Impact of environmental changes on the fish faunas of Western Australian south-coast estuaries

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Australian Government
Fisheries Research and Development Corporation

MURDOCH UNIVERSITY
PERTH, WESTERN AUSTRALIA

Centre for Fish and Fisheries Research

Project No. 2002/017

Fisheries Research and Development Corporation Report

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March 2006

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The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a statutory authority within the portfolio of the federal Minister for Agriculture, Fisheries and Forestry, jointly funded by the Australian Government and the fishing industry.

March 2006
ISBN: 86905-879-7

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OBJECTIVES:

1. Determine whether the compositions of the fish faunas of the basin and riverine regions of the Stokes, Culham and Hamersley inlets change seasonally and whether pools in the upstream regions of the saline reaches of their major tributaries act as refugia for Black Bream.

2. Relate any differences in the compositions of the fish faunas in the three estuaries to differences in the environmental characteristics within and between these estuaries, and in particular of salinity, dissolved oxygen and water levels.

3. Use age composition data to determine the extent of variations in annual recruitment of Black Bream in the Stokes, Culham and Hamersley inlets during recent years, and relate these variations to environmental conditions, and particularly of freshwater discharge and whether or not the bar at the estuary mouth had been breached.

4. Compare the growth of Black Bream in the above three estuaries and consider any differences in the context of variations in the environmental characteristics of those systems.

5. Determine the diets of Black Bream in the Stokes, Culham and Hamersley inlets and attempt to relate any differences to any variations in the growth rates of this species among those estuaries.

6. Provide to environmental and fisheries managers an assessment of the levels at which salinity and dissolved oxygen influence the abundance of the main fish species and how those critical levels vary amongst species.

NON TECHNICAL SUMMARY

OUTCOMES ACHIEVED TO DATE

Data on the fish communities and environmental conditions in three normally-closed estuaries (Stokes, Culham and Hamersley inlets) on the central south coast of Western Australia have been obtained seasonally for three years. The sampling regime and analyses were designed so that the data and their implications would be of value to both fisheries and environmental managers. Salinities in all three estuaries rose as a result of a combination of salt loading through land clearing, dry winters and high evaporation rates during summer. These increases were most marked in the Culham and Hamersley inlets, eventually resulting in the salinities in these two estuaries exceeding by several times that of sea water. Massive mortalities of Black Bream occurred in these two estuaries when salinities were approximately twice that of sea water, a finding that has been published in an international journal. The development of extremely high salinities was accompanied by a reduction in the number of species and density of fish in Culham and Hamersley inlets, with only a small species of hardyhead surviving when salinities reached levels equivalent to four times sea water. Dietary data emphasise that Black Bream is a highly opportunistic omnivore and thus able to withstand major changes in potential food types. Survival by Black Bream over several years was greatest in Stokes Inlet, the most environmentally stable estuary. Growth of Black Bream varied greatly among estuaries, which appeared to reflect differences in density rather than diet. The results emphasise that (1) the stocks of Black Bream can only be sustained permanently in the basins of estuaries if the quality of environmental conditions in those systems is maintained at an appropriate level and (2) upstream pools can act as refugia for Black Bream when extreme conditions exist downstream.

The Stokes, Culham and Hamersley inlets, which are located on the central south coast of Western Australia, are normally-closed from the ocean by a sand bar at their mouths. The fish faunas of their shallow and deep waters were sampled by seine and gill netting, respectively, in each season between summer 2002 and spring 2004. Shallow waters in Culham Inlet were also sampled in 2001. Sampling was focussed in the basin and lower part of the main tributary of each estuary, but was also undertaken in the closed, lagoonal-like entrance channel of Culham Inlet and in those upstream regions of the tributaries of Culham and Hamersley inlets, which become isolated as pools when water levels are low.

Seine and gill netting in each estuary yielded only five to eight fish species. This number is lower than those recorded in estuaries further to the west, such as Wilson Inlet and the Nornalup-Walpole Estuary, and, to an even greater extent, in those on the lower west coast of Western Australia, such as the Swan River and Peel-Harvey estuaries. The very low diversity of the fish fauna in the Stokes, Culham and Hamersley inlets is due to a combination of these estuaries being normally-closed, which restricts the entry of marine species, and the naturally low diversity of the fish faunas of the estuaries in this region.

Nearshore, shallow waters were dominated to such an extent by a small hardyhead (*Atherinosoma elongata*), that this species contributed between 74 and 95% to the total catch of fish in these waters in each estuary. Another small hardyhead and a small goby were also relatively abundant in these catches, as were juveniles of the Black Bream in the Stokes and Culham inlets but not Hamersley Inlet. The only marine species in the catches from nearshore waters was Yellow-eye Mullet, which was represented by very low numbers of juveniles in the Stokes and Hamersley inlets and had probably been swept over the bars at the mouths of these estuaries during high swells.

Black Bream dominated the fish faunas of offshore, deeper waters, contributing, in terms of numbers, 98% to the gill net catches in Stokes Inlet, 95% to those in Culham Inlet and 87% to those in Hamersley Inlet. Between two and five marine species were caught in relatively low numbers in the deeper waters of each estuary. The most abundant were Yellow-eye Mullet in Stokes Inlet, Mulloway in Culham Inlet and Sea Mullet and Western Australian Salmon in Hamersley Inlet. The minimum length of each of these and of the other marine species found in the deeper waters of these estuaries was far greater than that of Black Bream, which spawn and grow relatively rapidly. It is thus concluded that these marine species had been landlocked in these estuaries for a protracted period and almost certainly entered these systems when the estuary bar at their mouths was breached in 2000.

The mean seasonal salinities in the main body of each estuary increased during the study period. However, they never rose above about 60 in Stokes Inlet, but eventually exceeded 290 in Culham Inlet and 140 in Hamersley Inlet. Comparisons among estuaries emphasise the extent to which extremes in salinity can influence the composition of estuarine fish faunas. Thus, fish remained relatively abundant in both nearshore and offshore waters of the basin and lower reaches of the main tributary of Stokes Inlet, whereas the density and number of species of fish declined markedly in Culham and Hamersley inlets. A small hardyhead (*Atherinosoma elongata*) survived the longest and was caught in salinities that were more than four times greater than sea water. Black Bream was caught in Stokes Inlet throughout the study, but incurred massive mortalities as salinities reached 65-85 in the latter two estuaries as a result of a combination of increased salt loading, dry winters and high evaporation rates during summer. Consequently, no Black Bream were found in the basins and lower part of the tributaries of these estuaries during the latter period of this study. Black Bream was caught throughout the study in the closed entrance channel and upstream pool of Culham Inlet, in which salinities remained below 45. These regions thus act as refuges for Black Bream when salinities increase markedly in the main body of this estuary.

Black Bream spawn in late winter and spring in normally-closed estuaries, which is earlier than in permanently-open and seasonally-open estuaries, and allows them to produce offspring before salinities become high during the typically dry summer months. Black Bream typically reach maturity in Stokes Inlet at the end of their second year of life, when they are about 150 mm in length.

Plant material, polychaete worms, molluscs, crustaceans, insects and fish were ingested by Black Bream in each estuary, but the extents to which these different dietary components were consumed varied greatly among estuaries. This emphasises that Black Bream is an omnivore and feeds opportunistically. The diversity of the diet was far greater in Stokes Inlet than in the other two far more variably saline estuaries, presumably reflecting a greater diversity of prey in that estuary. The relatively greater contributions of fish to the diets of Black Bream in Hamersley and Culham inlets than to those of Stokes Inlet are consistent with differences in the densities of those species in those estuaries. The dietary changes undergone by Black Bream as it increases in size would reduce competition among the individuals of this species for food resources and would thus be particularly useful in Culham and Hamersley inlets, which probably contain a less diverse range of prey than Stokes Inlet.

An examination of annual growth rings in otoliths (ear bones) demonstrated that the population of Black Bream in Stokes Inlet bred successfully in all but one of the years between 1992 and 2003. The recruitment of juveniles was greatest in years of moderate flow in the months preceding and during the spawning period. Far fewer year classes were represented in the samples of Black Bream obtained from the main body of Culham Inlet and even fewer from Hamersley Inlet, prior to the mass mortalities that occurred in these regions as a result of the development of highly-elevated salinities. However, several year classes of Black Bream were

present in the upstream pools of Culham Inlet, where salinities did not increase to the same extent, emphasising the importance of this type of habitat as a refuge for this important species.

The marked differences of the growth of Black Bream among the three estuaries during the early years of life could not obviously be related to the pronounced differences in the composition of food consumed in those estuaries but could be density dependent as growth was least in Stokes Inlet in which the density of this species was greatest.

It is concluded that Black Bream populations in the basins of estuaries, such as those of the Culham and Hamersley inlets, are only sustainable if the quality of environmental conditions (and particularly salinity levels) in those regions is maintained at an appropriate level. It is also clear that upstream pools act as important refuges for Black Bream when extreme conditions exist downstream.

KEYWORDS: normally-closed estuaries, fish communities, salinity, dissolved oxygen, freshwater discharge, Black Bream, age composition, annual recruitment, growth.

ACKNOWLEDGEMENTS

Particular thanks are expressed to Richard Stevens and Frank Prokop for their continual interest in and support for this project. Gratitude is also due to Naomi Arrowsmith, Steve Janicki and Andrew Maughan (Department of Environment), Ian Hughes and Steve Miller (Department of Conservation and Land Management), Rod Lenanton (Department of Fisheries), Owen McIntosh and George Ebbett (commercial fishers), Ralph Cooper and Andrew Chapman, for their support and advice. Gavin Sarre willingly shared his extensive experience of south coast estuaries and Black Bream biology, Gordon Thompson (Murdoch University) prepared excellent histological sections of the gonads of Black Bream and Helena Kobryn (Murdoch University) kindly calculated the extent of clearing of the catchments of the three estuaries studied. Fiona Valesini and Margaret Platell (Centre for Fish and Fisheries Research) provided advice on the most appropriate ways of treating and analysing the dietary data for Black Bream and Bob Clarke (Plymouth Marine Laboratory) gave us access to an unpublished paper which enabled us to overcome the problems associated with using multivariate techniques to analyse fish community data in which some of the samples contained zero catches.

1.0 GENERAL INTRODUCTION

1.1 BACKGROUND

1.1.1 *Species composition of fish faunas in estuaries on the central south coast of Western Australia*

There is a limited amount of quantitative data on the relationships between the fish faunas and environmental conditions in the normally-closed estuaries of the central region of the south coast of Western Australia. Such data are required by both environmental and fisheries managers, because the salinity of many of the estuaries in this region undergo extreme increases during dry periods, and such changes must exert a strong influence on the diversity, abundance and composition of their fish faunas. Indeed, the only detailed data on the fish faunas of normally-closed estuaries in Western Australia, and of the biology of their most important recreational and commercial fish species, the Black Bream *A. butcheri*, are those derived from samples collected at regular intervals from the Wellstead Estuary, which is located well to the west of the estuaries that constitute the focus of the current study, *i.e.* Stokes, Culham and Hamersley inlets (Sarre & Potter, 1999, 2000; Sarre *et al.*, 2000; Young & Potter, 2002). Although caution must be exercised in extrapolating from the conditions in Wellstead Estuary to that in estuaries further east, the results of a recent study of Wellstead Estuary enable certain predictions to be made regarding the likely impact of extreme environmental changes on the fish faunas of estuaries in the central region of the south coast of Western Australia (Young & Potter, 2002). For example, that study indicated that atypically high salinities can lead to the death of all individuals of one species of goby (*Amoya bifrenatus*) and a species of hardyhead (*Leptatherina wallacei*) and to the movement of the much larger Black Bream to upstream areas where salinities were far lower. However, it also demonstrated that another species of hardyhead (*Atherinosoma elongata*) was able to survive salinities that exceeded by three times that of full strength seawater. Changes in the relative abundances and distributions of these species can thus be used as indicators of the extent to which, in the short to medium term, the biota of estuaries on the south coast of Western

Australia respond to extreme environmental changes. The only other published information on the ichthyofaunas of estuaries of the central south coast region of Western Australia, outside that of the Wellstead Estuary, is largely descriptive and based on restricted sampling conducted well over two decades ago, and thus prior to the changes that have occurred in these estuaries during recent years (Lenanton & Hodgkin, 1985; Hodgkin & Clark, 1989, 1990).

The reductions in water level and periods of high salinity that have occurred in Culham Inlet during recent times are also likely to occur in those estuaries of the same region where land clearing is increasing the salt load entering the estuary (Pen, 1999; Brearley, 2005) and extended dry periods will result in a marked rise in evaporation and thus salt concentration. These adverse environmental changes will have a deleterious effect on fish populations. Such a conclusion is supported by the fact that, even in Stokes Inlet, which does not undergo the same degree of environmental change, certain fish species have still occasionally experienced mass mortalities in this estuary during extended dry periods in the past (Hodgkin & Clark, 1990).

1.1.2 Acanthopagrus butcheri *in estuaries on the central south coast of Western Australia*

Many estuaries in the large, central region of the south coast of Western Australia, such as the Stokes, Culham and Hamersley inlets, which are the subject of the present study, are normally closed (Lenanton & Hodgkin, 1985). Some of these estuaries, which are very important tourist destinations, are fished heavily by recreational fishers, particularly during the summer tourist period. Stokes Inlet, for example, is the most important recreational fishing location on the south coast for the communities of the Goldfields region, *i.e.* Kalgoorlie, Coolgardie and Norseman. Furthermore, until the early 1990s, Culham Inlet supported not only a substantial recreational fishery for Black Bream (*Acanthopagrus butcheri*), but also the largest commercial fishery for this species in Western Australia, yielding up to 77 tonnes per annum (Hodgkin, 1997). However, in 1993, the water levels in this normally-closed estuary declined as a result of a combination of extended dry periods and the loss of water through the artificial breaching of the sand bar at the estuary mouth and thus of a marked elevation in salinity. The conditions, particularly in the basin, became far less favourable for Black Bream and thus led to a collapse in the fishery for this species in Culham Inlet. The highly deleterious effect of elevated salinities on Black Bream in this system, which may have been exacerbated by low dissolved oxygen concentrations and high water temperatures, would have been enhanced by the fact that a rock bar on the Phillips River would have prevented Black Bream from being able to escape to upstream refugia where salinities were far lower. Such a conclusion is consistent with the fact that data for the Wellstead Estuary demonstrated that, in this system, substantial numbers of Black Bream were able to survive through undergoing such a movement (Young & Potter, 2002).

A previous study has shown that the growth rate of Black Bream varies markedly amongst estuaries on the south-western Australian coast and that the environmental characteristics of those estuaries varied markedly (Sarre & Potter, 2000). The same study demonstrated that it was possible to use age composition data to determine the extents to which recruitment varies among years and then to relate years of extremes in recruitment success to the environmental conditions in those years. Such information could be used as a predictive qualitative model to determine the fate of Black Bream in other estuaries in the region that are facing similar environmental changes.

1.2 NEED

Reliable data are urgently required to underpin strategies to conserve or improve the ecosystems and fisheries of normally-closed estuaries in the central region of the south coast of Western Australia. Managers thus need the following.

1. An understanding of the current status of the fish fauna of the highly-degraded Culham Inlet, and particularly of its population of Black Bream, and how that status has been influenced by environmental perturbations which have been exacerbated by anthropogenic changes to the system.
2. An understanding of the current status of the fish faunas of the Stokes, Culham and Hamersley inlets, which have become degraded to varying extents as a result of the levels of land clearing within catchments.

3. An ability to predict the extent to which continuing degradation of any normally-closed estuary in the central region of the south coast of Western Australia will affect the fish faunas of those estuaries and, in particular, their recreational and commercial fish species. This information is required by the Department of Fisheries, Western Australia, for developing its overall plan for managing the recreational and commercial fisheries in these estuaries (R. Lenanton, pers. comm.) and by other governmental authorities for developing strategies for conserving or restoring the quality of the important environments afforded by these estuaries.
4. Reliable information on the extent to which the extreme environmental conditions experienced in certain of the last ten to fifteen years influenced either the spawning success and/or survival of the 0+ age class of Black Bream in the Stokes, Culham and Hamersley inlets.

2.0 GENERAL MATERIALS AND METHODS

2.1 SAMPLING LOCATIONS

The Stokes, Culham and Hamersley inlets are located in the semi-arid region of the central south coast of Western Australia (Figs 2.1, 2.2, 2.3). In this region, annual rainfall is relatively low, ranging from *ca* 500 mm at the coast to 350 mm inland and evaporation rates are high, *e.g.* 1754 mm per annum at Esperance (Hodgkin, 1997). During warm and dry periods, these conditions frequently lead to marked reductions in water levels in the above three estuaries and other estuaries of this region, such as the Wellstead Estuary (Hodgkin & Clark, 1989, 1990; Young & Potter, 2002). As with most other estuaries on the central south coast of Western Australia, the Stokes, Culham and Hamersley inlets are normally-closed to the ocean, due to the presence of sand bars at their mouths (Lenanton & Hodgkin, 1985). Thus, water levels in these estuaries are largely governed by the amount of discharge from their tributary rivers. The catchments of the tributaries feeding the basins of Stokes, Culham and Hamersley inlets vary in size and in the extent to which they have been cleared for agriculture and other purposes (Fig. 2.4) (Hodgkin & Clark, 1989; 1990; Pen, 1999; Brearley, 2005).

2.1.1 *Stokes Inlet*

The Stokes Inlet is located in the Stokes Inlet National Park and has an area of approximately 14 km^2 (Hodgkin & Clark, 1989) (Figs 2.1, 2.5). The sand bar at the mouth of this normally-closed estuary is approximately 200 m wide and extends in height from 1.5 to 2 m above mean seal level (MSL). The bar is reported to have been breached in 1919 and 1927, but not again until 1967. Since that year, the bar has been breached on six occasions in the period up to 1989. In years when the bar is breached, this typically occurs in either spring, following a particularly wet winter and heavy rains in October and November, or after heavy cyclonic rains in early summer (Hodgkin & Clark, 1989).

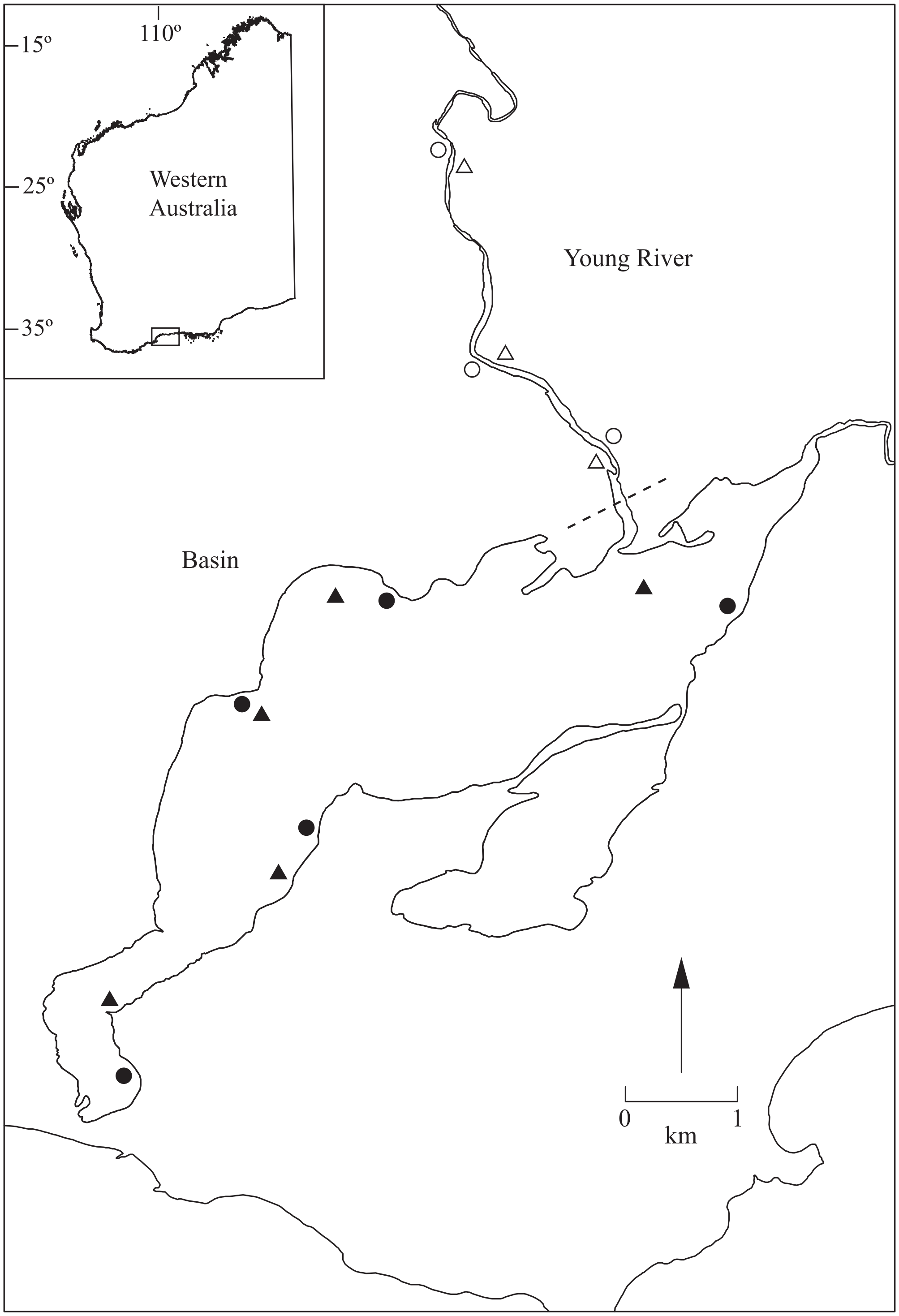

Fig. 2.1. Map showing location of Stokes Inlet in Western Australia (box in top left) and the sampling sites in the basin and main tributary (Young River) of this estuary. Circles represent the seine net sites and triangles the gill net sites.

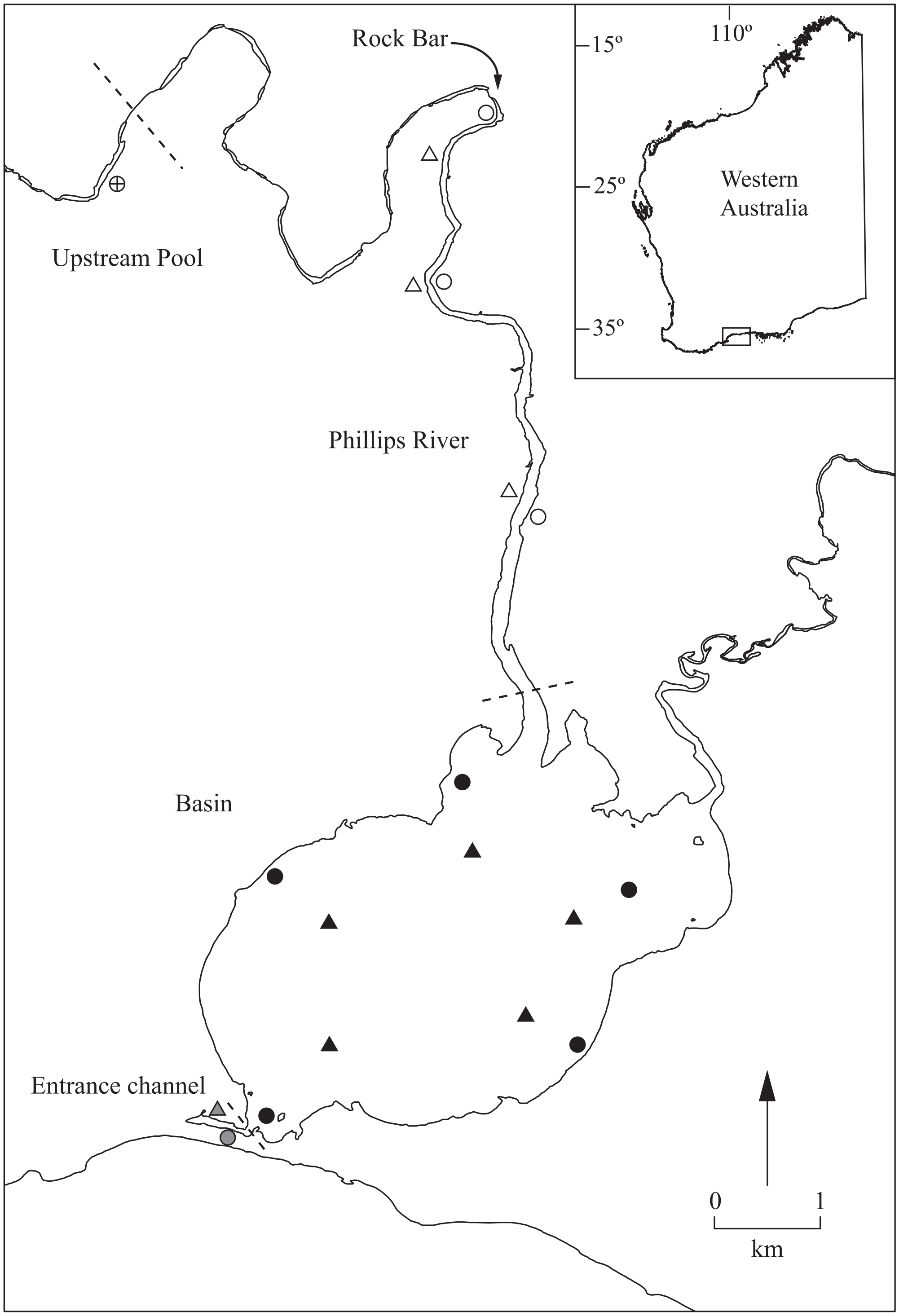

Fig. 2.2. Map showing location of Culham Inlet in Western Australia (box in top right) and the sampling sites in the entrance channel, basin, main tributary (Philips River) and upstream pool. Circles represent the seine net sites and triangles the gill net sites.

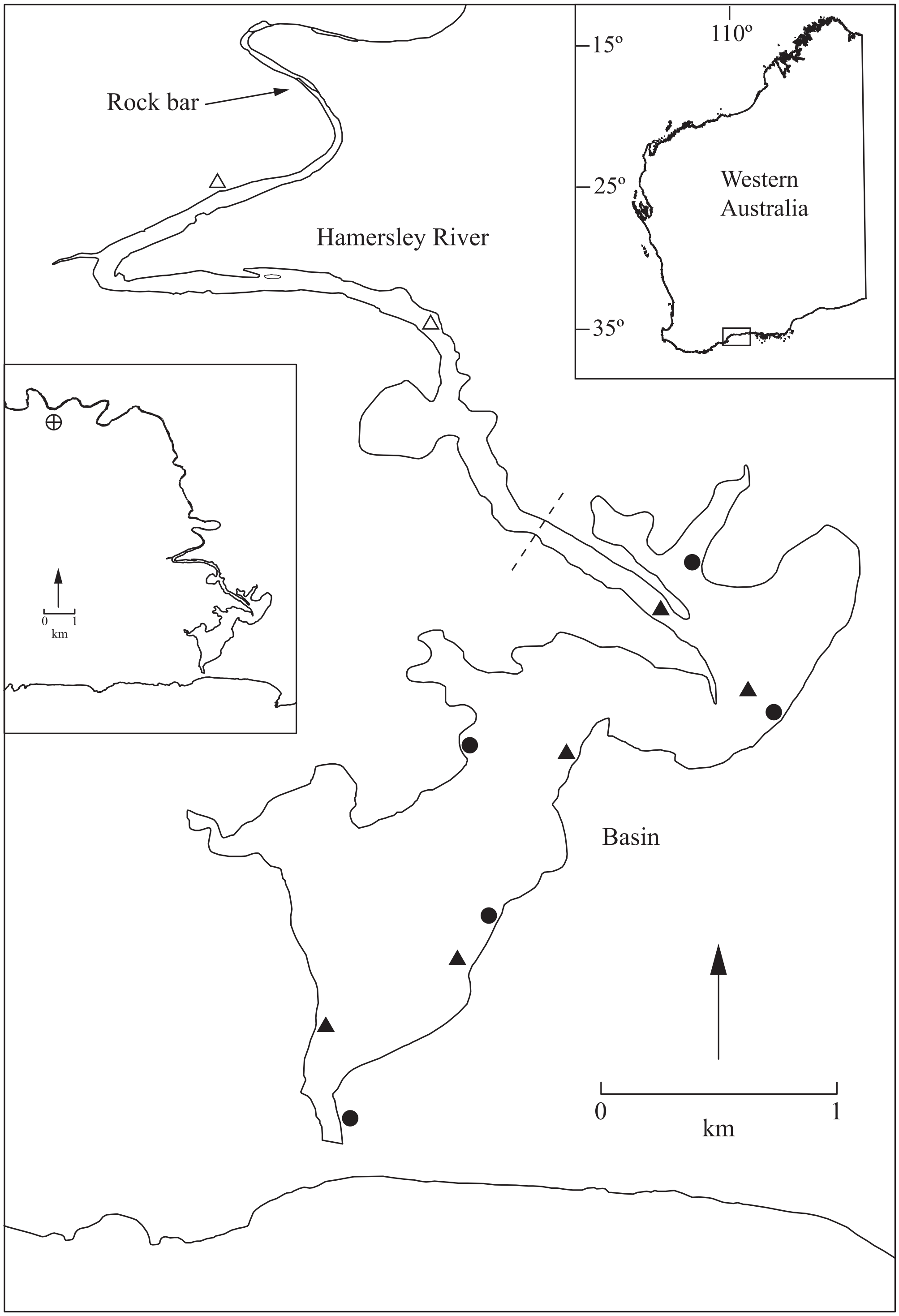

Fig. 2.3. Map showing location of Hamersley Inlet in Western Australia (box in top right) and the sampling sites in the basin, tributary (Hamersley River) and upstream pool (crossed circle in box on left) of this estuary. Circles represent the seine net sites and triangles the gill net sites.

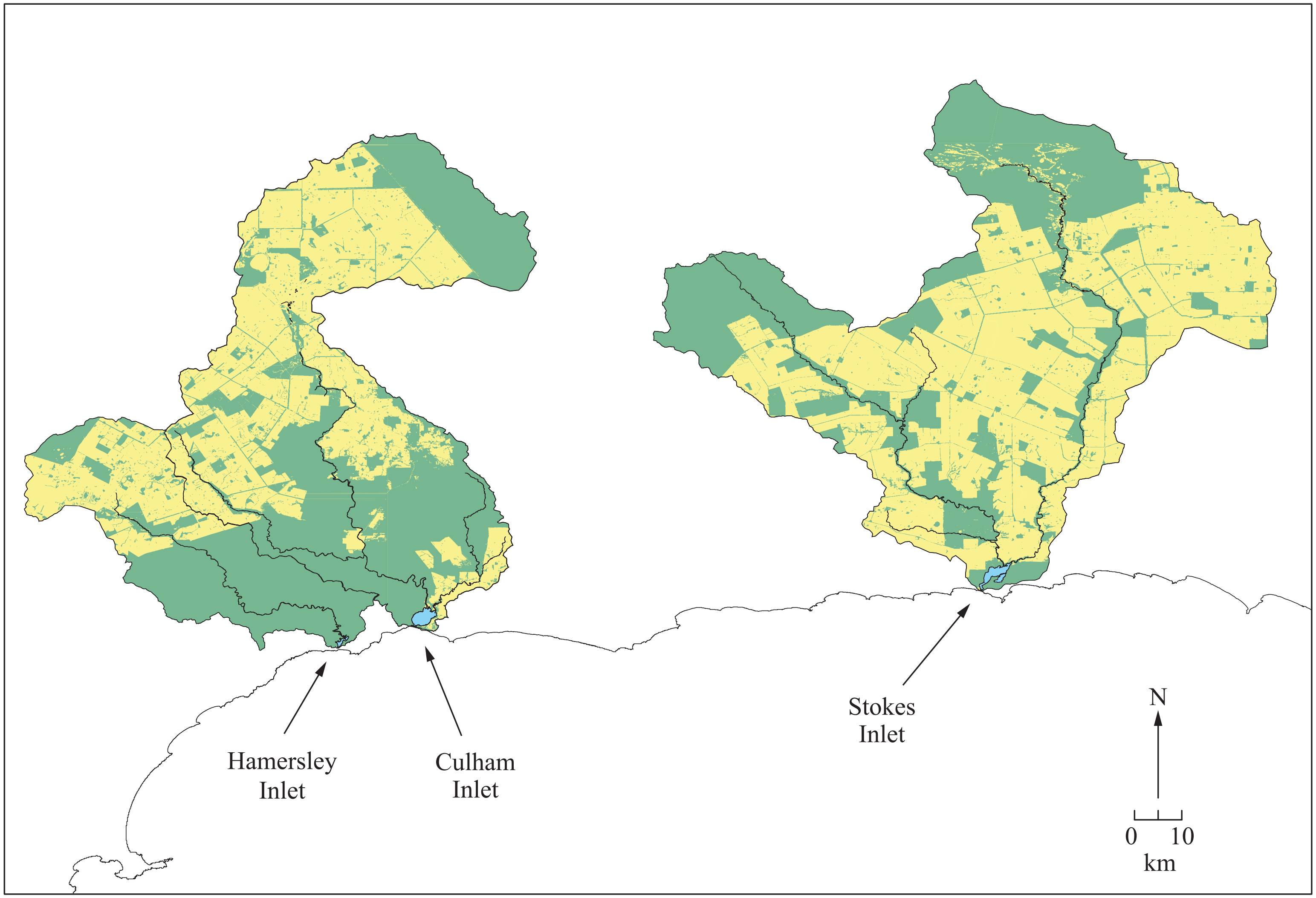

Figure 2.4. The locations of the catchments of Stokes, Culham and Hamersley inlets in the central southern region of Western Australia. Land cleared for agriculture is shown in yellow and the remnant vegetation is shown in green.

Figure 2.5. Composite aerial photograph of Stokes Inlet and its major tributary, the Young River.

The entrance channel behind the bar at the mouth of the inlet is *ca* 2 km long and 500 m wide and can attain depths of 5 m in some areas. The basin of Stokes Inlet, which is *ca* 10 km long, gradually widens and becomes progressively shallower from its junction with the entrance channel to attain a width of *ca* 2 km at its northern and upper end. The basin varies greatly in depth and, at certain times, its lower reaches can attain water depths of up to 10 m (Hodgkin & Clark, 1989).

Stokes Inlet is fed by the Young River, its major tributary, which extends 120 km inland from the basin and the Lort River, which also runs predominately through agricultural land. The combined catchments of these two rivers cover an area of approximately 5300 km^2, of which about 60% has been cleared (Department of Environment, Western Australia, unpubl. data) including 75% of that of the Young River (Pen, 1999). This catchment modification has resulted in a marked increase in runoff, which accounts for the increase in the frequency with which the bar has been breached since 1967 (Hodgkin & Clark, 1989; Pen, 1999). A weir is located on the Young River at a distance of *ca* 6 km upstream of its junction with the basin. This stretch of the river, downstream of the weir, which has rocky shorelines and overhanging vegetation, is markedly saline during the warmer and drier months of the year and is considered part of the estuary (Hodgkin & Clark, 1989). Although the basin and the Young River always contain water, even in low rainfall years, the part of the basin that lies near the river mouth can become dry and thus at such times the water in the basin and river are no longer continuous (Hodgkin & Clark, 1989).

2.1.2 *Culham Inlet*

The Culham Inlet, which borders the Fitzgerald River National Park, has a basin that occupies an area of approximately 11.3 km^2 (Figs 2.2, 2.6). The sand bar at the mouth of this normally-closed estuary is only recorded as having been breached naturally on one occasion, *i.e.* in 1849, but may have also been breached in the 1870s (Hodgkin, 1997). This bar was artificially breached in 1920 and 1993, the latter of which was aimed at alleviating the flooding of the surrounding farm lands that had resulted from several years of above average winter rainfall and

Figure 2.6. Composite aerial photograph of Culham Inlet and its major tributary, the Phillips River. NB. The causeway seperates the entrance channel and basin of Culham Inlet.

heavy rainfall in the late autumn of 1993. Before the breach in 1993, the large dune-like sand bar at the mouth of Culham Inlet was approximately 1 km wide, 4 to 15 m in height and densely vegetated (Hodgkin, 1997). This dune was sufficiently large to accommodate a road that enabled vehicles to pass between Hopetoun and the Fitzgerald National Park and was thus vital to allow tourists to visit that park. In early 1993, construction of a spillway at the western end of the bar commenced. This construction was aimed at preventing water levels reaching a height that would lead to the flooding of both nearby land and a section of the road that ran along the top of the sand bar. However, discharge increased markedly in the autumn of 1993 before the spillway could be completed and this led to the breaching of the bar and the production, through scouring, of a deep channel between the estuary and the ocean that was 70 m wide.

In 1997, a new access road to the Fitzgerald National Park was constructed, which cuts back into the basin of Culham Inlet and thus separates the basin of the estuary from the deeply scoured "entrance" channel and sand bar at the estuary mouth (Fig. 2.6). The design of this road facilitates, however, the flow of water between the basin of the estuary and entrance channel through two sets of culverts when the water in the basin increases to a certain level and allows the modified bar to be breached at a lower height, thus greatly reducing the "working level" of the estuary (Norriss *et al.*, 2002). Consequently, heavy summer cyclonic rains in January 2000 led to the modified bar at the mouth of Culham Inlet to be breached naturally in early 2000.

The basin of Culham Inlet is very shallow, with its floor typically lying at approximately mean sea level (MSL) (Norriss *et al.*, 2002) and is only *ca* 1 m below MSL at its deepest point (Hodgkin, 1997). Thus, as the maximum attainable water height in the basin is governed by the height of the sand bar at the estuary mouth, and this bar is now appreciably lower than prior to 1993, the amount of water that can potentially be retained within the basin has been greatly reduced. The basin is fed by the Phillips and Steere rivers, the former of which is the main tributary of Culham Inlet. Although the Phillips River extends *ca* 50 km inland, its flow is interrupted during periods of low water levels through the presence of a natural rock barrier at a distance of *ca* 7 km upstream of the basin (Fig. 2.2). In contrast to the basin, the Phillips River is relatively deep in parts, with its floor being 4 m below MSL at one point and water depths of approximately 8 m being recorded at times (Hodgkin & Clarke, 1990).

It has been estimated that, although the Phillips River, the main tributary of Culham Inlet, flows for a distance through the Fitzgerald National Park, as much as 35% of its total catchment has still been cleared for agricultural purposes (Fig. 2.4) (Hodgkin & Clark, 1990; Pen, 1999). The combined catchments of all tributaries of Culham Inlet cover an area of 3780 km^2, of which 50% has been cleared (Department of Environment, Western Australia, unpubl. data).

2.1.3 *Hamersley Inlet*

The Hamersley Inlet and its single tributary, the Hamersley River, are located in the Fitzgerald River National Park (Figs 2.3, 2.7). The mouth of this estuary is normally closed by a sand bar that is *ca* 300 m in width. During periods of prolonged closure, the bar can build up to more than two metres above MSL. Although the bar is only known to have been breached three times prior to 1955, it was subsequently breached in at least six of the following years up to 1999 and again in 2000 (Hodgkin & Clark, 1990; Brearley, 2005). While such breaches are usually associated with atypically heavy late winter or spring rains, the breaching in 2000 resulted from very large freshwater discharge caused by cyclonic rains that occurred in January 2000. The basin of Hamersley Inlet is approximately 4 km long, has a maximum width of *ca* 500 m and covers an area of *ca* 2.3 km^2. The floor of the basin is approximately 2 m below MSL near the mouth, but becomes gradually shallower towards its point of connection with the Hamersley River. The basin of this system has been reported to dry up almost entirely during prolonged periods of drought (Hodgkin & Clark, 1990).

Although the Hamersley River extends inland for *ca* 50 km (Pen, 1999), its flow is interrupted during dry periods by a substantial natural rock bar at a distance of *ca* 2.5 km upstream of the basin. The lower part of the small (1268 km^2) catchment of Hamersley Inlet is located in the Fitzgerald National Park and consequently this estuary was previously considered nearly pristine (Pen, 1999). However, the upper part of the catchment does extend into

Figure 2.7. Composite aerial photograph of Hamersley Inlet and its tributary, the Hamersley River.

agricultural land, which accounts for recent estimates that 37% of the vegetation of the total catchment has been cleared (Department of Environment, Western Australia, unpubl. data).

2.2 SAMPLING REGIME

2.2.1 *Nearshore, shallow and offshore, deeper waters*

The fish faunas of nearshore, shallow waters of the Stokes, Culham and Hamersley inlets were sampled using a 21.5 m seine net. This net, which consisted of two 10 m long wings, with 6 m of 9 mm mesh and 4 m of 3 mm mesh and a 1.5 m wide bunt of 3 mm mesh, swept an area of 116 m^2 and fished to a maximum depth of 1.5 m. The seine net was laid either parallel to the shore, or in a circle in the shallows and then hauled on to the bank. All seine netting was conducted during the day.

Offshore, deeper waters of the Stokes, Culham and Hamersley inlets were sampled using composite sunken gill nets, which comprised six panels, each with a length of 20 m and a height of 2.0 m and comprising a different stretched mesh size, *i.e.* 51, 63, 76, 89 or 102 mm. Gill nets were laid parallel to the shore at dusk and were set for one hour. The short gill netting period reduced the risk of catching very large numbers of Black Bream as can occur in these estuaries by gill netting for a longer period.

During preliminary reconnaissance, five sampling sites in both nearshore, shallow and offshore, deeper waters of the basins of Stokes, Culham and Hamersley inlets were identified. Three further sites were identified in both nearshore, shallow and offshore, deeper waters of the main tributaries of the Stokes and Culham inlets and at two sites in offshore, deeper waters of the tributary of Hamersley Inlet. It was not possible to deploy a seine net to sample the nearshore waters of the lower reaches of the Hamersley River, *i.e.* below the rock bar on this tributary, because of the steepness of the edges of the river bed and the presence of prominent sharp, layered rock and debris. Sampling sites were also identified in both nearshore, shallow and offshore, deeper waters of the small, lagoonal-like entrance channel of Culham Inlet and in nearshore, shallow waters of an upstream pool on the tributaries of both the Culham and

Hamersley inlets. These latter pools were located upstream of the rock bars that prevent water flow between the upstream and downstream regions of those tributaries when water levels are low.

Sampling was initiated in the basins and rivers of each estuary and in the entrance channel of Culham Inlet in the summer of 2002. Water levels were sufficient to enable most sites in the basin and river of Stokes Inlet, the river of Culham Inlet and the basin of Hamersley Inlet to be sampled in each season until spring 2004. However, they subsequently declined to levels at one or two sites in the basins of Stokes and Hamersley inlets and throughout most of those in the basin of Culham Inlet that it was not possible to sample those sites effectively using seine and/or gill nets (Table 2.1, 2.2). However, when there was still sufficient water for fish to occupy such a site, the mean value for the number of species and density or catch rates for the other sites (replicates) in that region of the estuary was used as a surrogate for those variables on that occasion (see Underwood, 2002). In contrast, when little or no water remained at a site, a zero value was accorded to the above three biotic variables (Table 2.1, 2.2). Details of the use of Analysis of Variance and Non-metric multidimensional scaling to analyse the data on the number of species, density/catch rate and composition of fish is given in Chapter 3.2.1.

2.3 ENVIRONMENTAL VARIABLES

2.3.1 *Environmental measurements*

Salinity, water temperature and dissolved oxygen concentration were measured at each sampling site on each sampling occasion using a Yellow Springs International Model 85 oxygen, conductivity, salinity and temperature meter. These environmental variables were measured at the middle of the water column in nearshore waters and at both the surface and bottom of the water column in offshore waters.

Table 2.1. The sampling frequency at which nearshore, shallow waters of each region of Stokes, Culham and Hamersley inlets were sampled. * indicates when a sample was taken, 0 indicates when no sample could be obtained due to lack of water and $\bar{x}$ indicates when a sampling site could not be reached by boat to be sampled, but was likely to still contain fish.

			2002				2003				2004			
	Region	Rep	Su	Au	W	Sp	Su	Au	W	Sp	Su	Au	W	Sp
Stokes	Basin	1	*	*	*	*	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*	*	*	*	*
		3	*	*	*	*	*	*	*	*	*	*	*	*
		4	*	*	*	*	*	*	*	*	*	*	*	*
		5	*	*	*	*	$\bar{x}$	$\bar{x}$	$\bar{x}$	*	*	$\bar{x}$	*	*
	River	1	*	*	*	*	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*	*	*	*	*
		3	*	*	*	*	*	*	*	*	*	*	*	*
Culham	EC	1	*	*	*	*	*	*	*	*	*	*	*	*
	Basin	1	*	*	*	*	*	*	*	*	*	*	0	0
		2	*	*	*	*	0	0	0	0	0	0	0	0
		3	*	*	*	*	0	0	0	0	0	0	0	0
		4	*	*	*	*	0	0	0	0	0	0	0	0
		5	*	*	*	*	0	0	0	0	0	0	0	0
	River	1	*	*	*	*	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*	*	*	*	*
		3	*	*	*	*	*	*	*	*	*	*	*	*
	Up.	1				*	*	*	*	*	*	*	*	*
Hamersley	Basin	1	*	*	*	*	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*	*	*	*	*
		3	*	*	*	*	*	*	*	*	*	*	*	*
		4	*	*	*	*	*	*	*	*	*	*	*	*
		5	*	*	*	*	0	0	0	0	0	0	0	0
	Up.	1						*		*	*	*		*

Table 2.2. The sampling frequency at which offshore, deeper waters of each region of Stokes, Culham and Hamersley inlets were sampled. * indicates when a sample was taken, 0 indicates when no sample could be obtained due to lack of water and $\bar{x}$ indicates when a sampling site could not be reached by boat to be sampled, but was likely to still contain fish.

			2002				2003				2004			
	Region	Rep	Su	Au	W	Sp	Su	Au	W	Sp	Su	Au	W	Sp
Stokes	Basin	1	*	*	*	*	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*	*	*	*	*
		3	*	*	*	*	*	*	*	*	*	*	*	*
		4	*	*	*	*	*	*	*	*	*	*	*	*
		5	*	*	$\bar{x}$	$\bar{x}$	0	0	0	*	*	0	$\bar{x}$	*
	River	1	*	*	*	*	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*	*	*	*	*
		3	*	*	*	*	*	*	*	*	*	*	*	*
Culham	EC	1	*	*	*	*	*	*	*	*	*	*	*	*
	Basin	1	*	*	0	0	0	0	0	0	0	0	0	0
		2	*	0	0	0	0	0	0	0	0	0	0	0
		3	*	*	0	0	0	0	0	0	0	0	0	0
		4	*	0	0	0	0	0	0	0	0	0	0	0
		5	*	0	0	0	0	0	0	0	0	0	0	0
	River	1	*	*	*	*	*	*	*	*	*	*	0	*
		2	*	*	*	*	*	*	*	*	*	*	0	*
		3	*	*	*	*	*	*	*	*	*	0	0	0
Hamersley	Basin	1	*	*	*	*	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*	*	*	*	*
		3	*	*	*	*	*	*	*	*	*	*	*	*
		4	*	*	$\bar{x}$	$\bar{x}$	*	*	*	*	*	*	0	0
		5	*	*	*	*	0	0	0	0	0	0	0	0
	River	1	*	*	*	*								
		2	*	*	*	*								

The YSI meter only records salinities up to 80. Thus, when salinities were >80, the conductivity, which is measured by this meter, was recorded and converted to a salinity value using the Practical Salinity Scale 1978 (Perkin and Lewis, 1980). However, as the accuracy of the conductivity measurements recorded by the YSI metre declines as salinity becomes progressively greater than 80, the salinity values derived from the above conversion process were adjusted using a calibration equation derived from a series of salt dilutions.

Similarly, dissolved oxygen concentrations (mg L^{-1}) could not be measured when salinities exceeded 80, and therefore, the percentage saturation of dissolved oxygen was recorded at these times. Percentage saturation values were converted to oxygen concentrations using the equation of Weiss (1970).

2.3.2 *Additional environmental data*

Monthly precipitation data were obtained from the Australian Commonwealth Bureau of Meteorology for stations at Young River (009652), Lort River Station (009816) and Lort River (012223) in the catchment of Stokes Inlet, Ravensthorpe (010633) in the catchment of Culham Inlet and Fitzgerald (010902) station in the catchment of Hamersley Inlet.

Geographical Information System (GIS) data (including remnant vegetation data) derived from Landsat images (1995) and corrected for gross errors with aerial photography comparisons (1996-1999) for the catchments of Stokes, Culham and Hamersley inlets, were supplied by the Department of Environment, Western Australia. These data were analysed using ARCINFO (ESRI 2000), and the area and percentage of cleared land in the catchment for each estuary determined.

3.0 FISH FAUNAS OF STOKES, CULHAM AND HAMERSLEY INLETS

3.1 INTRODUCTION

Estuaries perform an extremely important function for numerous fish species. Thus, some fish species live in these water bodies for part or all of their life cycle, while others use them as a migratory route between their spawning and main feeding areas. A thorough understanding of the different roles played by estuaries for fish species is enhanced considerably by the development of our knowledge of the ecology and behaviour of fish species in this type of environment in an historical context. Most of the early work on allocating fish species to various life cycle categories or guilds, according to how they use estuaries, was carried out in temperate regions of the northern hemisphere. These estuaries are macrotidal, *i.e.* have large tidal water movements, and consequently differ markedly from those in temperate regions of south-western Australia, in which they are microtidal and therefore experience far less tidal influence. Furthermore, as pointed out earlier (Chapter 1), only some estuaries in south-western Australia remain permanently open, as is typically the case in temperate regions of the northern hemisphere. As also pointed out earlier (Chapter 1), the other estuaries in south-western Australia are closed by a sand bar at their mouths, either intermittently, seasonally, normally or even permanently. Thus, comparisons between the characteristics of fish faunas of permanently open but microtidal estuaries of south-western Australia with those of macrotidal estuaries in temperate regions of the northern hemisphere and between the permanently open and various forms of “closed” estuaries in south-western Australia, provide invaluable insights which increase our knowledge of the factors influencing the characteristics of their fish faunas. They enable us, for example, to gain a greater understanding of the types of selection pressures that operate in these estuaries and which result in differences in the compositions of their fish faunas.

The diverse ways in which fish use estuaries were first categorized by Cronin & Mansueti (1971), based largely on their studies of the fish fauna and fisheries of Chesapeake Bay on the eastern seaboard of the United States. Those authors emphasized, in particular, the crucial role played by estuaries as a nursery area for numerous marine fish species, which they therefore referred to as estuarine-dependent. This theme was developed during the next two decades by a number of workers elsewhere in the United States and Europe (*e.g.* Haedrich, 1983; Dando, 1984; Kennish, 1990) and in eastern Australia (Pollard, 1976). As some of those marine species were of considerable commercial importance, fisheries and environmental managers recognized the need to protect estuarine environments in order to help conserve the stocks of those species.

Irrespective of whether an estuary is located in temperate regions of the northern or southern hemisphere, the ways in which the life cycles of those species can be categorized is described as follows (from Potter & Hyndes, 1999). ***Marine estuarine-opportunists.*** Marine species that enter estuaries in large numbers and typically as juveniles, *e.g.* Sea and Yellow Eye Mullet (*Mugil cephalus* and *Aldrichetta forsteri)*, Tailor (*Pomatomus saltatrix*), King George Whiting (*Sillaginodes punctata*), Banded Toadfish (*Torquigener pleurogramma*). ***Marine stragglers.*** Marine species that are found in estuaries, and usually in their lower reaches and in low numbers, *e.g.* Old Wife (*Enoplus armata*). ***Estuarine species.*** Species that complete their life cycles in estuaries and are generally found only in marine waters when they have been flushed out of estuaries during periods of heavy discharge, *e.g.* the Black Bream (*Acanthopagrus butcheri*) and certain species of atherinid and goby. ***Estuarine & marine species.*** These species complete their life cycles within estuaries, but are represented by other genetically distinct populations that live in coastal marine waters, *e.g.* Cobbler (*Cnidoglanis macrocephalus*) and the southern blue-spotted flathead (*Platycephalus speculator*). ***Anadromous species.*** Species that feed mainly in marine waters, but migrate through the estuary and into estuaries for spawning. The Pouched Lamprey *Geotria australis* is the only anadromous species in south-western Australia. A good example of this guild elsewhere is the Atlantic Salmon *Salar salar*. ***Semi-anadromous species.*** Species that feed mainly in marine waters but migrate into the upper reaches of estuaries to spawn. The Perth Herring *Nematalosa vlaminghi* is the sole representative of this guild in south-western Australia. ***Catadromous species.*** Species that feed in fresh water and migrate to sea to spawn. Although this guild is not represented in south-western Australia, it is represented by the eels *Anguilla australis* and *A. reinhardtii* in eastern Australia. ***Freshwater***

species. Species that are normally found in rivers and lakes but are occasionally present in the upper reaches of estuaries, *e.g.* the Mosquito Fish *Gambusia holbrooki*.

The estuaries used to provide data aimed at elucidating and categorizing the roles played by estuaries in the life cycles of fish species in the northern hemisphere have typically been located in temperate regions where the tides are very large. For example, the tidal height in the Severn Estuary, in which the fish fauna has been studied in great detail (see *e.g.* Claridge *et al*., 1986; Potter *et al*., 1986, 1997, 2001), is over 12 meters. This contrasts markedly with the situation in estuaries in south-western Australia, such as the Swan River Estuary where, even near its mouth, the tidal height is typically less than 1 m (Brearley, 2005). These differences in estuary type will inevitably influence the types of species found in those estuaries. For example, marine species will only be able to enter normally-closed estuaries on those rare occasions when the estuary mouth becomes open.

Bimonthly seine netting and gill netting over nearly two years in the normally-closed Wellstead Estuary, which is located to the west of the Stokes, Culham and Hamersley inlets, yielded only 13 species (Young & Potter, 2002). The nearshore, shallow waters of this normally-closed estuary was dominated by two species of both atherinids and gobies and the Black Bream *Acanthopagrus butcheri*, which all complete their life cycles in estuaries and collectively accounted for 96.6% of the fish caught in those waters. However, substantial numbers of marine estuarine opportunist species, and particularly of the Sea Mullet (*Mugil cephalus*), Yellow Eye Mullet (*Aldrichetta forsteri*) and Tarwhine (*Rhabdosargus sarba*), were caught in offshore deeper waters. The individuals of these marine species, which had substantial mean lengths of 359, 301 and 239 mm, presumably entered the estuary in a period when the bar at the estuary mouth was known to be breached prior to the commencement of the study. In contrast to the situation in nearshore, shallow waters, the marine species in offshore, deeper waters made a very considerable contribution (57.7%) to the catches taken in those waters. However, the estuarine species *Acanthopagrus butcheri* was by far the most abundant individual species, contributing over 41% to the number of fish collected in offshore, deeper waters.

During the study of Wellstead Estuary, the mean salinities in this system rose markedly and, in the basin, increased at one time to over 110 (Young & Potter, 2002). Regular sampling provided evidence that these high salinities resulted in the death of all of the *Leptatherina wallacei* and *Amoya bifrenatus* in the estuary and led to other species moving from the basin into the upper reaches of the tributary river where salinities were not as high. The atherinid *Atherinosoma elongata* was the only fish species caught at the sampling site where the maximum salinity of 122 was recorded.

The number of species recorded in Wellstead Estuary (13) was less than in the seasonally-open Wilson Inlet (20) and permanently-open Nornalup-Walpole Estuary (14) further to the west (Potter *et al*., 1993; Potter & Hyndes, 1994). It was also far less than those recorded in the permanently-open Blackwood River Estuary (42) on the south-western corner of Australia and in the permanently-open Leschenault (42), Peel-Harvey (43) and Swan River estuaries (71) which are located progressively further north on the lower west coast of Australia (Potter & Hyndes, 1999). The species diversity of the fish fauna, in at least the nearshore waters of these estuaries, thus showed a pronounced trend to decline southwards and eastwards along the south-western Australian coast.

The overall aim of this section of the study was to obtain sound quantitative data on the environmental variables, number and abundance of fish species and the compositions of the fish faunas at sites located throughout the Stokes, Hamersley and Culham inlets. An analysis of the data would then allow us to test the following hypotheses regarding these three normally-closed estuaries. 1) These estuaries will be highly depauperate and will typically only contain marine species if the bar at their mouths had been breached within the few years prior to the study or during the study. 2) As the three estuaries apparently vary in the extents to which they become markedly hypersaline, the number and abundance and of the species composition will vary among those estuaries, with the most severely-impacted estuary having the lowest species diversity and density of fish. 3) The pools that are left in the upstream reaches of tributary rivers during dry periods, when salinities rise markedly further down the river and in the basin, will act as refugia for species at such times.

3.2 MATERIALS AND METHODS

3.2.1 *Statistical analyses*

The number of species and density of fishes recorded at each replicate site in nearshore, shallow waters of the basin and main tributary of each of the Stokes, Culham and Hamersley inlets in each season of 2002, 2003 and 2004 were subjected to three-way analysis of variance (ANOVA). These analyses were used to determine whether the number of species and density of fish in each estuary were influenced significantly by region of estuary, year and season, and whether there were significant differences among comparable regions of the three estuaries. Each of these independent variables was considered a fixed factor. The same procedures were applied to the number of species and catch rates of fish in offshore, deeper waters of these estuaries. Note that the data for those regions in which less than three well separated replicate samples could be obtained were not included in these analyses and either a zero or mean value were assigned on those occasions when a replicate could not be obtained for a region in a given season (see Tables 2.1, 2.2 and General Materials and Methods for justification).

Prior to subjecting the number of species, density and catch rate of fish to ANOVA, the data for the first were square root transformed whilst the latter two were $\log_{10}(n+1)$ transformed. These transformations were shown to be appropriate from the relationship between the $\log_{10}$ of the standard deviation (SD) and the $\log_{10}$ of the mean of the replicates of each region in each season of all three years (see Clarke and Warwick (2001) for rationale and details of this approach). When there were significant main effects, the Student-Newman-Kuel (SNK) test was used to determine which variables within such effects were significantly different at $P= 0.05$. The SNK test was also employed, when there were significant interactions between two variables, to explore where significant differences occurred within each combination of those variables, having first adjusted the significance level ($P= 0.05$) using the Bonferroni correction (Underwood, 2002).

The log(n +1) transformed densities of the fish species in each region of the Stokes, Culham and Hamersley inlets in each season of 2002, 2003 and 2004 were employed to construct a Bray-Curtis similarity matrix using the PRIMER v6 multivariate statistics package (Clarke & Gorley, 2006). Before the similarity matrix was constructed, a dummy species with a value of 0.1 was added to the data matrix to allow comparisons to be made with those samples in which no fish were caught. As with ANOVA, zero or mean values were added for those replicates that could not be obtained (see Tables 2.1, 2.2 and General Materials and Methods).

The similarity matrix was then subjected to non-metric multidimensional scaling (MDS) ordination and one-way and two-way crossed Analysis of Similarity (ANOSIM- Clarke, 1993) to test whether the species compositions differed significantly between regions of estuary, years and seasons within each estuary or between estuaries. The *R*-statistic values determined by ANOSIM for significant comparisons were used to ascertain the degree to which *a priori* groups of samples were dissimilar (Clarke, 1993). *R*-statistic values approaching unity demonstrate that the compositions of the samples in each group are very different, while those close to zero show that they are very similar. Similarity percentages (SIMPER) was used to determine which species contributed most to any significant dissimilarities between groups (Clarke, 1993). Multivariate dispersion (MVDISP) was employed to measure the relative dispersion of the *a priori* groups of samples on the ordination plots (Somerfield & Clarke, 1997).

3.3 RESULTS

3.3.1 *Environmental data*

Stokes Inlet

Mean seasonal salinities in nearshore, shallow waters of the basin of Stokes Inlet were *ca* 29 in summer 2002, at the beginning of the three year study of the fish communities in this and the Culham and Hamersley inlets. They then subsequently rose progressively to *ca* 59 in autumn 2003, but then declined to *ca* 46 in spring, before rising again to reach their maxima of *ca* 64 in autumn 2004 (Fig. 3.1). The mean seasonal salinities in the Young River, the main

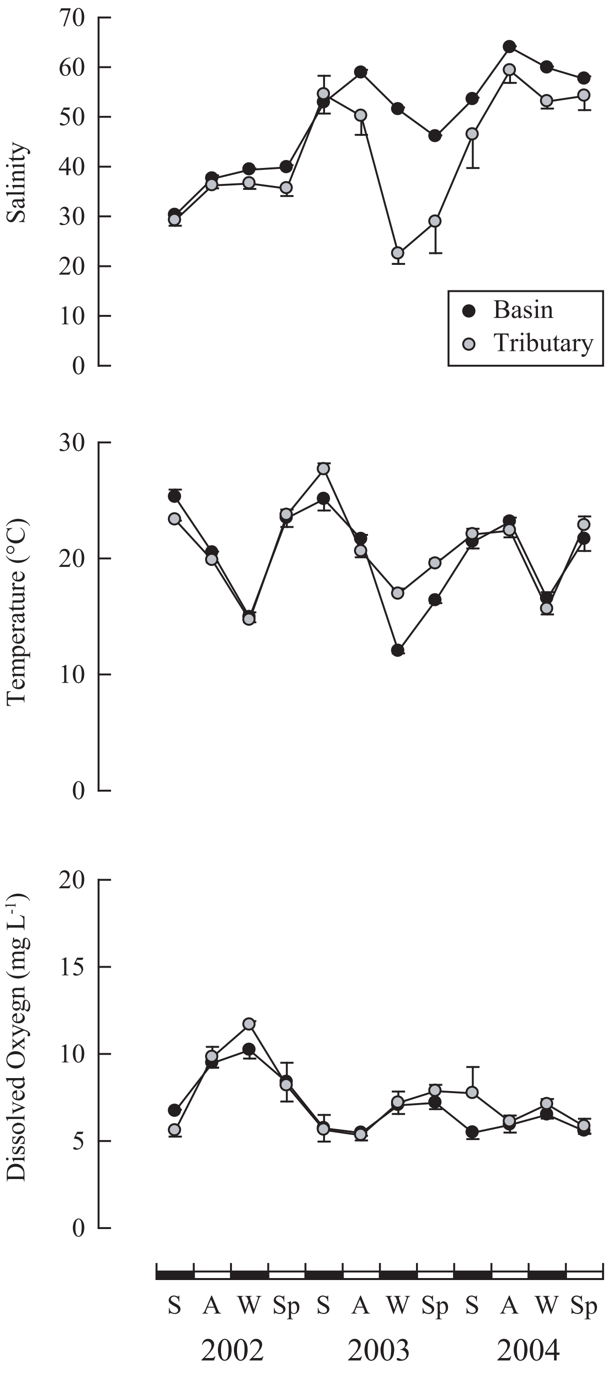

Figure 3.1. Mean seasonal salinities, water temperature and dissolved oxygen concentrations in nearshore, shallow waters of the basin and main tributary (Young River) of the Stokes Inlet in each season between summer 2002 and spring 2004. In this and following figures, standard errors are presented for the mean when three or more values were recorded for a variable in a region. As standard errors frequently overlap a single ± error bar is given to avoid this problem and increase visual clarity.

tributary of the basin of Stokes Inlet, followed similar trends, but were usually less than those in the basin and particularly so in the winter and spring of 2003, when they fell to 22.5 and 28.9, respectively (Fig. 3.1).

Mean seasonal water temperatures in both the basin and tributary reached their maxima during summer and declined to their minima in winter (Fig. 3.1). The greatest mean seasonal temperature of *ca* 28°C was recorded in the Young River in summer 2003, while the lowest minimum seasonal temperature of 16.9°C was recorded in the basin in winter 2003.

Mean seasonal values for dissolved oxygen concentrations in both the basin and tributary of Stokes Inlet always exceeded 5 mg L^{-1} and, during the winter of 2002, rose to as high as 10.2 mg L^{-1} in the basin and *ca* 11.7 mg L^{-1} in the river (Fig. 3.1).

In each season, the mean salinity, temperature and dissolved oxygen concentration at the surface and bottom of the water column in offshore, deeper waters of the basin of Stokes Inlet were very similar and comparable with those in nearshore waters of this region (*cf* Figs 3.1, 3.2). Furthermore, the trends exhibited by the mean seasonal values for salinity, temperature and dissolved oxygen concentration at the surface of the water column of the Young River were similar to those in nearshore, shallow waters of this tributary (*cf* Figs 3.1, 3.2). However, marked haloclines and dissolved oxygen stratifications were formed during the winter and spring of 2003. Thus, for example, the mean salinities at the surface and bottom of the water column in winter 2003 were 19.8 and 49.8, respectively, and the mean dissolved oxygen concentrations in spring 2003 were 6.1 and 4.2 mg L^{-1}, respectively (Fig. 3.2). There was no conspicuous tendency for a thermocline to form in the river.

Culham Inlet

Mean seasonal salinities in nearshore, shallow waters of the basin of Culham Inlet rose progressively from 52 in the summer of 2002 to 175 in the following summer, but then declined in the ensuing two months to 108 in winter 2003 and then rose sharply to 293 in spring 2004 (Fig. 3.3). In each season, the mean seasonal salinity was typically less in the Phillips River than

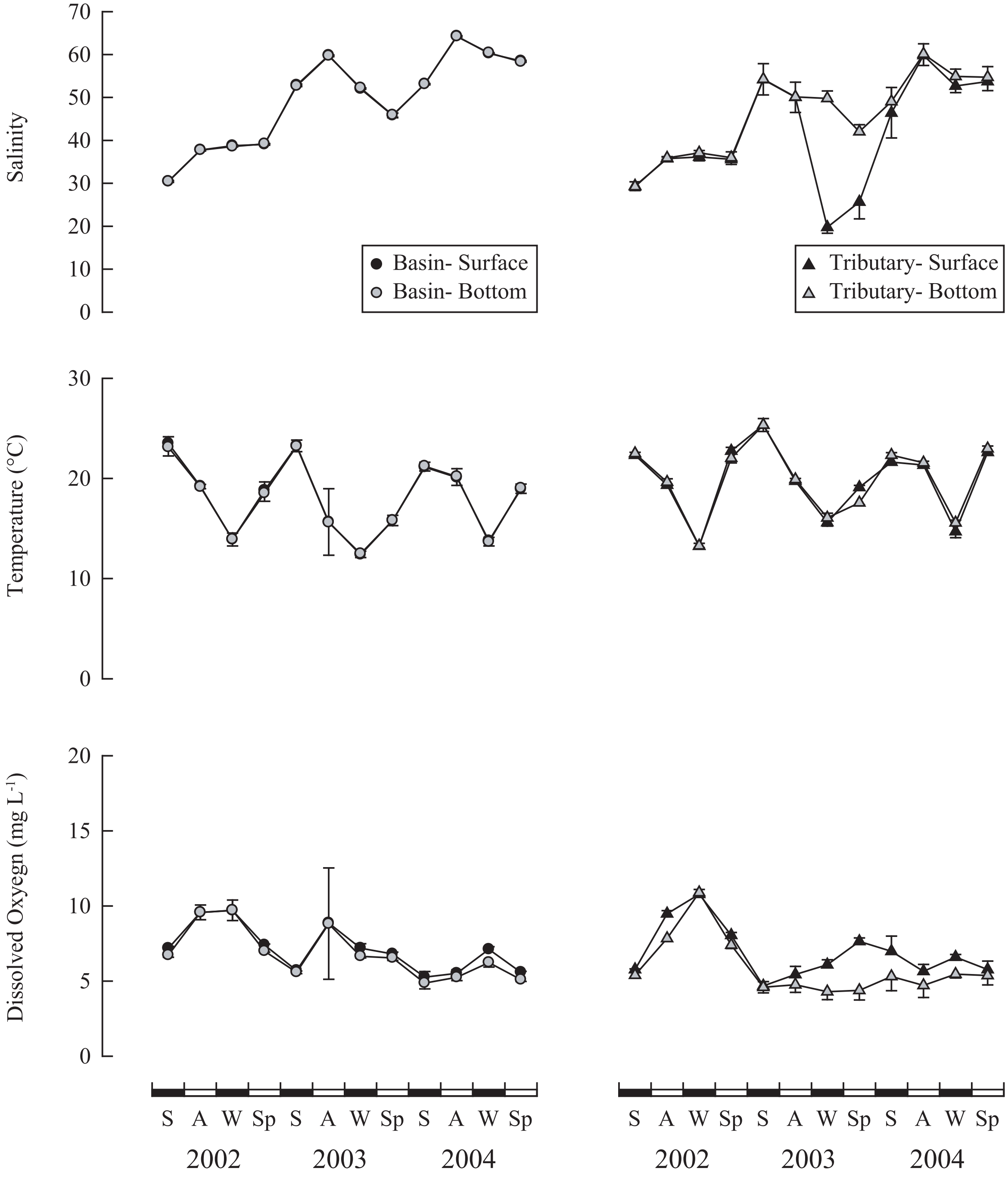

Figure 3.2. Mean seasonal salinities, water temperature and dissolved oxygen concentrations at the surface and bottom of the water column of offshore, deeper waters of the basin and main tributary (Young River) of the Stokes Inlet in each season between summer 2002 and spring 2004.

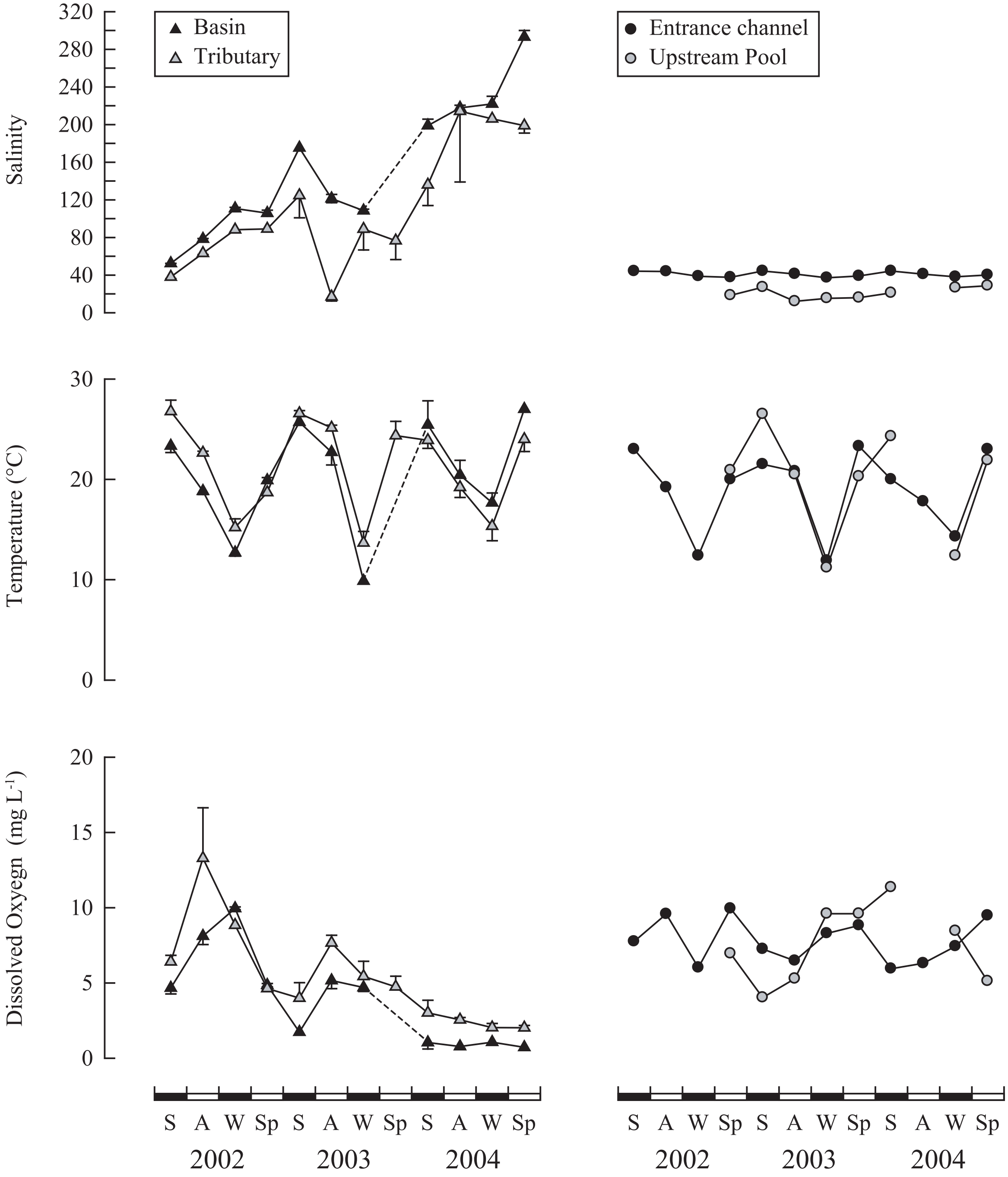

Figure 3.3. Mean seasonal salinities, water temperature and dissolved oxygen concentrations in nearshore, shallow waters of the basin, main tributary (Phillips River), entrance channel and upstream pool of Culham Inlet in each season between summer 2002 and spring 2004.

in the basin into which it discharges and particularly so in autumn 2003 and spring 2004, when salinities in the river and basin were 17 *vs* 121 and 199 *vs* 293, respectively.

Mean seasonal water temperatures in both the basin and tributary of Culham Inlet followed the same seasonal trends as those in Stokes Inlet, with the maximum mean seasonal temperature of 27°C being recorded in the basin in spring 2004 and the minimum mean seasonal temperature of 9.9°C being recorded in the basin in winter 2003 (Fig. 3.3).

Although mean seasonal dissolved oxygen concentrations in the basin and tributary of Culham Inlet were highly variable, they followed similar seasonal trends and, in any given season, were generally greater in the river than in the basin (Fig. 3.3). Mean dissolved oxygen concentrations of less than 2.5 mg L^{-1} were recorded in the basin in summer 2003 and in all seasons in 2004 and also in the river in the last three of those seasons (Fig. 3.3).

Mean seasonal salinities in the lagoonal-like and closed entrance channel of Culham Inlet ranged from only 36 to 44, while those in the upstream pool ranged from 12 to 29 (Fig. 3.3). The temperature regimes exhibited similar seasonal trends to those recorded in nearshore waters of the basin and tributary of Culham Inlet (Fig. 3.3). Dissolved oxygen concentrations always exceeded 5.9 mg L^{-1} in the entrance channel and 4 mg L^{-1} in the upstream pool and sometimes exceeded *ca* 9 mg L^{-1} in both regions (Fig. 3.3).

Mean seasonal salinities, water temperatures and dissolved oxygen concentrations in offshore, deeper waters of the Phillips River and entrance channel followed similar trends to those found in nearshore waters (*cf* Figs 3.3, 3.4). However, in autumn 2004, the water column of the tributary became stratified, with mean seasonal salinities at the surface being far less than at the bottom of the water column, *i.e.* 19 *vs* 78 (Fig. 3.4). There was sufficient water to employ gill nets in offshore waters of the basin of Culham Inlet only in the first two seasons of 2002, during which mean seasonal salinities, water temperatures and dissolved oxygen concentrations followed similar trends to those of nearshore, shallow waters of that region (see Fig. 3.3).

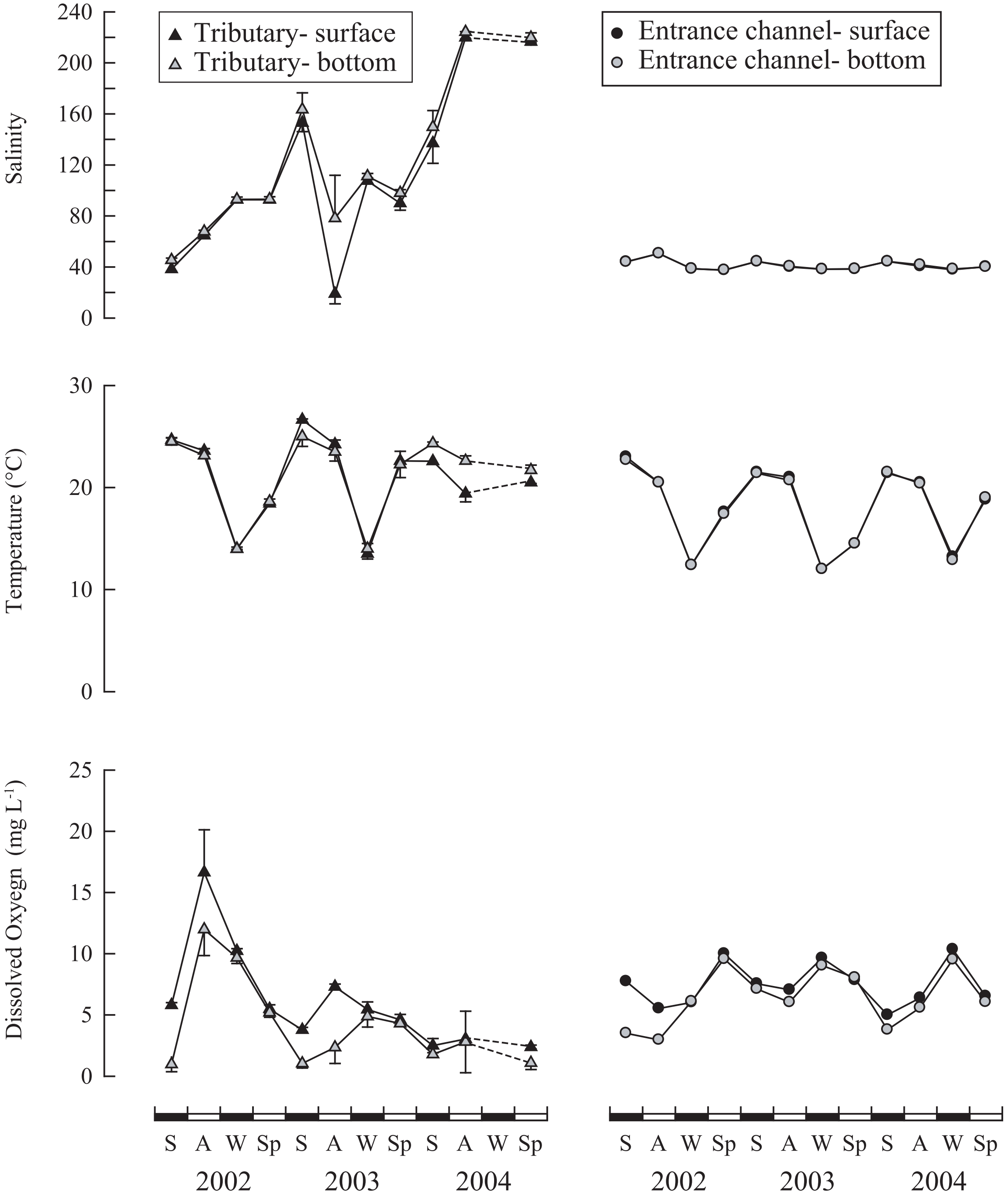

Figure 3.4. Mean seasonal salinities, water temperature and dissolved oxygen concentrations at the surface and bottom of the water column of offshore, deeper waters of the main tributary (Phillips River) and entrance channel of the Culham Inlet in each season between summer 2002 and spring 2004.

Hamersley Inlet

In the basin of Hamersley Inlet, mean seasonal salinities rose in an essentially progressive manner from 35 in the summer of 2002 to 143 in the spring of 2004 (Fig. 3.5). Mean seasonal salinities, for those seasons in which this variable was recorded in the upstream pool of the tributary of Hamersley Inlet, ranged from 16 to 24. Note that a progressive decrease in the volume of water in the basin meant that, by summer 2003, it had become impossible to gain access to the lower reaches of the river by boat and that, because of the presence of dense vegetation and the steep cliff-like banks of the river, it was never possible alternatively to enter those parts of the river from adjoining land.

Mean seasonal water temperatures in the basin ranged from a maximum of 24.9°C in summer 2004 to a minimum of 11.4°C in winter 2003 (Fig. 3.5). Mean seasonal dissolved oxygen concentrations in the basin exceeded 5 mg L^{-1} in each season in 2002, but were less than this in all but one of the subsequent seasons and declined progressively from winter 2003 to spring 2004, at which time they were only *ca* 2.5 mg L^{-1} (Fig. 3.5).

Salinity, temperature and dissolved oxygen at both the surface and bottom of the water column of offshore, deeper waters of both the basin and the river, in those seasons in which this region was sampled, were very similar to those of nearshore, shallow waters of the basin.

Catchment rainfall

The mean total annual rainfall in the catchments of the Stokes and Culham inlets during the fifteen years from 1990 to 2004 *i.e.* 458 and 457 mm, respectively, did not differ significantly ($P > 0.05$) from the mean for the corresponding estuary in the preceding 35 and 88 years for which records were kept, *i.e.* 505 and 421 mm, respectively (Fig. 3.6). Rainfall in the catchment of Hamersley Inlet was not recorded prior to 1990. The total annual rainfall in the catchment of Stokes Inlet has tended to increase, whereas those in the Culham and Hamersley inlets have tended to decline (Fig. 3.6). These trends reflect, in part, the tendency for the rainfall during the wet period of the year being relatively high in the catchment of Stokes Inlet in three of the five years and relatively low in all but one of those years in the catchments of the Culham and

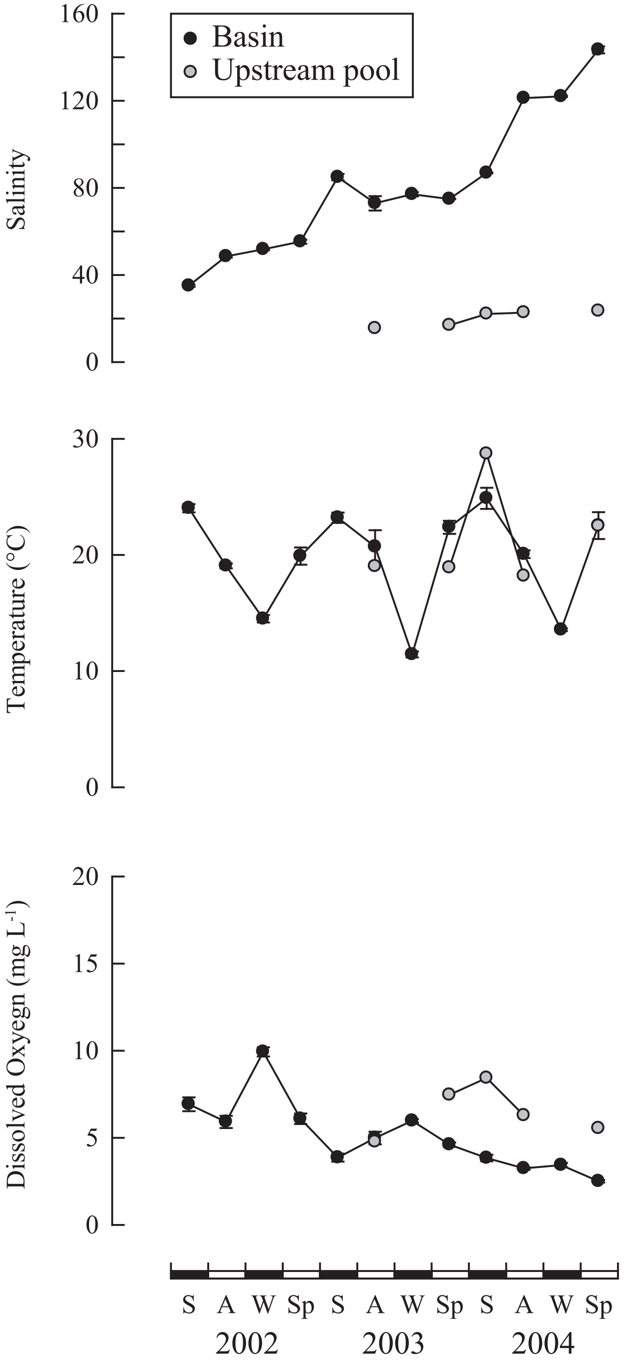

Figure 3.5. Mean seasonal salinities, water temperature and dissolved oxygen concentrations in nearshore, shallow waters of the basin and upstream pool of Hamersley Inlet in each season between summer 2002 and spring 2004.

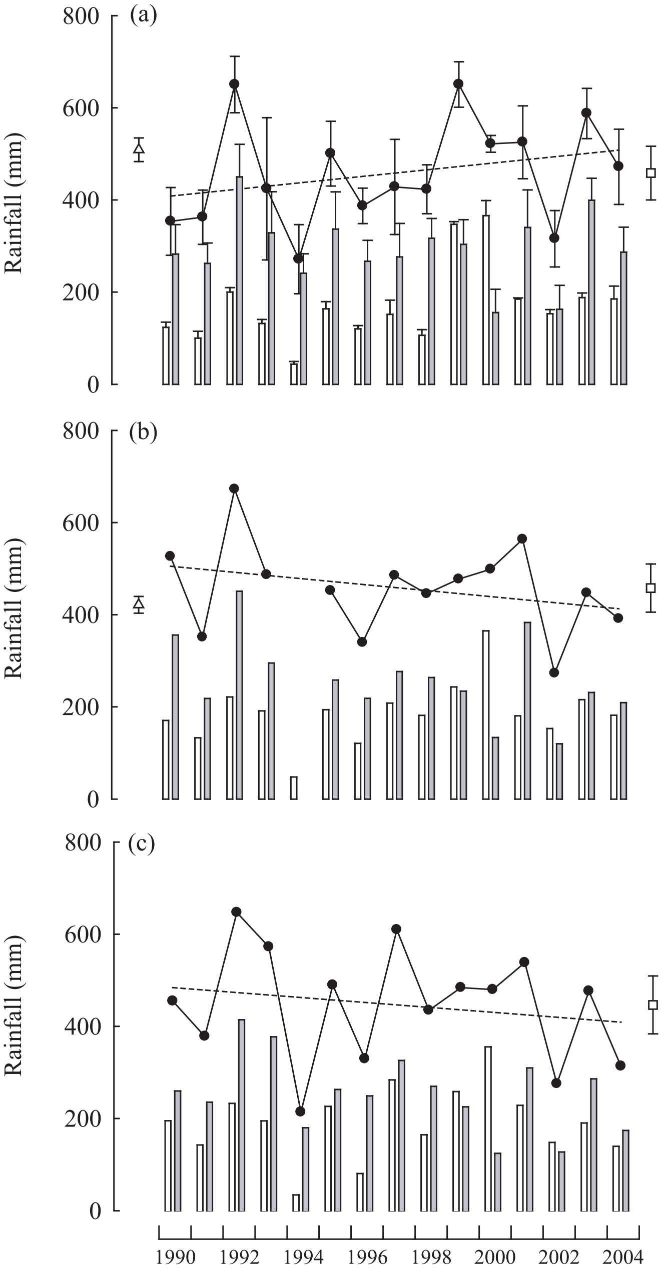

Figure 3.6. Total annual rainfall in the catchments of a) Stoke, b) Culham and c) Hamersley inlets in each of the 15 years between 1990 and 2004 (black circles) and in the dry (white bars- November to April) and wet (grey bars- May to October) periods in those years. Regression lines have been fitted to the total annual rainfall data for each estuary in those 15 years (dashed line). The mean total annual rainfall ± 95% confidence intervals for the above 15 years for the catchments of each estuary (white squares) and for the preceding 35 and 88 years for Stokes and Culham inlets (white triangles), respectively are shown on the figure. Note that comparable historical data were not available for the catchment of Hamersley Inlet.

Hamersley inlets. These differences among the catchments of the three estuaries could have contributed to the fact that salinity in Stokes Inlet did not increase to such high levels as in the Culham and Hamersley inlets.

3.3.2 *Abundances and contributions of fish species to nearshore fish communities*

Stokes Inlet

A total of 60 246 fish, weighing 23 478 g but representing just seven species, was caught using the 21.5 m seine net in nearshore, shallow waters of the basin and major tributary of Stokes Inlet in each season between the summer of 2002 and spring of 2004 (Table 3.1). The atherinid *Atherinosoma elongata*, the gobiid *Pseudogobius olorum* and the sparid *Acanthopagrus butcheri*, each of which completes its life cycle within estuaries, ranked first, second and third, respectively, in terms of abundance, and collectively contributed 99.8% to the total number of individuals caught in nearshore, shallow waters (Table 3.1). *Atherinosoma elongata* was by far the most abundant species, contributing 79.2% to the total catch, with *P. olorum* and *A. butcheri* the only other species to contribute more than 0.1%, *i.e.* 15.7 and 5.0%, respectively. The vast majority of fish caught in the basin of Stokes Inlet were *A. elongata* (97.8%), whereas this species, with 53.4% and *P. olorum* (36.0%) and *A. butcheri* (10.5%) all made substantial contributions to the catches in nearshore, shallow waters of the Young River (Table 3.1).

The five most abundant species in nearshore, shallow waters of Stokes Inlet, which each complete their life cycle in these waters, contributed 99.9% to the total number of individuals caught. The four individuals of the freshwater species *Galaxias maculatus* were caught in the Young River during a period of freshwater discharge, whereas the single and very small individual of the marine estuarine-opportunist species *Aldrichetta forsteri* was caught in the basin.

Table 3.1. Life cycle guild (LC), rankings by abundance (R), numbers (N), biomass (g), percentage contributions to the total catch (%), mean length (ML) and length range (LR) of fish species caught by seasonal seine netting between summer 2002 and spring 2004 in nearshore, shallow waters of both the basin and major tributary of Stokes Inlet collectively and of each region individually.

		Stokes Inlet						**Region of estuary**							
Species	**LC guild**	**Number of fish**			**Biomass of fish**			**Basin**			**Young River**			**ML**	**LR**
		R	**N**	**%**	**R**	**g**	**%**	**R**	**N**	**%**	**R**	**N**	**%**	**(mm)**	
Atherinosoma elongata	E	1	47 728	79.2	1	17 454.5	74.4	1	34 306	97.8	1	13 422	53.4	35	8-114
Pseudogobius olorum	E	2	9 458	15.7	3	1 030.8	4.4	2	391	1.1	2	9 067	36.0	23	8-55
Acanthopagrus butcheri	E	3	2 986	5.0	2	4 820.1	20.5	3	338	1.0	3	2 648	10.5	40	9-267
Favonigobius lateralis	E&M	4	38	<0.1	4	126.5	0.5	4	38	0.1	-	-	-	68	18-92
Engraulis australis	E&M	5	31	<0.1	5	43.5	0.2	5	17	<0.1	4	14	0.1	64	48-120
Galaxias maculatus	F	6	4	<0.1	6	2.4	<0.1	-	-	-	5	4	<0.1	41	18-57
Aldrichetta forsteri	O	7	1	<0.1	7	0.1	<0.1	6	1	<0.1	-	-	-	-	17
Total number of species			**7**						**6**			**5**			
Total number of fish			**60 246**						**35 091**			**25 155**			
Total biomass of fish (g)						**23 477.7**									

Culham Inlet

In Culham Inlet, seasonal seine netting in the entrance channel, basin and lower reaches of the Phillips River and a large upstream pool above the rock bar of that river yielded *ca* 62 000 fish, with a total weight of almost 20 000 g, but which represented only six species (Table 3.2). Five of these species complete their life cycles within this estuary, while the sixth, *G. maculatus*, is a freshwater species. The atherinid *A. elongata* was by far the most abundant species, contributing 74.5% to the total catch and, together with *P. olorum* and *Leptatherina wallacei*, comprised 96.9% of that catch (Table 3.2).

In terms of relative abundance, *A. elongata* ranked first in the entrance channel, basin and Phillips River, contributing between 65.7 and 99.3% to the catches in those three regions, but it ranked third and contributed only 7.3% to the total catch in the upstream pool (Table 3.2). Although *L. wallacei* was the second most abundant species overall, it was never caught in the entrance channel or basin. However, it ranked second and first in terms of abundance in the Phillips River and upstream pool, where it contributed *ca* 17 and 70% to the catches, respectively. The third most abundant species overall, *P. olorum,* was also far more abundant in those two regions (Table 3.2). *Favonigobius lateralis*, *A. butcheri* and *G. maculatus* were only abundant in the entrance channel, Phillips River and upstream pool, respectively.

Hamersley Inlet

The samples obtained by seasonal seine netting in nearshore, shallow waters of Hamersley Inlet contained a total of *ca* 45 500 fish, weighing *ca* 12 700 g, but this represented only six species (Table 3.3). The total catch was dominated by the atherinid *A. elongata* (94.5%) and the four most abundant species, which were all estuarine, constituted 99.9% of that total catch. Although the sparid *A. butcheri* contributed <0.1% to the total catch, it ranked second in terms of biomass, comprising 17.0% of the total weight of fish caught (Table 3.3). Six individuals of the marine estuarine-opportunist *A. forsteri* and just one of the freshwater species *G. maculatus* were caught in nearshore, shallow waters throughout Hamersley Inlet (Table 3.3).

Table 3.2. Life cycle guild (LC), rankings by abundance (R), numbers (N), biomass (g), percentage contributions to the total catch (%), mean length (ML) and length range (LR) of fish species caught by seasonal seine netting between summer 2002 and spring 2004 in nearshore, shallow waters of the entrance channel, basin, major tributary and upstream pool of Culham Inlet collectively and of each region individually.

		Culham Inlet							
Species	**LC**	**Number of fish**			**Biomass of fish**			**ML**	**LR**
	guild	**R**	**N**	**%**	**R**	**g**	**%**	**(mm)**	
Atherinosoma elongata	E	1	46 388	74.5	1	13 909.8	70.7	33	9-90
Leptatherina wallacei	E	2	8 201	13.2	3	1 276.8	6.5	33	9-63
Pseudogobius olorum	E	3	5 702	9.2	5	847.7	4.3	22	1-51
Favonigobius lateralis	E&M	4	1 306	2.1	4	1 214.7	6.2	40	15-88
Acanthopagrus butcheri	E	5	475	0.8	2	2 392.2	12.2	69	32-194
Galaxias maculatus	F	6	203	0.3	6	47.0	0.2	36	24-72
Total number of species			**6**						
Total number of fish			**62 275**						
Total biomass of fish (g)						**19 688.2**			

		Region of estuary											
Species	**LC**	**Entrance channel**			**Basin**			**Phillips River**			**Upstream pool**		
	guild	**R**	**N**	**%**	**R**	**N**	**%**	**R**	**N**	**%**	**R**	**N**	**%**
Atherinosoma elongata	E	1	14 210	91.2	1	12 116	99.3	1	19 737	65.7	3	325	7.3
Leptatherina wallacei	E	-	-	-	-	-	-	2	5 089	16.9	1	3 112	69.8
Pseudogobius olorum	E	3	63	0.4	2	79	0.6	3	4 744	15.8	2	816	18.3
Favonigobius lateralis	E&M	2	1 300	8.3	3	6	<0.1	-	-	-	-	-	-
Acanthopagrus butcheri	E	-	-	-	4	3	<0.1	4	466	1.6	5	6	0.1
Galaxias maculatus	F	-	-	-	-	-	-	5	4	<0.1	4	199	4.5
Total number of species			**3**			**4**			**5**			**5**	
Total number of fish			**15 573**			**12 204**			**30 040**			**4 458**	
Total biomass of fish (g)													

Table 3.3. Life cycle guild (LC), rankings by abundance (R), numbers (N), biomass (g), percentage contributions to the total catch (%), mean length (ML) and length range (LR) of fish species caught by seasonal seine netting between summer 2002 and spring 2004 in nearshore, shallow waters of both the basin and upstream pool of Hamersley Inlet collectively and of each region individually.

		Hamersley Inlet						**Region of estuary**							
Species	**LC**	**Number of fish**			**Biomass of fish**			**Basin**			**Upstream pool**			**ML**	**LR**
	guild	**R**	**N**	**%**	**R**	**g**	**%**	**R**	**N**	**%**	**R**	**N**	**%**	**(mm)**	
Atherinosoma elongata	E	1	43 067	94.5	1	10 076.8	79.2	1	43 067	96.3	-	-	-	33	9-91
Pseudogobius olorum	E	2	1 664	3.7	3	298.3	2.3	2	1 638	3.7	2	26	3.1	23	12-54
Leptatherina wallacei	E	3	804	1.8	4	177.5	1.4	-	-	-	1	804	96.9	31	12-65
Acanthopagrus butcheri	E	4	11	<0.1	2	2 161.8	17.0	3	11	<0.1	-	-	-	223	200-248
Aldrichetta forsteri	O	5	6	<0.1	5	6.0	<0.1	4	6	<0.1	-	-	-	51	38-61
Galaxias maculatus	F	6	1	<0.1	6	0.2	<0.1	5	1	<0.1	-	-	-	-	36
Total number of species			**6**						**5**			**2**			
Total number of fish			**45 553**						**44 723**			**830**			
Total biomass of fish (g)						**12 720.6**									

Atherinosoma elo*ngata* dominated the catches taken in the basin (96.3%), whereas another atherinid *L. wallacei* dominated those obtained from the upstream pool (96.9%) (Table 3.3). The upstream pool only otherwise contained *P. olorum*.

3.3.3 *Abundances and contributions of fish species to offshore fish communities*

Stokes Inlet

The 2 354 fish, that were caught in offshore, deeper waters of the basin and major tributary of Stokes Inlet by gill netting in the same seasons as seine netting was undertaken in the nearshore, shallow waters of this estuary, belonged to eight species and weighed *ca* 398 725 g (Table 3.4). The samples were dominated to such a great extent by *A. butcheri* that this species contributed over 97% to the total catch of fish.

The eight species caught in offshore, deeper waters comprised four that complete their life cycles in estuaries and four marine estuarine-opportunists, with the contribution made by the number of individuals belonging to the former category far outweighing that of the latter category, *i.e.* 98.6 *vs* 1.4% (Table 3.4). All individuals of the marine estuarine-opportunist species were caught in the basin of Stokes Inlet. The minimum length recorded for a marine estuarine-opportunist, *i.e.* 208 mm for *Rhabdosargus sarba*, far exceed that of the minimum lengths of those of the estuarine spawning *A. butcheri* and *Engraulis australis*, *i.e.* 58 and 81 mm, respectively.

Culham Inlet

The total catch of 504 fish obtained by gill netting in Culham Inlet was dominated by *A. butcheri*, with this species contributing nearly 95% to that total catch (Table 3.5). This species dominated the catch in the entrance channel of this system, where it contributed *ca* 78% to the number of individuals collected, and was the only species that was also caught in the basin of Culham Inlet and in the Phillips River (Table 3.5). The small numbers of the marine estuarine-opportunists *Argyrosomus japonicus* and *Pseudocarnax dentex*, the estuarine-spawning

Table 3.4. Life cycle guild (LC), rankings by abundance (R), numbers (N), biomass (g), percentage contributions to the total catch (%), mean length (ML) and length range (LR) of fish species caught by seasonal gill netting between summer 2002 and spring 2004 in offshore, deeper waters of both the basin and major tributary of Stokes Inlet collectively and of each region individually.

		Stokes Inlet						Region of estuary							
Species	**LC**	**Number of fish**			**Biomass of fish**			**Basin**			**Young River**			**ML**	**LR**
	guild	**R**	**N**	**%**	**R**	**g**	**%**	**R**	**N**	**%**	**R**	**N**	**%**	**(mm)**	
Acanthopagrus butcheri	E	1	2 303	97.8	1	383 921.7	96.3	1	1 181	96.2	1	1 122	99.6	206	58-333
Aldrichetta forsteri	O	2	17	0.7	2	7492.0	1.9	2	17	1.4	-	-	-	352	311-399
Engraulis australis	E&M	3	14	0.6	9	88.2	<0.1	3	10	0.8	2	4	0.4	100	81-113
Mugil cephalus	O	4	7	0.3	3	3030.3	0.8	4	7	0.6	-	-	-	349	313-381
Arripis georgiana	O	5	6	0.3	4	1519.8	0.3	5	6	0.5	-	-	-	269	249-293
Cnidoglanis macrocephalus	E&M	6	3	0.1	6	1121.4	0.3	6	2	0.2	3	1	<0.1	460	402-536
Platycephalus speculator	E&M	7	2	0.1	5	1149.9	0.3	6	2	0.2	-	-	-	432	388-475
Rhabdosargus sarba	O	7	2	0.1	8	401.1	0.1	6	2	0.2	-	-	-	227	208-245
Total number of species			**8**						**8**			**3**			
Total number of fish			**2 354**						**1 227**			**1 127**			
Total biomass of fish (g)						**398 724.4**									

Table 3.5. Life cycle guild (LC), rankings by abundance (R), numbers (N), biomass (g), percentage contributions to the total catch (%), mean length (ML) and length range (LR) of fish species caught by seasonal gill netting between summer 2002 and spring 2004 in offshore, deeper waters of the entrance channel, basin and major tributary of Culham Inlet collectively and of each region individually.

		Culham Inlet						Region of estuary										
Species	**LC**	**Number of fish**			**Biomass of fish**			**Entrance channel**			**Basin**			**Phillips River**			**ML**	**LR**
	guild	**R**	**N**	**%**	**R**	**g**	**%**	**R**	**N**	**%**	**R**	**N**	**%**	**R**	**N**	**%**	**(mm)**	
Acanthopagrus butcheri	E	1	477	94.6	1	62 237.9	54.8	1	95	77.8	1	8	100	1	374	100	181	71-517
Argyrosomus japonicus	O	2	15	3.0	2	45 017.8	39.7	2	15	12.3	-	-	-	-	-	-	642	566-727
Pseudocaranx dentex	O	3	5	1.0	3	3 075.0	2.7	3	5	4.1	-	-	-	-	-	-	342	305-417
Platycephalus speculator	E&M	4	4	0.8	4	2 817.2	2.5	4	4	3.3	-	-	-	-	-	-	467	431-498
Enoplosus armatus	S	5	3	0.6	5	337.3	0.3	5	3	2.5	-	-	-	-	-	-	194	174-204
Total number of species			**5**						**5**			**1**			**1**			
Total number of fish			**504**						**122**			**8**			**374**			
Total biomass of fish (g)						**113 485.2**												

Platycephalus speculator and the marine straggler *Enoplus armartus* caught by gill netting were all obtained from the small and normally-closed entrance channel. The minimum lengths of the above five species, which ranged from 174 to 566 mm, far exceed the minimum length of 71 mm recorded for *A. butcheri* (Table 3.5).

Hamersley Inlet

The 737 fish caught by gill netting in offshore, deeper waters throughout Hamersley Inlet, which represented six species, was dominated by individuals of the estuarine *A. butcheri* (87.4%). The other five species were all marine estuarine-opportunists, with minimum lengths ranging from 166 to 286 mm (Table 3.6). Only one of the individuals of this life cycle guild, a *Mugil cephalus* of 398 mm, was caught in the Hamersley River rather than the basin (Table 3.6).

3.3.4 *Numbers of species and densities of fish in nearshore, shallow waters*

Stokes Inlet

ANOVA demonstrated that, in nearshore, shallow waters of Stokes Inlet, the number of fish species was significantly influenced by year, season and region (basin and Young River) and that the density of fish was also significantly influenced by the first two of those variables (Table 3.7). There was also a significant interaction between year x season for density of fish. In the case of number of species, the mean squares were far higher for region than for year and season, while for density they were similar for year and season (Table 3.7).

The mean number of species was significantly greater in 2002 than in both 2003 and 2004 (Fig. 3.7a), was significantly greater in each of summer, autumn and spring than in winter (Fig. 3.7b) and was greater in the main tributary than in the basin of Stokes Inlet (Fig. 3.7c).

The density of fish in nearshore, shallow waters of Stokes Inlet was significantly greater in summer and autumn than in winter in both 2002 and 2003 and spring *vs* winter in 2003, but did not differ among seasons in 2004 (Fig. 3.7d). Furthermore, while densities in summer, autumn

Table 3.6. Life cycle guild (LC), rankings by abundance (R), numbers (N), biomass (g), percentage contributions to the total catch (%), mean length (ML) and length range (LR) of fish species caught by seasonal gill netting between summer 2002 and spring 2004 in offshore, deeper waters of both the basin of Hamersley Inlet and the Hamersley River collectively and of each region individually.

		Hamersley Inlet						**Region of estuary**							
Species	**LC**	**Number of fish**			**Biomass of fish**			**Basin**			**Hamersley River**			**ML**	**LR**
	guild	**R**	**N**	**%**	**R**	**g**	**%**	**R**	**N**	**%**	**R**	**N**	**%**	**(mm)**	
Acanthopagrus butcheri	E	1	644	87.4	1	116 770.9	72.1	1	475	83.8	1	169	99.4	211	127-292
Mugil cephalus	O	2	58	7.9	2	36 080.5	22.3	2	57	10.0	2	1	0.6	381	241-445
Arripis truttacea	O	3	15	2.0	3	5 514.1	3.4	3	15	2.6	-	-	-	312	263-360
Arripis georgiana	O	4	13	1.8	4	2 130.9	1.3	4	13	2.3	-	-	-	225	179-297
Aldrichetta forsteri	O	5	5	0.7	5	1 252.0	0.8	5	5	0.9	-	-	-	293	286-313
Pseudocaranx dentex	O	6	2	0.3	6	133.5	0.1	6	2	0.4	-	-	-	169	166-171
Total number of species			**6**						**6**			**2**			
Total number of fish			**737**						**567**			**170**			
Total biomass of fish (g)						**161 881.9**									

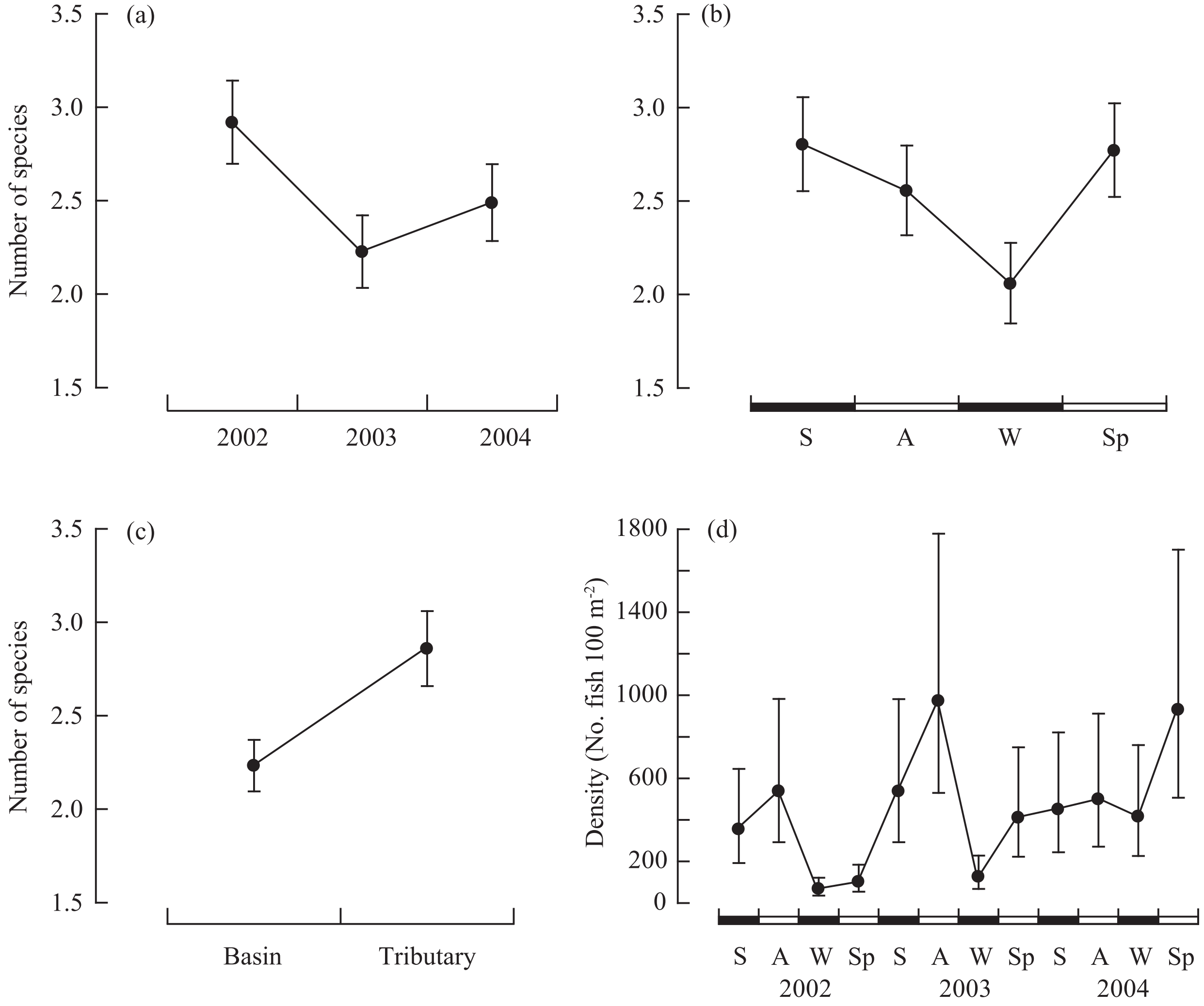

Figure 3.7. Mean number of species ± 95% CI in nearshore, shallow waters of Stokes Inlet in a) 2002, 2003 and 2004, b) each season and c) the basin and main tributary, and the mean density of fish ± 95% CI in d) each season of the three years.

and winter did not differ significantly between years, those in spring were significantly greater in both 2003 and 2004 than in 2002 (Fig. 3.7d).

Table 3.7. Mean squares and significance levels for three-way ANOVAs of the number of species and density of fish recorded in nearshore, shallow waters of Stokes Inlet between summer 2002 and spring 2004. **$p<0.01$, ***$p<0.001$.

	Main effects			
	Year (Y)	Season (S)	Region (R)	Residual
df	2	3	1	72
Number of species	0.356***	0.276***	0.867***	0.032
Density	1.668***	1.576***	0.000	0.130
	Two- and three-way interactions			
	Y x S	Y x R	S x R	Y x S x R
df	6	2	3	6
Number of species	0.072	0.010	0.030	0.058
Density	0.527**	0.248	0.032	0.197

Culham Inlet

In nearshore, shallow waters of Culham Inlet, the number of species and density of fish were significantly influenced by year and region and the density of fish was also significantly influenced by season (Table 3.8). The mean squares for year were always greater than those for region and season. There were significant year x season and year x region interactions in the case of both number of species and density (Table 3.8).

The mean number of species in summer and autumn was significantly greater in 2002 than in both 2003 and 2004 and was significantly greater in the winter and spring of 2002 than in the corresponding seasons of 2004 (Fig. 3.8a). The number of species was significantly greater in the main tributary than in the basin of Culham Inlet only in 2003 (Fig. 3.8b). However, in both the basin and tributary, the mean number of species was significantly greater in 2002 than in both 2003 and 2004, but was significantly greater in 2003 than 2004 only in the tributary (Fig. 3.8b).

The density of fish in nearshore, shallow waters of Culham Inlet was significantly greater in the summer and autumn than winter and spring of 2002, but did not differ among seasons in

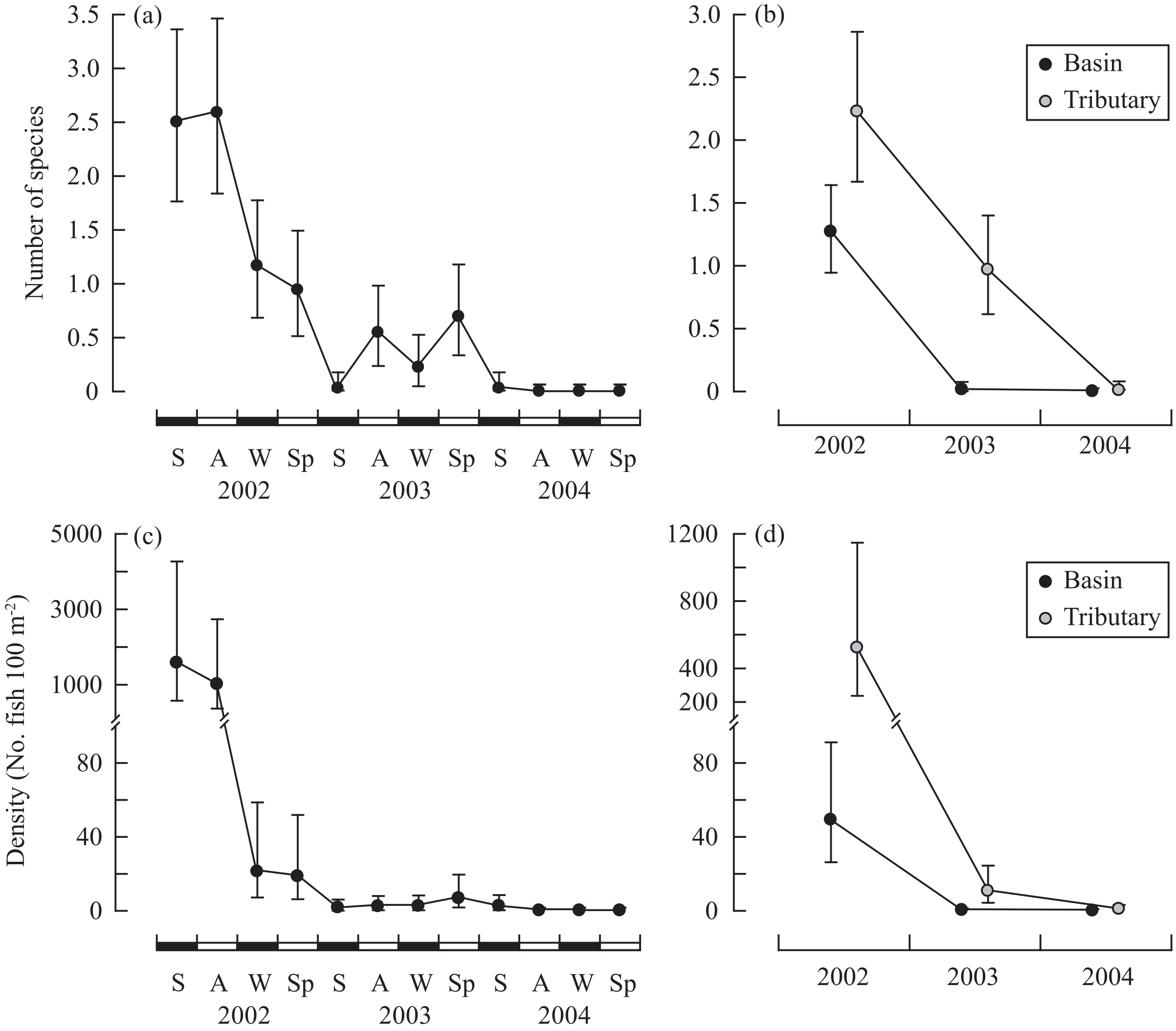

Figure 3.8. Mean number of species ± 95% CI in nearshore, shallow waters of Culham Inlet in a) each season of 2002, 2003 and 2004, and b) in the basin and main tributary in each year and the mean density of fish ± 95% CI in c) each season of the three years and d) the basin and tributary in 2002, 2003 and 2004.

both 2003 and 2004 (Fig. 3.8c). As such, both summer and autumn were significantly greater in 2002 than in both 2003 and 2004, with the winter of 2002 being significantly greater than that season in 2004 (Fig. 3.8c). As with number of species, the density of fish in the main tributary of Culham Inlet was significantly greater than in the basin only in 2003, but was greatest in both of these regions in 2002 than in either 2003 or 2004 (Fig. 3.8d).

Table 3.8. Mean squares and significance levels for three-way ANOVAs of the number of species and density of fish recorded in nearshore, shallow waters of Culham Inlet between summer 2002 and spring 2004. *$p<0.05$, ***$p<0.001$.

	Main effects			
	Year (Y)	Season (S)	Region (R)	Residual
df	2	3	1	72
Number of species	12.204***	0.276	4.299***	0.121
Density	35.627***	2.965***	12.553***	0.353
	Two- and three-way interactions			
	Y x S	Y x R	S x R	Y x S x R
df	6	2	3	6
Number of species	0.638***	1.169***	0.035	0.133
Density	2.956***	1.273*	0.137	0.272

Hamersley Inlet

The number of species in nearshore, shallow waters of the basin of Hamersley Inlet differed significantly among years but not seasons, while the density of fish was influenced significantly by both year and season, with the mean squares being far greater for season (Table 3.9). There were no significant interactions between year and season for either number of species or density of fish.

The mean number of species and density of fish both declined progressively between 2002 and 2004 (Fig 3.9a, b). The mean number of species was significantly greater in 2002 than in both 2003 and 2004 and the density of fish was significantly greater in 2002 than 2004. The mean seasonal densities of fish declined markedly from their maxima of 489 fish 100 m^{-2} in

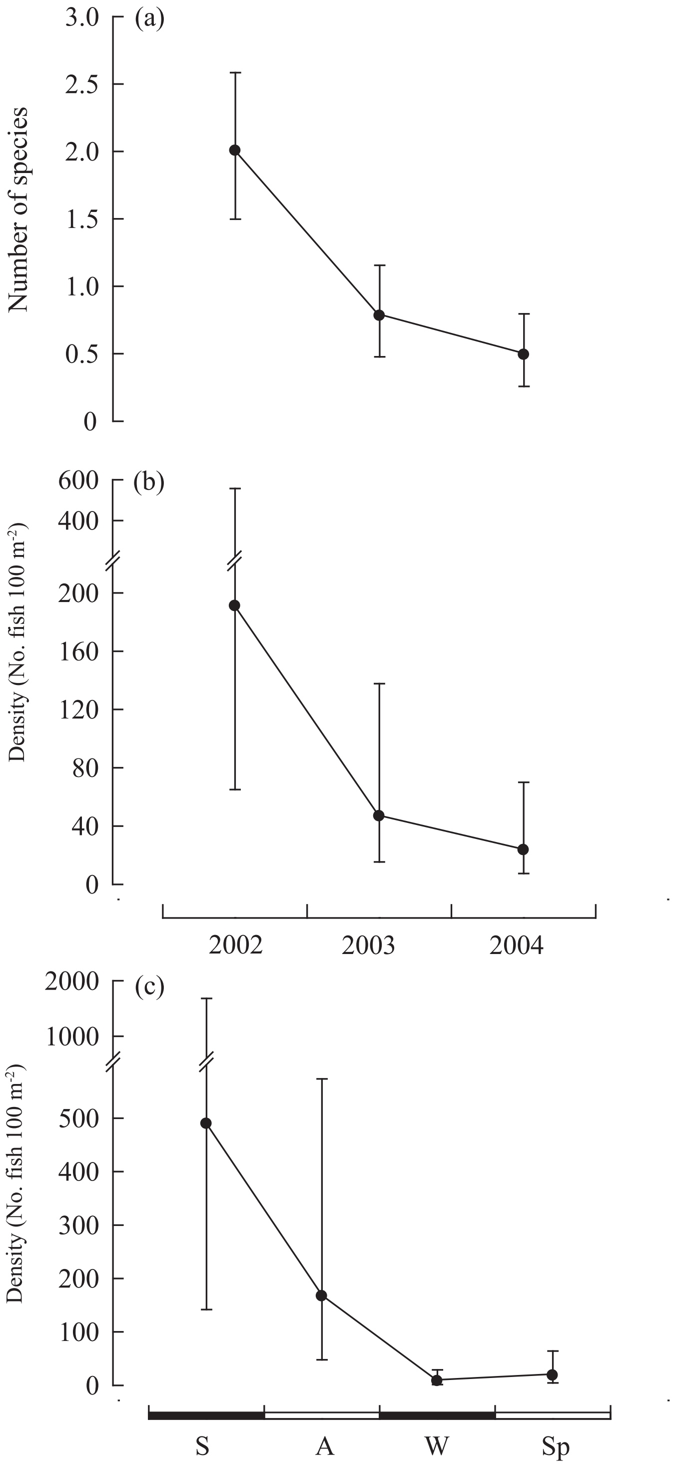

Figure 3.9. Mean number of species ± 95% CI in nearshore, shallow waters of the basin of Hamersley Inlet in a) 2002, 2003 and 2004, and mean density of fish ± 95% CI in b) 2002, 2003 and 2004, and c) summer, autumn, winter and spring.

summer to their minima of 7.7 fish 100 m^{-2} in winter and then underwent a small increase in spring (Fig. 3.9c). The mean densities of fish in summer and autumn were both were significantly greater than in winter and that in summer was significantly greater than in spring.

Table 3.9. Mean squares and significance levels for two-way ANOVAs of the number of species and density of fish recorded in nearshore, shallow waters of the basin of Hamersley Inlet between summer 2002 and spring 2004. *p<0.05, ***p<0.001.

Hamersley basin	**Main effects and interaction**			
	Year (Y)	Season (S)	Y x S	Residual
df	2	3	6	48
Number of species	2.765***	0.198	0.031	0.182
Density	4.173*	9.919***	0.245	1.063

Comparisons between the basins of Stokes, Culham and Hamersley inlets

When the data for nearshore, shallow waters in the basin of the three estuaries were subjected to ANOVA, the number of species and density of fish were found to be influenced significantly by estuary, year and season, with the mean squares for estuary being greatest in the case of both of those biotic variables (Table 3.10). There was a significant interaction between estuary x year with both number of species and density of fish and for estuary x season and estuary x year x season for density of fish (Table 3.10).

In their basins, the mean number of species in 2002 was significantly greater in Stokes Inlet than in Culham Inlet, and in both 2003 and 2004 was significantly greater in Stokes Inlet than in Hamersley Inlet, which, in turn, was significantly greater than in Culham Inlet in each of those years (Fig. 3.10a). Furthermore, while the number of species did not significantly differ between years in Stokes Inlet, that in 2002 was significantly greater than both 2003 and 2004 in both Culham and Hamersley inlets (Fig. 3.10a). Overall, the mean number of species was significantly greater in summer than in winter (Fig. 3.10b). The mean density of fish in each season of 2002, 2003 and 2004 was almost invariably greater in Stokes Inlet than Hamersley Inlet

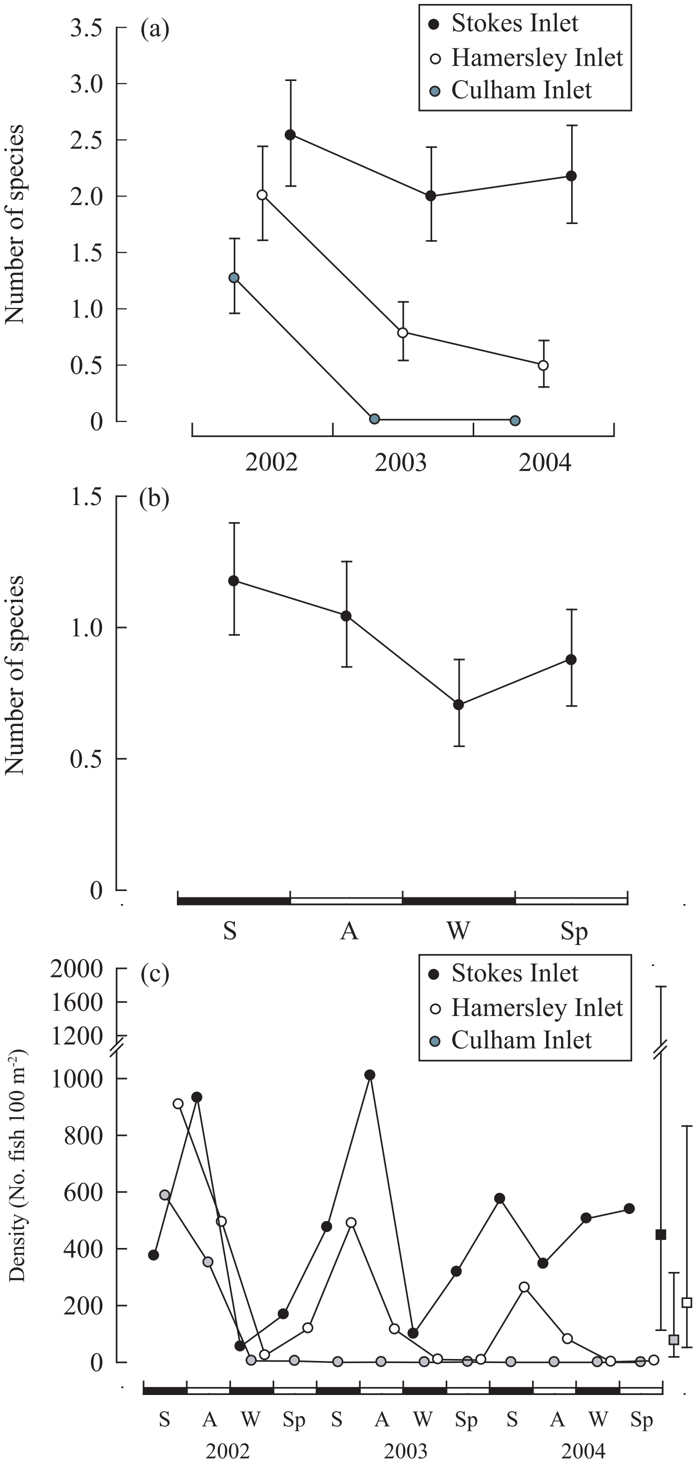

Figure 3.10. Mean number of species ± 95% CI in nearshore, shallow waters of the basins of Stokes, Culham and Hamersley inlets in a) 2002, 2003 and 2004 for each of these estuaries and b) in each season for all estuaries, and the mean density of fish ± 95% CI in c) the basins of each estuary in each season of the three years. For convenience, the overall mean and ± 95% CI are shown in c).

which, in turn, was greater than in Culham Inlet (Fig. 3.10c). The differences between the densities in Stokes Inlet and both of the other two estuaries were particularly marked after the summer of 2003 and few or no fish were caught in the basin of Culham Inlet after the autumn of 2002 (Fig. 3.10c).

Table 3.10. Mean squares and significance levels for three-way ANOVAs of the number of species and density of fish recorded in nearshore, shallow waters of the basins of each of Stokes, Culham and Hamersley inlets between summer 2002 and spring 2004. *$p<0.05$, **$p<0.01$, ***$p<0.001$.

	Main effects			
	Estuary (E)	Year (Y)	Season (S)	Residual
df	2	2	3	144
Number of species	17.462***	7.625***	0.510**	0.111
Density	56.971***	10.460***	10.148***	0.456
	Two- and three-way interactions			
	E x Y	E x S	Y x S	E x Y x S
df	4	6	6	12
Number of species	1.481***	0.062	0.192	0.103
Density	6.119***	1.490**	0.896	1.006*

Comparisons between the main tributaries of Stokes and Culham inlets

The mean number of species and density of fish in the main tributaries of the Stokes (Young River) and Culham (Phillips River) inlets were each influenced significantly by estuary and year, with density also being significantly influenced by season (Table 3.11). Furthermore, both the number of species and density of fish displayed significant estuary x year interactions, with the number of species also displaying an interaction between year x season.

In each of the three years, the mean number of species was greater in Stokes Inlet than in Culham Inlet in every season except autumn 2003 and although the number of species declined sequentially between 2002 and 2004 in Culham Inlet, it declined and then rose slightly in Stokes Inlet (Fig. 3.11a). Although the densities of fish in the two tributaries were not significantly different in 2002, they were significantly greater in the tributary of Stokes Inlet than in that of

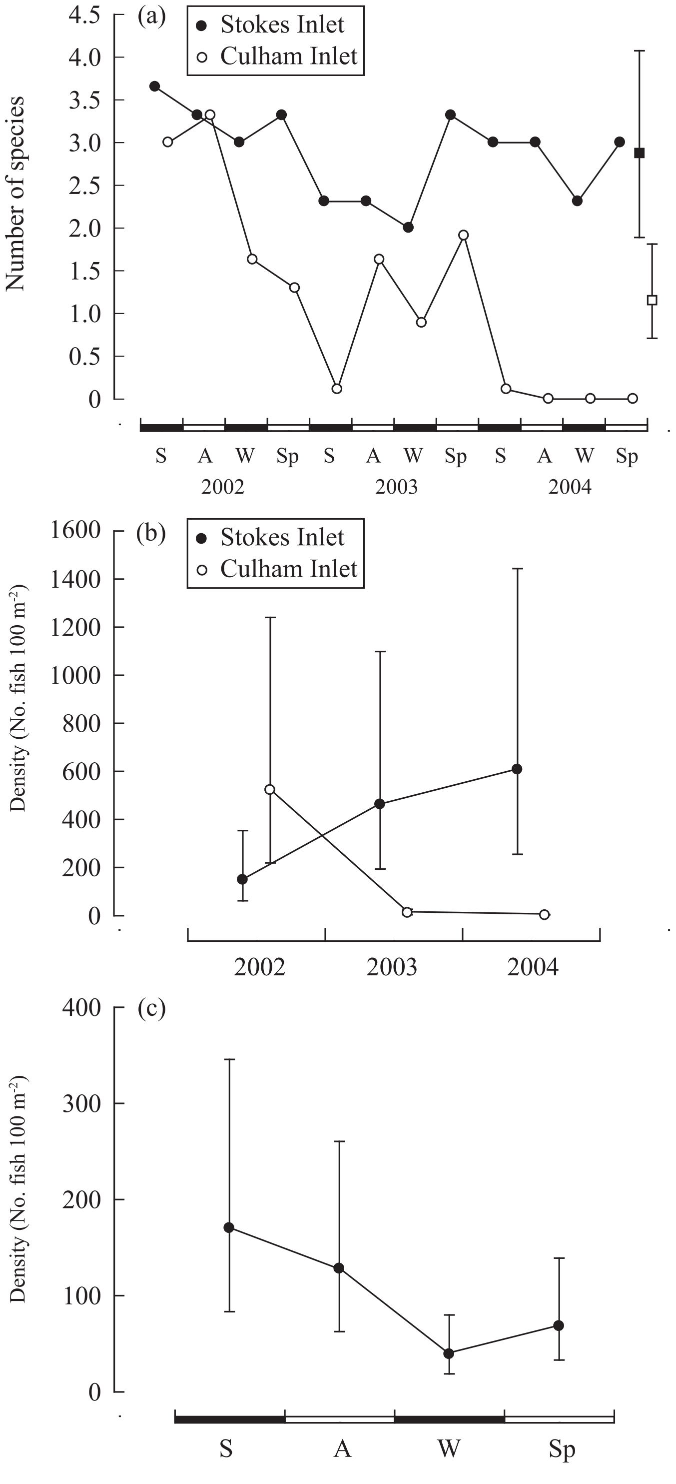

Figure 3.11. Mean number of species ± 95% CI in nearshore, shallow waters of the main tributaries of Stokes and Culham inlets in a) each season of 2002, 2003 and 2004 for both estuaries and the density of fish ± 95% CI in b) each estuary in 2002, 2003 and 2004 and, c) summer, autumn, winter and spring. For convenience, the overall mean and ± 95% CI are shown in a).

Culham Inlet in both 2003 and 2004 (Fig. 3.11b). The density of fish was significantly greater in summer than in winter (Fig. 3.11c).

Table 3.11. Mean squares and significance levels for three-way ANOVAs of the number of species and density of fish recorded in nearshore, shallow waters of the rivers of Stokes and Culham inlets between summer 2002 and spring 2004. **p*<0.05, ***p*<0.01, ****p*<0.001.

	Main effects			
	Estuary (E)	Year (Y)	Season (S)	Residual
df	1	2	3	48
Number of species	12.606***	3.608***	0.154	0.078
Density	25.477***	5.173***	1.437*	0.419
	Two- and three-way interactions			
	E x Y	E x S	Y x S	E x Y x S
df	2	3	6	6
Number of species	2.690***	0.079	0.323**	0.177
Density	14.766***	0.407	0.914	0.649

3.3.5 *Numbers of species and densities of fish in offshore, deeper waters*

Stokes Inlet

ANOVA demonstrated that the number of fish species in offshore, deeper waters of Stokes Inlet were not significantly influenced by either year, season or region (basin and major tributary) and that, of those three variables, only region significantly influenced the catch rate of fish (Table 3.12). There was a significant interaction between these variables only in the case of season x region for catch rate. The overall mean number of species recorded per sample ± 95% CI was 1.25 ± 0.13. The catch rates were appreciably greater in the Young River than the basin in each season except winter (Fig. 3.12). Although the catch rate in the basin of Stokes Inlet remained relatively constant among seasons, those in the Young River in summer, autumn and spring were significantly greater than that in winter (Fig. 3.12).

Table 3.12. Mean squares and significance levels for three-way ANOVAs of the number of species and catch rate of fish recorded in offshore, deeper waters of Stokes Inlet between summer 2002 and spring 2004. *p<0.05.

	Main effects			
	Year (Y)	Season (S)	Region (R)	Residual
df	2	3	1	72
Number of species	0.164	0.209	0.033	0.121
Catch rate	0.061	0.468	1.035*	0.223
	Two- and three-way interactions			
	Y x S	Y x R	S x R	Y x S x R
df	6	2	3	6
Number of species	0.120	0.204	0.157	0.078
Catch rate	0.122	0.493	0.738*	0.239

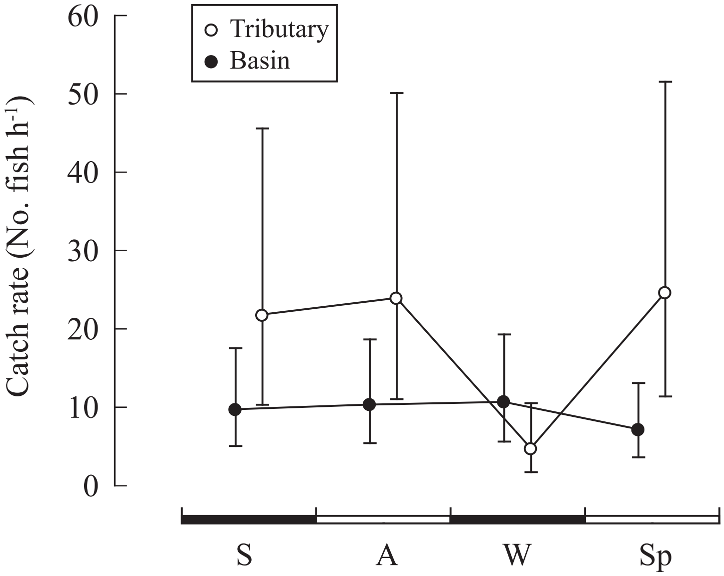

Figure 3.12. Mean catch rate of fish ± 95% CI in offshore, deeper waters of the basin and main tributary of Stokes Inlet in summer, autumn, winter and spring.

Culham Inlet

The number of species and catch rates of fish in the basin and major tributary of Culham Inlet were significantly influenced by year, season and region, with the highest mean squares being for year (Table 3.13). All of the two- and three-way interactions between these three variables were significant. The mean number of species was markedly greater in the main tributary of Culham Inlet than in its basin in the first three seasons of 2002 and, to a lesser extent, in autumn 2003 (Fig. 3.13a). No fish were caught in the offshore, deeper waters of either the basin or main tributary of Culham Inlet in any other season. The same trends were followed by the catch rate of fish in both the basin and tributary, but with catch rate in the tributary in autumn 2002 being substantially greater than in all other seasons (Fig. 3.13b).

Table 3.13. Mean squares and significance levels for three-way ANOVAs of the number of species and catch rate of fish recorded in offshore, deeper waters of the basin of Culham Inlet and Phillips River between summer 2002 and spring 2004. *$p<0.05$, **$p<0.01$, ***$p<0.001$.

	Main effects			
	Year (Y)	Season (S)	Region (R)	Residual
df	2	3	1	72
Number of species	1.715***	0.319***	0.756**	0.052
Catch rate	0.956***	0.297***	0.953***	0.019
	Two- and three-way interactions			
	Y x S	Y x R	S x R	Y x S x R
df	6	2	3	6
Number of species	0.208**	0.465***	0.153*	0.125*
Catch rate	0.215***	0.781***	0.256***	0.182***

Hamersley Inlet

Number of species in the basin of Hamersley Inlet, in which region sampling could be conducted throughout the three year study period, was influenced by both year and season, while the catch rate of fish was influenced only by the former variable (Table 3.14). There was a significant year x season interaction with both number of species and catch rate of fish.

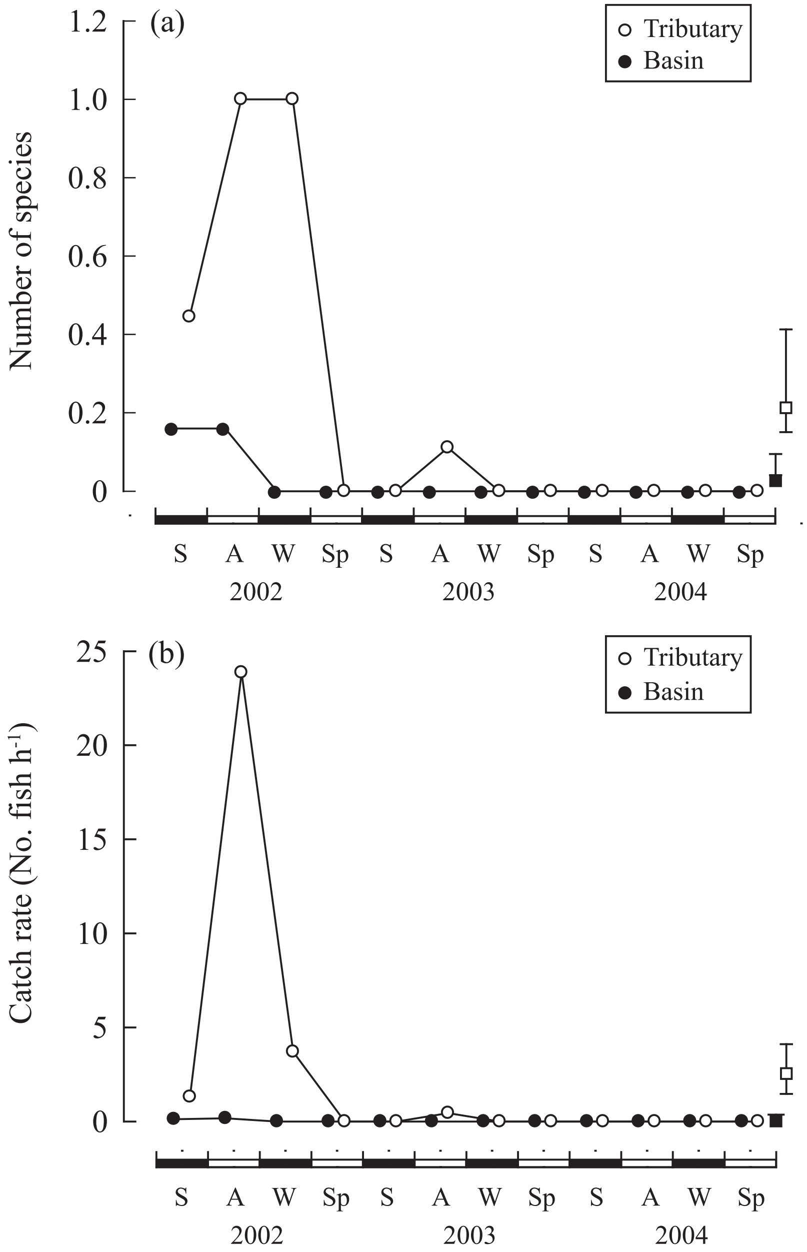

Figure 3.13. a) Mean number of species and b) mean catch rate of fish in offshore, deeper waters of the basin and main tributary of Culham Inlet in each season of 2002, 2003 and 2004. For convenience, the overall mean and ± 95% CI are shown in a) and b).

While the number of species did not significantly differ between seasons in 2002 and 2004, it was significantly greater in summer than in all other seasons in 2003 (Fig. 3.14a). Furthermore, number of species was significantly greater in the summers of 2002 and 2003 than in 2004, and those in the autumn, winter and spring of 2002 were significantly greater than in the corresponding seasons of both 2003 and 2004 (Fig. 3.14a). The catch rate of fish was only significantly greater for autumn and winter 2002 than for those seasons in both 2003 and 2004 (Fig. 3.14b).

Table 3.14. Mean squares and significance levels for two-way ANOVAs of the number of species and catch rate of fish recorded in offshore, deeper waters of the basin of Hamersley Inlet between summer 2002 and spring 2004. **p*<0.05, ****p*<0.001.

Hamersley basin	**Main effects and interaction**			
	Year (Y)	Season (S)	Y x S	Residual
df	2	3	6	48
Number of species	9.274***	0.373*	1.039***	0.104
Catch rate	7.876***	0.164	8.523***	0.090

Comparisons between the basins of Stokes, Culham and Hamersley inlets

When the data for offshore, deeper waters of the basins of Stokes, Culham and Hamersley inlets were subjected to ANOVA, the number of species was shown to be significantly influenced by estuary, year and season, while the catch rate of fish was influenced only by the first two of these variables (Table 3.15). Significant interactions for number of species were found with estuary x year and between all three variables, and with estuary x year and year x season for catch rate of fish.

Although number of species typically ranged between 0.8 and 1.5 in each season of 2002, 2003 and 2004 in Stokes Inlet, it ranged in Hamersley Inlet between 1.0 and 2.0 in summer 2002 to summer 2003, but then declined to zero or very low levels (Fig. 3.15a). The number of species in the basin of Culham Inlet was low in the first two seasons of 2002 and zero in every other season (Fig. 3.15a).

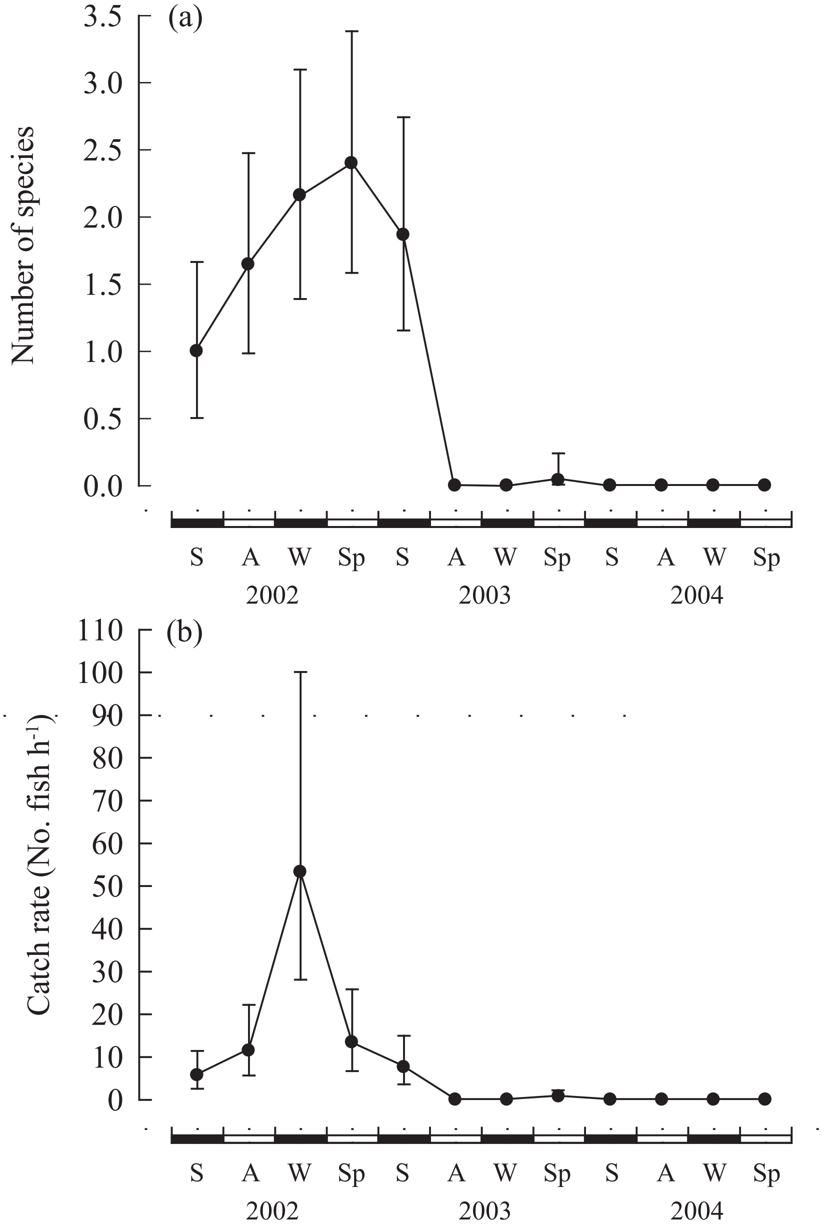

Figure 3.14. a) Mean number of species ± 95% CI and b) mean catch rate of fish ± 95% CI in offshore, deeper waters of the basin of Hamersley Inlet in each season of 2002, 2003 and 2004.

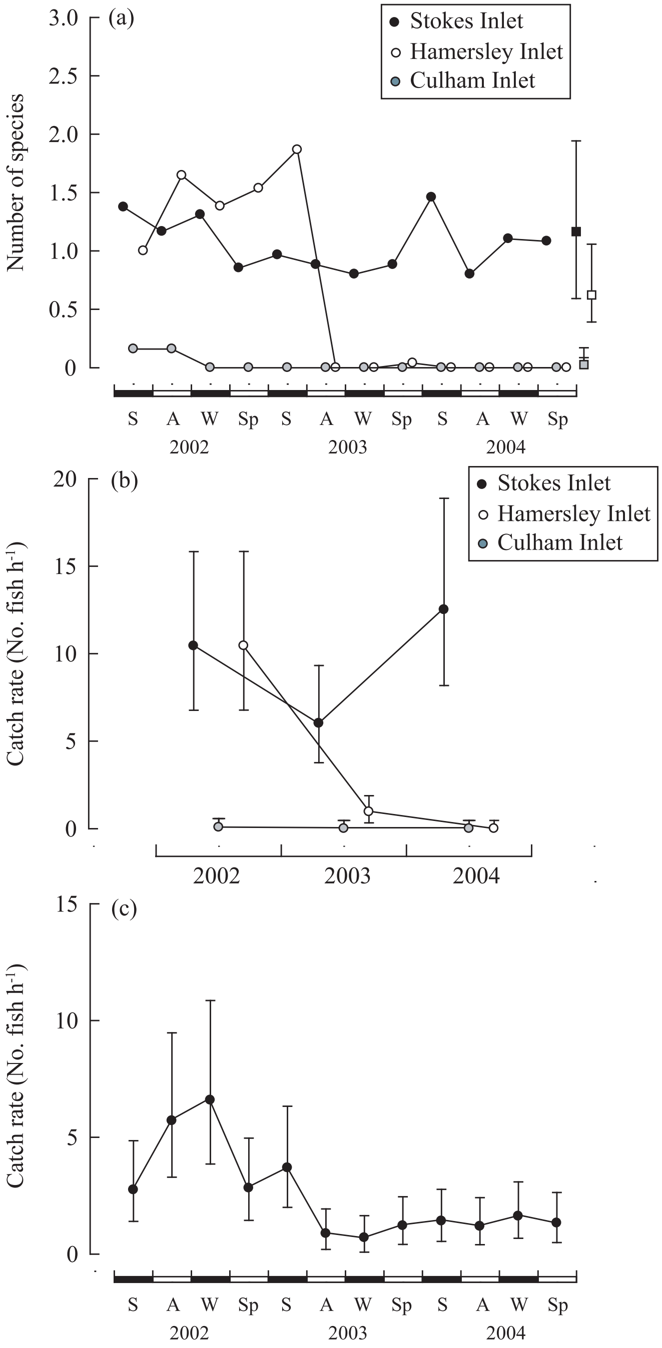

Figure 3.15. Mean number of species in offshore, deeper waters of the basins of Stokes, Culham and Hamersley inlets in a) each season of 2002, 2003 and 2004 and mean catch rates ± 95% CI of fish in b) each basin in 2002, 2003 and 2004 and c) each season of the three years. For convenience, the overall mean and ± 95% CI are shown in a).

Table 3.15. Mean squares and significance levels for three-way ANOVAs of the number of species and catch rates of fish recorded in offshore, deeper waters of the basins of each of Stokes, Culham and Hamersley inlets between summer 2002 and spring 2004. *$p<0.05$, **$p<0.01$, ***$p<0.001$.

	Main effects			
	Estuary (E)	Year (Y)	Season (S)	Residual
df	2	2	3	144
Number of species	14.738***	4.143***	0.662**	0.130
Catch rate	15.121***	2.277***	0.100	0.144
	Two- and three-way interactions			
	E x Y	E x S	Y x S	E x Y x S
df	4	6	6	12
Number of species	1.876***	0.134	0.253	0.430***
Catch rate	2.072***	0.064	0.453**	0.170

Whereas the catch rate of fish in Stokes and Hamersley inlets were very similar in 2002 and both declined in 2003, that in Stokes Inlet increased to its maxima of 12.5 fish h^{-1} in 2004, while that of Hamersley Inlet decreased to zero (Fig. 3.15b). Catch rates were always very low in the basin of Culham Inlet. Thus, the catch rate of fish in the basin of Stokes Inlet was significantly greater in each year than in Culham Inlet and in 2003 and 2004 than in Hamersley Inlet (Fig. 3.15b). The catch rate of fish was also greater in Hamersley Inlet in 2002 than in both 2003 and 2004. Furthermore, the seasonal trends for the catch rate of fish varied between years (Fig. 3.15c).

Comparisons between the main tributaries of Stokes and Culham inlets

ANOVA demonstrated that number of species and catch rates of fish in offshore, deeper waters of the rivers of Stokes and Culham inlets were each significantly influenced by estuary and year, and the catch rate of fish was also influenced by season (Table 3.16). All two- and three-way interactions were significant.

The number of species in the river of Stokes Inlet was always ≥ 1 in each season of 2002, 2003 and 2004, except for winter 2004, and it was typically greatest in summer or spring in each year (Fig. 3.16a). However, no fish were caught in the main tributary of Culham Inlet in the

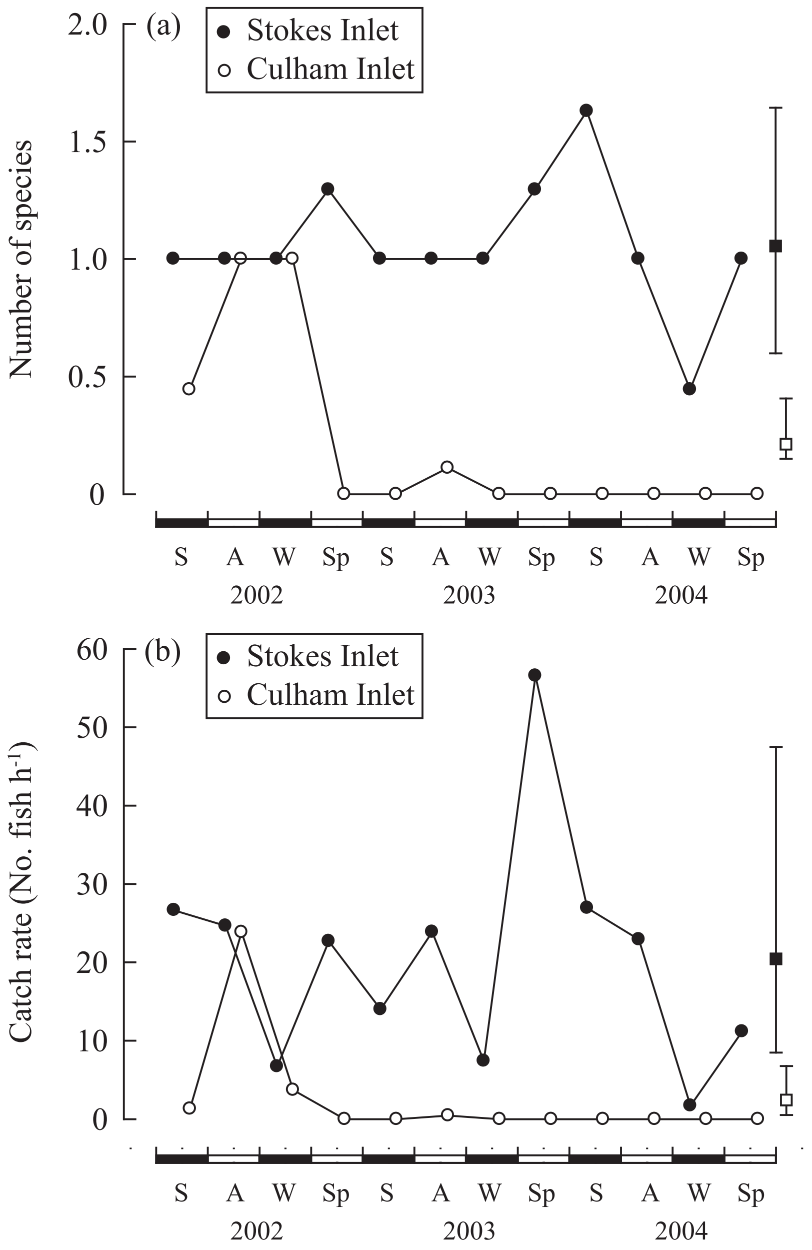

Figure 3.16. a) Mean number of species and b) mean catch rate of fish in offshore, deeper waters of the main tributaries of Stokes and Culham inlets in each season of 2002, 2003 and 2004. For convenience, the overall mean and ± 95% CI are shown in a) and b).

majority of seasons of each year, except in the summer, autumn and winter of 2002 and the autumn of 2003 (Fig. 3.16a).

Table 3.16. Mean squares and significance levels for three-way ANOVAs of the number of species and catch rate of fish recorded in offshore, deeper waters of the main tributaries of Stokes and Culham inlets between summer 2002 and spring 2004. *p<0.05, **p<0.01, ***p<0.001.

	Main effects			
	Estuary (E)	Year (Y)	Season (S)	Residual
df	1	2	3	48
Number of species	10.624***	0.870***	0.099	0.049
Catch rate	18.371***	0.994***	0.667***	0.093
	Two- and three-way interactions			
	E x Y	E x S	Y x S	E x Y x S
df	2	3	6	6
Number of species	0.723***	0.308***	0.140*	0.139*
Catch rate	0.573**	0.692***	0.237*	0.232*

Although the catch rates of fish in the main tributary of Stokes Inlet varied between seasons, it was always least in the winter of each year and that of the main tributary of Culham Inlet only exceeded 5 fish h^{-1} in autumn 2002 and no fish were caught in this tributary in most seasons (Fig. 3.16b).

3.3.6 *Regional, interannual and seasonal comparisons of ichthyofaunal compositions of nearshore, shallow waters*

Stokes Inlet

ANOSIM, using the densities of each fish species, derived from each replicate sample at the various sites in the basin and main tributary of Stokes Inlet in each season during 2002, 2003 and 2004, demonstrated that the composition of the ichthyofauna in this estuary was significantly influenced by region of estuary (P= 0.1%), season (P= 0.1%) and year (P= 1.7%). However, the Global R-statistic value was far greater for region (0.487) than for either season or year, *i.e.* 0.102 and 0.042, respectively, the latter two variables being very low.

Following ordination of the same density data as used for the above ANOSIM tests, the samples from the basin lay very largely to the left and/or below those from the main tributary (Fig. 3.17a). SIMPER demonstrated that the samples from both the basin and Young River were typified by *A. elongata* and *P. olorum*. However, the ichthyofauna of the basin was distinguished from that in the river by a relatively greater density and frequency of occurrence of *A. elongata* and the reverse trend for *P. olorum*. The ichthyofauna of the river was further distinguished from that of the basin by relatively greater densities and frequencies of occurrence of *A. butcheri* (Fig. 3.18).

When the density data for just the basin of Stokes Inlet were subjected to ordination and coded for year, the samples for the three years intermingled on the plot (Fig. 3.17b). However, the compositions did differ significantly among years (*P*= 0.1%), with a Global *R*-statistic of 0.318. Furthermore, the samples for 2004 tended to lie above those for 2003, and pairwise comparisons between the compositions in the three years yielded a far greater *R*-statistic value for 2004 *vs* 2003, *i.e.* 0.480, than for those for 2002 *vs* both 2003 and 2004, *i.e.* 0.214 and 0.227, respectively. Although *A. elongata* and *P. olorum* were both typifying species for the compositions in each year, both of these species were relatively more abundant and occurred more frequently in 2004 than in either 2002 or 2003.

Following ordination of the density data for the main tributary of Stokes Inlet (Young River), the samples for 2002 largely formed an approximately central and vertical band on the ordination plot (Fig. 3.17c). Eight of the 12 samples from 2003 lay in the lower left quadrant of the plot, while most of those for 2004 occupied the right half of that plot. The faunal composition differed significantly among years (*P*= 0.1%), with a Global *R*-statistic of 0.360. The compositions in 2002 and 2004 differed significantly from that in 2003 (*P*= 0.1% and 0.6%, respectively), with respective *R*-statistic values of 0.435 and 0.417, and also differed between 2002 and 2004 (*P*= 3.7%), but with a lower *R*-statistic value of 0.287. Although *A. elongata* and *P. olorum* typified the faunal compositions in each of the three years, *A. butcheri* also typified those of 2002 and 2004. Furthermore, each of these species was relatively more abundant and occurred more frequently in 2003 and 2004 than in 2002. However, only *A. elongata* was

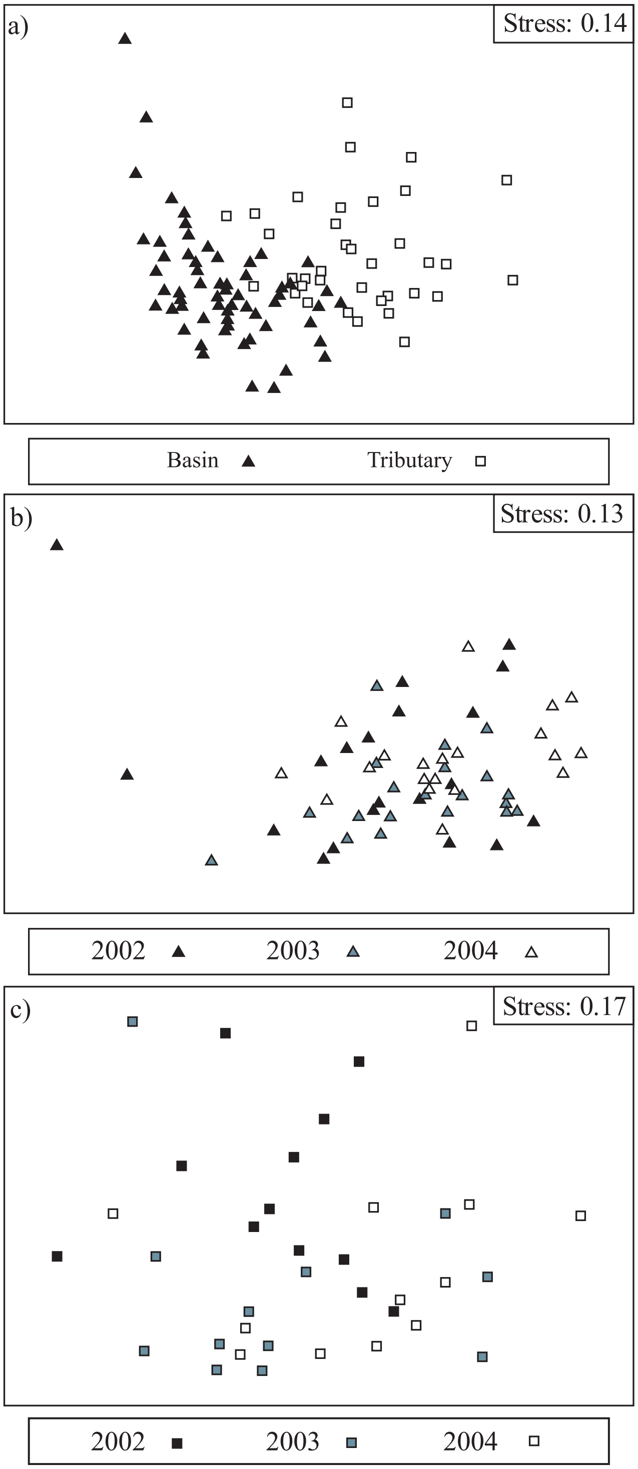

Figure 3.17. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of Stokes Inlet in a) its basin and main tributary, and for the years 2002-04 in b) the basin and c) main tributary.

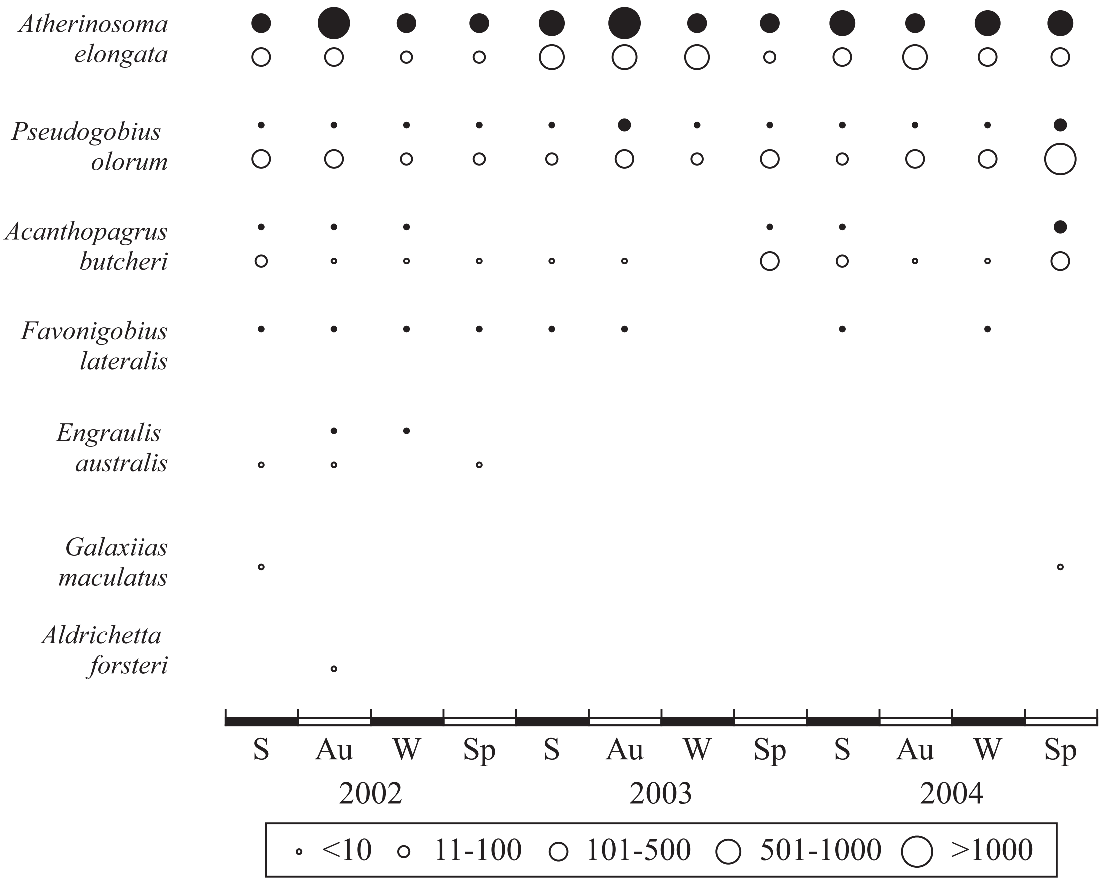

Figure 3.18. Relative abundance of each fish species in seasonal samples obtained from the nearshore, shallow waters of the basin (●) and main tributary (○) of Stokes Inlet between summer 2002 and spring 2004. Code at bottom of figure gives the range in mean values for the number of individuals in each seasonal sample from each region.

relatively more abundant and occurred more frequently in 2003 than 2004, with the reverse pertaining for both *P. olorum* and *A. butcheri*.

As there were significant inter-annual differences in the ichthyofaunal compositions of both the basin and its main tributary, the density data for each season in 2002, 2003 and 2004 in each region were subjected to ordination. The influence of season was significant in each year (*P*= 0.1-0.5%), with the *R*-statistic values being greater for 2004 (0.455) and 2003 (0.494) than for 2002 (0.212). On the ordination plot for 2002, all but one of the samples for summer and autumn formed a group that lay well to the left and/or below all but one of the samples from winter (Fig. 3.19a). The samples from spring formed a particularly tight group (MVDISP= 0.561, compared with > *ca* 0.900 for all other seasons) in the upper left-hand corner and between those

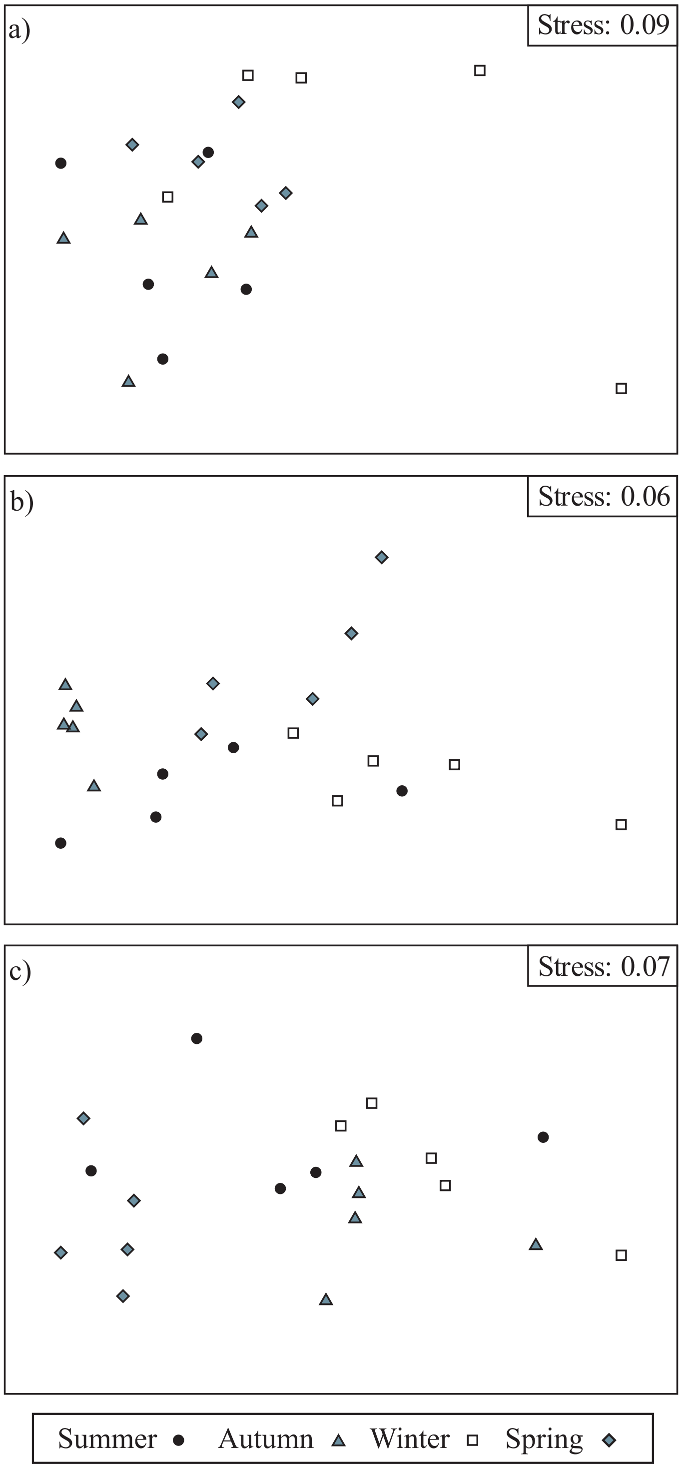

Figure 3.19. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of the basin of Stokes Inlet in a) 2002, b) 2003 and c) 2004.

for the summer/autumn and winter groups. All pairwise seasonal comparisons were significant, apart from those between summer and autumn and between winter and spring. The seasonal differences were greatest between autumn and spring, for which the *R*-statistic was 0.404 and was shown by SIMPER to result from *A. elongata*, *P. olorum*, *F. lateralis* and *A. butcheri* occurring in greater densities and more frequently in autumn than in spring.

On the ordination plot for 2003, the samples for autumn formed a tight group on its left side that was discrete from that for spring in the centre and that for winter on its right side, which lay below and/or to the right of the samples for spring (Fig. 3.19b). Significant inter-seasonal differences were found in each comparison involving autumn, with the differences between the ichthyofaunal composition in this season and those in winter and spring being particularly pronounced with *R*-statistic values of 0.880 and 0.752, respectively. SIMPER demonstrated that these differences were attributable to greater densities and frequencies of occurrence of *A. elongata* and *P. olorum* in autumn than in all other seasons and of *A. butcheri* in spring than in autumn. A further significant pairwise comparison was found between winter and spring (*P*= 3.2%), but with an appreciably lower *R*-statistic of 0.260.

Following ordination of the seasonal data for the basin of Stokes Inlet in 2004, the samples for spring lay to the left of all of the samples from all other seasons except for one of the summer samples, while those for autumn and winter lay to the right of all but one of the summer samples (Fig. 3.19c). Seasonal differences in composition were found only in the three pairwise comparisons involving spring, with the differences being greatest in the case of those with autumn and winter, for which the *R*-statistic values were 0.996 and 0.908, respectively. These substantial differences could always be attributed to greater densities and frequencies of occurrence of *A. butcheri* and *P. olorum* in spring.

Although only three sites could be regularly sampled in the main tributary (Young River), the data for these three replicate sites, when subjected to ANOSIM, still yielded significant seasonal differences in both 2003 (*P*= 0.2%) and 2004 (*P*= 0.5%), with corresponding *R*-statistic values of 0.522 and 0.370. Furthermore, although the samples were widely distributed on the ordination plot for 2002, those for summer and autumn lay to the left and/or above all of those for winter and spring (Fig. 3.20a). The samples for autumn and spring in 2003 and for autumn, spring and summer in 2004 each formed relatively discrete groups in those years (Fig. 3.20b, c).

Culham Inlet

ANOSIM, using the densities of each fish species, derived from each replicate sample at the various sites in the entrance channel, basin, main tributary and upstream pool of Culham Inlet in each season during 2002, 2003 and 2004, demonstrated that ichthyofaunal composition in this estuary was significantly influenced by region of estuary (*P*= 0.1%) and year (*P*= 0.1%), but not by season (*P*= 52.1%). The Global *R*-statistic was slightly higher for region (0.319) than for year (0.252).

After the densities at the various sites in the entrance channel, basin, main tributary and upstream pool of Culham Inlet in each season during 2002, 2003 and 2004 had been subjected to ordination, the samples from the entrance channel formed a tight group in the bottom left corner of the ordination plot, whereas those from the upstream pool formed a discrete group in the top left quadrant (Fig. 3.21a). The samples for the basin and main tributary intermingled and collectively lay largely to the right and/or above those from the entrance channel and to the right and/or below those from the upstream pool, with 40 and 14 samples from the basin and tributary, respectively, forming a very tight group on the far right of the plot. ANOSIM demonstrated that each pairwise comparison between the compositions of the four regions were significantly different (*P*= 0.1 or 0.6%). The *R*-statistic values were greatest for the upstream pool *vs* the entrance channel (0.952) and basin (0.691), and for the entrance channel *vs* basin (0.630) and were ≤ 0.225 for the tributary *vs* the upstream pool and entrance channel. The ichthyofauna of the entrance channel was distinguished from that of each other region by relatively greater densities and frequency of occurrence of both *A. elongata* and *F. lateralis*, while those of the river and upstream pool were each distinguished from that of the other two regions by greater densities and frequency of occurrence of *P. olorum* (Fig. 3.22). Furthermore, the densities and frequencies of occurrence of *L. wallacei* and *G. maculatus* were greater in the upstream pool than each other region, and in the basin and tributary, respectively.

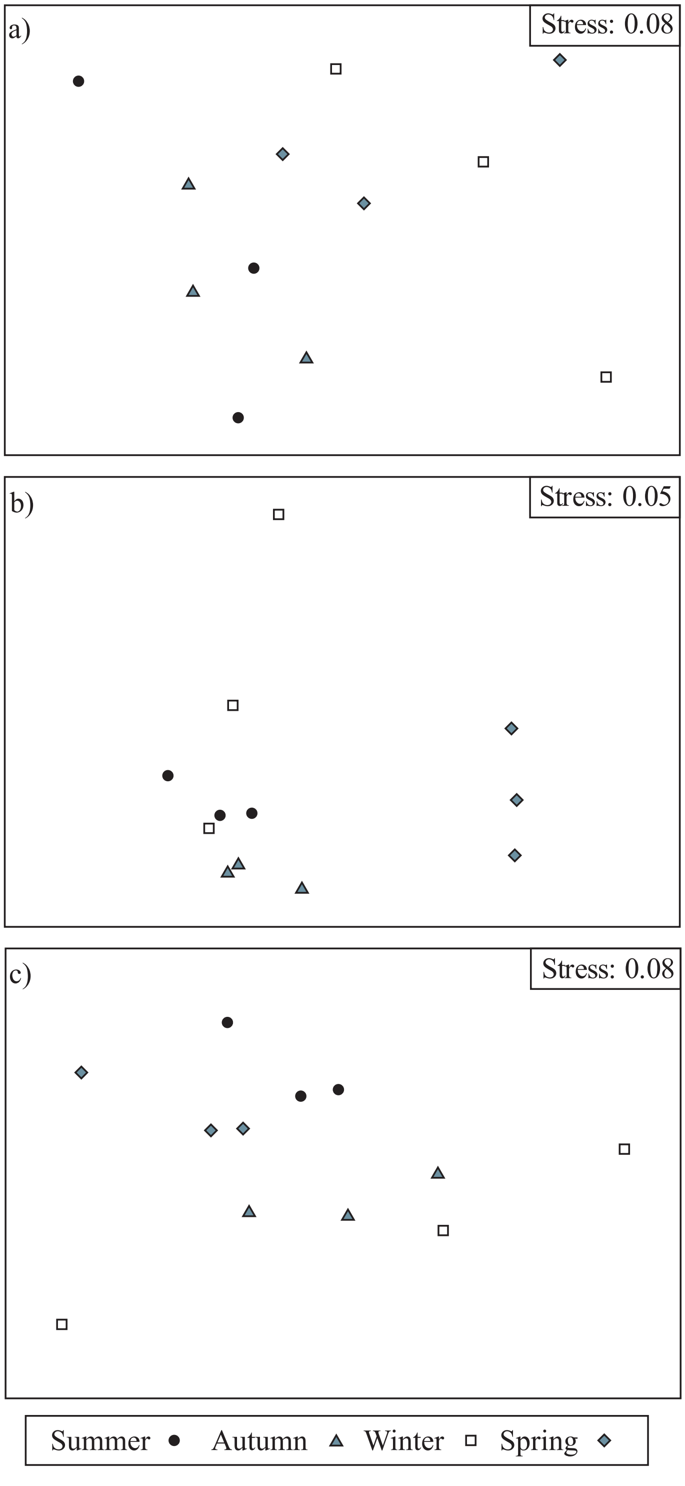

Figure 3.20. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of the tributary of Stokes Inlet in a) 2002, b) 2003 and c) 2004.

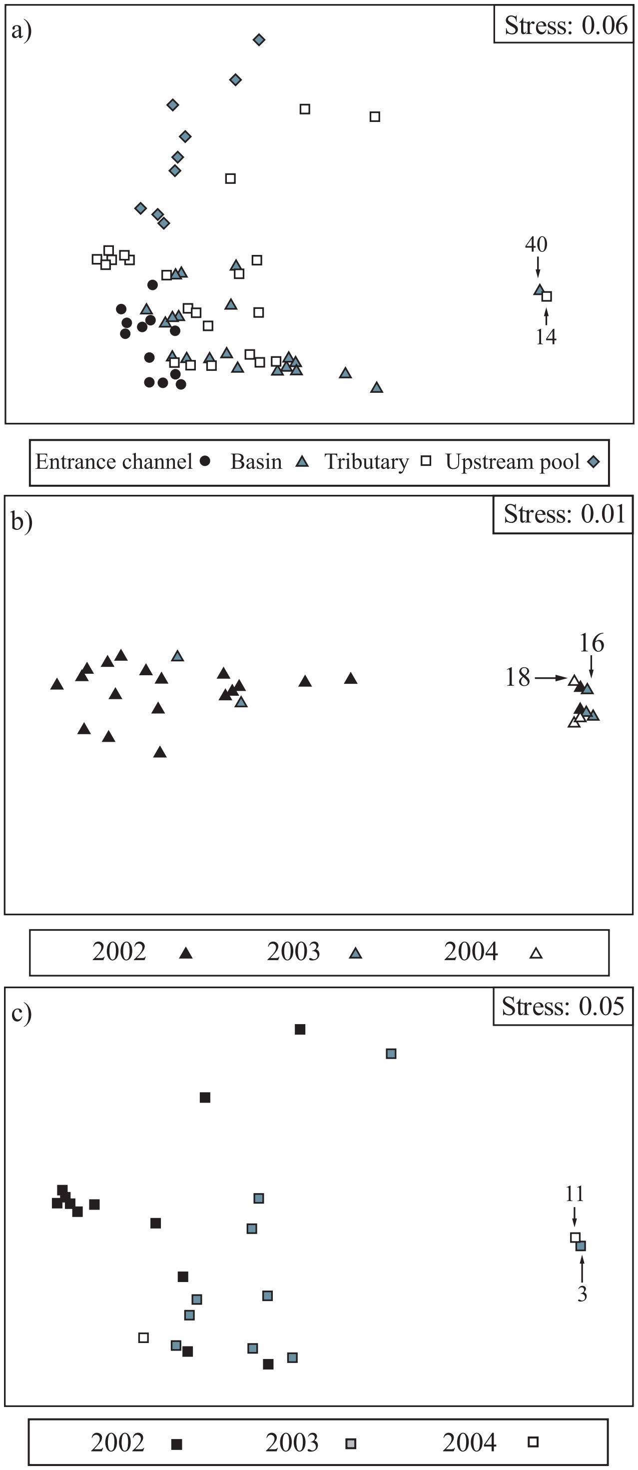

Figure 3.21. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of Culham Inlet in a) the entrance channel, basin, main tributary and upstream pool and for the years 2002-04 in b) the basin and c) main tributary.

When the density data for the basin of Culham Inlet in the three years was subjected to ordination, most of the samples for 2002 occupied the left third of the plot with some extending laterally across the width of that plot (Fig. 3.21b). Two of the samples obtained in 2003 also occupied this portion of the plot, while the rest obtained from that year formed a tight group with two samples from 2002 and all of the samples from 2004. The latter group of overlapping samples represents those in which no fish were caught. The species composition differed significantly among years (*P*= 0.1%; Global *R*-statistic= 0.427), with only the pairwise comparisons between 2002 and both 2003 (0.676) and 2004 (0.778) being significant (both *P*= 0.1%).

Following ordination of density data for the three years in the main tributary (Phillips River), the samples for 2003 lay predominantly in the central part of the plot and mainly to the right of those for 2002 and to the left of those for 2004 (Fig. 3.21c). The species composition in this river differed significantly among years (*P*= 0.1%), with a relatively high Global *R*-statistic value of 0.639. Furthermore, each of the pairwise comparisons between the compositions in the three years were significant (*P*= 0.1 or 1.4%), with the *R*-statistic for 2002 *vs* 2004 (0.944) being substantially greater than those for 2003 *vs* both 2002 (0.352) and 2004 (0.468). The former substantial difference resulted from *A. elongata* and *P. olorum*, and to a lesser extent *A. butcheri*, occurring more frequently and in relatively higher densities in 2002 than 2004. Indeed, the samples from 2004 contained *A. elongata* only in summer of 2004, and even then only in low numbers, and never contained either *P. olorum* or *A. butcheri* (Fig. 3.22).

When the density data for the different seasons in the basin in 2002, for which there were numerous samples containing fish, were subjected to ordination, the samples for summer and autumn invariably lay to the left of those for winter and spring, which were more widely dispersed (Fig. 3.23a). The compositions in the basin differed significantly among seasons (*P*= 0.3%; Global *R*-statistic= 0.326), with significant pairwise comparisons between summer and both winter and spring and between autumn and both winter and spring, with all four *P* and *R*-statistic values lying between 0.8 and 1.6% and 0.444 and 0.612, respectively. The ichthyofaunas of the basin of Culham Inlet were shown by SIMPER to be represented by greater

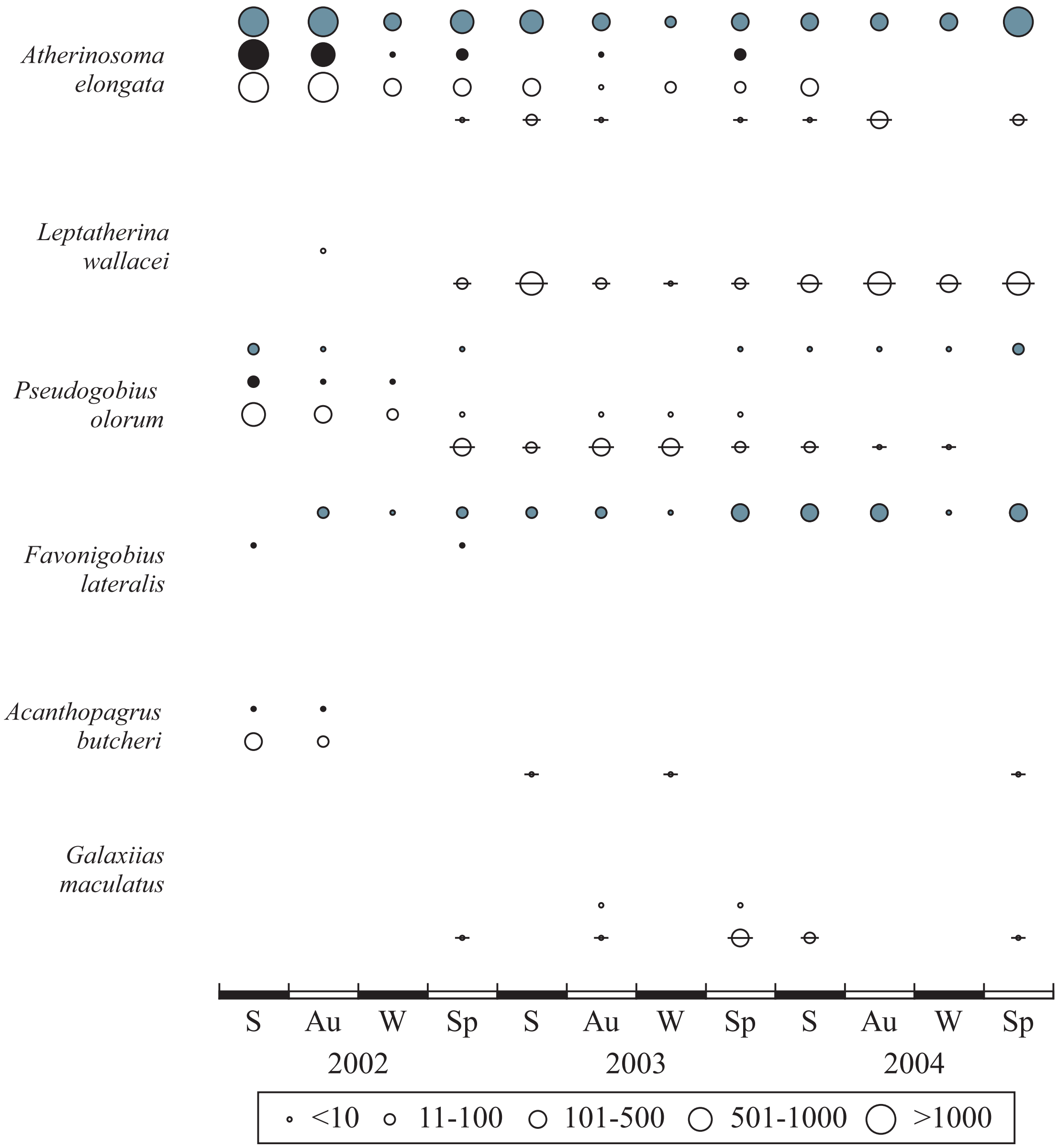

Figure 3.22. Relative abundance of each fish species in seasonal samples obtained from the nearshore, shallow waters of the entrance channel (●), basin (●), main tributary (○) and upstream pool (⊖) of Culham Inlet between summer 2002 and spring 2004. Code at bottom of figure gives the range in mean values for the number of individuals in each seasonal sample from each region.

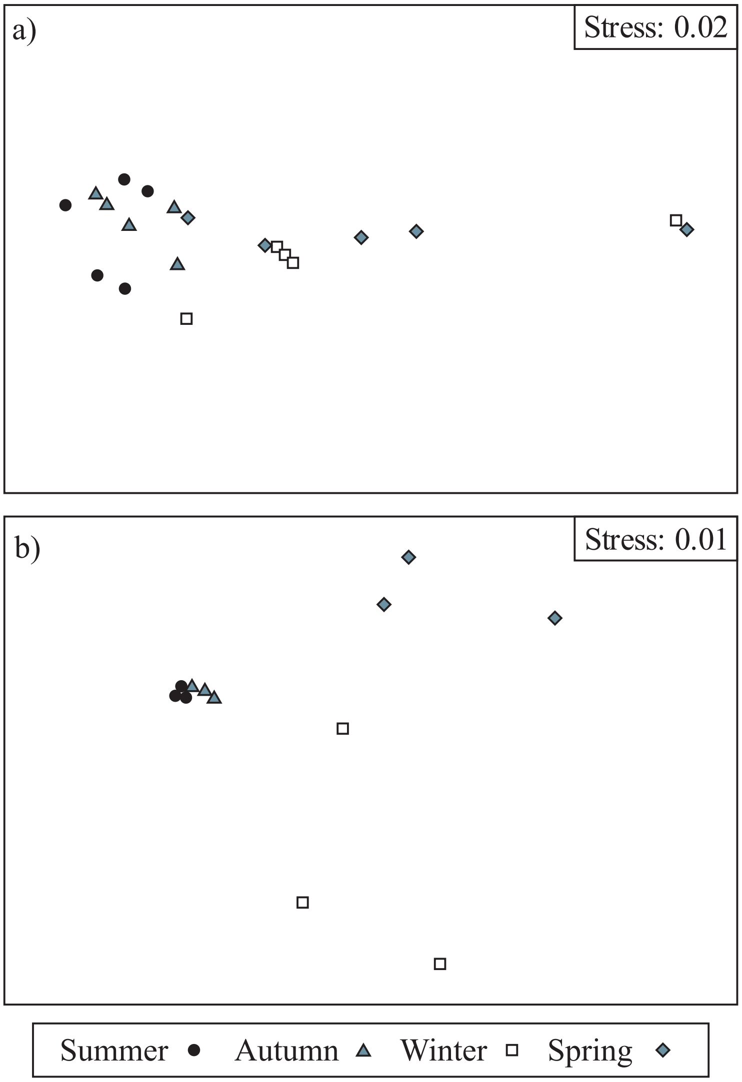

Figure 3.23. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of Culham Inlet in 2002 and coded for season in a) the basin and b) main tributary.

densities and frequencies of occurrence of *A. elongata* and *P. olorum* in both summer and autumn than in both winter and spring (see also Fig. 3.22).

After ordination of the density data for the Phillips River in 2002, the composition of those samples differed significantly among seasons (*P*= 0.2%; Global *R*-statistic= 0.633), with those for summer and autumn forming a very tight group to the left of those for spring which lay above those for winter (Fig. 3.23b). The far greater variability in the composition of the samples in spring and winter than in summer and autumn reflects the greatly reduced numbers or absence of the species found in summer and autumn, *i.e. A. elongata*, *P. olorum* and *A. butcheri* (Fig. 3.22).

Hamersley Inlet

ANOSIM, using the densities of each fish species, derived from each replicate sample at the various sites in the basin and upstream pool of Hamersley Inlet in each season during 2002, 2003 and 2004, demonstrated that ichthyofaunal composition in this estuary was significantly influenced by region of estuary, year and season (*P*= 0.1-1.3%). The Global *R*-statistic was far greater for region (0.672) than for either year (0.077) or season (0.072).

Ordination of the density data for Hamersley Inlet resulted in all of the samples for the basin forming a discrete group below and largely to the left of the limited number of samples obtained from an upstream pool in the Hamersley River (Fig. 3.24a). SIMPER demonstrated that the differences between the two regions were attributable to greater densities and frequencies of occurrence of *P. olorum* in the upstream pool than in the basin and to the occurrence of *A. elongata* in the basin but not the upstream pool and to the reverse occurring with *L. wallacei* (Fig. 3.25).

All but one of the twenty samples collected from the basin of Hamersley Inlet in 2002 formed a relatively tight group that lay above the vast majority of the samples from the other two years and particularly of those from 2004 (Fig. 3.24b). The ichthyofaunal composition in the basin differed significantly among years (*P*= 0.3%; Global *R*-statistic= 0.186) and that in 2002 differed significantly from that in both 2003 (*P*= 0.3%) and 2004 (*P*= 0.1%), with the *R*-statistic for the latter comparison being far greater, *i.e.* 0.427 *vs* 0.201. SIMPER demonstrated that the fauna in 2002 was typified by both *A. elongata* and *P. olorum*, but only by the former species in 2003 and 2004. The differences between these years were attributable to greater densities and frequencies of occurrence of both *A. elongata* and *P. olorum* in 2002 than in either 2003 or 2004. Furthermore, no *P. olorum* was caught in the basin of Hamersley Inlet after the winter of 2003 (Fig. 3.25).

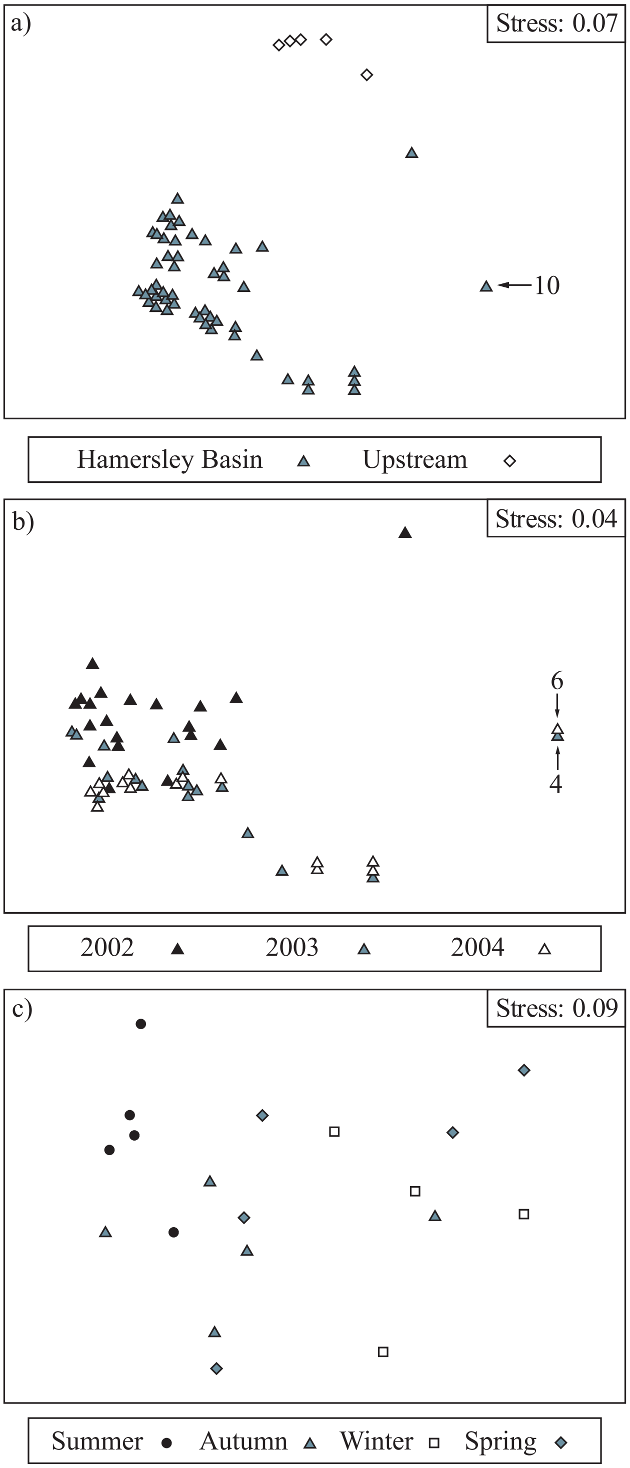

Figure 3.24. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of Hamersley Inlet in a) the basin and upstream pool, and b) for the years 2002-04 and c) coded for season in 2002, in the basin. NB. A sample of winter 2002 was removed from c) as it was an extreme outlier.

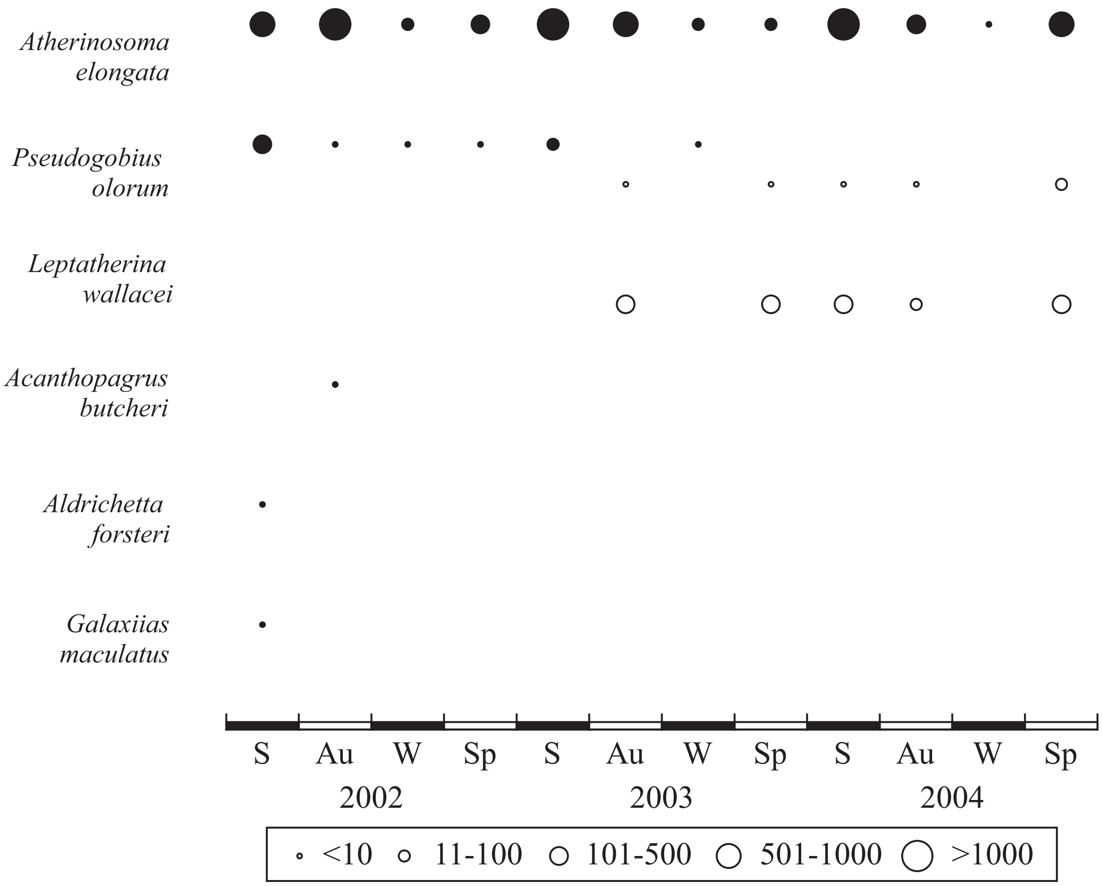

Figure 3.25. Relative abundance of each fish species in seasonal samples obtained from the nearshore, shallow waters of the basin (●) and upstream pool (○) of Hamersley Inlet between summer 2002 and spring 2004. Code at bottom of figure gives the range in mean values for the number of individuals in each seasonal sample from each region.

When the density data for the samples collected from nearshore, shallow waters of the basin of Hamersley Inlet were considered separately for each of 2002, 2003 and 2004 and coded for seasons, only the seasons in 2002 were shown by ANOSIM to be significantly different, *i.e.* *P*= 0.4%, with a Global *R*-statistic of 0.273 (Fig. 3.24c). On the ordination plot, the samples for summer formed a relatively tight group in the upper left quadrant, while four of the samples for winter were widely dispersed in the right side of the plot, with the remaining sample for this season being an extreme outlier (not shown). This accounts for the pairwise comparison between summer and winter being greater than those for all other comparisons (*P*= 0.8%; *R*-statistic= 0.620). SIMPER demonstrated that the seasonal differences in composition were the result of greater densities and frequencies of occurrence of *A. elongata* and/or *P. olorum* in summer and autumn than in winter and spring.

Comparisons between estuaries

Two-way crossed estuary x year ANOSIM, using the densities of each fish species, derived from each replicate sample at the various sites in the basins of Stokes, Culham and Hamersley inlets in each season during 2002, 2003 and 2004, demonstrated that the composition in these basins differed significantly (*P*= 0.1%) between estuaries and years, with the Global *R*-statistic being greater for the former variable, *i.e.* 0.439 *vs* 0.193. Consequently, differences between the compositions in the basins of each estuary in each of the three years are considered separately. The differences between the compositions in the basins of Stokes, Culham and Hamersley inlets were significant in each year (*P*= 0.1-0.2%), with the Global *R*-statistics increasing progressively from 0.102 in 2002 to 0.584 in 2003 and 0.632 in 2004. Furthermore, each combination of pairwise comparisons between the basins also increased progressively between 2002 and 2004, with the most pronounced increase being between the basins of Stokes and Culham inlets, *i.e.* 0.104 in 2002 to 1.000 in 2004.

When the density data for the basins of Stokes, Culham and Hamersley inlets were subjected to ordination in each of 2002, 2003 and 2004, the points on the plots showed a progressive change from 2002 to 2004 (Figs 3.26a, b, c). Thus, while the vast majority of points for the basins of each estuary in 2002 intermingled on the left side of the plot, all of the points for the basins of Stokes and Culham inlets in 2004 formed tight groups on the left and right sides of the plot, respectively, with those for the basin of Hamersley Inlet lying within or between these groups (*cf* Figs 3.26a, b, c).

SIMPER demonstrated that the difference in the composition between the basins resulted from greater densities and frequencies of occurrence of *A. elongata* in Stokes Inlet in each year, with this species declining in the basin of Culham Inlet from low levels in 2002 to zero in 2004. Furthermore, while *P. olorum* was present in greater densities and occurred more frequently in the basin of Hamersley Inlet than in either Stokes or Culham inlets in 2002, it was relatively more

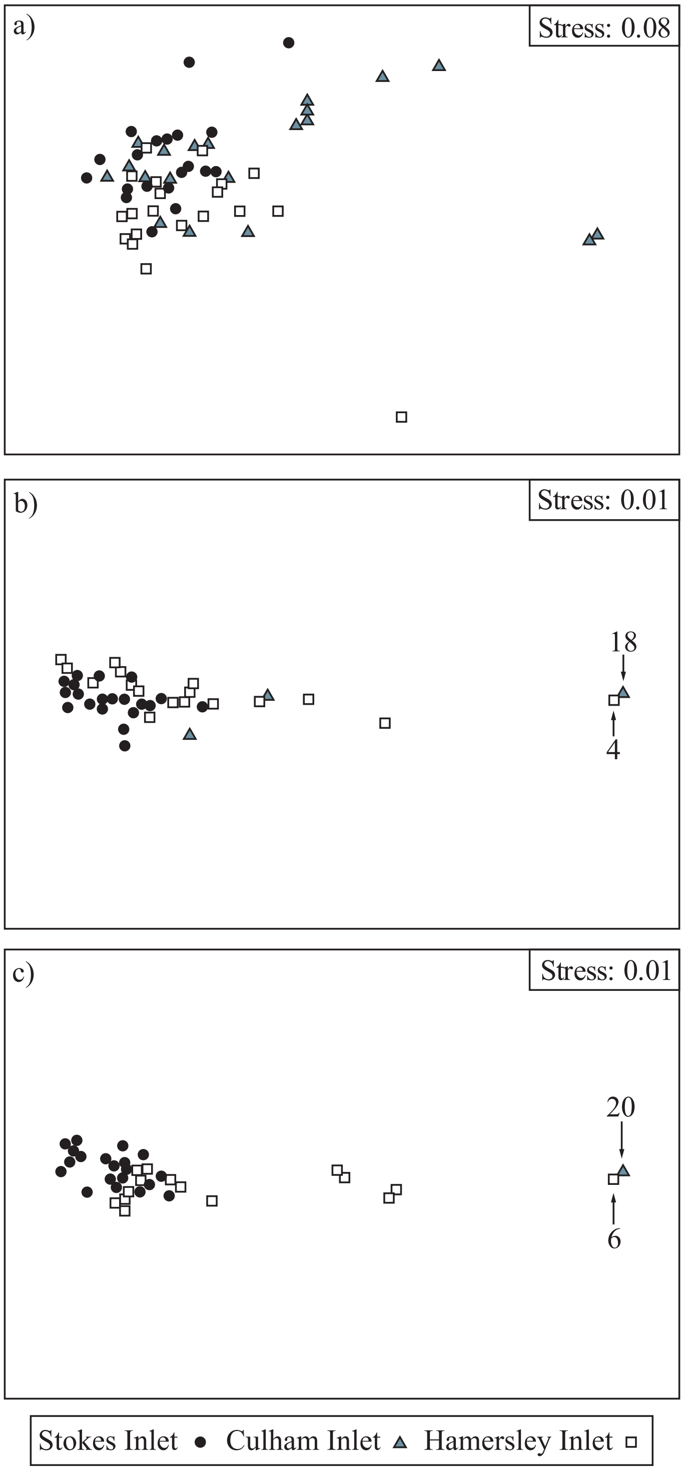

Figure 3.26. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of the basins of Stokes, Culham and Hamersley inlets for the years a) 2002, b) 2003 and c) 2004.

abundant in Stokes Inlet and absent from the basin of Culham Inlet in 2003 and in 2004 was only caught in Stokes Inlet (see also Figs 3.18, 3.22. 3.2).

Two-way crossed estuary x year ANOSIM, using the densities of each fish species, derived from each replicate sample at the various sites in the main tributaries of Stokes and Culham inlets in each season during 2002, 2003 and 2004, demonstrated that the composition in this region differed significantly (*P*= 0.1%) between estuaries and years, with the Global *R*-statistic being greater for the former variable, *i.e.* 0.534 *vs* 0.327. Thus, the differences between the compositions in the tributaries of Stokes and Culham inlets were significant in each year (*P*= 0.1-0.2%), with the Global *R*-statistic increasing progressively from 0.189 in 2002 to 0.451 in 2003 and 0.961 in 2004.

As with the basins, the points on the ordination plots showed a progressive separation between those of the tributaries of Stokes and Culham inlets from 2002 to 2004. Thus, in 2002, while the vast majority of points for the tributary of Stokes Inlet formed a group in the centre of the plot, surrounded by those for Culham Inlet, the samples from Stokes and Culham inlets did not overlap in 2003 and formed two tight and discrete groups in 2004, with the exception of one point from Culham Inlet that lay close to those for Stokes Inlet (Figs 3.27a, b, c). SIMPER demonstrated that the above differences resulted from greater densities and frequencies of occurrence of *A. elongata*, *P. olorum* and *A. butcheri* in the tributary of Culham Inlet than in that of Stokes Inlet in 2002, but with the reverse pertaining in both 2003 and 2004. Indeed, no *A. butcheri* were caught in the tributary of Culham in 2003 and 2004 and no *P. olorum* were caught in that region in the latter year. Furthermore, the density and frequency of occurrence of *A. elongata* progressively declined in that tributary to very low levels in summer 2004, with none of this species being caught after that season.

In the case of the ordination plot using the density data for upstream pools of Culham and Hamersley inlets, all but one of the samples from the former pool formed a group that was discrete from those of the latter pool (Fig. 3.28). The composition of the samples were significantly different (*P*= 3.5%; *R*-statistic= 0.295) and were attributable to greater densities and

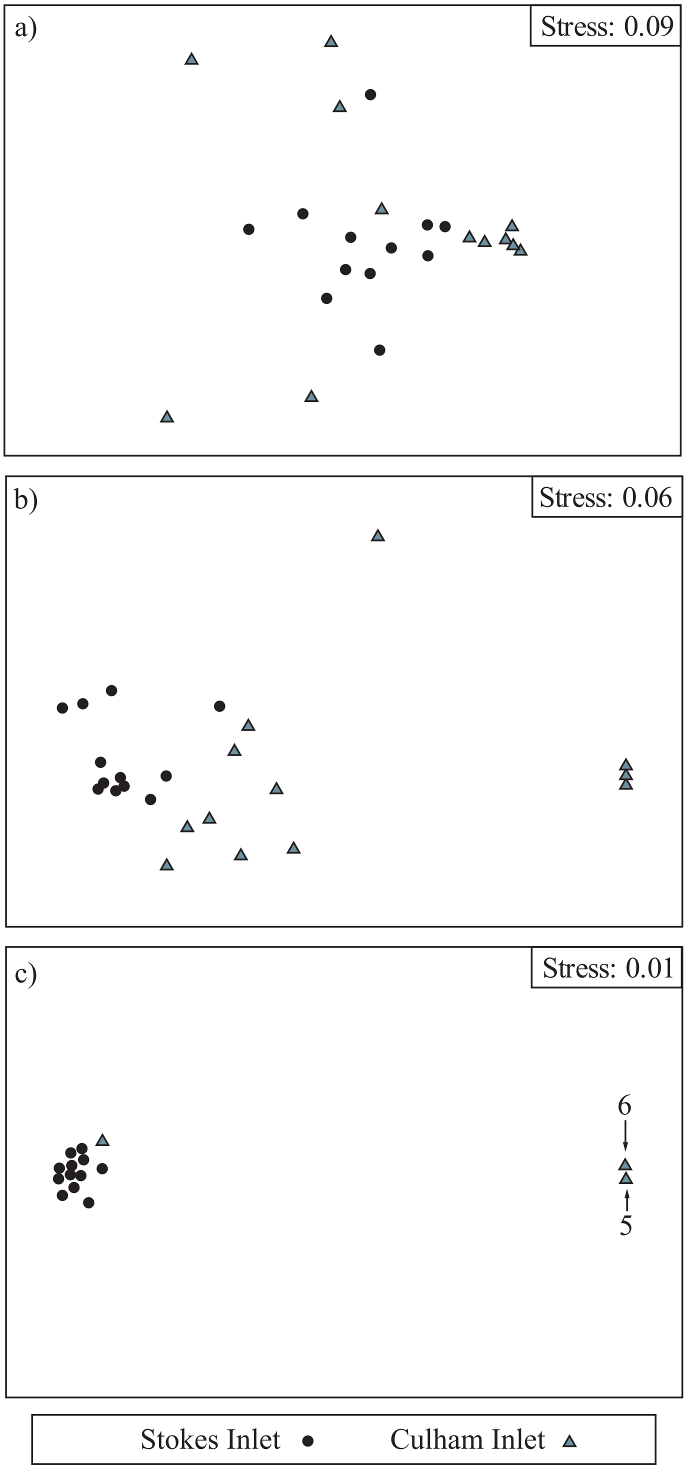

Figure 3.27. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of the main tributaries of Stokes and Culham inlets for the years a) 2002, b) 2003 and c) 2004.

frequencies of occurrence of *P. olorum*, *L. wallacei* and *A. elongata* in the upstream pool of Culham Inlet.

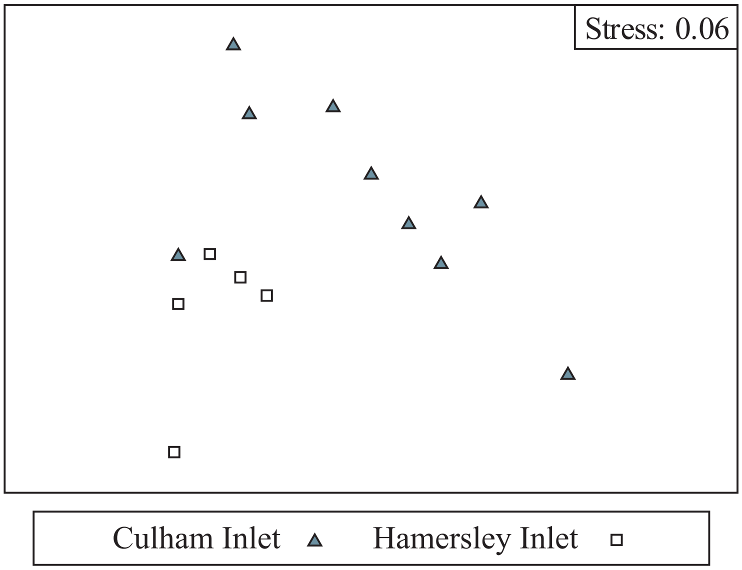

Figure 3.28. Non-metric multidimensional scaling (MDS) ordination of the densities of each species in replicate samples of fish obtained from nearshore, shallow waters of the upstream pools of Culham and Hamersley inlets collectively for the years 2002-2004.

3.3.7 *Regional, interannual and seasonal comparisons of ichthyofaunal compositions of offshore, deeper waters*

Stokes Inlet

One-way ANOSIM demonstrated that the compositions of the fish faunas of the basin and river and of both the different years and seasons were not significantly different (*P*= 97.4, 37.6 and 17.1%, respectively) and were accompanied by very low Global *R*-statistic values, *i.e.* -0.053, 0.002 and 0.012, respectively. Although, the *R*-statistic value for the two-way crossed ANOSIM for region x season was just significant (*P*= 3.9%), the Global *R*-statistic was only 0.037. Further exploration of the data revealed that, overall, seasons in the main tributary in the three years were significantly different, *i.e. P*= 0.4% and Global *R*-statistic= 0.146, and that these differences were driven by significant (*P*= 4.1%) seasonal differences in 2004 (Global *R*-statistic= 0.272). In both of these cases, pairwise comparisons between the compositions in winter and both summer and autumn produced the highest *R*-statistic values, *i.e.* 0.320-0.556. On the ordination plots, there was a tendency for the samples from summer and autumn not to overlap with those for winter (Fig. 3.29a, b).

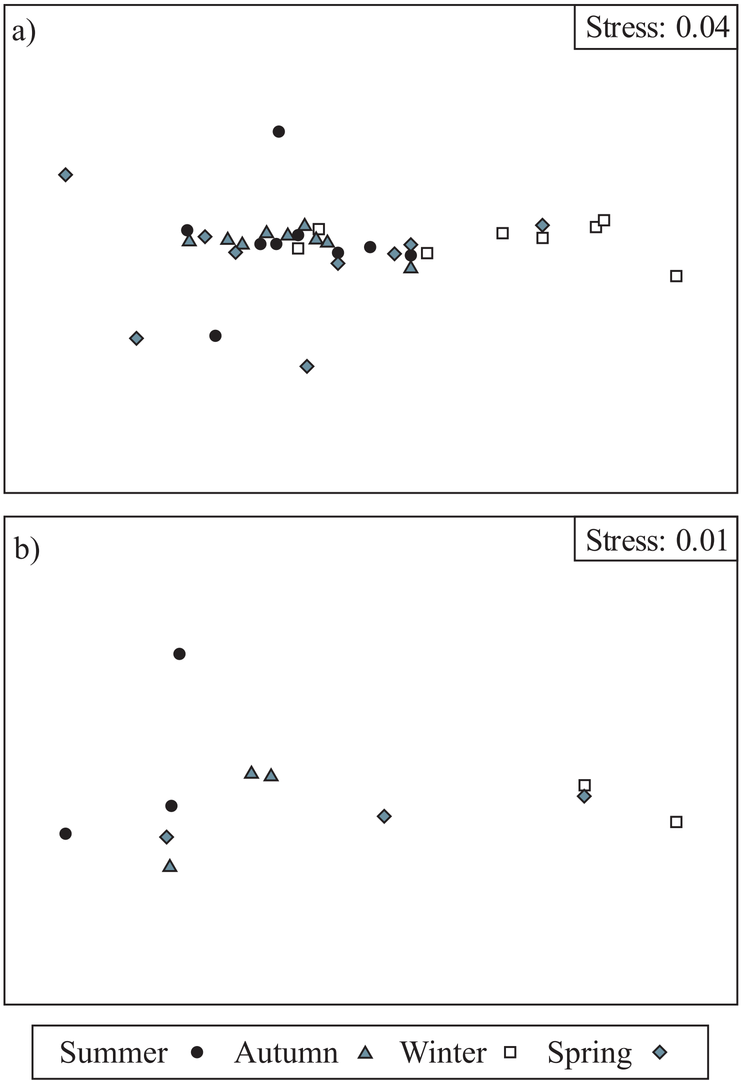

Figure 3.29. Non-metric multidimensional scaling (MDS) ordination of the catch rates of each species in replicate samples of fish obtained from offshore, deeper waters of the main tributary of Stokes Inlet and coded for season a) for the years 2002-04 and b) in 2004. NB. In both a) and b) a winter sample has been excluded from the ordination as it was an extreme outlier.

The composition of the ichthyofauna of the offshore, deeper waters of the basin and main tributary of Stokes Inlet did not differ conspicuously, did not change with year and only displayed a small seasonal difference in the case of the tributary and only conspicuously in 2004.

Thus, the composition of the ichthyofauna of Stokes Inlet can be considered relatively homogeneous, which is attributable to the extreme dominance of all samples by *A. butcheri* (see Fig. 3.30).

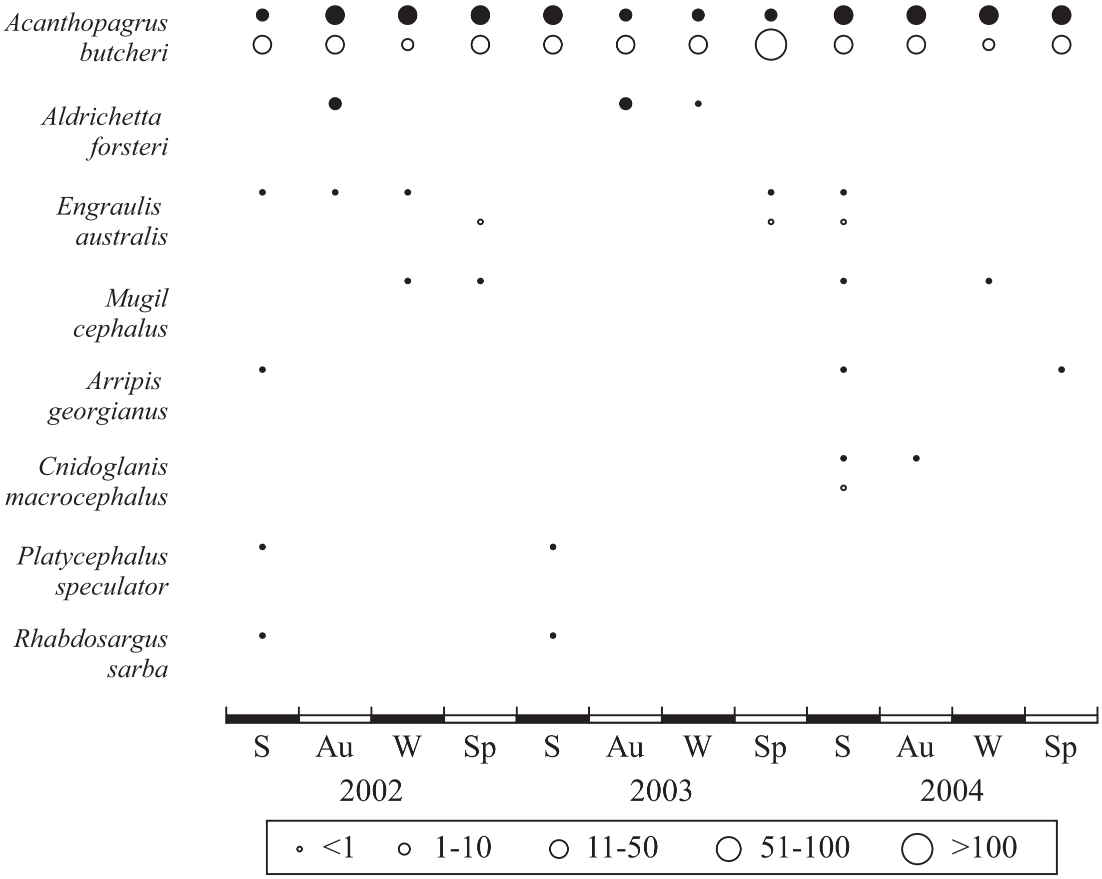

Figure 3.30. Relative catch rate of each fish species in seasonal samples obtained from offshore, deeper waters of the basin (●) and main tributary (○) of Stokes Inlet between summer 2002 and spring 2004. Code at the bottom of figure gives the range in mean values for the catch rates in each seasonal sample from each region.

Culham Inlet

Following ordination of the catch rates of fish in samples collected by gill netting in offshore, deeper waters of Culham Inlet, the samples from the entrance channel formed a group that lay very largely in the left of the plot, while those for the Phillips River extended from the extreme left to the extreme right of the plot (Fig. 3.31a). The vast majority of the samples from

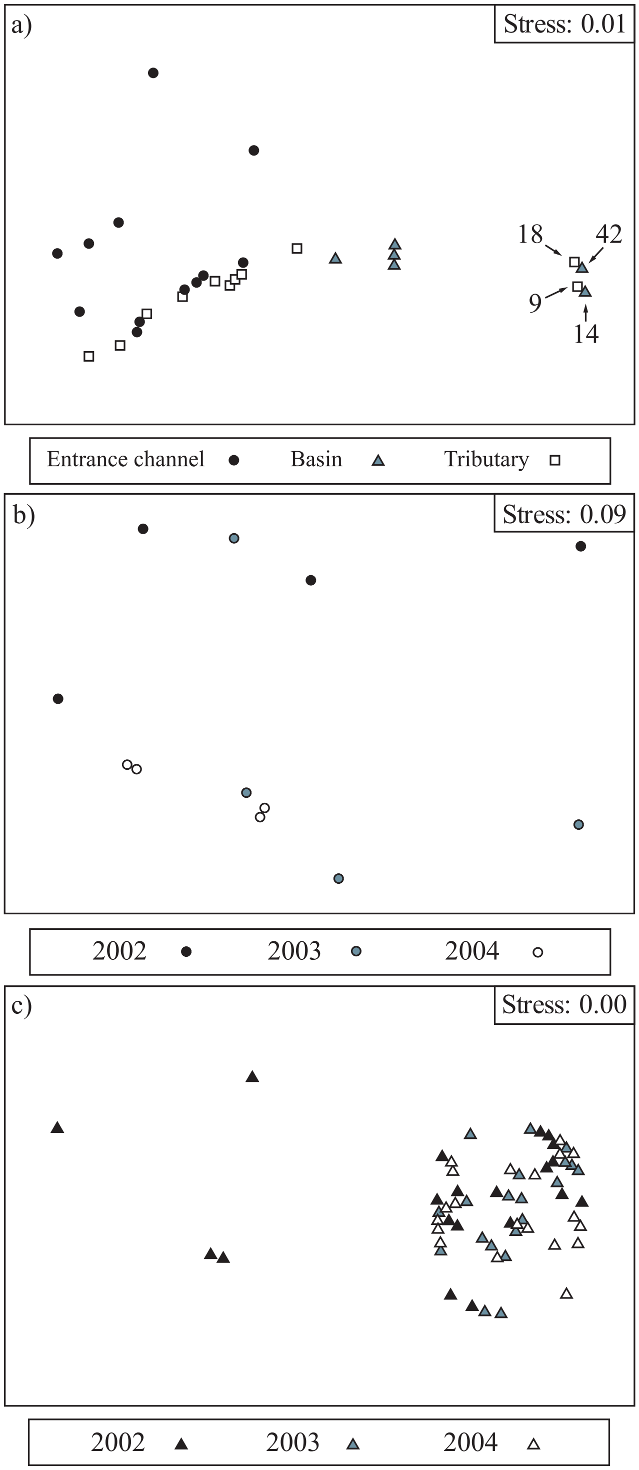

Figure 3.31. Non-metric multidimensional scaling (MDS) ordination of the catch rates of each species in replicate samples of fish obtained from offshore, deeper waters of Culham Inlet in a) the entrance channel, basin and river and for the years 2002-04 in b) the entrance channel and c) basin.

the basin of Culham Inlet lay in the right half of the plot. ANOSIM demonstrated that the ichthyofaunal compositions of the above three regions of Culham Inlet were significantly different (*P*= 0.1%; Global *R*-statistic= 0.375). Significant pairwise differences (*P*= 0.1%) were found between the compositions of all combinations of regions, with those between the entrance channel and both the basin and main tributary having far greater *R*-statistic values, *i.e.* 0.995 and 0.628, respectively, than that between the basin and tributary (0.109). These regional differences were shown by SIMPER to be largely attributable to greater densities and frequencies of occurrence of *A. butcheri* in the entrance channel than in either of the other two regions.

When the catch rates of fish derived from samples in the entrance channel were subjected to ordination, the samples from 2002 were distributed across the width of the plot and lay above all but one of those for 2003 and 2004 (Fig. 3.31b). The composition of samples from the entrance channel differed significantly between years (*P*= 4.1%; Global *R*-statistic= 0.215). Pairwise comparisons showed that the samples from 2002 differed significantly from those of 2004 (*P*= 2.9%; *R*-statistic= 0.448) and that this difference was attributable to greater densities and frequencies of occurrence of *A. butcheri*, *A. japonicus* and *P. speculator* in 2002 than in 2004. Indeed, the latter two species were not caught in 2004 (Fig. 3.32).

ANOSIM demonstrated that the composition of the basin of Culham Inlet differed significantly among years (*P*= 2.8%), but the Global R-statistic was very small, *i.e.* 0.016. On the ordination, four of the samples from 2002 lay in the left of the plot, while all of the other samples from 2002 and all of those from 2003 and 2004 formed a tight group on the right side of the plot (Fig. 3.31c). This small inter-annual difference reflects the fact that these four replicate samples from 2002 were the only samples to contain *A. butcheri* (Fig. 3.32).

On the ordination plot for the catch rate data in the main tributary of Culham Inlet (Phillips River), eight of the samples from 2002 lay in the left two thirds of the plot and to the left of two samples from that year and all but one of those for 2003 and 2004 (Fig. 3.33a). Two-way crossed ANOSIM for year x season demonstrated that the composition of the samples from the tributary differed significantly among years (*P*= 0.1%; Global R-statistic= 0.320) and among seasons (*P*= 0.5%; Global *R*-statistic= 0.178). The composition in 2002 was significantly

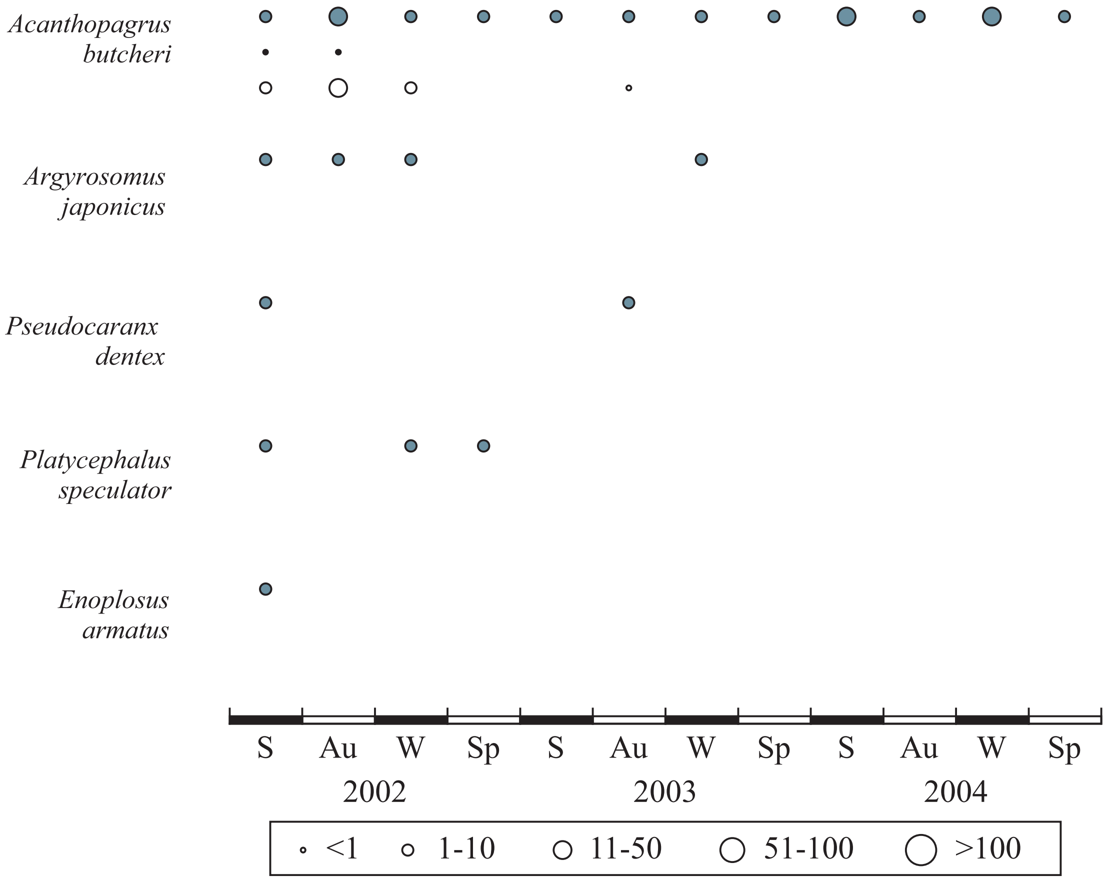

Figure 3.32. Relative catch rates of each fish species in seasonal samples obtained from offshore, deeper waters of the entrance channel (●), basin (●) and main tributary (○) of Culham Inlet between summer 2002 and spring 2004. Code at bottom of figure gives the range in mean values for the catch rates in each seasonal sample from each region.

different from that in 2003 (*P*= 0.3%; *R*-statistic= 0.305) and 2004 (*P*= 0.2%; *R*-statistic= 0.354). These inter-annual differences result from the greatly varying relative catch rates of *A. butcheri* in this region between 2002 and 2004. Thus, in 2002, appreciable numbers of *A. butcheri* were caught between summer and winter, very low numbers were only caught in autumn 2003 and no *A. butcheri* were caught in 2004 (Fig. 3.32).

ANOSIM demonstrated that only the composition in the tributary in 2002 differed significantly between seasons (*P*= 0.9%; Global *R*-statistic= 0.535). On the ordination plot, two of the samples from summer and all those from autumn and winter lay on the left side, while those for spring and a single summer sample formed a very tight group on the right side of the plot (Fig. 3.33b). Pairwise comparisons demonstrated that the greatest differences were between

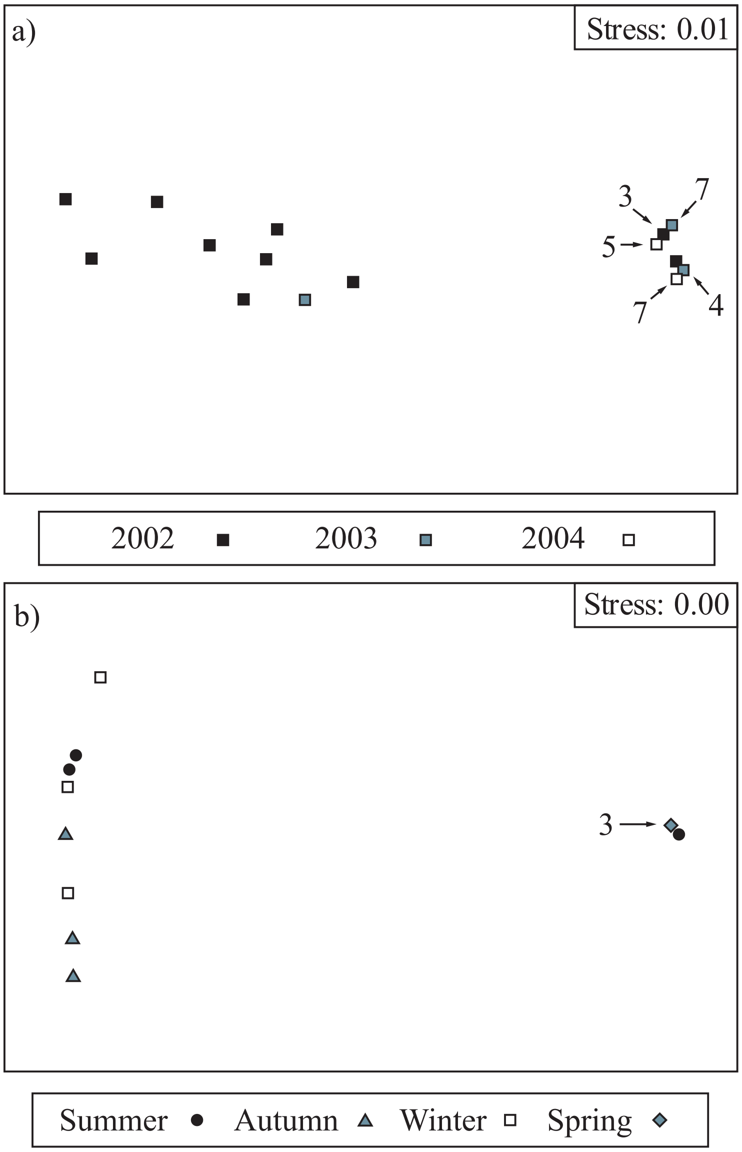

Figure 3.33. Non-metric multidimensional scaling (MDS) ordination of the catch rates of each species in replicate samples of fish obtained from offshore, deeper waters of the main tributary of Culham Inlet a) for the years 2002-04 and b) the seasons of 2002.

both autumn and winter, and spring and that these differences can be attributed to no *A. butcheri* being caught in the tributary in that latter season (Fig. 3.32).

Hamersley Inlet

The compositions of the samples collected from offshore, deeper waters of the basin of Hamersley Inlet and the Hamersley River were not significantly different (*P*= 17.1%) and the

Global *R*-statistic value was very low (0.071). Thus, on the ordination plot for the catch rate data for the basin and tributary of Hamersley Inlet collectively, the samples for 2002 lay almost exclusively above and/or to the left of those for 2003 and 2004 (Fig. 3.34a). The composition of the ichthyofauna of Hamersley Inlet differed significantly among years (*P*= 0.1%; Global *R*-statistic = 0.541), with that in 2002 differing significantly (both *P*= 0.1%) from that of both 2003 (0.669) and 2004 (0.991), and that in 2003 differing significantly from 2004, but the *R*-statistic was far lower, *i.e.* *P*= 4.6%, *R*-statistic= 0.033. SIMPER demonstrated that these differences were largely attributable to greater densities and frequencies of occurrence of *A. butcheri* in 2002 than in both 2003 and 2004. Indeed, no *A. butcheri*, together with none of the less abundant species, *i.e.* *Arripis truttacea*, *Arripis georgiana*, *A. forsteri* and *P. dentex*, were caught in Hamersley Inlet after the summer of 2003 (Fig. 3.35).

In the three years, a significant difference was found between seasons only in 2003. On the ordination plot for seasons in that year, four of the five samples for summer formed a discrete group in the lower left corner of the plot, while all but one of those for the other seasons were grouped on the extreme right of the plot and represented samples that contained no fish (Fig. 3.34b). These seasonal differences in 2003 can also be attributed to the fact that no fish were caught in Hamersley Inlet after the summer of 2003, with the exception of a small number of *Mugil cephalus* in one replicate sample in the spring of that year (Fig. 3.35).

Comparisons between estuaries

The composition of the fish faunas of offshore, deeper waters of the basin and main tributaries did not differ significantly in Stokes and Hamersley inlets and although they did differ significantly (*P*= 0.5%) in the case of Culham Inlet, the *R*-statistic was low, *i.e.* 0.109. Thus, the catch rates for fish species in the basins and main tributaries of Stokes, Culham and Hamersley inlets were each pooled, to enable comparisons between these systems. Two-way crossed estuary x year ANOSIM, using the catch rates of each fish species, derived from each replicate sample at the various sites in the basins and main tributaries of Stokes, Culham and Hamersley inlets in each season during 2002, 2003 and 2004, demonstrated that the composition in the main bodies

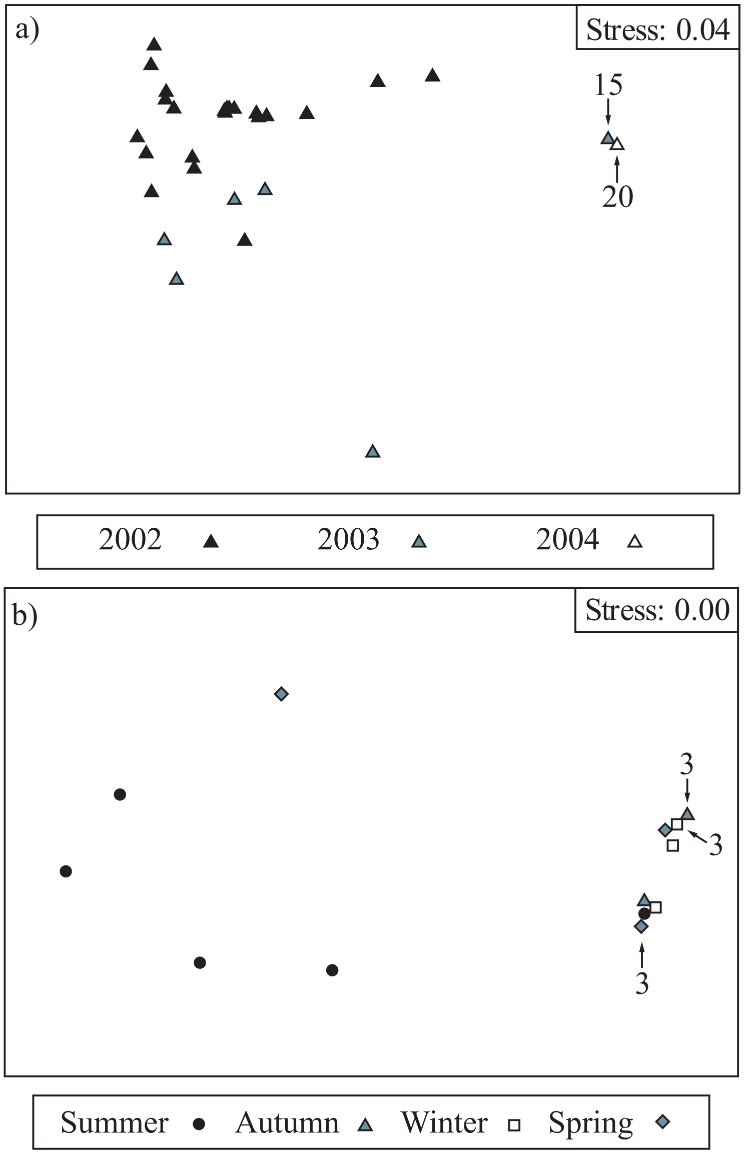

Figure 3.34. Non-metric multidimensional scaling (MDS) ordination of the catch rates of each species in replicate samples of fish obtained from offshore, deeper waters of Hamersley Inlet a) for the years 2003-04 and b) the seasons of 2003.

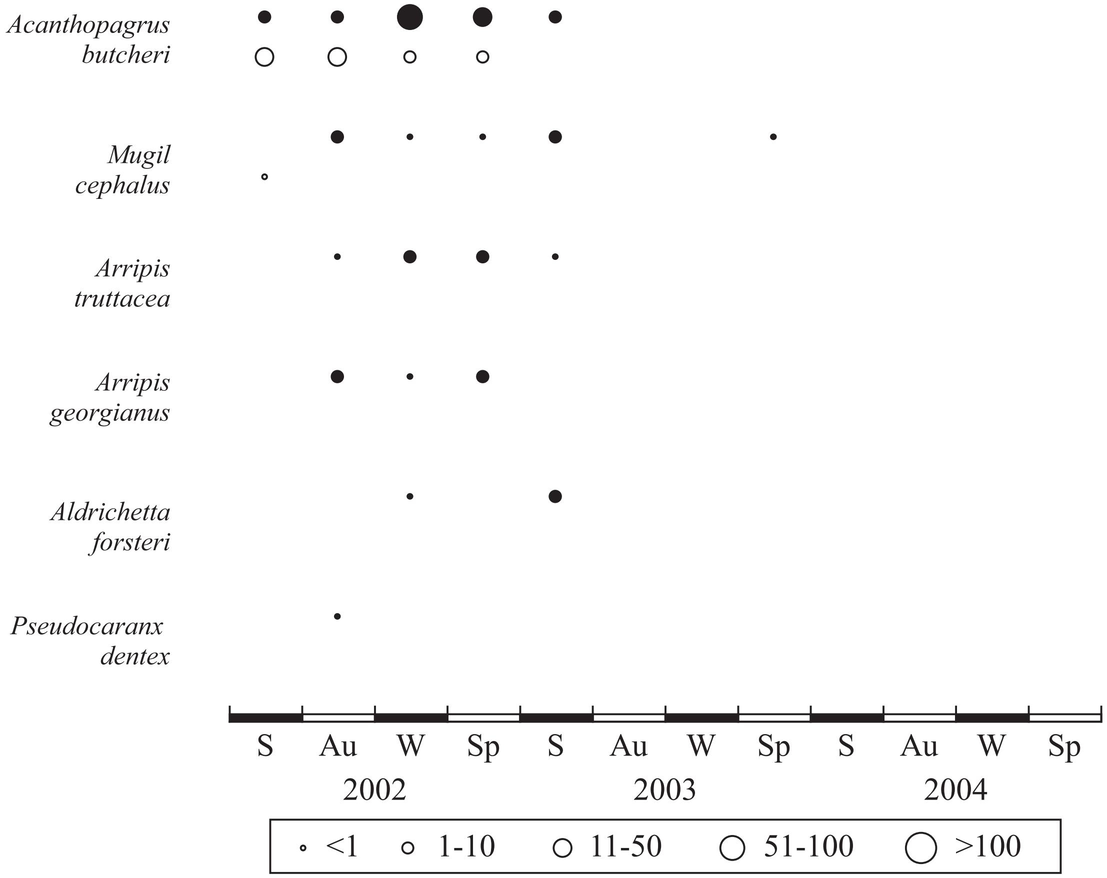

Figure 3.35. Relative catch rates of each fish species in seasonal samples obtained from offshore, deeper waters of the basin (●) and tributary (○) of Hamersley Inlet between summer 2002 and spring 2004. Code at bottom of figure gives the range in mean values for the catch rates in each seasonal sample from each region.

of these estuaries differed significantly (*P*= 0.1%) between estuaries and years, with the Global *R*-statistic being greater for the former variable, *i.e.* 0.443 *vs* 0.132. Consequently, differences between the compositions of the main bodies of each estuary in each of the three years are considered separately.

The differences between the compositions in the main bodies of Stokes, Culham and Hamersley inlets were significant in 2002, 2003 and 2004 (all *P*= 0.1%), and displayed relatively high and similar Global *R*-statistics in each year, *i.e.* 0.403-0.488. Each combination of pairwise comparisons between the main bodies of Stokes Inlet and both Culham and Hamersley inlets increased progressively between 2002 and 2004, with the most pronounced increase being between Stokes and Hamersley inlets, *i.e.* 0.073 in 2002 to 0.761 in 2004. The reverse trend pertained between Culham and Hamersley inlets, declining from 0.595 (*P*= 0.1%) in 2002 to 0.000 (*P*= 100%) in 2004.

When the density data for the basins and main tributaries of Stokes, Culham and Hamersley inlets were subjected to ordination in each of 2002, 2003 and 2004, the points on the plots showed a progressive change from 2002 to 2004 (Figs 3.36a, b, c). Thus, while the vast majority of points for the main bodies of Stokes and Hamersley inlets and a number of points for Culham Inlet intermingled on the left side of the plot in 2002, the vast majority of points for Stokes Inlet formed a discrete groups on the left sides of the plot, with those for Culham and Hamersley inlets forming a very tight group in the upper right hand corner, with two of those from Stokes Inlet (*cf* Figs 3.26a, b, c).

SIMPER demonstrated that the difference in the composition between the basins and main tributaries of Stokes, Culham and Hamersley inlets resulted from greater densities and frequencies of occurrence of *A. butcheri* in Stokes Inlet in each year, with this species declining from low and relatively high levels in Culham and Hamersley inlets, respectively, in 2002 to zero in both estuaries by 2004. Hamersley Inlet was further distinguished from both Stokes and Culham inlets in 2003 by low numbers of *M. cephalus* in the spring of that year (see also Figs 3.30, 3.32. 3.35).

3.4 DISCUSSION

This component of our FRDC project focused, in particular, on ascertaining the effects of highly elevated salinities on the fish faunas of normally-closed estuaries on the south coast of Western Australia. Our elucidation of these deleterious effects was enhanced by the opportunity that arose to compare the changes that occurred in the number of species, abundance and species composition of fishes in three estuaries in which salinities rose from less than 50 just prior to or at the beginning of the three year period of seasonal sampling to markedly different levels by the end of this study. As mean seasonal salinities of the basin and lower reaches of the main tributary river of Stokes Inlet rose slowly and never exceeded 65, the regime in Stokes Inlet acted as a type

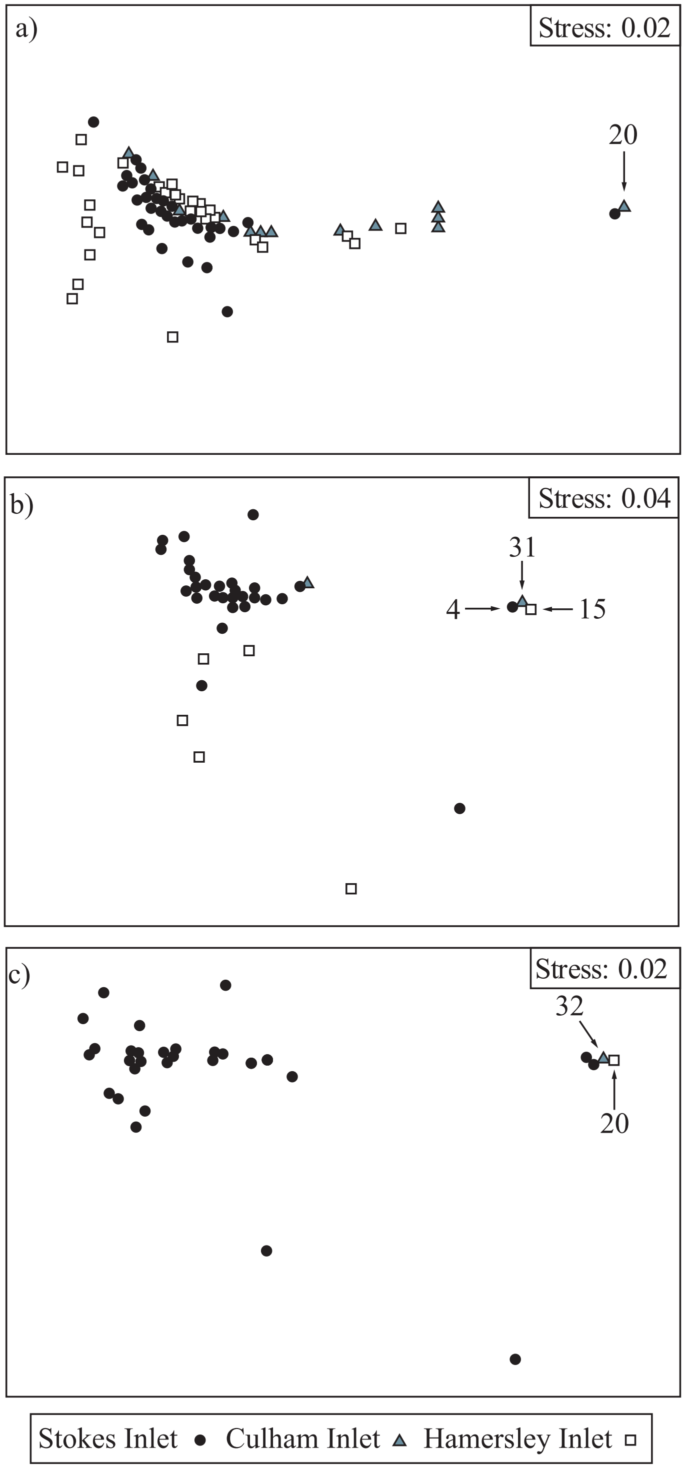

Figure 3.36. Non-metric multidimensional scaling (MDS) ordination of the catch rates of each species in replicate samples of fish obtained from offshore, deeper waters of the basins and tributaries of Stokes, Culham and Hamersley inlets for the years a) 2002, b) 2003 and c) 2004.

of control. In contrast, mean seasonal salinities eventually reached 143 in Hamersley Inlet and 293 in Culham Inlet. Furthermore, the massive amounts of evaporation that led to these extremely high salinities meant that there was little water left in the lower reaches of these latter two estuaries and particularly in upper part of the basin of Hamersley Inlet and throughout the whole of the basin of Culham Inlet. Not surprisingly, the combination of highly elevated salinities and greatly reduced water levels in Culham and Hamersley inlets had a disastrous impact on the fish populations in these estuaries. However, prior to discussing these effects, it is important to understand the characteristics of the ichthyofaunas of the three estuaries at the beginning of the study and whether these are likely to be typical of the estuaries of the central south coast of Western Australia in which region they are located.

Characteristics of the fish faunas of the three normally-closed estuaries

The fish fauna of Stokes Inlet, which typically does not undergo the same extreme salinity changes as the Culham and Hamersley inlets, was highly depauperate. This point is emphasised by the fact that extensive seine netting of nearshore, shallow waters and gill netting of offshore, deeper waters of the basin and lower reaches of the main tributary of this estuary yielded only 12 species. The most abundant of these species, by far, were two small species, an atherinid (*Atherinosoma elongata*) and a goby (*Pseudogobius olorum*) and the far larger and commercially and recreationally important species *Acanthopagrus butcheri*. Each of these species is also highly abundant in estuaries throughout south-western Australia and complete the whole of their life cycle within these systems. The fauna of Stokes Inlet also contained populations of *Cnidoglanis macrocephalus* and *Platycephalus speculator*, the individuals of which likewise complete their life cycles in estuaries. However, these species, which are also fished recreationally and commercially, were far less abundant and are represented by discrete marine populations. The above five species and the two other estuarine-spawning species found in Stokes Inlet (*Engraulis australis* and *Favonigobius lateralis*) were all caught during extensive sampling of the normally-closed Wellstead Estuary, which is located further to the west on the south coast of Western Australia and which becomes markedly hypersaline (Young & Potter, 2002). They were also recorded during both a two year study of the seasonally open and large Wilson Inlet and during a one year study of the permanently open and smaller Nornalup-Walpole Estuary, both of which are situated even further to the west and in which salinities typically do not exceed 40 (Potter *et al.*, 1993; Potter & Hyndes, 1994).

The number of recorded fish species that complete their life cycles within estuaries increases from seven in Stokes Inlet to 9 to 12 in the normally-closed Wellstead, seasonally-open Wilson and the permanently-open Nornalup-Walpole Estuary (Potter *et al.*, 1993; Potter & Hyndes, 1994; Young & Potter, 2002) and 14 in the permanently-open Blackwood Estuary at the western extremity of the south coast of Australia (Valesini *et al.*, 1997). This increase in the numbers of estuarine species in a western direction along the south coast was due to the appearance in samples of abundant species such as *Amoya bifrenatus*, *Afurcagobius suppositus*, *Leptatherina presbyteroides* and *Hyporhamphus malonochir* and in the Blackwood Estuary of *Apogon ruepellii*. Further estuarine spawning species, *e.g. Platycephalus endrachtensis, Craterocephalus mugiloides, Atherinomorus vaigiensis* and *Amniataba caudavittatus*, which have tropical or subtropical affinities, were caught in estuaries along the lower west coast of Australia and thus led to the number of species that belong to this guild becoming even greater in these estuaries (Potter *et al.*, 1990).

From the above trends, it is clear that the number of species that complete their life cycles in estuaries increases in a westward direction along the south coast and then northwards along the lower west coast of Australia, reflecting limits to the southwards penetration of warm water species. It is thus concluded that the highly depauarate nature of the current estuarine spawning component of the fish fauna of the basin and lower reaches of the main tributary of Stokes Inlet is likely to largely reflect the influence of the location of this estuary. However, the presence in the upstream pools of Culham Inlet of *Leptatherina wallacei*, which typically lives in the reduced salinities found in the upper reaches of estuaries (*e.g.* Prince *et al*., 1982), suggests that this species may well have occurred in the main body of Stokes Inlet in earlier times when salinities were not as high as they are at present.

Extensive seine and gill netting of the main body of Culham and Hamersley inlets yielded only six and ten species, respectively, of which five and four, respectively complete their life cycles within these systems. In comparison with the catches in Stokes Inlet, those in the Culham and Hamersley inlets did not contain *E. australis*, *C. macrocephalus* and *P. speculator* and those in Hamersley Inlet also did not include *F. lateralis*. As these four species are also represented by discrete marine populations, from which they were probably derived, it is possible that their absence from the main body of the Culham and Hamersley inlets reflects a lesser ability than the solely estuarine species to osmoregulate in the very wide range of salinities found in these two estuaries. Although *L. wallacei*, which was not found in the main body of the other two estuaries, was caught in the main tributary of Culham Inlet, where it was represented only by a single individual that was caught in autumn 2000.

Changes in ichthyofaunas with increasing salinity

To facilitate the development of generalisations regarding the impact of increasing salinities on the fish faunas of the Stokes, Culham and Hamersley inlets, we have inter-related the trends exhibited by the mean number of species and mean densities/catch rates of fish and the compositions of the fish faunas.

The mean seasonal number of species in nearshore, shallow waters of the main body of Stokes Inlet was significantly greater in 2002 than in both 2003 and 2004, which was largely due to *A. butcheri* and *F. lateralis* being caught more consistently during the first year and to *E. australis* being caught only in that year. However, *A. elongata* and *P. olorum* were each caught in both the basin and lower reaches of the main tributary of Stokes Inlet in each season of 2003 and 2004, as well as in each of those of 2002. Unlike the number of species, the mean seasonal densities in the nearshore, shallow waters of the main body of Stokes Inlet showed no conspicuous overall tendency to decline during the study. This reflects, in part, the fact that the mean densities of by far the two most abundant species, *A. elongata* and *P. olorum*, remained high throughout the whole of the three year period of this study.

In marked contrast to the situation in Stokes Inlet, the mean number of species and mean density of fish in the main body of Culham Inlet both declined precipitously during the second half of 2002 and remained very low in subsequent seasons through to summer 2004, after which no fish were caught during the rest of the study. The decline in the number of species was attributable to the sequential loss of *L. wallacei*, *F. lateralis* and *A. butcheri* from samples during 2002 and then of *P. olorum* during 2003 and finally of *A. elongata* early in 2004. These sequential changes occurred as salinities continued to rise markedly during the study period and presumably reflect differences in the salinity tolerances of those species. *Leptatherina wallacei*, *F. lateralis* and *A. butcheri* were rarely caught in salinities greater than 30, 50 and 65, respectively, while *P. olorum* and *A. elongata* were not caught in salinities greater than 76 and 136, respectively, in the basin and main tributary of Culham Inlet. The last value is greater than the maximum salinity of 122 in which *A. elongata* was recorded in the Wellstead Estuary (Young & Potter, 2002) and approached the 142 recorded for a cyprinid in a saline lake, which is apparently the highest salinity in which a teleost has been found naturally elsewhere (Haney, 1999). Although the mortality of these fish species in the main body of Culham Inlet is clearly related to the progressive attainment of salinity levels that are apparently lethal for those species, the potential role of reduced dissolved oxygen concentrations cannot be ignored, recognising that oxygen saturation levels are inversely related with salinity. However, mean seasonal dissolved oxygen concentrations in the basin of Culham Inlet remained greater than *ca* 5 mg L^{-1} in all but one season of 2002 and 2003 and were typically even greater in its main tributary during these years. Since virtually all fish had died in the basin and main tributary of Culham Inlet by the end of 2003, it seems unlikely that the level of dissolved oxygen concentration played a major role in the mortalities of fish in those regions.

Although the number of species and density of fish in nearshore, shallow waters of the basin of Hamersley Inlet also underwent marked declines during the study, these changes were not as extreme as in the basin of Culham Inlet. It is thus highly relevant that, although salinities likewise increased markedly, that rise was not as pronounced as in Culham Inlet and thus the levels reached in Hamersley Inlet were far less. This accounts for the fact that many *A. elongata*, the most salt tolerant of all of the fish species, were still being caught in nearshore, shallow waters of Hamersley Inlet during the last year of sampling. This atherinid, the sole fish species to be caught in these waters in 2004, was still obtained in appreciable numbers in the spring of that year at a site in the basin of Hamersley Inlet at which the salinity was *ca* 140 and in low numbers at two other sites where salinities were *ca* 143. Remarkably, the dissolved oxygen concentration had declined to only *ca* 2.5 mg L^{-1} at the sites at which these atherinid individuals were caught. However, as in Culham Inlet, all other fish species had died before dissolved oxygen concentrations had declined below *ca* 5 mg L^{-1}, again supporting the view that salinity is the main environmental variable leading to mortality in these normally-closed estuaries.

The trends exhibited by the number of species and catch rates of fish in offshore, deeper waters of the main body of the Stokes, Culham and Hamersley inlets were similar to those for number of species and densities of fish in the nearshore, shallow waters of these three estuaries. Thus, between 2002 and 2004, these two variables did not undergo a marked change in Stokes Inlet, but did decline markedly in both Culham and Hamersley inlets. This reflected the presence of *A. butcheri* and occasionally a few individuals of other estuarine spawning and also marine species in the samples collected from Stokes Inlet throughout the study period, whereas few or no fish were caught in either the Culham or Hamersley inlets after the summer of 2003. The above differences among estuaries are again clearly related to the fact that salinities remained below 65 in the offshore, deeper waters of Stokes Inlet, whereas they rose to far higher levels in the corresponding waters of Hamersley Inlet and even more particularly in Culham Inlet.

4.0 MASSIVE MORTALITIES OF *ACANTHOPAGRUS BUTCHERI* FOLLOWING EXTREME INCREASES IN SALINITY

4.1 INTRODUCTION

This short chapter describes the very high mortalities to which *A. butcheri* was subjected in Culham and Hamersley inlets following extreme increases in salinity and provides an estimate of the salinities that cause stress and are apparently lethal for this species.

4.2 MATERIALS AND METHODS

During reconnaissance sampling trips in 2001, aimed at identifying sampling sites for this FRDC project to study the ichthyofaunas of the Culham and Hamersley inlets, we observed massive mortalities of Black Bream in Culham Inlet. During one of those sampling trips, in April 2001, we photographed these fish mortalities along the bank of the main tributary (Phillips River) of Culham Inlet. The photographs were later subjected to computer enhancement to estimate the numbers of dead fish in one metre long transects along the banks of this river (Figs 4.1, 4.2). These counts were used, in conjunction with the distances of the stretches of dead fish along the bank, to estimate the total number of fish that died in that river in autumn 2001.

4.3 RESULTS

The very large discharge that followed exceptionally heavy rainfall in the early summer (December) of 1999 led, in the following month, to the breaching of the sand bar at the mouth of Culham Inlet and thus to a marked reduction in water level in its basin. Rainfall during the ensuing months of 2000 was very low and the water level thus declined even further during the following summer.

Figure 4.1. Photograph of band of dead *Acanthopagrus butcheri* lining the banks of the Phillips River.

Figure 4.2. Photograph of accumulation of dead black bream just downstream of the rock bar on the Phillips River and close-up (top right-hand corner) of area denoted by the rectangle.

In February 2001, a few dead Black Bream were found along the banks and in the waters of the basin of Culham Inlet and lower part of the Phillips River. At this time, maximum water levels in the basin and river had declined to less than 1 m and salinities were 77 and 67, respectively. The total length (TL) of dead fish ranged from 63-152 mm, with a mean ±SE of 112 ±9.9 mm. Seine netting of *ca* 270 m^2 of nearshore waters of the middle region of the Phillips River yielded 57 *A. butcheri*, ranging in TL from 49-95 mm, with a mean ±SE of 76 ±1.3 mm.

In April 2001, when salinities in the basin and river had increased to *ca* 82 and 95, respectively, very large numbers of dead Black Bream were found lining *ca* 5.8 km of the shore of the estuarine reaches of the Phillips River (Figs 4.1, 4.2). The TL of a subsample ranged from 38-174 mm, with a mean ±SE of 77 ±6.2 mm. It is assumed that, following their death, these fish had floated to the surface and then been transported by wind-driven currents to the waters lining the river bank. Subsequent rapid lowering of the water level, through high evaporation, resulted in the dead fish forming an approximately 0.3 m wide band along the bank (Fig. 4.2). From photographic analyses, 1.3 million ±400,000 Black Bream were estimated to have died in the estuarine reaches of the Phillips River during the high salinities that developed in late summer to mid-autumn of 2001. Seine netting at regular intervals along the Phillips River in April 2001 yielded only three Black Bream, all of which were caught directly downstream of the natural rock bar on that river and which, because of low water levels, would have prevented Black Bream moving upstream at this time. These fish were lethargic and the largest (332 mm) possessed numerous, large salt sores on its body and tail. Thus, few *A. butcheri* survived the very high salinities that developed in the lower Phillips River in late summer to mid-autumn of 2001 and the few that did survive were in poor condition.

Examination of sectioned sagittal otoliths of the dead Black Bream collected in February and April 2001 showed that these fish belonged to the 0+ or 1+ age classes, respectively. They were thus spawned in the springs of 2000 and 1999, respectively (see Sarre & Potter (1999, 2000) for details of ageing and reproductive biology of Black Bream). The single large individual caught in the Phillips River in April 2001 was nine years old.

Salinities in the basin of Hamersley Inlet rose sharply from 54 in October 2002 to 83 in January 2003. A massive mortality of Black Bream occurred in this estuary shortly thereafter in February 2003 (G. Bastyan, Department of Environment, Western Australia), when, due to some rainfall, salinities had remained similar to those in January 2003. Although fish were still present on the banks during our next visit in April 2003, they had decomposed to such an extent that they could not be counted. As this species has not been recorded in Hamersley Inlet during seasonal sampling in the two years since February 2003, all of the Black Bream in the basin and lower reaches of the tributary (*i.e.* below the rock bar) of Hamersley Inlet are assumed to have died as a result of those extreme salinities. The fact that our gill netting throughout Hamersley Inlet between the summer of 2002 and just prior to the fish kill yielded on average 129 Black Bream per season emphasises the extent of that mortality.

4.4 DISCUSSION

Although cultured juveniles of *A. butcheri* could be maintained in the laboratory in salinities of 60, they were osmotically stressed and grew far slower than in salinities < 35

(Partridge & Jenkins, 2002). Furthermore, we have observed salt sores on Black Bream in Stokes Inlet, *ca* 120 km east of Culham Inlet, when salinities reached *ca* 60. From the above observations, and the salinities at which Black Bream died in Culham and Hamersley inlets, *A. butcheri* apparently become stressed as salinities reach 60 and typically do not survive salinities beyond 85. Laboratory studies have shown that the critical salinity maximum of the congeneric *Acanthopagrus latus* ranged from 54-69 and decreased with increasing temperature (Jian *et al.*, 2003) and that another sparid *Rhabdosargus holubi* cannot tolerate salinities greater than 70 (Blaber, 1973).

In the basin of Wellstead Estuary, *ca* 80 km to the west of Culham Inlet, *Atherinosoma elongata* was apparently the only fish species to survive when salinities rose to 122 (Young & Potter, 2002). A remarkable example of salinity tolerance is provided by *Cyprinodon variegatus*, which can live in salinities ranging from 0 to 142 (Haney, 1999). However, laboratory studies showed that the routine metabolism of this species decreased in salinities > 50, possibly due to a reduction in the osmotic permeability of particularly the gills and thus of the potential for oxygen uptake (Nordlie *et al.*, 1991).

The mortalities of Black Bream in Culham and Hamersley inlets occurred in mid-summer to early autumn, when water temperatures attain their maxima of *ca* 25°C and dissolved oxygen concentrations were <4 mg L^{-1} and would have thus increased the stress to which this species was subjected to at this time. Moreover, the rock bars in the Phillips and Hamersley rivers prevented *A. butcheri* from moving further upstream and thus away from regions of very high salinity. Such a movement in response to high salinities was exhibited by Black Bream and other mobile fish species in the Beaufort Inlet and Wellstead Estuary (Lenanton and Hodgkin, 1985; Young & Potter, 2002) and by a suite of fish species in the St Lucia Estuary in South Africa (Wallace, 1975). However, more than 6000 fish, representing at least 11 species, died as salinities rose above 90 in the Seekoei Estuary in South Africa when it was temporarily-closed (Whitfield, 1999).

In Culham Inlet, the dead Black Bream collected from the banks in February 2001 were significantly longer than those caught live in that month and those collected dead in April 2001 (both $P < 0.05$). This suggests that large fish are more susceptible than smaller fish to high salinities, which is consistent with juvenile fish typically being able to tolerate a greater range of salinities and more pronounced salinity fluctuations than older fish (Kinne, 1964).

The massive mortalities of Black Bream we recorded in two normally-closed estuaries on the central south coast of Western Australia demonstrate that increases in salinity to levels between *ca* 65 and 85 have a highly detrimental impact on the populations of this sparid and can even result in the "extinction" of a population of this species in an estuary. Although high salinities developed largely due to high rates of evaporation in relatively shallow waters, it was enhanced by an increase in the salt load in runoff as a result of extensive land clearing (see Pen, 1999; Brearley, 2005). Thus, for conserving Black Bream, sufficient vegetation must be maintained or replanted in the catchments of estuaries on the central south coast of Western Australia to restrict the amount of surface salt available for runoff (Pen, 1999; Bowyer, 2001; Massenbauer, 2006). It should also be recognised that Black Bream will be particularly susceptible to highly elevated salinities when barriers restrict its upstream migration to riverine areas of lower salinity which can act as refugia.

The details of this chapter have been published as follows: Hoeksema, S.D., Chuwen, B.M. and Potter, I.C. (2006). Massive mortalities of the Black Bream *Acanthopagrus butcheri* (Sparidae) in two normally-closed estuaries, following extreme increases in salinity. *Journal of the Marine Biological Association of the United Kingdom* **86**, 893-897.

5.0 BIOLOGY OF THE BLACK BREAM *ACANTHOPAGRUS BUTCHERI*

5.1 INTRODUCTION

5.1.1 *Distribution and fisheries*

The Black Bream, *Acanthopagrus butcheri*, which is endemic to southern Australia, including Tasmania, is found southwards of Shark Bay at 24º 50' S, 113º 40' E on its west coast (Hutchins & Swainston, 1996) and Myall Lake at 32º 26' S, 152º 24' E on its east coast (Rowland, 1984). Although the Black Bream completes its life-cycle within estuaries (Potter & Hyndes, 1999), it is occasionally flushed out into coastal marine waters from permanently-open estuaries during periods of extreme freshwater discharge, and also sometimes from seasonally and normally-closed estuaries when freshwater discharge is sufficiently high to breach the bar at the estuary mouth (*e.g.* Hutchins & Swainston, 1996; Sarre & Potter 2000; Norriss *et al.*, 2002). Since there is no evidence that this species is represented by permanent populations in coastal marine waters, many of those individuals that are flushed into marine waters may subsequently re-enter estuaries. Populations of Black Bream are also found in a number of land-locked saline habitats in south-western Australia (*e.g.* Lenanton, 1974; Sarre & Potter, 2000), but the origins of these populations, which have probably resulted from "stocking", are not known (Chaplin *et al.*, 1998).

Acanthopagrus butcheri, which attains a maximum length of *ca* 530 mm and a maximum weight of 3450 g (Hutchins & Swainston, 1996), is an important recreational and commercial species and is often the main target for estuarine anglers, particularly in Western Australia (*e.g.* Caputi, 1976; Loneragan *et al.*, 1987; Penn *et al.*, 2005). This species also dominates the catches of many commercial fisheries in the estuaries of both Western Australia and Victoria (*e.g.* Hall & MacDonald, 1985; Lenanton & Potter, 1987; Department of Fisheries, Western Australia: Catch and Effort Statistics). The commercial fishery for Black Bream in Culham Inlet used to be the most important of any estuary in south-western Australia, yielding, in 1992/93, a total catch of 77 tonnes, which represented 74% of the total catch of this species taken in that region (Hodgkin, 1997). However, changes at the estuary mouth in the middle of 1993, aimed at reducing water levels in the estuary and thus the potential problems of flooding to local farmers, led to the bar at the mouth of Culham Inlet being breached for the first time in at least 70 years. The consequent release of large volumes of water, and thus greatly reduced water levels, resulted in the collapse of the Black Bream fishery after 1993 (Hodgkin, 1997).

Tagging experiments provide no evidence that, in south-western Australia, Black Bream move between estuaries (Lenanton, *et al.*, 1999; Dibden *et al.*, 2000). Furthermore, there are small but significant genetic differences between the populations of this species in different south-western Australian estuaries (Chaplin *et al.*, 1998). The above data provide overwhelming circumstantial evidence that the individuals of this sparid are restricted to their natal estuaries in south-western Australia. The populations of *A. butcheri* in the different estuaries of this region are thus considered to comprise separate breeding stocks, a feature which has important implications for managers when they are developing policies for conserving the stocks of this species (Norriss *et al.*, 2002).

5.1.2 *Reproductive biology*

Studies by Sarre & Potter (1999) and Haddy & Pankhurst (1998) demonstrated that, in Western Australia and Tasmania, *A. butcheri* is a rudimentary hermaphrodite, *i.e.* each individual possesses ovotestes, but spends the whole of its adult life as either a female or a male. In contrast, Rowland & Snape (1994) concluded that *A. butcheri* is not hermaphroditic in the Gippsland Lakes in Victoria, because its individuals did not contain ovotestes, but that it is a protogynous hermaphrodite in the Hoyers and Myall Lakes in New South Wales, *i.e.* it starts life as a female and later changes to a male. However, Dr G. Sarre (Northam TAFE, unpubl. data) found that the gonads of all of the 40 *A. butcheri* he examined from the Gippsland Lakes possessed ovotestes.

Black Bream spawn in spring and summer in south-western Australia and in salinities that range widely from 3.5-8, as in the intermittently open Moore River Estuary on the west coast, to 41-45 in the Wellstead Estuary on the central south coast (Sarre & Potter, 1999). Since spawning commenced earlier in the latter estuary than in other estuaries in which salinities did not exceed that of full-strength sea water, *i.e.* 35, it is possible that, in those estuaries where salinities rise rapidly to high levels during late winter and early spring, selection pressures have led to acceleration in the timing of gonadal recrudescence and maturation.

In the Swan River Estuary, Black Bream reach maturity at the end of their second year of life when they have reached a total length of *ca* 215 mm (Sarre & Potter, 1999). However, in the Moore River Estuary and Nornalup-Walpole Inlet, in which early growth is not as rapid, maturity is reached at a smaller size but older age. This indicates that maturity is dependent on the attainment of at least a certain minimum size. However, in the Wellstead Estuary, *A. butcheri* reaches maturity at only two years of age, as in the Swan River Estuary, but at a much smaller size. The combination of a young age and small size at maturity may reflect the influence of selection pressures brought about by high mortality rates and/or heavy fishing pressure in Wellstead Estuary (Sarre & Potter, 1999).

5.1.3 *Growth and recruitment success*

The growth of *A. butcheri* varies greatly among estuaries (*e.g.* Hobday & Moran, 1983; Morison *et al.*, 1998; Sarre & Potter, 2000), which has been attributed to differences in one or more of a number of factors, including water temperature, salinity, diet and genetic composition (*e.g.* Morison *et al.*, 1998; Sarre & Potter, 2000). However, Partridge *et al.* (2003) demonstrated that Black Bream cultured from brood stock from two adjacent estuaries on the lower west coast of Western Australia, in which this species grew at markedly different rates (Sarre and Potter, 2000), grew at the same rate when reared under identical environmental and dietary conditions. This implies that differences in growth rates among wild populations of *A. butcheri* reflect differences in environmental factors rather than genetic variation.

The recruitment success of *A. butcheri* has been shown to vary in the Gippsland Lakes in Victoria (Hobday & Moran, 1983, Morison *et al.*, 1998) and in the Wellstead Estuary in south-western Australia (Sarre & Potter, 2000). Hobday & Moran (1983) found evidence for a correlation between strong year classes and relatively dry springs and between weak year classes and low water temperatures and high spring river flows. Similarly, Sarre & Potter (2000) found evidence that there was little or no spawning and/or recruitment success in the Wellstead Estuary in those years when discharge was particularly heavy and the sand bar at the estuary mouth was breached and thereby provided the potential for numbers of Black Bream, and particularly of their juveniles, to be flushed out of the estuary. In contrast, in the Swan River, Moore River and Nornalup-Walpole estuaries, which lie in regions of south-western Australia where rainfall is greater and more seasonally predictable, Black Bream exhibited more consistent patterns of recruitment among years, with all age classes up to 15+ being represented (Sarre & Potter, 2000).

5.1.4 *Dietary compositions*

In estuaries, sparids such as Black Bream feed on a wide range of food items, including macrophytes, diverse invertebrate taxa and fish (*e.g.* Blaber, 1974, 1984; Sarre *et al.*, 2000). However, studies on *Sparus auratus* in two coastal lagoons in the Mediterranean demonstrate that this sparid fed on a more diverse range of prey in the lagoon that contained the most diverse range of potential benthic macroinvertebrate prey (Tancioni *et al.*, 2003). The diets of sparids undergo size-related changes. For example, although copepods are the main prey in the diet of all size classes of the sparid *Oblada melanura* in the Adriatic Sea, an increase in body size is accompanied by a decrease in the proportion of planktonic organisms and an increase in benthic prey (Pallaoro *et al.*, 2003). Furthermore, in the Mediterranean, the juveniles of the sparid *Sarpa salpa* feed on plankton, whereas its adults ingest plant material (Havelange *et al.*, 1997). The diet of *A. butcheri* also changes as this species increases in size (Sarre *et al.*, 2000). Examination of whether seasonal changes occur in dietary composition demonstrated that the diet of *Oblada melanura* underwent little seasonal variation (Pallaoro *et al.*, 2003) and that of *Pagrus caruleosticus* changed only slightly with season (Dia *et al.*, 2000).

The dietary compositions of Black Bream were shown to vary markedly among four estuaries and a saline lake in south-western Australia and between different regions within one of those estuaries, namely the Swan River Estuary (Sarre *et al.*, 2000). Those marked dietary differences presumably reflected differences in the amount and type of food available and emphasise the extent to which this species can feed opportunistically. Although such differences could contribute to the differences in growth found in those water bodies, it was concluded that variations in growth were more likely to be related to differences in density (Sarre & Potter, 2000; Sarre *et al.*, 2000).

Most studies on the diets of fish in estuaries have focused on individual species or on comparing the dietary compositions of different species in the same system (*e.g.* Almeida, 2003; Maes *et al.*, 2003; Platell *et al.*, 2006). No study has explored the ways in which the dietary compositions of a species vary among estuaries in the same region, which, through exhibiting different extents of degradation, are likely to differ in the relative species compositions of their potential prey. Furthermore, most comparisons between the diets of estuarine fishes have not taken into account such factors as body length and time of year (Elliott *et al.*, 2002).

5.1.5 *Aims and hypotheses*

The overall aim of this component of this study was to obtain sound biological data for *A. butcheri* in three normally-closed estuaries in the central south coast region of Western Australia, namely the Stokes, Culham and Hamersley inlets, which vary in the extent to which they become hypersaline. However, the sampling regime was designed specifically so that it would facilitate the acquisition of data that could be used to test the following hypotheses:

- Black Bream typically spawn in spring and early summer, but commence breeding earlier in estuaries where salinities are particularly high in the early part of that period.
- Marked interannual differences in environmental conditions, such as salinity, dissolved oxygen concentration and heavy water discharge, will result in marked variation in spawning and/or recruitment success. This will be reflected by some strong year classes, some weak year classes and some year classes that are not represented in the population.
- The growth rates of *A. butcheri* in the Stokes, Culham and Hamersley inlets will vary as a result of the marked differences in environmental conditions, and thus presumably of the composition of the potential food sources in those estuaries.
- Differences in growth rates in the three estuaries will be reflected in differences in the length and/or age at first maturity of *A. butcheri*.

- Upstream riverine pools will act as refugia for *A. butcheri* during those periods when salinities in the basin and lower reaches of the main tributaries reach particularly high levels and dissolved oxygen levels fall markedly.
- The diets of Black Bream in Stokes Inlet will be more diverse and differ in composition from that of the Hamersley and Culham inlets in which salinities rise to far higher levels and are thus likely to contain a less diverse range of potential prey.
- Although the diversity of prey is likely to be less in the latter two estuaries, we still hypothesise that the diet of Black Bream will undergo size-related changes in those estuaries, as occurs elsewhere in south-western Australia (Sarre *et al.* 2000). Such changes would reduce the potential for competition among the individuals of this species, a situation that is particularly advantageous when the range of potential food resources is restricted. We also explored whether there is evidence of seasonal changes in dietary composition.
- Finally, we explore whether the growth of *A. butcheri* among estuaries is obviously related to variations in diet or whether such differences were more likely to reflect differences in the density of this sparid.

5.2 METHODS

5.2.1 *Removal and preparation of gonads, otoliths and foreguts*

The total length and wet weight of each Black Bream were recorded to the nearest 1 mm and 0.1 g. The gonads of each fish, which could be identified under a dissecting microscope as either an ovary or testis, were removed, weighed to the nearest 0.01 g and assigned to one of eight gonadal maturity stages according to the criteria of Laevastu (1965) (see Table 5.1 in Results). The gonadosomatic index (GSI) of each *A. butcheri* in each estuary was calculated using the equation GSI = W1/W2 x 100, where W1 = wet weight of the gonad in g and W2 = total wet weight of the fish in g. Ovaries from up to 10 females were collected from each estuary in each season, fixed in Bouin's solution for 24-48 h and preserved in 70% ethanol. These gonads were later dehydrated in an ascending series of alcohols and their mid-region was embedded in paraffin wax, cut transversely into *ca* 6 µm thick sections and stained with Mallory's trichrome. The resultant histological slides were used to confirm that the macroscopic maturity staging criteria used were valid and to help determine the spawning period and when spawning peaks (see Table 5.1, Fig. 5.1 in Results).

The two sagittal otoliths of each fish were removed and stored in paper envelopes. One of the otoliths of each fish was later placed in resin, sectioned transversely through its primordium and mounted on a glass slide using DePX mounting adhesive. The opaque zones (annuli) on a section of each otolith were counted twice on different days under a dissecting microscope using reflected light and, on the few occasions (<10%) when the counts differed, the opaque zones were counted for a third time. The third count invariably agreed with one of the first counts and was the number recorded. The opaque zones on the otoliths of a subsample of 100 fish covering the full size range of Black Bream were counted by both B. Chuwen and A. Hesp. The counts of the two readers agreed in all but two cases and, after discussion, both readers came to the same conclusion regarding the correct number.

The foregut of each *A. butcheri* was examined macroscopically and recorded as either empty or containing food. Foreguts containing food were removed from randomly-selected seasonal subsamples of a wide size range of up to 30 Black Bream from the basin and lower reaches of the tributary of Stokes Inlet and stored in 70% ethanol. The same procedure was adopted for Black Bream from comparable regions of the Hamersley and Culham inlets until summer 2003 and autumn 2002, respectively, after which fish were no longer caught in those regions (see later). This procedure was also adopted for fish caught in upstream pools in Culham Inlet between autumn 2002 and winter 2004.

The fullness of each foregut was estimated visually on a scale of 1 (10% full) to 10 (100% full). The contents of each foregut were viewed under a dissecting microscope using reflected light and each dietary item identified to the lowest possible taxon. The frequency of occurrence of each dietary item in the foreguts of Black Bream from each estuary was recorded (% F) and the percentage contribution of each dietary item to the volume of the gut contents of each fish

(% V) was estimated. Each dietary item was then allocated to one of 33 taxonomic groups, subsequently referred to as dietary categories.

The above percentage volumetric data for individual fish were used to determine, for each estuary, the mean percentage contribution of each dietary category to the overall volume of the diets of all fish and of each of their sequential 50 mm length classes. The same data were also used to calculate the mean values ±95% CIs for the Shannon-Wiener diversity index for each length class in each estuary.

5.2.2 *Analysis of reproductive data*

The lengths and ages at which 50% of the females and males of *A. butcheri* reach sexual maturity (L_{50}s and A_{50}s, respectively) and their 95% confidence intervals were estimated for fish in the Stokes Inlet. The L_{50}s were calculated by using logistic regression analysis using data collected during the spawning season to determine the probability that a fish of each length will possess gonads at stages III-VIII. Note that, during the spawning season, fish with gonads at stages III-VI have the potential to spawn or have commenced spawning, while those with gonads at stages VII or VIII will have recently completed spawning. Consequently fish with gonadal stages of III-VIII are termed mature. The data were re-sampled randomly and analysed to create 100 sets of bootstrap estimates for the parameters of the logistic function relating probability to length. The form of the logistic equation used in this analysis is

$$P_L = \left[1 + \exp\left(-\log_e(19) \frac{L - L_{50}}{L_{95} - L_{50}} \right) \right]^{-1},$$

where P_L is the probability that a fish is mature at length L, and L_{50} and L_{95} are the total lengths at which 50 and 95% of individuals, respectively, are mature.

The ages at which female and male *A. butcheri* reached maturity (A_{50}s) in Stokes Inlet were estimated from the inverse von Bertalanffy growth equation

$$A_{50} = t_0 - \frac{1}{k} \log_e \left(1 - \frac{L_{50}}{L_\infty} \right),$$

using the corresponding values for t_0, k and L_∞ determined for each sex during the present study (see Stergiou, 1999).

Due to the absence of smaller individuals of *A. butcheri* (<120 mm) in the samples from the Culham and Hamersley Inlets during the spawning season (see results for reasons), the L_{50}s and A_{50}s could not be determined for this species in those two estuaries using logistic regression analysis in the manner described for the population in Stokes Inlet.

The timing, duration and main period of spawning of *A. butcheri* in each of the three estuaries were estimated from a combination of the trends exhibited by the mean monthly GSIs, the monthly prevalences of the various gonadal stages, cytological characteristics of the ovaries and the time of recruitment of the new 0+ age class.

5.2.3 *Determination of age composition and growth in the three estuaries*

The use of marginal increment analysis demonstrated that a single opaque zone is deposited annually in the otoliths of *A. butcheri* in the Swan River Estuary in south-western Australia (Sarre and Potter, 2000). It is thus assumed that an opaque zone is likewise deposited annually in the otoliths of Black Bream in the Stokes, Culham and Hamersley inlets, which are also located in south-western Australia.

The otoliths of each *A. butcheri* caught between October and January were examined to determine whether or not their outermost opaque zone had become delineated at the otolith edge. In cases where the opaque zone had become delineated prior to November, or had not become delineated by November, adjustments were made to the counts of the opaque zones to ensure that each fish was aged correctly.

The age of each individual of *A. butcheri* were determined using (1) date of capture, (2) middle of the main period of spawning for *A. butcheri* in each estuary (= birth date), (3) number of opaque zones in their otoliths and (4) knowledge of the time of year when the new opaque zone in the otoliths typically become delineated, *i.e.* November. The small juvenile fish, which could not be sexed macroscopically, were assigned randomly but in equal numbers to the female and male data sets.

The von Bertalanffy growth function was fitted to the lengths at age of female and male Black Bream from the Stokes and Culham inlets using SPSS (SPSS Inc., 1998). The von Bertalanffy growth equation is $L_t = L_\infty\left(1 - e^{-k(t-t_0)}\right)$, where L_t is the total length at age t years, L_∞ is the mean predicted asymptotic length, k is the growth coefficient and t_0 is the theoretical age at which the fish would have zero length.

The von Bertalanffy growth curves for female and male *A. butcheri* in both the Stokes and Culham inlets were compared using a likelihood-ratio test (Cerrato, 1990). The same likelihood-ratio test was then used to determine whether the growth curves for the corresponding sexes of *A. butcheri* in the Stokes and Culham inlets differed significantly. The null hypothesis (ω), that the growth could be described by a common growth curve for the two sexes or different estuaries or habitats, was compared with the alternative hypothesis (Ω), that the data would be described better by separate growth curves for each sex or estuary. The log-likelihood was determined for the null and alternative hypotheses as λ_ω and λ_Ω respectively, where each was calculated from the product of the values of the probability density function for the deviation of observed lengths at age from those predicted. The test statistic for the likelihood ratio test was then calculated as $2(\lambda_\omega - \lambda_\Omega)$. The null hypothesis was rejected at the $\alpha = 0.05$ level of significance if the test statistic exceeded $\chi^2_\alpha(q)$, where q is the difference between the numbers of parameters in the two growth curves, *i.e.* 3. Because Culham Inlet contains two very different habitat types, *i.e.* (1) the basin and lower reaches of the Phillips River and (2) riverine pools upstream of the rock-bar that is located on the Philips River at a distance of *ca* 7 km from its junction with the basin, von Bertalanffy growth curves were fitted separately to females and males from those regions. Furthermore, since Black Bream in Hamersley Inlet essentially comprised only two age classes, growth curves were not fitted to the lengths at age of fish in this estuary. However, t-tests were used to compare the mean lengths of individuals at a comparable age in that estuary with those in Stokes Inlet and in the regions above and below the rock bar in Culham Inlet.

5.2.4 *Analysis of dietary data*

The first series of multivariate analyses focused on determining whether the overall dietary composition of Black Bream in the Stokes, Hamersley and Culham inlets (excluding those from the pools above the rock pool in the tributary of the last estuary) were influenced by estuary, season and/or fish size and, if so, the relative extents of those differences. Thus, the mean percentage volumetric contributions of the dietary categories to the overall diet of fish of sequential 50 mm length classes, *i.e.* ≤ 49, 50-99 mm *etc*., in each estuary in each season were square-root transformed and subjected to the Bray-Curtis resemblance measure using the PRIMER v6.1.2 software (Clarke & Gorley, 2006). The first comparison used dietary data for length classes of fish > 100 mm, as those size classes were represented in all three estuaries, while the second employed dietary data for the two length classes of smallest fish in the Stokes and Culham inlets, in which, unlike Hamersley Inlet, the individuals of both of these length classes were caught. However, note that, because of their rapid growth, smaller fish were represented only in two seasons and thus did not provide a sufficient number of mean seasonal values for the dietary samples to test statistically for differences between the compositions of these length classes in those two estuaries. Thus, for such comparisons, the dietary data for individuals within each length class were randomly separated into groups of three and then meaned (for rationale and further details of this randomisation procedure see Platell & Potter, 2001).

The matrices produced for the dietary data for length classes both above and below 100 mm were each subjected to multidimensional scaling (MDS) ordination and, where appropriate, a series of one-way Analyses of Similarities (ANOSIM) tests were used to determine whether the diets of Black Bream were influenced significantly by estuary, season and/or fish length (Clarke, 1993, Clarke & Gorley, 2006). Note that MDS ordination, when used in conjunction with ANOSIM tests, is particularly well suited to comparing the dietary compositions of different *a priori* groups of fish as it does not rely on the data being linearly related and normally distributed (Platell *et al.*, 1998). The magnitudes of the Global *R*-statistic values in the MDS ordinations were used to ascertain the extents to which dietary composition was influenced by those factors. *R*-statistic values range from 1, if the composition of all samples within each group are more similar to each other than to any of the samples from any other group, down to *ca* 0 if the average similarities between and within groups are the same (Clarke, 1993). The null hypothesis for ANOSIM tests that the dietary compositions were not significantly different was rejected if the significance level (*P*) exceeded 5%. Similarity of Percentages (SIMPER) was used to determine which dietary categories typify *a priori* groups and distinguish between those groups that were significantly different (Clarke, 1993).

As the overall dietary composition of Black Bream was influenced to a greater degree by estuary than by either season or body size (see Results), the extents to which the diets of this species were influenced by the latter two variables in each estuary were then explored. Thus, separate matrices for the dietary data for Black Bream from each of the Stokes, Hamersley and Culham inlets were constructed and subjected to MDS ordination as described above.

A third and final series of analyses focused on determining whether the diets of Black Bream in the upstream pools of Culham Inlet differed from those in the main body of this estuary, *i.e.* below the rock bar on the tributary river. These analyses used dietary data for the length classes found in both regions, *i.e.* those between 150 and 249 mm. Thus, the volumetric contribution of each dietary category to the diets of individual fish was determined and subjected to MDS ordination, ANOSIM and SIMPER as described above.

5.3 RESULTS

5.3.1 *Reproduction*

Gonadal staging

The macroscopic characteristics of sequential stages in the development of the ovaries and testes of *Acanthopagrus butcheri* and the histological characteristics of the ovarian stages are given below in Table 5.1 (see Fig. 5.1 for photographs of histological sections of ovarian maturation stages). Stages follow the scheme of Laevastu (1965) and histological terminology follows that of Wallace & Selman (1981).

Stokes Inlet

During the spawning period (see later), all female *A. butcheri* caught in Stokes Inlet with lengths <140 mm possessed gonads at stages I and II, *i.e.* were immature (Fig. 5.2). Thirty three percent of females in the 140-159 mm length class, 76% of those in the 160-179 mm length class and the vast majority of those >200 mm possessed gonads at stages III-VIII, *i.e.* were mature (see Materials and Methods). In the case of males, 40% of the individuals in the 120-139 mm length class were already mature and, by the time they had attained 160 mm, virtually all were mature. The lengths at which 50% of female and male *A. butcheri* attained maturity, *i.e.* L_{50}s, in Stokes Inlet, determined using logistic regression analysis and data for fish with gonadal stages III-VIII, were 155 and 141 mm, respectively (Fig. 5.2). These L_{50}s were within 5% of the respective L_{50}s for each sex obtained when we used the same logistic regression analysis, but gonadal stages V-VIII as indicative of maturity, as employed by Sarre & Potter (1999). The A_{50}s for female and male Black Bream from Stokes Inlet, calculated by inserting the L_{50}s at maturity and the von Bertalanffy parameters for each sex (see later) into the inverse von Bertalanffy growth function (see Stergiou, 1999), were 2.2 years and 2.0 years, respectively.

In Stokes Inlet, the mean monthly GSIs of female *A. butcheri* $>L_{50}$ at first maturity increased from <1.0 in January and April to 2.4 and 2.2 in June and July and then to >4.2 between August and October, before declining markedly to 3.2 in November and 2.2 in December (Fig. 5.3). The mean monthly GSIs of males followed a similar seasonal trend to that described for females, but were slightly higher in each month between June and November.

Virtually all of the ovaries of those female *A. butcheri* that were $>L_{50}$ at first maturity and caught in January and April were either at stage VIII (recovering/spent) or stage II (immature/resting) (Fig. 5.4). Stage III (developing) ovaries were found between April and August and stage IV (maturing) ovaries were recorded from July to October. Stage V/VI (prespawning/spawning) ovaries were found between June and December and, collectively, were

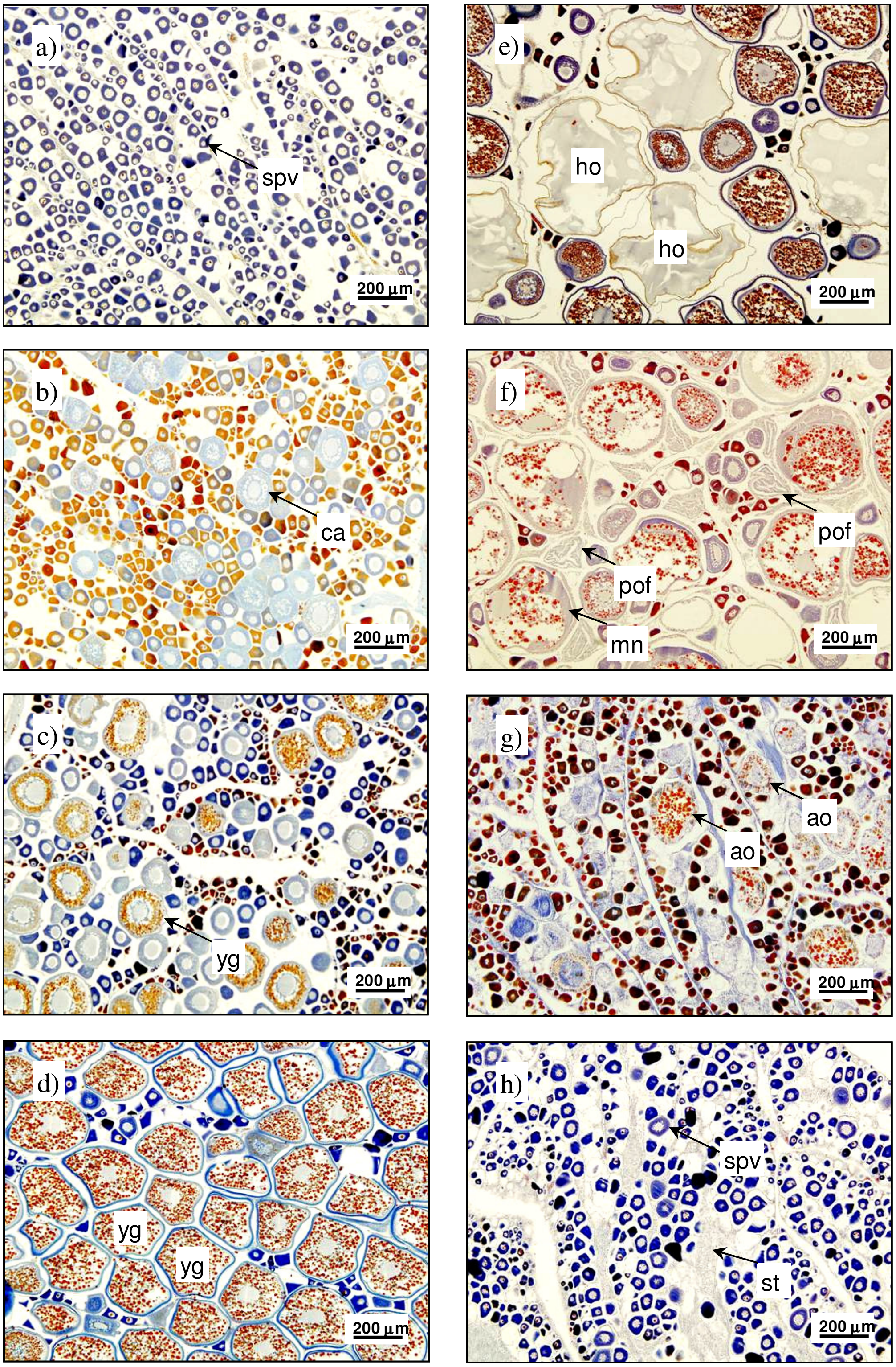

Figure 5.1. Histological sections of stage (a) II, (b) III, (c) IV, (d) V, (e,f) VI, (g) VII and (h) VIII ovaries from individual *Acanthopagrus butcheri* possessing small previtellogenic oocytes (spv), cortical alveolar oocytes (ca), yolk granule oocytes (yg), hydrated oocytes (ho), post-ovulatory follicles (pof), migratory nucleus oocytes (mn), atretic oocytes (ao) and scar tissue (st).

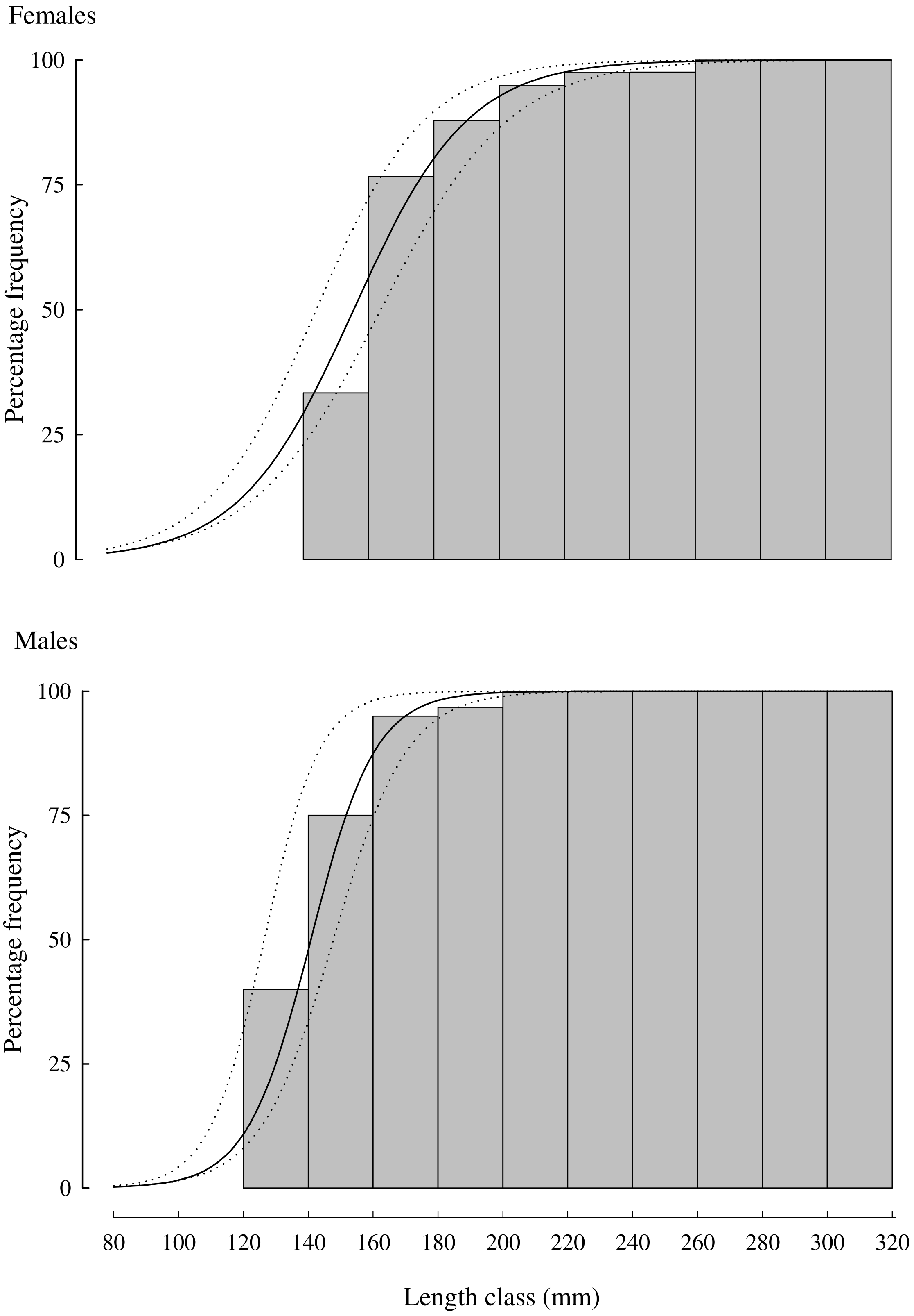

Figure 5.2. Observed percentage of fish in each length class that possessed gonads at stages III to VIII, and expected percentage of such fish at each length, with 95% confidence limits (dotted lines) estimated from logistic regression analysis for data collected during the spawning season in Stokes Inlet

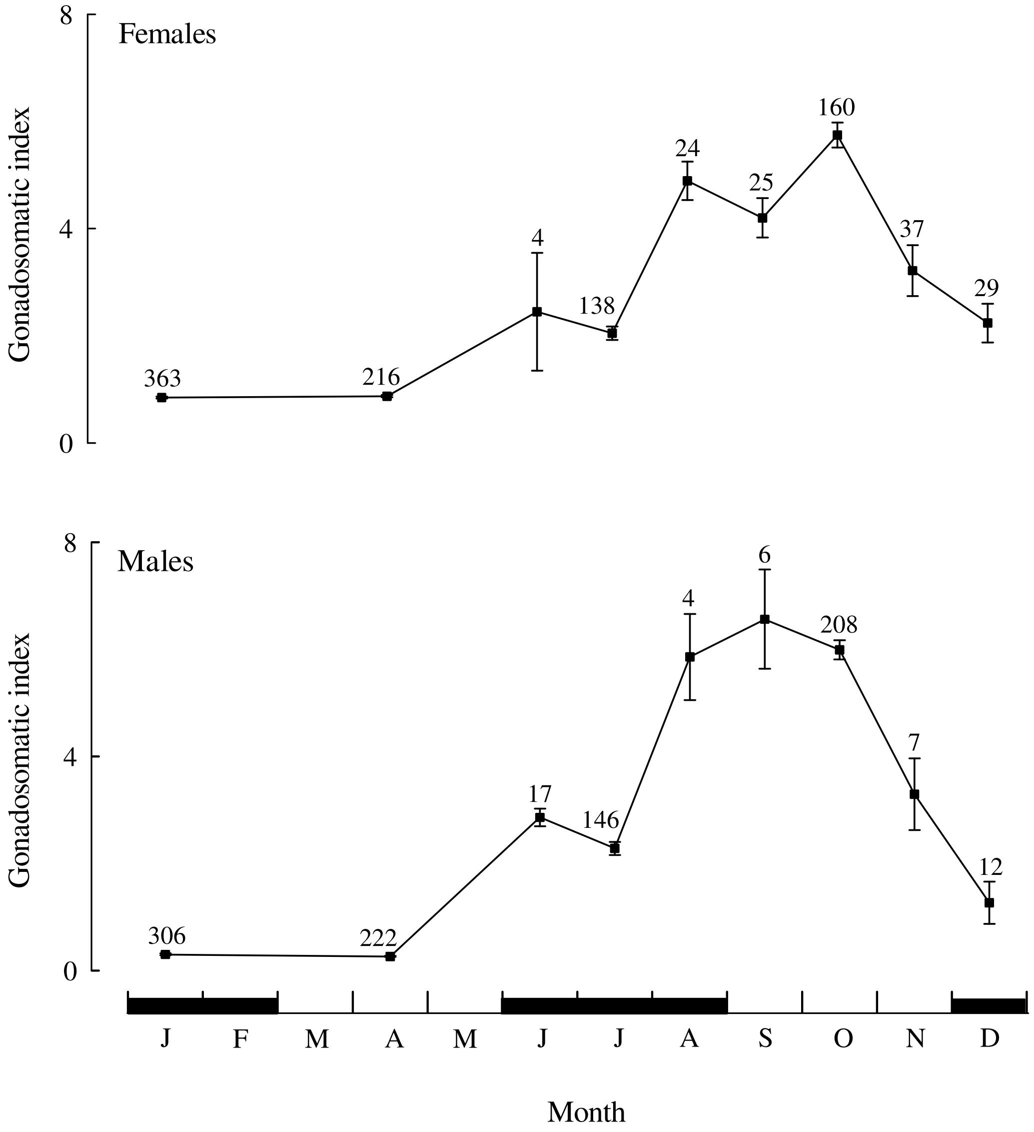

Figure 5.3. Mean monthly gonadosomatic indices ±1SE for female and male *Acanthopagrus butcheri* > L_{50} at sexual maturity from Stokes Inlet, derived from data collected in 2002, 2003 and 2004. Numbers of fish are shown above each mean. Closed bars represent winter and summer months and open bars represent autumn and spring months.

Table 5.1. Characteristics of stages in the gonadal development of *Acanthopagrus butcheri*.

Stage	Macroscopic characteristics	Histological characteristics
I Virgin	Gonads very small. Ovary transparent, no oocytes visible. Testes grey and strand-like.	Oocytes highly organised along ovarian lamellae, chromatin nucleolar and early perinucleolar oocytes (small previtellogenic oocytes) present.
II Immature	Gonads larger than stage I. Ovaries translucent. Testes white and ribbon-like.	Similar to stage I with late perinucleolar oocytes present. These oocytes are found in all subsequent stages.
III Developing	Ovaries becoming opaque, orange to red in colour with whitish oocytes visible. Testes white. Occupy up to 1/3 of the ventral cavity.	Cortical alveolar oocytes abundant.
IV Maturing	Ovaries orange with blood capillaries and yolk granule oocytes visible. No milt appears when pressure is applied to the trunk of males. Occupy 1/3 to 1/2 of the ventral cavity.	Cortical alveolar and yolk granule oocytes abundant.
V Prespawning	Gonads occupy 1/3 to almost entire ventral cavity. Milt appears when firm pressure is applied to the trunk of males. Ovaries large with numerous capillaries. No hydrated oocytes visible.	Many yolk granule oocytes tightly grouped. Few cortical alveolar oocytes present.
VI Spawning	Hydrated oocytes visible through ovarian wall. Milt appears when slight pressure is applied to the trunk of males. Gonads occupy 1/3 to almost the ventral cavity.	Hydrated oocytes and/or migratory nucleus oocytes and/or postovulatory follicles present.
VII Spent	Gonads smaller than stage V or VI. Ovaries and testes flaccid though not fully empty.	Large amounts of connective tissue. Remnant yolk granule and cortical alveolar oocytes generally undergoing atresia.
VIII Recovering/ spent	Testes and ovaries red to brown and flaccid, with scarring visible at ends of ovaries. No oocytes visible in ovaries.	Oocytes unorganised. Gonads contain extensive connective tissue and large "empty" areas.

the predominant category between August and November. Stage VII (spent) and stage VIII (recovering/spent) ovaries were first recorded in November. The monthly trends exhibited by the frequency of occurrence of the different stages in testicular development were essentially the same as those described for ovaries (Fig. 5.4). Particularly noteworthy was the fact that all of the males in June were running ripe.

The trends exhibited by the mean monthly GSIs and the monthly prevalences of different stages in gonadal development, in combination with the recruitment of large numbers of very small 0+ fish in October (see later), indicated that spawning peaked in late August/early

September. Thus, a birth date of 1 September was assigned to individuals in the population of *A. butcheri* in Stokes Inlet.

In 2003, when data were available for all months between July and the following January, the mean monthly GSIs of both sexes and the prevalences of females and males with gonads at stages V (prespawning) or VI (spawning) between late winter and mid spring in both the basin of Stokes Inlet and its major tributary, the Young River showed similar trends (Fig. 5.5). Although data were not available for as many months in 2002 and 2004, the trends exhibited by the above two reproductive variables clearly indicate that they peaked at the same time in those two years as in 2003. However, it may be relevant that the maximum mean monthly GSIs and prevalence of females with stage V or VI ovaries in the basin were far lower in 2002 than in 2003, but substantial numbers of such prespawning and spawning females were found in the river in mid-spring of 2002 (Fig. 5.5).

Culham Inlet

No female Black Bream <140 mm were caught in any region of Culham Inlet during spring, when this species spawns in this system (see later). During that period, the ovaries of the single female *A. butcheri* caught in Culham Inlet that was <180 mm in length were at stage II, whereas those of all of the 25 females >180 mm were at stages III-VIII. As only one immature female and few mature females <260 mm were captured, it was not possible to derive with confidence even a broad estimate of the size at first maturity of female *A. butcheri* in Culham Inlet.

All of the 40 males caught during the spawning period possessed gonads at stages III-VIII and this included at least two individuals in each length class between 140 and 320 mm. Thus, the males of this species are assumed to typically reach sexual maturity at a length <140 mm and thus probably at an age of two years or less.

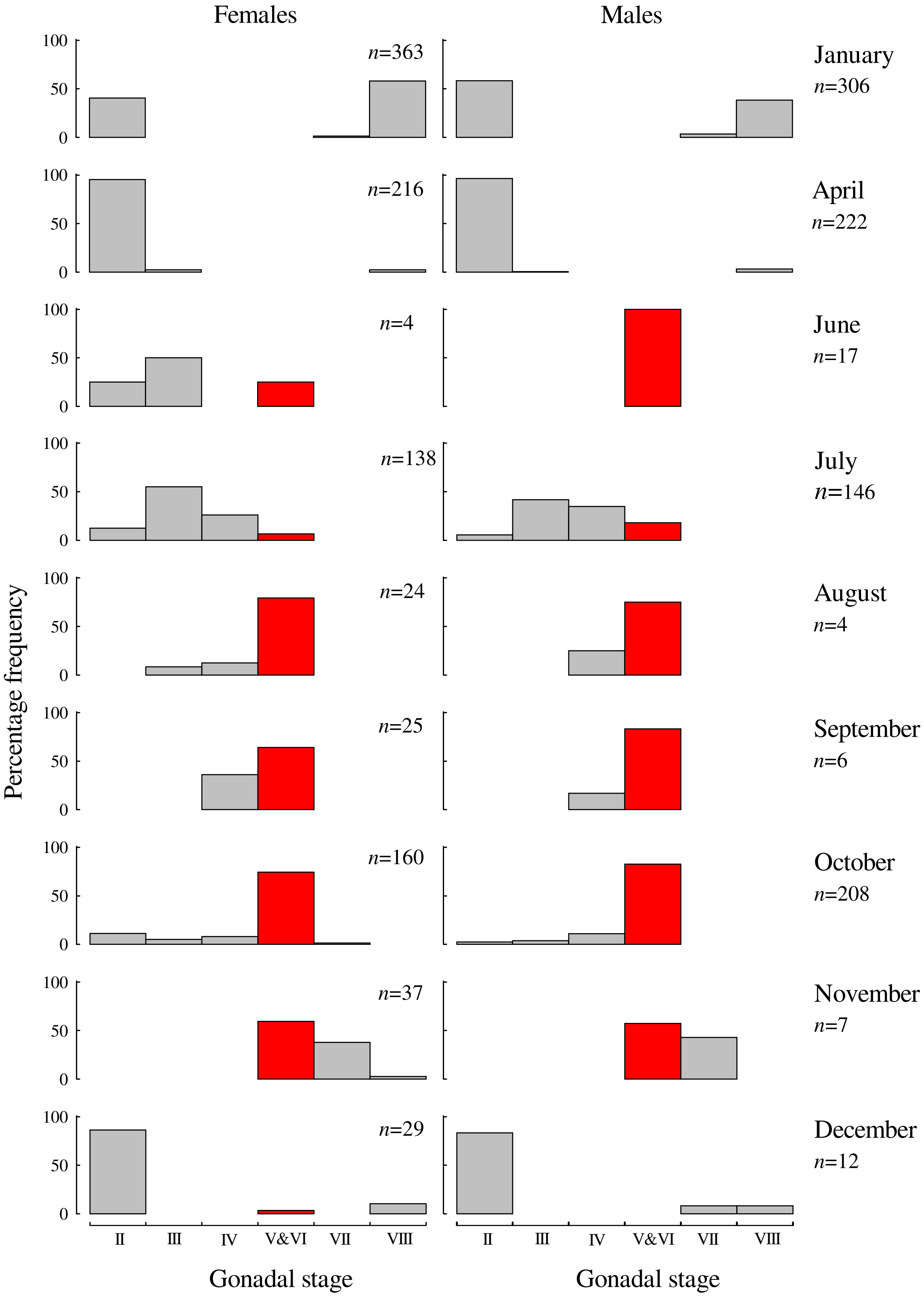

Figure 5.4. Monthly percentage frequencies of occurrence of gonads at various stages of development in female and male *Acanthopagrus butcheri* > L_{50} at sexual maturity from the Stokes Inlet. Data for fish collected between 2002 and 2004 have been pooled. Red bars represent prespawning and spawning fish.

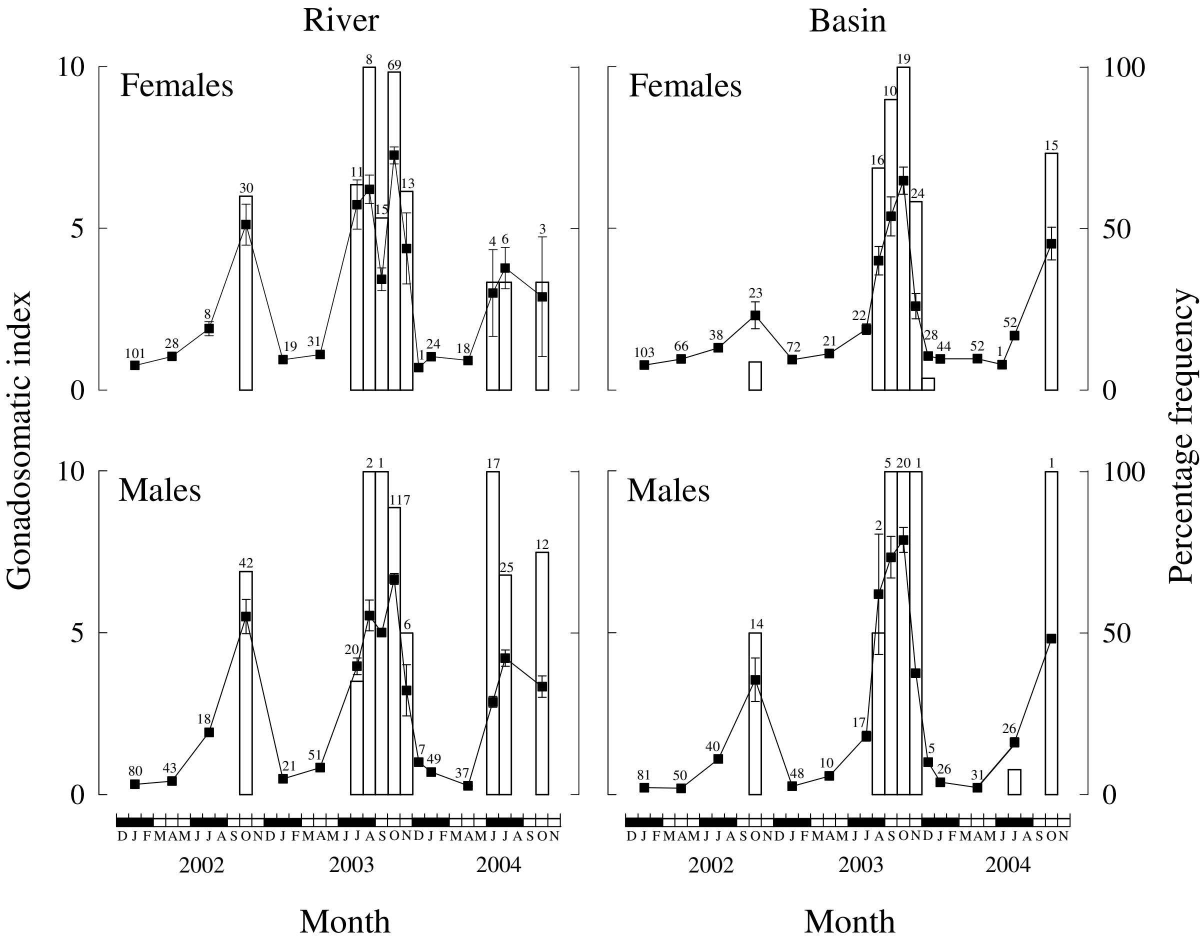

Figure 5.5. Mean monthly gonadosomatic indices ±1SE and percentage frequency of occurrence of *Acanthopagrus butcheri* >L_{50} at sexual maturity from the basin and river of Stokes Inlet with gonad stages V or VI. Numbers of fish are shown above each mean. Closed bars on the x axis represent winter and summer months and open bars represent autumn and spring months.

The mean monthly GSIs of female *A. butcheri* in Culham Inlet increased from 0.7 in April to 2.6 in July and 8.5 in October, before declining precipitously to 0.9 in January (Fig. 5.6). The mean monthly GSIs of males followed the same seasonal trend as that of females.

The majority of females >L_{50} possessed ovaries at stages II, IV and V/VI in April, July and October, respectively (Fig. 5.7). Two females in July possessed ovaries at stage V/VI. The January samples of females were dominated by fish with ovaries at either stage II (resting) or at stage VII (spent) or VIII (recovering spent). The seasonal changes in the pattern of gonadal development by males parallel very closely those of females.

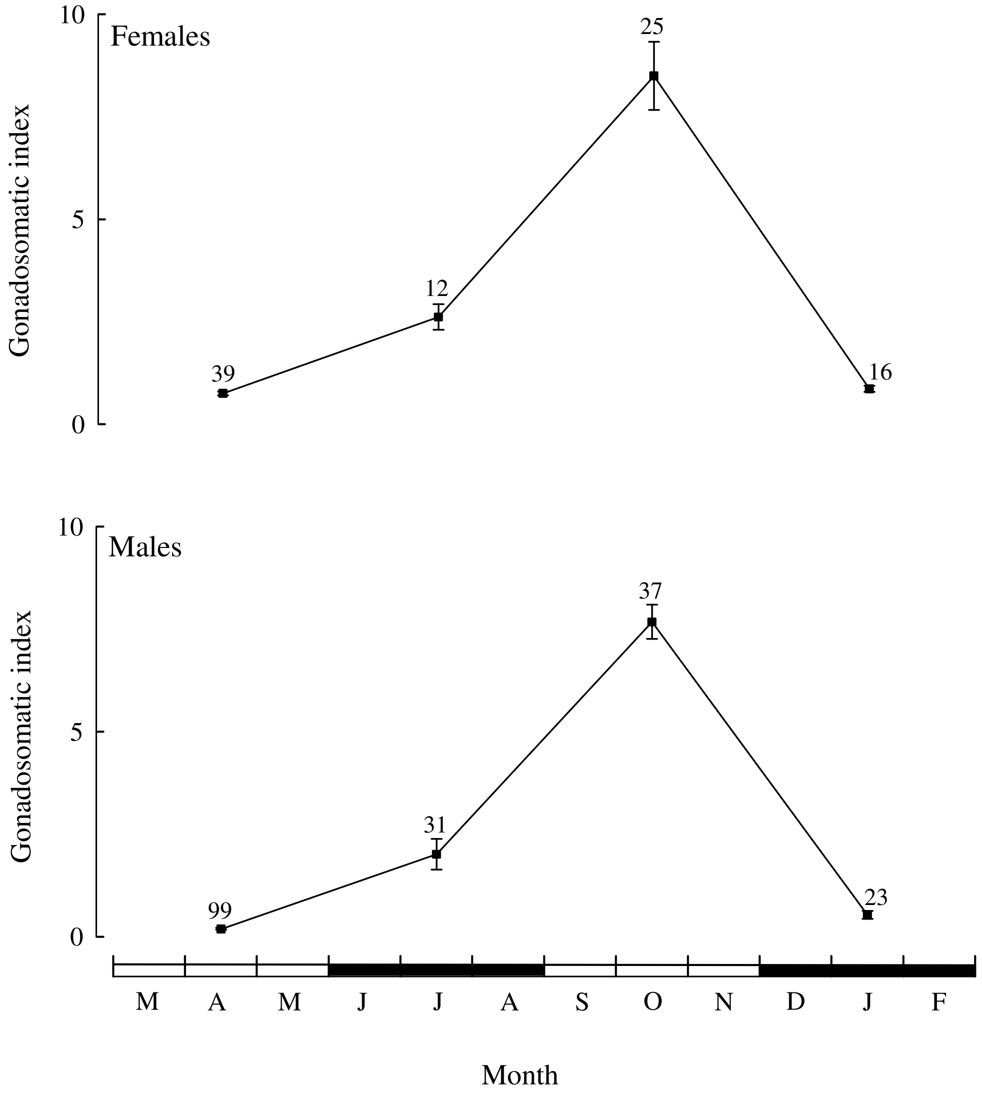

Figure 5.6. Mean monthly gonadosomatic indices ±1SE for female and male *Acanthopagrus butcheri* > the approximate length at first sexual maturity in Culham Inlet. Data were collected in 2002, 2003 and 2004. Numbers of fish are shown above each mean. Closed bars represent winter and summer months and open bars represent autumn and spring months.

The trends exhibited by the mean monthly GSIs and prevalences of the different stages in gonadal development, in combination with the time of first occurrence of new 0+ recruits (see later), indicated that spawning peaked in late winter/early spring. Thus, a birth date of 1 September was assigned to the population of *A. butcheri* in Culham Inlet.

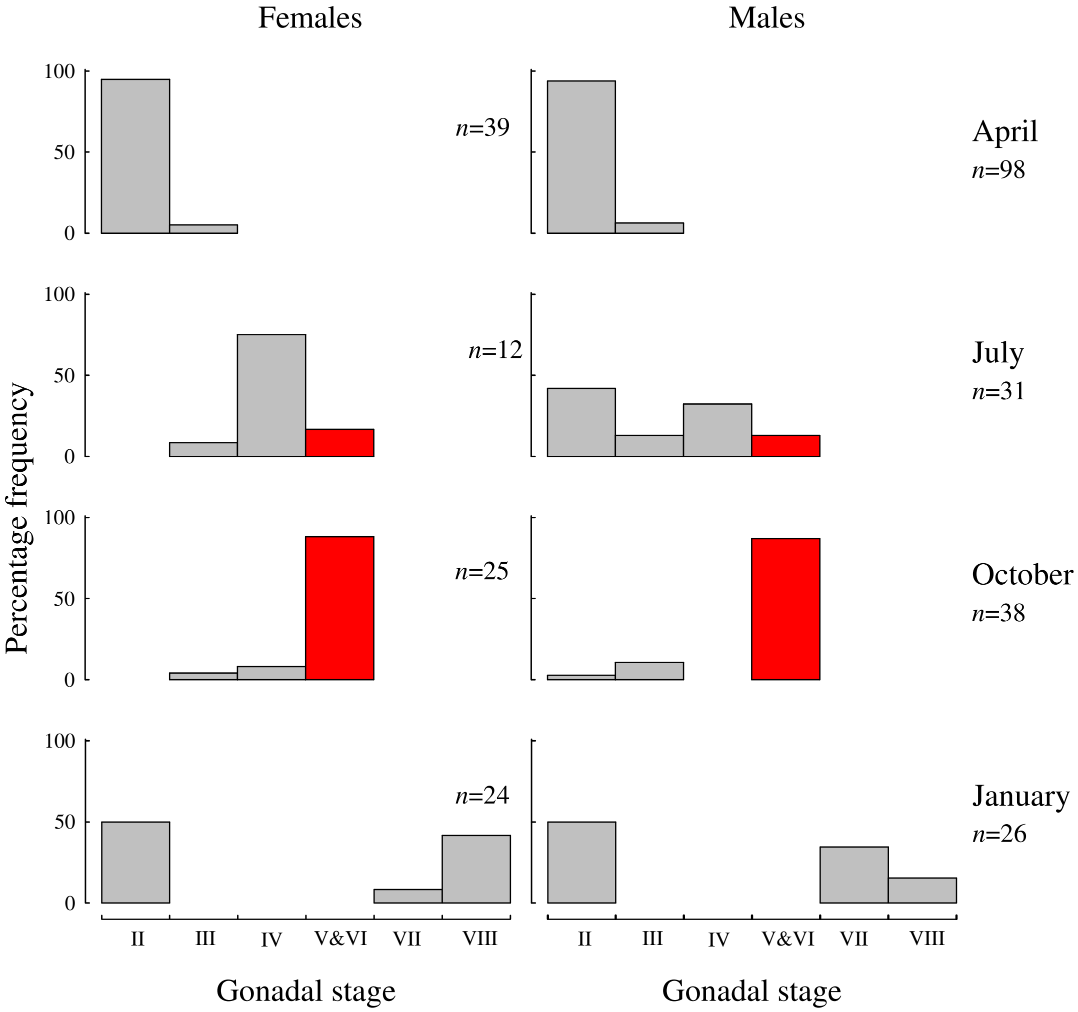

Figure 5.7. Monthly percentage frequencies of occurrence of gonads at various stages of development in female and male *Acanthopagrus butcheri* > the approximate length at maturity in Culham Inlet. Data for fish collected between 2002 and 2004 have been pooled. Red bars represent prespawning and spawning fish.

Hamersley Inlet

All of the 51 females and all but one of the 23 males of *A. butcheri* caught during the spawning period in Hamersley Inlet possessed gonads at stages III-VIII. Although only three of these females and five of the males were <180 mm, the data for these fish, which ranged upwards from 127 mm, provide strong indications that, in Hamersley Inlet, *A. butcheri* typically reaches maturity at lengths <130 mm.

The mean monthly GSIs of female *A. butcheri* in Hamersley Inlet increased from 0.7 in April to 1.2 in July and 5.5 in October, before declining to 0.5 in January (Fig. 5.8). The mean monthly GSIs of males followed essentially the same trend.

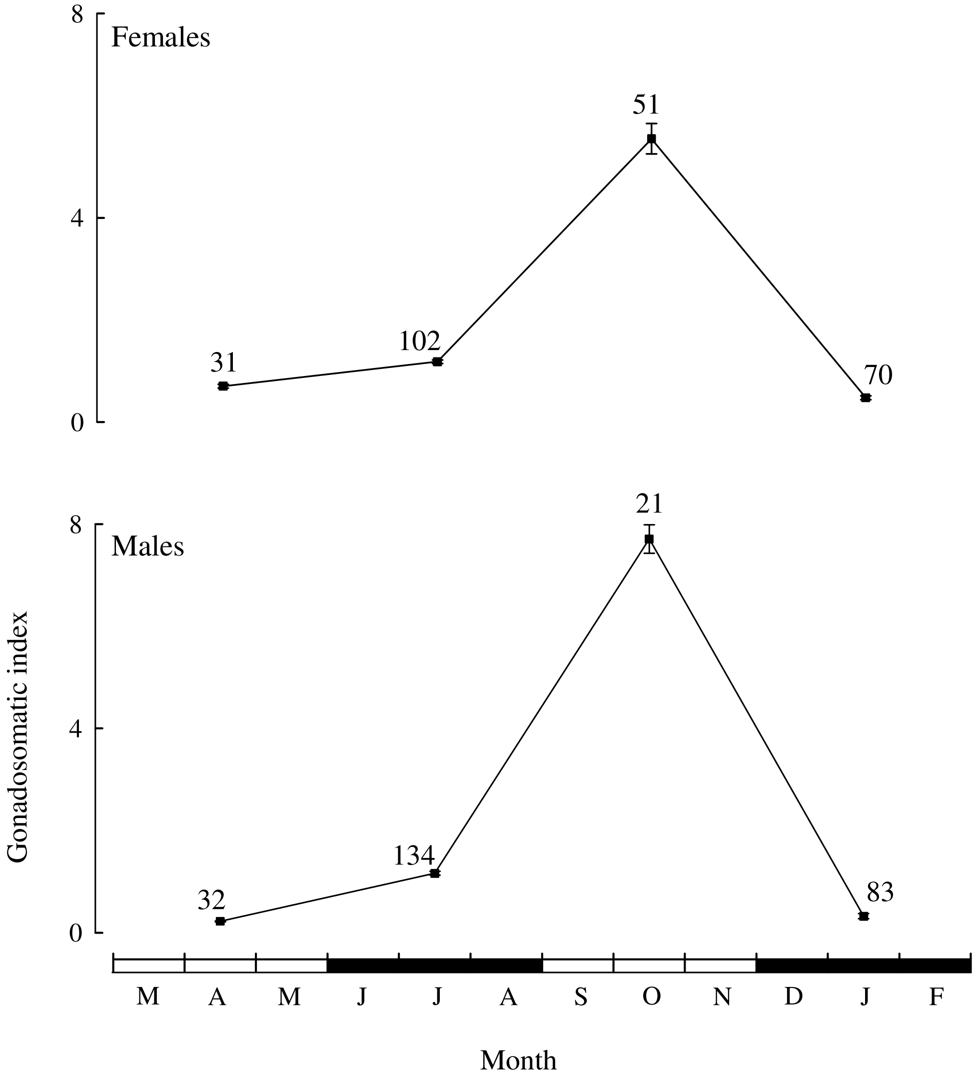

Figure 5.8. Mean monthly gonadosomatic indices ±1SE for female and male *Acanthopagrus butcheri* > the approximate length at first maturity in Hamersley Inlet. Data were collected in 2002 and 2003. Numbers of fish are shown above each mean. Closed bars represent winter and summer months and open bars represent autumn and spring months.

The predominant gonadal stages in both females and males in Hamersley Inlet were II, VI and V/VI in April, July and October, respectively (Fig. 5.9). The gonads of all fish caught in January were either resting (stage II) or spent/recovering spent (stages VII and VIII).

Based on the consistency between the data for the prevalence of gonads at different stages of development in each month and the mean monthly GSIs of *A. butcheri* from the Stokes and Culham inlets and their apparent correspondence with the more limited data from Hamersley Inlet, a birth date of 1 September was likewise assigned to this species in the latter estuary.

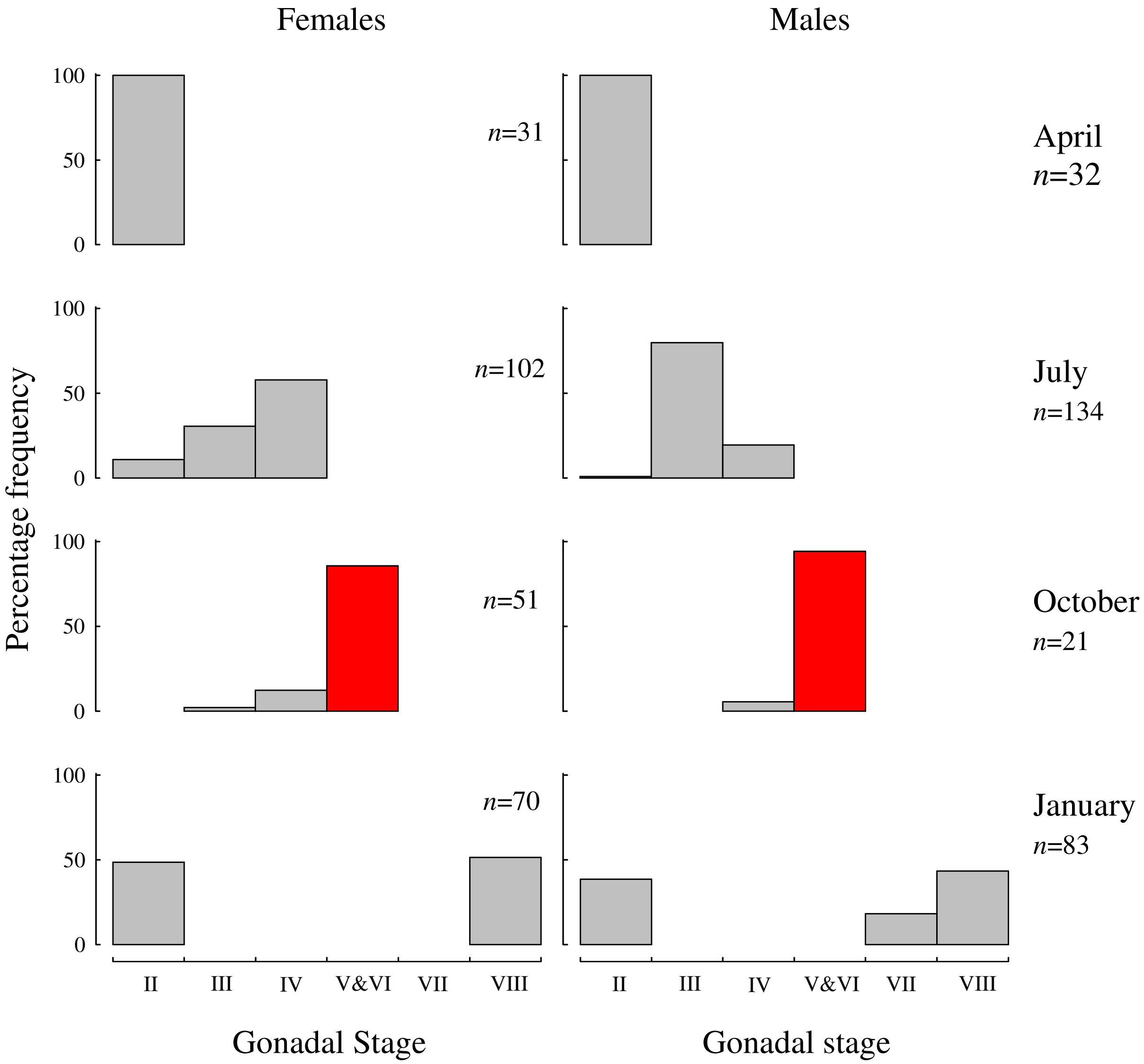

Figure 5.9. Monthly percentage frequencies of occurrence of gonads at various stages of development in female and male *Acanthopagrus butcheri* > the approximate length at maturity in Hamersley Inlet. Data for fish collected in 2002 and 2003 have been pooled. Red bars represent prespawning and spawning fish.

5.3.2 *Age composition and growth*

Stokes Inlet

All age classes from 0+ to 10+ were represented in the catch of *A. butcheri* obtained during the three years of this study (Fig. 5.10). All year classes between 1992 and 2003 were represented apart from that of 2002, and those of 1993, 1998 and 2003 were particularly strong (Table 5.2).

von Bertalanffy growth curves provided good fits to the lengths at age for female and male *A. butcheri* from Stokes Inlet, as demonstrated by the high values for R^2, *i.e.* 0.95 and 0.96, respectively, and the relatively narrow confidence limits for each of the three von Bertalanffy growth parameters (Fig. 5.10, Table 5.3). From the von Bertalanffy growth curves, the estimated lengths at ages 1, 2, 5 and 10 were 95, 149, 233 and 272 mm, respectively, for females, and 93, 143, 222 and 261 mm, respectively, for males (Fig. 5.10). The maximum lengths, weights and ages recorded for *A. butcheri* in Stokes Inlet were 373 mm, 889 g and 10 years for females and 318 mm, 534 g and 10 years for males (Table 5.3).

Table 5.2. Relative year class strengths of *Acanthopagrus butcheri* in the Stokes Inlet, the regions above and below the rock bar on Philips River in the Culham Inlet and Hamersley Inlet.

	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Stokes					*	***	*	**	*	*	***	**	**	**		***
Culham (above rock bar)	*			*	**			**	**	**	***	**	**	***		
Culham (below rock bar)										*	**	**	***	****		
Hamersley											*	*	****	*		

* = <1%, ** = 2-15%, *** = 16-50%, **** = >50%

The likelihood-ratio test demonstrated that the growth curves of female and male *A. butcheri* in Stokes Inlet were significantly different (p<0.001). However, the von Bertalanffy growth parameters k and t_0 for females and males were each very similar and the L_∞ of 281 mm for females was only slightly greater than that of 270 mm for males (Table 5.3). Furthermore, the difference in the estimated lengths at each age never differed by more than 4%. Thus, the difference between the two curves was unlikely to be of major biological significance.

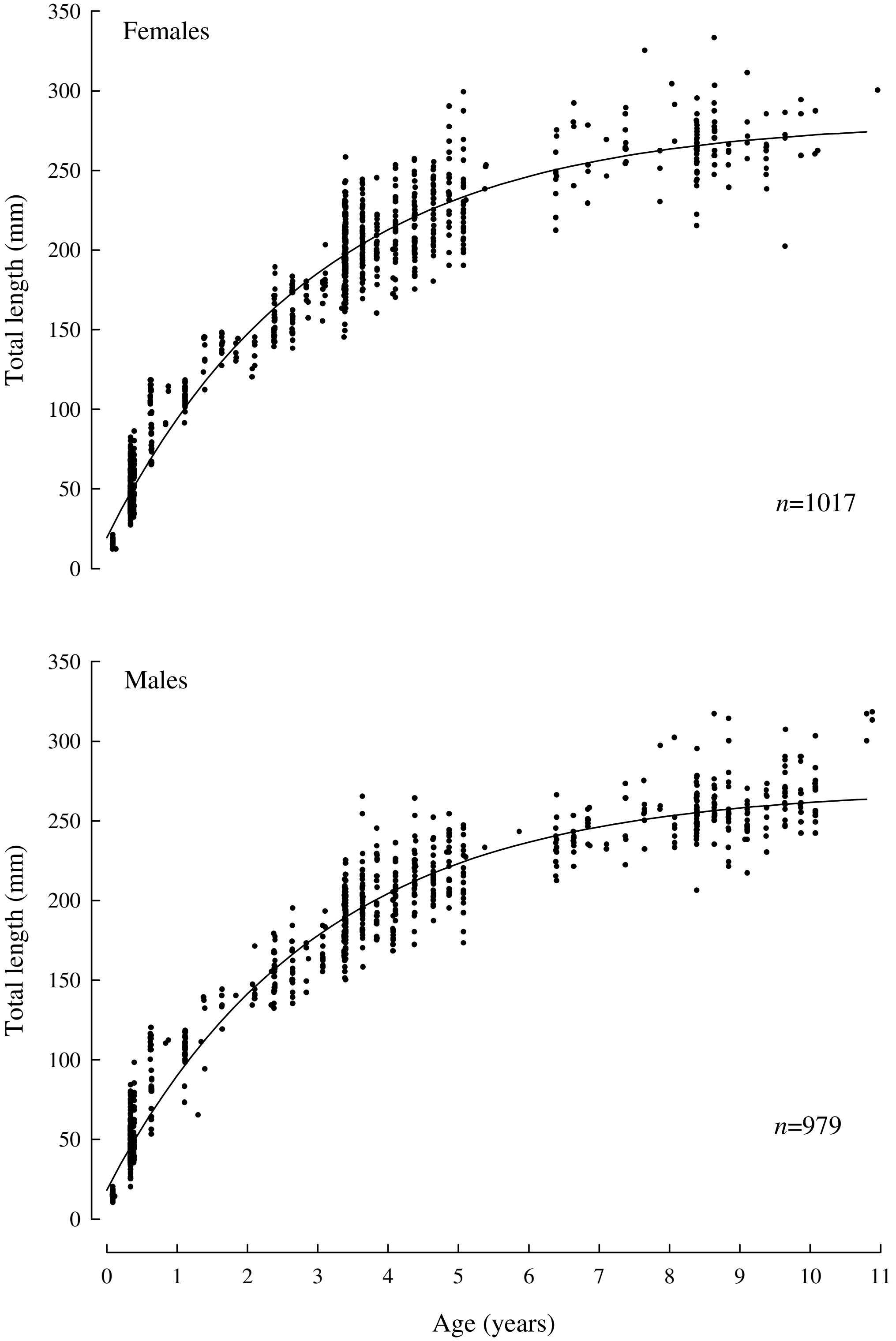

Figure 5.10. von Bertalanffy growth curves fitted to the lengths at age of female and male *Acanthopagrus butcheri* in Stokes Inlet. *n* = sample sizes.

Although only relatively small numbers of 0+ *A. butcheri* of the 2001 year class were caught in January, April and July 2002 and no representatives of the 2002 year class were caught throughout the study, very large numbers of early 0+ recruits of the 2003 year class were caught in October of that year. No representatives of the 2004 year class were obtained on the one sampling occasion where that year class could have been captured, *i.e.* October 2004.

Culham Inlet

All age classes from 0+ to 7+ of females and from 0+ to 9+ of males were represented in the total catch of *A. butcheri* obtained from throughout the Culham Inlet in the three years of this study (Fig. 5.11). The oldest female and male were 10 and 14 years old, respectively, and these were also the largest individuals of the two sexes, with lengths of 376 and 373 mm, respectively. All year classes between 1991 and 2001, except those of 1993 and 1994 were represented in our total catch. Recruitment was particularly strong in 2001 and moderate for each year class between 1996 and 2000 (Table 5.2). However, no individuals of the 2002, 2003 and 2004 year classes were caught.

von Bertalanffy growth curves provided good fits to the lengths at age for female and male *A. butcheri* caught throughout Culham Inlet, with respective R^2 values of 0.877 and 0.865 (Fig. 5.11, Table 5.3). The likelihood-ratio test demonstrated that the von Bertalanffy growth curves for female and male *A. butcheri* were significantly different ($p<0.001$). However, the von Bertalanffy growth parameters k and L_∞ for females were similar to those of males (Table 5.3) and differences between the estimated lengths of the two sexes at each age from 1 to 5 years were always less than 3%. When length-at-age data were separated according to whether the fish were collected in the lower riverine region, basin and entrance channel, *i.e.* below rock bar on the Philips River, or in pools above that rock bar, the patterns of growth of females and males were both found to differ markedly between those two areas (Fig. 5.12). These differences are reflected in very marked differences in the values for both k and L_∞ for both females and males in the two areas (Table 5.3). Thus, for example, the values for L_∞ and k were 274 and 0.96, respectively for females below the rock bar and 384 and 0.30, respectively, for females above the rock bar.

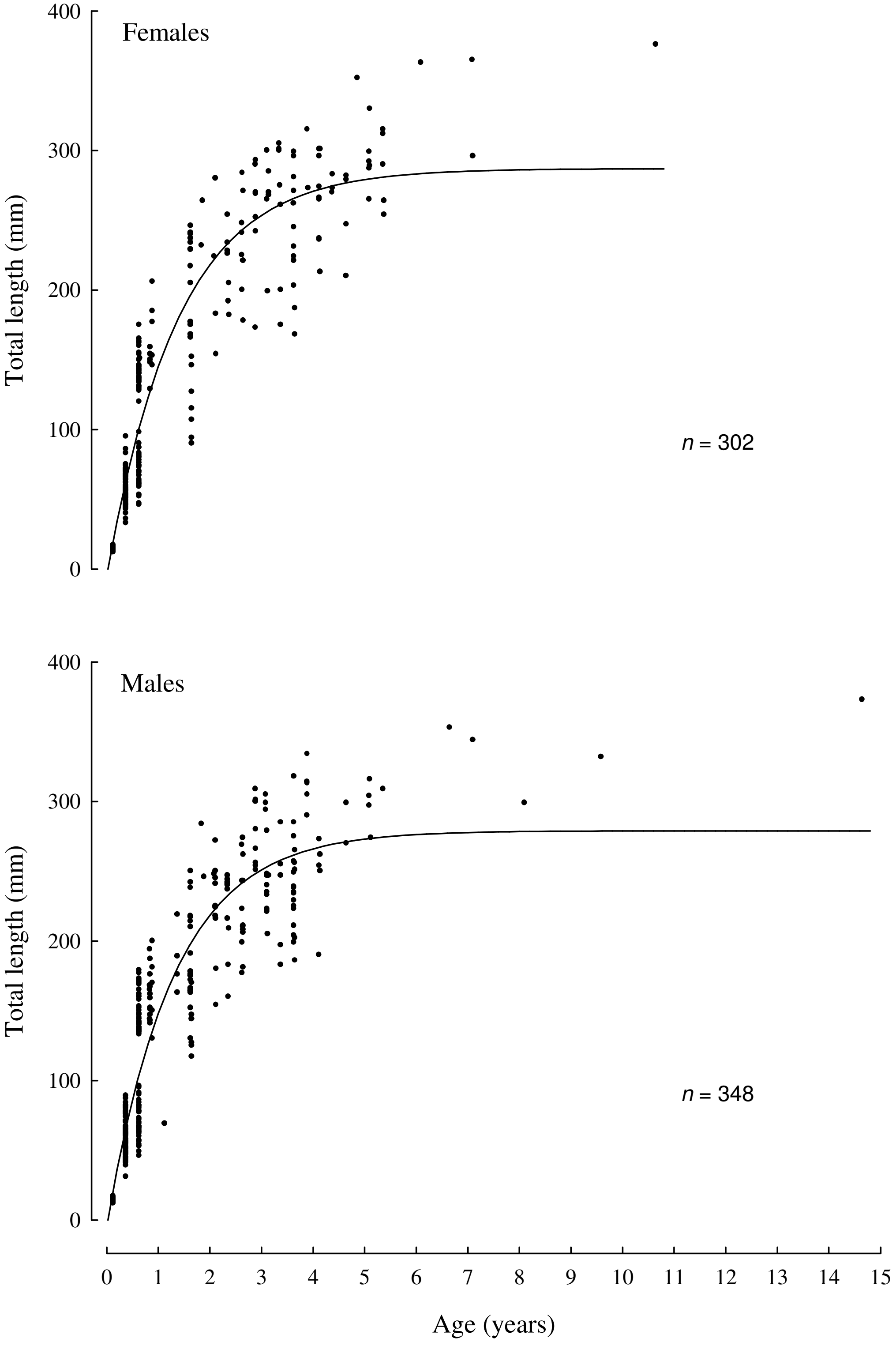

Figure 5.11. von Bertalanffy growth curves fitted to lengths at age for female and male *Acanthopagrus butcheri* from Culham Inlet. Data for the entrance channel, basin, major tributary and upstream riverine pools have been pooled.
n = sample sizes.

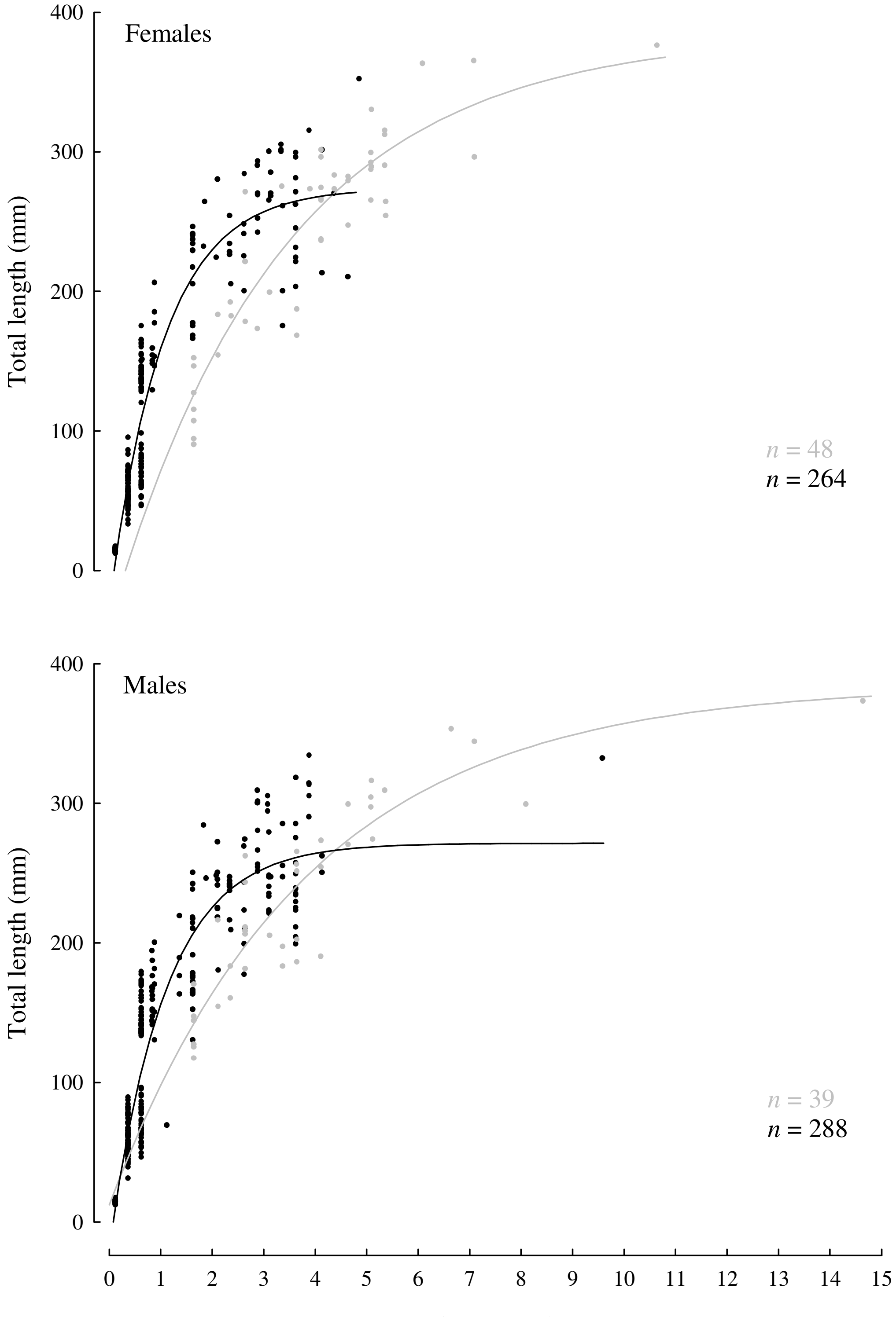

Figure 5.12. von Bertalanffy growth curves fitted to the lengths at age for female and male *Acanthopagrus butcheri* from the upstream riverine pools of Culham Inlet (grey) and the combined data for the major tributary, basin and entrance channel of Culham Inlet. *n* = sample sizes.

Furthermore, the proportion of fish older than 4 years was far greater in samples taken above than below the rock bar (Fig. 5.12). Indeed, the samples collected from above the rock bar contained far more year classes, *i.e.* 10, than were present in the larger samples collected from below the rock bar, *i.e.* 5 (Table 5.2).

Hamersley Inlet

Black Bream was only caught in Hamersley Inlet between the summers of 2001/2002 and 2002/2003. The absence of this species in samples since the summer of 2003 reflects the catastrophic effects of the massive mortality to which this species was subjected during the autumn of 2003 as a result of the development of extreme salinities in this estuary (see Chapter 4).

Almost all of the 227 females and 226 males of *A. butcheri* caught during this study in the Hamersley Inlet belonged to the 1+ or 2+ age classes (Fig. 5.13) and virtually all represented the 2000 year class. The lengths at age of both the females and males of Black Bream of both these age classes in this system varied markedly. For example, the lengths of females and males at *ca* 1.4 years of age ranged from 135 to 272 mm and 127 to 271 mm, respectively (Fig. 5.13). Although the females and males had grown so rapidly that, at *ca* 1.4 years of age, they had already reached mean lengths of 200 and 193 mm, the mean lengths of fish of *ca* 2.4 years in age had increased only to 238 and 220 mm, respectively. The maximum recorded lengths, weights and ages of female and male *A. butcheri* in Hamersley Inlet were 309 mm, 478 g and 3 years, and 292 mm, 454 g and 4 years, respectively.

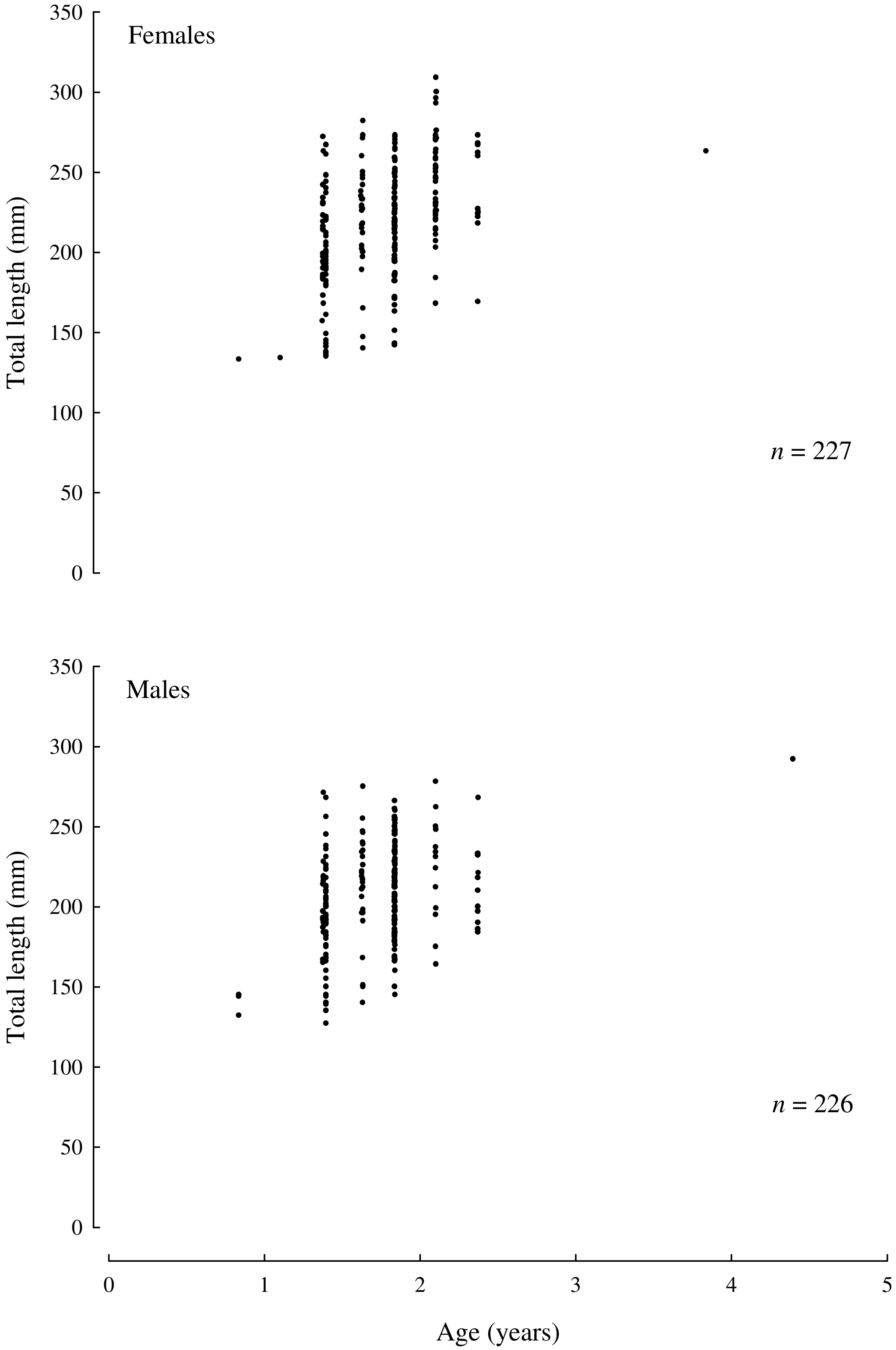

Figure 5.13. Lengths at age of female and male *Acanthopagrus butcheri* from Hamersley Inlet. *n* = sample sizes.

Table 5.3. von Bertalanffy growth parameters and their 95% confidence intervals (CI) derived from lengths at age of female and male *Acanthopagrus butcheri* caught in Stokes Inlet, throughout Culham Inlet, and below and above the rock pool in Philips River. L_∞ is the asymptotic length (mm), k is the growth coefficient (y^{-1}), t_0 is the hypothetical age at which fish would have zero length (y) and R^2 is the coefficient of determination. n, L_{max}, W_{max}, and A_{max} represent sample sizes, maximum lengths (mm), maximum weights (g) and maximum ages (y) respectively.

						von Bertalanffy Parameters			
		n	L_{max}	W_{max}	A_{max}	L_∞	k	t_o	R^2
Stokes Inlet	Females	1017	373	889	10	281.2	0.34	-0.21	0.95
	Lower CI					275.5	0.32	-0.25	
	Upper CI					286.9	0.35	-0.18	
	Males	979	318	534	10	270.4	0.33	-0.21	0.96
	Lower CI					266.5	0.32	-0.24	
	Upper CI					274.4	0.35	-0.18	
Culham Inlet (Total)	Females	38	352	798	4	287.1	0.72	0.02	0.877
	Lower CI					274.1	0.61	-0.03	
	Upper CI					300.1	0.83	0.08	
	Males	61	334	699	3	279.0	0.77	0.02	0.856
	Lower CI					266.3	0.66	-0.03	
	Upper CI					291.7	0.89	0.08	
Culham Inlet (below rock bar on Philips River)	Females	264	352	798	4	274.0	0.96	0.09	0.894
	Lower CI					261.9	0.83	0.06	
	Upper CI					286.2	1.08	0.12	
	Males	288	334	699	9	271.4	0.92	0.07	0.859
	Lower CI					258.7	0.78	0.03	
	Upper CI					284.1	1.06	0.12	
Culham Inlet (upstream pools above rock bar)	Females	48	376	946	10	384.4	0.30	0.31	0.83
	Lower CI					311.2	0.14	-0.29	
	Upper CI					457.8	0.46	0.46	
	Males	39	373	994	14	384.5	0.26	-0.13	0.82
	Lower CI					320.5	0.13	-0.90	
	Upper CI					448.4	0.39	0.65	

Comparisons between the growth of Acanthopagrus butcheri *in different estuaries*

The overall pattern of growth of both females and males of *A. butcheri* differed markedly between the Culham and Stokes inlets (both p values <0.001) (Fig. 5.14). The values for L_∞ and k emphasise that, in Culham inlet, growth is more rapid initially and undergoes a more marked

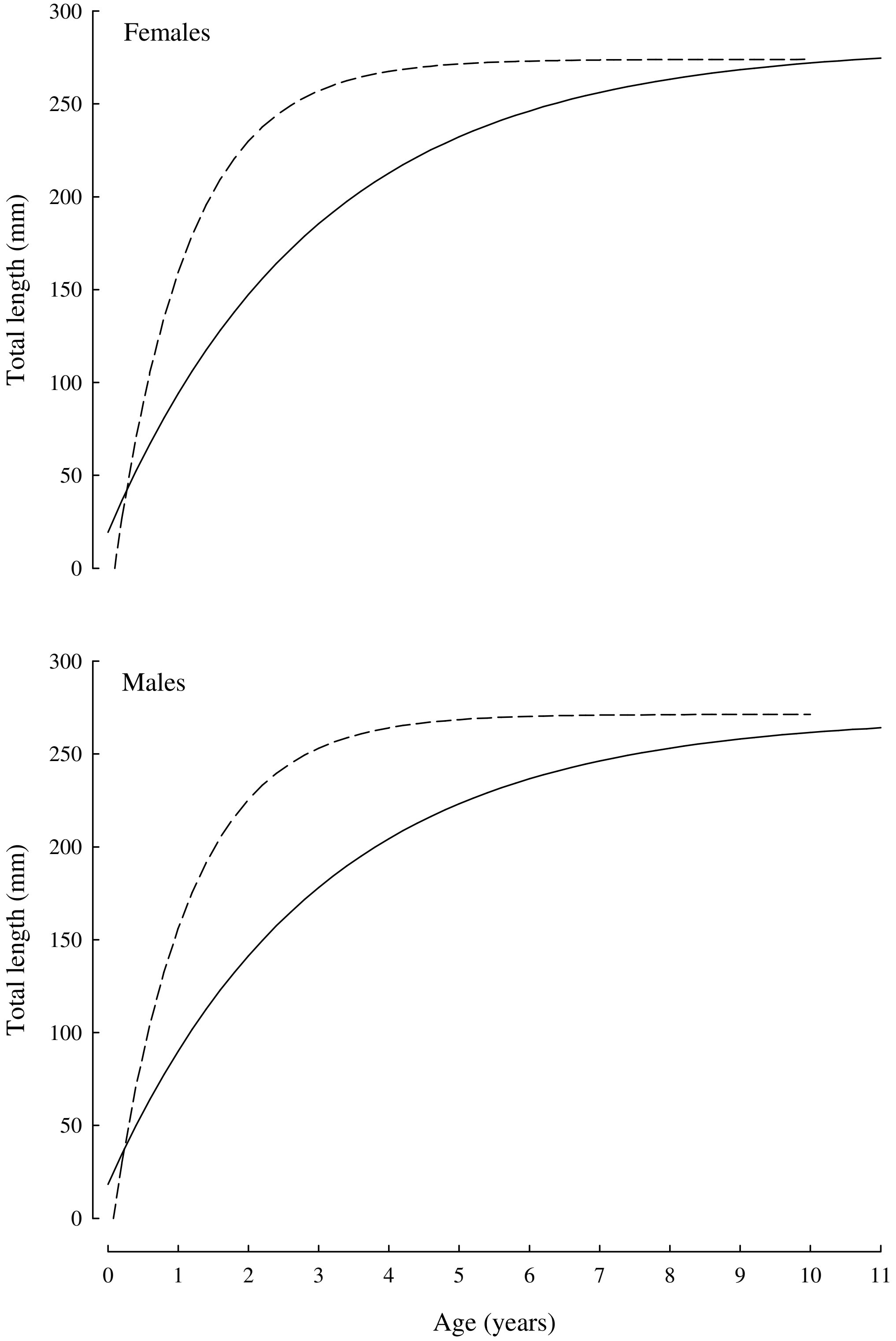

Figure 5.14. Comparisons of von Bertalanffy growth curves fitted to lengths at age for female and male *Acanthopagrus butcheri* from Stokes Inlet (solid) and pooled data for all regions of Culham Inlet (dashed).

asymptote (Table 5.3). The difference in the pattern of growth in the two estuaries, becomes even more pronounced when comparisons are made with comparable regions of those estuaries, *i.e.* that downstream of the rock bar on the Philips River in Culham Inlet and that downstream of the weir constructed on the Young River in Stokes Inlet (Fig. 5.15). This point is illustrated by the fact that the values for k for females and males in this region of Culham Inlet, *i.e.* 0.96 and 0.92, are nearly three times those in Stokes Inlet. Furthermore, the growth in the upstream pools of Culham Inlet differs markedly, not only from that in the region downstream of the rock bar, but also from that in Stokes Inlet (Fig. 5.15, Table 5.3).

As the fish from Hamersley Inlet were almost exclusively aged between 1.4 and 2.4 years, we have compared the lengths at age of the females and males of *A. butcheri* in this system at 1.4-1.7 years of age, for which there were substantial data, with those for fish of the same age in Stokes and Culham Inlet. The mean length of 200 mm for females at this age in Hamersley Inlet, did not differ significantly from the corresponding mean of 179 mm for females in Culham Inlet ($p>0.05$), derived from data for fish caught throughout the system. However, the mean length of 193 mm for males in Hamersley Inlet was significantly different ($p<0.05$) from the mean length of 175 mm for males in Culham Inlet. The mean lengths of both females and males in both the Culham and Hamersley inlets were significantly greater than the corresponding mean lengths of 137 and 130 mm for those sexes in Stokes Inlet (all p values <0.01). However, it should be borne in mind that, within Culham Inlet, the mean lengths of females and males downstream from the rock bar were 208 and 183 mm, and thus virtually the same as in Hamersley Inlet, while those upstream were only 129 and 139 mm, and thus much more comparable with those in Stokes Inlet.

5.3.3 *Diets*

Overall dietary compositions

Although macrophytes was the dominant dietary taxon of Black Bream in the Stokes, Hamersley and Culham inlets, their frequency of ingestion and more particularly their volumetric contribution to the overall diet varied greatly among estuaries (Table 5.4). Thus, macrophytes

Table 5.4 Frequency of occurrence (%F) and mean percentage volumetric contribution (%V) of major taxa (boldface) and 33 dietary categories (marked with an asterisk) to the overall diets of *Acanthopagrus butcheri* in Stokes, Hamersley and Culham inlets.

	Stokes Inlet		Hamersley Inlet		Culham Inlet	
Major taxa and dietary categories	%F	%V	%F	%V	%F	%V
Polychaetes	**60.5**	**22.5**	**49.0**	**7.8**	**16.9**	**4.6**
Nereidae*	2.2	0.7	0.7	<0.1	3.5	0.8
Capitellidae*	27.3	8.2	38.6	5.3	9.3	2.9
Spionidae*	4.4	2.1	-	-	-	-
Orbiniidae*	1.1	0.4	-	-	-	-
*Ficopomatos enigmatica**	40.6	11.1	15.9	2.5	5.8	0.9
Molluscs	**15.9**	**2.3**	**1.4**	**<0.1**	**27.9**	**11.5**
Bivalves	**8.9**	**1.8**	**0.7**	**<0.1**	**13.4**	**5.8**
Mytilidae*	3.7	1.5	-	-	12.8	5.8
*Arthritica semen**	3.0	<0.1	0.7	<0.1	0.6	<0.1
Other bivalves*	2.2	0.3	-	-	-	-
Gastropods	**9.2**	**0.4**	**0.7**	**<0.1**	**16.9**	**5.8**
*Hydrococcus brazieri**	7.0	0.2	0.7	<0.1	11.6	5.0
*Hydrobia buccinoides**	3.0	0.1	-	-	4.1	0.7
Assiminea sp.*	-	-	-	-	1.2	0.1
*Nassarius burchardii**	0.4	0.1	-	-	-	-
Trochidae*	-	-	0.7	<0.1	-	-
Crustaceans	**21.8**	**8.2**	**2.1**	**<0.1**	**9.3**	**2.9**
Parartemia sp.*	-	-	-	-	2.3	1.8
Ostracoda*	5.9	0.8	1.4	<0.1	-	-
Mysidacea*	0.7	<0.1	-	-	-	-
Amphipoda*	17.7	7.3	0.7	<0.1	5.8	0.8
Decapoda*	-	-	-	-	1.2	0.3
Teleosts	**9.6**	**4.2**	**42.8**	**23.4**	**26.7**	**19.5**
*Atherinosoma elongata**	3.3	1.6	39.3	23.1	7.0	5.2
*Pseudogobius olorum**	1.8	1.4	-	-	15.1	13.7
Unidentifiable teleosts	2.6	0.6	4.1	0.2	4.1	0.4
Teleost eggs*	1.5	0.6	1.4	0.1	1.2	<0.1
Teleost larvae*	0.4	<0.1	0.7	<0.1	-	-
Insects	**29.5**	**4.0**	**53.8**	**5.0**	**41.3**	**22.4**
Chironomidae*	27.3	3.6	43.4	1.3	38.4	20.6
Trichoptera*	1.5	0.2	11.7	3.5	4.1	1.1
Coleoptera (terrestrial)*	1.5	0.2	-	-	2.3	0.7
Egg cases*	0.7	<0.1	10.3	0.1	-	-
Macrophytes	**78.6**	**54.1**	**87.6**	**62.8**	**64.5**	**38.4**
Cladophora sp. 1*	32.1	14.3	46.2	17.9	35.5	10.5
Cladophora sp. 2*	29.5	7.5	66.9	23.8	26.2	9.6
*Polyphysa peniculus**	26.6	6.3	47.6	12.4	19.2	5.8
Vauchuria sp.*	15.9	3.9	0.7	<0.1	1.2	0.2
*Ruppia megacarpa**	18.8	5.6	23.4	7.5	1.2	0.6
Terrestrial vegetation*	5.5	0.5	20.7	1.1	7.0	0.5
Pleurosigna sp. (colonial form)*	26.6	16.1	-	-	20.3	11.2
Other Material						
Sediment	33.9	4.8	7.6	0.9	7.0	0.5
Number of foreguts	271		145		172	
Mean gut fullness (±95% CI)	4.62 ±0.25		4.1 ±0.31		3.9 ±0.34	

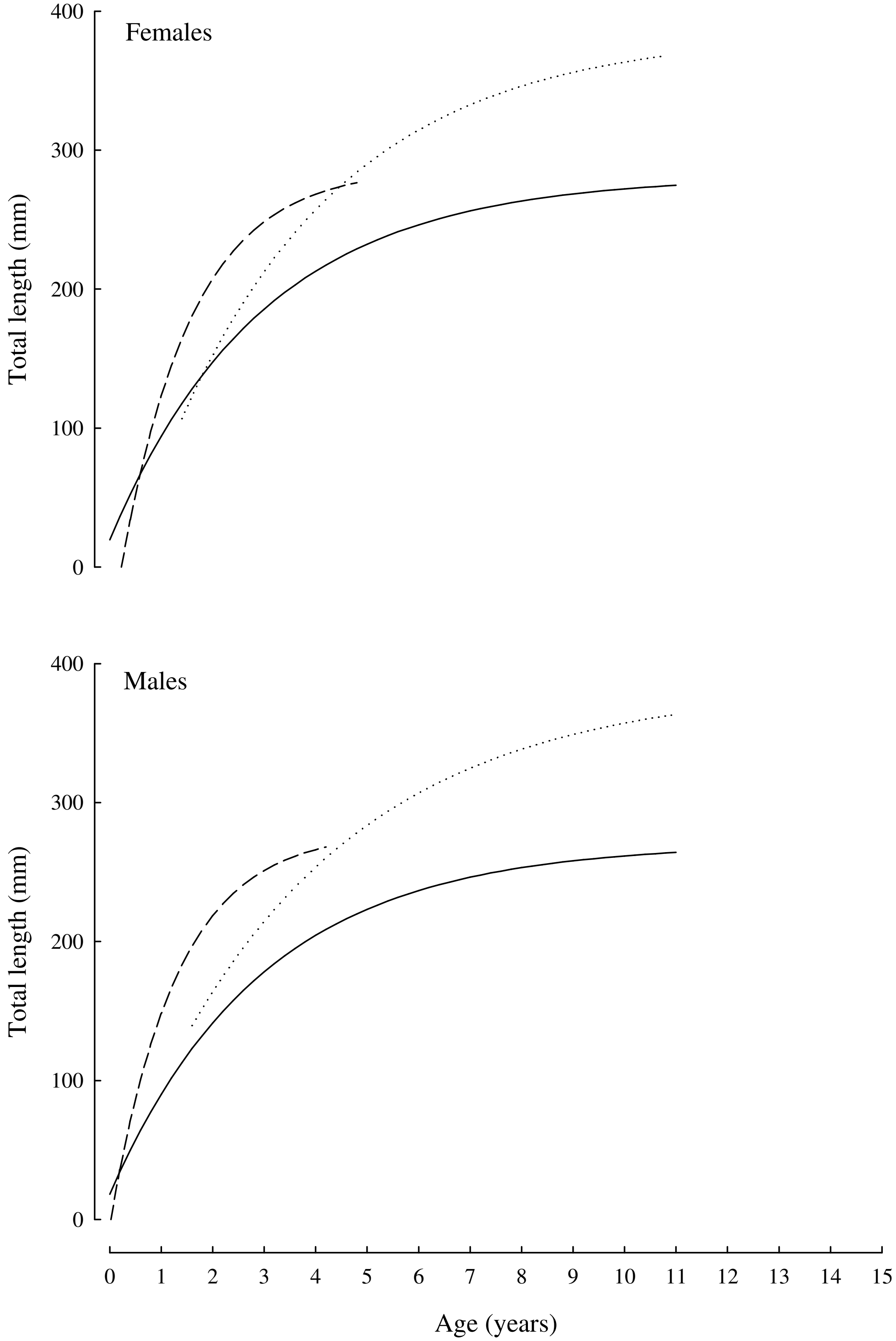

Figure 5.15. Comparisons of von Bertalanffy growth curves fitted to lengths at age for female and male *Acanthopagrus butcheri* from Stokes Inlet (solid) and from the region below (dashed) and above (dotted) the rock bar on the Philips River in Culham Inlet.

were present in *ca* 88 of the foreguts of *A. butcheri* in Hamersley Inlet compared with 79 and 65% in the Stokes and Culham inlets, respectively, and contributed *ca* 63% to the overall volume of the diets of this species in that estuary compared with 54 and 38% in the latter two estuaries, respectively. Two species of *Cladophora* were collectively by far the most important of the macrophyte component of the diets of Black Bream in each estuary (Table 5.4). In contrast to the considerable importance of the two *Cladophora* species collectively to the diet of Black Bream in Hamersley Inlet, no colonial diatoms of *Pleurosigna* sp. were found in the foreguts of fish from this estuary.

Among faunal prey, polychaetes were far more frequently ingested and contributed far more to the dietary volume of Black Bream in Stokes Inlet than in either Hamersley or Culham inlets (Table 5.4). Thus, in terms of volume, polychaetes, comprising mainly *Ficopomatus enigmatica* and capitellids, contributed 22.5% to the diet of fish in Stokes Inlet and only 7.8 and 4.6% to those in Hamersley and Culham inlets, respectively. Furthermore, crustaceans, consisting mainly of amphipods, contributed 8.2% to the volumes of the diets in Stokes Inlet, but a far smaller amount to those in Hamersley and Culham inlets. In contrast, the volumetric contribution made to the diets of Black Bream by molluscs, mainly represented by hydriid bivalves and *Hydrococcus brazieri*, was far greater in Culham Inlet, *i.e.* 11.5%, than in either of the other two estuaries, in which they contributed less than 3%. Likewise, insects, particularly chironomid larvae, were a very important volumetric component of the diets of fish from Culham Inlet, where they contributed 22.4% compared to 5% or less in the other two estuaries (Table 5.4).
Teleosts made similarly high volumetric contributions to the diets of Black Bream in Hamersley (23.4%) and Culham (19.5%) inlets, but only a small volumetric contribution (4.2%) to that in Stokes Inlet (Table 5.4). Although the teleost component of the diet in Hamersley Inlet comprised only *Atherinosoma elongata*, that in Culham Inlet contained both this atherinid and, in greater relative volumes, also the goby *Pseudogobius olorum*.

Relationships between dietary composition and body size

The smaller *A. butcheri* in Stokes Inlet, *i.e.* <99 mm in length, ingested mainly *F. enigmatica*, other polychaetes, amphipods, chironomids and macrophytes, with these dietary categories collectively contributing over 95% to the mean overall dietary volume of the ≤49 mm and 50-99 mm length classes (Fig. 5.16a). In general, as body size increased, the contribution made to the diets by amphipods, other polychaetes (Nereidae, Spionidae and Orbiniidae) and chironomids declined precipitously, whereas those of capitellid polychaetes and particularly macrophytes increased sharply. However, the contribution of *F. enigmatica* did not change conspicuously with body size (Fig. 5.16a).

In contrast to the situation in Stokes Inlet, the diets of both the ≤49 and 50-99 mm length classes of *A. butcheri* in Culham Inlet consisted almost exclusively of chironomid larvae and plant material (Fig. 5.16b). Yet, the contributions made by chironomids and the filamentous chrysophyte component of plant material to the diets of larger fish were, at best, very limited, while that of teleosts was particularly conspicuous. However, in the case of teleost prey, *P. olorum* contributed more to the diets of fish of 100-199 mm in length, whereas that of *A. elongata* was greatest in the diets of fish ≥200 mm. Gastropods were exclusively ingested by fish ≥200 mm in length. There was no conspicuous trend for the macrophyte component of the plant material in the diet of Black Bream in Culham Inlet to increase or decline with increasing body size (Fig. 5.16b).

The diets of each length class of *A. butcheri* caught in Hamersley Inlet, *i.e.* those >100 mm, collectively comprised largely the teleost *A. elongata* and macrophytes, with the contribution of the first of these dietary categories declining progressively with increasing fish size, while that of the second exhibited the opposite trend (Fig. 5.16c). Small amounts of capitellids, *F. enigmatica* and insects were ingested by the individuals of each length class >150 mm.

The mean values for the Shannon-Wiener index for the diversity of the diet of all but the first length class of Black Bream in Stokes Inlet were far greater than those of their corresponding length classes in Culham Inlet and their 95% CIs showed no overlap (Fig. 5.17).

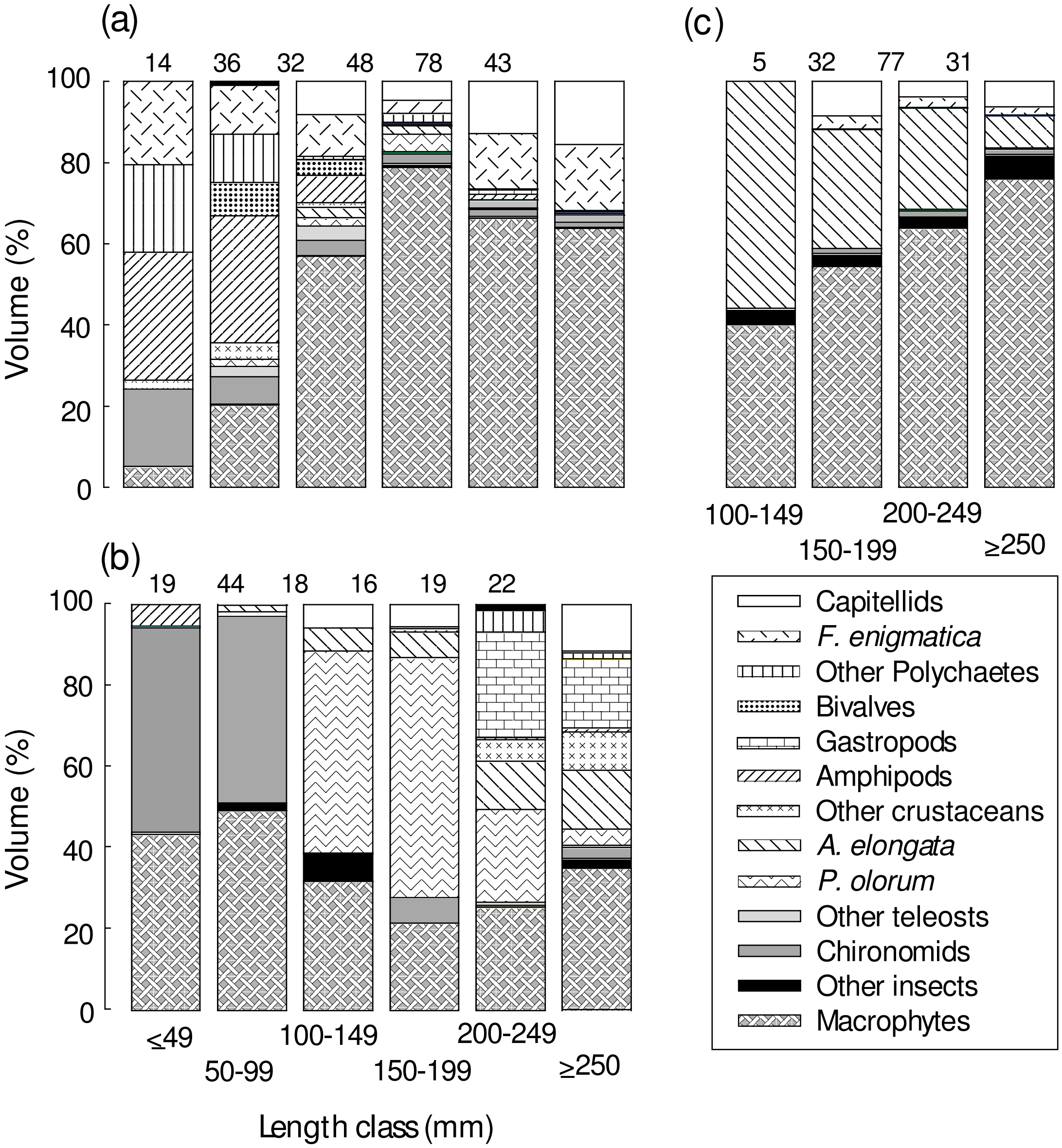

Figure 5.16. Volumetric contributions of the different dietary categories to the overall diets of sequential 50 mm length classes of *Acanthopagrus butcheri* in (a) Stokes Inlet, (b) Culham Inlet and (c) Hamersley Inlet.

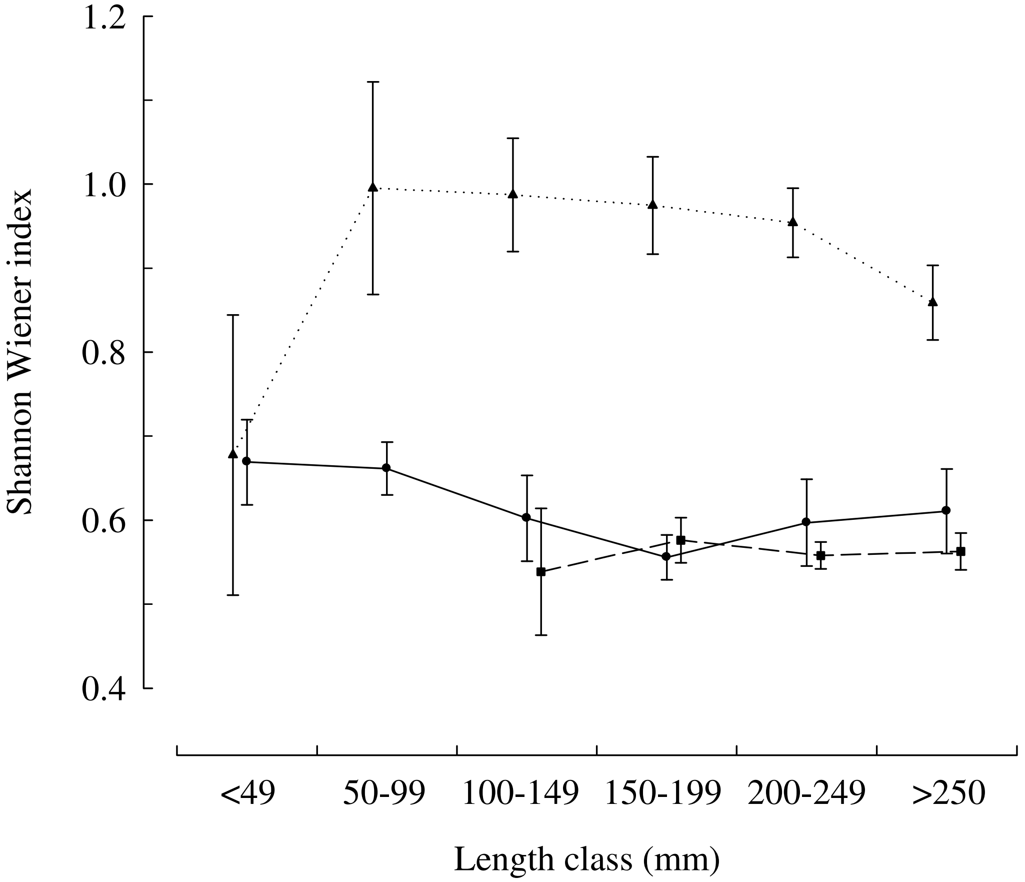

Figure 5.17. Shannon Wiener indices ±95% confidence limits for the dietary compositions of sequential 50 mm length classes of *Acanthopagrus butcheri* in the Stokes, Hamersley and Culham inlets.

The mean values for this index for fish in Stokes Inlet of each of the four length classes >100 mm were also greater and showed no overlap in their 95% CIs with those of the corresponding size classes of Black Bream in Hamersley Inlet. Note that no fish <100 mm were caught in Hamersley Inlet. The mean values for the Shanon-Wiener index of the four length classes >100 mm in the Hamersley and Culham inlets were similar and the 95% CIs for each length class overlapped markedly (Fig. 5.17).

Comparisons of dietary compositions among estuaries

Following ordination of the mean percentage volumetric contribution of each dietary category to the diets of the different length classes of *A. butcheri* >100 mm in each season in the Stokes, Hamersley and Culham inlets, the dietary samples for Black Bream in each estuary formed essentially discrete groups on the resultant ordination plot (Fig. 5.18a). Thus, those from Hamersley Inlet formed a tight group in the upper central part of the plot and to the right and/or above those from Stokes Inlet and very largely to the left and/or above those from Culham Inlet.

One-way ANOSIM demonstrated that, although the dietary compositions of *A. butcheri* differed significantly among estuaries (*P*= 0.1%), seasons (*P*= 2.5%) and length classes (*P*= 0.3%), the Global *R*-statistic values were far greater for estuary (0.373) than for either length class (0.149) or season (0.074). Pairwise ANOSIM tests demonstrated that the dietary compositions of *A. butcheri* in each pairing of estuaries differed significantly (*P*= 0.1%), with *R*-statistic values ranging only from 0.363 for Stokes *vs* Hamersley inlets to 0.391 for Culham *vs* Hamersley inlets.

SIMPER showed that, although the diets of *A. butcheri* in all estuaries were typified by *Cladophora* sp. 1 and 2, the ingestion of relatively greater amounts of *F. enigmatica* in Stokes Inlet, of *A. elongata* in Hamersley Inlet and of *H. brazieri* and *P. olorum* in Culham Inlet, distinguished the diet of this sparid in each of those estuaries, respectively, from those in the other two estuaries (Table 5.5).

When the mean dietary data for groups of three individuals of Black Bream in each of the ≤49 and 50-99 mm length classes in the Stokes and Culham inlets were subjected to ordination, all of the dietary samples for Stokes Inlet lay to the left of those for Culham Inlet (Fig. 5.18b). However, the dietary samples for the two length classes in both the Stokes and Culham inlets intermingled. The dietary compositions of the two size classes were not significantly different ($P > 5\%$) in either the Stokes or Culham inlets, for which the *R*-statistic values were very low, *i.e.* 0.031 and -0.126, respectively. The diets of the juveniles of *A. butcheri* in the two estuaries are

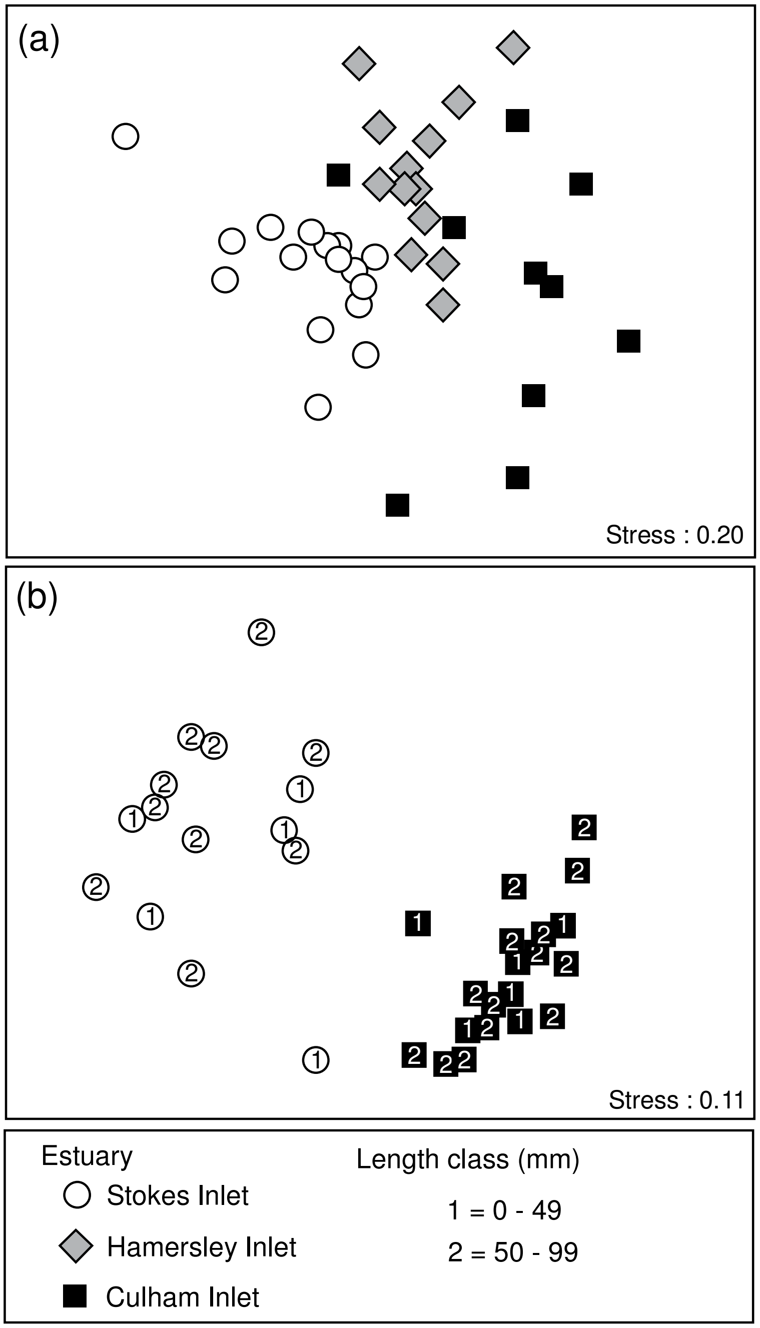

Figure 5.18. MDS ordination of the dietary compositions of *Acanthopagrus butcheri*, derived using the mean values for the dietary samples of fish in (a) each length class in each season in the Stokes, Culham and Hamersley inlets, and (b) randomly-selected groups of three fish in the <50 and 50-99 mm length classes in the Stokes, Culham and Hamersley inlets.

typified by completely different taxa and that of Stokes Inlet is distinguished, in particular, from that of Culham Inlet by a relatively far greater volume of amphipods and a relatively far smaller volume of chironomids and *Pleurosigna* sp.

Table 5.5. Dietary categories determined by SIMPER as those most responsible for typifying the dietary compositions of *Acanthopagrus butcheri* (non-shaded boxes) in Stokes, Hamersley and Culham inlets and distinguishing between the diets of that species in those three estuaries. Asterisks denote that the dietary category makes a greater contribution to the diets recorded for the species at the top of the column.

Estuary	Stokes Inlet	Hamersley Inlet	Culham Inlet
Stokes Inlet	*F. enigmatica* *Cladophora* sp. 1 *Cladophora* sp. 2 *Pleurosigna* sp.		
Hamersley Inlet	*A. elongata* *Pleurosigna* sp. *Cladophora* sp. 2 *F. enigmatica* *	*Cladophora* sp. 2 *Cladophora* sp. 1 *A. elongata*	
Culham Inlet	*F. enigmatica* * *H. brazieri* *P. olorum*	*A. elongata** *Cladophora* sp. 2* *H. brazieri* *P. olorum*	*Cladophora* sp. 1 *Cladophora* sp. 2 *H. brazieri*

When the dietary data for the different size classes of *A. butcheri* recorded in Stokes, Culham and Hamersley inlets in the different seasons were subjected to MDS ordinations, the dietary samples of the corresponding length classes in any estuary in any given season intermingled on the plot (Figs 5.19a-c). However, the points for sequential length classes in each estuary in a given season often tended to form a progression on the plot. Thus, for example, on the ordination plot for Stokes Inlet, the samples for sequential lengths of fish in winter and spring both progressed upwards and those for autumn and, to a lesser extent, summer shifted from left to right (Fig. 5.19a). Similar sequential trends were seen with the more limited data for winter and autumn in Hamersley Inlet and for spring in Culham Inlet (Figs 5.19b, c). Furthermore, the dietary samples for the smallest fish in both Stokes and Culham inlet, *i.e.* ≤49 and 50-99 mm, when both of these length classes were present in these estuaries, were located close together and well to the left of dietary samples of the length classes representing the larger fish (Figs 5.19a, c).

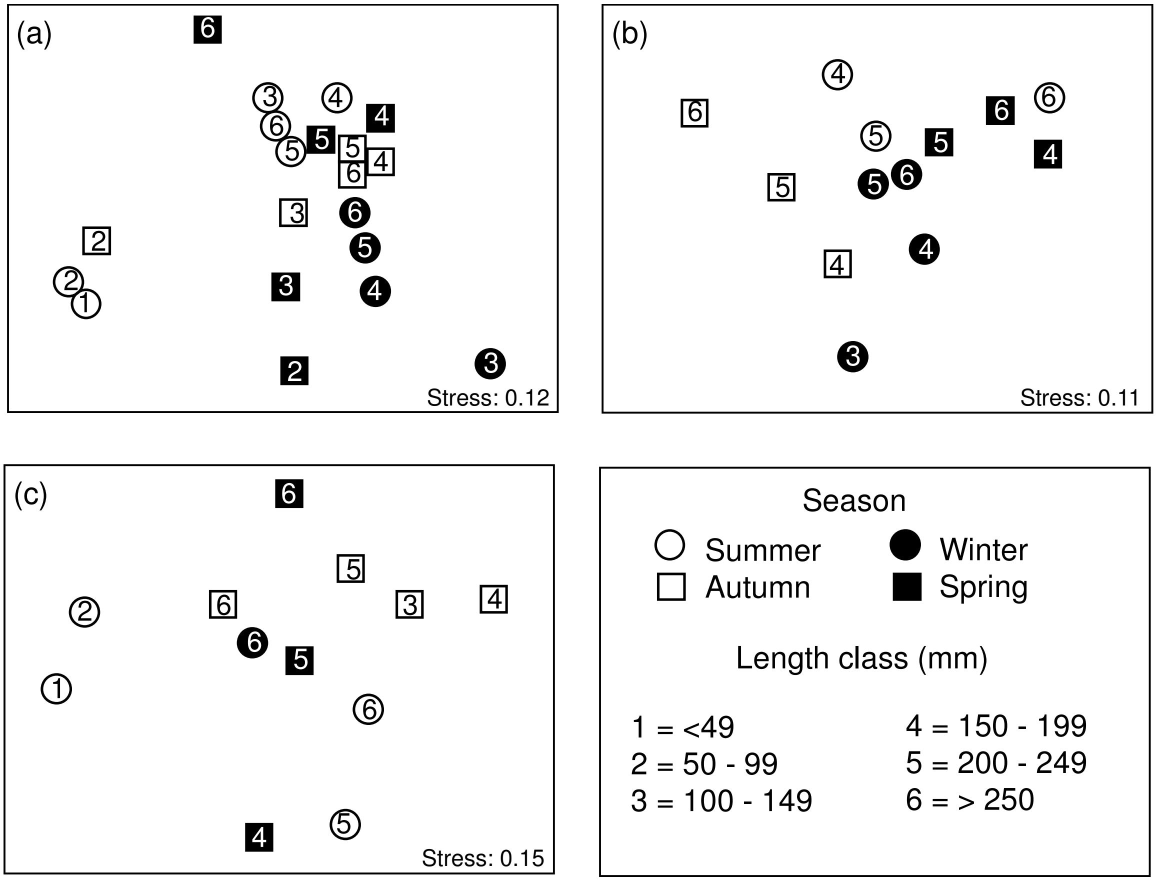

Figure 5.19. MDS ordination of the dietary compositions of sequential 50 mm length classes of *Acanthopagrus butcheri* in different season in (a) Stokes Inlet, (b) Hamersley Inlet and (c) Culham Inlet

Comparisons of dietary compositions in Culham Inlet

After the dietary data for individuals of *A. butcheri* with lengths of 150 to 249 mm from above and below the rock bar in Culham Inlet were ordinated and coded for region, the dietary samples for the downstream region were widely distributed in the right two thirds of the plot and generally above and/or to the right of those for the upstream pools (Fig. 5.20). The diets of *A. butcheri* in the two regions were significantly different (*P*< 0.1%, *R*-statistic = 0.259). The main typifying dietary categories included *P. olorum* and *H. brazieri* in the downstream region and hydriid molluscs in the upstream pools, and these species were also important in distinguishing between the diets of fish in these two regions.

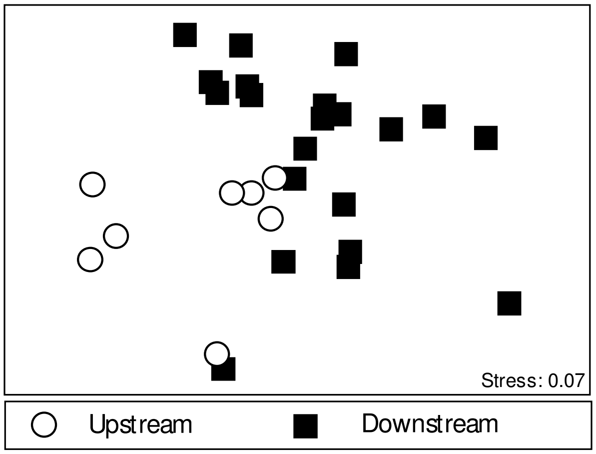

Figure 5.20. MDS ordination of the dietary compositions of *Acanthopagrus butcheri* in the upstream pools and downstream region (basin and lower reached of tributary) of Culham Inlet.

5.4 DISCUSSION

5.4.1 *Reproduction*

Spawning period

Since hydrated oocytes and/or post-ovulatory follicles were present in histological sections of the ovaries of *A. butcheri* collected from Stokes Inlet in each month between June and November, spawning occurs over the protracted period of early winter to late spring. This conclusion is consistent with mature males being caught in all months between June and November and with all of those obtained in June being running ripe. However, as the mean monthly GSIs and the prevalences of fish with gonads at stages V and VI were greatest between August and November, the individuals of *A. butcheri* in Stokes Inlet spawn predominantly during these months. Furthermore, the commencement of spawning in Stokes Inlet in winter is consistent with the fact that the larvae of this species settle at *ca* two months of age and at a length of *ca* 12 mm (Neira *et al.*, 1998) and we caught numerous juvenile Black Bream with lengths of 10-30 mm in October. Although reproductive data for *A. butcheri* in the Culham and Hamersley inlets were obtained only for the middle month of each season, the trends exhibited by the mean GSIs and prevalences of gonads at stages V and VI for those months were essentially the same as those recorded for Stokes Inlet in the same months. This implies that Black Bream spawn during a similar period in each of the three estuaries.

The onset of spawning as early as the beginning of winter in at least Stokes Inlet contrasts with the situation in the Swan River Estuary on the lower west coast of Australia, where spawning does not commence until spring (Sarre & Potter, 1999). Furthermore, Black Bream also spawn earlier in the Wellstead Estuary, which is located to the west of Stokes Inlet on the south coast of Western Australia, than in the Swan River Estuary (Sarre & Potter, 1999). This finding is perhaps surprising since the spawning of teleost fish can typically be related to water temperature (Lam, 1983) and water temperatures in south coast estuaries are lower than those in the Swan River Estuary. However, the early spawning of Black Bream in the Stokes and Wellstead estuaries might reflect a response to selection pressures that would ensure that the spawning and recruitment of juveniles occurs in these estuaries before salinities become elevated to their characteristically high levels during late spring and early summer (Sarre & Potter, 1999) and which are likely to be far less conducive to the survival of the eggs and larvae of this species. The view that an advancement in the onset of spawning in the Stokes, Wellstead and other central south coast estuaries reflects a response to the hypersaline conditions that characterise these estuaries is consistent with the fact that Black Bream spawn later in the Nornalup-Walpole Inlet, which is located at a similar latitude, but further to the west and does not become hypersaline (Potter & Hyndes, 1994). Furthermore, in two Tasmanian estuaries, in which temperatures are cooler and the water does not become hypersaline, the spawning season extends into summer (Haddy & Pankhurst, 1998).

Although *A. butcheri* commences spawning earlier in central south coast estuaries than in the Swan River Estuary, and thus when salinities in these hypersaline estuaries are typically near their annual minima, this species can still become fully mature in these estuaries in salinities that can range as widely as 17 to 59, *i.e.* females produce hydrated oocytes and males produce spermatozoa. Furthermore, in the intermittently-open Moore River Estuary, just to the north of the Swan River Estuary, Black Bream spawn when salinities are as low as 3 to 8. Elsewhere in Australia, *A. butcheri* spawns at salinities of 14 to 35 in the Meredith River in Tasmania (Haddy

& Pankhurst, 1998) and between 0 and 30 in the Gippsland Lakes in Victoria (Ramm, 1986). The above remarkable variability in the salinities in which Black Bream can develop to maturity emphasizes that, in this respect, this species is highly adaptable, which would contribute to the great success of *A. butcheri* in many estuaries in southern Australia, which differ in type, *e.g.* permanently-open *vs* seasonally-open or normally-closed, and in their salinity regime.

As females of *A. butcheri* with ovaries containing hydrated oocytes and/or post-ovulatory follicles were caught in the basin and river of both the Stokes and Hamersley inlets, this sparid apparently spawns in both of these regions of those two estuaries. This situation differs from that in the Swan River Estuary, where Black Bream spawn mainly in its upper regions, *i.e.* in the tributaries that feed the large central basins (Sarre & Potter, 1999), and the same situation is essentially true for two estuaries in Tasmania (Haddy & Pankhurst, 1998).

Lengths and ages at maturity

The lengths at which 50% of females and males of *A. butcheri* were estimated as becoming mature in Stokes Inlet (155 and 141 mm, respectively) are very similar to those estimated by Sarre & Potter (1999) for this species in Wellstead Estuary (157 and 145 mm, respectively). Furthermore, these lengths are attained at approximately two years of age in both systems. In contrast to the situation in Stokes Inlet, the reproductive data for *A. butcheri* in the Culham and Hamersley inlets are very limited, due to the paucity of fish caught during the spawning period around the lengths at which maturity would be attained, and which reflected the effects of the massive fish kills that occurred in those systems during the present study (see Chapter 4). However, it is relevant that, although no fish were caught at lengths <136 mm in the Hamersley Inlet and between 69 and 142 mm in the Culham Inlet during the spawning period, all but one of the limited numbers of *A. butcheri* in each 20 mm length class >120-139 mm in both systems were mature. Although the lengths at which 50% of *A. butcheri* become mature in the above four estuaries are apparently similar, the L_{50}s at maturity estimated by Sarre & Potter (1999) for females and males in the Swan River and Nornalup/Walpole estuaries were considerably higher, *i.e.* 218 and 201 mm, respectively, for females and 212 and 158 mm, respectively for males. An extreme expression of the extent to which the age at which Black Bream matures is illustrated by the ability of this species to attain spawning condition at *ca* six months of age when maintained in aquaculture ponds supplied with an abundant food source (G. Sarre, Northam TAFE, pers. comm.).

5.4.2 *Age compositions and recruitment success*

It is particularly noteworthy that no recruits of the 2002 year class were caught in the Stokes, Culham or Hamersley inlets and that, among these estuaries, recruits of the 2003 year class were caught only in Stokes Inlet (Table 5.2). Conditions must thus have been highly adverse for spawning and/or recruitment in 2002 in all three estuaries. In the case of Culham Inlet, the absence of the 2002 year class downstream of the rock bar on its main tributary is clearly due to the absence of fish in that region in 2002 as a result of the apparently total mortality of Black Bream caused by salinities exceeding 140, a level which is clearly lethal for this species (Chapter 4). However, there was also no recruitment in 2002 in regions upstream of the rock bar, where salinities were far lower and never exceeded 29 and were thus well within the range of salinities in which Black Bream is known to spawn successfully (Sarre & Potter, 1999; Partridge & Jenkins, 2002). Although salinity levels in the upstream pools were not apparently a factor limiting spawning success, rainfall in the catchment of Culham Inlet in 2002 was particularly low and, indeed, that year was the driest on record since 1901 (Bureau of Meteorology). Consequently, in the absence of water flow, the conditions required for spawning and/or recruitment success of *A. butcheri* may not have been present even in the upstream pools of Culham Inlet.

As a result of the very dry conditions in 2002, salinities in Hamersley Inlet had already reached 54 during the main part of the spawning period of Black Bream in this estuary and had exceeded 80 by January 2003, which led to such massive mortalities that all individuals of this species below the rock bar in this system apparently died. The maintenance of exceptionally high salinities in Hamersley Inlet in subsequent months would not have been conducive to the survival of Black Bream or to their possible successful replenishment from upstream pools.

In contrast to the situation in Culham and Hamersley inlets, Black Bream were found in the main body of Stokes Inlet during each sampling trip conducted after mass mortalities had occurred in those other two estuaries, and spawning in 2003 led to a substantial recruitment of the 2003 year class. The survival of Black Bream in Stokes Inlet throughout our study is attributable to the fact that salinities in this estuary remained below 65 and thus did not rise to anywhere near the same extent as in the other two estuaries. However, salinities in the basin did rise to 53 in January 2003 and this could have been sufficiently high to have been lethal for the eggs and larvae, which are presumably more susceptible than juveniles and adults to hypersaline conditions. This may account for the lack of the 2002 year class. However, alternatively, the very low rainfall and thus flow in Stokes Inlet in 2002 may not have provided conditions conducive to spawning and/or recruitment success, as was suggested to be the case in Culham Inlet in the same year.

Our sampling demonstrates that, at the time of this study, the year class compositions of the assemblages of *A. butcheri* in the basin and lower reaches of the Stokes, Culham and Hamersley inlets were very different. The presence of all year classes from 1992 to 2001 in Stokes Inlet demonstrates that environmental conditions in this system are consistently conducive to the spawning, recruitment and subsequent survival of Black Bream. In this context, it would appear highly relevant that, at least on the basis of the results of the current study, salinities in Stokes Inlet do not reach the very high levels found below the rock bars of the Culham and Hamersley inlets and which, at their most extreme, cause massive mortalities of Black Bream (Chapter 4).

Although all but two of the year classes between 1992 and 2001 were found in samples collected from throughout Culham Inlet, the region below the rock bar of this system did not contain any year classes older than 1997, whereas those of 1992, 1995 and 1996 were found in pools above that rock bar and these were all moderately abundant. These comparisons suggest that the upstream pools, which do not reach the same very high salinities as below the rock bar, provide more consistent conditions for the survival of Black Bream and thus act as refugia that can lead to replenishment of downstream areas, which would occur when discharge is sufficiently high to allow water to pass over the rock bar.

The numerous samples of fish collected from below the rock bar on the Hamersley River contained only the year classes of Black Bream between 1998 and 2001 and all but that of 2000 were represented by a single individual of this species. These data suggest either that conditions for recruitment of 0+ *A. butcheri* in Hamersley Inlet in many years are poor and/or that the assemblage of Black Bream in the basin and lower reaches of this estuary has suffered, at some time(s), massive mortalities in the years prior to this study. As only one year class was strongly represented in the basin and lower reaches of the tributary of Hamersley Inlet, it would appear relevant that the rock bar is higher in the Hamersley River (>5 m) than in the tributary of Culham Inlet (<3 m). This results in a frequent discontinuity between upstream and downstream regions and thereby reduces the potential for the downstream transport of larval and juvenile Black Bream. The far greater than normal flow in 2001, which would have resulted from relatively high rainfall in the latter part of that year, would account for the strong representation of the 2000 year class in the basin and lower reaches of the tributary of Hamersley Inlet.

The extreme paucity of fish representing year classes of Black Bream in Hamersley Inlet prior to 2000 implies either that, in earlier years, conditions were unsuitable for spawning and/or recruitment or there was massive mortality and/or flushing of this species out of the estuary. As the bar was breached by exceptionally heavy discharge in the summer of 2000, this event could have resulted in Black Bream being flushed out of Hamersley Inlet at that time. Alternatively, the low water levels that would have resulted from the breaching of the bar and the particularly dry period that followed for the remainder of 2000 may have led to salinities rising to levels lethal to Black Bream and therefore to massive mortality during that period.

Although all year classes of *A. butcheri* between 1992 and 2001 were recorded in Stokes Inlet, substantial differences in the relative abundances of the different year classes were observed, *i.e.* the 1993 and 1998 year classes were strong and the 1992, 1994, 1996, 1997 and 2001 year classes were weak. The variable recruitment displayed by *A. butcheri* in Stokes Inlet parallels the situation described for Wellstead Estuary on the south coast of Western Australia

(Sarre & Potter, 1999) and the Gippsland Lakes in Victoria (Hobday & Moran, 1983, Morison *et al.*, 1998). Weak year classes in those other estuaries were strongly correlated with heavy freshwater discharge in the months immediately following the spawning period and, in the case of Wellstead Estuary, the breaching of the sand bar at those times apparently resulted in the juveniles in that estuary being flushed out to sea (Sarre & Potter, 1999). The only year in which very heavy discharge occurred prior to and during the spawning period of Black Bream in Stokes Inlet, *i.e.* 1992, was represented by relatively low numbers of fish of that year class in our samples (see Table 5.2). The years when discharge was particularly low in those months, *i.e.* 1994, 1996, 2000 and 2002, were also poorly represented by the corresponding year classes of Black Bream. In contrast, when moderate flow was recorded in the months preceding and during the spawning period of Black Bream, *i.e.* 1993, 1998 and 2003, the corresponding year classes were well represented.

5.4.3 *Dietary composition*

Comparisons of dietary compositions and their diversity among estuaries

The results of this study emphasise that, even in the three environmentally-degraded estuaries that were the subject of the present study, *Acanthopagrus butcheri* still feeds on a wide range of plant and animal taxa, as it does in other estuaries elsewhere in south-western Australia (Sarre *et al.*, 2000). Thus, prior to the development of extreme hypersaline conditions in the Hamersley and Culham inlets, this sparid ingested polychaetes, molluscs, crustaceans, teleosts, insects and macrophytes in both of these estuaries as well as in Stokes Inlet. However, the dietary compositions of Black Bream in the three estuaries did vary markedly. Thus, this species ingested relatively greater volumes of polychaetes and crustaceans in Stokes Inlet than in the other two estuaries, while those in Hamersley Inlet consumed a particularly large volume of macrophytes and those in Culham Inlet fed to a greater extent on molluscs. Furthermore, relatively far greater volumes of teleosts were ingested by Black Bream in both the Hamersley and Culham inlets than in Stokes Inlet, and the colonial diatom *Pleurosigna* sp. was ingested in substantial amounts by

Black Bream in the Stokes and Culham inlets, but never by those in Hamersley Inlet. These comparisons of the dietary data within and among three normally-closed estuaries, together with those for permanently and intermittently-open estuaries and a coastal lake (Sarre *et al.*, 2000), demonstrate that *A. butcheri* is highly opportunist in its feeding behaviour, which would help account for the success of this sparid in a wide range of estuary types in south-western Australia (Potter & Hyndes, 1999; Sarre & Potter, 2000).

Although the wide range of food types ingested by Black Bream in the three estuaries implies that this species is also a generalist feeder, the diversity of the types of food ingested by all but the very smallest fish in Stokes Inlet was far greater than that of this species in both the Hamersley and Culham inlets. It is thus highly relevant that, during dry periods, the water in Stokes Inlet does not fall to such low levels and consequently does not become nearly as hypersaline as those of the Hamersley and Culham inlets (see Chapter 3 and Hodgkin & Clark, 1989, 1990). As Stokes Inlet is not so prone to becoming grossly hypersaline and Black Bream feed opportunistically, it is proposed that the greater diversity of biota in the diet of this species in Stokes Inlet reflects a greater diversity of potential food in that estuary. Unfortunately, there have been no detailed quantitative studies on the invertebrates in the above three estuaries, which are located in a relatively unpopulated region of the south coast of Western Australia.

Unlike the situation with all other length classes, the mean diversity of the smallest fish in Stokes Inlet was similar to that in Culham Inlet. However, it is evident from the mean volumetric contributions of each dietary category to the overall diet of fish $\leq$ 49 mm length class that, overall, the smallest fish consume a far wider range of dietary categories in the Stokes than Culham inlets. These comparisons imply that each small fish tends to feed on a restricted number of dietary categories, which is consistent with the results of an examination of the raw data for the diets of those small fish.

The massive mortalities undergone by Black Bream in both Hamersley and Culham inlets, as salinity levels rose markedly (Chapter 4), emphasise that the upstream pools in at least Culham Inlet, which were found to contain Black Bream, act as important refugia for this species. They can thus provide a source of replenishment of fish for downstream regions when water levels and discharge increase and the salinities in those regions thus decline to levels that can be tolerated by Black Bream. It was particularly noteworthy that the dietary compositions of *A. butcheri* in the two regions differed conspicuously, with the teleost *Psuedogobius olorum* and the small gastropod *Hydrococcus brazieri* typifying that of fish in the downstream region and mytilid mussels typifying that of fish in upstream pools. These differences will reflect not only differences in potential prey in these two regions, but also the fact that, even during the early part of the study, when environmental conditions were not so extreme, the presence of a large rock bar across the river greatly restricted flow and thus the movement of fish between upstream and downstream areas.

Size-related differences

Although the suite of potential prey was likely to have been limited in the Hamersley and Culham inlets, the diets of Black Bream in these two estuaries, as well as in Stokes Inlet, still underwent conspicuous size-related changes. For example, in Stokes Inlet, these changes involved *inter alia* a shift from the ingestion of relatively small prey, such as amphipods, ostracods and mysid crustaceans and chironomid larvae, to the consumption of larger prey including teleosts. However, the trends exhibited by the ingestion of plant material as Black Bream increased in size, differed among estuaries. Thus, the volume of plant material in the gut contents of Black Bream in Stokes Inlet rose progressively with each length class up to 199 mm and remained high in the two length classes of largest fish, whereas in those from Culham Inlet it was relatively high in the gut contents of fish <100 mm and did not increase in those of fish >100 mm, and, amongst those larger fish, never approached the levels recorded in Stokes Inlet.

The far wider range of invertebrate prey found in the gut contents of Black Bream <100 mm in the Stokes than Culham inlets, suggest that small *A. butcheri* ingest plant material to a greater extent in the latter estuary because the diversity and/or abundance of potential invertebrate prey in that more degraded estuary is less. Surprisingly, the reverse trend was exhibited by the diets of larger fish, with plant material comprising 60-78% of those of each length class above 100 mm in Stokes Inlet and ≤ 35% in those of the same length classes in

Culham Inlet. Furthermore, the faunal component of the diet of larger fish was dominated by invertebrate prey in Stokes Inlet and by teleost fish in Culham Inlet. It is thus relevant that the densities of small fish, *i.e.* comprising the atherinid *Atherinosoma elongata* and the goby *Pseudogobius olorum*, were approximately three times greater in the Culham than Stokes Inlet (S. Hoeksema, unpublished data). Moreover, the densities of these small fish were also approximately twice as great in Hamersley Inlet as the Stokes Inlet and likewise made a greater contribution to the diet of Black Bream in the former than latter estuary. Yet, it must be recognised that, as sparids often consume plant material and possess the amylase required for digesting the carbohydrates in that material (Fernandez *et al.*, 2001) and incorporate the C from that source in their tissues (Havelange *et al.*, 1997), macrophytes still act as an important food source. However, in general, plant material is less digestible than animal matter (Stevens & Hume, 1995).

Among the teleost prey, it was noteworthy that, while *A. elongata* and *P. olorum* were both ingested by Black Bream in Culham Inlet, only the former species was consumed by this sparid in Hamersley Inlet. This presumably reflects, at least in part, the fact that the ratio of the densities of *A. elongata* to *P. olorum* in Culham Inlet were twice that in Hamersley Inlet (S. Hoeksema, unpublished data). However, it was also evident that fish of 100-199 mm in Culham Inlet consumed relatively more *P. olorum* than *A. elongata*, and that the reverse was true for fish >200 mm. This difference in prey ingestion by Black Bream of different sizes presumably reflects the fact that, as Black Bream increase in size, they become more capable of catching the atherinid species which are faster swimming than gobies.

Although the dietary composition of Black Bream in the Stokes and Culham inlets underwent an essentially progressive change, the shift that occurred in the diet between the two length classes below 100 mm and four length classes above 100 mm was pronounced. It could thus be relevant that, at 80 mm length, the location of the area centralis in the retinal ganglion cell of the eyes of Black Bream changes and that, in the laboratory, this was found to be accompanied by a switch from feeding at the water surface or bottom of the water column to a bentho-pelagic feeding mode (Shand *et al.*, 2000). Our data do not reveal such a radical shift in the location of prey ingested, with all of the prey consumed by both small and large Black Bream typically living above or on the substrate (spionids, orbiniids, amphipods and teleosts). However, in the Stokes, Culham and Hamersley inlets, capitellid polychaetes, which are exclusively infaunal, are ingested in moderate quantities by fish >100 mm but not by smaller fish. Despite the fact that the dietary categories which contribute most to size-related dietary shifts in Black Bream vary among estuaries, any size-related changes in diet would help reduce the potential for intraspecific competition for food resources, and thus be particularly beneficial in estuaries where the diversity of food types is limited.

5.4.4 *Growth*

The early growth of Black Bream in the pools in the region above the rock bar on the main tributary (Phillips River) of Culham Inlet was slower than further downstream in the main body of this estuary. Thus, after 1.5 and 3 years, the lengths of female Black Bream in the upstream pools of Culham Inlet had only reached *ca* 115 and 213 mm, respectively, compared with 203 and 257 mm, respectively. These differences imply that the members of the upstream and downstream assemblages of Black Bream remain relatively discrete. This would be consistent with the fact that water levels prior to and during our study were low and consequently the rock bar on the Phillips River would have acted as a barrier to the movement of Black Bream between upstream and downstream regions during that period. A lack of intermingling between upstream and downstream assemblages of Black Bream would also help account for the very pronounced differences in the dietary compositions of this species in these two regions of Culham Inlet, especially as the environmental conditions, and thus presumably of the potential types of food, differed in the two regions. Mytilid mussels made a far greater contribution to the diet of fish in the upstream than downstream regions, whereas the reverse was the case with the small goby *P. olorum* and a small gastropod (see previous section). However, our visual observations and very high success rates in catching Black Bream by angling in the upstream pools of Culham Inlet provide very strong circumstantial evidence that the densities of this species in these pools were particularly high. Thus, the growth of Black Bream may be negatively correlated with the densities of this sparid.

The patterns of growth of *A. butcheri* in the main body of Stokes Inlet, *i.e.* basin and lower reaches of the rivers, differed from those found in the main body of Culham Inlet. Thus, whereas the L_∞s of the populations in this region of these two estuaries were similar, the individuals in Culham Inlet grew far more rapidly during the first two years of life. The marked difference in early growth is illustrated by the fact that at 1.5 and 3 years of age, the females of *A. butcheri* had reached 203 and 257 mm in Culham Inlet compared with 124 and 187 mm in Stokes Inlet. Although only two female fish < 1.3 years were caught in the basin and lower reaches of the tributary river of Hamersley Inlet, the substantial numbers of fish of 1.5 to 2.3 years in age enable a reliable comparison to be made between the lengths at age, and hence early growth in this estuary, with that in the Stokes and Culham inlets. Thus, the mean length of female *A. butcheri* at 1.5 years in Hamersley Inlet was *ca* 200 mm, which is similar to that in Culham Inlet, but far higher than in Stokes Inlet.

The growth of *A. butcheri* was also shown to vary markedly among four other estuaries in south-western Australia, namely the Swan River Estuary, Moore River Estuary, Nornalup/Walpole Estuary and Wellstead Inlet (Sarre & Potter, 1999). Growth of Black Bream during early life was far faster in our three normally-closed estuaries than in the intermittently-open Moore River estuary and in the Gippsland Lakes in Victoria (Morison *et al.*, 1998) and was greater in the downstream region of Culham Inlet than in any of the four estuaries studied by Sarre & Potter (1999).

The possibility that differences among estuaries in the growth of *A. butcheri* during the first 1.5 and 3 years of life are related to diets were broadly explored by plotting the lengths in mm at those ages against the percentage contribution of macrophytes to the diets of individuals of the corresponding size classes up to those two ages, respectively. The database was expanded by including the same type of data for four estuaries further to the west of the Stokes, Culham and Hamersley inlets (Sarre & Potter, 2000). The resultant slope of 1.29 had a coefficient of determination of only 0.26 and did not differ significantly from zero ($p > 0.05$). There was thus no evidence that the proportion of macrophytes in the total volume of food ingested, and thus likewise of animal prey in total, could be invoked as a major factor contributing to differences in the early growth of Black Bream among estuaries.

The early growth of Black Bream was greater in Culham Inlet than in Stokes Inlet (during the early period of the study when Black Bream were still present in the former estuary), whereas the reverse occurred with overall mean density in nearshore, shallow waters that are inhabited by juveniles and were sampled by seine netting, *i.e.* 40 *vs* 22 fish 100 m^{-2}. As the estuaries sampled for Black Bream by Sarre & Potter (2000) employed different seine nets, *i.e.* 41.5 *vs* 21.5 m, caution must be exercised in attempting to be too precise in drawing conclusions from the relationships between early growth and density in the estuaries sampled during that study. However, it appears relevant that early growth was slower in the Moore River Estuary than in the Swan River, Wellstead and Nornalup/Walpole estuaries, in which the densities were far lower (Sarre & Potter, 2000). There are thus indications that high densities of Black Bream can lead to slower growth, but no evidence that the relative volumes of macrophytes and prey ingested by Black Bream have a marked influence on growth.

5.4.5 *Implications for management of* Acanthopagrus butcheri *in central south coast estuaries*

This study has shown that the populations of Black Bream in the Culham and Hamersley inlets have suffered massive mortalities in recent years as a result of the effects of very high salinities. The extreme salinities that developed in Hamersley Inlet during our three year study were due to a combination of salt run-off over a number of years as a result of land clearing in the catchment of this estuary, lower than average winter rainfall and high evaporation in the warm and dry summer months. The problem in Culham Inlet was exacerbated by the fact that the breaching of the sand bar at its mouth in the summer of 2000 resulted in the water in particularly the basin falling to a very low level. Although there was appreciable discharge in late 2001, which led to a slight increase in water level, little precipitation occurred during the rest of the study and evaporation eventually led to the basin becoming little more than a salt pan.

The only record of the sand bar at the mouth of Culham Inlet being breached naturally was in 1849 (Hodgkin, 1997). Thus, the water levels of the estuary prior to 1993, when the sand bar was artificially breached and resulted in a dramatic decline in water level, can be regarded as "natural" for this estuary. This decline in water volume led to a massive reduction in the numbers of Black Bream in the basin and thus the collapse of the commercial fishery for this species in Culham Inlet. The water levels remained low until early 2000, when massive cyclonic rainfall resulted in water rising to such high levels that its volume applied sufficient pressure to breach the sand bar at the estuary mouth. However, it should be recognized that the sand bar had been modified since its breaching in 1993 and that these modifications included both a reduction in its height and thus in the maximum water volume that the basin can contain and an increased susceptibility of the bar to breaching by water pressure.

From the above, it follows that, because of the changes to the sand bar, the volume of water in the basin of Culham Inlet can never be sustained at the levels that characterized this estuary prior to 1993 and permitted the development of the most important commercial fishery for Black Bream in south-western Australian estuaries.

The fact that Stokes Inlet did not undergo such dramatic increases in salinity as Hamersley Inlet, whose sand bar at its mouth has not been modified, can be attributed to the level of the basin floor being much further below sea level. Thus, the surface area to volume ratio in the basin of Stokes Inlet is also far lower and consequently the effects of evaporation are less pronounced in this estuary.

The extreme effect of high salinities in the basin and lower reaches of the tributary rivers of Culham Inlet on Black Bream emphasises the importance of ensuring that the upstream pools of those tributaries are not allowed to become degraded and can thus continue to act as refugia for this important species. Although Black Bream were not found in upstream pools on the Hamersley River, they may have been present in the several pools that we were unable to sample due to difficulties of access and, if this was the case, would likewise act as refugia for Black Bream. The great value of these small water bodies for Black Bream suggests that managers might need to consider closing them to fishing in order to ensure that the individuals of this species are conserved in at least part of the system when massive mortalities occur elsewhere in the system at times when salinities become excessively high.

The collapse of the commercial fisheries for Black Bream in Hamersley Inlet and particularly Culham inlet as a result of massive mortalities brought about by highly elevated salinities, inevitably led commercial fishers to shifting their fishing activities from those two estuaries to others on the south coast. The resultant increase in exploitation of other Black Bream stocks and the stocks of other species has obvious implications for the management of the commercial estuarine fishery on the south coast of Western Australia.

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7.0 BENEFITS AND ADOPTION

This study has achieved the following:

1. Quantified the extreme rises that salinity can undergo in normally-closed estuaries on the central south coast of Western Australia over relatively short dry periods and demonstrated that such changes vary markedly among these estuaries.
2. Demonstrated that the above changes have catastrophic consequences for the fish faunas of some estuaries and can lead to the near or total extinction of all species in the main body of those estuaries.
3. Provided strong evidence that Black Bream do not typically survive salinities > 85 and that mortalities in excess of 1 million Black Bream can occur in small regions of an estuary when salinities reach 65-85.
4. Because salinities in Stokes Inlet rarely exceeded 60, and thus did not suffer heavy mortalities of Black Bream, this estuary could act as a type of control for monitoring the state of the stocks of this species in other south coast estuaries, as well as the health of those estuaries in general.
5. Provision of baseline data for the fish faunas of estuaries in a region where those estuaries are experiencing severe salinity problems, as a result of anthropogenic and climatic influences.
6. Environmental and fisheries managers and stakeholders will now be fully aware of the consequences of extremes of salinity for the fish of estuaries, and particularly of important species such as Black Bream, and the need to take into account the consequences of those anthropogenic changes that will inevitably exacerbate this problem.

8.0 FURTHER DEVELOPMENT

Once accepted by the FRDC, the final report will be provided to managers at the Department of Fisheries and Department of Environment in Western Australia. This will enable managers and stakeholders to develop more informed and thus more robust management strategies for ensuring that the environment of central south coast estuaries in Western Australia is of a quality that will facilitate the viability of its fish stocks.

The final report will also be provided to the Western Australian Fishing Industry Council, RecFishWest, South Coast Licensed Fisherman's Association, and Conservation and Land Management. Articles will be produced for ProWest and for local newspapers on the south coast of Western Australia. Presentations will also be given at selected venues on the south coast.

The results of the present study highlight the paucity of sound, quantitative data that could previously be used to explore the impact of extreme rises in salinities and modifications to the sand bar of normally-closed estuaries on the fish faunas of those systems. Although the present study has helped to fill some gaps, further work is urgently required to determine the full extent of these problems and to test the relevance of the implications of the present study to other estuaries in the region. It is thus hoped that an application for funding work on the fish faunas of seasonally and permanently-open estuaries, as well as normally-closed estuaries, and on the biology of its most important recreational and commercial fish species in south coast estuaries will be successful.

9.0 PLANNED OUTCOMES

The following outcomes, as outlined in B6 of the original project application, have been achieved.

1. The results of this study will enable managers to understand the consequences that ongoing environmental perturbations in normally-closed estuaries in the central region of the south coast of Western Australia are having on the fish faunas of those estuaries and, in particular, on the abundance of recreational and commercial species.
2. The results will thus enable the Department of Environment (previously Water and Rivers Commission) to provide advice to relevant authorities and stake holders of (a) the ways in which any proposed changes in the catchments are likely to lead to changes in the fish faunas in normally-closed estuaries and (b) of the biological implications of the breachings of the bars at the mouths of these estuaries.
3. The data on Black Bream will help the Department of Fisheries, Western Australia, to develop appropriate plans for managing this important species in estuaries in which marked seasonal and annual environmental changes have been shown to have major impacts on the spawning and recruitment success of this species.

In addition, this study has provided training for an Honours student in current techniques for collecting and analysing data on the growth and dietary compositions of fish and for a PhD student in contemporary methods for analysing faunal community data.

10.0 GENERAL CONCLUSIONS

Sound quantitative data have been obtained on the characteristics of the fish faunas and environmental conditions in three normally-closed estuaries (Stokes, Culham and Hamersley inlets) on the central south coast of Western Australia. These have been used to meet all of the objectives in our original application and those in an extension to the study which involved determining the dietary compositions of Black Bream in the above three estuaries. The major findings and conclusions are as follows.

- The main body of each estuary (basin and saline lower reaches of its tributary) became markedly hypersaline during the three years of the study (2002-2004). However, the trends exhibited by salinity in the three estuaries differed markedly. Thus, although mean seasonal salinities in the main region were less than 35 in Stokes and Hamersley inlets and less than 55 in Culham Inlet at the beginning of the study, they subsequently rose to only about 60 in Stokes Inlet, whereas they eventually exceeded 140 in Hamersley Inlet and 290 in Culham Inlet.
- The development of high salinities in the three estuaries was due to a combination of increased salt loading, dry winters and high evaporation rates during summer. In one estuary, Culham Inlet, anthropogenic changes to the sand bar at the estuary mouth also had a major influence.
- The above differences in salinity regime account for the fact that the fish communities underwent far greater progressive changes in the Culham and Hamersley inlets than in Stokes Inlet.
- The changes in Culham and Hamersley inlets involved a sequential loss of species as salinity rose. Thus, for example, the hardyhead *Leptatherina wallaceii* and the goby *Pseudogobius olorum* were the first to die out, followed by the Black Bream *Acanthopagrus butcheri* and finally, when salinities were very high, the hardyhead *Atherinosoma elongata*.

- Massive mortalities of Black Bream occurred when salinities reached 65-80 and apparently left no residual individuals of this species in the main body of the Culham and Hamersley inlets.
- Salinities in Stokes Inlet eventually approached levels that are lethal for Black Bream and thus account for this species developing salt lesions in this estuary.

The following points were derived from data that were obtained from Stokes Inlet throughout the study and from the Culham and Hamersley inlets prior to the mass mortalities that occurred in those estuaries.

- The fish faunas of the Stokes, Culham and Hamersley inlets are highly depauperate in terms of number of species. This reflects, in part, the fact that these estuaries are normally closed by a sand bar at their estuary mouth, which restricts the recruitment of marine species, except on the rare occasions that the bar is breached or, very infrequently, a few small individuals of such species are washed over the bar during heavy swells.
- The nearshore, shallow waters of each estuary were dominated to such an extent by a small hardyhead (*Atherinosoma elongata*) that this species contributed between 74 and 95% to the total catch of fish in these waters in each estuary. Another small hardyhead and a small goby were also relatively abundant in these catches, as were juveniles of the Black Bream in the Stokes and Culham inlets but not Hamersley Inlet.
- The only marine species caught in nearshore waters was Yellow-eye Mullet, which was represented by very low numbers of juveniles in the Stokes and Hamersley inlets and had probably been swept over the bars at the mouths of these estuaries during high swells.
- Black Bream dominated the fish faunas of offshore, deeper waters to such a marked degree that they contributed 98% to the gill net catches in Stokes Inlet, 95% to those in Culham Inlet and 87% to those in Hamersley Inlet.
- Between two and five marine species were caught in the deeper waters of each estuary, the most abundant of which were Yellow-eye Mullet in Stokes Inlet, Mulloway in Culham Inlet and Sea Mullet and Western Australian Salmon in Hamersley Inlet. Their

relatively large size indicates that these marine species had been landlocked in these estuaries for a protracted period and had probably entered those systems when the estuary bar was breached in 2000.

- Upstream pools in at least Culham Inlet, in which salinities remained below 30, act as refugia for Black Bream and other species when salinities downstream reach levels that are lethal to those species.
- Black Bream spawn in late winter and spring in normally-closed estuaries and thus earlier than in permanently-open and seasonally-open estuaries. This enables Black Bream to produce its offspring before salinities become high during the usually dry summer months.
- Black bream typically reach maturity in Stokes Inlet at the end of their second year of life, when they are about 150 mm in length. This length is far lower than the minimum legal length (MLL) of 250 mm for retention of this species. As the MLL is not attained by Black Bream until they are about 7 years old, the individuals of this species can potentially spawn in several years before they can be legally retained. As a consequence of massive mortalities and/or the characteristics of the age and length composition data, it was not possible to derive a L_{50} for first maturity for Black Bream in either the Culham or Hamersley inlets.
- Black Bream consumed plant material, polychaete worms, molluscs, crustaceans, insects and fish in each estuary, but the extents to which these different dietary components were consumed differed greatly among estuaries.
- This emphasises that Black Bream is an omnivore and feeds opportunistically. The diversity of the diet was far greater in Stokes Inlet than in the other two far more variably saline estuaries, presumably reflecting a greater diversity of prey in that estuary.
- The recruitment of juveniles of Black Bream in Stokes Inlet was greatest in years of moderate flow in the months preceding and during the spawning period.
- Several year classes of Black Bream were present in the upstream pools of Culham Inlet, in which salinities did not increase to the same extent and there was thus no salinity-

induced mortality, further emphasising the importance of this type of habitat as refugia for this important species.

- The marked differences in the growth of Black Bream among the three estuaries during the early years of life could not obviously be related to the pronounced differences in the composition of food consumed in those estuaries. However, growth was least in Stokes Inlet in which the density of this species was greatest.
- It is concluded that Black Bream populations in the basins of estuaries, such as those of the Culham and Hamersley inlets, are only sustainable if the quality of environmental conditions (and particularly the salinity levels) in those regions is maintained at an appropriate level. It is also clear that upstream pools act as important refugia for Black Bream when extreme conditions exist downstream.

11.0 APENDICES

11.1 APPENDIX 1: INTELLECTUAL PROPERTY

The FRDC's share of the intellectual property will be 29.85% based on Part C7 of the FRDC project proposal.

11.2 APPENDIX 2: STAFF

Prof. Ian Potter
Mr. Steeg Hoeksema
Mr. Ben Chuwen
Assoc. Prof. Norm Hall
Dr. Margret Platell
Dr. Alex Hesp