Department of Agriculture, Fisheries and Forestry, Queensland

Flow impacts on estuarine finfish fisheries of the Gulf of Carpentaria

FRDC Project No. 2007/002
Final Report

I.A. Halliday, T. Saunders, M.J. Sellin, Q. Allsop, J.B. Robins, M. McLennan, P. Kurnoth

Northern Territory Government

TRaCK Tropical Rivers and Coastal Knowledge

Australian Government
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TRaCK
Tropical Rivers and
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Front cover image: painting by Joseph Cummings, indigenous artist Cairns, depicting the links between water flow and plant and animal life in the Mitchell River.

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1 NON-TECHNICAL SUMMARY

2007/002: Flow impacts on estuarine finfish fisheries of the Gulf of Carpentaria

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Objectives

1. Analyse available datasets relevant to conceptual models (developed in LWA Project No QP155), linking freshwater flow and estuarine-dependent finfish fisheries for key catchments in the Gulf of Carpentaria.
2. Conduct targeted research, as identified by LWA Project No QP155 that will contribute to determining the role of freshwater in supporting estuarine-dependent finfish fisheries in the Gulf of Carpentaria.
3. Provide refined conceptual models and supporting information of the role of freshwater flow in supporting estuarine-dependent finfish fisheries production to the integration project.
4. Provide recommendations to water and fisheries managers on appropriate methods of assessing the effects of flows on estuarine finfish production.

OUTCOMES ACHIEVED TO DATE

The project has clearly shown that there are substantial benefits to fisheries related industries through increased production from allowing freshwater flows to reach the estuary. These can be viewed as: increasing catch though the delivery of fish from freshwater reaches to estuarine sections; facilitating movement of newly recruited fish from marine spawning areas to estuarine and freshwater habitats; and increasing recruitment of fisheries species by increased survival of young of the year probably through increased growth rates in the first months of life.

By using estuarine fisheries as an integral part of a whole-of-ecosystem approach the outcomes of this project and others within the Tropical Rivers and Coastal Knowledge (TRaCK) research consortium have elucidated the connections between rivers, floodplains and estuarine habitats through food webs. Understanding the sources of productivity in rivers ecosystems and the mechanisms by which productivity is achieved has demonstrated the important roles of each the habitats and how the connectivity between these habitats support healthy productive estuaries.

The economic values of fisheries production is one measure by which ecological values can be measured. Other valuations of the ecological assets of estuarine reaches include the importance of aquatic species that are used as food by indigenous communities located on rivers and associated floodplains. Information from the current project has been used by other TRaCK Consortium projects to identify the economic benefits to these communities by valuing all species collected in dollars terms. This has shown that estuarine fish production is of much lower value to these communities than that of freshwater turtles and water lilies which rely on the same habitats and flood connectivity for production.

The work presented herein, in conjunction with results from the TRaCK Consortium, have assisted in developing monitoring programs and water management rules for water resource plans with respect to maintaining river and estuarine health as well as providing a framework for assessing the need for freshwater to flow to tropical estuaries. These results have been received with enthusiasm by indigenous communities, commercial and recreational fishing communities, water resources managers and fisheries managers.

The current and increasing demand on Australian water resources requires that water efficiencies (i.e., achieving the same effect with less water) are made by all water users. In the case of the environment, by understanding key aspects of the flow regime that have subsequent effects on estuarine fisheries, decisions can be made about the availability of water for human use, whilst minimizing impacts on the environment.

Freshwater resources of Australia are limited and are under increasing demand for human use (i.e., urban, industrial and agricultural). However, the environment is a legitimate water user and must have an environmental flow allocation under state and Commonwealth legislation. Estuaries are the downstream section of rivers and streams, and freshwater flowing into estuaries is one of the key factors defining an estuary. However, how much water is required to sustain estuarine biota and the impact of changing freshwater flows on estuaries and the species contained within them is not fully understood and is rarely quantified.

This project was initiated in response to increasing requests about the freshwater requirements of estuarine fisheries for water resource management and planning in tropical Australia. In addition, the effects of extended droughts and climate change on estuarine fisheries species require greater understanding of the environmental influences on estuarine-dependent stocks. Many tropical estuarine fish species are likely to be highly responsive to the flood-drought cycle of northern Australia, but the lack of quantitative information precludes the inclusion of such factors in stock assessment.

The current study provides quantitative evidence that freshwater flows to estuaries are crucial in supporting fisheries production. This is principally through effects on fish movement (access to nursery habitats), recruitment (number of fish surviving the first year of life) and catchability. As such, freshwater flowing to estuaries is not wasted. In the current study, we developed conceptual models of the life-cycle of selected fish species (i.e., barramundi and king threadfin salmon) and super-imposed how and when freshwater flows might affect these species. This process was formalised into a generic framework that could be applied to any Australian estuary.

We then analysed commercial catch statistics for barramundi and king threadfin from the Mitchell, Flinders, Roper and Daly River estuaries of tropical Australia. Commercial barramundi catches in all four estuaries were significantly correlated with annual rainfall and flow one to five years previous; the time lag being the period post-spawning over which recruitment to the fishery occurs. The Daly River was the only system where river flows significantly increased the catchability of barramundi. King threadfin catches were not correlated with flow or rainfall in any of the catchments studied.

We also looked at the age-structure of barramundi and king threadfin catches to determine whether ‘strong’ or ‘weak’ year-classes were present; if these persisted through time; and were correlated with freshwater flow or rainfall. The year-class strength of barramundi was positively correlated with rainfall in autumn and during the dry season (i.e., May to October). We speculated that it is the duration of freshwater flows (and/or rainfall) in rivers and across their associated flood plains that is important in delivering nutrients to the estuary, creating connectivity between habitats and thereby creating environmental conditions favourable to species eaten by juvenile barramundi. King threadfin year-class strength was not correlated with any flow or rainfall variables.

Analysis of otolith micro-chemistry of barramundi from all estuaries showed varying degrees of freshwater habitat use by different populations. Barramundi populations associated with the perennially flowing Daly River showed the highest rate of freshwater habitat use, with ~86% of Daly River fish sampled having spent time in freshwater. Fifty-five percent of the barramundi sampled from the Mitchell River estuary had entered freshwater, while lesser proportions of fish sampled the Roper River estuary (39%) and Flinders River estuary (37%) had entered freshwater habitats for a time sufficient to leave isotope markers in fish otoliths (i.e., >3 months). The Flinders River and the Roper River are much drier rivers, with flow ceasing over the dry season.

Understanding the role of freshwater flow on fisheries species and their productivity (and therefore catch) has important implications for water and fisheries management. During extended low-flow decades (e.g. 1960's, 1980's and 2000's), the size of estuarine fish populations are probably reduced as a consequence of successive years of low recruitment. During such times, fisheries populations are likely to be at greater risk from fishing pressure, water extraction and other anthropogenic impacts. During extended high-flow years, estuarine fish populations probably increase in size and are likely to be at lower risk of over-fishing, and water extraction may have lesser impacts, although this is unquantified. The most critical period to ensure the occurrence of freshwater flows to estuaries is probably during and just after extended dry periods. Only through greater quantification of the key aspects of freshwater flows and subsequent effects on estuarine fisheries will we be able to sustainably manage water and fisheries resources so that the maximum amount of water is available for human use whilst minimizing impacts on the environment.

KEYWORDS: environmental flows, freshwater flows, estuarine fisheries, water regulation

2 ACKNOWLEDGEMENTS

The project was jointly funded by the Fisheries Research and Development Corporation (FRDC project 2007/022), the National Water Commission, and the Queensland and Northern Territory Governments via the Tropical Rivers and Coastal Knowledge (TRaCK) Consortium. We thank the fishers of tropical northern Australia who offered their extensive knowledge and provided catch for the project. We also thank the remote local communities and regional organisations who supported this work, eagerly assisted and showed great enthusiasm in listening to our findings. Thanks also to staff from the Department of Agriculture, Fisheries and Forestry Queensland and the Northern Territory Department of Resources who assisted with field and laboratory work.

3 BACKGROUND

This project was developed in response to the growing community concern about the development of water resources in northern Australia, especially in the Gulf of Carpentaria. Numerous river systems within the Gulf of Carpentaria have been proposed as possible sites for the development of water infrastructure. With the publication and distribution of the results of the FRDC report “Environmental flows for estuaries”, showing the positive influences of freshwater flows on the catch, recruitment and growth of commercially and recreationally important species, numerous stakeholder groups, extending from fisheries managers, water managers, NRM groups and commercial fishers, have supported the concept of applying the methodologies developed in the Fitzroy River (Queensland east coast) to the rivers of the Gulf of Carpentaria.

Further, Land and Water Australia invested in the production of a report conceptualising the role of freshwater flows on the life history of major commercial and recreational species, and identified research gaps to be investigated. Prior to the development of water resources in the Gulf of Carpentaria, this project will provide information on the likely impacts of modifications to the hydrological regime of rivers in the Gulf of Carpentaria. The information generated will allow management to consider the likely impacts of water infrastructure developments on the estuarine fisheries in the Gulf region, thereby reducing the risk of making the same mistakes that have been made in southern Australian river systems. The desire not to make these mistakes has been strongly articulated in discussions by stakeholders from tropical Australia. Without the necessary evidence of the role of freshwater flow in estuarine fisheries production and the consequent need to explicitly consider these as freshwater users in water resource planning, the role of freshwater in fisheries production would likely be ignored or overlooked once again. This project addresses the highest priority area of “Understanding the relationships between freshwater flow and estuarine biota” from the March 2006 meeting on “flows for estuaries” held jointly between FRDC and Land and Water Australia.

The use of freshwater resources for cities, industry and agriculture has altered the magnitude, duration and timing of freshwater flowing into estuaries and impacted estuarine species (Drinkwater and Frank 1994; Gillanders and Kingsford 2002). The sustainable management of freshwater requires an understanding of the role (or importance) of freshwater flows in downstream biological processes, and how changing natural river flows impacts upon estuarine populations. A number of estuarine species are exploited by commercial, recreational or subsistence fisheries. The management of these fisheries would benefit from an understanding of factors other than fishing effort (i.e., environmental factors) that influence the population size (Shepard *et al.* 1984; Hilborn and Waters 1992).

The link between freshwater flows and estuarine organisms has often been investigated by comparing catch data from commercial fisheries with patterns in naturally variable, or highly altered, freshwater flows (e.g., Sutcliffe *et al.* 1977; Lloret *et al*. 2001). Significant covariation between freshwater flow and catch has been reported for numerous marine and estuarine species, often with time lags equalling the approximate age at which a species enters the fishery (e.g. Lloret *et al*. 2001; Quiñones and Montes 2001). This pattern has been used to generate or support hypotheses that freshwater flows influence the spawning, survival and growth of fish during their first year of life (Drinkwater and Frank 1994). Although some studies have undertaken further investigation into the variation in abundance and distribution of early life history stages (e.g., North and Houde 2003), few have been able to confirm the postulated causal mechanisms.

3.1 CONCEPTUALISING FLOW AND FISHERIES RELATIONSHIPS

3.1.1 Barramundi

Barramundi *(Lates calcarifer*) is one of the main finfish species caught by commercial, recreational and indigenous fishers in the Gulf of Carpentaria. This species is strongly associated with estuaries, utilising freshwater, estuarine and coastal areas adjacent to rivers during different life stages.

Barramundi have a complex life history, being catadromous (i.e., migrating from freshwater to saltwater to spawn) and protandrous (changing sex from male to female). Catadromy in barramundi is not obligatory, as a proportion of barramundi in estuaries of the Northern Territory do not enter freshwater (Pender and Griffin 1996; Griffin and Walters 1999). However, where access and habitats permits, barramundi will typically move into freshwater habitats as juveniles, returning to estuaries and coastal foreshores when mature. Generally, barramundi are not catadromous where rivers are ephemeral or where the construction of barriers associated with water infrastructure prevents the movement of fish upstream (Russell 1990).

Gametogenesis in barramundi is initiated by the seasonal increase in water temperate and photoperiod (Russell 1990). Movement to spawning areas is triggered by the seasonal increase in water temperature (Grey 1987; Griffin 1987). High salinity appears to be the main requirement of spawning grounds (Davis 1987), i.e., 32 to 38 ppt (R. Garrett, *pers. comm*. 2000). Mature female barramundi reside mostly in this habitat within the lower reaches of estuaries and along the coastal foreshore (Dunstan 1959). The life cycle of barramundi generally results in some spatial separation of male and female fish, with smaller and younger male fish residing in the upper estuary or in freshwater reaches, and females residing predominantly in lower estuarine and coastal areas. However, male fish also inhabit lower and coastal areas. Mature males resident in freshwater habitats must move downstream to spawn in the estuary. Mature barramundi are thought to be stimulated to move downstream to areas of higher salinity by the first freshwater flow in spring that lowers the salinity of estuarine waters (R. Garrett, *pers. comm*. 2000). This effect could be achieved by small freshwater flows that do not necessarily release landlocked individuals. However, barramundi in the perennially flowing Daly River (Northern Territory) move downstream in August and September, possibly as a consequence of a rise in water temperature and/or increase in day length (Griffin 1987). In addition, large barramundi (800 to 900 mm Total Length) in the waterholes of the Princess Charlotte Bay area were repeatedly caught in the same waterhole over a number of years, suggesting that not all large barramundi move downstream (J. Russell, *pers. comm*. 2005).

In Australia, barramundi spawn during spring and summer. The timing and duration varies between regions, rivers and years. In the southern Gulf of Carpentaria, spawning occurs from November to March, with a peak in December (Davis 1985), while in the northern Gulf of Carpentaria (Queensland side), spawning occurs over summer, but may start as early as October (Williams 2002). Spawning in the Northern Territory occurs between September and February (Davis 1985), but most spawning activity occurs before there is any reduction of coastal salinity i.e., before the main freshwater flows that occur after mid-December (Davis 1985; R. Griffin, *pers. comm*. 2005).

The commencement and completion of a major part of the breeding cycle before the onset of the wet season is possibly a strategy for avoiding low-salinity water (Russell and Garrett 1985). Davis (1985, p 188) commented on the variation in the timing and duration of barramundi spawning and concluded that "there is considerable variation in the timing and duration of breeding between regions, rivers and from year to year, but essentially it is synchronized so that juveniles can take advantage of the aquatic habitat that results from rains in the monsoon season". Davis (1985, p189) goes onto say that "vast aquatic habitats formed during the summer monsoons provide juvenile barramundi with an almost predator-free, prey-rich environment promoting rapid growth and improved survival". Griffin and Kelly (2001, p7) also suggest that "rainfall is an important influence, presumably through its effect on the availability and habitability of swamp habitat, particularly in the early part of the spawning season".

Spawning in Australia (*cf* Papua New Guinea) is generally localised because of the relatively small discharge of freshwater from northern Australian rivers (Russell and Garrett 1985). Garrett (1987, p 39) suggests that "the position of spawning grounds probably differs slightly from year to year, depending on coastal salinities" and that "these in turn vary with the degree of river discharge".

Barramundi in the Gulf of Carpentaria (Embley and Hay Rivers), are multiple spawners, with speculation that a prolonged spawning season might be the result of landlocked fish arriving at spawning grounds "late" (Davis 1987). Dunstan (1959) suggested that "spawning of river barramundi occurs just prior to or during the wet season, usually October to January (spawning season 1)" and that "the barramundi land-locked in coastal lagoons and swamps are released when the wet season floodwaters connect these areas with the estuaries or open sea; they usually spawn from January to March (spawning season 2)". Dunstan (1959) suggested that "in years when the wet season is not pronounced, and floodwaters are insufficient to release land-locked adult barramundi, the number of spawning fish at sea is greatly reduced". However, this is unlikely to have major implications for reproductive dynamics because: (i) most spawning occurs before the onset of floods; and (ii) virtually all the fish in the land-locked water bodies are males, making their contribution to egg production late in the season negligible (R. Griffin, *pers. comm*. 2005). The prolonged spawning season of barramundi is unlikely to provide significant recruitment late in 'normal' wet seasons because these juveniles are unlikely to survive the high predation pressure from early-spawned recruits that are already occupying nursery areas. However, multiple recruitments could be important in overcoming climatic variability, such as late or interrupted monsoons (Garrett 1987).

In general, spawning activity peaks during new and full moon periods (Grey 1987) i.e., the week following new and full moon in northern Gulf of Carpentaria estuaries (Garrett 1987). Spawning on the incoming tide may help eggs to move into estuaries or coastal swamps. Fertilized barramundi eggs are pelagic, with optimal hatching occurring at salinities between 20 and 30 ppt (Maneewong 1987). Barramundi larvae spend about three weeks in inshore waters.

Barramundi post larvae move to nursery habitats and utilise freshwater habitats if available (Russell and Garrett 1985). Davis (1987) caught small barramundi larvae 77 km upstream in the South Alligator River in the Northern Territory. Moore (1980) suggested that barramundi larvae are attracted upstream by chemical cues released from swamps. Peak "spring" tides and seasonal flooding assist barramundi post larvae to enter supra-littoral habitats (Davis and Kirkwood 1984; Russell and Garrett 1985; Davis 1987), coastal lagoons (Grey 1987) and other seasonal habitats that form during the monsoon season (Williams 2002). Monsoon rains also create a variety of temporary nursery habitats for juvenile barramundi that are highly productive in food resources and are thought to offer protection from larger predatory fish. These swamps rely on “flood rains” to connect with more permanent waters (Russell and Garrett 1985). Griffin (1985) suggests that rainfall replenishes the water levels in supra-littoral habitats between high tides, thereby maintaining these nursery habitats for longer periods, and that “the amount of time that the young-of-the-year fish are able to utilise this safe and rich environment is limited by the amount and extent of rainfall during the wet season”. Griffin (1987) confirmed this relationship, reporting a significant correlation (r=0.81) between juvenile abundance (i.e., young-of-the-year) and early wet season rainfall. Griffin (1985) only considered rainfall, although it is equally likely that floods that inundate flood plains may have a similar effect in extending the spatial and temporal extent of these high-quality nursery habitats. Significant correlations between otolith-based assessment of year-class strength and freshwater flow were reported for the Fitzroy River on the east coast of Queensland (Staunton-Smith *et al.* 2004; Halliday *et al.* 2011).

Many juvenile barramundi move to permanent freshwater habitats when the seasonal coastal habitats dry out (Russell and Garrett 1985). Such movement may be stimulated by the lowering of water levels and depletion of food sources (Russell and Garrett 1985). In the Gulf of Carpentaria, floodwaters recede around March. As such, juvenile barramundi are moving upstream to freshwater habitats at about three to five months of age. Movement upstream to freshwater habitats can also occur when barramundi are between one and two years old (Milton *et al*. 2008). Dunstan (1959) suggested that “1+ fish are found in deep holes of the upper reaches, with 1+ fish being plentiful below the falls on the Burdekin River that are about 120 miles from the mouth, 1+ fish are common in the Dawson River and other tributaries of the Fitzroy River”. Fishway studies on the Queensland east coast have recorded juvenile barramundi (120 to 500 mm Total Length (TL)) moving upstream primarily between spring and early summer i.e., October to December (Stuart 1997), when the fish are nine- to 12-months-old. The greatest numbers of moving barramundi were recorded during low flows when salinities below the barrage were high (i.e., October, November and December). However, barramundi were recorded moving through the Fitzroy River fishway throughout the year (i.e., June, September, January, February, March, May). All barramundi ascending the Fitzroy River fishway were < 600 mm Fork Length (FL) and immature (Stuart and Mallen-Cooper 1999) and moved upstream in equal numbers in the day and night. Stuart and Mallen–Cooper (1999) noted that most barramundi <310 mm FL were collected during the two days immediately after the barrage gates were closed and the only sources of freshwater flow to the estuary was from the fishway.

Dunstan (1959) suggested that the “abundance of barramundi in Queensland east coast rivers appears to be closely associated with the flow of freshwater”. Annual wet-season rainfall is thought to influence adult spawning success and juvenile recruitment (Williams 2002). Strong and weak year-classes were correlated with the amount of rainfall during the spawning season (particularly the early wet season) in the Yellow Water Billabong (Kakadu, Northern Territory) (Griffin 1994). Breeding success is enhanced in high-rainfall years and such events are often followed by a strong year-class (Staunton-Smith *et al.* 2004; Halliday *et al.* 2011) that is evident in the fishery some years later as evidenced by higher catches (Williams 2002; Robins *et al.* 2005). Rainfall levels in the southern Gulf of Carpentaria are thought to influence catches four to seven years later (Williams 2002), with a direct correlation between monthly freshwater discharge and monthly catch (Williams 2002). In Queensland, commercial catches of barramundi are highest prior to and following the wet season (Williams 2002) i.e., October/November and February to May, which also coincides with the seasonal closures. Landlocked fish released by floods will move to estuarine and coastal areas where commercial fishing occurs and will contribute to the commercial catch.

Barramundi stocks in the Gulf of Carpentaria are genetically different from those of the Queensland east coast (Shaklee and Salini 1985). Davis (1985, p189) suggests that because of localised spawning and genetic evidence of stock heterogeneity, as reported by Shaklee and Salini (1985), "recruitment into major river systems would depend largely on the successful spawning of local populations" and that "the populations in different river systems may be quite independent of each other, and it may be appropriate to manage them as separate stocks".

Size at onset of sexual maturity also differs between areas. Davis (1982) reported that size-at-maturity for males was 600 and 550 mm TL for fish in the Northern Territory and south-eastern Gulf of Carpentaria respectively; corresponding lengths for females were 900 and 850 mm TL. Size at maturity is probably related to age, with slower growth rates occurring in the Gulf of Carpentaria (Davis 1982). Griffin (1988) also speculates that growth rates differ between the Daly and Liverpool River (Northern Territory) based on differences in the size-at-age structure in the two rivers. Barramundi in the north-eastern Gulf of Carpentaria (i.e., north of 13°S, Embely River northwards) are sexually precocious (although stunted in size), maturing up to two years earlier than barramundi in other rivers in the Gulf of Carpentaria (Davis and Kirkwood1984).

Barramundi are opportunistic predators and are likely to exploit increased abundance or accessibility of prey species (such as banana prawns) that are linked to freshwater flows (i.e., a trophic cascade effect). Analysis of tag-recapture data from the Fitzroy River system on the Queensland east coast demonstrated statistically significant positive effects of freshwater flow on growth rates of barramundi (Sawynok 1988; Robins *et al.* 2006). After accounting for length-at-release, time-at-liberty and seasonality of growth (Xiao 2000), growth rates were significantly and positively related to freshwater flowing to the estuary (Robins *et al.* 2006).

Populations of barramundi are likely to be highly responsive to freshwater flows given their preference to utilise freshwater habitats where accessible or available and the residency of most individuals within a region, thereby reflecting local freshwater flow conditions over time. The influence of freshwater flows on barramundi populations in the Gulf of Carpentaria can be summarised as follows (Figure 1):

H_1: Affecting the distribution of eggs and larvae; large flows may wash eggs and larvae away from the estuarine area (i.e., a negative effect);
H_2: Creating chemical signals that cue larvae to enter the estuary[1] (although high tides may also facilitate chemical cues);
H_3: Provides a connection between the estuary and ephemeral supra-littoral nursery habitats (e.g. flooded floodplains and coastal swamps); post-larval and small juveniles use these connections to enter temporary nursery habits, which allow good growth and survival (i.e., enhances the available nursery areas);
H_4: Provides a connection between the estuary and perennial freshwater habitats; large juveniles use the connections to move into freshwater habitats, which allow good growth and survival[2];
H_5: Provides a connection between perennial freshwater habitats and the estuary, enabling mature individuals to move downstream and participate in seasonal spawning[2];
H_6: Stimulates mature barramundi to move downstream in preparation for seasonal spawning, although the stimulation is unknown. Potentially it could be changes in salinity for estuary-based individual, or flow rates for freshwater-based individuals;

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[1] The flooding of supra-littoral habitats by high tides may also: (a) provide a connection between the estuary and nursery habitats; (b) prolong the life of ephemeral nursery habitats; and (c) create chemical cues that attract larvae into the estuary (John Russell, *pers. comm*. 2005).

[2] Timing of the flow in relation to the spawning season is probably critical. A late flow will assist wider dispersal of recruits upstream (Roland Griffin, *pers. comm*. 2005).

H_7: Enhances the biological productivity of the estuary, thereby increasing the availability of food for juveniles, adolescents and adults resident in the estuary, which potentially results in improved growth, survival and 'condition' of the estuarine population (e.g., fat barramundi syndrome, leading to earlier maturation or greater reproductive output for a season).

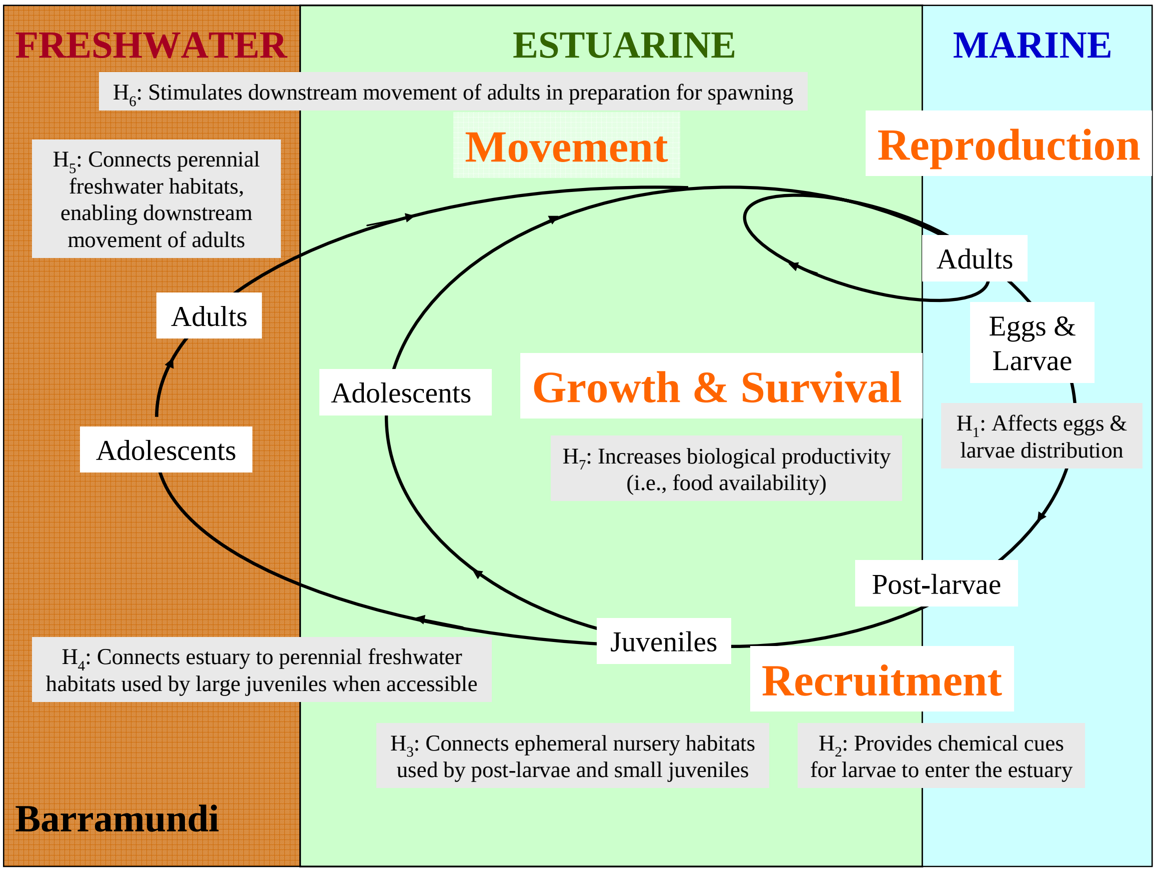

Figure 1. Conceptual model of the hypothesised influences of freshwater flows on the life-cycle of the barramundi (*Lates calcarifer*) in the Gulf of Carpentaria

3.1.2 King threadfin

King threadfin (*Polydactylus macrochir*) is another important fishery species that uses estuaries in northern Australia. They have a complex life history, being protandrous hermaphrodites (i.e., males first then females). They utilise estuarine and associated coastal foreshore waters. Adults can be found in the upstream reaches of estuaries during winter, presumably as salinity in these areas increases (I. Halliday, unpublished records 2005).

Adults spawn in inshore coastal waters away from river mouths (Williams 2002), and are likely to have an extended spawning season (Garrett 1996; Welch *et al.* 2002). Spawning peaks in September and October for "northerly stocks" and in November and December for more "southerly stocks" (Garrett 1997). In the Northern Territory, king threadfins are reported to spawn from October to March, with a peak in December (Kailola *et al*. 1993). In the Fitzroy River in central Queensland, anecdotal reports suggest that king threadfin spawn on the first full moon tides in September (Stevenson 1998, p5), at a site within the estuary (Cattle Point, probably with a high salinity at this time of year) which is "a salmon hot spot" for fishing.

Genetic studies indicate that distinct populations of king threadfin occur throughout northern Australia (Welch *et al*. 2010). Spawning is thought to occur in high salinity water (>32 ppt R. Garrett, *pers. comm*.), and it is likely that the pelagic eggs require high salinity water for high survival rates. The early life history of this species is relatively poorly quantified, although nursery areas are probably inshore, shallow and of low salinity (Kailola *et al*. 1993; Williams 2002). Juvenile fish (~10 cm FL) appear in estuaries between Townsville and Cairns (Queensland east coast) in January (I. Halliday unpublished records 2005). Juvenile king threadfin have not been recorded in the temporary supra-littoral pools in the Gulf of Carpentaria (Russell and Garrett 1983; R. Griffin, *pers. comm*. 2005; P. DeLestang, *pers. comm*. 2005). This suggests that king threadfin restrict their use of estuarine habitats to permanent water areas of the main channels and tributaries of creeks and rivers.

King threadfin reach maturity at between 2 and 5 years and a size at 600 to 800 mm FL (Roelofs 2004). Most individuals change from males to females between 6 and 10 years of age and at a size of 750 and 1000 mm FL. Minimum legal size is 400 mm TL for Queensland east coast and 600 mm TL for the Queensland side of the Gulf of Carpentaria (Welch *et al*. 2010). There is no legal size limit for king threadfin in the Northern Territory (P. DeLestang, *pers. comm*. 2005). In Queensland, peak inshore catches occur in late summer and autumn, coinciding with the movement of commercial fishers from riverine to foreshore areas (Williams 2002), reflecting a change in targeting by commercial fishers from barramundi to king threadfin. In the Northern Territory, peak catches occur in February and March (P. DeLestang, *pers. comm*. 2005).

King threadfin are carnivorous, eating a variety of the seasonally available small fish and crustaceans, including penaeid pawns (Salini *et al*. 1998). Commercial net fishers in the Northern Territory also anecdotally report king threadfin consuming banana prawns (R. Griffin *pers. comm*. 2005).

The level of wet season rainfall may influence adult spawning success and juvenile survival (Williams 2002), but this has not been investigated and quantified. King threadfin can move large distances along the coastline (550 km Kailola *et al*. 1993), potentially confounding relationships between freshwater flow and species abundance and distribution. Significant correlations between the year-class strength of king threadfin and river flow have been found for the population in the Fitzroy River, Queensland east coast (Halliday *et al*. 2008).

Based on the limited information in the literature, it is possible that freshwater flow influences the catchability and/or the recruitment of king threadfin. There is also likely to be a trophic productivity effect as king threadfin exploit increased abundances of prey associated with freshwater flow events. The influence of freshwater flows on king threadfin populations could potentially occur through the following speculated mechanisms (Figure 2):

H_1: Stimulating the downstream movement of juvenile and sub-adult king threadfin, potentially increasing their catchability in set-net fisheries through increased movement or increased densities in fished areas. The stimulus is possibly salinity changes.
H_2: Affecting the transport of larvae through currents. Large freshwater flows may prevent larval immigration to estuarine nursery habitats by washing eggs and larvae away from the estuary.
H_3: Creating chemical signals for larvae or juveniles to enter the estuary.
H_4: Affecting the survival of larval or juvenile fish in estuarine habitats, with freshwater (i.e., salinities of 0) being unsuitable habitat.
H_5: Enhancing the biological productivity of the estuary, thereby increasing the availability of food in the estuary for larvae, juveniles and adolescents which results in improved growth and survival, potentially leading to greater year-class strength or biomass available to the fishery.

H_6: Affecting the area of favourable habitat for juveniles and adolescents, potentially through larger areas of decreased salinity, the creation of a salinity gradient (i.e., salinities of 5 to 30 ppt) or turbid conditions reducing predation, which increases the survival of juveniles and adolescents.

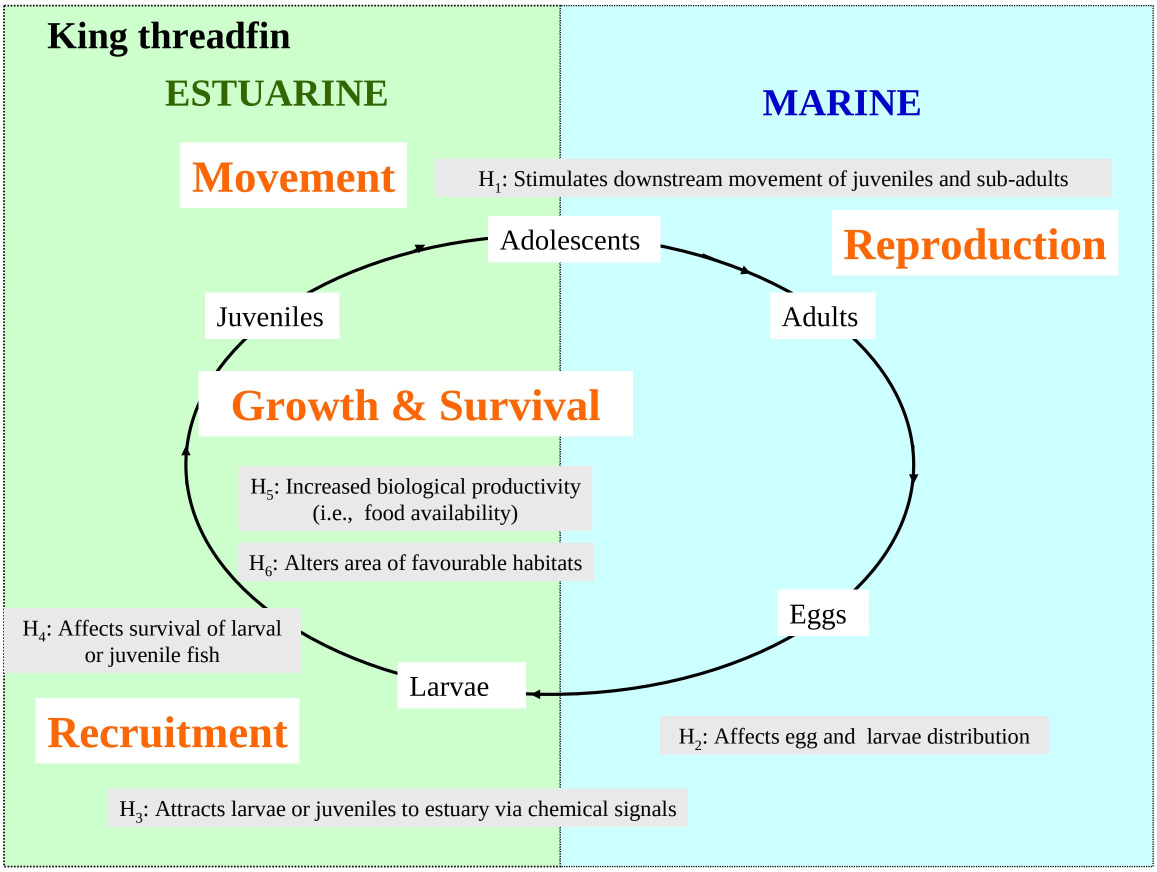

Figure 2. Conceptual model of the hypothesised influences of freshwater flows on the life-cycle of king threadfin (*Polydactylus macrochir*) in the Gulf of Carpentaria

3.2 CORRELATING CATCH AND FRESHWATER FLOW

Fisheries landings are often thought to be linked to environmental variables, such as rainfall, freshwater flow and temperature. The postulation justifying such relationships is often based on theoretical or known aspects of the life cycle of fish species, anecdotal reports from experienced commercial or recreational fishers and or significant correlations between environmental variables and catch statistics either demonstrated for a species in a location or a similar species in another location (see Robins *et al*. 2005; Gillson 2011 for reviews). Fish landings are attractive in the investigation of relationships between environmental variables and biological production (of which fish landings is a component), because fisheries data sets are often the only data available over a sufficient length of time to enable an analysis across a range of environmental variation. Fish landings (i.e., recreational or commercial catch or landings) are also attractive because they have a tangible, economic and social value, making them useful when considering the effects of environmental variation that can be manipulated by humans—that is, freshwater flow or habitat availability.

3.3 YEAR-CLASS STRENGTH

If freshwater flows do affect recruitment by influencing the survival of young fish, then year-class strength (YCS) should vary with freshwater flow and persist through time in order to affect the subsequent abundance of adult fish and associated commercial catch. Studies of YCS frequently quantify the abundance of specific young age-classes on an annual basis (Helle *et al*. 2000; DiCenzo and Duval 2002; Sutela *et al*. 2002). However, strong and weak year-classes can persist through time and are often detected in the age-structure of adult populations of freshwater and marine species (Mills and Mann 1985; Maceina 1997; Morison *et al*. 1998; McGlennon *et al*. 2000; DiCenzo and Duval 2002). Therefore, examining the age-structure of an adult population of fish provides an opportunity to examine the relative strength of a number of consecutive year-classes, especially for long-lived species. Such an approach can be completed with relatively few years of sampling compared with surveys of early life history stages (e.g. 0+ or 1+ age-classes), which yield one estimate of year-class strength per year, and therefore require many years of sampling.

3.4 OTOLITH MICROCHEMISTRY

Mechanisms by which freshwater flow enhances estuarine fish populations varies between species and depends on their life history (Robins *et al.* 2005). For anadromous and catadromous fish species, freshwater flow is required to maintain natural migrations throughout river and floodplain components of their habitats. Catadromous fish species, such as barramundi, may have enhanced survival and growth in years when coastal spawning grounds receive good flooding rains (Staunton-Smith *et al*. 2004; Robins *et al.* 2006). Otolith chemistry analysis is used increasingly to improve our understanding of fish habitat use and movements. This is largely due to changes in water chemistry that can be detected in the otolith concentrations of several metals and their isotopes (Kennedy *et al.* 1997; Campana 1999; Milton and Chenery 2001). Otoliths are primarily aragonitic calcium carbonate and the concentrations of common metals, such as strontium (Sr), barium (Ba), magnesium (Mg) and manganese (Mn), change in response to environmental conditions (Campana 1999; Gillanders 2005). Strontium has been the most widely used trace metal to infer movements between freshwater and marine habitats (Secor and Rooker 2000, Milton *et al*. 2008).

4 NEED

The estuaries of Australia's tropical rivers support commercial fisheries for finfish and shellfish valued at over $220 million per annum. There are also significant tourism-related and local recreational and indigenous fisheries for iconic species such as barramundi. Development of water resources in Australia's Tropical Rivers region is under consideration for the Gilbert, Flinders, Mitchell, McArthur, Roper, Daly and Victoria catchments. Greater knowledge of the freshwater requirements of tropical aquatic ecosystems, including estuaries, is crucial so that the communities of catchments where water resource development occurs can be assured that the downstream effects of such development are considered and managed based on the best available knowledge.

Most research into the role of freshwater flows in aquatic ecosystems that support fish and fisheries has occurred in freshwater reaches of southern Australian rivers, except for that in the Fitzroy River, Queensland, (a large, dry tropical river). Conceptual models of the role of freshwater in estuaries of the Gulf of Carpentaria (GoC) and the effects on estuarine-dependent fisheries (i.e., LWA project QP155) is being based on available knowledge gained from research in the Fitzroy River. However, these conceptual models lack confirmation of the underlying mechanisms, mostly as a consequence of a lack of process understanding as it occurs in Gulf of Carpentaria estuaries.

4.1 FRESHWATER ALLOCATIONS TO SUSTAIN FISHERIES

The 1994 COAG Water Reform Agreement and various state legislation (e.g., Queensland *Water Act 2000*) require that managers allocate water to maintain downstream ecosystem health. One aspect of ecosystem health is estuarine and coastal fisheries production. Information on the role of freshwater in maintaining the productivity of commercial and recreational fisheries is needed to ensure that estuaries and their stakeholders are duly represented in water allocation processes. Managers of fisheries and water resources need to be made aware of the vulnerability of fish stocks, and their fisheries, to the impacts of non-fishing activities, such as water regulation. Using a logical framework developed for investigating the role of freshwater flows on fisheries production in estuaries (Robins *et al*. 2005), we assessed the current state of four tropical river systems and the influence of freshwater flows on fisheries production.

4.2 ENHANCING THE RESEARCH OUTCOMES - INTEGRATING ACROSS RESEARCH DISCIPLINES

An integrated research program is needed to develop a robust sampling program that can investigate the role of freshwater flows in estuaries and the impacts of modified flows on fisheries production. The Tropical Rivers and Coastal Knowledge (TRaCK) Commonwealth Environmental Research Facility offered the opportunity to integrate flow-influenced fisheries data with other hydrological (i.e., coastal modelling) and primary production (i.e., nutrient cycling) research projects to provide greater insight into ecosystem processes.

5 OBJECTIVES

1. Analyse available datasets relevant to conceptual models (developed in LWA Project No QP155), linking freshwater flow and estuarine-dependent finfish fisheries for key catchments in the Gulf of Carpentaria.

2. Conduct targeted research, as identified by LWA Project No QP155 that will contribute to determining the role of freshwater in supporting estuarine-dependent finfish fisheries in the Gulf of Carpentaria.

3. Provide refined conceptual models and supporting information of the role of freshwater flow in supporting estuarine-dependent finfish fisheries production to the integration project.

4. Provide recommendations to water and fisheries managers on appropriate methods of assessing the effects of flows on estuarine finfish production.

6 METHODS

The specific methods of the study were to:

1. Analyse the commercial catch and effort data for barramundi and king threadfin in four catchments of tropical Australia to determine if there were correlations between catch and freshwater flowing to the estuary.
2. Develop an estimate of year-class strength for barramundi and king threadfin populations in four catchments of tropical Australia using sampled age-structures and investigate whether variation in year-class strength was related to patterns in the freshwater flowing to the estuary;
3. Examine barramundi otolith trace element concentrations from four tropical estuaries to assess freshwater habitat use and determine at what age barramundi within each system move into freshwater habitats and its potential impact of growth of each individual; and
4. Propose possible causal mechanisms for the observed relationships.

6.1 STUDY ESTUARIES

Four estuaries across northern Australia were selected in the current project because these rivers and their estuaries were research hubs for the Tropical Rivers and Coastal Knowledge Consortium, in which numerous projects were based. The study estuaries were (Figure 3):

1. the Mitchell River estuary, (western Cape York, Qld);
2. the Flinders River estuary, (south eastern Gulf of Carpentaria, Qld),
3. the Roper River estuary, (western Gulf of Carpentaria, NT); and
4. the Daly River estuary, (south west of Darwin, NT).

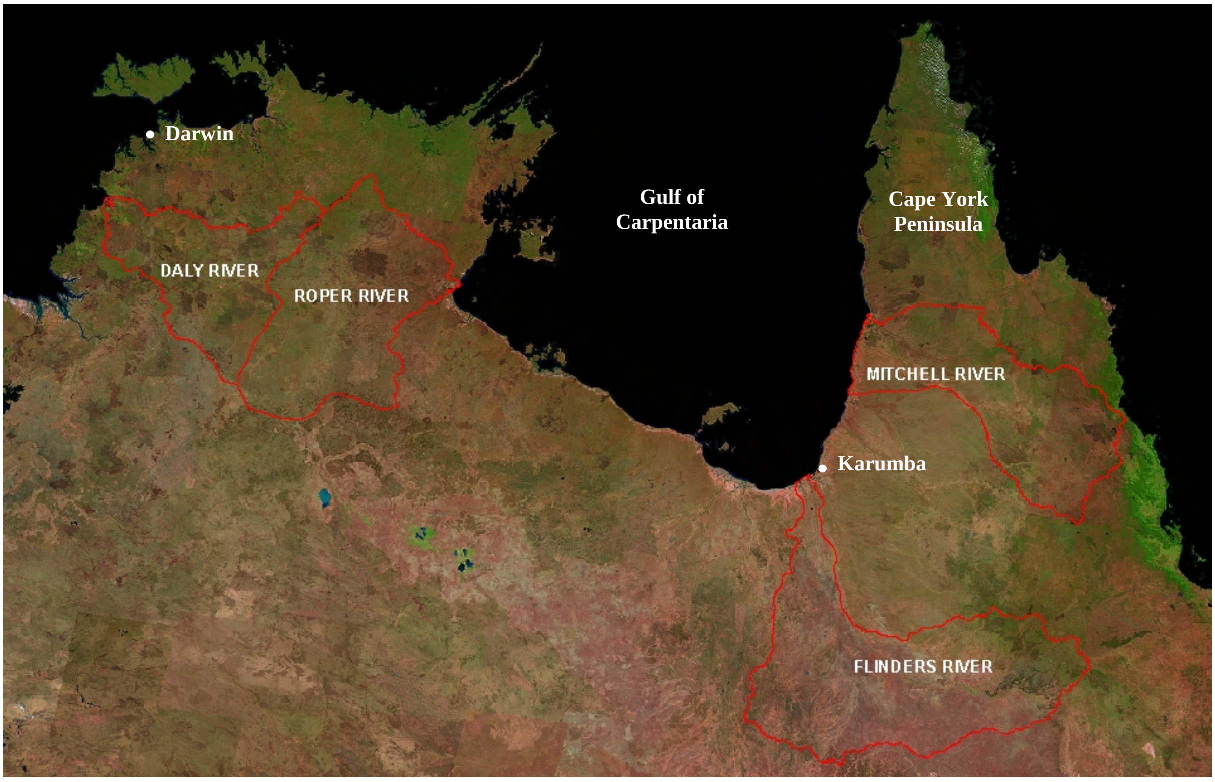

Figure 3. Locality map of the four study estuaries in tropical northern Australia

The Mitchell River estuary is located at 15°12’10’’S; 141°35’30’’E; and its headwaters are located in the wet tropics (Figure 3). The Mitchell River is one of Queensland’s most significant river systems, accounting for about 8% of the state’s total water runoff but only 4% of its area. The catchment covers 71000 km² of far north Queensland and encompasses the Mitchell, Lynd, Walsh, Alice and Palmer Rivers and Rifle and Bushy creeks. On average, the Mitchell River system discharges 11.3 million mega litres (ML) a year to the Gulf of Carpentaria. Although the upper reaches of the Mitchell and Walsh Rivers fall within the catchment, they are an intrinsic part of the Mareeba Dimbulah Water Supply Scheme and are dealt with under the Barron Water Resource Plan (Queensland Dept. of Natural Resources 2008; accessed 25 August 2010). The Mitchell River supports about 2668 km^2 of wetlands, of which 20% are estuarine.

The Flinders River has a large catchment of about 109,400 km^2 and a mean annual discharge of 3.86 million ML. It flows into the southern Gulf of Carpentaria, west of Karumba. The Flinders River supports about 3220 km^2 of wetlands, of which 13% are estuarine (Queensland Department of Natural Resources 2008; accessed 25 August 2010).

The Roper River extends for over 500 km and enters the western Gulf of Carpentaria via Limmen Bight. It has a catchment of about 81800 km^2. Annual rainfall over the catchment averages approximately 860 mm, with 90% falling between November to March. This results in a four month wet season with significant runoff and an eight month dry season with negligible surface runoff. The Roper River has perennial flows that are sustained by groundwater inflow underground aquifers, although at times evaporation can exceed baseflow and result in the river ceasing to flow (Knapton 2009). The average annual discharge of the non-tidal section of the river is 3289 GL (Knapton 2009). Commercial fishing activity is limited to outside of the Roper River mouth. This area is typical mud/mangrove habitat.

The Daly River is located approximately 200 km to the south of Darwin, is about 371 km in length and has a catchment of about 54400 km^2. Annual rainfall over the catchment averages approximately 1000 mm, with 90% falling between November and March. The Daly River is a perennial system, with dry season flows that are sustained by groundwater inflow underground aquifers. The mean annual stream flow of the Daly River is estimated to be about 8653 GL (CSIRO 2001). Commercial fishing activity is restricted to outside the Daly mouth. Within the Daly river estuary, there is a large floodplain (i.e., the Daly-Reynolds Floodplain) that covers an area of 1590 km^2.This is one of the largest floodplains in the Northern Territory and contains a diverse mixture of wetland types, including the typical mud/mangrove habitats.

6.2 COMMERCIAL CATCH DATA

We selected barramundi and king threadfin for analysis of relationships between commercial catch and flow/rainfall variables because these species are highly estuarine, commercially important and comparable to similar studies in other catchments.

Catch data were obtained from the daily commercial fisheries logbook (CFISH) of Fisheries Queensland (DAFF), from January 1989 to December 2010. CFISH data represent the catch (by weight or number) recorded in spatial grids of 30^{2}nm (=1,668 km^2). For the CFISH data, catch in the Mitchell River region was assumed to be represented by CFISH grid AC13, and in the Flinders River by CFISH grid AD18. Northern Territory catch data were obtained from the daily commercial fisheries logbooks where data are reported by area. Consequently, data could be obtained specifically from the Roper River and the Daly River. Catch was aggregated into annual totals to investigate inter-year trends.

All data were transformed ($\log_{10}(X+1)$) prior to analysis to normalise variances. Correlation coefficients were calculated between annual catch and freshwater flow and rainfall variables. Then, an "all sub-sets general linear model" (GLM, Genstat 2008) was used to more thoroughly explore potential relationships between catch and the freshwater flow and rainfall. This analysis allows a number of 'best' models to be identified and allows screening of multiple variables in different orders to provide an estimate of the variation explained by the model terms. Correlations and the GLM were checked for the degree of auto-correlation amongst the residuals and where significant, the degrees of freedom were adjusted to account for serial auto-correlation (Pyper and Peterman 1998). Following Staunton-Smith *et al*. (2004), ridge regressions were investigated. These methods adjust for any colinearity amongst the independent (X) variables. As this was not a notable feature of our data (R^2 between the independent variables, averaged across all models, was 0.032), the ridge adjustments had very little effect on either the degree of fit or the coefficients, so the simpler GLM were retained.

6.3 YEAR-CLASS STRENGTH

The study aimed to determine whether there was evidence of variation in year-class strength (YCS) in the adult population of barramundi and king threadfin for which variability in YCS at large geographic scales has not yet been demonstrated; and if so, whether the variation could be related to freshwater flows into the estuary. We examined the age-structure of the adult population because the temporal and spatial scale of the estuarine commercial and recreational fisheries was sufficient to adequately sample the adult population of the study estuaries, negating the need to kill large numbers of fish during fishery-independent surveys.

6.3.1 Sampling of barramundi and king threadfin catch

Sampling of the commercial and recreational catch was carried out opportunistically throughout each sample year. Because of the remoteness of the sampling locations only heads were collected as this minimised the freezer space needed for storage. Barramundi head lengths (nose to end of second operculum) were measured (in mm) and converted to total length (TL in mm) using the equation TL = 3.5867 x head length (mm) + 10.566477 (R^2 = 0.976) derived from the measurement of 477 head and total lengths collected from numerous locations across northern Australia (Figure 4). King threadfin head lengths (nose to back of second operculum) were measured and converted to total lengths using the equation TL = 5.0524 x head length (mm) – 33.038 (R^2 = 0.9838)derived from the measurement of 64 head and total lengths from various locations across northern Australia (Figure 5).

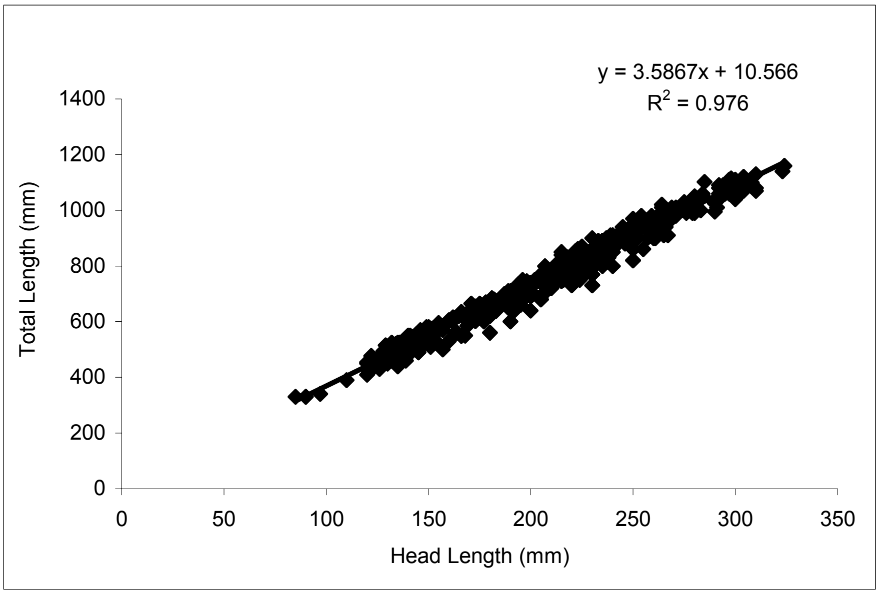

Figure 4. Barramundi head length vs total length

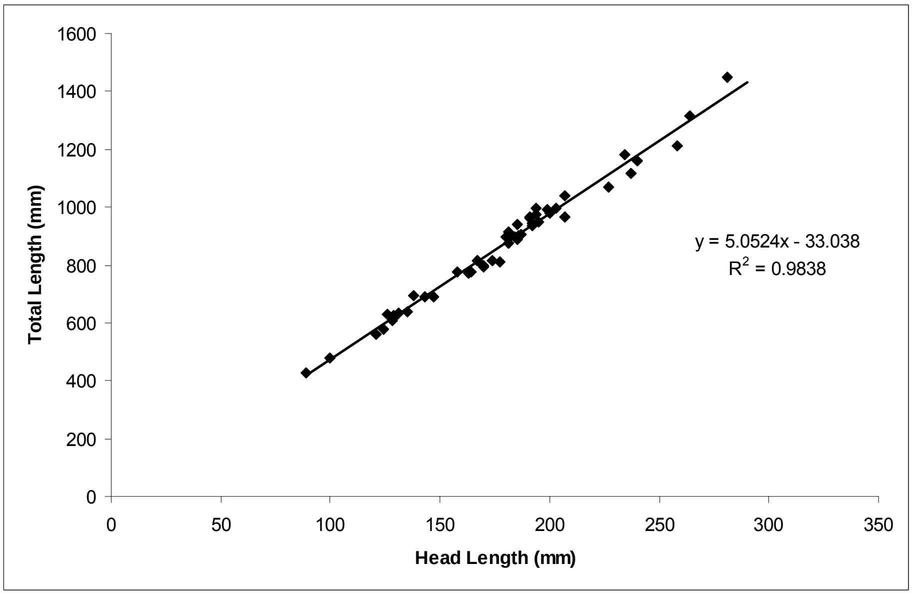

Figure 5. King threadfin head length vs total length

Otoliths from barramundi and king threadfin were collected from the Mitchell, Flinders and Roper River estuaries over three consecutive years (2008, 2009 and 2010). Otoliths were collected from the Daly River estuary over four consecutive years (2007 to 2010).

Individual otoliths were blocked in resin, then sectioned at 300 µm. Sections were viewed using a microscope and reflected light. In general, there was very clear differentiation between the slow (narrow, opaque, light) and fast (broad, translucent, dark) growth zones in otoliths from fish from all regions. Distinct increments probably occur because feeding and growth rates slow greatly during the cooler/dry months. Counts of the narrow, opaque increments have been validated as being laid down yearly (Staunton Smith *et al*. 2004) and were counted to determine fish age.

Once ages were estimated, year-classes were assigned on the basis of spawning year. When spawning occurs over spring and summer, an assumed 1 January birthday was allocated (i.e., fish born in November 2008 and February 2009 are in the 2009 year-class).

Only barramundi between 600 and 800 mm total length were included in the analysis as it was considered that these best represented the sampled population and allowed for comparisons between river systems that have different minimum legal sizes. The minimum size limits (total length) for barramundi is 550 mm and 600mm for Northern Territory waters and Queensland Gulf of Carpentaria respectively. For similar reasons, only the length classes of king threadfin between 600 and 1100 mm total length were included in the analysis.

6.3.2 Estimating year-class strength

We used the method described by Maceina (1997) to estimate year-class strength (YCS) objectively from population age-structures using catch-curve regressions (i.e., regression of the natural log of the number of fish in each year-class against age). Deviation from an expected abundance of each year-class, given its age and the catch-curve regression equation, is assumed to reflect variable recruitment. Therefore, residuals from the catch-curve regressions are indices of YCS, with large positive and negative residuals representing strong and weak year-classes respectively.

6.3.3 Correlating year-class strength with environmental variables

We investigated the relationship between YCS and freshwater flowing into the estuary by:
(i) correlation analyses of YCS and freshwater flow variables (river flow and rainfall); and
(ii) all sub-sets general linear modelling (GenStat 2008) with year-class strength as the response variable, and age, sample year as forced variables and freshwater flow and rainfall as independent variables.

Age was forced into the model, as was sampling year, because the abundance of individual age-classes is not comparable between years (Staunton Smith *et al.* 2004). Significant models with up to three additional independent terms were reported. We examined serial auto-correlation of regression residuals using residual maximum likelihood (REML, GenStat 2008), to investigate for evidence that recruitment success was auto-correlated (e.g. due to stock-recruitment relationships). The results showed no significant auto-correlations, thus standard general linear modeling methods were used for data exploration and model screening.

Where available, we used two variables, expressed as seasonal totals, as indices of freshwater flowing into the estuary: (i) river flow; and (ii) rainfall at sites within each river catchment of the estuary. River flow data for the Mitchell and Flinders Rivers were obtained from the Department of Environment and Resource Management (DERM) Queensland. Rainfall data were obtained from Bureau of Meteorology. Years were defined as ‘water-year’ (e.g. October 2009 to September 2010 = 2010 water year). Seasons are defined as: spring (September to November), summer (December to February), autumn (March to May) and winter (June to August). We also included dry (May to October) and wet (November to April) to reflect the highly seasonal nature freshwater in tropical northern Australia.

We made the following assumptions in our analysis: (i) age-structure was determined mainly by recruitment; (ii) migration rates between estuaries were low; and (iii) age-structure of the adult population was estimated accurately. The details and validity of these assumptions are discussed in Staunton-Smith *et al.* (2004) and Halliday *et al.* (2011).

6.4 OTOLITH MICROCHEMISTRY

6.4.1 Sample collection

We selected a sample of 135 otoliths from barramundi caught by commercial, recreational and indigenous fishers in the Flinders River, Mitchell River, Daly River and Roper River estuaries. These samples were obtained as part of the age estimations during 2008 and 2009. Barramundi from a number of age-classes were analysed from each of the four study estuaries. We examined the Strontium/Calcium (Sr/Ca), Barium/Calcium (Ba/Ca), Magnesium/Calcium (Mg/Ca) and Manganese/Calcium (Mn/Ca) ratios in otoliths of barramundi from each estuary to determine freshwater usage by populations from different systems.

In the laboratory, otoliths were blocked in clear casting resin. All plastic-ware used was washed with 10% nitric acid for 24 hrs and rinsed with millipore water. Blocked otoliths were sectioned transversely through the core using a low speed saw lubricated with millipore water. Each 400 µm section was polished with 1500 grit wet and dry paper moistened with millipore water. Polished sections were stored in acid washed plastic vials until mounted. Up to five sections were mounted on microscope slides using clear casting resin. The exposed polished surfaces of the otoliths were wiped with tissue and 0.5M nitric acid. Dried slides were returned to plastic bags before analysis by LA-ICPMS (Laser Ablation - Inductively Coupled Plasma Mass Spectrometer).

6.4.2 Trace metals

Elemental concentrations in the otoliths were determined by making ablations with a New Wave UP-213 laser ablation system coupled with an Agilent 7500 ce octopole ICPMS. The ICPMS was operated in time-resolved mode and with a dwell time of 20 ms per mass. The LA-ICPMS system was calibrated with NIST 610 and 612 glass standards. For both the NIST glass and otoliths, we used Ca as an internal standard to control for variation in ablation and aerosol transfer efficiency. Otoliths were analysed in blocks of three to five with standard runs before and after each block. For each sample, we acquired a 20 sec blank to correct for background. During ablation, we sampled each otolith continuously along our reading axis from the distal edge through the core to the proximal edge. This resulted in a track of ablated material, 80 µm wide and 15 µm deep at a laser repetition rate of 5 Hz and a scan speed of 10 µm s^{-1}. Sixty-second spot acquisitions of standards were made with similar methods to those used for otolith analysis. Based on this analytical procedure, we were able to quantify the concentrations of ^{24}Mg, ^{55}Mn, ^{86}Sr, ^{88}Sr, ^{137}Ba and ^{138}Ba. Overall Sr and Ba concentrations were calculated as the mean of the values obtained from the two isotopes measured for each element.

Ablation tracks were matched to fish increment counts by calibrating the ablation rate with measured distances along the track. Distances between otolith increments along the ablation track were measured using Image-Pro Plus Image Analysis software with a microscope at 10x magnification (± 0.01 mm). Mean Sr/Ca ratios of 1.5 mM.M^{-1} were considered to indicate that barramundi were residing in freshwater and mean Sr/Ca ratios of greater than 2.0 mM.M^{-1} that barramundi were residing in the estuary (Milton *et al.* 2008).

7 RESULTS

7.1 COMMERCIAL CATCH DATA

7.1.1 Mitchell River, Qld

High annual flows in this catchment have roughly followed a 10 year cycle during the late 1980’s, 1990’s and 2000’s, with years in between having substantially lower flows (Figure 6).

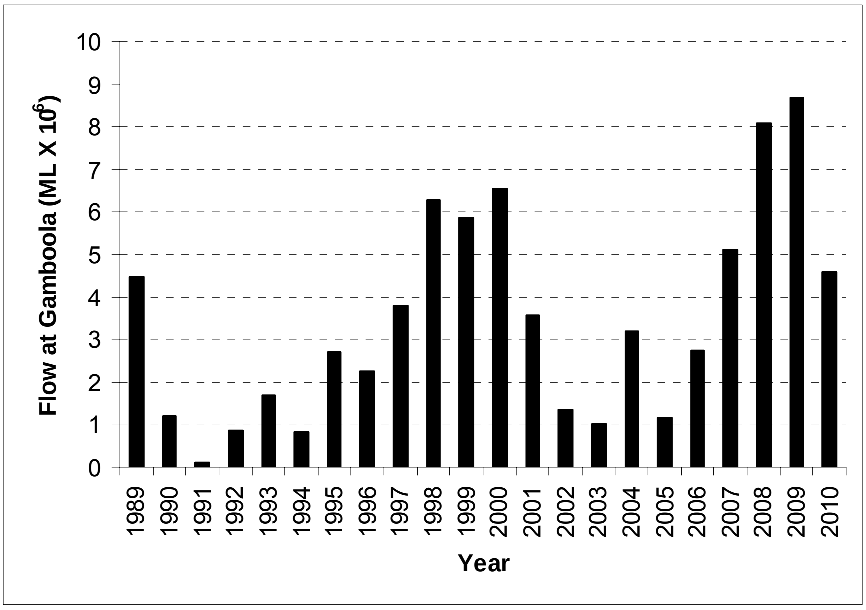

Figure 6. Calender year flows measured at Gamboola, Mitchell River, Qld

7.1.1.1 Barramundi

Annual barramundi catch reported to CFISH has fluctuated between 30 and 67 tonnes between 1989 and 2010 in the Mitchell River catchment (Figure 7).

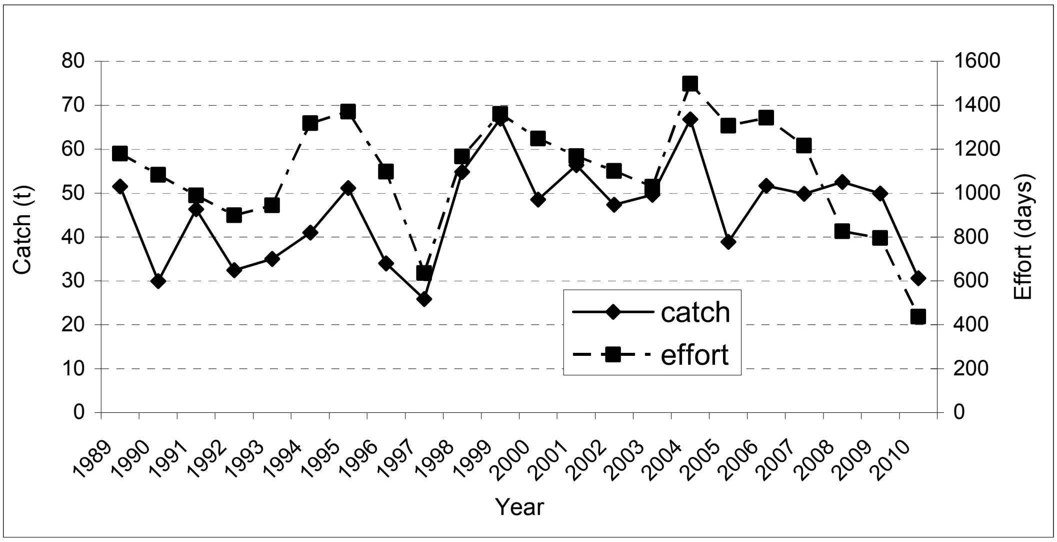

Figure 7. Barramundi catch and effort for the Mitchell River estuary, Qld (CFISH grid AC13)

For the Mitchell River, fishing effort explained a significant proportion of the variation in catch (r=0.61, P<0.01). Barramundi catch adjusted for effort (i.e., residuals from the catch effort correlation) was significantly correlated with water-year flows lagged by two and three years (Table 1). Auto-correlation was not evident, once catch had been adjusted for effort.

Table 1. Correlation coefficients (r) between annual CFISH barramundi catch (adjusted for effort) and freshwater flow at Gamboola, Mitchell River, Qld

Effect[A]	Variable	r
R	water-year^{-2} flow	0.49*
R	water-year^{-3} flow	0.43*

* = P<0.05, ** = P<0.01; Auto-correlation was not a feature of the CFISH data after catch had been adjusted for effort. [A] Variables are proposed to affect Recruitment (R) or Catchability (C).

All sub-sets GLM identified one uni-variate model that explained 48% of the variation in the barramundi catches in the Mitchell River system (Table 2).

Table 2. Best all sub-sets regression for annual CFISH barramundi catch and freshwater flow at Gamboola, Mitchell River, Qld

Data source	Regression model [A]	Percent variance accounted for (adjusted R^2)
CFISH	effort, water-year flow^{-2}	48

[A] Factors in the multiple regressions are positively related to catch unless otherwise indicated.

7.1.1.2 King threadfin

The annual catch of king threadfin reported to CFISH fluctuated between two and nine tonnes between 1989 and 2010 in the Mitchell River (Figure 8).

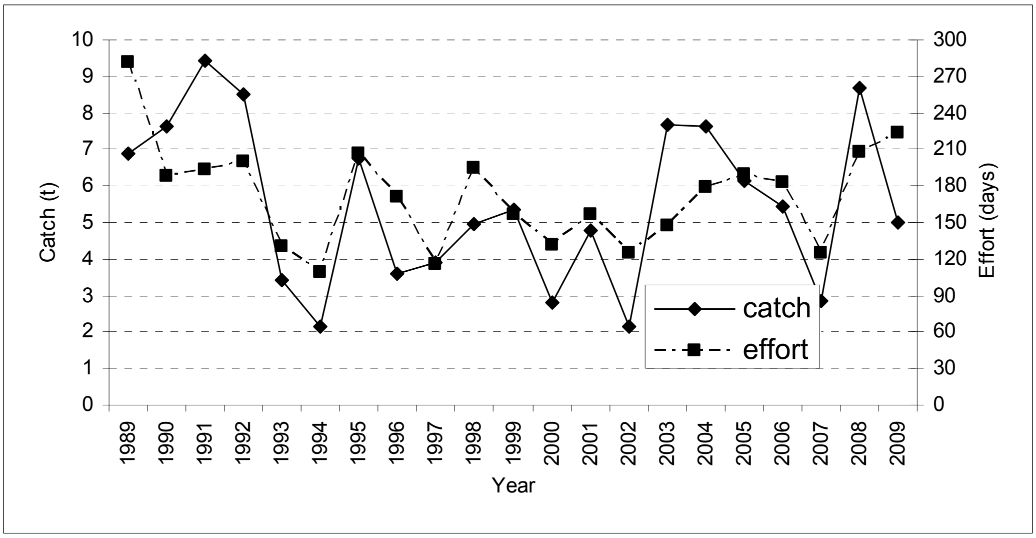

Figure 8. King threadfin catch and effort for the Mitchell River estuary Qld, (CFISH grid AC13)

For the Mitchell River king threadfin, fishing effort explained a significant proportion of the variation in catch (r=0.75, P<0.01). After adjusting for effort, no variables were positively correlated with catch.

7.1.2 Flinders River, Qld

Annual flow events in the Flinders River have been typically low with the exception of flood events in 1991 and 2009 (Figure 9).

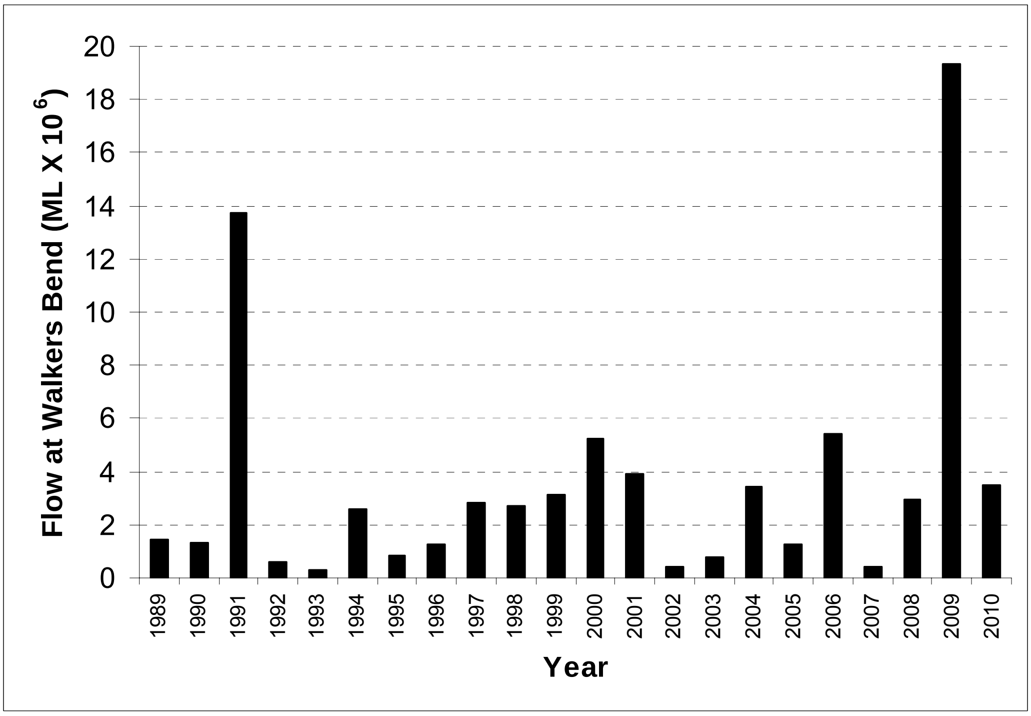

Figure 9. Calender year flows measured at Walkers Bend,Flinders River, Qld

7.1.2.1 Barramundi

Annual barramundi catch reported to CFISH for the Flinders River fluctuated between 20 and 127 tonnes between 1989 and 2010 (Figure 10).

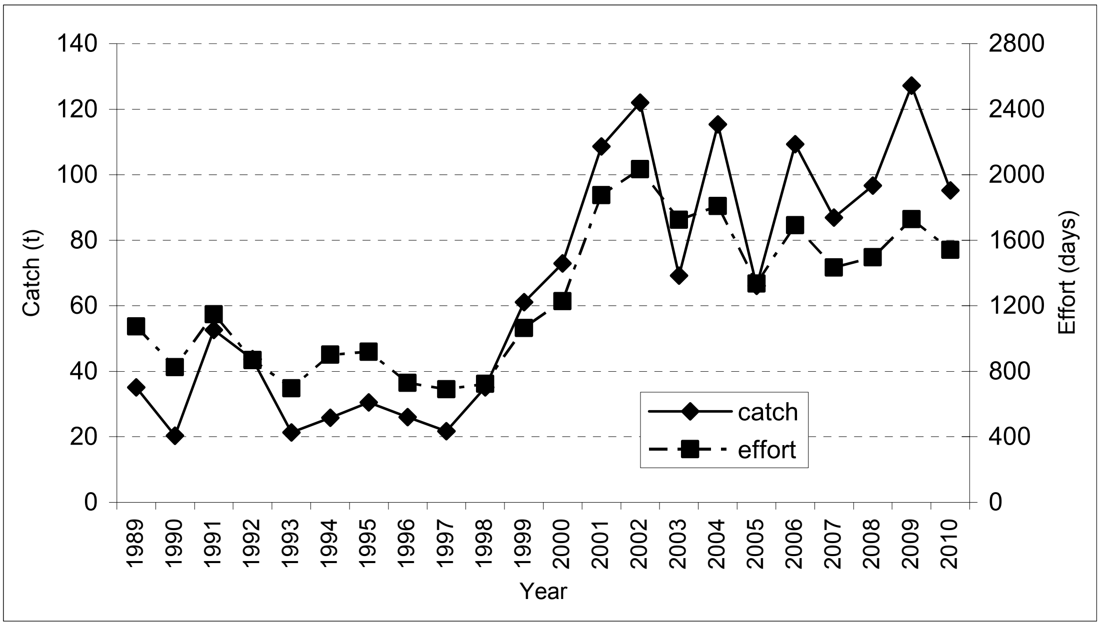

Figure 10. Annual barramundi catch and effort for the Flinders River estuary, Qld (CFISH grid AD18)

For Flinders River barramundi, fishing effort explained a significant proportion of the variation in catch ($r=0.94$, $P<0.01$). Barramundi catch adjusted for effort (i.e., residuals from the catch effort correlation) was significantly and positively correlated with water-year flow lagged by one year (Table 3). Auto-correlation was not evident, once barramundi catch had been adjusted for effort.

Table 3. Correlation coefficients (r) between annual CFISH barramundi catch and freshwater flow at Walkers Bend, Flinders River, Qld

Effect[A]	Variable	r
R	water-year^{-1} flow	0.56**

* = $P<0.05$; Auto-correlation was not a feature of the CFISH data, after catch had been adjusted for effort.

[A] Variables are proposed to affect Recruitment (R) or Catchability (C).

All sub-sets GLM identified only one uni-variate model that explained 91% of the variation in the barramundi catch of the Flinders River (Table 4).

Table 4. Best all sub-sets regression for annual CFISH barramundi catch and freshwater flow at Walkers Bend, Flinders River, Qld

Data source	Regression model [A]	Percent variance accounted for (adjusted R^2)
CFISH	effort, water-year^{-1} flow	91.0

[A] Factors in the multiple regressions are positively related to catch unless otherwise indicated.

7.1.2.2 King threadfin

Annual king threadfin catch reported to CFISH fluctuated between 38 and 120 tonnes between 1989 and 2010 in the Flinders River (Figure 11).

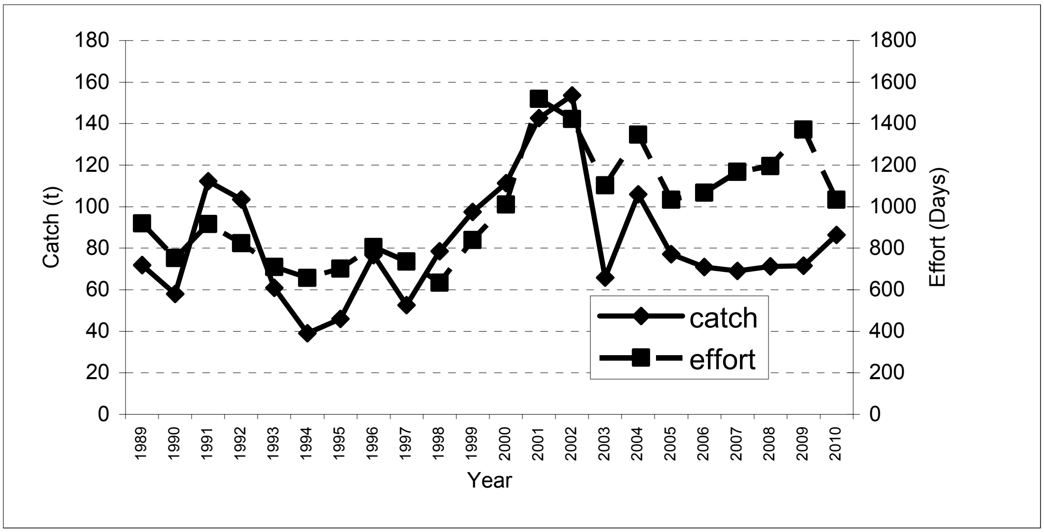

Figure 11. Annual king threadfin catch and effort for the Flinders River estuary, Qld (CFISH grid AD18)

For the Flinders River king threadfin, fishing effort explained a significant proportion of the variation in catch (r=0.61, P<0.01) and after adjusting for effort, water-year-1 was the only variable positively correlated with catch (Table 5).

Table 5. Correlation coefficients (r) between annual king threadfin CFISH catch (adjusted for effort) and freshwater flow at Walkers Bend, Flinders River, Qld

Effect[A]	Variable	r
R	water-year^{-1} flow	0.47*

* = P<0.05, ** = P<0.01; Auto-correlation was not a feature of the CFISH data after catch had been adjusted for effort. [A] Variables are proposed to affect Recruitment (R) or Catchability (C).

All sub-sets GLM identified two alternative models, each of three variables that explained 66% and 65% of the variation in the CFISH king threadfin catch (Table 6). The inclusion of effort in the models of the CFISH king threadfin catch data was the main driver for the increased fit of the multiple linear models.

Table 6. Best all sub-sets regression for annual king threadfin CFISH catch and freshwater flow at Walkers Bend, Flinders River, Qld

Data source	Regression model [A]	Percent variance accounted for (adjusted R^2)
CFISH	effort, water-year^{-1} flow, autumn^{-2} flow, spring^{-2} flow	66
	effort, water-year^{-1} flow, autumn^{-2} flow, spring^{-1} flow	65

[A] Factors in the multiple regressions are positively related to catch unless otherwise indicated

7.1.3 Roper River, NT

Annual rainfall in the Roper River catchment has been consistently around 800 mm, except for 2000, 2003 and 2004; which were all years of substantially higher rainfall (Figure 12).

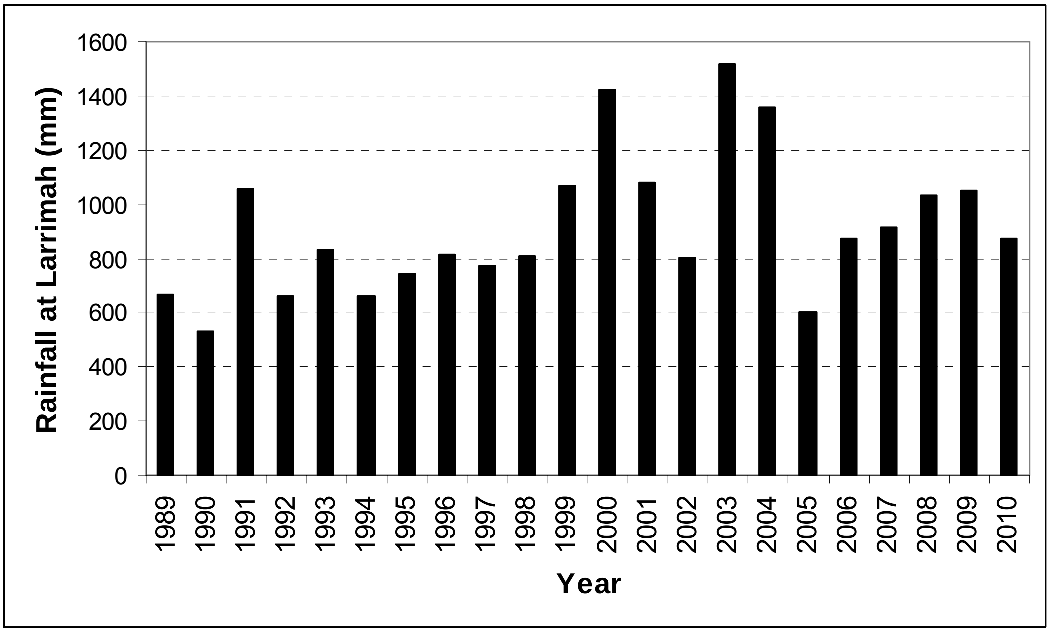

Figure 12. Calendar year rainfall measured at Larrimah, Roper River, NT

7.1.3.1 Barramundi

The annual catch of barramundi reported in the NT DoR data has fluctuated between 25 and 102 tonnes between 1990 and 2009 in the Roper River (Figure 13).

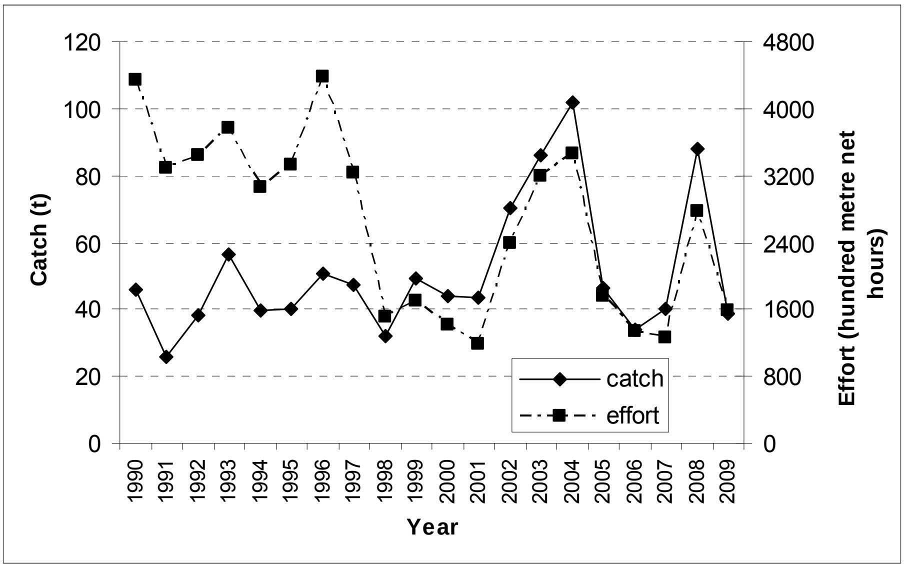

Figure 13. Annual barramundi catch and effort for the Roper River estuary, NT

Fishing effort explained very little of the variation in the barramundi catch (r=0.32, NS). Barramundi catch adjusted for effort (i.e., residuals from the catch effort correlation) was significantly and positively correlated with spring rain lagged by three years ($P<0.01$), autumn rain lagged by four years catch ($P<0.01$), water-year rain lagged by one year ($P<0.05$), summer rain lagged by one year ($P<0.05$) and water-year lagged by two years ($P<0.05$; Table 7). Auto-correlation was not a feature of the Roper River data.

Table 7. Correlation coefficients (r) between annual barramundi NT DOR catch and rainfall at Larrimah, Roper River, NT

Effect[A]	Variable	r
R	spring^{-3} rain	0.58**
R	summer^{-1} rain	0.45*
R	water-year^{-1} rain	0.54*
R	autumn $^{-4}$ rain	0.58**
R	water-year^{-2} rain	0.45*

* = $P<0.05$; ** =$P<0.01$; Auto-correlation was not a feature of the NT DoR data, after catch had been adjusted for effort. [A] Variables are proposed to affect Recruitment (R) or Catchability (C).

All sub-sets GLM identified three alternative models, each of three factors that explained between 48% and 56% of the variation in the NT DoR barramundi catch (Table 8).

Table 8 Best all sub-sets regression for annual barramundi NT DoR catch and rainfall at Larrimah, Roper River, NT

Data source	Regression model [A]	Percent variance accounted for (adjusted R^2)
NT DoR	effort, autumn^{-4} rain, water-year^{-2} rain	56
	effort, spring^{-3} rain, autumn^{-4} rain	52

	effort, water-year^{-1} rain, water-year^{-2} rain	48

[A] Factors in the multiple regressions are positively related to catch unless otherwise indicated.

7.1.3.2 King Threadfin

Annual catch reported to the NT DoR for king threadfin in the Roper River catchment has fluctuated between three and 27 tonnes (Figure 14).

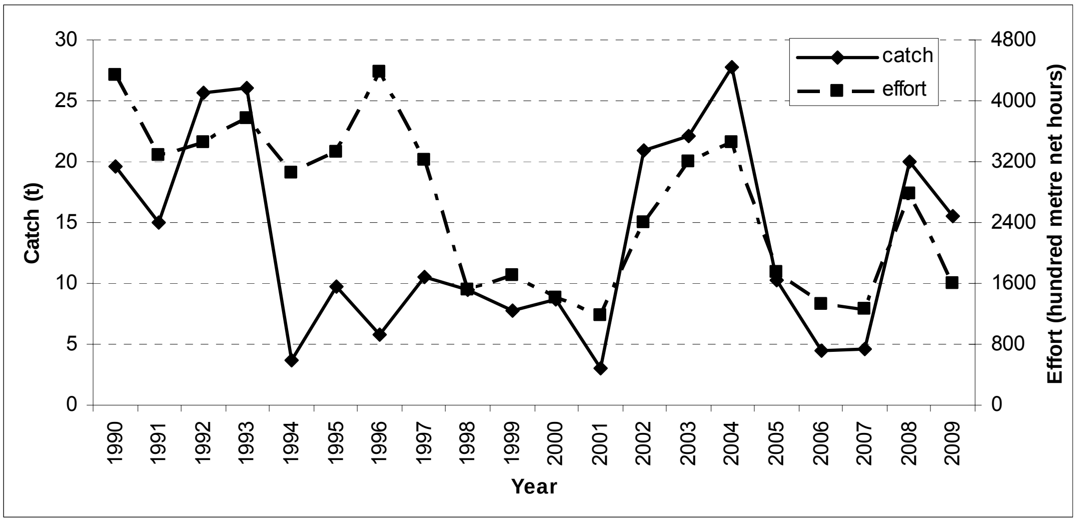

Figure 14. Annual king threadfin catch and effort for the Roper River estuary, NT

For the Roper River, fishing effort explained a significant proportion of the variation in king threadfin catch (r=0.55, P<0.05). King threadfin catch adjusted for effort (i.e., residuals from the catch effort correlation) was significantly and positively correlated with spring rain lagged by three years (Table 9) and significantly and negatively correlated with autumn rain in the year of catch (Table 9).

Table 9. Correlation coefficients (r) between annual king threadfin NT DoR catch (adjusted for effort) and rainfall at Larrimah, Roper River, NT

Effect[A]	**Variable**	**r**
R	spring^{-3} rain	0.50*
C	autumn rain	-0.47*

*= P<0.05; Auto-correlation was not a feature of the NT DoR data, after catch had been adjusted for effort.
[A] Variables are proposed to affect Recruitment (R) or Catchability (C).

All sub-sets GLM identified a single ‘best’ model, of three variables, that explained 83% of the variation in king threadfin catch in the Roper River (Table 10).

Table 10. Best all sub-sets regression for annual king threadfin NT DoR catch and rainfall at Larrimah, Roper River, NT

Data source	**Regression model** [A]	**Percent variance accounted for (R^2)**
NT DoR	effort, winter rain^{-1}, December rain, spring^{-3} rain	83

[A] Factors in the multiple regressions are positively related to catch unless otherwise indicated.

7.1.4 Daly River, NT

Annual rainfall in the Daly River has been around 1000 to 1200 mm, with falls greater than 1400 mm occurring in 1998, 2001, 2004 and 2006 (Figure 15).

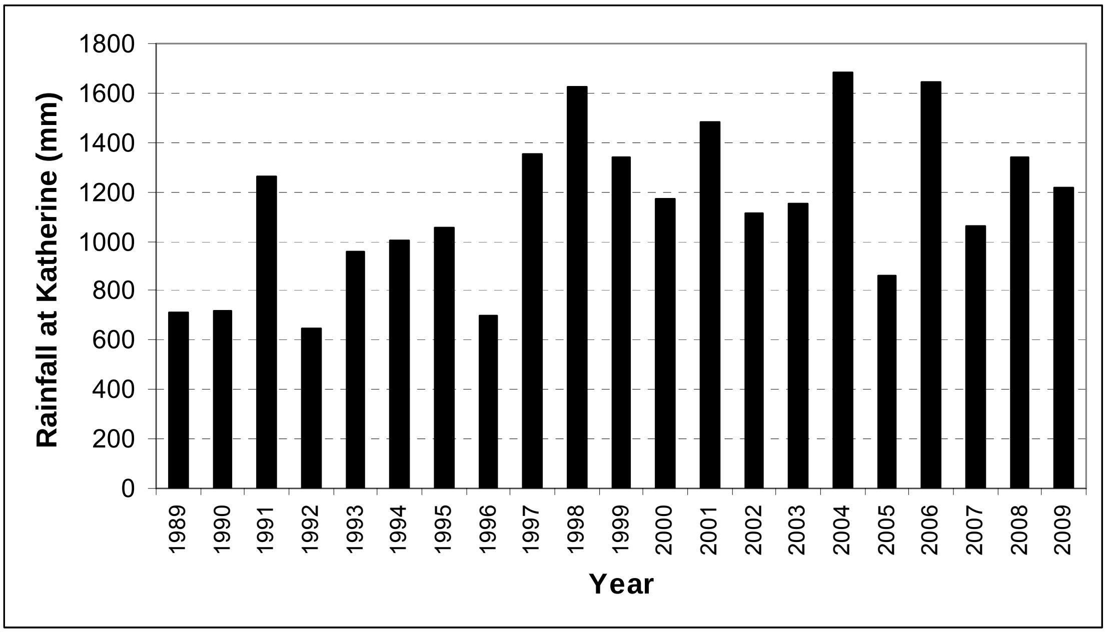

Figure 15. Annual rainfall measured at Katherine, headwaters of the Daly River, NT

7.1.4.1 Barramundi

The annual catch of barramundi in the Daly River estuary reported to NT DoR has fluctuated between 38 and 112 tonnes (Figure 16).

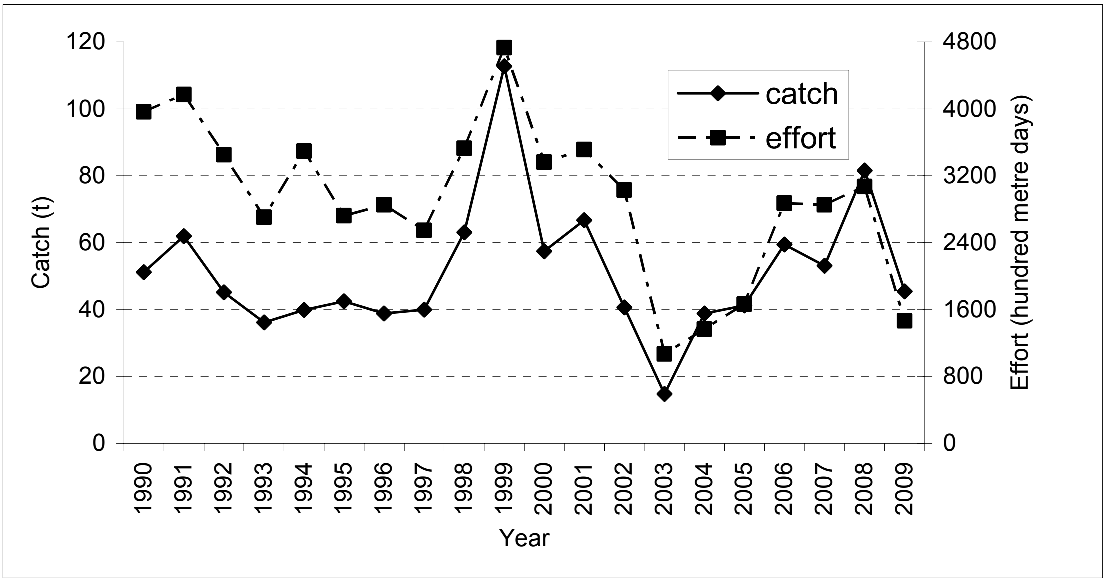

Figure 16. Annual barramundi catch and effort of the Daly River estuary, NT

For the Daly River, fishing effort explained a significant proportion (49.5%) of the variation in commercial barramundi catch ($r=0.72$, $P<0.01$). Barramundi catch adjusted for effort (i.e., residuals from the catch effort correlation) was significantly correlated with December rain, winter rain lagged by one year and water- year rain lagged by five years (Table 11). All sub-sets GLM identified a single "best" three factor model that explained 82.3% of the variation in the barramundi catch (Table 12).

Table 11. Correlation coefficients (r) between annual barramundi NT DoR catch and rainfall at Katherine, Daly River, NT

Effect[A]	Variable	r
C	December rain	0.57**
R	winter^{-1} rain	0.54*
R	water-year^{-5} rain	0.53*

* = P<0.05; Auto-correlation was not a feature of the NT DoR data, after catch had been adjusted for effort.
[A] Variables are proposed to affect Recruitment (R) or Catchability (C).

Table 12 Best all sub-sets regression for annual barramundi NT DoR catch and rainfall at Katherine, Daly River, NT

Data source	Regression model [A]	Percent variance accounted for (adjusted R^2)
NT DoR	effort, winter rain^{-1}, December rain, spring^{-3} rain	82

[A] Factors in the multiple regressions are positively related to catch unless otherwise indicated.

7.1.4.2 King Threadfin

Annual catch of king threadfin in the Daly River estuary reported in to DoR data has fluctuated between 38 and 112 tonnes (Figure 17).

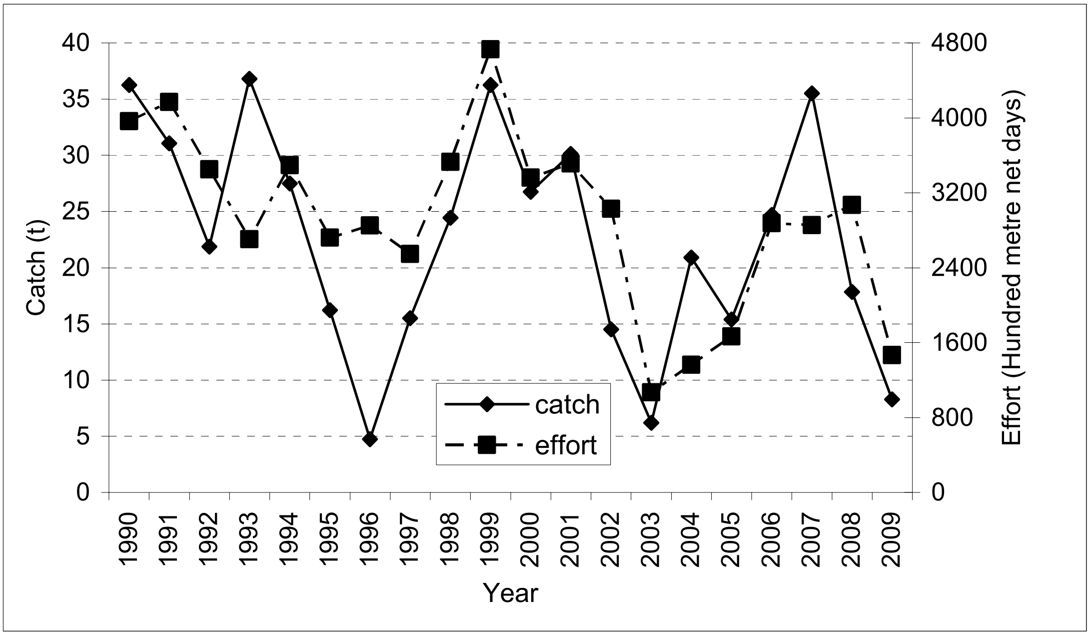

Figure 17. Annual king threadfin catch and effort for the Daly River estuary

For the Daly River, commercial king threadfin data, fishing effort explained a significant proportion of the variation in catch (r=0.62, P<0.01). King thread catch adjusted for effort (i.e., residuals from the catch effort correlation) was significantly correlated with no flow or rainfall variable, and therefore no further GLM's were undertaken.

7.2 YEAR-CLASS STRENGTH

7.2.1 Mitchell River

7.2.1.1 Barramundi

7.2.1.1.1 Length-frequencies

A total of 384 barramundi from the Mitchell River estuary were sampled and aged over the three years, with 298 of these between 600 and 800 mm in total length. These 298 were therefore included in the year-class strength analysis (Table 13). Length frequencies were similar across years, with highest abundances in the 600 to 750 mm size range (Figure 18).

Table 13. Number (n) of barramundi sampled from the Mitchell River estuary that were aged and used in the analysis of year-class strength

Sample year	**Barramundi (n)**	
	Aged	**Used in YCS analysis**
2008	118	95
2009	129	95
2010	136	108
Total	384	298

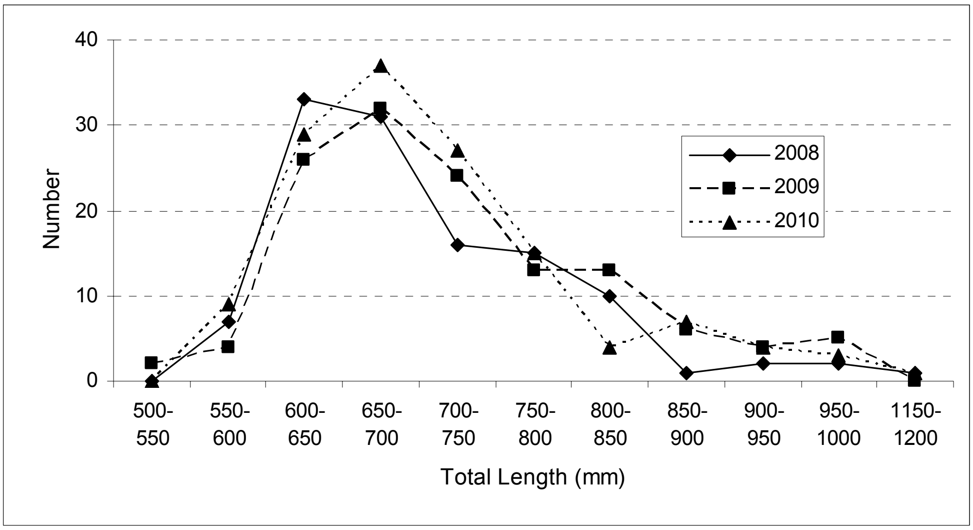

Figure 18. Length frequencies of barramundi sampled from the Mitchell River estuary

The catch of barramundi from the Mitchell River ranged in age from one- to 10-years-old with 94% of the catch aged between two- and five-years-old (Figure 19). There was large variation in the length-age relationship of barramundi, indicating that total length is not a not a reliable indicator of age for barramundi in the Mitchell River estuary. For example, 600mm TL barramundi range in age from two- to six-years-old; and three-year-old barramundi range in length range from 580 mm to 1000 mm TL (Figure 19).

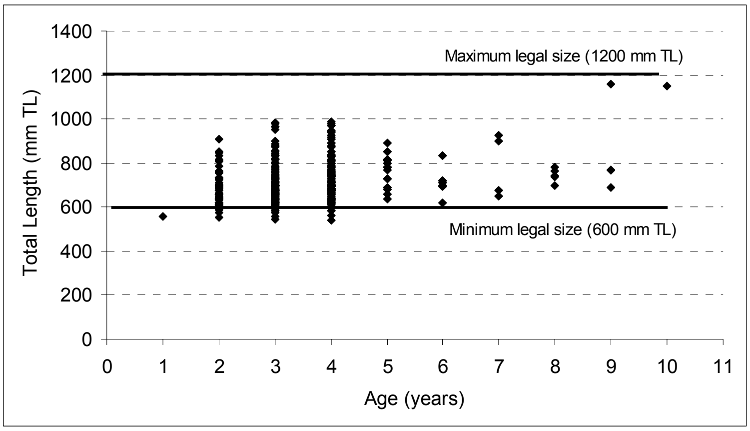

Figure 19. Length-at-age for barramundi sampled from the Mitchell River estuary

7.2.1.1.2 Age-structure

Barramundi from the Mitchell River estuary showed a systematic change in age-structure between 2008 and 2010 (Figure 20). In 2008, the two-year-old age-class was 'strong' and could be followed in the yearly age-structures over the following two years.

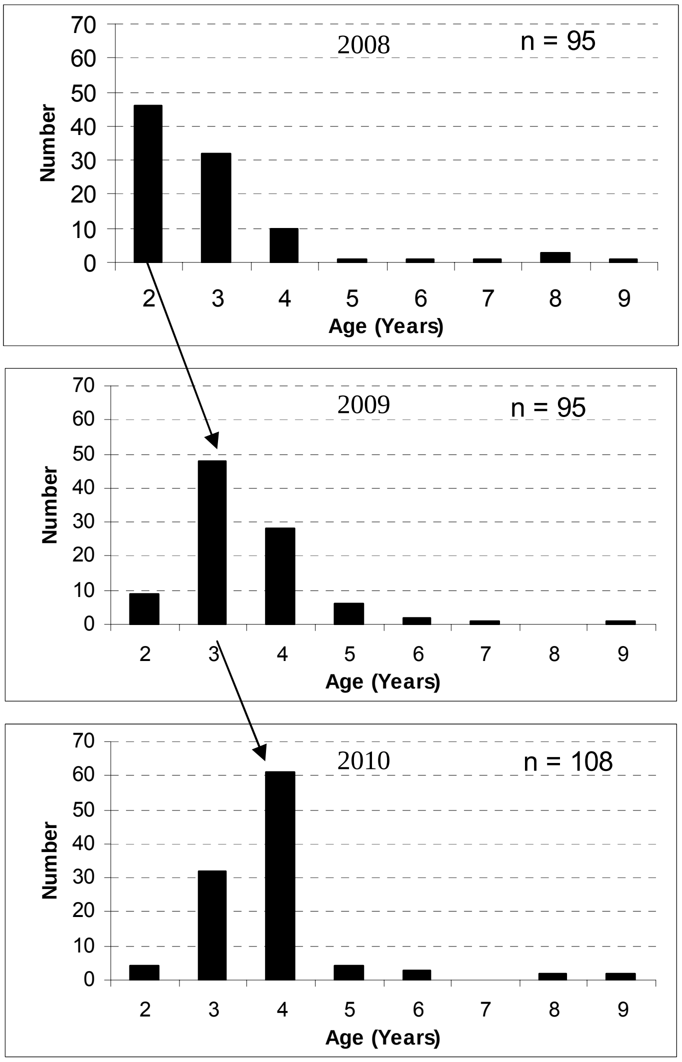

Figure 20. Annual age-structures for barramundi (600 to 800 mm TL) sampled from the Mitchell River estuary

7.2.1.1.3 Using residuals from the catch-curve regression

The standardised residual from catch-curve regression gives an indication of relative year-class strength (YCS). Barramundi year-classes ‘born’ in 1999, 2000 and 2006 had large, positive residuals (>0.05), indicating ‘strong’ recruitment, whilst those ‘born’ in 2003 and 2008 had large, negative residuals (<0.05), indicative of ‘weak’ recruitment (Figure 21). Of the remaining year-classes, 2005 had small, positive residuals (0.0 to 0.5) while 2001, 2002, 2004 and 2007 had small, negative residuals (-0.5 to 0.0) and thus could not be classified as either ‘strong’ or ‘weak’.

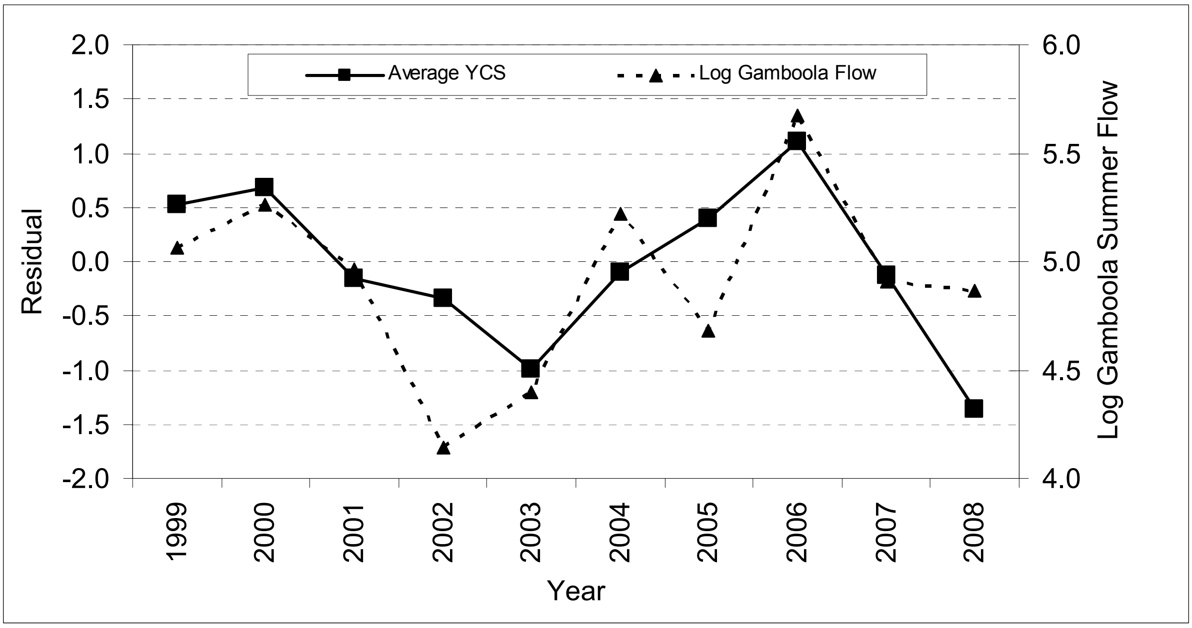

Figure 21. Residuals from the catch-curve regression for barramundi against summer freshwater flows in the Mitchell River estuary

7.2.1.1.4 Correlating environmental variables with year-class strength

River flow and rainfall at Gamboola, Mitchell River catchment, were significantly correlated in spring and autumn (r= 0.57 and 0.67 respectively, P<0.01, n=24), but not in summer or winter. They were also significantly correlated with water-year (r = 0.51) and wet and dry seasons (r = 0.43 and 0.67 respectively). Seasonal river flow and rainfall in spring, autumn and the wet and dry season should have similar correlations with the measures of YCS, but this was not always so. Year-class strength of barramundi was significantly correlated with freshwater flow in spring, winter and the dry season; while rainfall was not correlated with YCS for any time frames examined (Table 14).

Table 14. Correlation coefficients (r) between year-class strength (YCS) and seasonal water variables for barramundi sampled from the Mitchell River estuary

Season	**r**	
	Flow	**Rain**
water-year	0.28	-0.07
spring	0.42*	0.16
summer	0.26	-0.35
autumn	0.00	0.33
winter	0.51**	0.03
dry	0.57**	0.15
wet	0.16	-0.12

*= P<0.05, ** = P<0.01, *** =P<0.001

All sub-sets general linear modelling identified several alternate models that explained ~67 to 78% of the variation in the abundance of age-classes of barramundi (Table 15).
For barramundi, the base model of age and sample year (i.e., forced variables) explained 51% of the variation in the abundance of age-classes. The 'best' model, with an adjusted R^2 of ~78% included the additional terms of dry-season flow and autumn flow (Table 15). Another model with the additional terms of water-year rainfall and summer rainfall (a negative effect) also had a high adjusted R^2 (Table 15). Two other models that were plausible had the additional terms of: (i) summer rain (negative effect) and wet season rain (adjusted R^2 = ~73%); and (ii) summer rain (negative effect) and autumn rain (adjusted R^2 = 67%).

Table 15. Best all sub-sets regression models for the abundance of age-classes of barramundi sampled from the Mitchell River estuary

Species	Regression model[A]	Percent variance accounted for (adjusted R^2)
Barramundi	age, sample year, dry-season flow, autumn flow	77.7
	age, sample year, water-year rain, summer rain (-ve)	75.3
	age, sample year, summer rain (-ve), wet season rain	72.7
	age, sample year, summer rain (-ve), autumn rain	67.0

[A] Factors in the multiple regression are positively related to age-class abundance unless otherwise indicated.

7.2.2 Flinders River

7.2.2.1 Barramundi

7.2.2.1.1 Length-frequencies

A total of 642 barramundi from the Flinders River estuary were sampled and aged (Table 16), with 493 of these between 600 and 800 mm in total length (Figure 22). Length-frequencies showed a change in modal size over the three years of sampling, with barramundi caught in 2008 smaller than in other years.

Table 16. Number (n) of barramundi sampled from the Flinders River estuary that were aged and used in year-class strength analysis

Sample year	**Barramundi (n)**	
	Aged	**Used in YCS analysis**
2008	214	181
2009	206	150
2010	222	162
Total	642	493

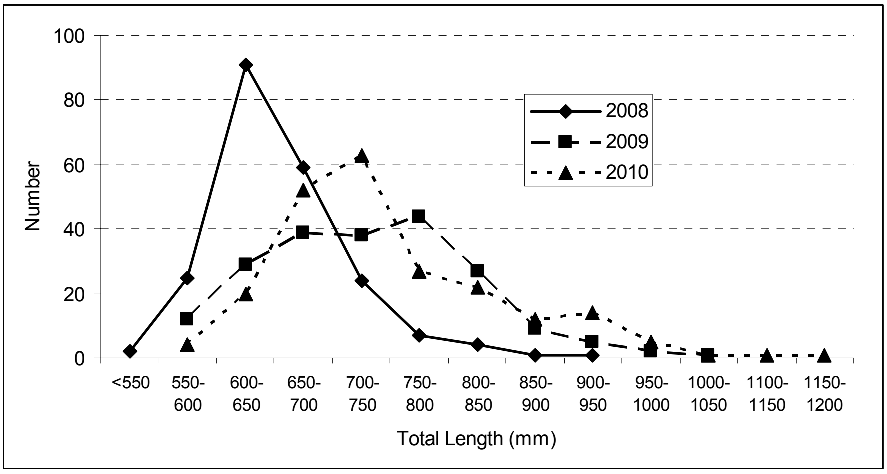

Figure 22. Length frequencies of barramundi sampled from the Flinders River estuary

The catch of barramundi from the Flinders River estuary ranged in age from one- to 11-years-old. The majority of the catch (96.3%) was aged between two- and four-years-old (Figure 23). Barramundi greater than five-years-old made up only 1.8% of the commercial catch. There was large variation in the length-at-age of barramundi from the Flinders River, indicating that total length is not a not a reliable indicator of age (Figure 23). For example, three-year-old barramundi may range in length range from 580 mm to 1000 mm TL.

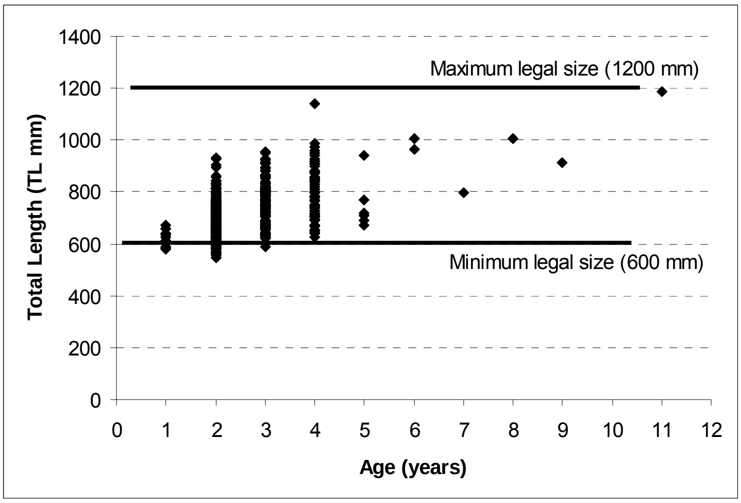

Figure 23. Length-at-age for barramundi sampled from the Flinders River estuary

7.2.2.1.2 Age-structure

The age-structure of barramundi in the Flinders River estuary indicates that the fishery is heavily dependent on young fish, with two-year-old fish comprising most of the catch in two of the three years sampled (Figure 24).

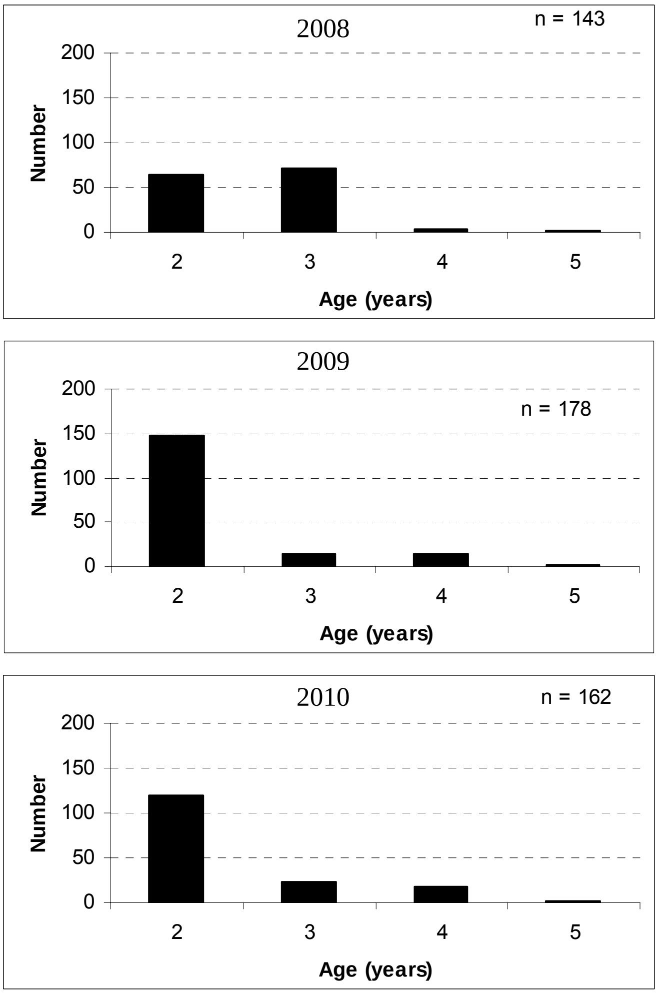

Figure 24. Annual age-structures for barramundi (600 to 800 mm TL) sampled from the Flinders River estuary

7.2.2.1.3 Using residuals from the catch-curve regression

The standardised residuals from the catch-curve regression give an indication of relative year-class strength (YCS). The barramundi year-class in the Flinders River estuary 'born' in 2006 had a large, positive residual (>0.5), indicating 'strong' recruitment, whilst the year-class 'born' in 2005 had a large, negative residuals (<-0.5), indicative of 'weak' recruitment (Figure 25). All of the remaining year-classes had small residuals (i.e. -0.5 to 0.5) and therefore could not be classified as either 'strong' or 'weak'.

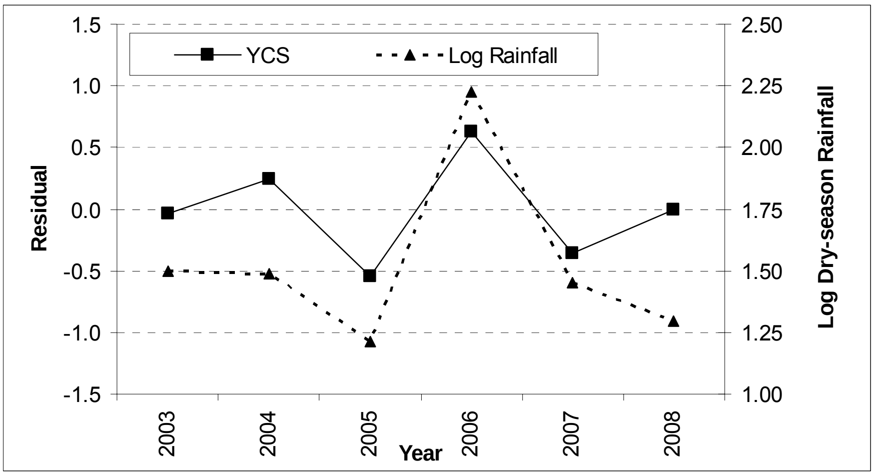

Figure 25. Residuals from the catch-curve regression for barramundi against dry-season rainfall for the Flinders River estuary

7.2.2.1.4 Correlating environmental variables with year-class strength

All sub-sets general linear modelling identified a single model that explained ~95% of the variation in the abundance of age-classes of barramundi in the Flinders River estuary (Table 17). Dry season rain (i.e., May to October) was the main environmental influence on barramundi YCS in the Flinders River estuary.

Table 17. Best all sub-sets regression model for the abundance of age-classes of barramundi sampled from the Flinders River estuary

Species	Regression model[A]	Percent variance accounted for (adjusted R^2)
Barramundi	Age, sample year, dry-season rain	94.9

[A] Factors in the multiple regression are positively related to age class abundance unless otherwise indicated.

7.2.2.2 King threadfin

A total of 685 king threadfin were sampled from the Flinders River estuary and aged (Table 18), with 635 of these between 600 mm and 1100 mm total length and thus used in the analysis of year-class strength. The modal size of king threadfin length-frequency changed over the three years of sampling, with king threadfin caught in 2008 being smaller than the other two years (Figure 26).

Table 18. Number (n) king threadfin sampled from the Flinders River estuary that were aged and used in year-class strength analysis

Sample year	King threadfin (n)	
	Aged	Used inYCS analysis
2008	260	233
2009	221	214
2010	204	188
Total	685	635

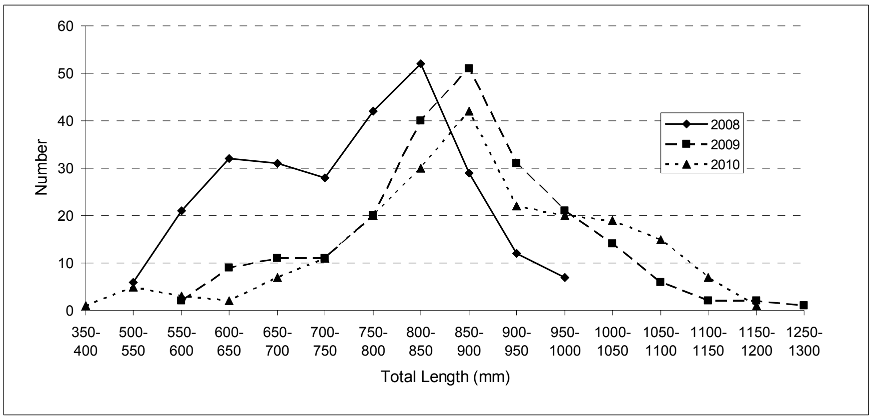

Figure 26. Length frequencies of king threadfin sampled from the Flinders River estuary

The catch of king threadfin ranged in age from two- to seven-years-old (Figure 27). Ninety two percent of the king threadfin sampled were two- to five-years-old. King threadfin showed a high degree of variation in length-at-age, with three-year old fish ranging in length from 650 to 950 mm and fish of 800 mm total length ranging in age from two- to seven-years old.

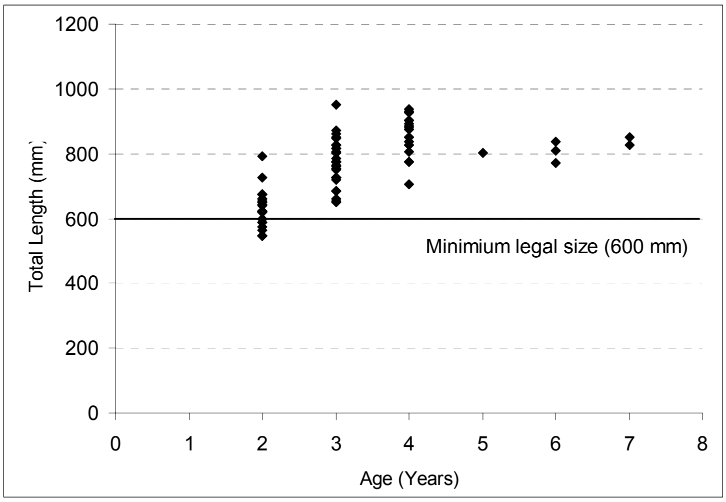

Figure 27. Length-at-age of king threadfin sampled from the Flinders River estuary

The age-structure of king threadfin in the Flinders River estuary indicates that the fishery is heavily dependent on young fish, with the catch comprised of fish mostly less than five-years-old. There was a systematic change in the age-structure of samples from 2008 to 2010 (Figure 28). In 2008, the two-year-old age-class was 'strong' and could be followed in the yearly age-structures over the three sample years.

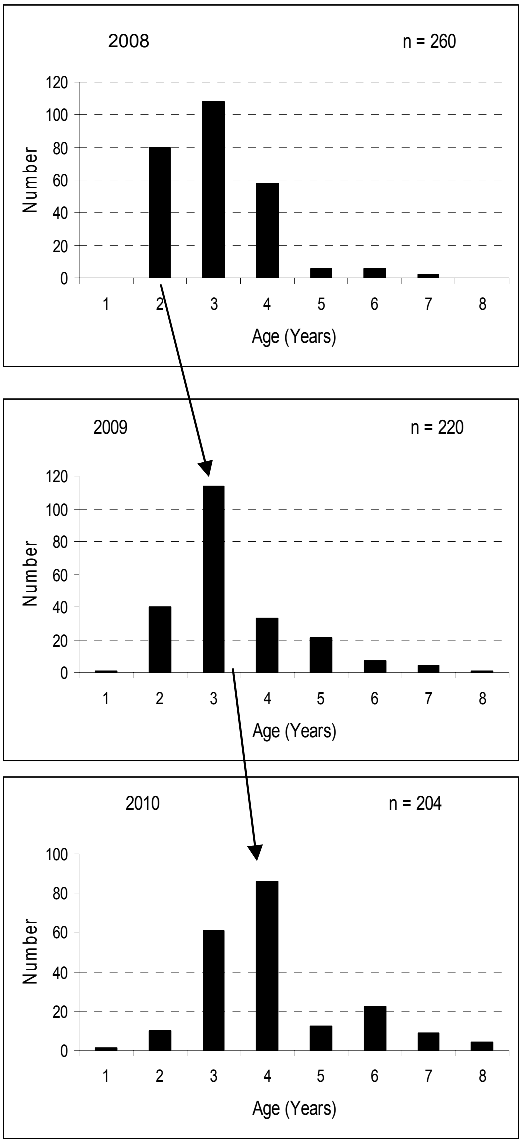

Figure 28. Annual age-structures for king threadfin (>600 mm TL) sampled from the Flinders River estuary

Year-class strength of king threadfin was significantly correlated with water-year rain and wet season rain at Cloncurry (Table 19). For king threadfin, the base model of age and sample year (i.e., forced variables) explained 64% of the variation in the abundance of age-classes. All sub-sets general linear modelling did not identify any alternate rainfall variable that produced a better model fit than the base model of age and sample year.

Table 19. Correlation coefficients (r) between king threadfin year-class strength (YCS) and rainfall in the Flinders River estuary

Season	r
water-year rain	0.52*
wet rain	0.51*

*= P<0.05, ** = P<0.01, *** =P<0.001

7.2.3 Roper River

7.2.3.1 Barramundi

7.2.3.1.1 Length-frequencies

A total of 663 barramundi from the Roper River estuary were sampled and aged, with 566 measuring between 600 and 800 mm in total length and therefore used in the analysis of year-class strength (Table 20). Most barramundi sampled were between the 650 to 850 mm size classes (Figure 29). The catch of barramundi ranged in age from two- to 11-years-old, 83% of the catch was aged between four- and nine-years-old (Figure 30).

Table 20. Number (n) of barramundi in the Roper River estuary that were aged and used in the year-class strength analysis

Sample year	Barramundi (n)	
	Aged	Used in YCS analysis
2008	88	58
2009	350	315
2010	225	193
Total	663	566

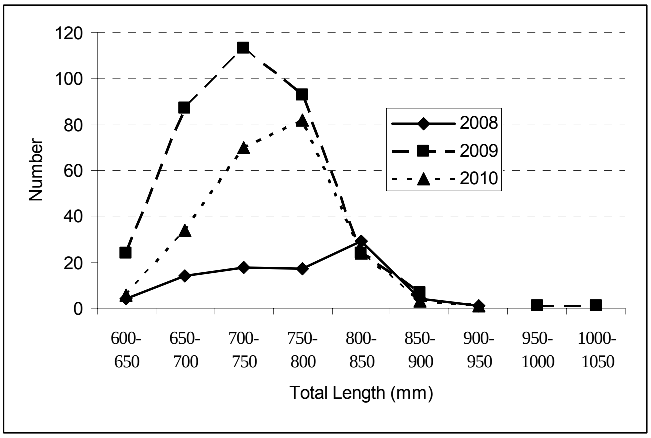

Figure 29. Length frequencies of barramundi sampled from the Roper River estuary

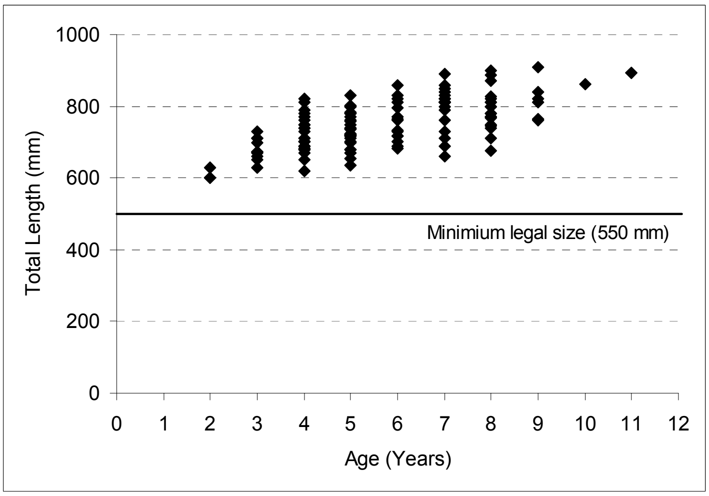

Figure 30. Length-at-age of barramundi sampled from the Roper River estuary

7.2.3.1.2 Age-structure

Barramundi sampled from the Roper River estuary showed a systematic change in age-structure between 2008 and 2010. In 2008, the four-year-old age-class and the seven-year-old age-class were relatively ‘strong’ and could be followed in the annual age-structures. Conversely, the six-year-old age-class was relatively ‘weak’ in 2008 and this pattern persisted over time (Figure 31).

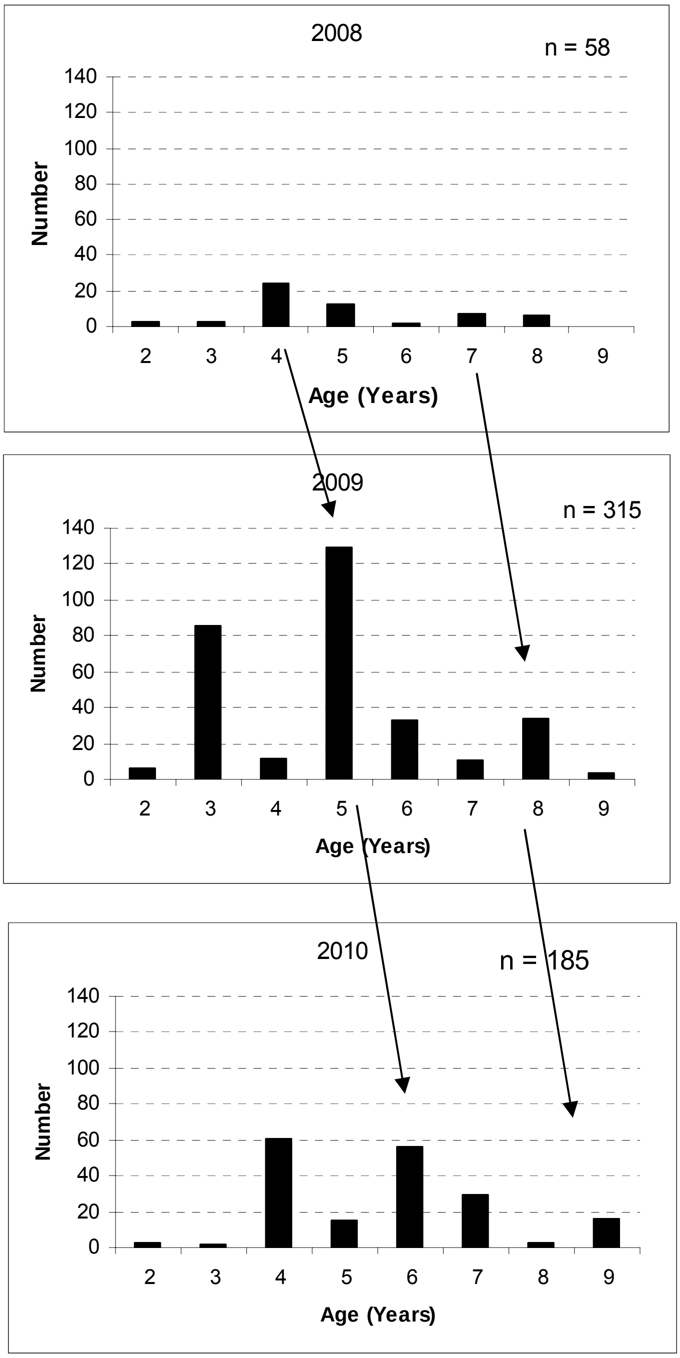

Figure 31. Annual age-structures for barramundi (600 to 800 mm TL) sampled from the Roper River estuary

7.2.3.1.3 Using residuals from the catch-curve regression

The standardised residuals from the catch-curve regression gives an indication of relative year-class strength (YCS). The barramundi year-classes in the Roper River estuary 'born' in 2001 and 2004 had large, positive residuals (>0.5), indicating 'strong' recruitment, whilst those 'born' in 1999, 2002 and 2005 had large, negative residuals (<-0.5), indicative of 'weak' recruitment (Figure 32). All of the remaining year-classes had small residuals (i.e. 0.0 to 0.5) and therefore could not be classified as either 'strong' or 'weak'.

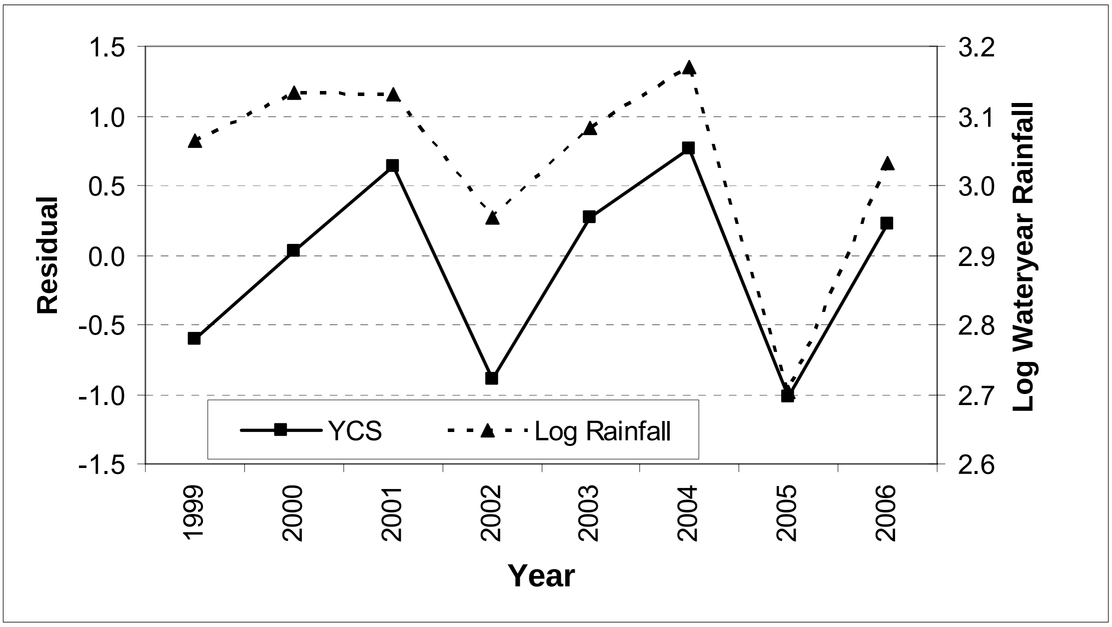

Figure 32. Residuals from catch-curve regression of barramundi against summer rainfall from the Roper River estuary

All sub-sets general linear modelling identified several alternate models that explained ~84% of the variation in the abundance of age-classes of barramundi (Table 21). For barramundi, the base model of age and sample year (i.e., forced variables) explained 44.8% of the variation in the abundance of age classes. The additional terms of summer rain and autumn rain was the 'best' model (adjusted R^2 = 84.2%) while the other 'best' model was water-year rain (adjusted R^2 = 83.8%). These two models account for ~70% of the unexplained variation from the base model. This implies that rainfall measured at Larrimah is a good predictor of barramundi YCS in the Roper River estuary. Barramundi did not appear to be fully recruited to the Roper River fishery until they were four-years-old. Therefore, only fish between four- and nine-years-old were used in the catch-curve regression.

Table 21. Best all sub-sets regression models for the abundance of age-classes of barramundi sampled from the Roper River estuary

Species	Regression model[A]	Percent variance accounted for (adjusted R^2)
Barramundi	Age, sample year, summer rain, autumn rain	84.2
	Age, sample year, water-year rain	83.8

[A] Factors in the multiple regression are positively related to age class abundance unless otherwise indicated.

7.2.4 Daly River

7.2.4.1 Barramundi

7.2.4.1.1 Length-frequency

A total of 1229 barramundi from the Daly River estuary were sampled and aged over the four sample years, with 840 of these between 600mm and 800 mm in total length (Table 22).

Table 22. Number (n) of barramundi caught in the Daly River estuary that were aged and used in the year-class strength analysis

Sample	Barramundi (n)	
year	Aged	Used in YCS analysis
2007	183	141
2008	371	189
2009	348	297
2010	327	213
Total	1229	840

The catch of barramundi ranged in age from two- to nine-years-old (Figure 33), with 80% of the catch aged between three- and nine-years-old.

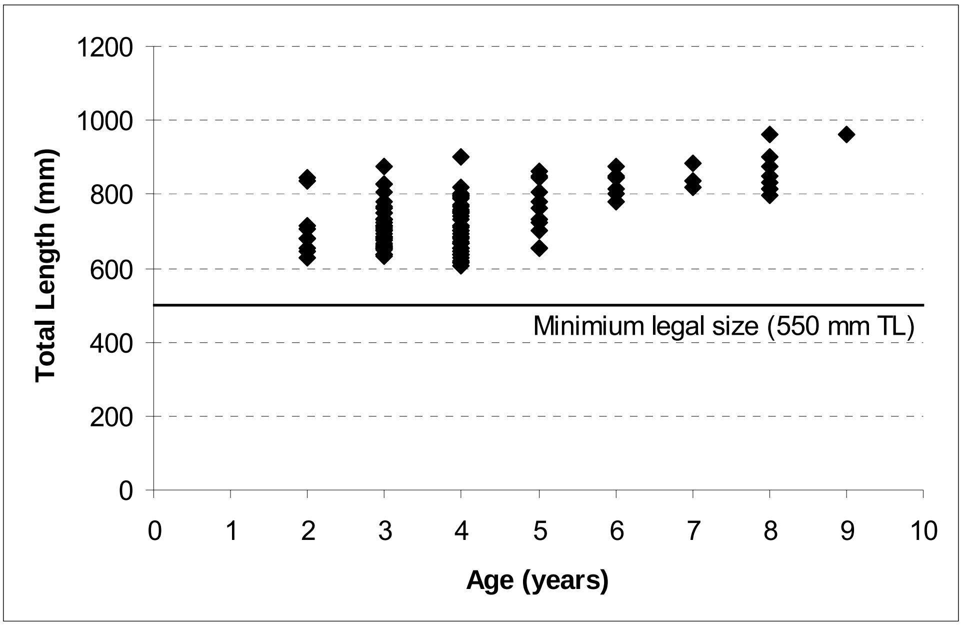

Figure 33. Length-at-age for barramundi sampled from the Daly River estuary

7.2.4.1.2 Age-structure

Barramundi caught in the Daly River estuary showed a systematic change in their age-structure from 2007 to 2010 (Figure 34). In 2007, the three-year-old age-class was 'strong' and could be followed in the annual age-structures over the four sample years. Whilst the six-, seven- and eight-year-old age-classes were 'weak' in 2007 and this pattern persisted throughout the sampling.

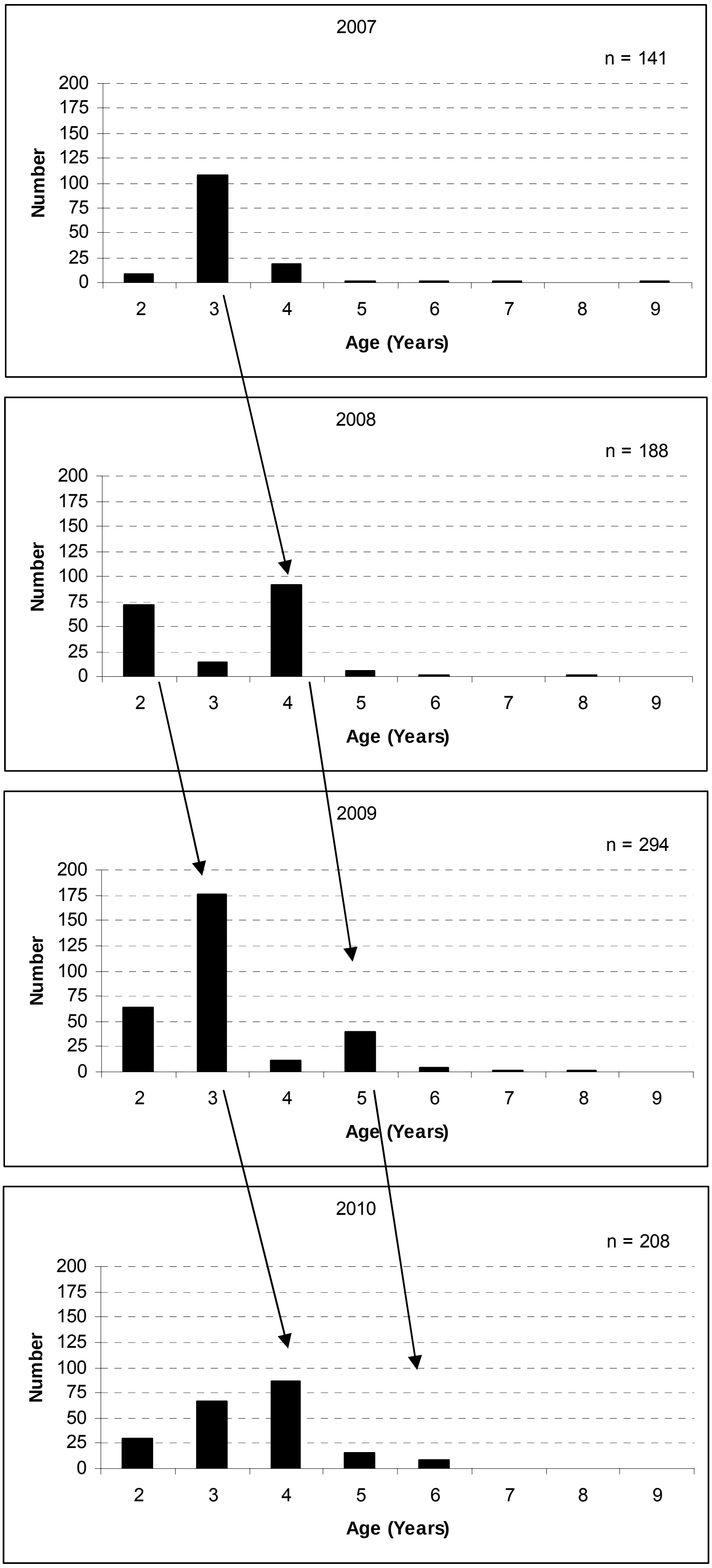

Figure 34. Annual age-structures for barramundi (600 to 800 mm TL) sampled from the Daly River estuary

7.2.4.1.3 Using residuals from the catch-curve regression

The standardised residuals from the catch-curve regressions give an indication of relative year-class strength (YCS). The barramundi year-classes 'born' in 2004 and 2006 had large, positive residuals, indicating 'strong' recruitment (Figure 35). None of the years sampled had large, negative residuals (i.e., <-0.5) indicative of 'weak' barramundi recruitment in the Daly River system. Year-classes born in 2001, 2002, 2003, 2007 and 2008 had small residuals (i.e., between +0.5 and -0.5) and thus could not be classified as either 'strong' or 'weak' (Figure 35). Barramundi YCS in the Daly River was only significantly correlated with water-year rain (Table 23).

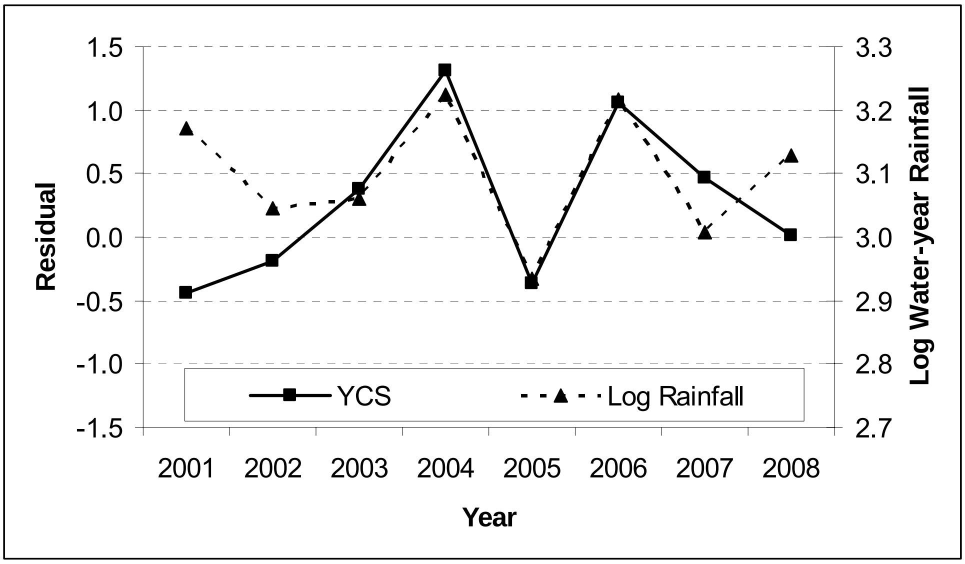

Figure 35. Residuals from catch-curve regressions of barramundi from the Daly River estuary against water-year rainfall at Katherine

Table 23. Correlation coefficients (r) between year-class strength (YCS) and rainfall variables for barramundi in the Daly River estuary

Season	**Barramundi YCS**
water-year rain	0.54*
spring rain	-0.19
summer rain	0.34
autumn rain	0.39
winter rain	0.04
dry rain	0.50
wet rain	0.49

*= P<0.05, ** = P<0.01, *** =P<0.001

All sub-sets general linear modelling identified only one 'best' model that explained ~84% of the variation in the abundance of age-classes of barramundi in the Daly River estuary, and included the variable water-year ($R^2 = 83.5$). This was a significant improvement ($P<0.001$) on the base model of age and sample year ($R^2 = 41.2$).

7.2.4.2 King threadfin

7.2.4.2.1 Length-frequency

A total of 534 king threadfin were aged, with 318 in the size range of 600 mm to 1100 mm total length (Table 24).

Table 24. Number (n) of king threadfin sampled from the Daly River estuary that were aged and used in the year-class strength analysis

Sample year	King threadfin (n)	
	Aged	Used in YCS analysis
2007	84	64
2008	166	105
2009	210	90
2010	74	59
Total	534	318

There is no minimum legal size limit for king threadfin in the Northern Territory. The catch of king threadfin from the Daly River ranged in age from one- to eight-years-old (Figure 36), with 91% of the catch aged between two- and five-years-old.

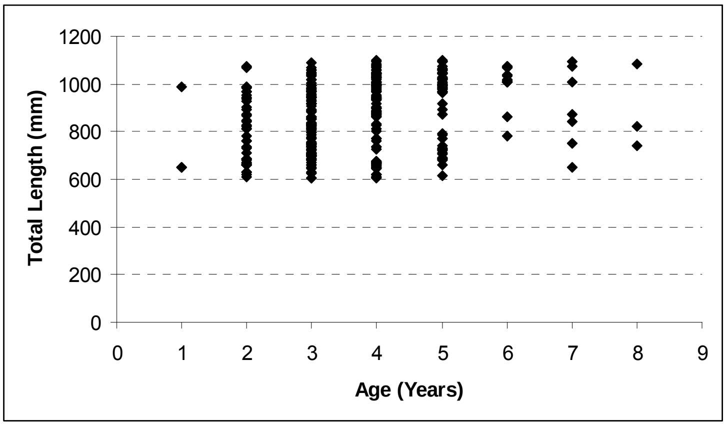

Figure 36. Length-at-age for king threadfin (>600 mm TL) sampled from the Daly River estuary

7.2.4.2.2 Age-structure

The age-structure of king threadfin in the Daly River estuary indicates that the fishery harvests depends on young fish, with the catch comprised mostly of fish less than five-years-old (Figure 37).

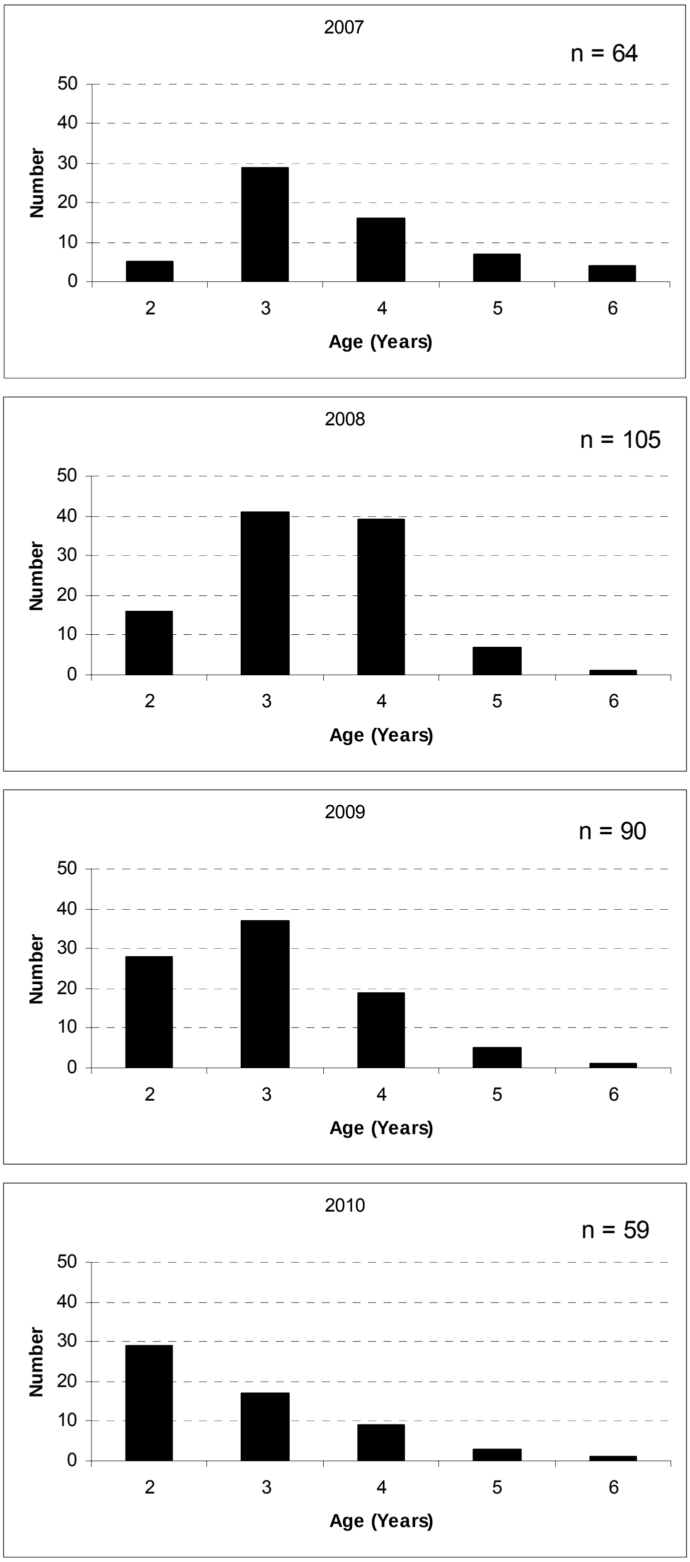

Figure 37. Annual age-structures for king threadfin (>600 mm TL) sampled from the Daly River estuary

The YCS of king threadfin in the Daly river estuary was not significantly correlated with any rainfall variables (Table 25) and as such, no general linear regressions models were explored.

Table 25. Correlation coefficients (r) between year-class strength (YCS) and rainfall variables for king threadfin in the Daly River estuary

Season	King threadfin YCS
water-year rain	0.19
spring rain	-0.25
summer rain	0.31
autumn rain	0.21
winter rain	-0.13
dry rain	0.15
wet rain	0.22

*= P<0.05, ** = P<0.01, *** =P<0.001

7.3 OTOLITH MICROCHEMISTRY

A total of 135 adult barramundi were examined for trace metals. Individuals were selected from year-classes that were born in a low flow year, an average flow year and a high flow year. There was a significant difference in the use of freshwater habitats by barramundi between the four study estuaries (Table 26).

Table 26. Movement of barramundi determined by otolith Sr/Ca ratios in four tropical river estuaries of northern Australia

Moved into fresh water	Mitchell River		Flinders River		Roper River			Daly River			
	Low flow	High flow	Low flow	High flow	High flow	Low flow	Avg. flow	Avg. flow	High flow	Low flow	High flow
	2005	2006	2005	2006	2004	2005	2006	2003	2004	2005	2006
Total	5	35	15	20	6	6	19	2	6	6	15
No	4	14	10	12	4	2	13	1	0	0	3
Yes	1	21	5	8	2	4	6	1	6	6	12

Barramundi from the Mitchell River estuary had the second highest overall use of freshwater (Table 26), with 22 out of the 40 examined (i.e., 55%) entering freshwater for some period of their life (i.e., >3 months). No barramundi born in 2005 (i.e., low flow) moved into freshwater habitats as 0+ or 1+ year-old individuals. The one individual born in 2005 that moved into freshwater did so as a 2+ year-old fish. Barramundi born in 2006 (i.e., high flow) showed greater freshwater use than the 2005 year-class, with 21 out of 35 (i.e., 60%) entering freshwater for some period of their life. Of a total of 21 initial freshwater movements, seven barramundi moved into freshwater as 0+ individuals, 12 as 1+ year-old individuals and two as 2+ year-old individuals (Table 27).

Barramundi from the Flinders River estuary entered freshwater habitats at a significantly lower rate than those of the Mitchell River estuary (Table 26), with only 13 out of a total of 45 examined (i.e., 37%) entering freshwater for a period of their life (i.e., >3 months). Of the barramundi born in 2005 (i.e., low flow), five out of the 15 examined (i.e., 30%) entered freshwater habitats; with no 0+ individuals moving, four individuals moving as 1+ year-old and one moving as a 2+year-old individual. Of the barramundi born in 2006 (i.e., high flow), eight out of 20 showed freshwater use (i.e., 40%); with five moving as 0+ individuals and three moving as 1+ year-old individuals (Table 27).

Twelve out of the 31 barramundi examined (i.e., 39%) from the Roper River estuary had entered freshwater (Table 26). Seventy five percent of barramundi (nine fish) from the Roper River estuary moved as 0+ individuals, with two moving as 1+ year-old individuals and one fish moving into freshwater for the first time as a 3+ year-old individual (Table 27).

Barramundi from the Daly River estuary had the highest level of freshwater use with 25 of the 29 fish examined (i.e., 86%) entering freshwater habitats for some period of their life (Table 26). Migration into freshwater was restricted to 0+ individuals in the Daly River; i.e., all fish that moved were within their first year-of-life (Table 27). This annual movement of the majority of 0+ individuals each year suggests that the Daly River barramundi population has continual access to freshwater habitats during their juvenile phase as a consequence of perennial flow of the Daly River.

Table 27. Percentage of initial movement of barramundi year-classes (YC) into freshwater in four of tropical river estuaries of northern Australia

System	Age Moved	% Moved 2003 YC	% Moved 2004 YC	% Moved 2005 YC	% Moved 2006 YC
Mitchell River	0+	-	-	0	33
	1+	-	-	0	57
	2+	-	-	100	10
Flinders River	0+	-	-	0	63
	1+	-	-	80	37
	2+	-	-	20	0
Roper River	0+	-	100	100	50
	1+	-	0	0	33
	2+	-	0	0	17
Daly River	0+	100	100	100	100
	1+	0	0	0	0
	2+	0	0	0	0

Generally, there were four patterns shown by barramundi that typified their access to freshwater across the study river systems. These were:

(i) Never entering freshwater (Figure 38a);
(ii) Initial moving from marine habitats to freshwater habitats, staying in freshwater for some years before returning to salt water (Figure 38g & h);
(iii) Moving once from salt to freshwater as 0+ and returning within a year (Figure 38c); and
(iv) Moving numerous times between salt and freshwater on: (a) an annual basis (Figure 38e & f) to (b) those that had just returned to the estuary where they were caught but did not show any salt water signal.

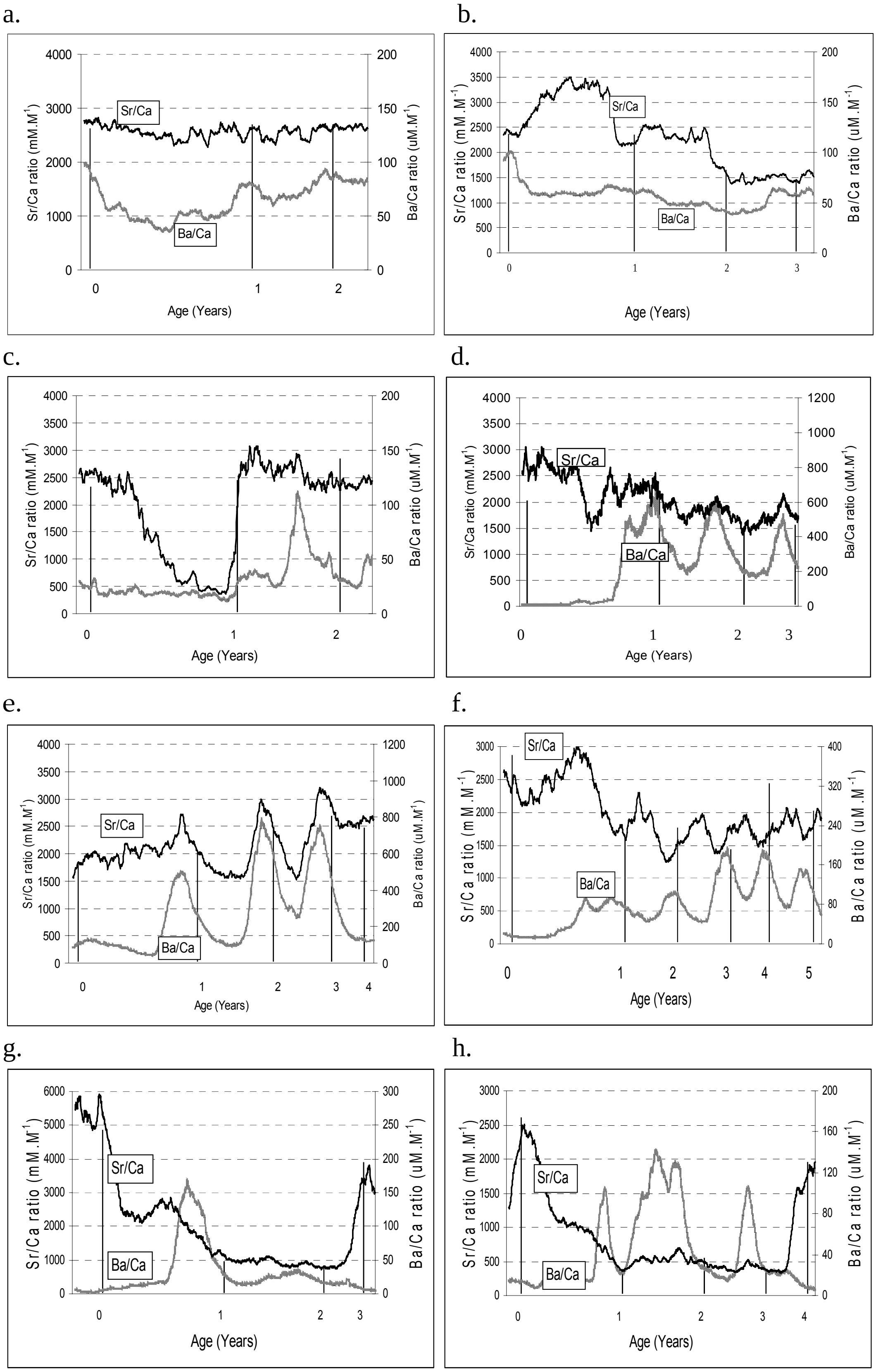

Figure 38. Examples of the Strontium/Calcium (Sr/Ca mM.M-1) and Barium/Calcium (Ba/Ca µM.M-1) ratios of individual barramundi sampled from the estuaries of the Mitchell (a & b), Flinders (c & d), Roper (e & f) and Daly (g & h) Rivers

8 DISCUSSION

Australia’s tropical river systems and their associated biota are driven by the hydrology of the monsoon season (Warfe *et al*. 2011). Each catchment has its’ own geomorphology, flow regime and associated habitats. The importance of river flow in these harsh environments through the inundation of wetlands and flood plains has been shown to influence the faunal communities of tropical rivers with high connectivity’s between marine, riverine and floodplain habitats (Jardine *et al*. 2011). Within this large scale variation, we have attempted to explore the drivers that support commercial, recreational and indigenous fisheries in tropical Australia.

8.1 AGE-STRUCTURES FROM COMMERCIAL CATCHES

Opportunistically sampling commercial and recreational catches of barramundi and king threadfin provided reasonable estimates of the age-structure of the populations of these species in tropical estuaries. This approach was cost and time efficient, and allowed project staff to build a strong rapport with local fishing industry and communities (including indigenous Australians). The value of this approach for tropical Australia has been recognised by the Long Term Monitoring Program of the Fisheries Queensland (DAFF), who have adopted an annual sampling program for barramundi based on this approach (i.e., via seafood processors and selected fishers). Information from the Queensland LTMP sampling program contributes to barramundi stock assessment. Despite myths about the difficulty of aging tropical species, the otoliths from barramundi and king threadfin from the tropical estuaries studied herein had clearly defined opaque and translucent bands (Figure 39a and 39b) and were aged with high repeatability. Known-age barramundi from other areas were used to validate our age estimates (Staunton-Smith *et al*. 2004).

Figure 39. Transverse sections of otoliths from a) barramundi and b) king threadfin sampled from the commercial catch of the Flinders River estuary

8.2 ESTIMATING YEAR-CLASS STRENGTH

By using the method of Maceina (1997) to estimate year-class strength (YCS), we objectively, quickly, and cheaply obtained information on large-scale variability in the recruitment of barramundi and king threadfin in four remote tropical estuaries of northern Australia. The success of the method, i.e. using otoliths to estimate age-structure and hindcast year-class strength was dependent on: (i) representatively sampling the population; (ii) confidently estimating the absolute age of individual fish (compared to estimating relative age) so that a birth-year could be assigned; and (iii) sequentially sampling the population for a number of years, with a required minimum of three years.

The ability to sample a species adequately is a potential problem when estimating relative rates of annual recruitment, especially if measuring the abundance of a single life history stage. The distribution of small and juvenile barramundi and king threadfin is not known for any of the study estuaries and as such would be difficult to sample representatively. In contrast, sampling the adult life history stage of barramundi and king threadfin in the estuary (e.g. from the commercial, recreational or indigenous catch) represented a convenient method for comparing the relative abundance of numerous year-classes (see Staunton-Smith *et al.* 2004).

8.3 CAUSE OF RELATIONSHIPS BETWEEN YCS AND FRESHWATER FLOW

In general, long-lived species, which have numerous age-classes in the population, are buffered against vast recruitment-based variation in stock size, unless there is a series of strong or weak year-classes (McGlennon *et al*. 2000). However, the large variability in YCS that we observed, and the persistence of strong and weak year-classes in barramundi and king threadfin populations over several consecutive years, suggests that recruitment variability has the potential to influence adult stock size in at least these species.

We would not expect barramundi and king threadfin to show the same patterns in their strength of recruitment (i.e., year-class strength), as barramundi are more tolerant of (and able to use) freshwater (habitats) whilst king threadfin do not tolerate (or use) zero salinity water (or habitats). However, we would expect some overlap in years of strong (or weak) recruitment as both species are carnivorous and would probably exploit any trophic blooms occurring in the estuary. Thus, although there may be some overlap in the causal mechanisms between year-class strength and freshwater flow for barramundi and king threadfin, we will consider each species separately.

In all of the tropical study estuaries, commercial catch was not significantly correlated with current water-year flow, indicating that flow and or rainfall was not increasing the catchability of barramundi or king threadfin. However, correlations between year-class strength and flow (or rainfall) lagged by one to five years suggested flow volume does influence barramundi recruitment and the subsequent size of the population. This relationship is further supported by evidence of flow related recruitment success when seasonal rainfalls are above average and extend beyond their normal range.

Freshwater flows may enhance the survival of young-of-the-year barramundi by: (a) enhancing the access of larvae, post-larvae and juvenile barramundi to suitable nursery habitats in the estuary, such as temporary supra-littoral pools; (b) enabling a proportion of juvenile barramundi to access freshwater habitats intermittently linked to the estuary; and (c) increasing the productivity of the estuary (i.e., increased prey species abundance), with increased growth rates of post-larval and very young barramundi increasing the number of individuals that survive the first year of life.

8.3.1 Refined concepts about barramundi

The significant correlations between rainfall and or flows and the year-class strength (YCS) of barramundi supports the hypothesis that flows affect the abundance and survival of very young barramundi (i.e., < 6 months old), which use estuaries during the spring and summer of their first year of life (Dunstan 1959; Russell and Garrett 1983, 1985; Davis 1985). Life history assessment identified four causal mechanisms by which the recruitment (of which YCS is an index) of barramundi could be related to freshwater flow. These were:

i) transporting eggs and larvae away from the estuary (negative effect);
ii) creating chemical signals for larvae to enter the estuary and locate nursery habitats (positive effect);
iii) enabling post-larvae and small juveniles to move into supra-littoral nursery habitats; and
iv) enabling large juveniles to migrate into freshwater habitats intermittently linked to the estuary.

Life history assessment also identified a casual mechanism affecting the productivity of the estuary, which through increased food availability, could improve the growth and survival of post-larvae, juveniles, adolescents and adults.

The above mechanisms are not mutually exclusive, and it is unlikely that they represent the only mechanisms by which freshwater flows affect the survival of juvenile barramundi. For example, YCS may be related to the size of the spawning population. This causal mechanism is based on increased egg-production and subsequent numbers of juvenile fish in years when floodwaters release land-locked fish, as proposed by Dunstan (1959). However, most fish migrating from freshwater habitats are likely to be males and there is no evidence to suggest that sufficient numbers of additional mature females arrive from freshwater habitats to greatly egg production above that generated from females already inhabiting the estuary and coastal foreshores.

Our results provide no evidence that freshwater flows transport the eggs and larvae of barramundi away from the estuary (i.e., mechanism (i) above). The remaining causal mechanisms relate to access or attraction to estuarine nursery habitats (i.e., mechanisms (ii) and (iii) above), access to freshwater habitats (i.e., mechanism (iv) above) and enhanced productivity (i.e., a trophic response) within the estuary. As the method reported herein is correlative, the following discussion is speculative and requires further investigation.

Freshwater flows may enhance the survival of barramundi during their first months of life, by enhancing the access of larvae, post-larvae and juveniles to suitable nursery habitats. The larvae and very young juveniles of barramundi have been observed in ephemeral supra-littoral nursery habitats in close proximity to spawning areas, such as coastal swamps and lagoons and supra-littoral pools on salt pans (Dunstan 1959; Moore 1982; Russell and Garrett 1983, 1985; Davis 1985; Griffin 1987). The spatial and temporal extent of many of these nursery habitats is affected by the amount of freshwater runoff, and access to and from them is dependent on seasonally high tides and or freshwater flows (Russell and Garrett 1983; Davis 1985; Griffin 1987). It is possible that high coastal rainfall and freshwater flows in these tropical rivers enhance survival of the early life history stages of barramundi by generating, and improving access (e.g. frequency, extent and duration of access routes) to supra-littoral nursery areas, extending the spatial or temporal extent of ephemeral nursery areas, increasing their productivity and carrying capacity (i.e., abundance of prey species), and or increasing their suitability in some other way (e.g. physico-chemical characteristics). However, otolith microchemistry indicates that barramundi are not using freshwater habitats until they are at least three-months-old and spring tides are probably more important in allowing juvenile barramundi (i.e., <50 mm TL) access to important supra-littoral nursery habitats (Russell and Garrett 1985). Movement into and out of supra-littoral habitats on each tide has been reported (Russell 1987).

Freshwater flows may enhance the survival of juvenile barramundi and the subsequent size of the adult population by enabling a proportion of juvenile barramundi to access freshwater habitats intermittently linked to the estuary. Migration of juvenile barramundi into upstream habitats typically occurs at the end of the wet season (Russell and Garrett 1983, 1985). Individual barramundi can complete their entire life-cycle in estuaries and coastal waters (Griffin 1987; Russell 1990), therefore it is not obligatory for barramundi to migrate to freshwater. Only a proportion of juvenile barramundi migrate upstream, and results from the current work show that this varies between river systems and between years within the same river system.

Freshwater flows may enhance the productivity of the estuary, with enhanced growth rates of post-larval and juvenile barramundi increasing the number of individuals that survive the first year of life. If this occurs, then it is productivity resulting from spring and summer freshwater flows that is important in driving the growth and survival of young-of-the-year barramundi. Tag-recapture data shows significant positive correlations between growth rates of juvenile and adolescent barramundi and the size and timing of freshwater flows (Robins *et al.* 2006). If these results hold true for post-larval and young-of-the year barramundi, then it is highly likely that year-class strength of barramundi is driven by the effects of freshwater flow on trophic productivity. There is probably a time lag between the occurrence of a freshwater flow and a bloom in trophic productivity of the estuary, especially at the trophic level of barramundi, which even as a juvenile is a higher order carnivore.

8.3.2 Refined concepts about king threadfin

Variation in catch and year-class strength (YCS), as an indicator of the overall recruitment and survival of juvenile king threadfin, was not explained by variations in the flow regimes across the four tropical Australian estuaries studies herein. This was probably a result of king threadfin not accessing freshwater habitats and avoiding waters of zero salinity. However, it is likely that king threadfin use the salinity gradient in estuaries created by freshwater flows. In contrast to the results for the tropical estuaries, king threadfin in the Fitzroy River estuary show consistent and positive relationships with fresh water flow and coastal rainfall during spring and summer (Halliday *et al*. 2008). The differences in response of king threadfin between the tropics and the sub-tropics might be explained by the lack of variability in the monsoonal nature of flows in tropical estuaries. In the tropical estuaries studied, it is unusual for the rainy season to completely fail. This is unlike the Fitzroy River estuary on the Queensland east coast that has large variations on a decadal scale in the amount of flow that reaches the estuary.

8.4 OTOLITH MICROCHEMISTRY

8.4.1 Validation of metal/Ca ratios

Previous work on barramundi otolith trace metal/Ca ratios has successfully identified fish habitat histories (Milton *et al*. 2008). Only Sr/Ca ratios showed a pattern consistent with that expected i.e., a pattern of higher Sr/Ca ratios in estuarine and marine waters (Milton and Chenery 2001).

Most studies of fish migration with otolith chemistry have relied on Sr/Ca ratios. However, recent studies have also found that Ba/Ca ratios may be a sensitive indicator of freshwater residency (Elsdon and Gillanders 2005; Martin and Thorrold 2005). Ba/Ca ratios in barramundi otoliths reflect the Ba/Ca ratios of the water in which a fish has been resident (Milton and Chenery 2001). Our results suggest that the often high values and large variation in Ba/Ca ratios in the otoliths of barramundi when in the estuary may be related to the location of individual fish relative to the estuarine Ba maxima (Coffey *et al.* 1997; Colbert and McManus 2005). This was shown in a number of fish examined in the current study that had not travelled into freshwater, but that showed considerable variation in their Ba/Ca ratios while remaining in salt water.

Most fish migration studies usually examine annual or semi-annual changes in otolith chemistry (Secor and Rooker 2000). The variations in otolith chemistry at this scale are not influenced by temperature. This was despite temperature having a strong influence on the length of the growing season of barramundi (Robins *et al*. 2006). The finer scale correlations between temperature and otolith Sr/Ca ratios are likely to magnify the effects on otolith Sr/Ca of fish movement into higher salinity water during summer spawnings.

There was considerable fine-scale variation in otolith Ba/Ca ratios in barramundi otoliths that were significantly correlated with the yearly monsoon event.

8.5 ROLE OF FRESHWATER FLOWS

We found that most barramundi that migrate into freshwater do so during their first year of life. This appears to be mostly after three months of age and these fish have all migrated into the estuary by sexual maturity at two- to four-years-old.

Results from the trace metal/Ca ratio analysis demonstrated that barramundi in tropical estuarine habitats use areas of marine salinity during their larval and early juvenile phases. Of the seven mechanisms proposed as influences of freshwater flows on barramundi populations see section 3.1.1), our results supports that it is the connectivity to supra-littoral marine habitats and increased productivity derived from freshwater floodplains that provides conditions favourable to increased juvenile survival. These flooded conditions have been shown to support older barramundi by providing large levels of food subsidies to marine environments (Jardine *et al*. 2011). There is no indication that juvenile barramundi use freshwater floodplain habitats in the first few months of their lives. Habitats that support increased juvenile survival might include the extensive areas of supra-littoral pools and saltpans in the lower estuaries directly behind the mangrove fringe (Moore 1982; Russell and Garrett 1983, 1985). These habitats fill during the large spring tides that occur from October to February and coincide with the spawning season. Barramundi spawning is known to coincide with periods of maximum tidal height (Moore 1982). Thus, these habitats would be saline during early growth, except following a large annual flood or heavy coastal rains. At that time, the whole lower coastal plain of these tropical rivers can become inundated with freshwater and many barramundi would be able to redistribute to more permanent freshwater habitats.

Staunton-Smith *et al.* (2004) hypothesized three possible mechanisms to explain why barramundi year-class strength was correlated with river flows and coastal rainfall. Firstly, by increasing the spawning population with migrants from land-locked freshwaters. Secondly, by increased survival of larvae and early juveniles through improved access to, or conditions in inundated supra-littoral nursery habitats. And lastly, by increased survival (and growth) of older juveniles and sub-adults by enabling them to access more productive permanent freshwater habitats (Salen-Picard *et al.* 2002). Our results, and that of Milton and Chenery (2005), suggest that barramundi do not access freshwater during their larval and early juvenile stages. This supports the third hypothesis that access to more permanent freshwater lagoons by older juveniles is contributing to increased survival and growth of barramundi during years of high flow in tropical river systems of northern Australia.

The return migration of barramundi from more permanent local creeks into the estuary probably occurs during annual floods when fish activity greatly increases (Dunstan 1959) and when permanent lagoons reconnect to the main river. Barramundi that have spent time in these freshwater systems were significantly more likely to be fast-growing than fish that had remained in the estuary throughout their life. Thus, barramundi that mature in freshwater appear to take advantage of the higher productivity in these ephemeral systems (Gillanders and Kingsford 2002).

Barramundi born during years with above average floods and coastal rainfall had better survival than fish from poorer years (Staunton-Smith *et al*. 2004). Robins *et al.* (2006) have taken this further and shown that increased river flow also increases barramundi growth rates. Our study supports these findings and suggests improved access of juveniles to productive coastal freshwater habitats during more substantial flood years may be the mechanism that provides increased growth rates associated with higher flows as reported by Robins *et al.* (2006).

In order to better manage the scarce freshwater resources in tropical Australia and provide advice on the optimal freshwater flows (including environmental allocations) to maintain estuarine fish populations, we need a better understanding of the relationship between flood characteristics (e.g. timing, magnitude and duration) and freshwater habitat use. We found that barramundi moved into freshwater habitats during most years and this did not appear to be correlated with flow volume. In order to estimate the freshwater flow that is associated with access to freshwater habitats by juvenile barramundi, a larger, more random sub-sampling of the entire barramundi population across years and river systems would be required, preferably with a greater contrast in flood conditions.

8.6 IMPLICATIONS FOR FISHERIES PRODUCTION

Fisheries catch (commercial, recreational and indigenous) is affected by the cumulative history of everything that has happened to all year-classes of the fished stock plus factors that effect fisheries, such as gear selectivity, effort, and management restrictions. The results of the present study (i.e., variation in YCS related to freshwater flow) have implications for the fisheries management of barramundi and king threadfin. In particular, our results suggest that stock assessments should consider the impacts of freshwater flows and or coastal rainfall on the annual recruitment of barramundi and king threadfin. Furthermore, the catchment scale effects of freshwater flows on recruitment provide further evidence of the need for regional stock assessment.

8.7 IMPLICATIONS FOR WATER MANAGEMENT

For barramundi fisheries in tropical Australia, summer and autumn flows are important in determining the size of year-classes of fish, which subsequently mature and enter the fishery. Currently, water infrastructure in tropical Australia (west of Cape York) is minimal and river flows are relatively unimpeded. It is important that natural resource managers, politicians and the general public are made to realise that freshwater flowing to estuaries is not wasted, but rather supports the maintenance of estuarine fish populations.

Further research and numerical modelling is required before a robust estimate can be made of the extent to which the quantity, duration or frequency (e.g. number per decade) of freshwater flows could be modified and what effects these modified flows would subsequently have on estuarine fish populations (e.g. Tanimoto in press). The aim of such work would be to achieve water efficiencies in environmental flow allocations i.e., how to achieve the same effect with less water.

9 BENEFITS AND ADOPTION

Estuarine and near-shore finfish fisheries are iconic in the Gulf of Carpentaria and Top End of Australia. They support several fishing sectors (i.e., commercial, charter-boat and recreational fishing, and associated fishing-related tourism) and a significant indigenous harvest sector. Finfish have major economic, social and cultural values to the communities of the northern Australia. The current study has benefited fishing related industries, enabled a whole-of-ecosystem approach to understanding river ecosystems including estuarine reaches of rivers; assisted in valuations of the ecological assets of estuarine reaches and freshwater related processes; and supported sustainable water and fisheries resource management in the northern Australia.

Researchers have provided information on the links between freshwater flow into estuaries and the productivity of two important species inhabiting this environment to the Daly River Management Advisory Committee, Northern Territory Government, Australian Federal Government, Gulf of Carpentaria Commercial Fishermen's Association, Northern Territory Seafood Council, Northern Gulf Natural Resource Group and several indigenous forums. Researchers have also had input in several leading scientific papers on broader ecosystems of Australian tropical rivers addressing the structure and function of these river systems as well as showing the importance of connectivity between rivers and their associated floodplain in maintaining fisheries productivity.

10 FURTHER DEVELOPMENT

Activities and other steps that may be undertaken to further develop or disseminate the results of this research include:

- Detailed quantitative modelling of barramundi stocks in northern Australia (as per Tanimoto *et al.* in press) to integrate the impact of environmental drivers and regional life history traits (e.g. narrow age-structures) on barramundi productivity; and
- Quantifying the amount of water required to get maximum productivity so additional water during high rainfall years can be allocated to other users.;

11 PLANNED OUTCOMES

The project has clearly shown that there are substantial benefits to fisheries related industries through increased production from allowing freshwater flows to reach the estuary. These can be viewed as: increased catch from the delivery of mature fish from freshwater reaches to estuarine sections; facilitating movement of newly recruited fish from marine spawning areas to estuarine and freshwater habitats; and increasing recruitment of fisheries species by increased survival of young-of-the-year, probably through increased growth rates in the first months of life.

By using estuarine fisheries as an integral part of a whole-of-ecosystem approach to understanding river ecosystems, the outcomes of this project and others within the Tropical Rivers and Coastal Knowledge consortium have elucidated the connections between rivers, floodplains and estuaries habitats through food webs. In understanding the sources and mechanisms of river and estuarine productivity, this project as part of TRaCK has demonstrated the important roles of each of these habitats and the connectivity between them in supporting healthy productive estuaries (see Jardine *et al.* 2011; Warfe *et al.* 2011). Further to this, barramundi from the Mitchell and Flinders Rivers were shown to have low levels of mercury accumulated in their flesh, a potential threat caused by historic gold mining within the catchments (Jardine *et al.* 2011).

The economic values of fisheries production is one measure by which ecological values can be measured. Other measures by which ecological assets can be valued include the use of aquatic species as food by indigenous communities located on rivers and associated floodplains. Information from this project was used by other TRaCK projects to identify the economic benefits to these communities by valuing all species collected in dollars terms. This has shown that estuarine fish production is of much lower value to these communities than that of freshwater turtles and water lilies, which rely on the same habitats and flood connectivity for production (see Finn and Jackson 2011, Stoeckl *et al.* 2011).

The work presented here, in conjunction with results from the TRaCK consortium have assisted in developing monitoring programs and water management rules for water resource plans with respect to maintaining river and estuarine health as well as providing a framework for assessing the need for freshwater to flow to tropical estuaries. These results have been received with enthusiasm by indigenous communities, commercial and recreational fishing communities, water resources managers and fisheries managers.

12 CONCLUSION

Results of the current study provide quantitative evidence that freshwater flows to estuaries are crucial in supporting barramundi productivity. This is principally through the positive effect that increased flow has on recruitment (i.e., number of fish surviving the 1st year of life). As such, freshwater water flowing to estuaries is not wasted. Surprisingly, correlations were not detected between catch (adjusted for effort) and current water-year flow, accept for the Daly River. The concentrating effect that has been proposed as a mechanism for increased catches during years of high flow (i.e., fish being pushed or stimulated downstream to the estuaries) was not apparent in three of the four rivers studies. This may be a consequence of a limited and varying proportion of fish using freshwater habitats during their life cycle.

Barramundi productivity appears to be increased by high flows in previous years that have allowed increased juvenile survival. The mechanisms that allow higher survival may be directly related to increased productivity from the flood plains providing more food to juveniles. Otolith microchemistry demonstrated clearly that juvenile barramundi (i.e., <3 months) were not using the freshwater floodplains as a refuge. All barramundi examined for otolith microchemistry remained in salt water for at least the first three months of their life. Increased flow may provide ‘floodplain’ like habitat in the form of inundated salt pans and supra-littoral fringes that has lowered salinity but is not freshwater.

While the pattern of juvenile habitat usage was consistent, otolith microchemistry showed varying degrees of freshwater habitat use by different barramundi stocks. Populations associated with the perennially flowing water (e.g. the Daly River) showed the highest rate of freshwater habitat use; with ~ 86% of fish sampled having spent time in freshwater. Between 37% and 55% of barramundi sampled from the Roper, Flinders and Mitchell River estuaries had used freshwater habitats. In the majority of systems in the current study, the use of freshwater habitats varies temporally and is probably opportunistic occurring when freshwater connections permit and possibly when prey items move into these areas.

King threadfin populations showed no correlation with flow for either catch or year-class strength. It appears that the differing biology of this species and its preference for saline water results in less obvious relationships between flow and population productivity, particularly in tropical northern Australia.

Understanding the role of freshwater flow on fisheries species and their productivity (e.g. catch) has important implications for water and fisheries management. During extended low flow decades (e.g. 1960’s, 1980’s and 2000’s), the size of estuarine fish populations are probably reduced as a consequence of successive years of low recruitment. During such times, fisheries populations are likely to be at greater risk from fishing pressure, water extraction and other anthropogenic impacts. During extended high flow years, estuarine fish populations probably increase in size and are likely to be at lower risk of over-fishing and water extraction may have lesser impacts, although this is unquantified. The most critical period to ensure freshwater flows to estuaries occur is probably during and just after extended dry periods. Only through greater quantification of the key aspects of freshwater flows and subsequent effects on estuarine fisheries, will we be able to sustainably manage water and fisheries resources, so that the maximum amount of water is available for human use, whilst minimizing impacts on the environment.

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APPENDIX 1: INTELLECTUAL PROPERTY

All intellectual property arising from this research project has been made publicly available.

APPENDIX 2: STAFF

Ian Halliday	Agri-Science Queensland, DAFF
Julie Robins	Agri-Science Queensland, DAFF
Michelle Sellin	Agri-Science Queensland, DAFF
Mark McLennan	Agri-Science Queensland, DAFF
Thor Saunders	DoR Fisheries, NT
Quentin Allsop	DoR Fisheries, NT
Poncie Kurnoth	DoR Fisheries, NT

APPENDIX 3: COMMUNICATION

Schedule 3, special condition 3: Presentations to and engagement with appropriate water management forums and fisheries management agencies.

Oral presentations

2007

- I. Halliday - Queensland Water Policy and Planning Unit, DERM, November 2007
- I. Halliday - National Estuaries Network, November 2007

2008

- I. Halliday - Kowanyama land council office staff and rangers, October 2008
- I. Halliday - Gulf Fishermen's Association Inc. AGM, Karumba, October 2008
- I. Halliday - Indigenous Engagement Forum TRaCK and NAILSMA, Mt Carbine, November 2008, one of several TRaCK presentations

2009

- I. Halliday - Southern Fisheries Centre, DAFF Brisbane, September 2009.
- I. Halliday - Gulf of Carpentaria Commercial Fishermen Inc. AGM, Karumba, September 2009 General project update
- I.Halliday - Northern Gulf Natural Resource Management Group Mareeba, October 2009. "Flow impacts on tropical estuarine finfish"
- I. Halliday - Mitchell River Traditional Custodian Advisory Group Cairns, November 2009. "Flow impacts on tropical estuarine finfish"
- I.Halliday - Daly River Management Advisory Committee, December 2009
- I. Halliday - Mitchell River Watershed Management group
- I. Halliday - Riversymposium Conference, Brisbane, September 2009. "The significance of water flows to estuaries"

2010

- I.Halliday - Australian Rivers Institute, Griffith University, Gold Coast Campus, March 2010 Campus "Wasted or not? It's a matter of perspective"
- I. Halliday – Water assessment and management planning group, DERM, July 2010
- I. Halliday - Australian Society of Fish Biology, Melbourne, July 2010 "Wasted or Not?"
- I. Halliday - Mitchell River Traditional Custodian Advisory Group, Kondaparinga, August 2010 "Flow impacts on tropical estuarine finfish"
- I. Halliday - Gulf of Carpentaria Commercial Fishermen Inc. AGM, Karumba, September 2010 General Project update
- I. Halliday - TRaCK annual meeting, October 2010
- I. Halliday - Northern Gulf Natural Resource Management Group, Karumba, November 2010 "Flow impacts on tropical estuarine finfish"
- T. Saunders - NT Seafood Industry Council, October 2010

Written material

- September 2009. Project media release. Appeared in the Courier Mail and the Mackay Mercury on the 21/09/2009 and the 2009 summer edition of Farm Weekly, a Fairfax digital press
- November 2009. TRaCK Fact sheet: Foodwebs and Biodiversity, Estuarine Fish, Flow impacts on estuarine finfish fisheries of the Gulf of Carpentaria http://www.track.gov.au/sites/track.boab.info/files/uploads/TRaCK_Foodwebs_Project5_6_web.pdf [accessed 7th March 2012]
- July 2010. Newsletter article. Floods, fish and water flows http://www.track.gov.au/sites/track.boab.info/files/uploads/OnTRaCK_Issue4.pdf [accessed 7th March 2012]
- November 2010. Magazine article. T. Jardine, B. Pusey and I. Hallliday. “Big Floods = Big Barra”. Australasian Science (2010). 31, 28-29 http://www.australasianscience.com.au/article/issue-november-2010/big-floods-big-barras.html [accessed 7th March 2012]