rates must be considered uncertain, as it is likely that these also may be biased. Thus, the third objective of the study, to estimate migration rates, has not yet been achieved.

Catchabilities used within the model are assumed to be dependent on the region, but constant over time (month and year). Following a study of the behaviour of prawns in aquaria, Penn (1988) concluded that, unlike western king prawns, Western Australian tiger prawns exhibited no major response to temperature changes and accordingly, vulnerability was likely to be relatively consistent. The model may need modification before it is applied to the western king prawn fisheries of Western Australia, in order to represent the seasonal changes in water temperature that affect the monthly catchabilities for this species.

This study has provided, for the first time, estimates of the proportion of recruitment of brown tiger prawns occurring in Shark Bay within each month. It has also produced indices of the annual recruitment of brown tiger prawns in the Shark Bay fishery, based on assumptions that are sounder than those used in earlier studies. The study has assisted in identifying research needs for the fishery and has provided managers of the Shark Bay tiger prawn fishery with a model that matches the spatial resolution of the strategies by which the fishery is currently managed. The model that has been developed will allow more detailed and informed evaluation of proposals for the future management of the Shark Bay tiger prawn fishery.

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Table 1. Estimates of migration for brown tiger prawns in Shark Bay.

Estimates of proportions migrating obtained by fitting the model to the fishery data when the minimum annual harvest fraction was set to either 0.2 or 0.1. Parameter estimates and approximate lower and upper 95% confidence intervals are presented. Regions are Quobba (Q), Koks Island (KI), Western Ground (WG), Elbow Shoals (ES), Peron (P), and West Peron (WP).

Source and desination regions	Min. harvest fraction = 0.2			Min. harvest fraction = 0.1		
	Estimate	Lower CL	Upper CL	Estimate	Lower CL	Upper CL
KI to Q	1.000	0.997	1.000	1.000	0.995	1.000
WG to KI	1.000	0.997	1.000	1.000	0.998	1.000
ES to WG	0.627	0.542	0.713	1.000	0.989	1.000
P to ES	0.338	0.284	0.392	0.410	0.365	0.455
WP to P	0.289	0.234	0.345	0.318	0.265	0.370

Table 2. Estimates of relative monthly recruitment parameters for brown tiger prawns in Shark Bay.

Estimates of proportions recruiting within each month obtained by fitting the model to the fishery data when the minimum annual harvest fraction was set to either 0.2 or 0.1. Parameter estimates and approximate lower and upper 95% confidence intervals are presented. The proportion recruiting in October may be calculated by subtracting from 1 the sum of the monthly proportions. Regions are Quobba (Q), Koks Island (KI), Western Ground (WG), Elbow Shoals (ES), Peron (P), and West Peron (WP).

	Min. harvest fraction = 0.2			Min. harvest fraction = 0.1		
Month	Estimate	Lower CL	Upper CL	Estimate	Lower CL	Upper CL
Jan	0.226	0.152	0.322	0.274	0.188	0.381
Feb	0.304	0.232	0.357	0.248	0.166	0.318
Mar	0.316	0.273	0.270	0.311	0.263	0.252
Apr	0.104	0.145	0.044	0.118	0.186	0.043
May	0.000	0.000	0.008	0.000	0.000	0.007
Jun	0.000	0.000	0.000	0.000	0.000	0.000
Jul	0.000	0.000	0.000	0.000	0.000	0.000
Aug	0.000	0.000	0.000	0.000	0.000	0.000
Sep	0.000	0.000	0.000	0.000	0.000	0.000

Table 3. Estimates of relative regional recruitment and catchability parameters for brown tiger prawns in Shark Bay.

Estimates of proportions recruiting to each region and catchabilities obtained by fitting the model to the fishery data when the minimum annual harvest fraction was set to either 0.2 or 0.1. Parameter estimates and approximate lower and upper 95% confidence intervals are presented. The proportion recruiting to West Peron may be calculated by subtracting from 1 the sum of the regional proportions. Regions are Quobba (Q), Koks Island (KI), Western Ground (WG), Elbow Shoals (ES), Peron (P), and West Peron (WP).

		Min. harvest fraction = 0.2			Min. harvest fraction = 0.1		
	Region	Estimate	Lower CL	Upper CL	Estimate	Lower CL	Upper CL
Regional recruitment proportion	Q	0.118	0.063	0.212	0.225	0.155	0.314
	KI	0.173	0.124	0.221	0.181	0.133	0.228
	WG	0.029	0.007	0.099	0.045	0.020	0.086
	ES	0.203	0.181	0.181	0.101	0.086	0.097
	P	0.318	0.366	0.213	0.321	0.388	0.214
Catchability (1000 hours trawling)$^{-1}$	Q	0.008			0.004		
	KI	0.065			0.035		
	WG	0.085			0.050		
	ES	0.053			0.051		
	P	0.039			0.025		
	WP	0.094			0.071		

Table 4. Estimated recruitment parameters for brown tiger prawns in Shark Bay from 1969 to 1984.

Estimates of annual recruitment (millions of prawns) obtained by fitting the model to the fishery data when the minimum annual harvest fraction is set to either 0.2 or 0.1. Parameter estimates and approximate lower and upper 95% confidence intervals are presented. No estimate is available for 1981.

	Min. harvest fraction = 0.2			Min. harvest fraction = 0.1		
Year	Estimate	Lower CL	Upper CL	Estimate	Lower CL	Upper CL
1969	142	115	170	309	239	379
1970	160	134	186	297	229	365
1971	103	81	126	179	133	225
1972	89	68	109	164	123	205
1973	147	118	176	281	220	342
1974	184	158	209	300	300	300
1975	169	143	196	300	299	301
1976	164	139	189	291	236	345
1977	130	107	153	239	192	287
1978	184	155	212	300	300	300
1979	165	141	188	276	227	326
1980	51	39	62	94	70	118

Table 5. Estimated recruitment parameters for brown tiger prawns in Shark Bay from 1985 to 1998.

Estimates of annual recruitment (millions of prawns) obtained by fitting the model to the fishery data when the minimum annual harvest fraction is set to either 0.2 or 0.1. Parameter estimates and approximate lower and upper 95% confidence intervals are presented.

	Min. harvest fraction = 0.2			Min. harvest fraction = 0.1		
Year	Estimate	Lower CL	Upper CL	Estimate	Lower CL	Upper CL
1985	49	39	59	85	64	106
1986	56	46	67	97	74	120
1987	49	38	59	85	63	106
1988	63	53	73	112	85	140
1989	71	60	82	135	102	168
1990	61	50	72	123	93	153
1991	94	79	109	182	145	220
1992	98	81	115	197	156	239
1993	84	70	99	167	130	203
1994	131	114	149	232	187	276
1995	190	170	210	300	300	300

Table 6. Estimates of migration and relative monthly recruitment parameters with actual parameters used to generate simulated data sets.

The actual parameters used to generate 10 sets of synthetic data, and the average, minimum, maximum, and lower and upper 95% confidence limits for the estimated parameters obtained when fitting the model to the simulated data. The proportion recruiting in October may be calculated by subtracting from 1 the sum of the monthly proportions. Regions are Quobba (Q), Koks Island (KI), Western Ground (WG), Elbow Shoals (ES), Peron (P), and West Peron (WP). Confidence levels for proportions were constrained to lie between 0 and 1.

	Regions or Month	Actual	Mean	Minimum	Maximum	Lower CL	Upper CL
Migration proportion	KI to Q	1.000	0.967	0.782	1.000	0.801	1.000
	WG to KI	1.000	0.916	0.811	1.000	0.740	1.000
	ES to WG	0.626	0.564	0.361	0.870	0.191	0.936
	P to ES	0.338	0.371	0.281	0.488	0.231	0.511
	WP to P	0.289	0.312	0.237	0.393	0.210	0.415
Monthly recruitment proportion	Jan	0.226	0.207	0.172	0.265	0.150	0.264
	Feb	0.305	0.275	0.235	0.321	0.210	0.340
	Mar	0.316	0.304	0.215	0.420	0.171	0.438
	Apr	0.102	0.118	0.000	0.173	0.000	0.245
	May	0.000	0.026	0.000	0.078	0.000	0.087
	Jun	0.000	0.013	0.000	0.048	0.000	0.054
	Jul	0.000	0.001	0.000	0.006	0.000	0.005
	Aug	0.000	0.005	0.000	0.019	0.000	0.021
	Sep	0.000	0.002	0.000	0.011	0.000	0.010

Table 7. Estimates of regional recruitment and catchability parameters with actual parameters used to generate simulated data sets.

The actual parameters used to generate 10 sets of synthetic data, and the average, minimum, maximum, and lower and upper 95% confidence limits for the estimated parameters obtained when fitting the model to the simulated data. The proportion recruiting to West Peron may be calculated by subtracting from 1 the sum of the regional proportions. Regions are Quobba (Q), Koks Island (KI), Western Ground (WG), Elbow Shoals (ES), Peron (P), and West Peron (WP). Confidence levels for proportions were constrained to lie between 0 and 1.

	Region	Actual	Mean	Minimum	Maximum	Lower CL	Upper CL
Regional recruitment proportion	Q	0.117	0.167	0.034	0.365	0.000	0.389
	KI	0.173	0.173	0.139	0.221	0.110	0.236
	WG	0.029	0.040	0.027	0.071	0.011	0.068
	ES	0.204	0.235	0.135	0.322	0.115	0.355
	P	0.319	0.240	0.135	0.357	0.085	0.395
Catchability	Q	0.008	0.008	0.003	0.012	0.002	0.015
$(1000 \text{ hours trawling})^{-1}$	KI	0.065	0.070	0.054	0.084	0.048	0.092
	WG	0.085	0.091	0.074	0.117	0.056	0.125
	ES	0.053	0.056	0.035	0.082	0.020	0.093
	P	0.039	0.061	0.033	0.093	0.018	0.104
	WP	0.094	0.117	0.089	0.171	0.058	0.176

Table 8. Estimates of recruitment (millions of prawns) from 1969 to 1984 with actual parameters used to generate simulated data sets.

The actual parameters used to generate 10 sets of synthetic data, and the average, minimum, maximum, and lower and upper 95% confidence limits for the estimated parameters obtained when fitting the model to the simulated data. No estimate is available for 1981.

Year	Actual	Mean	Minimum	Maximum	Lower CL	Upper CL
1969	142	147	126	210	89	206
1970	160	164	134	236	98	229
1971	103	108	88	154	60	155
1972	88	92	73	154	39	145
1973	147	153	131	238	80	225
1974	183	192	160	287	102	282
1975	169	176	144	264	95	258
1976	164	175	141	255	97	252
1977	129	142	115	225	68	216
1978	183	189	163	266	115	262
1979	164	173	145	256	98	248
1980	50	54	41	82	26	81
1982	58	62	49	97	29	96
1983	107	112	95	174	61	164
1984	74	79	66	121	39	118

Table 9. Estimates of recruitment (millions of prawns) from 1985 to 1998 with actual parameters used to generate simulated data sets.

The actual parameters used to generate 10 sets of synthetic data, and the average, minimum, maximum, and lower and upper 95% confidence limits for the estimated parameters obtained when fitting the model to the simulated data.

Year	Actual	Mean	Minimum	Maximum	Lower CL	Upper CL
1985	49	51	39	81	22	80
1986	56	61	45	93	30	92
1987	49	52	41	77	27	77
1988	63	66	56	96	36	96
1989	71	76	60	111	43	109
1990	61	63	51	88	35	90
1991	94	98	81	147	53	143
1992	98	106	88	160	55	156
1993	84	89	72	141	44	133
1994	131	138	116	209	74	202
1995	189	198	167	285	119	277
1996	138	146	119	215	80	212
1997	110	114	89	168	61	167
1998	105	110	94	172	56	164

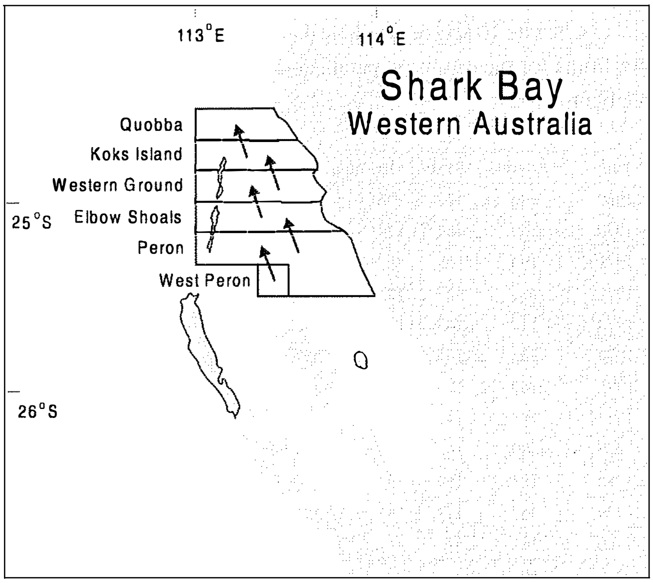

Figure 1. Fishing regions within the Shark Bay prawn fishery. Arrows indicate the migration assumed within the fishery model.

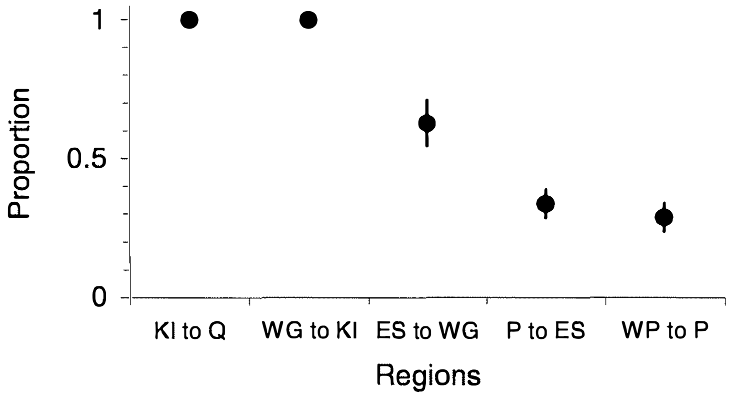

Figure 2. Estimated proportions of brown tiger prawns migrating each month between different fishing grounds in Shark Bay (Q=Quobba, KI=Koks Island, WG=Western Ground, ES=Elbow Shoals, P=Peron, and WP=West Peron). The error bars represent values between 0 and 1 lying within two standard deviations of the parameter estimates.

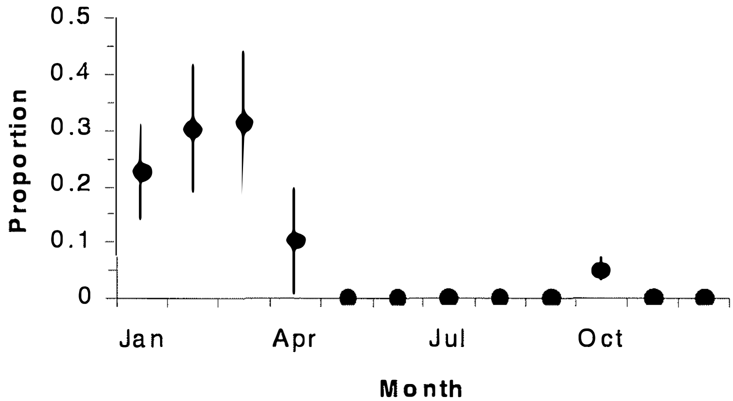

Figure 3. Estimated proportion of the recruitment of brown tiger prawns occurring within each calendar month in the Shark Bay fishery. The error bars represent

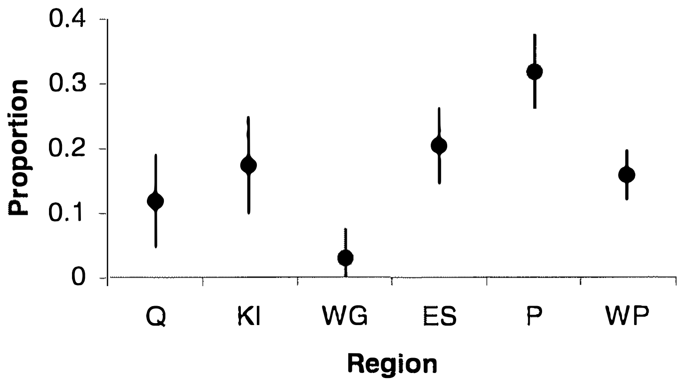

Figure 4. Estimated proportion of the recruitment of brown tiger prawns occurring within each region in the Shark Bay fishery (Q=Quobba, KI=Koks Island, WG=Western Ground, ES=Elbow Shoals, P=Peron, and WP=West Peron). The error bars represent positive values within two standard deviations of the parameter estimates.

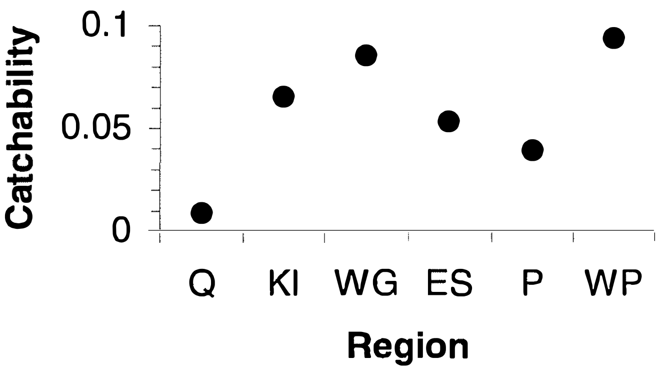

Figure 5. Estimated catchability of brown tiger prawns within different fishing regions of Shark Bay (Q=Quobba, KI=Koks Island, WG=Western Ground, ES=Elbow Shoals, P=Peron, and WP=West Peron).

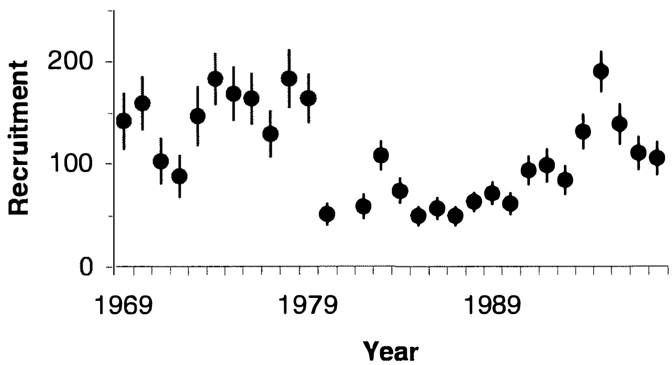

Figure 6. Estimated annual recruitment (millions of prawns) for the Shark Bay tiger prawn stock. The error bars represent values within two standard deviations of the parameter estimates.

Discussion of Session 3

Chaired by André Punt

CSIRO Division of Marine Research
GPO Box 1538, Hobart TAS 7001

Recorded by Robin Thompson

CSIRO Division of Marine Research
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This record brings together the discussions which followed individual invited speakers, after which there was a time for general discussion.

Terry Walker (MAFRI) presented an assessment of school shark that includes movement of sharks among seven areas. John Pogonoski (Australian Museum) asked what further research was needed to improve the accuracy of the results from shark models. Terry Walker replied that there could never be enough information on shark movement, especially by age group - it might not even be enough to tag every individual in the population. However, the current assessment method takes account of this uncertainty. The available data are used to gain an overview of shark movement and to generate alternative hypotheses for areas of uncertainty. Fisheries models that make use of all available data (tagging, catch and effort data, selectivity and biological information) are used to update initial estimates of movement parameters. A range of models is produced, consistent with a range of alternative hypotheses, and their fits to the available data are compared - some are clearly better than others.

Simon Nicol (NRE) spoke on the use of Bayes theorem to examine the hypothesis that increased river flow triggers migration of Murray cod. Malcolm Haddon (TAFI) commented that while river flow seemed important there was one year in which it appeared to have had no effect on migration at all, so it was clearly not the only causal factor. Neither the frequentist, nor the Bayesian, approach could be very powerful in rejecting this nul hypothesis. It would have been better to examine the hypothesis that river flow was the only trigger for migration of cod. Furthermore, he asked what use could be made of the probability values that the author had calculated using Bayes theorem. Simon Nicol noted that while Bayesian theory is not a substitute for well-structured hypothesis testing, it does allow the estimation of the probability of a hypothesis being true. Bayesian theory tells us that, given the data, there is a 60% probability that increased flow triggers migration of Murray cod. André Punt (CSIRO) pointed out that Bayesian theory has the advantage that it gets around the problem of having to specify the probability of Type I error, which he felt is a meaningless concept in a risk assessment context. Managers should not wait until there is a 95% chance of a stock being severely depleted before taking management action. Bayesian theory is the only way of linking management actions with their possible consequences, which it does by assigning probabilities to these consequences.

André Punt (CSIRO) presented a method for including spatial structure into yield-per-recruit models and applied it to data for flathead. Rob Day (University of Melbourne) commented that yield-per-recruit is an equilibrium method. The illustrative application to flathead was, he believed, not an adequate test of the method because flathead data would be expected to conform with the equilibrium assumption. He wondered whether other, less well-behaved, datasets had been tried and under what circumstances this approach would fail. André Punt agreed that a fundamental assumption of the model was that of equilibrium, so the model would not work well for stocks that show large variation in year-class strength. The model did not incorporate migration or return migration and would therefore probably fail if applied to species such as school shark. He mentioned that he had successfully applied the method to data from ling, morwong and warehou. Malcom Haddon noted that he has tested a similar approach and found that the addition of stochastic dynamics made a great difference to the results. However, as he did not have as much data this observation may not be true in the flathead case.

Charles Todd (NRE) presented a model that he used to improve understanding of the movement of freshwater fish. Paul Brown (MAFRI) felt that there was a contradiction within the model, which assumes a stable, equilibrium, population structure but nevertheless incorporates flow-driven variability in annual recruitment. Charles Todd answered that it was desirable to be able to reject the model because this would show that the underlying assumptions were incorrect and would therefore add to our understanding. Tony Fowler (SARDI) commented that the model presented has a large number of parameters and asked what the chance was of finding an incorrect set of parameter values that nevertheless lead to a good fit to the observations. André Punt responded that this phenomenon is called observational equivalence. For example, a model could be constructed that assumes that whales lay pelagic eggs but nevertheless fits the observed data well and even makes better predictions than a correctly parameterised model. However, while the accuracy of interpolation with such models is normally good, extrapolation may be poor. Malcolm Haddon commented that this illustrates the difference between using models to describe and to explain data. Models can be constructed which have many parameters and fit the data well, but which have poor predictive power.

Rob Kenyon (CSIRO) talked about the migration of banana prawns in the Joseph Bonaparte Gulf. Sandy Morison (MAFRI) asked whether prawns migrate actively or drift passively in water currents. Rob Kenyon said that more hydrological work was needed in this area. A north-west / south-east current exists in the Gulf and prawns that were tagged in the south moved towards the north but there is also movement from inshore to offshore (by as much as 200 km). Rob Day asked whether the non-random distribution of recaptured prawns that was observed during the study could be the result of the aggregation of tagged prawns after their release, i.e. those prawns that were released together stayed together. Rob Kenyon answered that this might be the case. His analysis is still preliminary and much work is needed in the future. John Pogonoski asked why there was such a large difference in the size of prawn catches between years. Rob Kenyon replied that this was due to environmental effects. John Gunn (CSIRO) asked why all the releases of tagged animals were in the south of the Gulf; given that the aim of the study was to investigate movement of prawns within the Gulf, the releases should have occurred in a variety of areas. Rob Kenyon replied that prawns aggregate in their juvenile habitat in the south and then move towards the north-west. During this study a wide area had been searched but prawn aggregations had only been found in the south. Furthermore, a cyclone had caused a delay so that tagging occurred while the fishery was operating. Some tagged prawns had therefore been transported south for release in order to prevent their immediate recapture by the fishery. John Gunn reiterated that releasing prawns only in the south had imposed conditions on the movement that could be observed by study and that this was undesirable, given the aim of the study.

Following a talk by *James Scandol* (QTUF) on computer visualisation tools, Richard Tilzey (BRS) stated that good visualisation tools can be over-persuasive. For example, in the case of SharkSim the managers may have been convinced that the model was correct when in fact it was not. Will Zacharin (PIRSA) stated that visualisation tools lead to more informed debate, not necessarily to better science. Whether or not this results in better management is a value judgement. James Scandol agreed that visualisation tools accelerate understanding and therefore lead to more informed debate. However, this could result in greater discussion of uncertainties and hence to greater uncertainty in what management action should be taken. He reiterated that it is important to study how these tools are being used and what effects they have. André Punt asked what is the difference between a visual model (which has to be simple so that it can run quickly) and a model that has visual output (and could be quite complex). James Scandol answered that the latter is described as scientific visualisation whereas the former is a gaming-type model, to which users can make changes and run for themselves. Both have a role to play. Rob Day said that the most important aspect of a model that ought to be communicated to interested parties is the model's limitations - where it can go wrong. SharkSim and AbaSim lacked this. It is important that users know the limitations of the models and don't simply believe their outputs. David Smith (MAFRI) agreed and wondered how much information those involved had.

Norm Hall (Fisheries WA) presented a spatial model of the tiger prawn fishery in Western Australia. There was confounding in the model between migration and recruitment. The data did not provide information on the size of the stock and the level of natural mortality. André Punt stated that this illustrates that some questions simply cannot be answered given available data. Rob Day commented that this is an example of a situation where models can be used to tell us what we don't know and therefore where research effort is needed. Norm Hall agreed that it is important to expose our uncertainties and communicate them to managers so that they can make decisions that are robust. He reminded workshop participants that simulation tests of his model showed that it could fit the data very well but that its estimates of recruitment were not good. Cautioning against the use of over-parameterised models, Malcolm Haddon asked how many data points were available to fit this 192 parameter model. Norm Hall stated that there are 29 years of CPUE data in each of six regions for roughly 10 months of each year. Furthermore, there are duplicated parameters within the model so that the true parameter number for each dataset could be regarded as 192 divided by six for each dataset. Norm Hall intends simplifying the model further in future, possibly using a single recruitment figure for each year, which would then be divided between regions. The assumption of constant recruitment is invalid and more parameters are needed to describe the data because the regions seem to differ.

The chair, *André Punt*, started the *general discussion* by highlighting the following themes that had emerged during the session:

- Using models to understand processes or to make predictions
- Visualisation tools
- Limitations of models and communication of these to managers
- Direct use of tagging data in models (which seems not to be happening).

Rod Connolly (Griffith University) recalled that Simon Nicol had indicated that the use of Bayesian theory was a way around rigorous data collection and he questioned this assertion. Simon Nicol replied that he believes that rigorous data collection is important regardless of the form of analysis used. The difference between the frequentist and Bayesian approach is between rejecting a single hypothesis and examining belief structures, using data to weight alternative hypotheses. Bayesian theory allows the investigator to make use of data that might otherwise not be easily incorporated into models. For example radio-tagging data are often collected in ways that make them difficult to incorporate into models. André Punt added that the method by which the data were collected is often less important than knowing what that method was; neither frequentist nor Bayesian methods will be usable if this is not known. An advantage of Bayesian theory is that it allows you to integrate over nuisance / unmeasurable parameters such as natural mortality. Norm Hall pointed out that bad, *ad hoc* experimental designs are inefficient as the data that are collected are unlikely to contain maximum information content.

On the topic of using computer visualisation tools to stimulate debate, Malcolm Haddon asked whether it was important to distribute source code so that others could easily make changes to the models and present alternative outputs. This might solve the problem of managers blindly accepting the results of single, highly visual models. James Scandol agreed but cautioned that institutions often spend large amounts of money in developing these tools and are therefore often reluctant to give them away. The same is true of datasets that are not made available outside the institutions that collected them until they have been analysed rigorously. Malcolm Haddon raised the question of educational models whose development had been funded by the Fisheries Research and Development Corporation. James Scandol mentioned the WWW site Marine Models Online, through which authors of models make their compiled programs available to others. Marine Models Online polled its contributors, asking them whether they would be willing to make their source code available to others. Only 10% were willing to agree to this.

James Scandol raised the question of whether a very complex model with many parameters would be able to distinguish between two hypotheses. Should the level of complexity be set according to the question to be answered? André Punt answered that if the conclusion was clear, e.g. fishing mortality has to be reduced, then a very simple model would be sufficient to show this and there would be no need to construct a very complex model.

Tony Fowler asked about methods to test the applicability of a visualisation tool. James Scandol replied that it was necessary to investigate whether the decisions made by managers were altered as a result of the use of that tool. André Punt mentioned that visual models tend to be too complex in an attempt to be more realistic. People are often uncomfortable if important biological processes are left out of a model, even though this may be better statistically because simpler models are often better at prediction.

Rob Day pointed out that what matters is what the model is to be used for - the "right model" is decided by the aim of that model. He questioned whether visualisation tools should be used to convey an understanding of a single model, or to educate managers about models and their limitations? Will Zacharin stated that they are used for both. For example, in South Australia a game-type model (developed by Prescott and McGarvey) was used to illustrate to managers the effect of an increase in the size limit for rock lobsters. Rob Day reiterated that visualisation tools are good for communicating this sort of information, but poor at communicating the limitations of these models. James Scandol commented that the results of models are inevitably uncertain and it is difficult to know how to deal with this. It has been shown that humans are inherently poor at interpreting uncertainty. André Punt agreed that people usually ignore the probability intervals and simply look at the solid line. Models don't get rid of the problem of uncertainty but they do allow debate structuring. Malcolm Haddon said that he had communicated uncertainty successfully by having the users run a single iteration of a stochastic model several times, getting a different answer each time. Only then had he moved to graphs that showed the spread of results. This method had been successful in improving the users' intuitive understanding of uncertainty. Models can be regarded as formalised intuition.

Terry Walker commented that visualisation tools are regarded as forming a bridge between managers and scientists, but they are also important to form bridges between scientists, particularly biologists and modellers. Biologists are sometimes uncomfortable with models that do not capture all the known biology of a particular stock. Alternative models should be produced and debated. As some of these are discredited, so progress is made.' Simon Nicol agreed - uncertainty is narrowed by building alternative models and discarding those that don't explain the data. Models that have been produced to describe threatened freshwater fish have allowed scientists to identify the key parameters. André Punt stated that his experience in building models to describe Commonwealth fish stocks was that some parameters (which may be of great biological interest) are irrelevant to the results of the model whereas others are vital. Models can also be used to show that some questions cannot be answered, even with a high degree of research effort. Thus models can serve to end lengthy debates on issues which are either irrelevant to management, or which cannot be elucidated.

Peter Stephenson (Fisheries WA) described a population dynamics model that he developed years ago. Managers asked him to incorporate discards and environmental factors to make the model more realistic. However, Norm Hall advised him not to attempt this but rather to mention these factors as caveats in his report, thus requiring a conservative use of the model's results when making management decisions. Otherwise the discussion of the model might have concentrated on these factors rather than on the more important aspects of the model.

David Smith asked what the effect was of using tagging data in the very complex school shark model. Terry Walker replied that its use had decreased the uncertainty in the model results. Prior to their incorporation into the model (the 1996 assessment), the estimates of school shark depletion lay between 15% and 47% whereas afterwards (the 1999 assessment) this range was 12%–18%. The tagging experiment was designed with uniform effort over each of the four regions of interest, long before it was known that its results would be used in a Bayesian model. Nevertheless its results were usable in the 1999 assessment where eight regions were adopted.

Session 4

Management implications

Chair:	Nick Rayns
Speakers:	Stephen McCormack Will Zacharin Dorothea Huber Andrew Sanger Ray Clarke Wayne Fulton John McGuckin
Rapporteur:	Patrick Coutin

Chair's Introduction

Nick Rayns

Fisheries Division
Northern Territory Department of Primary Industries and Fisheries
PO Box 990, Darwin NT 0801

Before considering the management implications of fish movement and migration I would like to provide my view of the role of a fisheries manager. This is needed to assist in understanding the management response to fish movement and migration issues.

The role of a fisheries manager is to:

1. Be aware of all the information on a fishery;
2. Engage those who have an interest in the resource and its habitat in the fisheries management process;
3. Negotiate outcomes that are consistent with sustainable use and are accepted by key stakeholders.

A seemingly simple enough set of tasks!

So why is fish movement and migration important to fisheries managers?

First, it influences who is involved in the management process and is essentially a matter of scale, i.e. local, interState or international. Examples of whitebait in Tasmania, Australian salmon, and central and western Pacific tuna management will be given by speakers to demonstrate this.

Second, it affects what the dominant influences will be on decision making; biological, social, economic or political. International fisheries management is typically dominated by political issues, with science often playing a minor role.

Third, it can drive the option(s) for management, i.e. whether to pursue input or output controls. The international Southern Bluefin Tuna (SBT) convention only permits a Total Allowable Catch (TAC) approach.

So what issues do fish movement and migration present to fisheries managers?

At a local level, the primary issue is competition with other fishery, but more importantly non-fishery, users. Factors such as coastal development and water use (through storage, diversion and pollution) all impact on fishery resources. These are matters generally managed at a State or local government level.

At an interState level, in most cases the main issues are fishery-related. Each State may have differing priorities and policies for a fishery. At least I suppose this shows there is often more than one good answer to a fisheries problem! It also can lead to conflict; size restrictions in particular are an issue - for example rock lobster in South Australia and Victoria, and flathead in Victoria, Tasmania and New South Wales.

Internationally, the issues are again policy-related, but there are the complicating factors of culture and international politics. In regard to SBT, Australia comes from a position of resource conservation and Japan from food security. Australia is sometimes seen as arrogant and inconsiderate by Japan, whilst Japan is seen by Australia as denying the obvious truths about SBT sustainability. Clearly there is a need for understanding that each other's value systems are also important.

The seven speakers in this session will cover finfish and crustaceans, freshwater and marine environments, international through to local issues. I believe they provide a flavour of the diversity of issues created by the movement and migration of fish for managers.

The fishery for Australian salmon: management issues

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Abstract

Australian salmon is an important commercial and recreational species that is taken in Western Australia, South Australia, Victoria, Tasmania and New South Wales. There are two separate species (eastern and western) both of which undertake extensive migrations. However, for the purposes of this discussion they are treated as one. Commercial catches have remained relatively stable except in Victoria, where the catch has steadily increased, and in Tasmania, where catches have decreased over the same period. Reliable assessments indicate that the western species is being managed on a sustainable basis but assessments of the eastern species are not so reliable.

In Victoria the bulk of the commercial catch is taken from ocean waters between Wilson's Promontory and Mallacoota. The average price is in the order of $1 per kg with the catch being sold mainly for rock lobster bait and pet food. Smaller quantities are taken from bays and inlets. Australian salmon is the dominant species taken by Victorian surf anglers and could make up more than 80% of the total catch. On weekends when the salmon are "running" many anglers pursue this species, travelling to popular locations such as the Ninety Mile Beach, Lakes Entrance and Marlo. The commercial netting of Australian salmon using beach seine and purse seine nets is often carried out in sight of anglers. Anglers claim that targeted commercial fishing effectively removes entire salmon schools or, at least, displaces salmon from where anglers can reach them.

The Australian salmon that make up the eastern Victorian commercial and recreational fisheries are part of a stock that is shared with Tasmania and New South Wales. Any action Victoria may wish to contemplate that has an impact on the commercial fishery must have regard for the fact that New South Wales and Tasmania have a long history of exploiting the same stock.

Introduction

Australian salmon is an important commercial and recreational species that is abundant in Western Australia, South Australia, Victoria, Tasmania and New South Wales. There are two species of Australian salmon found in Australian waters; the eastern Australian salmon (*Arripis trutta*) and the western Australian salmon (*Arripis truttaceus*) (Gomon *et al.* 1994). The former is also found in New Zealand where it is abundant and commonly called kahawai.

Australian salmon is a relatively quick-growing species, sexually mature at about five years of age. Fish up to seven kg in weight are not uncommon particularly from the western species. Australian salmon is a highly mobile species capable of travelling considerable distances over a relatively short period of time.

Eastern Australian salmon are found in waters from mid-NSW to central Victoria including Tasmania. Mature fish migrate from Tasmania and central Victoria to waters off southern NSW and north-eastern Victoria to spawn during summer (Kailola *et al.* 1993). After spawning, fish disperse into Bass Strait and NSW waters.

Western Australian salmon are generally found from central Victoria and Tasmania to Western Australia (Gomon *et al.* 1994). Maturing fish migrate from the eastern States to the south-western coast of Western Australia. Spawning occurs in late summer/autumn (Kailola *et al.* 1993).

In Victoria and Tasmania there can be some aggregation of both species but they are generally found separately. Preferred habitat for adult fish is shallow open coastal waters with juveniles generally found in bays and inlets.

In Victoria, it is an important recreational species and it is caught commercially along the coast and in bays and inlets. The bulk of the commercial and recreational catch is eastern Australian salmon, taken from east Gippsland. The species is also exploited by the commercial and recreational sectors in Tasmania and New South Wales.

There is considerable conflict between sectors over this resource which is compounded by the migratory nature of the species. In this paper the fisheries are briefly described and issues concerning their management discussed.

The Fisheries

Nation-wide commercial catches have been stable in recent years (Anon 1999) with total average annual landings of about 5 000 tonnes.

In Victoria the catch has been steadily increasing as shown in the following table:

Production (live weight, tonnes)

1993/94	1994/95	1995/96	1996/97	1997/98
162	324	333	307	708

The recent increase in landings in Victoria is being offset by a reduction in catches over the same period from Tasmania.

In Victoria the bulk of the commercial catch is taken from ocean waters between Wilson's Promontory and Mallacoota. The main port of landing is Lakes Entrance. Prices are relatively poor in the order of one dollar per kg, with the catch being mainly sold for rock lobster bait and pet food. The lack of recent opportunity to sell this species for canning, combined with limited acceptance at fresh fish markets, are likely to be the main inhibiting factors to any substantial increase in the commercial catch.

Smaller quantities are taken from bays and inlets where, because the catch is mainly comprised of juvenile fish, they are more acceptable at fresh fish markets. The eating qualities of Australian salmon are generally considered to be poor. Larger fish do not keep well but smaller fish, if well handled, and conveyed to market quickly, will generally obtain a reasonable price.

The most common methods used by commercial fishers include beach and purse seining.

Australian salmon is a popular species with anglers, and it is the dominant species taken by Victorian surf anglers and could comprise more than 80% of the total catch. The popularity of surf fishing in Victoria (and for that matter other States as well) should not be underestimated. It is a major tourist attraction particularly in the east of the State.

On any weekend when the salmon are "running", anglers in their thousands pursue this species, many travelling to popular locations such as the Ninety Mile Beach, Lakes Entrance and Marlo.

Anglers also pursue salmon in bays and inlets, where because of their smaller size they are commonly called bay trout. Quite large schools of fish are common providing good sport to boat anglers who take them by trolling, and pier and jetty anglers who use bait and lures.

Issues

There is general agreement that stocks of the western species are in good shape and that the fisheries from Victoria to Western Australia are being managed on a sustainable basis. Although assessments for the eastern species are not so reliable, landings overall are not increasing and are probably sustainable. However, there is considerable conflict between the recreational and commercial sectors.

Recreational fishers and tourism industry representatives frequently put the argument that from an economic perspective the value of Australian salmon to the recreational sector far outweighs the return that the commercial sector receives.

Conflict between the commercial and recreational sectors is compounded by the fact that commercial netting of Australian salmon is often carried out in sight of anglers. Anglers claim that targeted commercial fishing effectively removes entire salmon schools or at least displaces salmon from where anglers can reach them. Commercial fishing frequently occurs in daylight hours close to the shoreline.

Restraints on the commercial catch of salmon, or the closure of certain areas to reduce the conflict, may do little to improve the angling opportunities for this species but they would be well received by opponents of the commercial fishery. Victoria has a number of regulations in place, which restrict commercial fishing on weekends and during key holiday periods. They have the sole objective of reducing conflict between commercial and recreational fishers and apply mainly in bays and inlets.

The Australian salmon that make up the eastern Victorian commercial and recreational fisheries are part of a stock that is shared with Tasmania and New South Wales. Any action Victoria may wish to contemplate that has an impact on the commercial fishery must have regard for the fact that New South Wales and Tasmania have a long history of exploiting the same stock.

Any action taken by Victoria to address the resource-sharing conflict could be challenged by the commercial sector on at least two grounds:

1. The stocks appear to be healthy and existing catch rates are sustainable, and
2. What is the point of Victoria considering a reduction in its commercial catch if the two adjacent States that share the same resource are not prepared to consider taking similar action to reduce their commercial catches? Their catches may well increase in this event as they have access to an increased share of the resource and the markets that Victoria no longer supplies.

Many fisheries that are located in south-eastern Australia flow across State borders and may also occur in both State and Commonwealth waters. Generally when this occurs the relevant management agencies will set up an arrangement generally known as an Offshore Constitutional Settlement Agreement, provision for which is made in all State legislation. The Commonwealth is generally a party to all agreements, which enable a particular fishery to be managed by a single jurisdiction.

Because of their inshore nature Australian salmon are only occasionally found outside the 3 nautical mile territorial limit of State waters. All fishing for Australian salmon occurs within State waters which has led to the Commonwealth entering into arrangements with the States on an individual basis to hand over any jurisdiction/interest that they have for the commercial fishery for this species.

Further refinement of management responsibilities by this means is unlikely. Given the number of States involved, and the lack of justification for the Commonwealth to become involved in management in what is basically an inshore fishery, the States themselves will have to sort out management issues for this species.

Conclusions

- Stocks of Australian salmon are basically healthy across their entire range.
- Market demand for this species is unlikely to increase in the immediate future and recreational fishing poses no threat to stocks.
- Highly migratory species like Australian salmon that range across several jurisdictions can be extremely difficult to manage.
- From a Victorian perspective any reduction in commercial catches may do little more than provide an opportunity for fishers in other States to increase their share of the catch.
- Any attempt Victoria may make in the future to redistribute the catch of Australian salmon from the commercial to the recreational sector may well result in a redistribution of the catch from the Victorian commercial sector to the commercial sectors in other States.
- The primary objective of fisheries management agencies is to manage the harvesting of fish resources on a sustainable basis. The concept of redistribution of the catch from the commercial sector to the recreational sector based on economic considerations is not a common feature of fisheries management in Australia and therefore provides a unique challenge.

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Management implications for movement and migration in a rock lobster fishery

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Abstract

Rock lobsters may migrate significant distances and this phenomenon can create implications for the management of these fisheries. Abundance may be influenced by depth, season, temperature, shelter, food and other environmental factors. Scientific advice on migration, including settlement of juvenile rock lobsters, can be critical for development of sustainable management strategies. Changes in catch rates across fisheries due to annual changes in abundance alter the impact of fishing effort and may lead to localised depletion. Movement and migration of rock lobsters can also have regional economic impacts due to loss of catch or increased fishing costs. Stock assessment advice needs to consider issues related with movement and migration to ensure appropriate management action can be considered.

Speaker did not submit a full manuscript.

Managing Pacific tuna fish: an Australian perspective

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Speaker did not submit an abstract or full manuscript.

Fisheries management implications of barriers to movement and migration by fish in New South Wales

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Abstract

There are an estimated 4 700 barriers to fish passage in New South Wales, ranging from partial barriers such as low weirs, to complete barriers such as large dams. The biological impacts of these barriers can range from reduced recruitment and increased mortality, through to local extinction of affected species.

Management of these impacts in NSW focuses on a number of issues, including:

- *Assessment of existing barriers and prioritisation of remedial action*
- *Construction of fishways*
- *Stocking programmes for important recreational species*
- *Use of barriers as fish traps for pest species*
- *Regulatory and compliance actions to protect vulnerable aggregations of desirable species*
- *Novel approaches to overcoming problems created by barriers.*

Stocking programmes are relatively inexpensive and are widely appreciated by the public as a positive initiative to overcome problems created by barriers. However, there are limitations with stocking programmes, including the fact that there is only a small group of species available for stocking.

Construction of fishways is expensive and, to gain maximum benefit, must be co-ordinated with other fisheries management actions. However, well-constructed and maintained fishways can be an important factor in rehabilitation of migratory fish stocks within affected catchments.

Introduction

Barriers to migration cause severe problems for fish and fisheries management, particularly in freshwater and estuarine environments. Like all management problems, there is no single solution or management action that can be taken to address the problems caused by barriers to migration. That is because there is a range of problems caused by barriers, and the severity of their impact varies.

For freshwater fish the major biological problems caused by barriers to migration can be summarised as:

- Reduced recruitment resulting from spawning failures or other life cycle interruptions
- Increased mortality
- Local extinction of some species
- Resultant changes to community structure.

There are thousands of physical barriers to fish movement on NSW rivers. The barriers range from small low-level weirs and suspended culverts that obstruct fish movement at low river levels, but are more readily traversed at higher river levels; through to high dams which can act as complete barriers to upstream movements by fish. The abundance and great diversity of these barriers in NSW has been recognised for some time, and as a result there has been extensive research into and management of the impact of barriers to fish migration. Much of the current management actions have been guided by the results of research into fish movements and fishway technology at several key locations in NSW. This work was undertaken by John Harris, Martin Mallen-Cooper, Garry Thorncraft and others at NSW Fisheries throughout the 1980s and 1990s (see Mallen-Cooper and Harris 1990; Harris and Mallen-Cooper 1994; Thorncraft and Harris 1996 for reviews).

Management of these impacts in NSW focusses on a number of issues, including:

- An extensive audit of existing barriers that documents the nature of each barrier and prioritisation of remedial action
- Construction of fishways on high priority barriers
- Stocking programmes for important recreational species where barriers have resulted in a decline of sportfish
- The use of barriers as fish traps for pest species
- Regulatory and compliance actions to protect vulnerable aggregations of desirable species
- Novel approaches to overcoming problems created by barriers.

Each of these management actions is discussed in more detail below.

Assessment and prioritisation of barriers

Thorncraft and Harris (in prep.) tabulated the existence of over 4 700 instream barriers to fish movement in rivers in NSW. These include over 2 900 weirs and dams, 175 gated weirs or similar regulating structure, almost 1 400 tidal barriers, and about 200 smaller structures such as road crossings and culverts. With such a large number of barriers, the task of assessing and addressing the problems they cause is immense.

In many cases to date, problems have been dealt with on an opportunistic basis whenever funds become available for particular sites, or when legislation requires such action. For example, whenever a dam, weir or reservoir is modified or altered in any way, the Fisheries Management Act 1994 stipulates that the Minister may require such works as may be required to enable fish to pass through or over the structure. However, a ranking scheme has been developed to assist with prioritising decisions on allocating resources in a structured way.

The ranking scheme allows each barrier in the State to be assessed using a consistent framework. The criteria included in the ranking scheme are outlined in Pethebridge *et al.* (1998) and include:

1. The size of the river or stream
2. The location of the barrier in that stream
3. The presence of threatened or endangered species
4. The amount of fish habitat upstream of the structure
5. The number of obstructions which occur downstream
6. The proportion of the river obstructed by the barrier
7. The drownout frequency of the barrier
8. The type of barrier
9. The presence and effectiveness of any existing fishways
10. The cost of building a fishway, and
11. The level of support from community and other groups for providing fish passage.

Each barrier can be given a score against each of these criteria, and the individual scores totalled to arrive at the score for that site. Sites can then be ranked, with those sites having the highest scores being considered most important and feasible as sites for fishway construction.

Over time, construction of fish passage facilities in NSW is expected to be guided by this priority ranking scheme, in order to gain the most benefit from the considerable funding commitments that will be required.

Construction of fishways

There is a large number of ineffective fishways in NSW. Research has shown that many of the early attempts to overcome the problems by construction of fishways were ineffective due to poor design and maintenance of the facilities. Designs based on overseas hydrology and biology were utilised in many of them. However, research results have shown that a variety of suitable designs do exist.

Details of effective fishway designs are given in Thorncraft and Harris (in prep.). Design selection involves a detailed site-specific analysis of the characteristics of each barrier and assessment of the options for fish passage. However, it is possible to generalise about the characteristics of each design, and the types of barriers for which they may be suitable.

Rock-ramp fishways offer a relatively low technology solution to fish passage at low barriers. A ramp of large rocks placed at a gradient of 20:1 provides a series of interconnected pools and riffles that fish can use to pass a barrier. These designs have been shown to be effective for small fish over a range of flows, but for larger species, their effectiveness is limited under low flow conditions.

Bypass channels are sometimes constructed to provide a simulated stream environment through which fish pass around a weir or other man-made barrier. These channels are usually low gradient (20:1 or more) and include in-channel and riparian structures that mimic a natural stream. Flow regulation in the bypass channel is necessary to ensure their effectiveness under a range of flow conditions.

Vertical slot fishways have been shown to be successful for Australian native fish. They are often installed at moderately-sized weirs. One of the key features of this design is that it remains effective over a wide range of water depth and flow conditions.

Denil fishways are similar in design to vertical slot fishways, and offer an advantage in that they are generally cheaper to construct. However, they are not suitable for some sites and do not offer the same flexibility as vertical slot design over a range of flow conditions.

Lock fishways operate in much the same way as a navigation lock on a river. Fish are attracted into a holding chamber at the base of the lock. This holding chamber is then sealed and filled with water to upstream water level. Fish are then able to swim out into the upstream environment. These designs are suitable for installation at larger barriers where vertical slot and Denil type fishways are less effective and more expensive.

Trap and transport type fishways are often required where very large barriers limit the use of other designs. Essentially these trap and transport operations involve the use of some type of trap where migrating fish are collected at the base of a barrier. The fish are then transported around the barrier by vehicle or rail and released into the upstream environment. Although expensive to operate due to ongoing staff and transport costs, trap and transport operations may be viable over the short term.

It needs to be noted, however, that lock fishways and trap and transport operations do not provide good opportunities for fish to migrate downstream past barriers. This is increasingly being recognised as an area for additional research.

Stocking programmes

Many anglers and other interested parties see stocking as one of the major successful management solutions to the problems caused by barriers. Species commonly stocked in NSW are Murray cod, golden perch, silver perch, trout cod, Australian bass and the salmonid species. There are good examples where significant recreational fisheries have been restored as a result of a stocking programme, particularly with species such Australian bass.

However, there are a number of limitations to the improvements that can be achieved with stocking programmes. For example, in most cases the barriers continue to affect the species that are stocked, so continual stocking is required. This commitment to continued stocking can tie up resources that may be put towards other programmes. Also, stocking programmes focus on desirable recreational and commercial species and ignore the smaller and less desirable or less charismatic species. Unfortunately some of these smaller species such as Australian grayling and migratory galaxiids which are seriously affected by barriers, and can be lost from significant stretches of stream, are unlikely to ever be considered for a restocking programme. Stocking programmes can act as a disincentive to the adoption of more long-term or holistic solutions, because the immediate public symptom of the problem is masked.

Where a local extinction has been caused by other factors, such as a pollution incident or stochastic event, such as severe drought, and a barrier is stopping recolonisation by a migratory species that would otherwise successfully complete its life cycle in the affected section of stream, stocking programmes can help to permanently re-establish those species. However, this is the exception rather than the rule.

Making use of barriers

Barriers have been used for thousands of years to take advantage of the migratory behaviour of fish to assist in their capture. In NSW, probably the best known example of the ancient use of this is the stone fish traps constructed and maintained by the local aboriginal people on the Barwon River at Brewarrina. These traps were used to capture Murray cod, golden perch and silver perch during both upstream and downstream movements that were triggered by changes in water level and their reproductive season.

The concept has been adapted into a wide variety of barrier traps that make use of the movement of fish. In recent years, installation of fish traps at some fishways to allow for sorting of the catch and removal of pest species such as carp has been pursued. The fishway at Torrumbarry weir on the Murray River near Echuca has been operated in this way, firstly as a research project, and more recently as a commercial fishing operation.

The opposite approach has been followed for several endangered native fish that are threatened by introduced fish. In some circumstances barriers have been constructed to stop predatory fish colonising the habitat of threatened species. For example, in Tasmania and Victoria barriers to trout migration have been constructed to protect remnant populations of two endangered galaxiid species. At this stage this has not been part of a deliberate programme in NSW. However, now that threatened fishes legislation has been enacted and the recovery plans are being developed, it is likely that such approaches will be used in the future.

Compliance programmes

Major problems can occur where particularly vulnerable aggregations of species with a high market value and easy to capture and market accumulate at natural or artificial barriers. Recreational and commercial fishers are 'guilty' of targeting these aggregations. For some species, this targeted fishing is not considered a problem. However, regulations are often put in place to prohibit fishing within certain distances from barriers, or during certain seasons. These areal and seasonal closures are designed to protect the fish while they are vulnerable because their free passage either upstream or downstream is being constrained by a barrier.

Compliance with these closures is generally reasonably good. However, there are exceptions, such as the whitebait fishery in Tasmania, which represent substantial problems for compliance staff.

Similar things occur during trout spawning runs, below major barriers during the bass season, and at barriers on the inland Murray-Darling streams during the Murray cod and golden perch spawning migrations.

Getting increased compliance with such things as closures is always going to be a combination of public education, adequate signage and other advisory material and enforcement, and is difficult. However, while the barrier problems remain, a focus on the regulatory solution, implemented through active enforcement programmes, will remain and be a substantial drain on the resources of many management agencies.

Novel approaches

Harvesting pest species and protecting threatened species are two of the novel ways of using barriers to improve management of freshwater fishes that were discussed briefly above. However, barriers cause more problems than they solve, and there are a number of innovative measures that have been undertaken to address these problems in NSW.

Elaborate trap and transport operations to overcome fish passage problems are uncommon in Australia. A large-scale programme has been in operation for many years at Trevallyn in Tasmania to facilitate passage of juvenile eels past a large dam and associated hydroelectricity generation infrastructure. More recently a similar solution has been implemented as an interim measure at the Yarrawonga Weir on the Murray River. A sophisticated lock fishway was constructed as part of a development of a small-scale hydroelectricity generation plant at this weir. Problems with the lock fishway have necessitated it being used as a trap for the time being, with transport of fish to the upstream impoundment (Lake Mulwala) by vehicle.

While this approach may be considered unsatisfactory for the long term, it has provided an opportunity to further research the behaviour of fish in the lock fishway and the seasonal nature of movements of fish at this weir. This information will be valuable in determining the future operational and structural solutions to the problems with the lock fishway. The operation has also demonstrated a commitment by the management agencies, including the Murray-Darling Basin Commission, River Murray Water, Goulburn Murray Water and NSW Fisheries, to overcoming the problems of fish passage at this major barrier.

Summary

The riverine environments of NSW are seriously impacted by the construction of barriers. Fish movement and migration is but one of the many ecological processes that has been compromised by these barriers. Recognition of the diversity of species and life history stages of fish that are affected has been gradually building over the latter part of this century following the major construction phase which occurred during the early to mid 1900s. Hence, management has continually been challenged with overcoming the problems of fish passage.

The shortcomings of overseas designs for fishways were not recognised prior to this major construction phase, and consequently inappropriate facilities were built at many weirs. However, as a result of solid research into the solutions to these problems in NSW, a number of alternatives exist for low to medium level barriers that will allow many of the migratory native species to pass both upstream and downstream. The challenges that remain include overcoming the problem of high dam fishway construction, and ensuring that facilities that are built accommodate movements in both upstream and downstream directions at all phases of the life cycle. Novel approaches to these challenges will continue to be trialled within the adaptive management framework that influences natural resource management at present.

Stocking has a role to play in the solution to the problems caused by barriers. Where the alternative of fishway construction is possible or economically viable, stocking will provide short-term relief, particularly for the larger angling species which receive considerable government funding support. Smaller cryptic species and/or less desirable species that are impacted by barriers will be the losers if stocking programmes are seen as the sole answer to barrier problems.

While some commercial and recreational fishing activity, both legal and illegal, will always be focussed on the opportunities presented by the aggregations of migrating fish that occur at barriers, management of these fisheries is not seen as the major challenge posed by the barriers. Rather it is the interruption to fundamental ecological processes such as completion of life cycles, recolonisation and community structure that has the most profound impact on fisheries management. Fishway construction and ongoing maintenance is an integral component of the way forward for the long term (along with a suite of other measures designed to restore the habitat of freshwater fish).

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The challenge of spatially managing fish movement and migration throughout Northern Australia: the experience with tropical snappers

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Abstract

Management strategies for wildstock fisheries throughout northern Australia (the Top End) provide particular recognition of State/Territory boundaries in preference to the ecological stock boundaries. Much has been achieved in refining jurisdictional arrangements over the last decade or so with the aim of ensuring compatible and complementary strategies, by adjacent and regional resource agencies, in managing their often-shared aquatic resources. It is widely acknowledged that with even a low level of movement, the wellbeing of a fish population in one jurisdiction can be detrimentally affected by actions undertaken within another.

An overview of the management strategies of the tropical snapper fisheries throughout the Top End and beyond provides a valuable stage for discussions on spatial management of stocks, given the strong likelihood of movement across intra-national and international jurisdictional boundaries.

Tropical snappers and emperors are harvested by high-tech line, trap and fish trawl fleets operating in the Kimberley and Pilbara regions of Western Australia. A line fishery operates from Darwin and a fish trawling vessel operates in Northern Territory and Queensland waters of the Gulf of Carpentaria. A developmental trawl fishery for red snappers and emperors within Queensland-managed waters of the Gulf of Carpentaria has been held over pending improved economic conditions. In Indonesia, tropical snappers and emperors are harvested by lines (longlines and handlines) and trawling by subsistence and commercial operators.

Established research strategies seek to gain an understanding of the degree to which stocks are shared, through the gathering of comprehensive catch and effort information together with a detailed understanding of the biology, life-cycles and movement patterns. This approach generally relies on fishery-dependent estimates, with a view to incorporating the outcomes as the principal basis for fisheries management strategies to ensure long-term sustainability. A challenge confronting managers is implementing arrangements for the long-term sustainability of commercial, recreational and subsistence fisheries in the absence of a good understanding of the degree of mixing and migration.

Introduction

The Commonwealth and the States have shared responsibility for the management of Australia's fisheries resources since Federation in 1901. Generally speaking, the States have maintained responsibility for managing coastal fisheries resources until 1968, when the Australia's declared fishing zone was extended to 12 nautical miles. In 1979, Australia declared the Australian Fishing Zone (AFZ). This declaration afforded Australia sovereign rights over the living resources found generally within the exclusive economic zone (EEZ).

The resultant jurisdictional arrangements required commercial fishers to hold multiple licences, with the State managing fisheries within the 3 mile territorial sea and Commonwealth jurisdiction between 3 miles and the outer limit of the AFZ. At the Premiers' Conference in 1979, the Commonwealth, States and the Northern Territory agreed on the need for a formal framework to resolve a range of contentious and complex offshore constitutional issues.

More recently, the management arrangements for northern Australia were refined with the passage of the Offshore Constitutional Settlement (OCS) arrangements of 1988 and 1995. The Offshore Constitutional Settlement provides a framework for the States/Territory to either manage fisheries resources in all adjacent waters, or pass management responsibility to the Commonwealth; or alternatively, for the Commonwealth and the States/Territory to come together and jointly manage a fishery. The OCS arrangement and associated formal administrative measures provide for cooperative and complementary arrangements between the States/Territories and the Commonwealth.

The passage of the 1995 OCS saw the appointment of the 'small' Fisheries Joint Authorities for the management of the offshore demersal snapper fisheries within Queensland waters of the Gulf of Carpentaria and waters adjacent to the Northern Territory. Management responsibility for the adjoining snapper fisheries in northern Western Australia passed to the State. As an outcome of these arrangements, snapper fisheries formally managed by the Northern Territory and Queensland together with the fish trawl fishery passed to respective Joint Authorities.

Formal administrative arrangements agreed to at that time between the Commonwealth, States and the Northern Territory seek to provide an adequate level of consultation to ensure a complementary and compatible approach in managing what are likely to be shared fisheries resources. These arrangements also provide for the States/Northern Territory to establish mechanisms for the allocation of fisheries resources. Formal consultation on the allocation of fisheries resources between adjoining intra-national jurisdictions is in its infancy.

Australia is a signatory to international region agreements and fisheries management and technical organisations for highly migratory species, most notably for tunas. Such arrangements provide for the cooperative management of straddling stocks occurring in coastal states and on the high seas. It should be noted that Australia's exclusive economic zone directly adjoins that of its northern neighbours. A regional agreement is yet to be discussed for northern Australia, other than for tuna species adjacent to northern Western Australia.

The tropical fisheries resources of northern Australia provide a valuable stage to review the evolution of spatial intra-national and international management arrangements for what are likely to be shared stocks of demersal fishery resources.

A brief history of 'Top End' demersal fisheries

The harvesting of demersal fisheries resources throughout northern Australia pre-dates European settlement. Commercial fishing throughout northern Australia may be traced to the 1700s when Macassan fishers from Sulawesi, Indonesia, harvested fisheries resources from coastal waters adjacent to the Top End.

In more recent times, the demersal fish resources of northern Australia have been commercially explored by Japanese stern trawlers during 1959-1963, and extensively fished by Taiwanese pair trawlers from 1971 to 1990. In addition, stern trawlers operated in the Arafura Sea during 1985-1990 whilst Chinese pair trawlers operated in the Timor Sea in 1989. Feasibility studies by Japanese vessels using droplines saw substantial landings throughout 1975-1982 within the Timor Reef region, located 150 nautical miles north of Darwin.

Foreign trawling was phased out in 1991 given interest by domestic operators and concerns about the long-term sustainability of red snapper stocks. It should be noted that landings within the Northern Fish Trawl Fishery peaked at about 18 000 tonnes in 1974 and regularly exceeded 10 000 tonnes throughout the 1970s and early 1980s. Current landings in Australian waters are around 800 to 1 000 tonnes per annum. More recently, a developmental fishery has been commenced within the Queensland component of the Gulf of Carpentaria. Management arrangements have established an upper ceiling on landings of commercial tropical snapper species.

High-tech vessels operating from Darwin currently harvest tropical snappers using lines and traps from what is known as the Timor Reef fishery. Lines and traps in an adjacent fishery in Western Australia also commercially harvest tropical snapper. A single fish trawler operates in NT waters, with a developmental trawl fishery planned for the Qld component of the Gulf of Carpentaria. These fisheries operate immediately adjacent to the Australian Fishing Zone. In Indonesia, tropical snappers and emperors are harvested by lines (longlines and handlines) and trawling by subsistence and commercial operators.

Management of tropical snappers

Management decisions within the Australian context centre on the quest to ensure that fisheries are managed in accordance with ecological sustainable development principles. Whilst individual State/Territories and the Commonwealth have prescribed legislative obligations, the general goal of domestic fisheries management agencies is to maximise yield while ensuring the long-term viability of the resource. These legislative objectives generally apply within the confines of their respect jurisdictions, whether it is a State-, Territory- or Commonwealth-managed fishery.

Much has been written about the complexities of achieving the goals of ecological sustainable development in managing marine resources. It is acknowledged that fisheries, in common with other natural systems, are subject to intra- and inter-seasonal variations that are often difficult to interpret in the first instance. This is to say that even in a simple biological system there is a complex relationship that governs reproduction and recruitment to a fishery, growth, and natural mortality. The underlying assumption is that losses from the system (natural mortality) are in relative balance with gains through recruitment and growth. A further level of complexity results from the removal of fish by commercial fishing. A range of biological, economical, sociological and ethnological factors will influence the overall harvest rate.

Fisheries managers must concern themselves with predictions of sustainable harvest rates, which in many respects rely on indirect measures for determining the status of the resource. In many cases, trends in catch rates may be interpreted as an index of stock availability and abundance. A further addition to the conceptual model is movement, both migration and immigration, across jurisdictional boundaries. For tropical snappers throughout the Top End, the degree of mixing across national and international boundaries is unknown. For example, we are unsure as to the extent of shared stocks, the degree of partitioning of various age classes, or the migration of recruits (whether random or fixed). Research currently underway is seeking to examine genetic variability and the practicality of tagging tropical snappers as a qualitative indicator of mixing. Comprehensive catch and effort information is collected within some sectors of the fisheries for tropical snappers. Our understanding of the biology and life-cycles has to be improved to assist in the quantitative estimation of sustainable yields.

Broadly speaking, management decisions have focussed on the sustainable management of fisheries resources bounded by a jurisdictional boundary. Legislative arrangements, notably the Offshore Constitutional Settlement, have engendered the overarching principles of cooperative and complementary management of shared stocks. In practice, this approach has resulted in individual jurisdictions implementing arrangements that simply recognise existing jurisdictional boundaries with little regard to the geographical boundaries of tropical snapper stocks.

Conclusion

Contemporary management approaches generally rely on fishery-dependent yield estimates to ensure long-term sustainability. Managers throughout the Top End are seeking to establish management arrangements and discuss allocation of resources prior to the activation of commercial fisheries within the Northern Territory and Queensland components of the fishery. The challenge in managing the resources is the simultaneous exploitation of shared resources in the absence of a good understanding of the degree of mixing and migration.

Footnote:

The opinions expressed in this article are those of the author and do not represent the views of any other person or government agency.

Tasmanian whitebait – a multi-species fishery targeting migrating fishes

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Abstract

The Tasmanian whitebait fishery reached a peak commercial harvest of just over 500 tonnes in 1947. It declined to compulsory closure in 1974. The populations recovered somewhat to the extent that an open season was being requested in the mid-1980s.

A research programme was undertaken to establish whether any harvest was sustainable and if so, how should it be regulated as the multi-species nature of the fishery posed some interesting challenges. For example, the fishery contained at least six main species of fish, some of which were adults and some were juveniles at time of migration. The fishery had been based primarily on the Tasmanian endemic species Lovettia sealii *that was no longer as common in the migrations.*

The research concentrated on the timing and composition of the migrations with a view to determining implications for the management of the species if an open season was declared.

Introduction

The issue was the potential for a fishery, either recreational or commercial, for whitebait in Tasmanian rivers.

Whitebait is a collective term used throughout the world to describe small fishes that are collected *en masse* and eaten whole. Many species and many fisheries fit into this definition. In the Tasmanian situation the fishery contains a number of species, some of which are adult fish and some are juveniles. They are all migrating into the estuaries around spring. The fishery had been based primarily on the endemic *Lovettia sealii.*

The commercial fishery for whitebait in Tasmania dates back at least until the early 1930s. Figure 1 shows that significant commercial fisheries began in the south of the State in 1941 and in the north in 1943. Licensing of the fisheries was introduced in 1944. Production was always greater in the northern rivers, probably largely due to differences in river topography and tidal amplitude.

The fishery reached a peak catch of around 550 tonnes in 1947. However catch-per-licence was already down on the previous year and a classic decline was already underway. A closed season was imposed in 1949 and future annual quotas were proposed. The season was again opened in 1950 but in this and subsequent seasons the catches did not even approach the quotas set.

There were various weak attempts at regulating the fishery over the next 20 years or so but catches did not exceed 50 tonnes in any year. The fishery was eventually closed after the 1973 season.

The numbers of whitebait increased somewhat in subsequent years and in the early 1980s there was pressure to once again open the fisheries. Staff at the

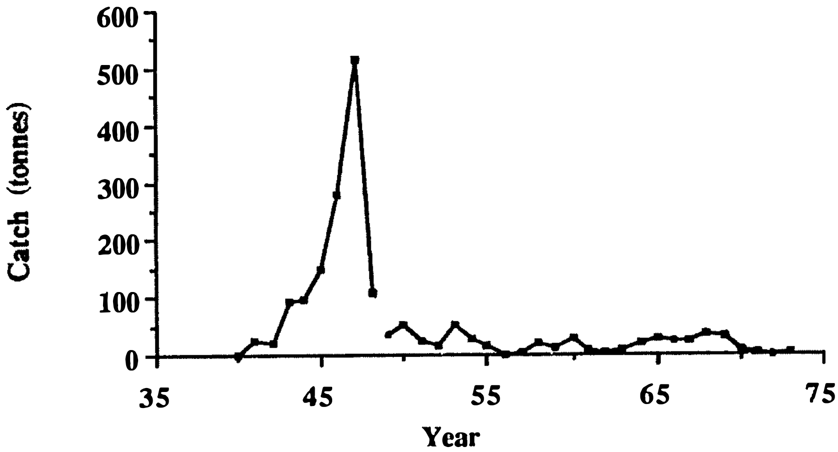

Figure 1. Commercial catch from the Tasmanian whitebait fishery.

Inland Fisheries Commission (IFC) in Tasmania understandably had little direct knowledge of the dynamics of this fishery and put forward a proposal for study. The study was supported by the Fisheries Research and Development Corporation (then Fishing Industry Research Trust Account).

For management the major issue was;

Is any level of exploitation of whitebait sustainable?

And following on from this;

If a fishery could be justified, what measures, if any, need to be taken to protect particular elements of the whitebait populations?

Methods

Former licensed commercial whitebait fishers were hired to undertake the routine sampling primarily at the Mersey and Rubicon rivers in northern Tasmania. Other samples were collected by IFC staff using the same methods and equipment.

Traditional open-ended D nets and scoop nets were used. These were constructed with a supporting frame covered with fly wire mesh. They had an opening at one end of approximately 2m circumference. The standard method was to choose a site where the current was quite strong close to the bank. The nets were set with the entrance facing downstream.

The sites and times chosen for fishing were primarily selected according to the tides with fishing on an incoming tide usually being the most productive.

More detailed description of sampling methodologies for *Lovettia* is given in Blackburn (1950) whilst the present study is described in more detail in Fulton and Pavuk (1988).

Results

Six main species of fish were found to be present in the Tasmanian whitebait migrations (Table 1). Other species may also occur as part of the runs, whilst others are also caught during the fishing process.

Table 1 also shows that the component species are not all at the same life history stage. The significant issue is that *Lovettia sealii* is a pre-spawning adult at time of capture (in the northern rivers at least) and it has only a one-year life-cycle. The galaxiids are all juveniles but each has a different life history strategy.

The requirement was to look at the implications of a fishery on these species individually not just the overall quantity of whitebait.

Table 1. Major species of fish found in whitebait runs in Tasmania.

Lovettia sealii (Johnston)	Tasmanian whitebait	adult
Retropinna tasmanica McCulloch	Tasmanian smelt	adult or juvenile
Galaxias maculatus (Jenyns)	Jollytail	juvenile
Galaxias truttaceus Valenciennes	Spotted galaxias	juvenile
Galaxias brevipinnis Gunther	Climbing galaxias	juvenile
Neochanna cleaveri (Scott)	Tasmanian mudfish	juvenile

Numerous other sources of variation were found during the course of the work. Some of the more important elements of this variation are summarised as follows;

- The extent of upstream migration varies between species: for example, *Lovettia sealii* only migrates to the top of the estuarine areas whilst the climbing galaxias moves through to the upper reaches of streams. Other species move intermediate distances upstream.
- Timing of migrations may vary within the one species;
  - Between rivers: historical catch information indicates that the timing of the *Lovettia sealii* runs was consistently different across the northern rivers and between the north and the south of the State.
  - From one year to the next: Figure 2 shows the variation in *Lovettia sealii* catches from the same river over three consecutive years.
  - With time of day: the tidal cycle has a strong influence on migrations, although it varies in its effect between species as well.
- Timing of migration varies between species: Figure 3 shows the variation in timing of the peak migration of the six whitebait species within one stream over a full season. Some of the short-term temporal variation was due to river levels but other elements of it were more consistent.
- There is also a consistent variation in species composition between rivers: whilst comparisons can largely depend on the site in a river, as a generalisation, there were usually more jollytails in the clearer northern rivers and more climbing galaxias and mudfish in the darker-coloured rivers of the west and south.

Management Recommendations

From these data a set of criteria for future management was developed and recommended:

A commercial harvest could not be justified.

A limited recreational season appeared sustainable.

The rules for the season would therefore need to ensure that;

- *Lovettia* was not the target species: the public would be fishing for 'whitebait' and they would not be able to identify a particular species. The rules of the season had to do that for them. This could be achieved either through specific timing or siting of the season.
- Any other species that had a restricted migratory period or restricted distribution should also not be specifically targeted. From the migration information it appeared that the spotted galaxias might be vulnerable in this way. This could again be achieved through specific timing or siting of the season.
- A large short-term harvest should be avoided. If a vulnerable species did migrate *en masse* during the open season then good levels of escapement needed to be ensured. This could be achieved through daily and total bag limits as well as gear and fishing method restrictions.

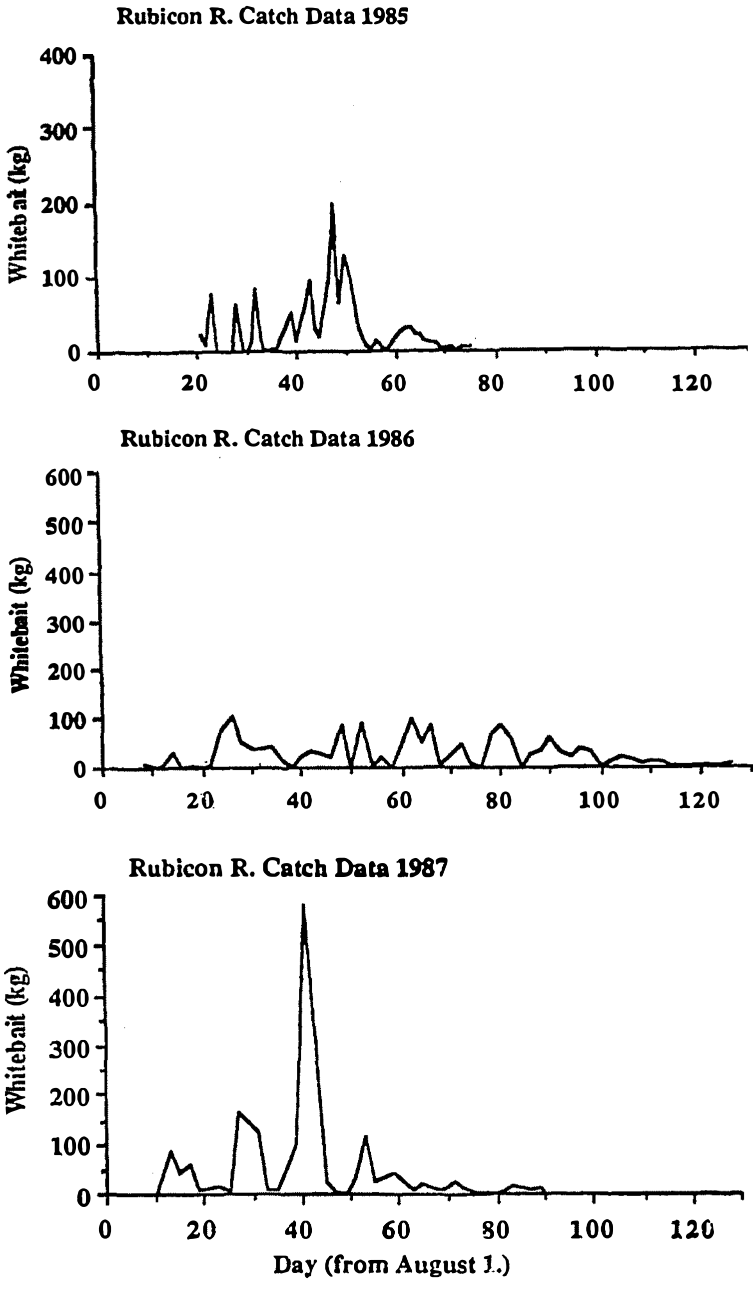

Figure 2. Catches of *Lovettia* over three years from the same river (Rubicon River, Tasmania).

Mersey River 1985

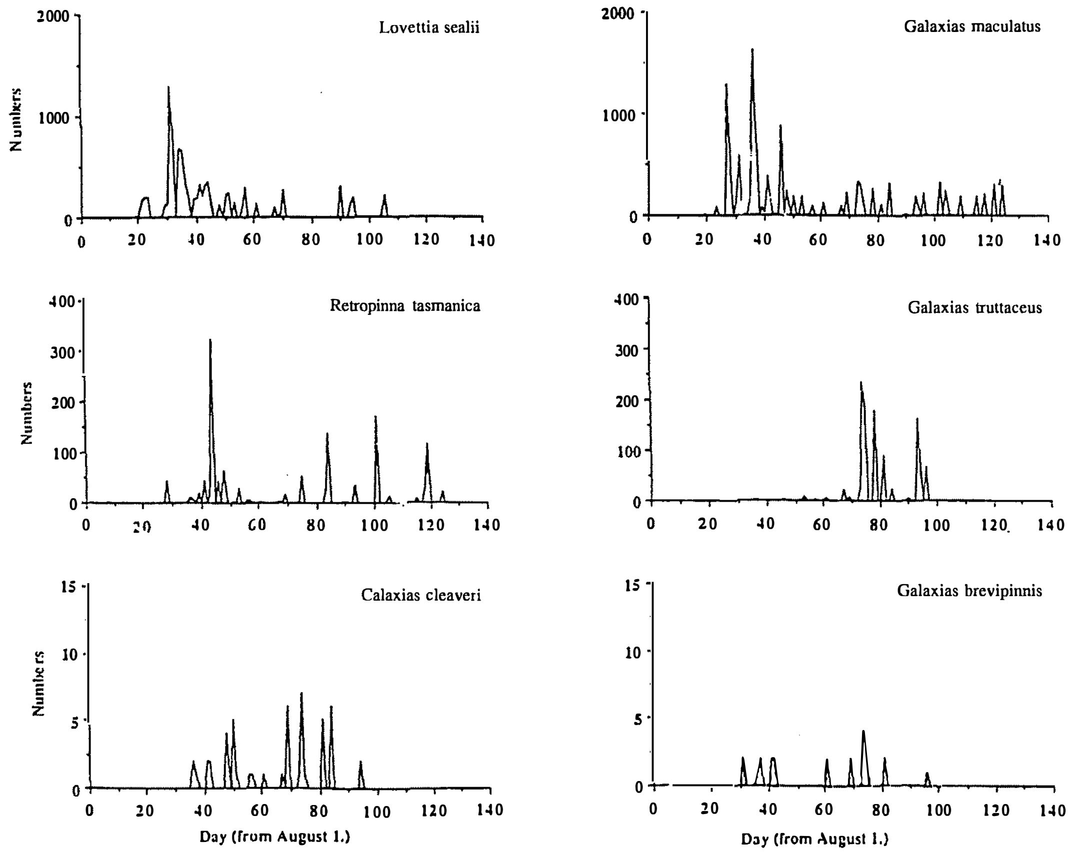

Figure 3. Catches of individual whitebait species throughout one season (Mersey River, 1985).

In summary, a limited harvest of these migratory fishes could be provided for without compromising the status of individual species.

The end result was a one-month recreational season in 1990 with tight gear and bag restrictions. The season has been opened each year since, with some further extensions in relation to the rivers to be opened. The major concern is that, if the fishery is extended in the future, managers may not take into account the original reasons for the specific timing and tight restrictions of the original season.

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Management implications of fish movement and migration - the role of the consultant

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Abstract

Biological consultants have an important role in documenting fish communities as part of Environmental Impact Assessments. Developments that affect fish movement and migration may destroy or degrade the condition of aquatic habitat. Mitigation measures like fishways can be used to assist fish passage past instream barriers. Appropriate management of our waterways is needed to protect existing fish habitat and diversity.

Introduction

As part of environmental assessment, biological consultants should outline the impact of a proposed development upon fish diversity and habitat, highlighting the importance of fish movement and migration. Options to mitigate potential impacts should be given. Managers can in turn make informed decisions that may assist in approval of developments and the application of mitigation measures to protect existing aquatic habitat and diversity.

Potential developments that may affect fish movement and migration include processes that degrade or destroy habitat, alter water quality and those that extract water from waterways.

Fish habitat and water quality

Loss of aquatic habitat is the most serious factor that can affect fish movement and migration. Loss of habitat is generally associated with loss of aquatic biota. Straightening and desnagging of streams may remove resting, feeding and spawning opportunities for fish. Piping and concrete lining of streams can totally destroy fish habitat, as these sections of stream have a uniform substrate lacking pools, riffles and runs. In these waterways, streamflow tends to be highly variable and linked to runoff from rainfall events. Furthermore, the stream modification may prevent fish passage.

Deterioration of water quality in waterways may restrict or prevent fish movement and migration. Agriculture practices, clearing of native vegetation and increased water extraction can all contribute to changing the quantity and quality of water in a waterbody. Short-term effects can be caused by poor water quality inflows. Long-term effects of reduced inflows may occur over a period of months or years. Water extraction for town supply or for irrigating crops and pasture may result in diminished streamflows or in cessation of flow. Altered flow regimes may reduce aquatic habitat, potentially interfering with food availability and restricting fish passage. The consequences can be particularly deleterious when migratory species are prevented from completing their life-cycles.

Environmental Impact Assessment - fish movement and migration considerations

Ideally the role of the consultant is to provide all available information to the authority that will be reviewing the potential impact of a proposed development. Reporting should include:

- background information,
- the condition of the waterways in the study area,
- potential impacts of proposed works, and
- mitigation measures.

Background information can be sourced from database searches, literature reviews and from people familiar with the study area. Local knowledge is often the most valuable of all of these components, as database and literature searches generally reveal that little or no research has been conducted within a study area.

Fish habitat types need to be defined to establish whether potential impacts will be made to rivers, lakes or wetlands or to a combination of these waterways. A field investigation is recommended to establish the quality of the habitat that could be affected by the development. Potential protection of waterways is most likely at sites that exhibit a range of natural attributes (e.g. native riparian vegetation, unaltered flow regime, significant flora and fauna); degraded habitats exhibiting a lack of natural attributes are given a lower level of protection.

If the fish fauna of the study area is not known, survey work may need to be conducted to provide some clues to the diversity of fish species. Knowing the fish fauna allows for some assessment of the minimum water depths necessary for fish movement. The presence of deep-bodied species like Murray cod (*Maccullochella peeli peeli*) will require a minimum water depth of say 50 cm, whereas a stream that only supports small-bodied fish like Galaxiids (*Galaxias* spp.) will only require a minimum water depth of 10 cm to allow adequate fish movement or migration. In regulated streams, seasonal minimum water levels may be needed to allow spawning and recruitment opportunities for migratory species.

Instream barriers should be evaluated. Man-made barriers like weirs, culverts, fords, farm dams and levees can all have an impact upon fish movement, particularly for migratory species. Some barriers may permanently restrict upstream movement but others can be drowned out for periods, allowing for fish passage. If migratory fish cannot move past barriers, spawning and recruitment will be prevented resulting in the loss of species.

Water quality barriers often also occur. In coastal streams water quality changes between freshwater and estuary reaches need to be considered in the protection of anadromous species. For inland waterways, barriers caused by thermoclines, oxyclines and haloclines need investigation.

Only after all of the above factors and their inter-relationship have been considered is it possible to assess the potential impact of a proposed development and suggest mitigation measures to prevent or to restrict damage to waterways. These measures may impose limitations upon the proponent, but the ultimate aim is to protect existing fish habitat and diversity. Allowances for fish movement and migration should be considered in the mitigation procedures that are recommended.

Management implications of fish movement and migration

The key aspect of managing waterways is to appreciate that each is unique. Rivers, lakes and wetlands provide a variety of aquatic habitat with a range of water quality conditions. Different management is needed for permanent, intermittent and ephemeral streams as each have different flow regimes. For instance, rises in spring water temperatures are an important cue needed for the breeding of many native fish species. For lakes and wetlands, the wetting/drying cycle is important. With appropriate use of environmental flows, critical periods of flow for fish movement and migration can be provided.

Some issues that are indirectly associated with water movement within a catchment may play a part in the quantity and quality of water that enters waterways. Groundwater pumping and new farm dams are two factors which may result in reduced inflows to waterways. It is important for water authorities to adopt a catchment-wide assessment process for overviewing water resources, to ensure that water continues to be available for environmental purposes. Fish movement and migration will only occur if waterways continue to receive groundwater and surface water inflows.

Occasionally, the provision of fish passage is not advantageous. Barriers are sometimes used to exclude unwanted species from entering valued habitat. In Victoria, the insertion of instream barriers has been used to prevent the invasion of brown trout (*Salmo trutta)* into remnant habitat of the threatened barred Galaxias (*Galaxias olidus* var. *fuscus*) (Flora and Fauna Guarantee 1995). In the headwaters of Swindlers Creek, a water supply weir has excluded brown trout, allowing for mountain Galaxiids (*Galaxias olidus*) to recolonise the main channel upstream of the weir. In both instances, native fish populations have been protected by barriers. The lesson to managers is that the provision of fish passage may not always be the most appropriate management procedure.

Managing fish movement and migration with fishways

In Victoria, experimentation with fishways extends back to 1981 when a fish ladder on the Lerderderg River was trialled (Beumer and Harrington 1982). Only adult fish were found to use the fish ladder and then only under certain flow conditions (Beumer and Harrington 1982). A fish ladder adjacent to the Morwell River (based on the Lerderderg River fishway) was tested in the mid-1980s by the State Electricity Commission. Although no reporting of experiments conducted at the site was made, it is likely that the structure was unsuitable for passage of native fish species which exist in the Morwell River. From these early studies, improvement in fish ladder design has occurred, with the focus now being upon providing gradients of less than 1:20 and the addition of resting areas within the fishways.

Within Victoria, 29 fishways have been installed over the past five years, the majority of which have been funded by the Department of Natural Resources and Environment under the State Fishway Program (McGuckin and Bennett 1999). Vertical slot fishways have been the preferred approach in barriers that exceed two metres in height, while rock fishways have been utilised where the barriers are less than two metres high. Both systems provide for fish passage under a range of flows and are suitable for a variety of native fish species.

Conclusion

The role of the biological consultant is important to informing managers of appropriate practices that will assist fish passage. With increased installation of fishways over the past five years, the importance of fish movement and migration is finally being recognised by managers. However, as hundreds of barriers to fish movement and migration exist throughout Victoria, there is still a long way to go before fish passage has been reinstated in all of the waterways.

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Discussion of Session 4

Chaired by Nick Rayns

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Each presentation was followed by a time for individual questions, after which Session 4 was opened for more general comments and discussions.

Following *Steve McCormack's* (Fisheries Victoria) presentation, the author posed the question as to whether a limit on commercial catches of eastern Australian salmon (*Arripis trutta*) would improve angling quality? Richard Tilzey (Bureau of Resource Sciences) responded that for migrating or shared stocks, the single biggest problem is multi-jurisdiction. New South Wales is moving towards output controls. If you could cap existing commercial catches that would keep the recreational anglers happy.

Steve McCormack asked Richard Tilzey to offer any suggestions on how to go about doing that? It is not a species that could be managed by the Commonwealth under the Offshore Constitutional Settlement. If the eastern Australian salmon fishery was managed with catch quotas, cooperative management arrangements would need to involve the fisheries in NSW and Tasmania that harvest the same stock. Richard Tilzey said this would require some form of output control such as a quota allocated to each State.

Murray MacDonald (Fisheries Victoria) commented that eastern Australian salmon in Victoria is not a resource issue because the level of fishing appears to be sustainable. The main problem is due to commercial fishing access to recreational fishing grounds in East Gippsland, particularly in the vicinity of Lakes Entrance. The difficulty is that this type of access issue can not be solved with legislation written for stock conservation.

Malcom Haddon (TAFI University of Tasmania) referred to New Zealand, where the same species is managed with quotas, but suggested that what is needed for eastern Australian salmon in the Victorian situation is a coastal exclusion zone. This may solve the main problem which is the irritation of anglers who see commercial fishing vessels operating close inshore near the recreational fishing grounds.

Steve McCormack's understanding was that the commercial fishery for eastern Australian salmon is based on fishing in shallow water with fishing gear that is a hybrid between a modified purse seine and beach seine. The fishing gear is set near the beach and pursed back towards the fishing boat. If the beach area was closed to commercial fishing, this type of gear would not function and there would be no commercial fishery.

Following the presentation by *Will Zacharin* (PIRSA), Richard Tilzey asked whether the offshore movement of the southern rock lobster (*Jasus edwardsii*) occurs across its whole distribution? Will Zacharin said he understood that of the 700 lobsters tagged off

Kingston, all the tagged lobsters moved consistently offshore. There was some evidence of movements from east to west, and lobsters from South Australia have been recaptured by Portland fishermen, but there is always insufficient information. In South Australia, the southern zone fishery is managed alongside the northern zone fishery and the Victorian rock lobster fishery, with different management regimes in each region. The southern zone of the SA fishery has a minimum legal size of 98.5 mm carapace length whereas in Victoria the minimum legal size for females is 110 mm and 105 mm for males. Essentially, the fisheries in South Australia and Victoria are fishing the same stock, but it is not known whether or not the fishery is in bad shape in Victoria. There is a lot of reef area between Pt MacDonnell (SA) and Portland (Vic) and there could be a situation when large numbers of lobsters are removed from the Portland area to be replenished by dispersal from higher density stocks off Pt MacDonnell.

David Smith (MAFRI) questioned whether there was any evidence of stock movements across management zones? For instance whether there have been any large movements of lobsters from Victoria to Tasmania or South Australia to Victoria? Will Zacharin referred to Jim Prescott's (SARDI) tagging results but thought the farthest movement of a tagged rock lobster was 70 km, but it remained in South Australian waters. Rob Day (University of Melbourne) mentioned Rod Treble's work which showed limited movement of tagged lobsters off Apollo Bay with only a few moving offshore. Will Zacharin continued that in South Australia, tagged rock lobsters have been re-caught in the same offshore location four years later, but the smaller lobsters moved the greatest distance and the movement of tagged rock lobsters was always offshore.

After the presentation by *Dorothea Huber* (AFMA) on 'Managing Pacific tuna fish: an Australian perspective', John Gunn (CSIRO) commented that the influence of the El Ninō phenomenon had caused a shift in warm core eddies in the western Pacific that had changed the distribution of tuna stocks in the territorial waters of 16 countries. How do you manage migratory stocks with such large oscillations in stock distribution?

Dorothea Huber responded that one method of managing these tuna stocks would be to set a global total allowable catch (TAC) for the region and then allocate a tradable quota to each country. Countries would then be able to buy and sell quota as the stock distribution changes. One of the difficult issues in the current international negotiations is how to recognise a country's right to a resource that fluctuates highly.

James Scandol (University of Sydney) asked how account is taken of the financial dependency of some countries on their fish stocks when fish distribution changes and fishers are not allowed to operate beyond their territorial waters, and was told by Dorothea Huber that management of the tuna fishery recognises the rights of the coastal States whose economy depends on the fisheries resources and this can be taken into account in the allocation of quota.

Andrew Sanger (Fisheries NSW) spoke of 'Fisheries management implications of barriers to movement and migration by fish in NSW', following which Clare Peterken (Queensland DPI) commented that stocking is a short-term, band-aid solution to the problem of declining stocks in freshwater fisheries. Fisheries management in Queensland tried trapping and transporting stock above river barriers for many years but has recently rejected these stocking policies. Compared to the costs of installing a permanent fish lift, stocking costs more due to the expense involved in translocation of the stock. Andrew Sanger agreed on both points. The objective of the stocking is to enhance recreational fisheries not conservation of the stocks. In a lot of cases stocking is going to occur anyway whether there is a barrier or not.

Darren Cameron (GBRMPA) suggested that all this work on fishways is very commendable but it is very costly. To instal fishways around all the barriers would invoke a huge cost in the order of several $A100 million. Isn't it time for scientists to urge Governments installing new waterway constructions to include fishways costs automatically so that this problem is avoided in the future?

Bryan Lawrence (Murray-Darling Basin Commission) raised the important issue of jurisdiction. It is up to Queensland to ensure that fishways are installed on new river constructions in Queensland. Andrew Sanger advised that in Queensland, new dams are currently being planned for construction, whereas in other States, dams have already been constructed without fishways. While retro-fitting of fishways is a worthwhile goal, it is very expensive and it will take many years to fund their construction.

After *Ray Clarke's* (NT Department of Primary Industries and Fisheries) presentation, Alex Wells (FRDC) commented that it seemed that while one of the objectives was to maximise employment, another was to maximise economic efficiency. How is a balance achieved between these two management objectives?

Ray Clarke replied that there is a policy to reduce fishing effort in the Timor reef fishery (two-for-one licence reduction based on yield estimates and economic return). There are about 60 licences in the demersal fishery, which excludes the Timor reef area, and operates 15 nm offshore out of the Australian Fishing Zone. This management arrangement provides a measure of economic efficiency. But there is also a fishery development policy that only permits passive fishing methods in the Joseph Bonaparte Gulf to promote employment and provision of high quality line-caught fish to the market.

Tony Fowler (SARDI) suggested that it would be better to use otolith microchemistry to determine stock discrimination and localised mixing, than genetic techniques which are more useful for examining mixing on evolutionary time scales. Ray Clarke advised that a range of genetic techniques is being used in the Northern Territory and Western Australia to examine this issue, but agreed that other approaches would also be worthwhile. John Gunn thought that it would be difficult for managers to negotiate changes in Indonesian artisanal fishing effort and fishing methods. Ray Clarke replied that there is funding from the Australian Centre for International Agricultural Research for research on migration, biology and some genetic work on stocks of the tropical snapper fisheries of the Northern Territory and Eastern Indonesia. So there is already a commitment to gather biological information. However, it is estimated that there are 6 000 line fishing boats for which there are no catch data currently available. By initially establishing a joint collaborative research programme to collect and analyse fishery data, it is hoped that cooperative management arrangements will develop over a 5-10-year time frame.

John Gunn commented that the Commonwealth is only interested in the sustainability of fish stocks in Australian waters. How do managers take into account stock depletion outside Commonwealth waters in a shared stock such as tropical snapper? Nick Rayns answered that it is the same as for southern bluefin tuna, i.e. by maintaining a presence in the fishery, monitoring the fishery and negotiating through the Commonwealth Government with Indonesia on fishery management issues. Ray Clarke pointed to the similar situation for the shared stocks of Western Australia and Queensland and the development of the trawl and longline fisheries. At the end of the day, the decision on whether to develop the trawl fishery lies with the Queensland Government.

There was no discussion following the presentation by *Wayne Fulton* (MAFRI) 'A multispecies fishery targeting migrating fishes'.

John McGuckin (Streamline Research) described the 'Role of the consultant', following which Clare Peterken wanted to know how he reconciled the information needed with the time lines that consultants get to complete their work? John McGuckin replied that a consultant's livelihood depends on producing quality work on time and within the budget. The information needed can be obtained by networking with people who have a good knowledge of the ecological systems and he works closely with the scientists at MAFRI. The exchange of information can be mutually beneficial. Bruce Pease (NSW Fisheries) asked the speaker if he often recommended that a barrier to fish movement should not be installed? What are the engineering options and alternatives? to which John McGuckin replied that he would rather not recommend installing a barrier, but if one was necessary he would advise on the installation of a fish passage. He further commented that at Swindler's Creek, monitoring began before construction commenced and the impact will be determined from annual monitoring.

Summing up by Chair Nick Rayns

We heard from Steve McCormack about the difficulties of managing migrating stocks of eastern Australian salmon that move between Tasmania, Victoria and NSW and the conflicts over access to beach fishing grounds between the recreational and commercial fisheries. Will Zacharin highlighted the different management regimes for the same stock of southern rock lobster in southern Australia that were possible because of the limited and mostly offshore movements. The difficulty of resolving tuna management issues in international waters was explained by Dorothea Huber. In freshwater systems, Andrew Sanger pointed out the long-term problems of major habitat modifications caused by dam construction and barriers to fish movement along rivers. John McGuckin emphasised the importance of monitoring water quality and habitats before and after construction as well as the modifications to drains to enable fish movements for spawning and feeding. Wayne Fulton described a neat example of the application of research that led on to the development of a fishery management solution. Now I would like to open the floor for a *general discussion* on the fishery management implications of fish migration and movement.

Richard Tilzey opened with a question – 'Is there a resource allocation problem between commercial and recreational fisheries?' to which Dorothea Huber responded that there are many resource allocation problems between commercial and recreational fisheries, such as in the blue and black marlin fishery in Queensland. Allocation is one of the most difficult management issues between and within the commercial and recreational sectors as well as between different States or countries.

André Punt (CSIRO Marine Research) agreed that management problems involve allocation issues. Stock mixing and migration lead to uncertainty in stock assessment and fishery management. Fishers will often ask in stock assessment meetings "What about the cryptic biomass?". Sometimes this uncertainty about movement is used to delay the implementation of management strategies. Models often assume the extreme scenarios of either fully-mixed or fully-separated, but the usual situation is somewhere in the middle.

Dorothea Huber agreed that managers usually consider the extremes of stock movements. They need to know the uncertainty of stock structure and movement patterns.

Nick Rayns commented that the concept of orange roughy given by Tony Smith is one of a partially-mixed stock. But the important question of how much mixing there is between stocks, 20% or 50%, is one that needs to be addressed and understood by managers. The answer would be easier if it was a black or white solution but it is usually grey and often expensive for modelling and data gathering.

Andrew Sanger emphasised that the issue is not only relevant to marine fisheries. For instance, there are important issues of stock movements and stock structure of shortfinned and longfinned eels in several Australian States and New Zealand.

Bruce Pease suspected that eels, which are managed as a *panmicke* stock, have a stock structure for eels in southern Australia rather like the eel stocks in Europe.

André Punt said we haven't even come to terms with the concept of stock structure, let alone movement between the stocks. It is important to know the boundaries of stocks for management and stock assessment and then progress on to the issue of movement, but it may take decades.

Steve McCormack considered that the first management consideration is jurisdiction. The Commonwealth is not interested in eastern Australian salmon, so it is up to the States to sort it out. The same applies to blue warehou, which is a highly mobile species, but in spite of this, it has been decided that it should be managed as one stock. To a certain extent, quota management and trading has overtaken the need for understanding the biology of the stocks and their movements and it is difficult to get away from assets and fishing rights.

André Punt added that the monitoring data for blue warehou have been collected assuming a single stock hypothesis. If there is more than one stock, there will be insufficient data to do stock assessments so it is very important to obtain information on stock structure at an early stage in the development of a research programme.

James Schofield asked whether it is it possible to manage with less information and reduce fishery management costs, to be told by Steve McCormack that in Victoria, recreational fishing licences have been introduced so managers can now access more funds to enhance the capacity to gather information and to improve fishery management of the stocks.

Dorothea Huber informed the Workshop that for Commonwealth fisheries, except for 50% of enforcement costs, cost recovery funds all management and research. In the case of the east coast tuna fishery, the industry is very willing to contribute to research to reduce uncertainty about the resource.

Richard Tilzey offered a general observation. The issue of shared stocks moving across State boundaries and between jurisdictions applies to many fish stocks in Australia, e.g. pilchards and snapper, and not just eastern Australian salmon. Perhaps we should move towards one stock assessment group with members from every State for each fish stock. Steve McCormack believed that with similar jurisdiction for whatever stock, management would still be difficult without the Commonwealth involved. A catalyst is needed to sort out the jurisdiction for eastern Australian salmon. Richard Tilzey said that in the South East Fishery, for every species we will find there is a stock structure. How is that going to be managed with a TAC?

Nick Rayns's view is that managers will be compelled to make decisions at a particular point in time, for example to introduce a TAC for warehou, cap the catch, take a precautionary approach. Then ten years down the track, we may find out that it was not a good idea. Stakeholders want certainty in their share of the resource, but need the flexibility to alter arrangements in the future. You can not avoid it in fishery management and you just have to do the best you can at that particular point in time.

André Punt warned that while cost recovery is a reality, it is still a difficult issue. What are those who pay going to get? As we learn more about uncertainty and because assessments are uncertain, the lower the quotas have to be. But why pay for research into your own demise when more research leads to more uncertainty and a lower allocated catch? Bruce Pease commented that there are programmes in Denmark to remove engineering works in rivers that obstruct fish movements along rivers, to which Andrew Sanger added that in Australia, there have been several proposals to remove weirs used for stream gauging in several States – Tasmania, Victoria, and NSW. However, there are no examples of a large dam being removed in Australia, but no doubt it will come at some stage when they have outlived their usefulness.

Martin Mallen-Cooper (Fishway Consulting Services NSW) was of the view that although there is a high diversity of migrating fish species in Queensland the purposes of these migrations are poorly understood. The attitude of the engineering community in Queensland is to be pro-active and to include fish passage designs in water resource development. But perhaps ASFB could be pro-active too and provide written advice to Queensland and suggest that these barriers should not be constructed in the first place.

Andrew Sanger's impression was that the irrigation industry through the water reform process would also like to do positive things for fish. There is a large degree of goodwill amongst developers and increasing requests for designs of fish pathways. It's not all doom and gloom.

Martin Mallen-Cooper agreed that there is a lot of goodwill in the community, but it is not just about preventing the construction of barriers across rivers. Water flows and temperature are also important. You can have fishways, but the impacts from altered environmental flows must also be considered.

John McGuckin said that in alpine areas, where there are streams and threats from soil erosion, there are rules about transporting equipment, which has to be flown in to avoid damage from vehicle access. So he thought biologists are getting somewhere by putting restrictions on the developers to do things in an environmentally sensitive way. The message is getting across slowly.

Andrew Sanger warned that if you stop fish moving by constructing a barrier, the fish population upstream declines or disappears. Well-documented examples include Australian bass, golden perch and Murray cod. For these species, movement is an essential part of their life history. But we are not dealing with a trivial issue – it is a fundamental issue for freshwater fish stocks, and priority schemes in NSW and Victoria for fishways do take fish movements into account.

John McGuckin described the situation in Victoria, where a large number of small coastal streams covering all regions has a higher priority than one big dam in a single location like Dartmouth dam. It is also part of a public education process to let people know that fish passages are being constructed in Victoria.

David Pollard (NSW Fisheries) asked, given this burst of building activity in Queensland, what is the legislative requirement for the construction of a dam, weir or river barrier? Clare Peterken responded that in the Queensland legislation, there is an option to provide a fish passage. There may be cases where the Queensland Government would not insist on a fish passage, but in most cases fish movement and habitat issues would need to be addressed by the developers.

Session 5 – General Discussion

Chaired by David C. Smith

Marine and Freshwater Resources Institute
PO Box 114, Queenscliff VIC 3225

Recorded by Alexander Morison

Marine and Freshwater Resources Institute
PO Box 114, Queenscliff VIC 3225

David Smith, from the Chair, queried the notion of whether we needed to wait for models to tell us what data are needed? Geoff Arnold (CEFAS) responded that we do not, and that to take such an approach was blinkered and contained some circularity. He argued that you can't foresee what data we need, and that if we waited for models to prescribe data needs we would never make a conceptual advance. He noted that there has been some polarisation between modellers and biologists, but the track record of biologists has not been that good, and we need a wider view of what we need to know. He also raised a serious concern at the need to constantly justify research work on the short term.

André Punt (CSIRO) agreed in the broader context. He contended that models help rank the importance of research activities, and that stock assessment models help in this context. The issue is not in deciding what to do, but in what has to be dropped off. You have to decide what new data will assist in reducing uncertainty. Data are needed to start with in formulating models, which are then useful in deciding when more data are needed.

Nick Rayns (NT Fisheries) felt that the emphasis on sustainability indicators and the recent involvement of Environment Australia, has contrasted model-based approaches involving uncertainty reduction, with other broader approaches.

André Punt said that these areas need to be treated differently. We don't have sufficient data for the broader environmental models. He argued that environmental models need to be reduced to simple models but that even changes in species composition can be difficult to interpret. One thing that models allow you to do is to test whether you are modelling what you think you are.

Malcolm Haddon (TAFI) referred to new models which are based on growth of individuals. However, he believed that we usually don't have the large amounts of data needed for such models, and suggested that we need to strike a balance between the simple and the complex models. He also pointed out the need to have regard for the needs of managers, and that it is easy to lose sight of the objectives of modelling.

Geoff Arnold had been asked to give advice at the spatial and temporal scales you can get from commercial fishing. He believed that we do have data now to make individual-based models and that these models will be of use to management.

Malcolm Haddon suggested that we are not at the same stage in Australian fisheries, and that we are not yet ready to make generalisations from individuals to populations.

Geoff Arnold said that they were seeing patterns in the data now and that these allowed them to make predictions of what happens to populations and to test them. He believed that we will be able to describe a lot of the structure in marine fish populations and how they behave. Malcolm Haddon said that he didn't disagree.

John Koehn (NRE) also believed models will be useful in the freshwater environment where movement data are one of the important components. Models are generators of some of the key questions, but there are a lot of other issues to include, such as habitat, competing species, and predation pressure.

Simon Nicol (NRE) said that models are just an aid to management, but that they make you be explicit about assumptions. John Koehn added that they also help develop thoughts about scenarios that may not have been considered.

Tony Fowler (SARDI) asked for an explanation of the problem about incorporating individual data into models. Malcolm Haddon responded that we usually don't have enough data on individual variation to include in such models.

André Punt proposed three other reasons – demographic uncertainty, movement, and environmental variation. He argued that with the large populations found in many marine organisms, the law of large numbers comes into play, and it is legitimate to subsume individual variation into the population. You can infer from the individual level to the population, and work at that scale. He also suggested that different models are useful at different scales from the individual level to that of populations. For example the model for movement in the Southern Shark Fishery is based on hundreds of cells with migration rates modelled between adjacent cells. He pointed out that the model would take much longer to run and fit if based on individuals.

James Scandol (Sydney University) raised the question with respect to Marine Protected Areas (MPAs) and ecosystem management and how to tie this in with current fisheries management. He pointed out the need for good spatially-based management of marine resources.

Nick Rayns referred to three important features needed for a system of MPAs: that they be comprehensive, adequate and representative. Representativeness needs to be assessed at the scales of bioregions, communities and habitats. In undertaking this planning there has been a mixed response from commercial and recreational fishers. MPAs are also often more localised than the scale at which fisheries management operates, but there are some common goals.

Alex Wells (FRDC) mentioned that a review and synthesis of current research was currently underway, including an attempt to establish priorities, look at a gap analysis and future directions.

John Koehn believed that the issues are more complex in freshwater systems. The linearity of riverine systems makes them more difficult, as do the multiple jurisdictions and spatial variability, and there is a need to look at a more holistic approach to issues. Andrew Sanger (NSW Fisheries) said that it would be a major challenge for managers to do this.

Will Zaccarhin (PIRSA) queried the use of representative systems as a bad model adopted from terrestrial systems. He thought there should be management of whole ecosystems, rather than picking out some areas to preserve and some to degrade. John Eiler (National Marine Fisheries Services) said that this was a similar situation to that with salmon. There was a lot of fighting between interest groups. Over the last 15 years there were attempts to bring these groups together, but that it has been a slow process.

André Punt raised the example of the work being done on the Great Barrier Reef CRC in the Effects of Line Fishing Project. On a small scale there was not much benefit from closed areas, but no one was willing to make quantitative objectives explicit for ecosystem management. It is not possible to provide advice without objectives being set, and it seems that the only objectives were just to have MPAs. However, these were not scientific objectives.

Richard Tilzey (BRS) discussed the example of eastern gemfish and asked how to come to terms with trawl survey data when there is movement of fish through survey areas. André Punt said that it had been ignored completely! He argued that the aim was not to have a survey but to use it as a proxy for the fishery that had taken advantage of the migration of gemfish. The two would not have been comparable if the movement hadn't been ignored.

Rob Day (Melbourne University) asserted that there is a difference between the issues of selecting places for MPAs and the objectives for having them in the first place. MPAs provide a reference point that allows us to model the dynamics of systems that we don't know enough about yet. Problems over the issue of having MPAs did not release you from the need to manage the rest of the system. The real question was the numbers and locations of MPAs not whether you need them or not.

André Punt said that Rob Day's point was the 'Insurance Policy' argument for MPAs, but asked how do you draw the limit? He contended that there was no scientific basis for describing the differences between hypotheses about the appropriate level of coverage by MPAs. Rob Day agreed with this but also suggested that the insurance argument needs to be considered at the community level and that it is not a debate for scientists.

Patrick Coutin (MAFRI) said that tagging can give some useful information on the appropriate depth zones and relevance of MPAs. It can also help with the issue of fishing mortality and what proportion of the stock is interacting with the fishing gear.

Richard Tilzey raised the issue of orange roughy on the South Tasman Rise. There is a lot of talk about straddling stock but no legal definition of what one is. Movement is an important part of it, but with the example of salmon, should they be considered as a migratory or a straddling stock?

Concluding remarks from the Keynote Speakers

John Eiler

David Smith had asked both Geoff Arnold and myself to give some impressions of the Workshop as observers from out-of-town. It has been interesting to hear about some of the different issues and the different species that are being worked with. One of the things I enjoyed was the wide range of topics that were covered, with a mix of methodological issues to interpretation of data and some of the modelling work. One thing that struck me, having sat through similar sorts of meetings back in North America, was that there were parallel themes that run through, particularly with the marine issues. The inter-State issues were of interest to me, whereas often with the marine side of things there is only Federal management, although there are the international issues particularly with the US and Canada. One thing that was also of interest to me with the freshwater zones, was the importance of the availability of water as an issue. In SE Alaska water is not an issue except in the opposite extreme, and there is a real shift in perspective needed in the Australian context.

Some of the other similarities concerned the discussion yesterday on research needs and funding: the balance between some long-term research that will give you a basic understanding of what is going on, and the need to have some applied work that can meet the immediate needs of constituents.

Geoff Arnold

Like John Eiler I have also very much enjoyed my visit which was my first time south of the Equator, and found it highly educational. The balance between biology and management is very different here from what one would find in the British Society for Fish Biology; there would be more biology there and less management.

When Session 4 started this afternoon I thought it wasn't going to be quite as well focussed on the subject of the meeting. But as it went on it became more focussed and the last talk focussed it down beautifully indeed. Global warming and El Niño came up in questions this afternoon and that I suppose is an area that is going to become even more important in the next few decades.

We had very interesting debates on how you move from individual behaviour to population behaviour, and that has been rounded out nicely in this last Session. The Session on the reality and utility of spatial models was fascinating. I enjoyed that and again we have developed that further this afternoon. I came out of that reinforced in my view that we really do need to get more fishery-independent data, wherever we possibly can. Recent examples of pop-up tags are clearly showing how flawed some of the management models are where, for example, they treat the northern bluefin tuna stocks as being divided right down the middle of the Atlantic Ocean. The early tag returns suggest that that is simply not true.

John Eiler has made the point about funding and the argument about where you should put the dollars. We are suffering the same problem, and somehow one has to hang on to what we call the applied strategic work. We have to keep a view over the horizon and not just answer the immediate questions, because if we don't, in five or ten years time we won't be able to answer the questions that will be coming up then. We will be in the same state of relative ignorance. It is worth reminding ourselves that for example a pharmaceutical company may take up to 20 years to develop a new drug and get it from the basic concept onto the market.

So to conclude, in an attempt to answer André Punt's question that he posed this afternoon when he asked in rather despairing tone how many decades will it be before we have a real handle on spatial migration and movement. And having started with a 30-year perspective, I would like to take a slightly more positive view and say that in one or two more decades we will have made substantial progress.

Workshop Programme

Monday 27 September 1999

7.00pm Workshop Welcome Function
(Bendigo Art Gallery)

Tuesday 28 September 1999

8.40am Welcome and Introduction
David Smith

Opening remarks from FRDC
Alex Wells

9.00 Overview Address - Unravelling mechanisms of fish migration: a 30-year perspective
Geoff Arnold

9.45 Morning Tea

10.00 Session 1 - Techniques for Measuring

Chair's Introduction
John Gunn

Why use radio tags to study freshwater fish?
John Koehn

Fishways as tools for monitoring movement patterns of large fish populations
Ivor Stuart

Is there a role for 'uncontrolled' tagging in 'real' fisheries science?
Julian G. Pepperell

Acoustic tracking
Geoff Arnold

From plastic darts to pop-up satellite tags
John Gunn

Acoustic tracking of small-scale movement in juvenile southern rock lobster (*Jasus edwardsii*)
David Mills, Caleb Gardner, Sam Ibbott and Simon Willcox

Shark tagging: a brief history of methods
John Stevens

Application of otolith chemistry to studies of fish movement and migration
Naomi Clear and John M. Kalish
(Presented by John Gunn)

12.45 Lunch

1.30 Overview Address - Fish movements – the missing piece
John Eiler

2.15 Session 2 - Environmental determinants, barriers and human interference

Chair's Introduction and Overview
John Koehn

Taking the mystery out of migration
Martin Mallen-Cooper

Environmental cues in the reproductive migrations of brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) in Lake Eucumbene, New South Wales
Richard Tilzey

3.00 Tea

3.30 Environmental determinants of the movement and migration of juvenile southern bluefin tuna
John Gunn and Jock Young

Overcoming physical barriers to fish migration
Tim O'Brien

Sampling to detect the impact of barriers on fish movement
Tim Marsden

Characteristics of movement of adult King George whiting (*Sillaginodes punctata*) in South Australian waters
A. J. Fowler and W. A. March

Migration and assessment of glass eels (*Anguilla australis*) in the Snowy River system, south-eastern Australia
Lachlan J. McKinnon, Geoff J. Gooley and Richard J. Gasior

5.15 Close

Wednesday, 29 September 1999

9.00 Session 3 - Analysis, interpretation and spatial models

Chair's Introduction
André E. Punt

Modelling school shark (*Galeorhinus galeus*) movement in the Southern Shark Fishery
Terence I. Walker, André E. Punt, Bruce L. Taylor and Lauren P. Brown

Do Bayesian concepts assist the ability to interpret migration and movement patterns of freshwater fish?
Simon Nicol

Including spatial structure when conducting yield-per-recruit analysis
André E. Punt and Gurong Cui

Directing experiments in freshwater ecology using spatial population models developed for freshwater fish
Charles Todd

10.15 Tea

10.45 Preliminary analysis of migration of adult, red-legged, banana prawns in Joseph Bonaparte Gulf, northern Australia
R. A. Kenyon, D. J. Die and N.R. Loneragan

Computer visualisation of spatial models for communication and management
James Scandol

A spatial representation of the tiger prawn (*Penaeus esculentus*) fishery in Shark Bay, Western Australia
N. G. Hall and R. A. Watson

12.00 Lunch

1.00 Session 4 - Management Implications

Chair's Introduction
Nick Rayns

The fishery for Australian salmon: management issues
Stephen McCormack

Management implications for movement and migration in a rock lobster fishery
Will Zacharin

Managing Pacific tuna fish: an Australian perspective
Dorothea Huber

Fisheries management implications of barriers to movement and migration by fish in New South Wales
Andrew C. Sanger

The challenge of spatially managing fish movement and migration throughout Northern Australia: the experience with tropical snappers
Ray Clarke

Tasmanian whitebait – A multi-species fishery targeting migrating fishes
Wayne Fulton

Management implications of fish movement and migration - the role of the consultant
John McGuckin

3.30 Tea

4.00 General Discussion

5.15 Close

Abstracts from ASFB 1999 Annual Conference

Lobsters that go 'ping': preliminary acoustic tracking of on-grown and wild juvenile southern rock lobster (*Jasus edwardsii*)

David J. Mills, Sam Ibbott, Simon Willcox and N. Caleb Gardner

Tasmanian Aquaculture and Fisheries Institute
Nubeena Crescent, Taroona TAS 7053

A rock lobster aquaculture industry based on on-growing wild-caught puerulus (late larval stage) is likely to commence in Tasmania in the near future. To ensure that puerulus extraction has no effect on the wild fishery, it is proposed that, after a year of on-growing, a number of lobsters be released equivalent to the proportion that would have survived in the wild (estimated at 25%). Information on survival of released animals is required before this method of compensation can be employed. Preliminary information on short-term movement, behaviour and survival was obtained by acoustic tracking on-grown and wild-caught lobsters over a period of 12 days. Few differences were found in behaviour or habitat usage of treatments. All lobsters were successfully recovered at the completion of the trial, and gut contents revealed that feeding rates were similar between wild-caught and on-grown animals. Movement data were used in the development of a robust method of assessing short-term survival of released on-grown lobsters.

Long-term movement patterns of four commercially and recreationally important estuarine fish species in New South Wales

Bruce Pease and Trudy Walford

NSW Fisheries
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During the period from 1980 to 1998, NSW Fisheries has conducted seven studies which involved tagging 11 fish species in 14 estuaries in New South Wales. The tag and recapture data from these studies has been compiled into an ACCESS database with 56 915 tag and 6 408 recapture records. We have analysed this database to determine long-term movement patterns for yellowfin bream (*Acanthopagrus australis*), luderick (*Girella tricuspidata*), dusky flathead (*Platycephalus fuscus*) and sand whiting (*Sillago ciliata*). This study focusses primarily on patterns of emigration from the estuary, and compares movement characteristics among species and regions. The influence of commercial and recreational fishing effort and reporting bias is discussed. All four species appear to have low emigration rates from the estuary where they were tagged. Bream emigrated at the highest rate and travelled the greatest distances. All four species showed a consistent tendency to migrate northward after emigration from the estuary in which they were tagged.

Golden perch otoliths as recorders of environmentally-induced growth fluctuations

Janet Pritchard[1], John Kalish[1] and Mark Lintermans[2]

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[2] *Wildlife Research and Monitoring, Environment PO Box 144, Lyneham ACT 2602*

The Murray-Darling Basin species of golden perch, *Macquaria ambigua*, is distributed over a wide geographic range. Around Canberra, golden perch are at the upper altitudinal and lower thermal limits of their distribution (M. Lintermans pers.comm.). We hypothesise that golden perch growth in the ACT is seasonally limited and that fluctuating environmental conditions can have profound impacts on relative fish growth across years. Investigation of otolith annual increment widths from 600 golden perch from Googong Reservoir (adjacent to the ACT), has produced retrospective records of somatic growth over a period of 15 years. Otoliths displayed years of suppressed growth (narrow increments) which correspond well with years of poor somatic growth (low mean length-at-age). The converse situation applies equally well, with wide increments representing years of good growth. Such environmentally-induced growth patterns are robust: the growth of all cohorts respond in a similar manner, irrespective of age. With further calibration, golden perch otoliths have great potential for use as an environmental proxy, with utility for studies of life history evolution and climate change.

A valuable new technique for sampling sedentary glass eels and its potential for assessing estuarine movement patterns

Veronica Silberschneider[1], Bruce Pease[1] and David Booth[2]

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Glass eels (postlarvae) of *Anguilla* spp. have been extensively studied world-wide because of their use in the global eel aquaculture industry. The actively moving component of the glass eel population has typically been sampled using a range of netting techniques. We have developed a new technique to sample the resting or non-migratory glass eels of *Anguilla australis* and *A. reinhardtei* using artificial habitat collectors. A series of experiments was conducted to determine the effectiveness and optimum design of the collectors. We analyse the results of these experiments and discuss settlement behaviour in relation to collector design factors and conclude that these new habitat collectors provide consistent, statistically quantitative samples of sedentary glass eels. Some preliminary findings on spatial and temporal patterns of settlement are also discussed, along with potential future applications for this sampling technique.

Movements and habitat use of the Mary River cod as determined by radio-telemetry

Robert Simpson

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The decline of the Mary River cod (*Maccullochella peelii mariensis*) is attributed largely to changed habitat conditions, although little specific information is available on the ecological requirements of this endangered species. In this study, radio-telemetry was used to investigate movements and habitat use of the Mary River cod. Nine cod with surgically-implanted transmitters were tracked for up to 20 months. Movements up to 40 km were recorded during flow events. Cod tended to move upstream during spring and summer and downstream in autumn. Homing behaviour and use of a well-defined home range were also observed. Cod showed a strong preference for habitats comprising log piles and individual large logs (>300 mm diameter). Open-water habitats were usually avoided. High priority should be given to maintenance of fish passage, and protection and rehabilitation of large woody debris habitats if cod populations are to recover.

Movement of gummy shark in southern Australia

Bruce L. Taylor, Terence I. Walker and Lauren P. Brown

Marine and Freshwater Resources Institute
PO Box 114, Queenscliff VIC 3225 and

Zoology Department
The University of Melbourne
Parkville VIC 3052

Gummy sharks (*Mustelus antarcticus*) are endemic to southern Australia and have been tagged and released during three separate studies (587 during 1947-56, 1525 during 1973-76 and 6535 during 1990-96). The 1990s tags were released in four general regions (Bass Strait, Tasmania, eastern South Australia and the Great Australian Bight, including Western Australia) (few were released off New South Wales); the earlier releases were mainly in Bass Strait and Tasmania. Most of the 1990s recaptures occurred within their release zones with the inter-zone recapture rate being 6% for males and 7% for females. There are no recorded movements between GAB and Bass Strait or between GAB and Tasmania, with the exception of one female released in Bass Strait and recaptured in GAB. Preliminary results are presented from a model designed for estimating proportions of the population moving between the regions. The model takes account of the different levels of fishing effort and the highly length-selective characteristics of the gill-nets of various mesh sizes deployed throughout the fishery.

An evaluation of clove oil for anaesthesia of *Anguilla reinhardtei*

Chris Walsh, Bruce Pease and Darren Reynolds

NSW Fisheries
PO Box 21, Cronulla NSW 2230

In order to handle adult river eels during procedures such as measuring and tagging for field and aquaculture studies, they must be anaesthetised. During the initial phase of our current biological studies of *Anguilla reinhardtei* we determined that benzocaine is expensive, and even when used at a relatively high concentration elicited a variable response. Human health risks are also a concern, since many of the eels are later sold for human consumption. Therefore, we conducted experiments to evaluate the optimum use of clove oil (a safe, naturally-occurring product) for anaesthesia of this species at a range of temperatures (17 and 25°C) and salinities (0 to 32 ppt). It was found that 100 mg/l clove oil provided a suitable anaesthetic response through the range of temperatures and salinities tested. Clove oil is recommended for anaesthesia of anguillid eels because it is effective, relatively inexpensive and very safe.

A tagging study on tailor (*Pomatomus saltatrix*) in Western Australian waters: their movement, exploitation, growth and mortality

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A total of 3 949 undersize, 1 015 sub-adult and 143 adult tailor, *Pomatomus saltatrix*, was tagged between November 1994 and August 1996 at 24 sites along 1200 km of Western Australian coastline. Undersize tailor were recaptured at lower rates than sub-adult tailor. The majority of recaptured undersize and sub-adult fish moved less than 25 km, remaining in sheltered estuarine and marine areas. In contrast, recaptured tailor that had become sexually mature adults whilst tagged, displayed behaviour consistent with a northward or offshore winter movement. Commercial and recreational tag returns reveal that recreational fishers take the vast majority of the total catch of tailor in Western Australia. Modelling indicates there was higher recreational fishing mortality in the metropolitan region, consequently, tailor occupying these nursery habitats are vulnerable to localised depletion . Estimated growth was between 0.41± and 0.44mm day^{-1}, indicating that tailor reach legal size in 18 to 22 months.

Conference Posters from ASFB 1999 Annual Conference

Victoria's State Fishway Program

Tim O'Brien

Freshwater Ecology
Arthur Rylah Institute for
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123 Brown Street, Heidelberg VIC 3084

The Victorian Government has initiated a State Fishway Program to reinstate important pathways for migration of native fish, now recognised as an integral component in restoring river health. The Program provides important conservation and recreational benefits to the State through the preservation and enhancement of both endangered and recreational species.

A recently-completed inventory of instream structures identified more than 2600 potential barriers to fish migration. The Program will ensure that fishways are constructed at existing dams and weirs on a priority basis and that future dams, weirs and culverts will be constructed in such a way that they do not obstruct fish.

More than 26 fishways ranging in size from vertical slot fishways on the Broken Creek to culvert modifications in the Otways have been completed and a further 56 are being funded for works over the next two years.

Eels - the journey continues

Bruce Pease, Chris Walsh and Darren Reynolds

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The two most common species of eels endemic to Australia are the longfinned eel (*Anguilla reinhardtei*) and the shortfinned eel (*Anguilla australis*). Along with their ecological value, they support significant commercial fisheries along the east coast. Until recently there has been only limited research into the basic ecology of longfinned eels (mainly in Victoria and Tasmania) with no biological studies being conducted in New South Wales.

In July 1998, NSW Fisheries commenced a three-year study of longfinned eels funded by the Fisheries Research and Development Corporation. Eels are being sampled and tagged to determine age, sex and reproductive condition along with growth, mortality and movement rates. The results of this study will be used to develop techniques for assessing and monitoring longfinned eel stocks in NSW.

Determining escapement in the whitebait fishery of New Zealand

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The New Zealand whitebait fishery is a popular springtime recreational fishery for five species of galaxiids. This fishery includes four species considered threatened and the fishery as a whole has been in decline for at least fifty years. Whether the fishery is sustainable is unknown. Escapement had not been determined and catch records are rarely kept. We used dye-marked whitebait to assess escapement rates of migrating fish and to determine their movement rates through the fishing area. Releases of marked fish were made in two rivers, and recaptures by whitebaiters were monitored. The escapement of marked fish was variable, ranging from 98% to 55%, and actual escapement rates are estimated to be lower. Recapture locations of the fish indicated that movements in the estuarine areas were complex and at least some fish were available for capture for several days before they ascended up river past the whitebaiters.

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