# Evaluating the environmental drivers of mud crab (*Scylla serrata*) catches in Australia

## Final Report
## FRDC Project 2008/012

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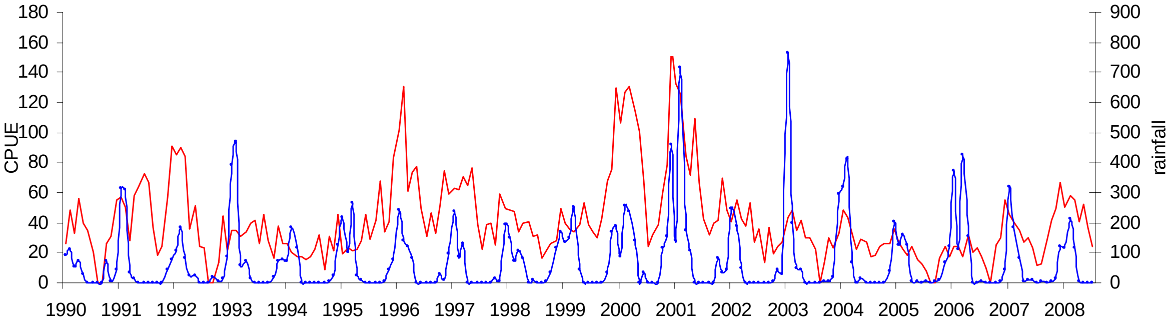

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# Table of Contents

## List of Tables

## List of Figures

# 2008/012 Evaluating the environmental drivers of mud crab (*Scylla serrata*) catches in Australia

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## Objectives

1. Determine the links between selected environmental factors and mud crab (*Scylla serrata*) catches in representative areas within the species' range in Australia
2. Document possible time lags between environmental phenomena and mud crab catches
3. Develop predictive models for Australian mud crab fisheries based on the information gathered from Objectives 1 and 2

# Non-Technical Summary

**Outcomes Achieved to Date:**

Mud crabs are a highly valuable commodity harvested in four Australian jurisdictions. The fisheries they support are small to medium scale and prone to variation in catch rates. The degree of variation in catch rate can exceed a factor of eight in Northern Australia and is thought to be driven by climate parameters. Such fluctuations may increase in regularity and/or magnitude in future due to climate change and its associated impacts.

This work documents the links between environmental drivers (particularly temperature and rainfall) and mud crab catches in representative areas throughout Australia. A conceptual model was developed to improve our understanding of the relationship between mud crab catches and environmental drivers. Time lags related to the mud crab's life cycle were described and predictive models for domestic mud crab fisheries developed. Regional differences between river systems have been identified and rivers of similar catch and environmental characteristics grouped.

The information presented here enables the prediction of 30-50% of annual mud crab catches. The findings can assist fishery managers in developing regional management plans for mud crabs and apply protective measures to the resource when necessary. The mud crab industry, and in particular mud crab fishers, can use the information herein to predict and then adjust catches to influence the market price of mud crabs and reduce their operational costs.

Both the market demand and catch rate of mud crabs have increased substantially over the past decade but there has also been large variations in catch, particularly in northern Australia in the Gulf of Carpentaria and the Northern Territory. Fluctuations in catch rates greater than a factor of eight were thought to be driven by climate parameters and are likely to increase further with climate change. Such variations may pose a challenge to the viability of the fishery. In this study, we analysed the relationship between physical environmental drivers and mud crab catches for 52 river or lake systems in New South Wales, Queensland and the Northern Territory, as well as examining Western Australia's developing mud crab fisheries, via trends and anecdotal reports. The time series used spanned up to 24 years and constituted a total catch of 20,815t.

The data were sourced from monthly logbook returns submitted by commercial mud crab fishers to the New South Wales Department of Primary Industry, Fisheries section (NSW Industry & Investment), the Queensland Department of Employment, Economic Development and Innovation (QLD DEEDI), the Northern Territory Department of Resources, Fisheries section (NT Fisheries) and Western Australian Fisheries (WA Fisheries). The investigations concentrated on several regions, namely: Northern New South Wales, central Queensland, north-east Queensland, western Cape York, the Gulf of Carpentaria, Van Diemen Gulf and the Joseph Bonaparte Gulf/Kimberley coast. A classification system to select river systems for the analyses was established based on the highest catches, consistency of catch data, and a representative number of systems for each geographic region. The catch data were temporally matched and compared with available environmental records (i.e. river flow, rainfall, sea surface temperature, and Southern Oscillation Index) for the most productive river systems for each state. The strength of the relationship was then quantified through statistical analysis. Mud crab catch data were compared between regions and jurisdictions and prepared for statistical analyses. Multiple regressions, non-metric multi-dimensional scaling (nMDS) and correlation analyses were conducted to detect patterns and relationships. Catch data were adjusted for effort using days fished and also adjusted using unstandardised residuals from a regression model based on log transformed catch and effort (days and pots or boats). We also investigated time lags between environmental events and mud crab catch, and the influence of extreme weather.

We identified rainfall and temperature as the most important potential environmental drivers affecting mud crab catch throughout Australia and were able to establish the extent to which environmental factors correlate with variability of mud crab catch. A major outcome of this work was the development of predictive linear models that can be incorporated into future, more complex models for assisting with forecasting Australian mud crab catches in the face of Climate Change.

The Southern Oscillation Index (SOI) was identified as an influential factor for mud crab catches throughout northern Australia. Between 30 and 40% of the catch variability can be explained by La Niña phases which are associated with increased rainfall and higher temperatures over large parts of northern Australia. For Northern Territory, a strong relationship was identified between annual maximum SOI values (indicating a strong monsoon) and catch adjusted for effort. A regression model that included a measure of annual maximum SOI values explained 30-40 % of the variance in catch. Temperature was found to be a less important driver for annual and seasoned mud crab catches in northern Australia, but the link between mud crab catches and environmental flow (with either a six month or one year lag) was particularly strong in the same region.

In Queensland, the strength and type of the relationship between temperature, rainfall and flow varied between regions and river systems examined. The majority of river systems showed a strong positive relationship with SOI or average catchment rainfall for annual data time configurations, such as the Burdekin and Flinders Rivers, whereas some systems had no relationship with any of the selected environmental drivers. Meta-analyses revealed a general grouping of the selected systems into three major regions: southeast Queensland, central Queensland and northern Queensland, with some overlap between the regions.

Temperature was the most important driver of mud crab catches explaining between 30-50% of seasonal and monthly catch variability in NSW. Stepwise multiple regression showed that temperature and rainfall together explained up to 70% of catch variability in some New South Wales river systems. The river systems were grouped into the northern and central bioregions based on catch and environmental variables.

Analyses of reports from fishers in Western Australia also suggested that periods of good rainfall enhanced the concurrent catch. However, statistical analyses of available data sets were not possible due to the low catch rates over time.

We established an overview of river systems with the highest mud crab catches in Australia and demonstrated selected environmental drivers explained between 20-70% of the catch variation that existed between river systems during the observed periods.

Our outputs suggest adjustments to current management policies: Management of this fishery should include regional characteristics of the river systems such as size and flow volume, and incorporate the source of changes in stock abundance that may result from predicted changes in climatic conditions, to enhance the positive effects of climate change and, where possible, mitigate any negative effects that may arise from variations in temperature and rainfall that may be induced by this phenomenon.

**KEYWORDS: mud crab catch, environmental drivers, linear model, SOI, rainfall, SST**

## Acknowledgements

This work could not have taken place without the support of the Fisheries Research Development Cooperation (FRDC), NT Fisheries, NSW DPI Fisheries, QLD DEEDI and WA Fisheries. Other agencies like the Bureau of Meteorology (BOM) and the New South Wales, Queensland, and Northern Territory Department for Natural Resources (DNR) also provided valuable data on rainfall and freshwater flow. In addition, we recognise and thank commercial fishers Tam Van Nguyen and Paul Reed from the Roper River, Tian and Greg Quayle from the McArthur River, Goldie Tybell from the Finniss River, and Neil and Yvonne Bradley from the Wearyan River for their hospitality and information on mud crab fisheries in the Northern Territory. We also wish to express our appreciation to Brooke Hay from Western Australia Fisheries for compiling mud crab catch data, Chris Errity from NT Fisheries for valuable company in the field, Doug Neville from the NT Mud Crab Licencee Committee for his personal interest in this study and the valuable information he provided about the Australian mud crab industry, and Chris Calogeras of C-AID Consultants for his interest and information on the Northern Territory mud crab fishery. We like to thank Dr Peter Bayliss from CSIRO for sharing his knowledge about Northern Australia's river systems and ,last but not least, sincere thanks to Jordyn de Boer and Julie Hunter from Griffith University for their contributions to the preparation of this report.

# 1. Introduction

## 1.1 Background

The years 2000 and 2001 saw record mud crab (*Scylla serrata*) catches throughout its range in Australia, presumably due to a combination of high fishing effort and favourable recruitment in the preceding years. This peak was followed by a significant decrease in catch in all relevant jurisdictions, with the magnitude of the decline being greatest in the Northern Territory. The widespread nature of this phenomenon is thought to be due to one or more environmental drivers, such as rainfall/river flow or water temperature. The dramatic reduction in catch caused financial hardship for crabbers, processors and allied industries. Crabbers that entered into expensive multi-year leases towards the end of the "boom" were particularly disadvantaged. There were also heated sectoral disputes over the cause of the decline in crab numbers. Understandably, the commercial crabbing industry wishes to avoid this situation in the future. Predictive catch models for mud crabs were one key research need identified by industry at the (FRDC funded) 2007 National Mud Crab Fishery Research Strategy Workshop (FRDC report 2007/026). Driven by that initiative, this study will examine the relationship of environmental variables with mud crab catches and develop such models.

## 1.2 Need

Mud crabs (*Scylla serrata*) are a fast growing, short-lived species whose abundance appears to be strongly linked to the prevailing environmental conditions during their life history. Mud crab fisheries are typically subject to high fishing mortality rates, with little carryover of stock from one cohort to the next. The combination of these factors can result in extreme inter-annual variation in mud crab catches. Such variability may be observed across several jurisdictions, and can produce uncertainty for both fishers and resource managers alike, while hindering further investment in the mud crab fishing industry. A better understanding of the environmental processes that drive mud crab catches will enable the development of models that could remove some of this uncertainty. Crab fishers need some forecasting ability not only to predict catch, but also to assist in their business planning. While market prices are often high when supply is low, this is not always the case. Therefore, fishers operate in an industry with high uncertainty and variable economic returns. One of the challenges faced by fishers in the mud crab fishery is maintaining economic viability during low abundance years. This is exacerbated by the fact that fishers must make a significant investment in license lease fees and remote area establishment expenses without certainty about future catch volumes or market prices (Grubert *et al.*, 2008). For example, crabbers entering into expensive two- or three-year lease agreements when mud crabs are abundant may experience financial difficulties if crab (through natural circumstances or otherwise) abundance drops suddenly. This study will examine potential environmental driver-catch cause and effect relationships at the regional, jurisdictional and national levels and take into account the various environmental/meteorological conditions operating at these different scales to improve the understanding of mud crab catch fluctuation.

Figure 1. Douglas Neville from NT Mud Crab Licencee Committee pointing out high market prices of mud crabs in a restaurant.

# 2. Literature Review

## 2.1 Global and Australian Mud Crab Fisheries

Mud crabs of the genus *Scylla* are considered a delicacy throughout the Asia-Pacific region, representing a valuable fishery resource for areas in which they are distributed. Fisheries currently exist in South Africa, Pakistan, Japan, Taiwan, Philippines, Malaysia and Australia (Knuckey, 1999). Though not formally reported or reviewed, significant fisheries also exist in Vietnam, China, and other parts of Southeast Asia. Mud crabs are an important component of small-scale coastal fisheries, particularly in places like tropical and subtropical Asia, where their capture generates significant revenue for coastal communities (Le Vay *et al.*, 2001). Due to its fast growth, large size and extended distribution, *Scylla serrata* is generally favoured by fisheries and has recently become a target species for aquaculture. Mud crab farming is largely based on the capture and fattening of wild caught juvenile crabs, as viable and economically feasible broodstock sources have not yet been established (Nurdiani and Zeng, 2007). A combination of over-fishing and habitat loss has resulted in both reduced landing rates and smaller mean capture size (Le Vay *et al.*, 2001). In Asia, mud crab populations are typically associated with mangroves, and may act as a useful indicator of mangrove habitat condition. Although mud crabs are not considered to be a keystone species in their natural environment, they make a significant contribution to coastal ecosystem processes. For example, their burrowing and foraging habits aid the process of bioturbation and various ontogenetic stages also provide an important source of nutrition for planktivores, macro-crustaceans, teleosts fish, sharks, rays, and birds (Webley, 2009). In Australia, mud crabs are widely used for commercial and recreational fisheries as well as for indigenous purposes including subsistence and artefacts.

Figure 2. Standard tray used by commercial mud crabbers for distribution to wholesalers. Crabs are tied up to avoid higher mortality.

Queensland, with 431 licences accessing the fishery, has the highest catch weight of all Australian jurisdictions. The combined harvest from all sectors according to the 2009 Annual Status Report was approximately 1676 t. Of this, 1025 t were harvested commercially, generating a Commercial Gross Value of Production of approximately AUD$16.4 million (Qld. DPI, 2009). Harvest peaks during the warmer months of February and March, and revenue is generated from local, interstate and export markets (Shelley, 2008). Recreational catches also represent a valuable component of Australia’s mud crab fishery, contributing to approximately 38% of the total fishery harvest (or 638 t) in 2005 (Qld. DPI, 2009).

The mud crab fishery in the Northern Territory has a large wild commercial harvest, extending to areas of adjacent commonwealth waters. Annual catches range between 400 t and 550 t, with the giant mud crab, *S. serrata,* representing 99% of catches and the brown mud crab *S. olivacea* playing a minor role. The estimated value of this catch is AUD $13 million (Environment Australia, 2002). The highest catches come from river systems in the Gulf of Carpentaria. Most of the catch is for live export to large Australian cities like Sydney and Melbourne.

The New South Wales mud crab fishery has annual catches between 100 and 120 t (NSW DPI, 2008). Recreational catches are estimated at 30 – 60 t per year (Henry and Lyle, 2003). Catches are relatively small (10-20%) compared to Queensland and the Northern Territory but have been consistent over the past 23 years. The catch consists of *S. serrata* that are usually smaller in size and weight than those from the tropical regions.

In Western Australia, the mud crab fishery is currently relatively small and still developing, with a total annual commercial catch of only 6.4 t in 2008. The industry is in an exploratory stage, with a small number of commercial exemption holders in addition to indigenous community exemption holders. However, mud crabs remain significant to the recreational and indigenous fishing sectors, although little data are available on recreational catch. The catch consists of *S. serrata* and *S. olivacea* in an unknown ratio. An overview of the status of the mud crab fisheries in Australia is provided in Table 1.

Table 1. Overview of mud crab fisheries in Australian jurisdictions based on 2008 catch, effort and licences and status (Brown, 2010).

| **Type** | **Queensland** | **Northern Territory** | **New South Wales** | **Western Australia** |
|---|---|---|---|---|
| Recreational bag limit (per person) | 10 | 10 | 5 | 5 |
| Commercial fishing units/licences current | 431 | 49 | 217 | 6 |
| Commercial catch 2008 (t) | 1025 | 412 | 107 | 6.4 |
| Commercial effort 2008 (fishing days) | 38000 | 11122 | 15000 | 323 |
| Commercial CPUE 2008 (kg/fishing day) | 27 | 37 | 7 | 20 |
| Est. recreational annual catch (t) | 600-800 | ~135 | 30-60 | 21 est. |
| Monitoring arrangements | Compulsory daily logs; annual fishery independent survey; limited 'research' logs | Demographic data collected from comm. samples monthly at Darwin | Port-based monitoring of comm. catch demographics and catch rates | Logbooks; No regular monitoring programme |

## 2.2 Global Distribution of Mud Crabs

Mud crabs of the genus *Scylla* commonly occur throughout tropical to warm temperate areas of the west Pacific and Indian Oceans (Keenan, 1999) (Figure 3). Their distribution covers regions of the Asian sub-continent and Japan, northern and eastern Australia and from the east coast of Africa across to Tahiti (Ryan, 2003). In Australia, they inhabit regions extending from Exmouth Gulf on the coast of Western Australia, through to the Northern Territory and Queensland to the southern Coast of New South Wales (Knuckey, 1999).

Historically, mud crabs were grouped into a single species *S. serrata*; however, recently, four distinct species have been described based on morphological and genetic characteristics: *S. serrata*, *S. tranquebarica, S. olivacea* and *S. paramamosain* (Keenan, 1999). The giant mud crab, *S. serrata,* is the largest and most common of the genus Scylla, and has a wide distribution throughout the western Indian Ocean, Japan and South Pacific Islands. *Scylla tranquebarica* and *S. olivacea* are more commonly found in the South China Sea, extending into the Indian Ocean and western Pacific. *Scylla paramamosain* appears to have a comparatively limited distribution, restricted to regions of south China and the Java Seas (Le Vay *et al.*, 2001).

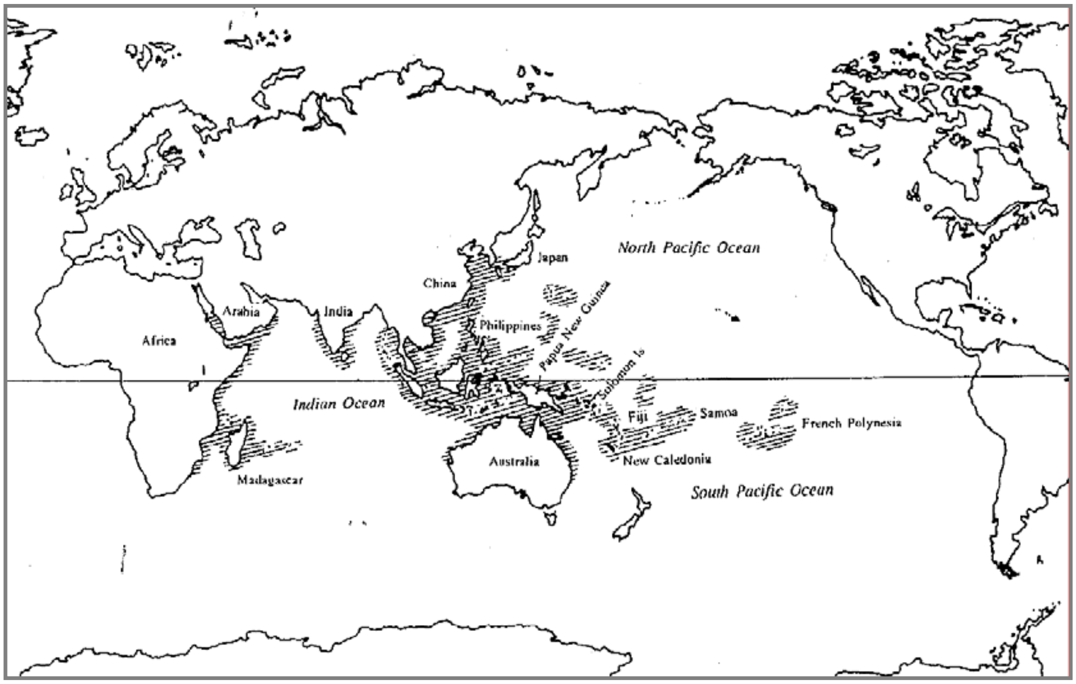


Figure 3. World map showing potential *Scylla* spp. distribution throughout the Indo-west Pacific region (Brown, 1993).

## 2.3 Size and Maturity

Male mud crabs can reach a maximum carapace width (CW) of 280 mm, and weigh 3 kg. Females mature between 80-120 mm carapace width, with the transition from

Table 2. History of minimum legal sizes for Australian commercial mud crab fisheries. Sizes are carapace width (CW) with the exception of New South Wales where carapace length (CL – measured from front to back) is used. The year of implementation is given in brackets.

| **Jurisdiction** | **Minimum legal size (as CW unless otherwise indicated)** | **Additional regulations** |
|---|---|---|
| Queensland | ♂: 150 mm (1926) | Females must not be taken |
| Northern Territory | ♂ and ♀: 130 mm (1985)<br>♀: 140 mm (1996)<br>♂: 140 mm; ♀: 150 mm (2006) | Ovigerous (berried) females and commercially unsuitable (soft) crabs must not be taken |
| New South Wales | ♂ and ♀: 85 mm CL (1982) | Ovigerous (berried) females must not be taken |
| Western Australia | ♂ and ♀ *S. serrata*: 150 mm* (1984)<br>♂ and ♀ *S. olivacea*: 120 mm<br>♂ and ♀ *S. paramamosian:* 150 mm* (not formally recognised)<br>*MLS regulations under review | Ovigerous (berried) females must not be taken |

juvenile stage to physiological maturity occurring at between 90-110 mm CW. Upon reaching adult morphology of between 140-160 mm CW, crabs are able to compete successfully for mates and reproduce (Heasman *et al.*, 1985; Lloris, 2001). In Australian fisheries, the average catch size of *Scylla* lies between 150-170 mm CW and weigh between 0.7-1.2 kg (NSW DPI, 2008).

## 2.4 Habitats and Movement

Mud crabs usually inhabit muddy estuaries and sheltered coastal habitats associated with well established mangrove communities. While juvenile mud crabs usually reside in the intertidal zone, adults tend to move to sub-tidal regions with the ebbing tide. Those that remain in intertidal zones hide themselves in burrows and dig into the mud as the tide changes (Davenport and Wong, 1987). This also allows them to keep cool and avoid predation during low tide (Moser *et al.*, 2005).

Hill (1982) observed that subadults lived in sub-tidal habitats but feed in the intertidal, while adults both live and feed sub-tidally (Hill and Williams, 1982). In contrast, juveniles (up to 8 cm carapace width) are most abundant on intertidal flats, amongst seagrasses, algae and mangrove roots. According to Webley (2009), mud crabs actively select for these habitats in their vulnerable juvenile stages in an attempt to seek shelter and find food. Diverse, complex habitats such as seagrass are likely to provide a greater abundance of food and refuge from predators and other pressures, thereby offering more suitable survival conditions (Webley *et al.*, 2009).

In early life stages, the movement of mud crabs is passive and usually dictated by currents. After the adult females spawn offshore, the migration of larvae back to coastal areas and estuaries is facilitated by the process of selective tidal streaming. Although crabs are relatively capable swimmers, they are usually unable to maintain their position against the tidal flow of estuaries. The megalopae may rise into the water column during the night-time flooding tides, which transport them further upstream. As the tide changes and turbulence increases, the larvae descend back to the substratum where drag reduces the current, allowing them to remain stationary until the tide changes direction. In addition to assisting the migration of larvae upstream, this mechanism reduces their exposure to visual predators by allowing them to remain close to the substratum during the day (Webley *et al.*, 2009).

Aside from the migration of mature females offshore to spawn, and selective tidal streaming of larvae back to estuaries, there is little evidence of large-scale movement in *Scylla* species (Heasman *et al.*, 1985; Nurdiani and Zeng, 2007).

Hill (1982) demonstrated that movement in mud crabs is largely restricted to the mangroves, estuarine water channels, and shallow tidal flats making up their habitat. They tend to move freely between these environments (Hill 1982). Both adult and subadult crabs were observed migrating into the intertidal zone at high tide in order to feed; however, movement is generally confined to subtidal areas (Le Vay *et al.*, 2001). Hyland *et al.* (1984) found very little movement of mud crabs between mangrove creeks and adjacent bays. An overview of estimated size of maturity for each jurisdiction and suggested potential environmental drivers affecting the population with references are shown in Table 3.

Table 3. Estimated size of maturity for each jurisdiction and suggested potential environmental drivers affecting population size. References provided in brackets.

| Jurisdiction | Maturity Size | Relevant environmental driver information |
|---|---|---|
| Australia and Asia | Females 90 - 120 mm<br>Males >120 mm | Low survival at 20°C, best survival at 30°C-32°C water temp. and 12-20ppt salinity, faster growth in lower salinities (20-22ppt) (Prasad, 1990, Ruscoe *et al.*, 2004, Heasman *et al.*, 1985, Robertson, 1996)<br>Preferred salinity 34ppt (Le Vay *et al.*, 2001)<br>Juveniles more abundant post-wet season (Hill, 1974) |
| Queensland | Recruitment to Fisheries: 18- 24 months | Peak mating activity in spring and early autumn, spawning only in summer >22°C water temp., maturation in females appears to be associated with seasonal high rainfall (Heasman *et al.*, 1985) |
| Northern Territory | Females 90-110 mm<br>Adult morphology 140–160 mm<br>Recruitment to fisheries: 18 months | Juvenile abundance may be related to seasonal variation in rainfall and salinity (Knuckey, 1996, Poovichiranon, 1992, Knuckey, 1999) Spawning around Oct-Nov, soft crabs around December and January (pers observation) Freshwater run-off important for juveniles to identify estuary systems (Chandrasekaran and Natarajan, 1994, Robertson, 1996). Can grow up to 130 mm in 8-9 month over the wet season (pers. comment Chris Errity)<br>Usually 90% females in Oct and Nov (pers. comment wholesaler) |
| New South Wales | Recruitment to Fisheries: approx. 24 months | Low activity in the winter month<br>Key stimulus for recruitment settlement, water depth, tidal pressure or chemical cues in temperate Australia (Webley and Connolly, 2007) |
| Western Australia | Males 120 mm<br>Adult morphology unknown | Three species are recorded *S. serrata, S. olivacea, S. paramamosain* with *S. olivacea* being dominant in King Sound. No specific other information is available for WA (Taylor, 1984, Keenan *et al.*, 1998) |

## 2.5 Food

Mud crabs are omnivorous scavengers, feeding predominately on slow moving or stationary benthic invertebrates such as barnacles, molluscs, worms and dead fish (NSW DPI, 2008). Foregut content analysis also revealed the presence of other crabs, suggesting cannibalistic behaviour (Ryan, 2003). Mud crabs generally emerge from the intertidal burrows at dusk, move slowly over the substrate to capture prey and return to their burrow by dawn (NSW DPI, 2008). They have a range of approximately 500 m, and use their larger claw for crushing while the smaller claw is used for biting, cutting and manipulating the prey (Ryan, 2003).

## 2.6 Life Cycle

Reproduction occurs in the warmer months, triggered by pheromones released into the water column by females to attract the males. As mating can only occur when the female is in soft shell condition, the successful male will carry the female around for the period it takes for her to moult and re-harden. Following ecdysis (i.e. the moult) a spermatophore is deposited into the female where it is stored until the developing ova are ready for fertilisation (Qld. DPI, 2009). Moulting of females often occurs from October to November, which is also the major mating time. At this time, the female migrates offshore as the deeper waters provide more chemically and thermally stable environment for development. Spawning involves the release of eggs in batches of two to five million at a time. Catches of mud crabs are usually lower during this time. New hatchlings then undergo a series of five zoeal larval stages before becoming megalopae. During this stage the larvae migrate back to benthic habitats where they settle and moult into juvenile crabs (Shelley, 2008). Moulting involves swelling of soft body tissues to expand a new soft shell after shedding of the old exoskeleton.

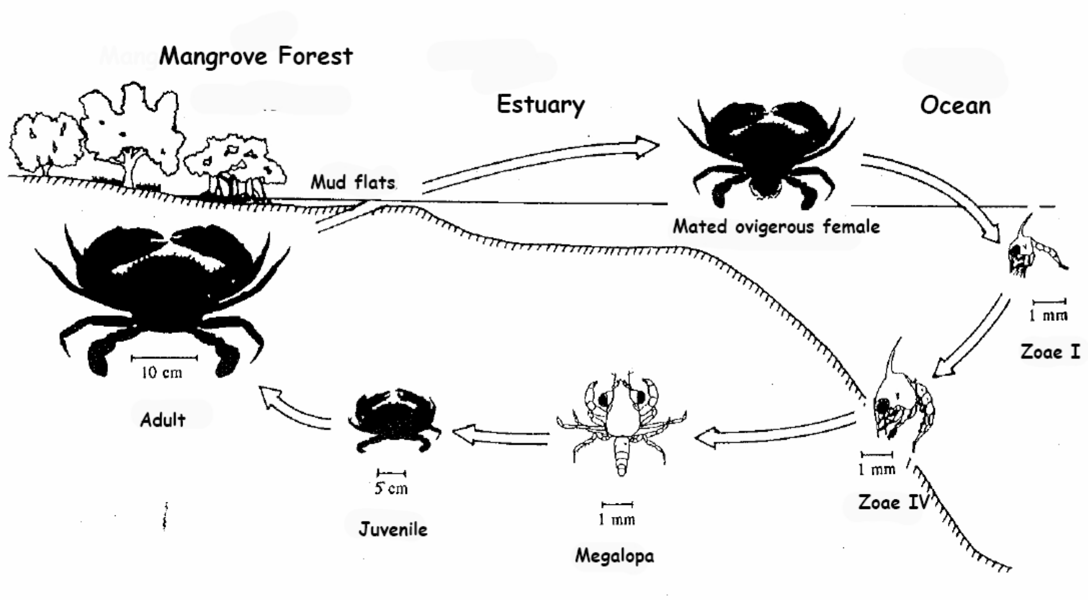


Figure 4. Simplified life cycle of *Scylla* spp. showing the different life-history stages of Scylla spp. (Brown, 1993).

## 2.7 Environmental Drivers

### 2.7.1 Physical Environmental Drivers

Studies have been undertaken to understand linkages between physical environmental conditions such as El Nino events in the ocean environment and biological processes that influence commercial important fish stocks (Evans *et al.*, 1995; Schwartzlose *et al.*, 1999; Lea, 2000; Byrne *et al.*, 2002; Currie and Small, 2005). Studies in Australia and elsewhere, predominantly on prawns and estuary dependent species, are suggesting a sensitivity of these species to freshwater runoff leading to fluctuation in catch (Meynecke *et al.*, 2006; Gillson *et al.*, 2008). River flow is known as a critical factor in maintaining nutrient and detrital input to estuaries, as well as preventing the development of hypersaline conditions (Blaber and Milton, 1990; Robertson and Duke, 1990; Forbes and Cyrus, 1992; Whitfield, 1994). Analysis of catch (landings) and freshwater flow of fisheries is based on the analysis of catch (landings) and freshwater flow or catchment rainfall. Impacts of changing environmental conditions can be estimated by running a regression of physical parameters such as rainfall or SOI (Xie and Hsieh, 1989; Beamish and Bouillon, 1993; Aaheim and Sygna, 2000). This method has been applied successfully to a number of studies (Vance *et al.*, 1985; Loneragan and Bunn, 1999; Growns and James, 2005) and can provide first ideas on the relation between physical parameters and catch. Gillson *et al.*, (2008) for example developed a statistical model for estuarine-dependent fisheries species and freshwater flow in New South Wales. Meynecke *et al*. (2006) already demonstrated a link between Queensland mud crab catch, the Southern Oscillation Index and coastal rainfall. Here, significant positive correlations resulted from analysis between mean annual and seasonal coastal rainfall, SOI and total annual commercial catches of mud crabs.

Complex environmental parameters often determine the distribution and abundance of mud crabs depending on their stage of development. High levels of recruitment for mud crabs occurred in the Northern Territory between 1995 and 2002 and were believed to be due to favourable environmental drivers (Haddon, 2005). In particular freshwater flow has been attributed by mud crab fisher to enhance catches.

Temperature and salinity are considered to be the most significant factors influencing the distribution and abundance of marine populations. These variables are central to energy flow and metabolism, thereby affecting the growth of aquatic organisms. In general, temperature effects may become stronger and species interactions weaker at the latitudinal limits of a species (Myers and Mertz, 1998). *Scylla serrata* has wide temperature and salinity tolerances, as evidenced by its natural range and preferred environment (Davenport and Wong, 1987; Ruscoe *et al.*, 2004).

According to studies on similar species, variation in temperature is known to affect the survival and development of larva in brachyurans and is an important variable in regulating the rate of egg development in *Scylla* species. Poole *et al* (2008) have demonstrated that time of larval development decreased (from 30 to 10 days) with increasing temperature up to 32°C, and observed higher mortalities in mud crabs with seasonal increases in temperature and suggesting that the optimal temperature range for larval survival is between 25 between 30°C, a range typical of their natural environment (Hamasaki, 2003; Poole *et al.*, 2008). Feeding activity of adult mud crabs is greatly reduced at water temperatures under 20°C (Hill, 1980).

Given the large geographic range of *S. serrata*, the potential for site specificity in regard to temperature optima needs to be considered. Larvae of South African *S. serrata* suffered high mortality at temperatures above 25°C (Hill, 1974); whereas Japanese *S. serrata* larvae had the best survival at 29°C (Hamasaki, 2003). There are also large temperature differences between northern Australia and the southeast of Australia. For example, average air temperatures in Cairns range from 17 to 31°C, while ocean temperature ranges between 23 and 29°C.

In contrast, annual air temperatures in New South Wales range from 8 to 26°C (http://www.bom.gov.au/lam/climate/levelthree/climch/clichv3.htm) and a range of sea surface temperature of 18 to 24°C around Sydney. Certain adaptation mechanisms occur with differing habitat temperatures, which enable *Scylla* to tolerate the abovementioned variations. Mechanisms of temperature adaptation largely involves regulation of the activities of specific enzymes and/or proteins (Kimmel and Bradley, 2001).

### 2.7.2 Salinity and Freshwater Flow

Freshwater flow is a central variable influencing the geomorphology of estuaries and physio-chemical properties of estuarine waters (Wolanski, 2007). It is believed to have a significant role in determining fisheries production in these areas, with the abundance and distribution of aquatic communities changing with seasonal and inter-annual variation in freshwater flow (Myers, 1998; Meynecke *et al.*, 2006; Gillson *et al.*, 2008; Gillson *et al.*, 2009). In northern Australia, freshwater flow into estuaries increases during late spring and summer, depending on the seasonal summer monsoon trough. Robins *et al.* (2005) reported a positive correlation between catchability of mud crabs and summer freshwater flow, suggesting that the freshwater influx encourages seaward movement of adults and spawning migration of females. This small-scale migration of adults also increases the survival of juveniles by reducing cannibalism and competition for burrows, thereby increasing the overall abundance of the species. The difference in distributions of the four *Scylla* species is also suggested to be a result of varying tolerances to salinity at larval or juvenile stages. The common *S. serrata* is more dominant in oceans and mangroves with high salinity (about 34 ppt), and may experience higher mortalities with sudden salinity decreases associated with freshwater flooding. Conversely, *S. paramamosain* prefers estuarine habitats where salinities are lower than 33 ppt and maintains high catch rates through seasonal periods of low salinity and freshwater conditions (Le Vay *et al.*, 2001).

### 2.7.3 Other Potential Physical Environmental Drivers

Other physical environmental drivers that are likely to influence the abundance, distribution and ultimately the catchability of *Scylla* spp. include currents, tides, wind, the lunar cycle and dissolved oxygen in the water column. The mangroves and mudflats inhabited by mud crabs are often rich in organic material and microorganisms, thereby having a high biochemical oxygen demand. The shallow water of these areas with ebbing or flooding tides is likely to contain low levels of dissolved oxygen. Therefore, mud crabs may be subject to hypoxic stress (Davenport and Wong, 1987), especially during high temperatures. The lunar cycle is likely to affect time of moulting and migration, but a measurable influence on the catch has not been reported (Hay *et al.*, 2005). Currents, tides and winds influence the distribution of mud crab larvae and egg dispersal and therefore regional abundance (Webley *et al.*, 2009). Most of the potential physical environmental drivers are of a cryptic nature and their influence is difficult to measure for a large area, within which these drivers may vary widely. These parameters have therefore only been indirectly considered in the analyses.

### 2.7.4 Biological Drivers

Similar to physical drivers, biological factors also have an influence on mud crab populations. They were not the subject of this report, but their influence should not be underestimated. Most environmental factors are correlated and are subject to feedback mechanisms. Biological drivers can include predation by crabs themselves (cannibalism) or through predators like crocodiles, sharks, rays, fish and humans. In addition, the distribution of estuarine habitats such as mangroves and mudflats drives the presence and abundance of mud crabs (Meynecke *et al.*, 2007). Biological drivers were not the focus of this research but require inclusion into a holistic predictive model of mud crab catches for Australia.

## 3. Conceptual Model and Hypothesis

Catchability can vary for reasons associated with abundance, mud crab behaviour, population biology including its dynamics, quality and amount of fishing effort, fishing strategy and environmental conditions (Arreguin-Sanchez, 1996). A conceptual model was developed to aid an understanding of how physical environmental drivers may influence mud crab catch (Figure 5). Current literature suggests that temperature and salinity were the major influence on different life stages of mud crabs (Hill, 1974). Other physical parameters also related to water temperature, such as wind, water depth and currents (lunar cycle), can also influence the mud crab's life cycle and subsequently catch rates. For example, salinity is influenced by rainfall; rainfall by barometric pressure; and barometric pressure to some extent by temperature. Water temperature is influenced by currents, wind and water depth - factors that also directly drive mud crab daily behaviour. The measurable direct impact of salinity and temperature on catch per unit effort increases with the life stage. This is also reflected by the type of data, with most data coming from adult crabs due to the fact that catchability increases with age.

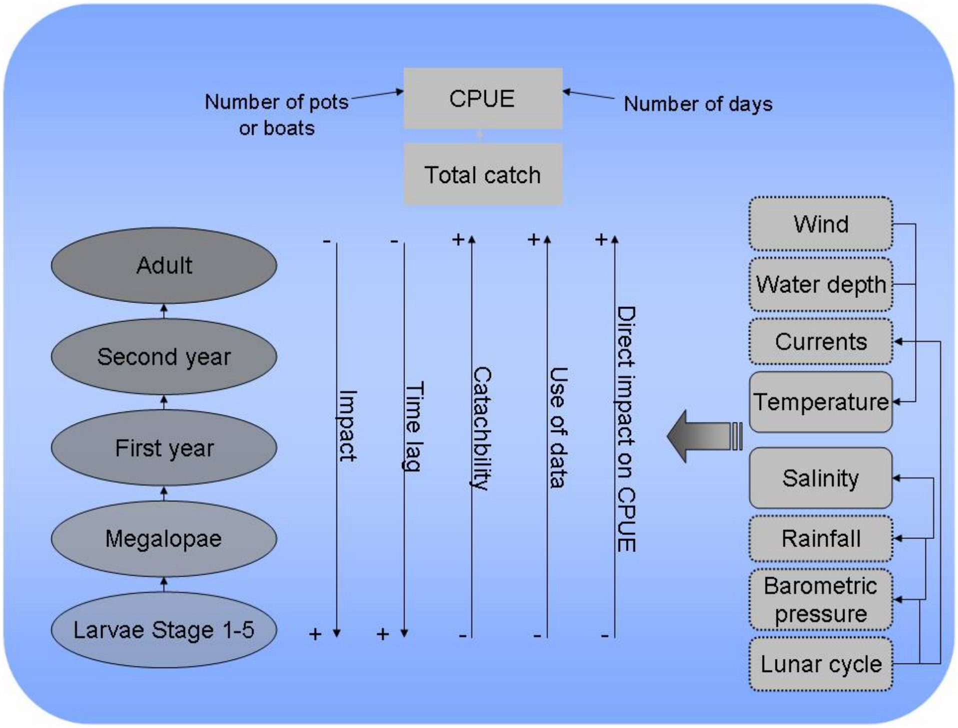


Figure 5. Conceptual model for the effect of salinity and rainfall as two main physical environmental drivers on mud crab catch in consideration of the various mud crab life stages.

In contrast, the impact of environmental drivers on mud crabs is strongest in their early life stages and the time lag between the impact of environmental drivers and effect on the CPUE decreases with more advanced life stages. Figure 5 shows an *a priori* conceptual model for the relationship between physical environmental factors, catch and the mud crab lifecycle. The proposed relationships in the conceptual model are important for interpreting the results derived from analyses of mud crab catch with the physical drivers. Using catch or catch adjusted for effort provides an indirect measure of the influence of physical drivers. Therefore, catch data as an abundance measurement of a population are limited, but in most cases, the only available, information at this stage.

***Hypotheses***

Based on the findings from previous research and observations from mud crab fishers, the following hypotheses were established. We hypothesise that temperature has more influence at the southern distribution of mud crabs and rainfall more influence on the catch at the northern distribution of *S. serrata*. This would be reflected by strong positive relationships between sea surface temperature (SST) and mud crab catch per unit effort (CPUE) in southeast Australia and positive relationships between rainfall and/or flow and mud crab CPUE in northern Australia.

In general, and throughout Australia, we expected high SST and high rainfall to result in correspondingly high coastal productivity (primary and secondary production increases), and consequently, a positive relationship between these combined factors and mud crab catches. In a similar way, we expected high positive SOI values that are indicating strong monsoonal effects such as rainfall and warm temperatures in northern Australia, to be positively related to mud crab CPUE. The positive relationship is likely to weaken towards southeast Australia. We also expected a positive annual relationship with SST and mud crab CPUE for Queensland, as catches are highest between February and March (note: this is not the case for the Gulf of Carpentaria systems).

Extreme flooding peaks (in particular in the early wet season in northern Australia), are expected to result in higher mortality of juveniles, which would subsequently have a negative impact over a period of years. This will be detectable in the catch data. However, depending on the timing of the flooding, it can extend the habitat for post-settlement of larvae and may have a positive effect on catch in subsequent years.

Depending on the recruitment time of mud crabs to fisheries, there will be a lagged effect of between 18 to 24 months for physical environmental driver/s and the resultant impacts on catch. The lag effect is expected to increase by a few months towards the southern distribution of *S. serrata*.

# 4. General Methods and Data Management

## 4.1 Statistical Analyses

For the statistical analyses of mud crab catch data and environmental drivers for the Northern Territory, Queensland and New South Wales, we applied Pearson Correlation, forward stepwise regression, multiple regression and non-metric multi dimensional scaling (nMDS) for annual, monthly and seasonal data configurations. Due to differences in the way mud crab catch data were collected between jurisdictions, the data sets were not directly comparable; however, meta-analyses using the results from each jurisdiction were possible.

### 4.2 Adjusting Catch for Effort

In order to adjust catch by effort, CPUE (as kg/day) was used. Analyses were also undertaken in which adjusted catch for effort using unstandardised residuals from a regression model based on log-transformed catch and effort (days and pots or boats) calculated for each month and used in the analyses. Outliers that were falling outside the 95% distribution were marked but not discarded from the analyses.

### 4.3 Correlation Analyses

Relationship between selected physical environmental drivers and mud crab CPUE were explored using Pearson Correlations. We tested for homogeneity of variance and normality as underlying assumptions for correlation analysis. We expected strong seasonality in the data set and therefore a likely high incidence of autocorrelation. Data were therefore also analysed as separate seasons (wet and dry, or summer, spring, autumn and winter).

### 4.4 Multiple Regression and Forward Regression Analyses

Statistical modeling was employed to quantitatively determine how much of the variance in Australian mud crab catch (adjusted for effort) could be explained by environmental variables. Co-linearity between variables was compensated for through the use of forward regression, a process that tests the residuals from each model step before selecting the next variable, therefore ensuring that only variables that improve the model are included. The forward regression model was built from variables likely to affect mud crabs during their lifecycle as shown in the life cycle model. The adjusted $r^2$ took into account co-linearity between variables and the degrees of freedom in the model.

General linear models (GLMs) can be used to predict future catch. The capacity of regression-based models to predict future catch has been questioned by some authors (Stergiou and Christou, 1996; Myers and Mertz, 1998); however, the GLMs provide a good base model for further modelling approaches (Wheeler and Hendon, 2004). The use of regression models has been criticised because of: (1) the confounding effects of stock size and fishing pressure (Walters and Collie, 1988); (2) the likely non-linearity of linking mechanisms (Baumann, 1998) and the probability of multiple mechanisms; (3) the lack of ability to prove causality (Quiñones and Montes, 2001); and (4) their uncertain predictive capability as a consequence of long-term climatic variation or human-induced changes (e.g., habitat loss, pollution). However, points 3 and 4 are a general problem that persists with all modeling approaches. Points 2 and 3 can be addressed by reducing autocorrelations, meta-analyses and the selection of relationships that support current scientific and anecdotal knowledge and point 1 can be eased by a thorough selection of catch data that provides consistent information.

## 4.5 Reduction of Autocorrelation

In order to reduce autocorrelation (Pyper and Peterman, 1998) between variables we only selected parameters that were likely to be biologically relevant according to our conceptual model and have the strongest influence on the mud crab's life cycle (refer to Figure 5). We therefore concentrated on sea surface temperature, and flow or rainfall as a proxy for freshwater runoff. Other variables considered included the SOI and three phases of the Maiden-Julian Oscillation for the Northern Territory. Further physical environmental factors such as moon phase, tidal range, currents and geomorphic features were also examined but not included in the analyses due to the lack of information available on these factors and their often cryptic nature of time lag effects. We also generated and tested relationships using Principal Components from variables as a method to reduce autocorrelation between the variables.

Autocorrelation is especially a problem in data sets that are dominated by low frequency variability (Bence, 1995). This problem is similar to spatial pseudo-replication because it violates the assumption of independence among observations (Hurlbert and Chang, 1984). In general, this means that a sample correlation between two autocorrelated time series has fewer degrees of freedom than assumed by the significance test. If this is ignored, the test will have a Type I error rate greater than the specified α, and a significant correlation may be detected when none are actually present.

We used the Bonferroni adjustment in SPSS 17 to reduce the probability to make a Type I error, providing a new α that is significantly lower than 0.05. If the adjustment was not undertaken, this is clearly stated in the results. In the Bonferroni adjustment for multiple comparisons, the p-value was adjusted by:

$$p_B = \min\left(\frac{p * C * (C * -1)}{2}; 1\right)$$

The number of categories is described by C and B is the Bonferroni multiplier which is the sum of the number of possible ways of merging two categories at each iteration and p is the p-value.

A method to adjust for the degrees of freedom for the sample correlation can be undertaken by adjusting of the $R^2$ that penalises the addition of extraneous predictors to the model. We adjusted the degrees of freedom of the univariate *F* test statistic using the formula $1 - ((1 - R^2)((N - 1) / ( N - k - 1))$ where k is the number of predictors and N is the number of subjects.

## 4.6 Meta-Analyses

For meta-analyses of the total catch, mean CPUE, mean annual rainfall and temperature, and average flow (if available) for each river system were used for nMDS analyses in Primer 6.0 (Clarke and Warwick, 2001). For regional comparison we used the Euclidean Distance similarity measure and to investigate regional trends and variations within the mud crab fishery and dependencies on temperature and rainfall. Characteristics for each region and river system were displayed using ArcGIS 9.3. In addition, trends between States were observed by analysing the investigated relationships.

## 4.7 Data

### 4.7.1 Mud Crab Catch Data

Catch data for mud crabs for the Northern Territory were provided by NT Fisheries. There are a total of 49 licenses in the Northern Territory consisting of two units. Each unit contains 30 pots, giving a total of 2940 pots. The mud crab catch is derived from logbooks submitted by licensees. The log returns consist of two components. The first component provides catch and market data for the mud crab catch; the second, catch information for their bait. A high degree of compliance with reporting requirements has been achieved. Returned log sheets are entered into a proprietary Oracle data base, Fishdat. All data are validated before release.

Monthly catch data for the period 1990-2008 for seven river systems were selected. These provided information on monthly catch per area and grid code, monthly fishing days, pots and potlifts. River systems were selected based on the highest catch during the observation period and the continuity of data (except for the Daly River). Seven catchments were selected that represented seven major river systems: the Roper, McArthur, Robinson, Wearyan, Adelaide, Daly, and Mary Rivers. These systems accounted for 6532 t of mud crab catch between 1990-2008 in the pot fishery out of a total of 8650 t of mud crab harvested territory-wide during that period. The selected systems represent 75% of the Northern Territory catch for this time period and provided a solid basis for the analyses. For seasonal analyses, dates were split into a seven-month dry season (April-October) and a five-month wet season (November-March). Only mud crab catch that was caught by pots were extracted from the database.

Mud crab catch data for Queensland were provided by Queensland Fisheries. There are currently 431 licences held in Queensland. Fishers have to provide logbook information including daily catch in kilograms (kg) and fishing location (6 x 6 n.mi. grid in recent years). Fourteen Queensland catchments were selected, including 29 river systems. Due to the aggregation of mud crab catch data in 30-nm grids, river systems had to be combined when closer than 60 km. These systems produced a total catch of 9575 t in the pot fishery from 1988 to 2008 out of a total of 15,015 t of mud crab catch in this time period. The selected systems therefore represented 64% of the total catch for this time period. For seasonal analyses, data were split into a six-month dry season (May-October) and a six-month wet season (November-April). This also included data from southern Queensland. Only pot data were extracted from the database.

Mud crab catch data in New South Wales were provided by New South Wales Fisheries. The monthly catch data were collected for each estuary within fiscal years providing information on monthly catch for pots and traps in kg, fishing days, area of catch and boats. Data were available from 1984/85 until 2008/2009. Data until 1996/97 were not collected for each type of fishery method and was therefore treated separately for analyses. The data set from 1984/85-1996/97 were adjusted for effort by selecting catch from trap/pot gear only, and by dividing weight (kg) by the number of days this gear was used. Other methods (e.g. nets) were excluded from the analyses. Months with multiple gear use were excluded from the analyses. For New South Wales, 10 catchments that represented 17 river or lake systems were selected. Out of 1216 t of mud crab catches in the pot and trap fishery from 1996/97-2008/09, a total of 1146 t from the pot fishery, covering 94% of New South Wales mud crab catches, was represented by the selected river systems. The total mud crab catch data for New South Wales between 1984/85-1996/97 was 1233 t for all fishery types, from which 849 t was provided by the selected river systems. This represents 69% of the total catch in New South Wales for this time period. For seasonal analyses, data were split into four three-month periods - winter (June, July, August), spring (September, October, November), summer (December, January, February) and autumn (March, April, May). Note that the summer period included data from the December of the previous year.

Mud crab catch data for Western Australia were provided by Western Australia Fisheries. Mud crab catch data for Western Australia were available from 1975-2009, providing information on monthly pots, trap and net catch in kg, grids fished, area fished, days and hours fished and number of boats. Mud crab catch data for Western Australia were sparse and related to two different species (*S. serrata* and *S. olivacea*). The mud crab fishery is currently a small developing fishery, with a total annual commercial catch of 3-7 t per year over the last decade. It is concentrated around York Sound, King Sound, Cambridge Gulf and Admiralty Gulf. Data were analysed in terms of general trends and anecdotal reports from fishers.

When using effort to adjust catch data, it is important to understand that the returns can only provide an indication of the amount of fishing undertaken. Crab fishers record the number of days fished in the month, and the average number of pots used on these days (in the Northern Territory and New South Wales), along with the number potlifts deployed during the month. Fishers do not have the option to record the actual number of pots used on any given fishing day in that month except in Queensland. Consequently, it is possible that a fisher used more or fewer pots than the average on any given day, which is not reflected in the data.

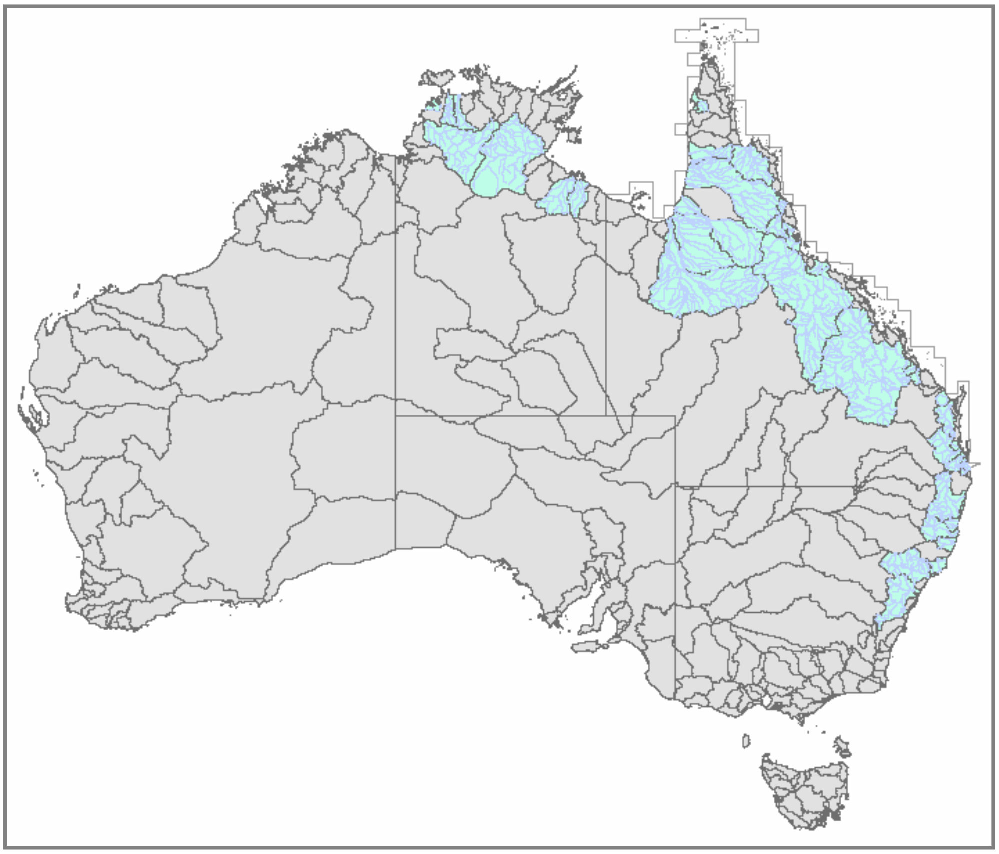


Figure 6. Selected catchments (in blue) for numerical analyses of Australian mud crab catch data from Northern Territory, Queensland and New South Wales. Western Australian catch data that mainly included King Sound were subject to qualitative analyses only.

### 4.7.2 Rainfall Data

We selected mean monthly rainfall data within each catchment area (Figure 6) using a 5 km rainfall grid for Australia, covering the years from 1984-2008. Data were provided by the Bureau of Meteorology (BOM). The original ASCII data were converted into raster data in ArcGis 9.3, then converted into point data and intersected with selected catchment areas to calculate rainfall data for each catchment. The mean of rainfall points per catchment area was used to calculate monthly average rainfall per catchment area. The catchment area was based on the Australian River Basin 1997 data provided by Geoscience Australia.

### 4.7.3 Freshwater Flow Data

Daily fresh water flow data for Queensland were obtained from the Queensland Department of Environment and Resource Management stream gauge website database (http://www.derm.qld.gov.au/watershed/index.html) for the selected river systems. Daily freshwater flow data either in megalitres/day, $m^3$/day or height in m/day, were provided by the Northern Territory Department for Natural Resources, Environment, the Arts and Sport for selected river systems. A runoff model, developed for the Northern Australia Sustainable Yields Project by CSIRO's Water for a Healthy Country Flagship, provided additional information on flow for the Roper River (Figure 7). This flow data were tested against the used mean catchment rainfall (Figure 8). Freshwater flow information for New South Wales was provided by the New South Wales Department of Water and Energy and Sydney Catchment Authority for gauging stations in the Hunter, Hawkesbury and Clarence River systems. Daily minimum, maximum and mean flow rates in megalitres/day, $m^3$/day or height in m/day, were obtained for 21 river systems and time periods (Table 4).

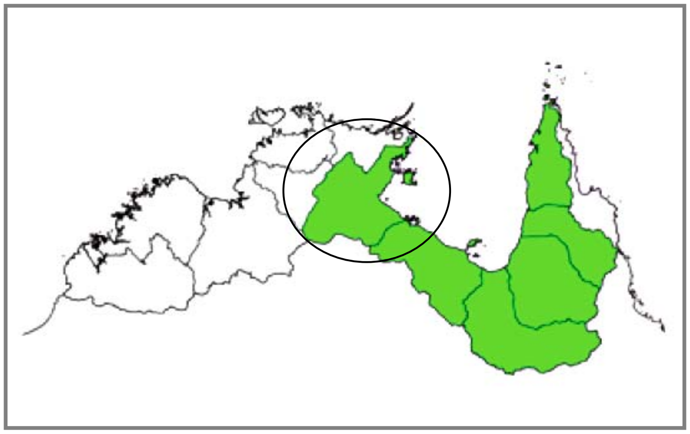


Figure 7. The Gulf of Carpentaria Drainage Division and its six regions (Roper River lies in the circled region), for which a runoff model was developed for the Northern Australia Sustainable Yields Project by CSIRO's Water for a Healthy Country Flagship.

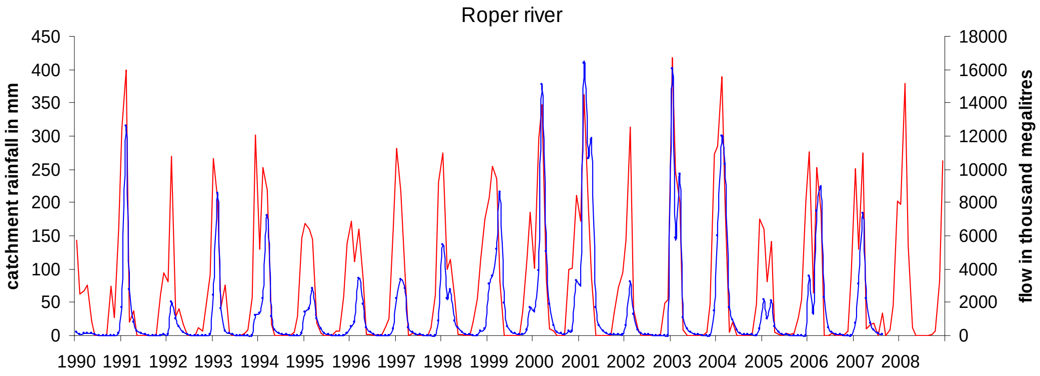


Figure 8. Mean catchment rainfall (mm) used for this study and calculated flow from a runoff model for the Roper River shown for the time period 1990-2007. Pearson Correlation between catchment rainfall and modelled flow has r = 0.70, P<0.01 A lag between rainfall events and flow is evident, and not all rainfall peaks translate into high flows (e.g. depending on soil saturation).

Table 4. River system and gauge ID as well as availability of freshwater runoff information and its Pearson Correlation with monthly average catchment rainfall. All correlations were significant at $P < 0.01$.

| River system State in brackets | Gauge ID | Available time period with minor data gaps | Pearson's r between average monthly flow and rainfall |
|---|---|---|---|
| Barron (Qld) | 110001D | 1988-2005 | .64 |
| Burdekin (Qld) | 120015A | 1988-2005 | .62 |
| Mitchell (Qld) | 919014A/919009A | 1995-2007 | .22 |
| Fitzroy (Qld) | 130002B | 1995-2001 | .48 |
| Gilbert (Qld) | 917001D | 1988-2005 | .74 |
| Burrum (Qld) | 137303A | 1988-2004 | .67 |
| Mary (Qld) | 138013B | 1992-2002 | .77 |
| Haughton (Qld) | 120015A | 1988-2005 | .66 |
| Calliope (Qld) | 2001A | 1988-2004 | .80 |
| Flinders (Qld) | 915003A | 1988-2004 | .63 |
| Tully (Qld) | 113006A | 1988-2005 | .83 |
| Herbert (Qld) | 116001E | 1988-2004 | .83 |
| Normanby (Qld) | 105101A | 1988-2005 | .70 |
| McArthur (NT) | G9070142 | 1990-2008 | .84 |
| Mary (NT) | G8180085 | 1990-2008 | .82 |
| Adelaide (NT) | G817005 | 1990-2008 | .81 |
| Daly (NT) | G8140040 | 1990-2008 | .60 |
| Roper (NT) | G903250 | 1990-2008 | .65 |
| Clarence (NSW) | 204007 | 1985-2008 | .61 |
| Hunter (NSW) | 210064 | 1985-2006 | .44 |
| Hawkesbury (NSW) | 212296, 212228, 212290, 2122001, 2122951, 212297, 212291 | 1997-2008 | .63 |

Flow rates in all river systems showed significant positive correlations with monthly average rainfall in the catchment area. In almost all cases, the strength of the relationship justified the use of catchment rainfall in mm as a proxy for freshwater runoff. This was the more consistent and continuous parameter compared to data from gauge stations. For example, some river systems like the Wearyan and Robinson Rivers in the Northern Territory had no gauge data available for the observed time period. Missing daily freshwater flow values were estimated using a linear model based on the mean daily rainfall of the catchment.

### 4.7.4 Madden-Julian Oscillation (MJO)

The MJO is an oscillation of atmospheric pressure that migrates eastward along the equator from Africa. It is considered to be the strongest intra-seasonal signal in the tropical atmosphere (Madden and Julian, 1972; Maloney and Kiehl, 2001). Pulses of the MJO are associated with increased convection and modulation of monsoonal westerlies, which often results in increased rainfall and short 'active bursts' of the north Australian monsoon, followed by a strong stabilising and drying influence after passing (Hendon and Liebmann, 1990). In the Austral summer, the MJO reaches maximum intensity over the Indonesian-New Guinea region (December-February), and weakens towards the International Date Line. It is suggested that the MJO influences the timing but not the intensity of monsoon activity periods, and therefore the likelihood and timing of extreme rainfall events across much of northern Australia.

All Season Real Time Multi-Variate MJO Indices were obtained from the Bureau of Meteorology Research Centre website and include longitudinal positions of the centre of the oscillation (phase) and the number of days in each phase (http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/RMM/index.htm). The variable used in the analysis was a summation of the number of days for phases 2, 5 and 6. The MJO phase 2 is associated with a significant suppression of rainfall for the Northern Territory coastal area during the pre-wet and wet season. Conversely, Phase 5 and 6 of the MJO are both associated with significant enhancement of rainfall over the same period (Wheeler and Hendon 2004).

### 4.7.5 Southern Oscillation Index (SOI)

Monthly SOI values were obtained from the BOM website. The SOI is the difference in air pressure between Tahiti and Darwin. Positive values of the SOI are generally associated with a La Niña pattern in the central and eastern equatorial Pacific and above average rainfall for northeast Queensland. Negative values of the SOI are associated with El Niño conditions and below average rainfall across northeast Australia. We used mean and maximum SOI values for analyses with maximum SOI values being an indicator of La Niña events. Therefore, it was predicted that there would be positive correlations between mud crab catch and the maximum SOI values for each season.

### 4.7.6 Sea Surface Temperature

Sea surface temperature (SST) was selected as a more reliable source of temperature information than air temperature from weather stations. We accessed free SST data from NASA (http://poet.jpl.nasa.gov) satellites from AVHRR Pathfinder Version 5, providing a 4-km resolution of monthly daytime temperature information for the time periods 1985-2007. For 2008, SST data from MODIS Aqua with a 4-km resolution of monthly daytime temperature were selected. The data were downloaded as point data in ASCII files with an original projection in WGS 1984. The data were then converted into shapefiles in ArcGIS 9.3 and monthly average values calculated for each river system. It was assumed that water surface temperature in the estuaries was similar to water temperature within a 20-km proximity to the river mouth. Air temperature data from nearby stations was often inconsistent and some times far away from the river mouth. For the selection of SST data, points with a 20-km buffer were generated along the river mouth and data points that fell within this buffer were selected to generate monthly average SST.

# 5. Results and Discussion

## 5.1 Northern Territory Mud Crab Catches and Environmental Drivers

### 5.1.1 State-Specific Background Information

The Northern Territory shallow water tropical environment is characterised by a five-month warm, wet season (November to March), and a seven-month cooler, dry season (April to October). This exposes mud crabs to wide annual, and often daily, fluctuations in temperature and salinity. Darwin is the central forwarding point, and control of the fisheries is therefore concentrated and relatively easy to manage. A quota for the mud crab fishery has not been introduced in the Northern Territory so far and generally fishers try to catch as many mud crabs as possible, whenever possible. Therefore, the data should reflect true fluctuations in mud crab abundance. The catch season varies with road access but is usually from March to November. During the wet season many roads are closed and only a few fishers deliver crabs. The highest volume of catch is reported for March, April, May and June every year. For the analyses, the following variables were considered: average rainfall in the catchments, sea surface temperature within 20 km of the river mouth, flow data, SOI, maximum SOI, MJO in monthly, seasonal (two seasons) and annual temporal configurations.

Northern Territory mud crab catches increased from 150 t in 1990 to over 200 t in 1994. In 1995, the catches almost tripled and reached a peak that was followed by a slight drop in 1997. From 1998-2001 catches increased to over 1000 t and then sharply dropped to 350 t in 2002. In the past three years a slow increase to over 500 t can be seen (Figure 9).

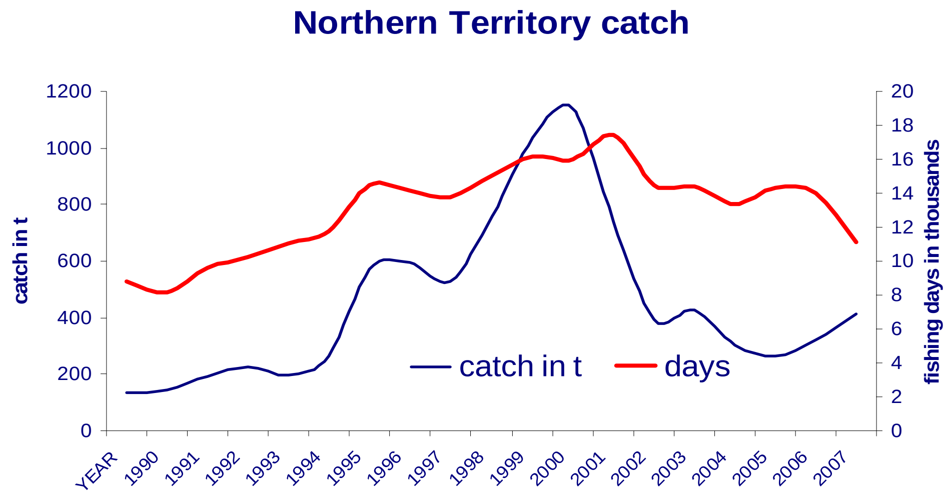


Figure 9. Northern Territory mud crab catch in tonnes and fishing days for the years 1990-2008.

The initial analyses showed large differences between the systems, with the Gulf systems being most productive. The Roper River was exceptionally productive, with an estimated three million crabs being harvested in the river system between 1990-2008. The Roper, McArthur and Robinson/Wearyan river systems contributed significantly to the overall mud crab catches in the Northern Territory. On average, half of the Northern Territory catches were derived from these systems (Figure 10).

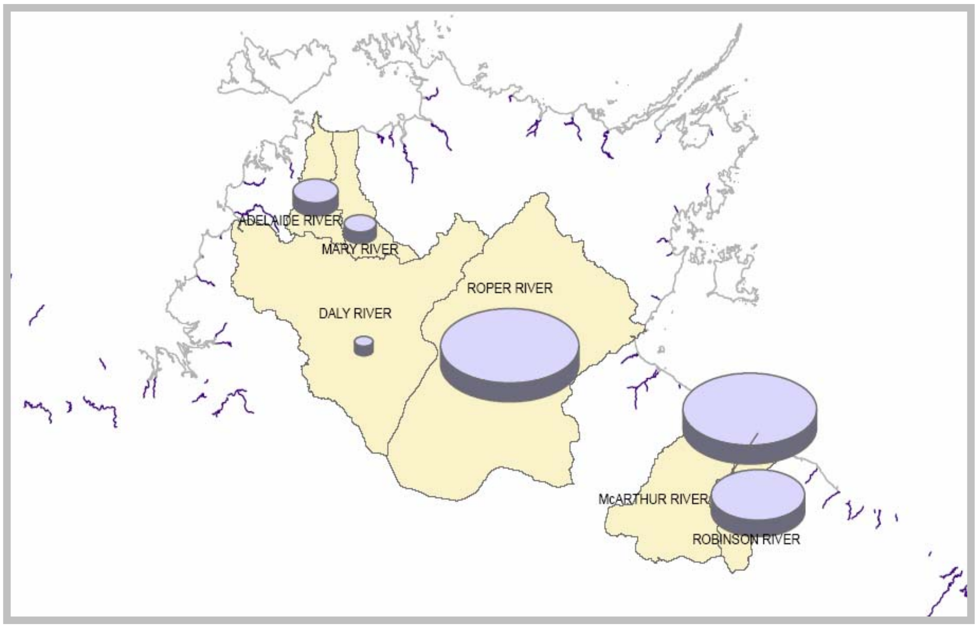


Figure 10. Six of the seven selected river systems (Bynoe Harbour not included) showing relative proportion of total catch between 1990-2008 by the size of the discs. The selected systems represent 75% of the total NT mud crab catch between 1990-2008.

### 5.1.2 Correlation Analyses

*Annual*

A first set of Pearson correlation analyses for annual relationships between CPUE and SST revealed only weak correlations that were generally negative. However, significant positive correlations exist for mud crab CPUE and annual catchment rainfall. The significance of this relationship increases with a one-year lag and then decreases with a two-year lag. This correlates with the estimated time of 18 months needed for mud crabs to recruit to the fisheries. Significant correlations (between r = 0.40 and r = 0.80) were detected for annual maximum SOI values. As seen in Figure 11, there was a lag effect of approximately six months in comparison to the SOI values. Given the strong relationship with SOI, we identified a six- to seven-year cycle of high catch rates that were reflected by the 1994/95-1999/2000/2001-2008/2009 La Niña phases. No significant annual relationships between mud crab CPUE and SST were found; however, a negative relationship for western systems (Mary, Daily and Adelaide

Rivers) was indicated by the analyses. When modelled flow data from the Northern Australia Sustainable Yields Project were used for the Roper River instead of the mean monthly catchment rainfall, the Pearson r improved from 0.40 to 0.53.

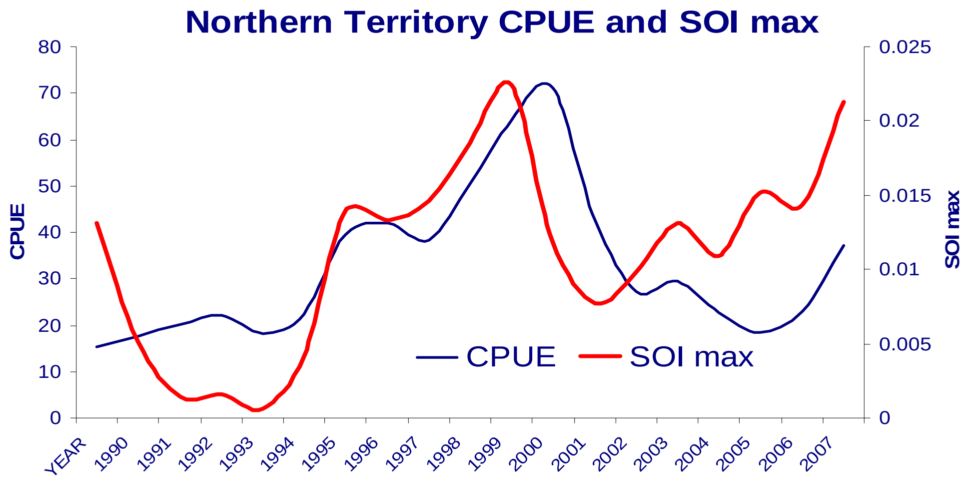


Figure 11. Northern Territory mud crab CPUE (kg/day) and maximum SOI values for the years 1990-2008, showing a six- to twelve-month lag response of the mud crab CPUE.

### *Seasonal*

There were significant positive Pearson correlations between seasonal CPUE and average rainfall when lagged by one season. Monthly flow or, if this data were not available, rainfall, showed a clear positive relationship when lagged by six months. This indicates that a good wet season translates to high catches in the following dry season, as confirmed by anecdotal reports from fishers. There was also a significant relationship with maximum SOI values. High positive SOI values indicated strong monsoonal effects such as rainfall and warm waters. These factors most likely contributed to enhanced productivity and increased material (organic matter and nutrients) movement. Seasonal analyses of the data set with temperature showed that temperature (SST) did not have a strong influence on mud crab catch, with a negative relationship for the Mary and Adelaide River systems. This was likely due to the relative small fluctuation of temperatures in the Northern Territory. However, if SST was lagged by six month a positive relationship with CPUE was identified.

Table 5. Pearson correlation for annual mud crab CPUE with SST and rainfall, as well as lagged by one or two years. Significant correlations are in bold (* $P < 0.05$).

| System | Annual CPUE-SST | Annual CPUE-SST 1-yr lag | Annual CPUE - rainfall | Annual CPUE-rainfall 1-yr lag | Annual CPUE-rainfall 2-yr lag |
|---|---|---|---|---|---|
| McArthur | 0 | 0 | .38 | **.48*** | 0 |
| Mary | -.25 | -.13 | **.57*** | .22 | .40 |
| Bynoe | 0 | 0 | .37 | **.57*** | **.48*** |
| Robinson | 0 | 0 | .18 | .32 | .15 |
| Adelaide | -.13 | 0 | **.49*** | **.57*** | **.46*** |
| Daly | .14 | -.23 | 0 | .40 | .20 |
| Roper | 0 | 0 | .40 | **.49*** | .20 |

Table 6. Pearson correlation for 36 wet and dry seasons of mud crab CPUE with a time lag of five seasons. Significant correlations in bold (* $P < 0.05$).

| System | LogCPUE-SOImax df 31 | LogCPUE-rain df 31 |
|---|---|---|
| McArthur | .26 | **.37*** |
| Mary | **.35*** | **.33*** |
| Bynoe | **.37*** | **.47**** |
| Robinson | .26 | .26 |
| Adelaide | .30 | **.55**** |
| Daly | 0 | 0 |
| Roper | .14 | **.38*** |

### 5.1.3 Regression and Forward Stepwise Multiple Regression Analyses

Regression analyses using Northern Territory mud crab CPUE and the climate variables revealed significant relationships between seasonal rainfall (using average data for wet and dry seasons) lagged by one season and annual maximum SOI values (Figure 12, Table 8). These two variables explained 30-40% of the catch variability for four of the investigated river systems. The Daly River showed no relationship with any of the variables; however, it only has sparse data with gaps over long periods of time. The Daly River clearly demonstrates that if catch data are low and not continuous over time, statistical analyses reveal no significant relationships.

A summary of all Northern Territory annual mud crab CPUE and comparison with maximum SOI values demonstrated the possible influence of this variable on mud crab catch, with an $r^2$ of 0.32 ($P < 0.05$). The $r^2$ values were slightly lower for a two-year lag ($r^2 = 0.30$) (Table 7).

Further investigation of the relationship between environmental drivers such as flow/rainfall and catch for the two larger systems (Roper, Figure 13, and Robinson Rivers) showed an exponential rather than a linear relationship.

Catch adjusted for effort by residuals from a linear distribution has been tested in addition to kg/day; however, this did not conform to the overall underlying trend in the catch data, and indicated the lack of a linear relationship for some river systems such as the Roper River. Principal components generated to reduce autocorrelation resulted in similar outcomes when using log-transformed climate variables but with slightly lower performance than for catch adjusted for effort just using the number of fishing days. Therefore, we concentrated the analyses on a small number of variables and catch in kg per day. The three MJO selected phases (phase 6, 5 and 2) were not significantly related to mud crab catch in any of the statistical analyses.

Table 7. $r^2$ values from a linear model for relationships between mud crab catch, SOI and rainfall in the Northern Territory. Significant values are in bold (* $P < 0.05$, ** $P < 0.01$)

| **System** | **$r^2$ values for annual CPUE/SOI max, n=18** | **$r^2$ values for seasonal CPUE/ catchment rainfall lagged by one season, n=36** |
|---|---|---|
| McArthur | **.38**** | **.30**** |
| Robinson$^{++}$ | **.38**** | **.27*** |
| Roper$^{++}$ | **.27*** | .24 |
| Mary | **.41**** | .17 |
| Bynoe | **.25*** | .17 |
| Adelaide | **.39**** | **.33**** |
| Daly$^{+}$ | .1 | .1 |

$^{+}$ Daly River has low and non-continuous data, $^{++}$ Power regression applied

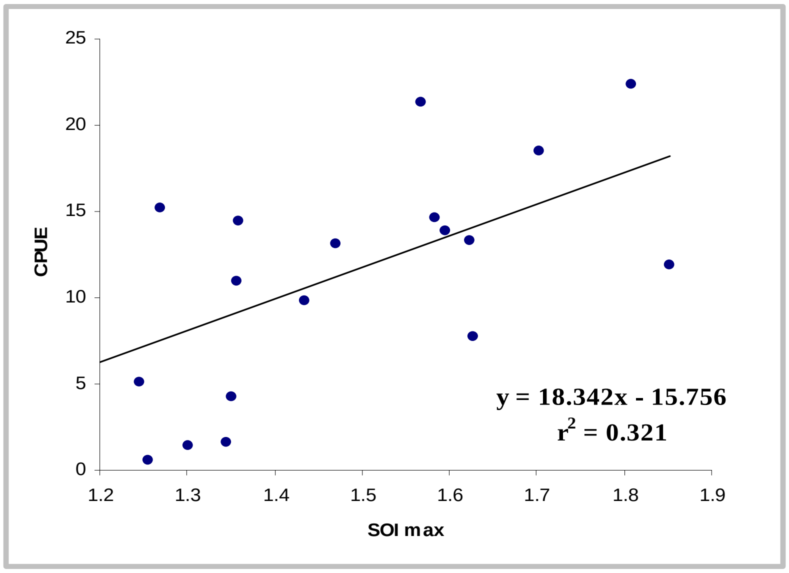


Figure 12. Linear relationship between mud crab CPUE and maximum SOI values in the Northern Territory for 18 years of observation. SOI values explained about 32% of the CPUE variability.

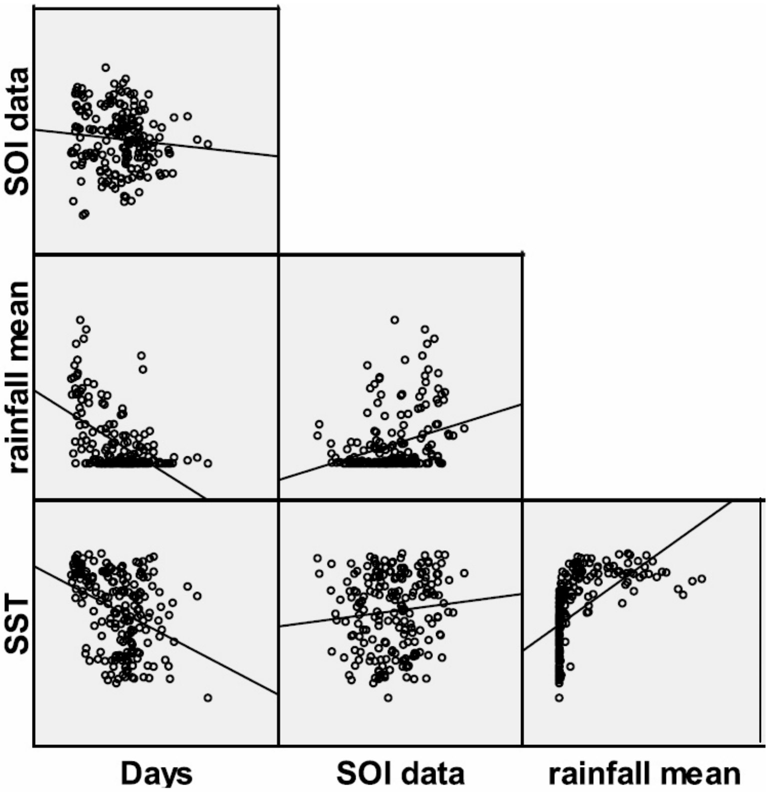


Figure 13. Samples from the Roper River monthly data set of scatter plots between predictors for the multiple linear regression models. Rainfall mean = mean monthly rainfall in the catchment in mm; SOI data = mean monthly SOI values; SST = mean monthly sea surface temperature within 20 km of river mouth; Days = number of fishing days per month. There are significant relationships between mean rainfall and SST, number of fishing days and SST, mean rainfall and number of fishing days).

Table 8. Forward stepwise regressions performed for seasonal data configurations. Significant adjusted $r^2$ values for seasonal data configuration were shown for log-transformed mud crab CPUE, SOI and mean catchment rainfall.

| System | Fisheries measure | Climatic parameter | $r^2$ | adjusted $r^2$ | P-value < |
|---|---|---|---|---|---|
| Adelaide | Log(CPUE) | SOI mean | .386 | .368 | .01 |
| Daly | Log(CPUE) | NSC | | | |
| Mary | Log(CPUE) | SOI mean | .277 | .257 | .01 |
| Bynoe H | Log(CPUE) | Rainfall mean | .202 | .179 | .05 |
| McArthur | Log(CPUE) | SOI max | .429 | .412 | .00 |
| Roper | Log(CPUE) | SOI mean | .214 | .191 | .05 |
| Robinson/W | Log(Catch) | SOI mean | .353 | .343 | .01 |

### 5.1.4 Meta-Analyses

A nMDS plot using total catch, rainfall and sea surface temperature (SST) showed a clear separation between the entered systems, with the Adelaide, Daly, Mary, and Bynoe Harbor (no river system) as one group, and the Robinson, Wearyan and McArthur as a second group of systems (Figure 14). The regions with less mean rainfall have higher average catches. This indicates that the catch is not driven by total rainfall, but by the timing of rainfall and other factors such as size of the catchment area and biological factors.

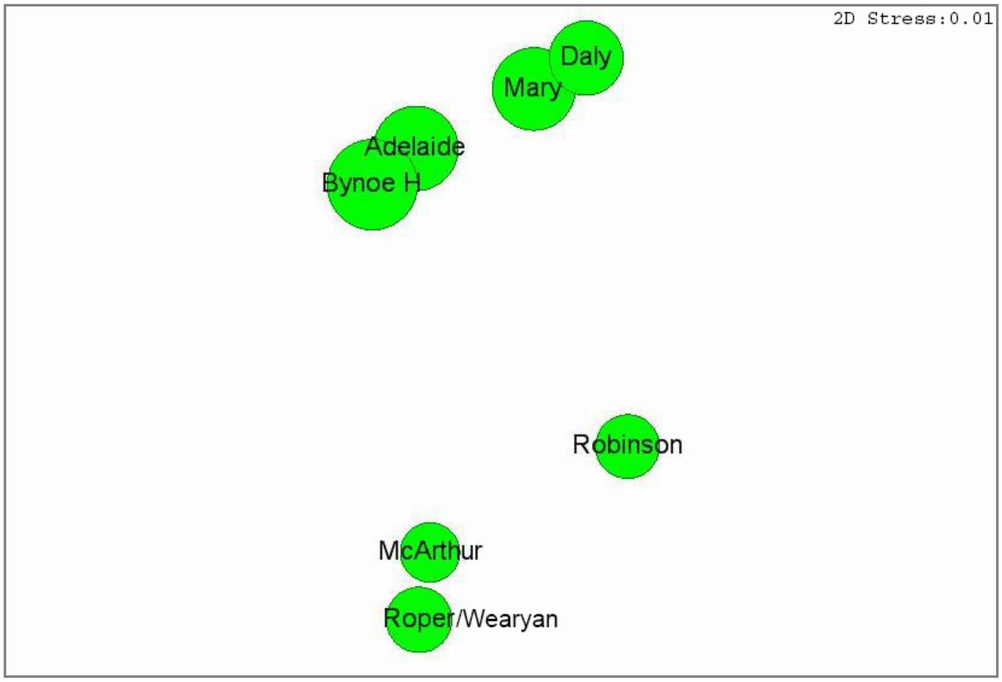


Figure 14. nMDS plot displaying the seven selected river systems for the Northern Territory mud crab catch analyses. The diameter of the green circles represent the average rainfall. The plot is based on standardised average catch, CPUE, SST and rainfall between 1990-2008. Data were square-root transformed and Euclidean distance applied. The nMDS separated the data into a Gulf of Carpentaria group and a western group of systems.

### 5.1.5 Discussion

The Borroloola and Roper River systems are the most important systems in terms of catch contribution. They collectively contributed 45-80% of the total annual catch in most years. The western regions only contributed a small proportion to the total catch. Interannual trends in the catch from the Borroloola and Roper Rivers follow the same general trend as the entire fishery in Northern Territory, with a steady rise in catches between 1983 and 1995, a rapid rise between 1996 and 2001, and a rapid decline from 2001 till 2006. The total annual catch in 1984 was just over 24 t, increasing steadily to reach 264 t in 1995. Catch increased to 573 t in 1996 and peaked at 1139 t in 2001 before declining to 265 t in 2006, probably due in part, at least, to a 10 mm increase in the commercial minimum legal size (MLS) implemented in May that year.

Analyses of the Northern Territory Mud Crab Fishery catch revealed significant variation over time. This is most likely due to environmental factors affecting recruitment success rates. In the late 1990s and early 2000s, large increases in catch and CPUE occurred in the Northern Territory. Similar patterns of fluctuation in recruitment and relative fishing power (i.e. up to eight-fold) would have been required to explain these interannual variations in catch rates (Figure. 9). Such variation is not particularly driven by effort in a pot-based fishery. Similar increases were experienced in the Queensland Gulf of Carpentaria Fishery (see 5.2.).

The results for the Northern Territory showed that monsoonal activities with high rainfall over longer periods of time explained between 30-40% of the catch variability. Sea surface temperature and the selected MJO phases were, however, not significantly related to annual and seasonal mud crab catch but significant positive relationships with monthly SST lagged by 6 month and log CPUE were indicated.

There were significant positive Pearson correlations between seasonal CPUE and average rainfall when lagged by one season. Good rainfall in the wet season appeared to stimulate overall productivity of the river system which, in turn, stimulated higher catch rates five to six months after the event. However, severe flooding can have long-lasting negative effects, as seen in the 2001 floods in the McArthur and Wearyan, which destroyed seagrass beds in the area with a corresponding decrease in catch (Appendix 7).

The identified lag effect of rainfall on catch between five and six months after rainfall events is followed by a positive lag effect on catch two years after a good wet season. However, a negative two-year lag effect of heavy rainfall events (causing major flooding) on mud crab catch can be seen in the data (Appendix 7). This can most likely be explained by the associated dieback of seagrass beds (which are needed by juvenile crabs) having a negative effect on recruitment success (Webley *et al.*, 2009).

Enhanced freshwater flow has beneficial short-term effects by increasing catches for up to two weeks after the rainfall events; however, these were not covered by the monthly resolution of the data and therefore not shown. Fishers have reported this phenomenon, which can likely be attributed to enhanced activity of mud crabs leaving their burrows and thus increasing catchability.

There were some indications from the analyses that years of very high temperatures had a negative effect on mud crab catches, particularly for regions where crabs are caught on intertidal flats rather than in deep water. In general, the annual water temperature variation is small and therefore has a small effect on the mud crab catch data. Monthly SST variation is larger and might therefore have a stronger influence on the mud crab life cycle. High temperature may have negligible negative effects on mud crab catches, particularly for western systems such as the Mary, Adelaide and Daly, where average water temperatures can exceed 35°C. High temperatures may also have negative effects where/when mud crabs are caught on mud flats. In this case, catches are generally reduced due to high temperatures increasing mortality in the crab pots but also increased post-harvest mortality and reduce the fisher eagerness to go crabbing.

Two distinct groups were identified using nMDS plots that included measurements of catch, effort, temperature and rainfall. These groups were the western group of river systems - Bynoe Harbour Adelaide, Daly and Mary Rivers, and the Gulf of Carpentaria group including Roper, Robinson/Wearyan and McArthur Rivers. These groups are mainly caused by the distinct differences in catch and rainfall attributes. This is also reflected in the general habitat differences between the Gulf of Carpentaria systems and other river systems (Hay *et al.*, 2005).

Analyses of the Daly River demonstrated that catch data with significant gaps over time were not suitable for the performed analyses. No significant results were obtained for this river system; however, it is expected that the same relationship would have existed as for the other systems if higher and continuous catch data had been available. The results of the Daly River were in line with the observation that in regions with high catches (and therefore a high abundance of mud crabs); catch was more likely driven by environmental factors, whereas in regions with low catch rates, effort was the most important driver of catches.

The results from the regression analyses suggested the following possible general linear model for the Northern Territory annual mud crab catches: annual CPUE = Log (total rainfall November – April, two years prior to catch) + (SOImax same year) – (max flow volume two years prior to catch). In order to improve the model the total catchment size could be included. If the flow volume is available, this could be a better explaining factor than catchment rainfall, as is indicated by the higher correlation between modeled flow and mud crab CPUE.

Attempts have been made to use linear models to predict prawn catch in the Gulf of Carpentaria or maximum likelihood estimation (MLE) for depletion analysis based on a more complete specification of the process (Schnute, 1983; Bedrick, 1994; Wang and Loneragan, 1996; Loneragan and Bunn, 1999; Wang, 1999; Burridge *et al.*, 2003). However, large fluctuation in effort and unknown parameters made these models unreliable. In recent years, hierarchical Bayesian model were used for parameter estimation. Zhou *et al*. (2008) applied a hierarchical Bayesian model to the Northern Banana Prawn (*Penaeus merguiensis*) Fishery to assess abundance and catchability. Hierarchical Bayesian models are likely to become increasingly popular, especially for the assessment of short-lived invertebrates.

## 5.2 Queensland Mud Crab Catches and Environmental Drivers

### 5.2.1 State-Specific Background Information

The Queensland coastal environment is characterised by large variations in rainfall and temperature, ranging from subtropical conditions in the southeast, dry tropical in central Queensland, and wet tropical in north Queensland. Previous studies on mud crab catches found positive relationships between mud crab catches and river flow in southeast Queensland (Loneragan and Bunn, 1999), as well as positive relationships between rainfall and coastal wetland presence for most parts of Queensland (Meynecke *et al.*, 2006; Meynecke *et al.*, 2007). Queensland's mud crab fishery is very seasonal, with catches following a regular trajectory of highs during the warmer months of November to May and lows in the cooler months of June to October. Effort tracks catches seasonally, but changes in effort are not the sole determinant of catch, as catch rates also vary with great seasonal regularity.

It is common for fishers to hold a number of different fisheries licences and switch between the licences depending on the season and market prices of species. Catch data, particularly for river systems that experienced changes of regulations such as implementation of marine protected areas, may not provide reliable catch data. Queensland is the only state with a fishery-independent annual mud crab survey with the objective to monitor mud crab abundance independently. The fishery experienced a steady increase in catch from 1988-2008. For example, in 2004, Queensland took the lead in mud crab catches over New South Wales, Northern Territory and Western Australia with almost 1200 t (Figure 15). However, fluctuations of mud crab catches occurred between 2001 and 2005 - similar to those experienced in the Northern Territory. Wholesalers are along the coast of Queensland in major capital cities such as Brisbane, Rockhampton, Townsville and Cairns. From these locations, mud crabs are sold to either local markets or transported to capital cities.

For the Queensland mud crab catch analyses, the following variables were considered: average rainfall in the catchments, sea surface temperature within 20 km of the river mouth, SOI, maximum SOI and freshwater flow when available in monthly, seasonal (two seasons) and annual temporal configurations. A total of 14 catchments (that included 29 large river systems) were selected based on catch and geographic location to cover most Queensland conditions. The selected systems represent 64% of the total Queensland commercial mud crab catch between 1988 and 2008.

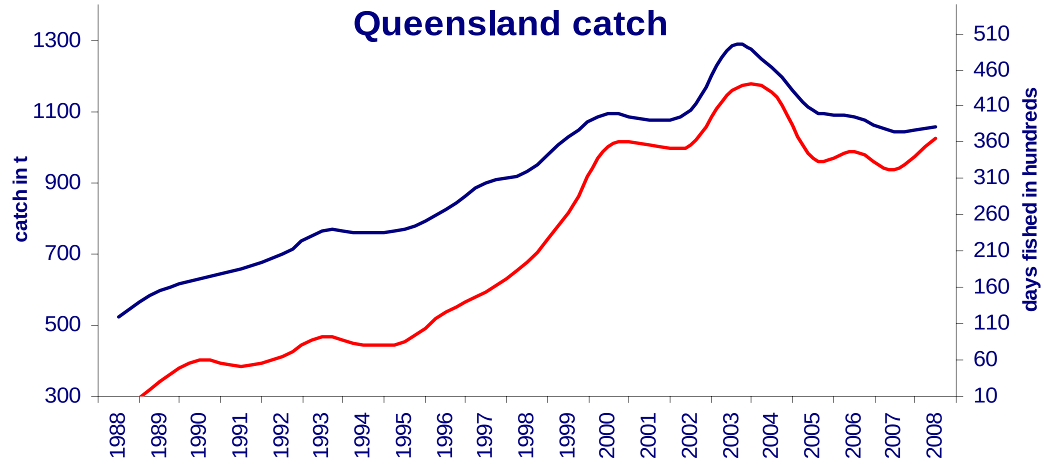


Figure 15. Queensland commercial mud crab catch in tonnes and fishing days for the years 1988-2008. Red represents number of fishing days and blue represents CPUE.

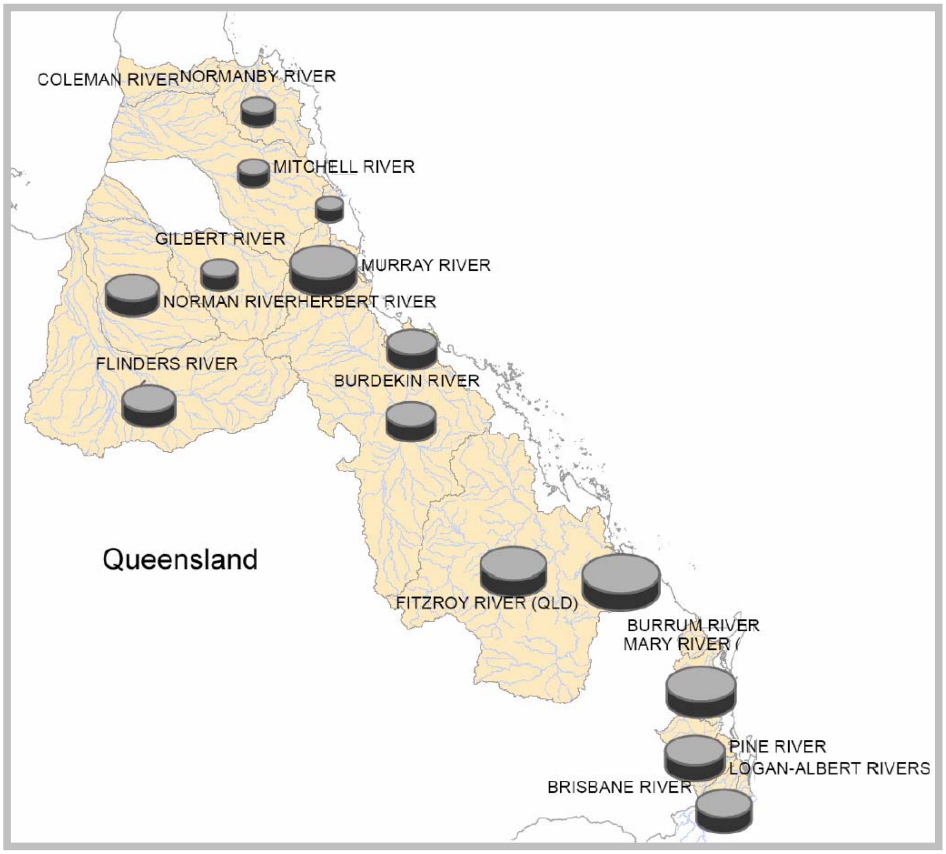


Figure 16. Fourteen selected catchments for 29 river systems showing relative proportion of total catch between 1988 and 2008. The selected systems represented 64% of the total Queensland mud crab catch between 1988 and 2008.

### 5.2.2 Correlation Analyses

*Annual*

Analyses of annual data using Pearson Correlation showed a high variability in the relationships between the selected river systems. A general trend was identified showing that maximum SOI values, rainfall and mud crab CPUE were positively correlated for 12 of the 13 systems (Table 9). Temperature was in some cases negatively correlated with mud crab CPUE but no trend was shown by the data. Catch data from the Herbert, Flinders, Embley, Baratta and Burdekin Rivers were significantly correlated with maximum SOI and/or rainfall. A good relationship for lagged environmental drivers with mud crab CPUE was identified with a one-year lag. However, analyses indicated that a lag of between one and two years provided the highest r values.

*Seasonal and Monthly*

Analyses of monthly mud crab CPUE and average catchment rainfall indicated significant correlations for some of the river systems. Monthly temperature was positively related with mud crab CPUE for seven river systems and negatively with the Gulf and Far North Queensland river systems. As the main harvest period for the east coast systems is during the wet season, and for the Gulf of Carpentaria systems is the dry season, this pattern and the associated relationship is not surprising. Significant relationships were also detected for monthly rainfall lagged by two years (e.g. the Burdekin River).

Analyses of wet and dry season configured data revealed significant relationships between mud crab CPUE and SOI, SST, flow or rainfall for nine river systems. Only the Gilbert had a negative r value due to the catch being recorded only for the dry, and therefore cooler, season (Table 10).

Table 9. Example of Pearson's r values for analyses between annual mud crab CPUE, catchment rainfall, SST and SOI max lagged by one and two years. Significant correlations are indicated in bold (* P<0.05, ** P<0.01).

| System | Annual CPUE - SST | Annual CPUE - SST 1-yr lag | Annual CPUE – SOI max | Annual CPUE – SOI max 2-yr lag | Annual CPUE - rainfall | Annual CPUE - rainfall 1-yr lag | Annual CPUE - rainfall 2-yr lag |
|---|---|---|---|---|---|---|---|
| Albert | - | - | - | - | .27 | **.44*** | **.49*** |
| Barron | - | .24 | .37 | .19 | - | - | - |
| Burdekin | - | - | **.69**** | **.51*** | **.57**** | **.59**** | .23 |
| Mitchell | .21 | - | .21 | - | - | .40 | **.47*** |
| Fitzroy | - | -.25 | - | .42 | -.21 | -.15 | - |
| Gilbert | -.29 | .22 | .38 | .25 | .26 | .16 | - |
| Mary | -.25 | - | -.25 | - | .35 | .23 | - |
| Baratta | .13 | .21 | **.61**** | .20 | **.58**** | .37 | - |
| Brisbane | - | -.33 | - | - | .41 | .36 | .41 |
| Calliope | .30 | .14 | - | .29 | 0 | -.16 | -.31 |
| Embley | - | - | .19 | -.31 | **.53*** | **.50*** | .22 |
| Flinders | - | - | .28 | **.51*** | 0 | .31 | .30 |
| Herbert | -.10 | .15 | **.81**** | **.50*** | **.61*** | .42 | .19 |
| Normanby | .27 | .13 | - | - | - | -.27 | - |

Table 10. The most significant relationship between seasonal CPUE and selected environmental drivers.

| System | Season | Variable | r for CPUE |
|---|---|---|---|
| Albert | dry | SST | **.32**** |
| Barratta | wet | SST | **.24**** |
| | dry | SOI | **.23*** |
| Barron | dry | Flow | **.36**** |
| Brisbane | wet | SST | **.32**** |
| Burdekin | wet | SOI | **.26**** |
| | dry | Flow | **.26*** |
| Calliope | wet | Flow | **.22*** |
| Gilbert | wet | SST | **-.39**** |
| Herbert | wet | SOI | **.57**** |
| | dry | SOI | **.55**** |
| Normanby | dry | rainfall | **.51*** |

### 5.2.3 Regression and Forward Stepwise Multiple Regression Analyses

The analyses for Queensland mud crab CPUE showed that the SOI and rainfall played similar important roles, explaining 30-50% of the variation in mud crab catch for six of the selected river systems. Sparse or non-continuous data for the Gulf systems often led to non-significant results for these systems. When mud crab CPUE and environmental drivers were lagged by two years, data still showed significant $r^2$ values for most of the analysed river systems, with rainfall and SOI being the most relevant drivers. Significant relationships between Queensland annual mud crab CPUE over 20 years of observation and annual maximum SOI values, explained about 34% of catch variability (Figure 17, 18). The Calliope, Normanby and Mary River systems showed no significant results (Table 11).

Table 11. Forward stepwise regression and multiple regression for Queensland river systems using annual mud crab CPUE and environmental variables (n = 20) lagged by two years (n = 18). Significant $r^2$ values are indicated in bold (* P<0.05, ** P<0.01).

| **System** | **Climatic parameter** | **$r^2$** | **Adj. r2** | **Climatic parameter** | **$r^2$** | **Adj. $r^2$** | **Climatic parameter** | **$r^2$ (2yr lag)** | **Adj. $r^2$** |
|---|---|---|---|---|---|---|---|---|---|
| Albert | SST/rainfall/ SOI | NSC | | | NSC | | Rainfall mean | .235* | .19 |
| Barratta | SOI max | .474** | .441 | Rainfallmax, SOImax, Rainfallmean | .614** | .546 | SOI max | NSC | |
| Barron | SOImax | NSC | | SST, SSTmax, flow, rainfall, rainfallmax, SOImax, SOI | .514* | .248 | SOI max | NSC | |
| Brisbane | Rainfallmax | .268* | .23 | Rainfallmax, SOI | .505** | .45 | Rainfall max | .202* | .155 |
| Burdekin | SOImax | .598** | .573 | SOImax, SSTmax | .757** | .725 | SOI max | .265** | .219 |
| Calliope | SST | NSC | | SST, rainfall max | .222 | .136 | SST, rainfall max | NSC | |
| Coleman | SOImax | NSC | | SOImax | NSC | | Rainfall max | .407** | .365 |
| Embley | Rainfallmean | .365** | .323 | Rainfall mean | NSC | | Rainfall max/mean | NSC | |
| Fitzroy | SOImax | NSC | | SOImax | NSC | | SOI max | .577** | .492 |
| Flinders | SOImax | NSC | | SOImax | NSC | | Max SST | .243* | .195 |
| Gilbert | SOImax | .267* | .226 | Flow | .220* | .171 | Flow | .203* | .154 |
| Herbert | SOImax | .613** | .589 | SOImax, rainfallmean | .665** | .627 | SOI max, SOI, flow | .717** | .656 |
| Mary | Rainfallmax | NSC | | Rainfallmax | NSC | | Rainfall max | NSC | |
| Norman. | SST | NSC | | SST | NSC | | Rainfall mean | NSC | |

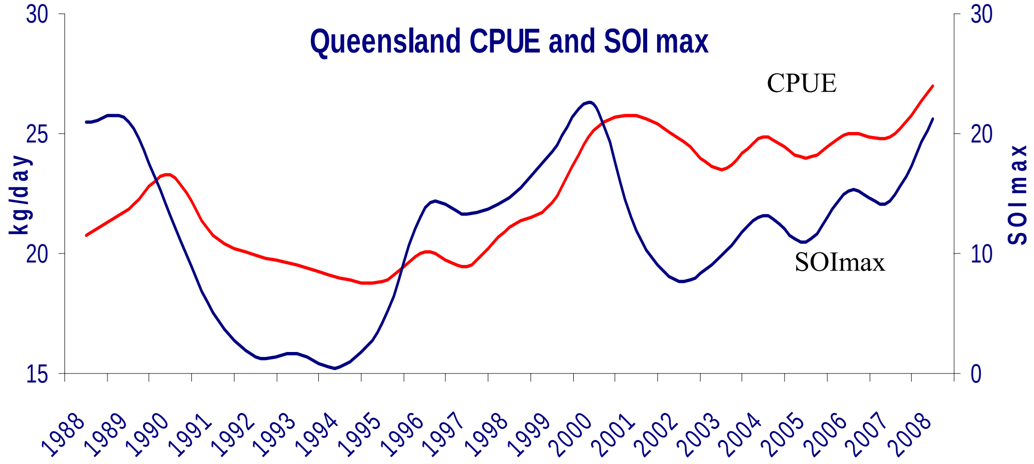


Figure 17. Queensland CPUE and SOI maximum values between 1988 and 2008. Similar to the Northern Territory, the relationship between kg/day of mud crab catch and SOI max is significant with an $r^2 = 0.34$, i.e. explaining about 34% of the mud crab catch variability. Blue shows maximum SOI values and red represents CPUE.

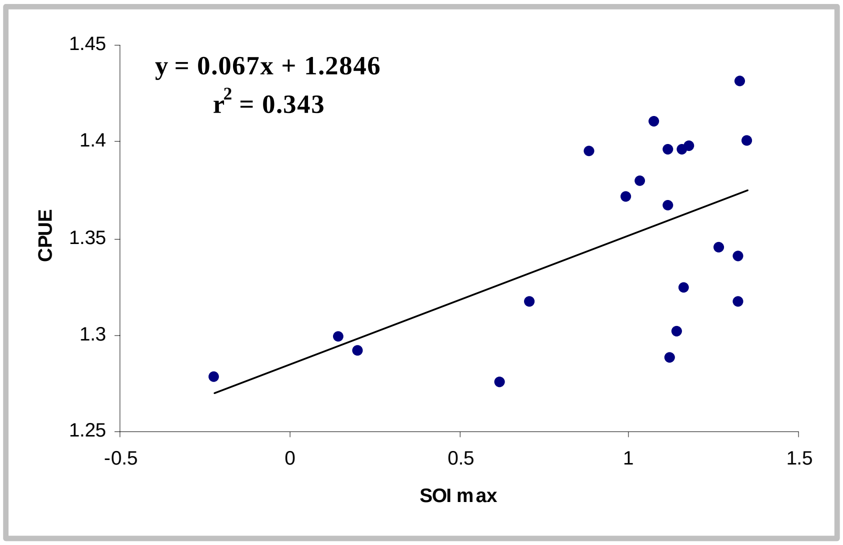


Figure 18: Linear relationship between mud crab CPUE and maximum SOI values in Queensland for 20 years of observation. SOI values explained about 34% of the CPUE variability.

### 5.2.4 Meta-Analyses

A nMDS using mud crab catch, kg/day, mean rainfall and mean temperature separated the data in three major groups: Gulf/northern Queensland, central Queensland, and southern Queensland. The Gulf has smaller catches, which is likely not a reflection of the productivity of the systems in this region, but rather, fishery accessibility. However, the southeast and central Queensland river systems overlapped and, as indicated by the data, there were similar relationships between mud crab CPUE and environmental drivers for these river systems.

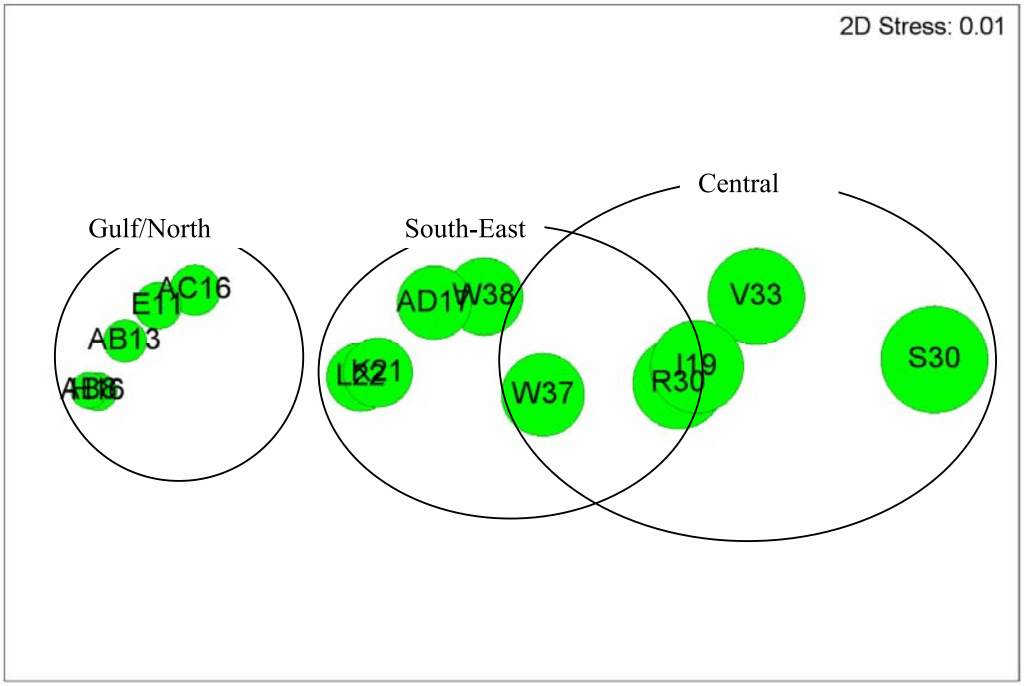


Figure 19**.** nMDS plot displaying the 14 selected catchment systems for Queensland mud crab catch analyses. The green circles represent the total mud crab catch between 1988 and 1990. The plot is based on standardised average catch, CPUE, SST and rainfall between 1990 and 2008 using Euclidean distance. Gulf systems – AC16 (Coleman/Mitchel River), E11 (Normanby River), AD17 (Flinders, Norman rivers) AB8 (Embley River), AC16 (Gilbert River), AB13 (Mitchell, Coleman River). Central systems: R30 (Fitzroy, Raglan River), S30 (Calliope, Boyne rivers), I19 (Herbert, Tully River), K21 (Barratta, Houghton River), L22 (Burdekin River), H16 (Barron River). South-East systems: W37 (Brisbane River), W38 (Albert, Logan, Nerang, Coomera rivers), and V33 (Burrum, Mary rivers).

### 5.2.5 Discussion

The overall trend showed that SOI values were a good predictor for mud crab CPUE throughout Queensland and results were similar, though less significant in some cases, to those of the Northern Territory. Catchment rainfall, and in some cases flow, also provided significant results for a number of river systems. The same principles for the cause of this relationship apply to both the Northern Territory and Queensland. High, positive SOI values indicate higher rainfall and temperatures for most parts of coastal Queensland. These factors enhance estuarine productivity. Good wet seasons with higher than average rainfall which increases river flow and flooding while reducing salinity - factors that have been attributed to enhanced mud crab growth and survival (Hill, 1974, Hill and Williams, 1982, Heasman *et al.*, 1985, Le Vay *et al.*, 2001).

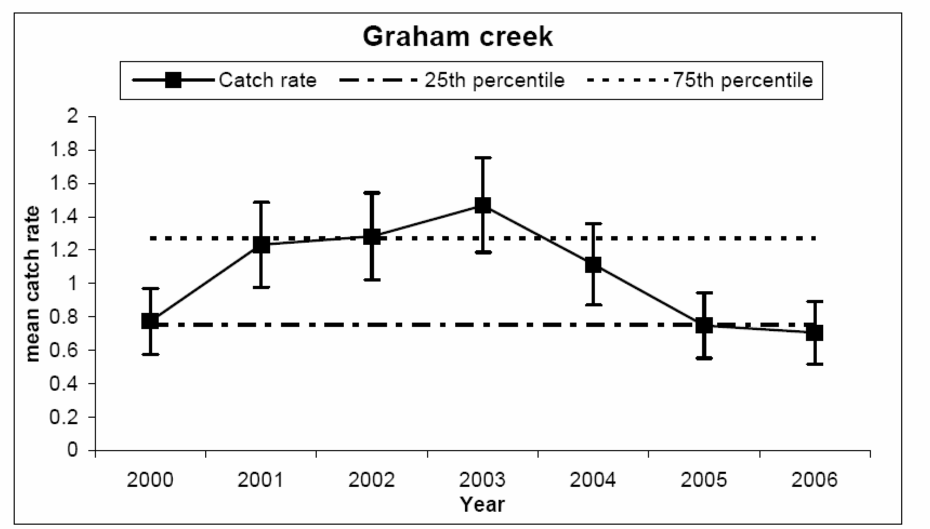
The strength of the relationship varied between regions, and besides biogeographical factors, a strong influence of market demand on mud crab catch, regulations and changes in the reporting made analyses of the data difficult. For example, the Fitzroy River is a system that is under the influence of the abovementioned factors; it is interesting to note that no significant relationships were detected with environmental drivers for this river system. The Gulf of Carpentaria river systems showed positive relationships with catchment rainfall but their catch data were concentrated over the dry season and was poorly, if at all, reported in the first years of catch data recordings. Therefore, the relationship between selected environmental variables and mud crab catch was not consistent throughout the river systems. The following systems had significant relationships with either the SOI or rainfall: Barratta, Brisbane, Burdekin, Herbert, Embley, Gilbert, Albert and Mary; whereas the Flinders, Fitzroy and Normanby systems had no strong signal throughout the analyses.

As expected, the data analyses showed a strong positive relationship for monthly configuration with temperature (SST), particularly for southeast Queensland. This is due to the fact that mud crabs are less active and abundant in the cooler dry season and most catches occur between February and April.

A lag effect of rainfall and maximum SOI values by two years was shown in the correlation and regression analyses. The time it takes for mud crabs to recruit to fisheries is between one and two years depending on the region. The relationship was therefore weaker for a one-year lag and for a three-year lag. These lag effects are similar to the Northern Territory, but were in general not as significant. This can most likely be attributed to the way mud crab catch data were collected.

We discovered a distinct grouping between Gulf of Carpentaria/Far North Queensland systems and central/southeast Queensland systems using nMDS plots. Both the Gulf of Carpentaria and Far North Queensland river systems had lower catch and CPUE as well as generally higher temperatures. The central and southeast Queensland systems did separate using mud crab catch, CPUE, temperature and rainfall; although not all river systems were separated indicating a gradual transition between these two regions. The difference between the Gulf of Carpentaria and the east coast of Queensland is also reflected in the results of the long term monitoring program by Queensland Fisheries. Catch data from Weipa followed a similar trend to the catch from the Northern Territory whereas the catch data from the Graham Creek showed no decline over the 2002-2004 period.

a.



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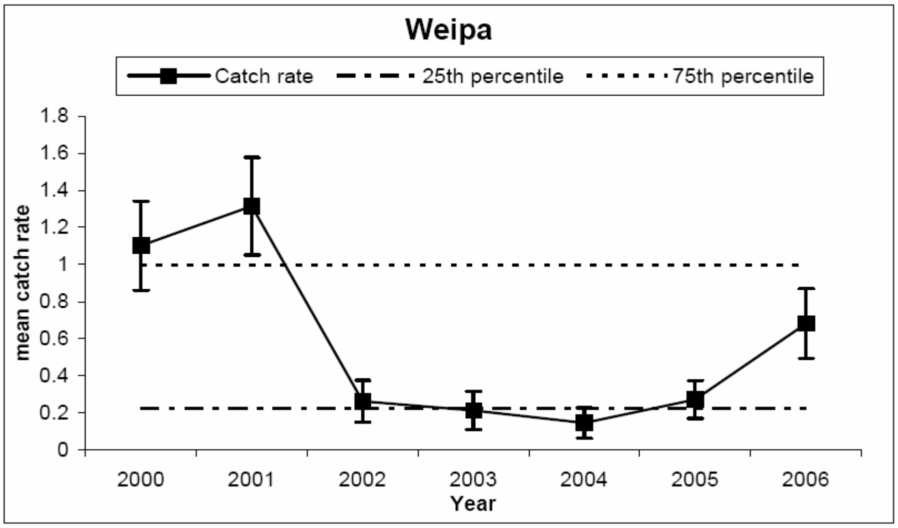


Figure 20a/b. Mud crab catch-rate (CPUE) trends at three of the long term monitoring program sampling locations over the period 2000-2006 (Brown, 2010).

The results from the regression analyses suggested the following possible general linear model for Queensland annual mud crab catches: annual CPUE = Log (maximum SOI value) + (mean annual rainfall). To improve the model the total catchment size could be included and, if available, flow volume would be a better factor over catchment rainfall.

## 5.3 New South Wales Mud Crab Catches and Environmental Drivers

### 5.3.1 State Specific Background Information

The New South Wales coastal environment is characterised by a subtropical to temperate climate and four recognisable seasons. There are distinct temperature differences between summer and winter influencing the mud crab life cycle. Pease (1999) divided the estuarine systems into Northern, Central and Southern bioregions. Saintilan *et al*. (2004) found that higher catches of mud crabs were associated with barrier estuaries, tidal sand flats, mangroves and saltmarsh presence.

Fisheries in New South Wales have been the most regulated over time compared to the Northern Territory and Queensland. The monthly recording of New South Wales mud crab catch data started in the fiscal year 1984/1985; however, it was not possible to relate catch to effort until 1997/1998. Therefore, we treated the two data sets (1984/1985-1996/1997 and 1997/1998-2008/2009) separately for analyses and used fiscal years instead of calendar years.

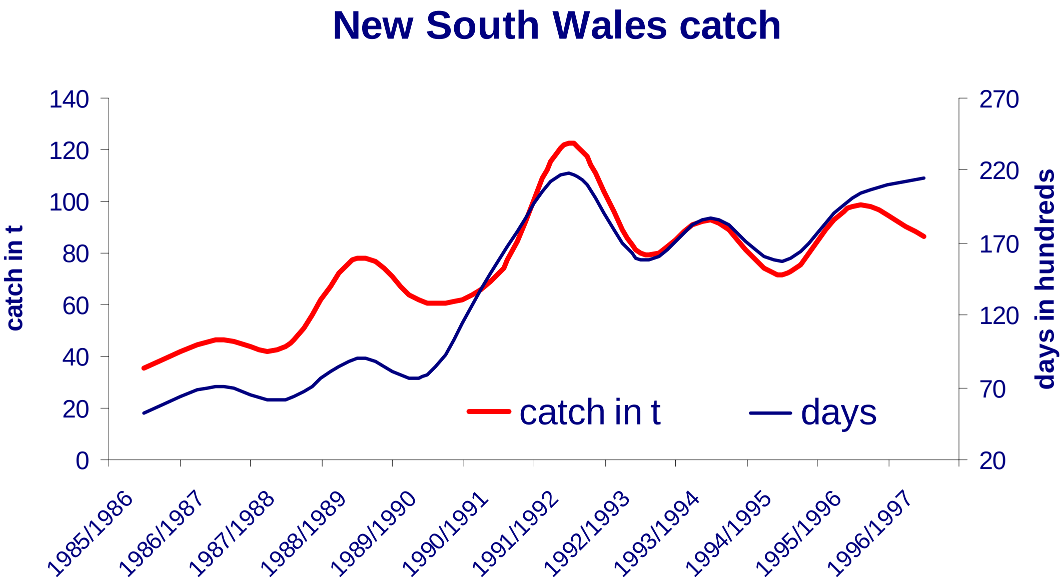
New South Wales mud crab fishery has experienced several management restructures and changes to control measurements, particularly in the last 10 years. Commercial fishing has ceased in some areas, such as Camden Haven, which has been declared a recreational fishing haven. Legal limits and restrictions for mud crabs in New South Wales were introduced in 1982. Consequently, black marketing may have occurred in the beginning of catch recording since 1984. Sydney functions as the main market for mud crabs; however, a number of smaller cities such as Coffs Harbour, Newcastle and Port Macquarie also provide local markets.

Analyses of long-term catch data starting from 1940-1991 showed a high catch of crustaceans in Tweed Heads, Brunswick, Ballina, Evans Head, Iluka, Batemans Bay, Clarence, Wallis Lake, Manning River, Camden Haven, Hunter River, Hawkesbury and Port Jackson. Most of these systems were included in the analyses for this report. For the analyses, the following variables were considered: average rainfall in the catchments, sea surface temperature in close proximity to the river mouth, SOI, maximum SOI and freshwater flow when available in monthly, as well as seasonal (four seasons) and annual temporal configurations. For New South Wales, 10 catchments that represented 17 river or lake systems were selected. The New South Wales river systems were selected based on total catch between 1997-2008. Systems that contributed at least 5 t per year to the total catch in New South Wales were chosen for further analyses to avoid smaller areas that may not have had a continuous operator.

Of the 1216 t of mud crab catch in the pot and trap fishery from 1996/97-2008/09, a total of 1146 t from the pot fishery, covering 94% of New South Wales mud crab catches, were represented by the selected river systems. The total mud crab catch data for New South Wales between 1984/85 and 1996/97 were 1233 t for all fishing methods. About 849 t, or 69%, of the overall NSW catch were caught in the selected river systems for this time period. The selected river systems therefore represent over two thirds of the New South Wales mud crab catch.

For the period 1985-1997, mud crab catches increased from 40 t to a peak of 120 t in 1991/1992 followed by oscillating peaks of 100 t per fiscal year and lows of 80 t per fiscal year until 1996/1997.

Catch rates decreased gradually from 120 t to less than 80 t per fiscal year for the time period 1997/1998-2007/2008. For both periods effort in number of fishing days followed the trend in catch.



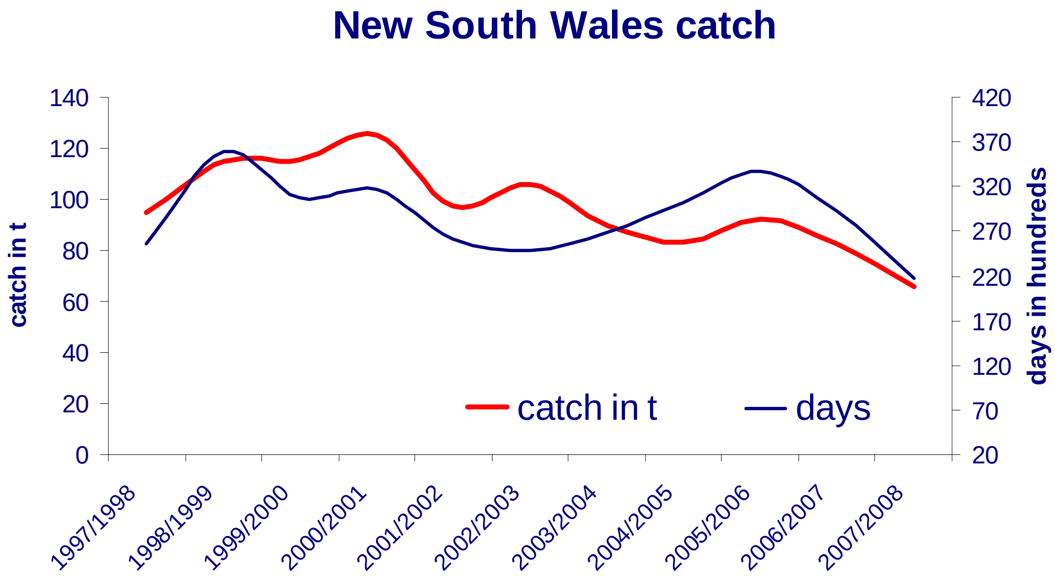


Figure 20a and b. New South Wales mud crab catch in tonnes and fishing days for the fiscal years 1985-1997 (Figure 20 a) and 1998-2008 (Figure 20 b).

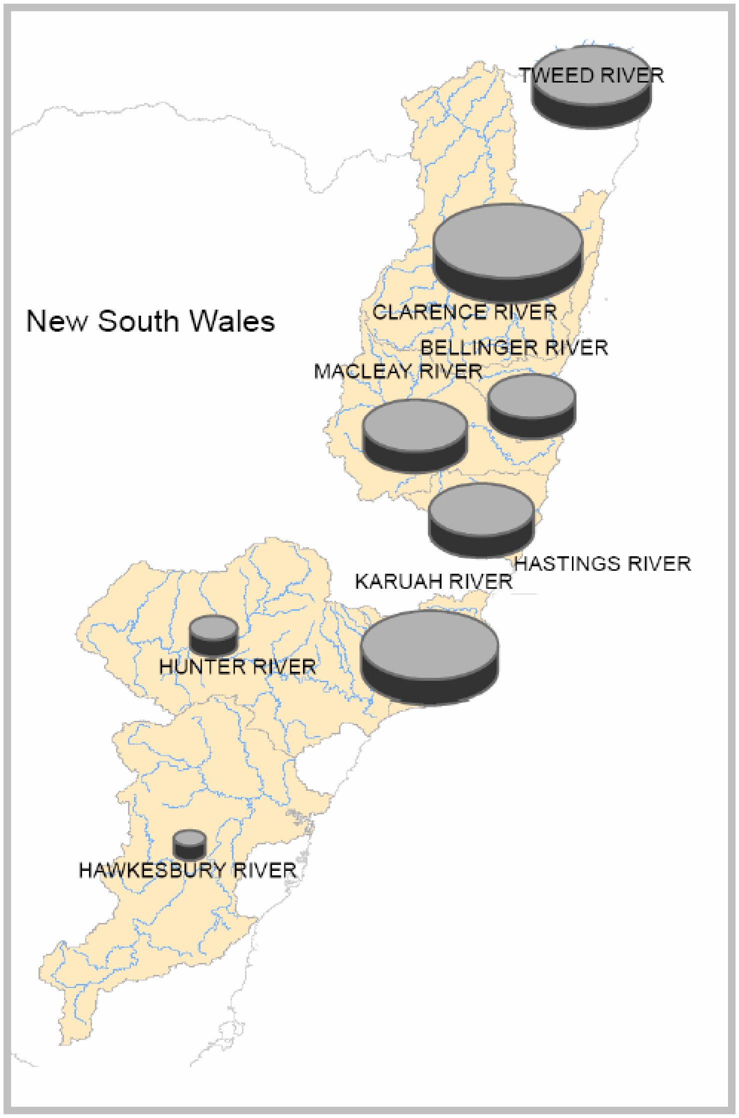


Figure 21. Eight selected catchments for 17 river or lake systems showing relative proportion of total catch between 1997-2008. The selected systems represented 94% of the total New South Wales mud crab catch between 1997-2008. The systems that contributed most to the catch were the Clarence and Karuah catchments.

### 5.3.2 Correlation Analyses

*Annual*

Analyses of fiscal years, rainfall and/or flow, temperature and SOI values revealed mixed relationships with no obvious trends in the data set. None of the Pearson correlation analyses provided significant results and, in some cases, the relationship with temperature and/or rainfall was negative. This is likely due to the strong effect of effort and management changes on the mud crab catch.

### *Seasonal and Monthly*

The strongest Pearson correlations were found between monthly SST and mud crab CPUE. All of the analysed river systems showed significant relationships between SST and CPUE. This was also true when the data were lagged by one and subsequent years. There was no significant, consistent, inter-annual trend. The relationship between mud crab CPUE and mean catchment rainfall was not as strong; however, it increased for almost all tested river systems when data were lagged by one and two years.

Table 12. Example of Pearson correlations between monthly mud crab CPUE, mean catchment rainfall and SST lagged by one year for the time period 1997-2008. Significant r values are indicated in bold (* P<0.05, ** P<0.01).

| **System** | **monthly CPUE-SST** | **monthly CPUE-SST 1-yr lag** | **monthly CPUE-rainfall** | **monthly CPUE-rainfall 1-yr lag** |
|---|---|---|---|---|
| Clarence | **.68**** | **.64**** | .25 | **.40** |
| Hastings | **.77**** | **.70**** | **.37** | **.37** |
| Hawkesbury | **.36** | **.39** | .17 | .25 |
| Hunter | **.45** | **.53**** | .24 | .19 |
| Macleay | **.34** | **.45** | 0 | **.31** |
| Nambucca, Bellinger | **.33** | **.23** | 0 | .15 |
| Port Stephenson, Karuah River | **.53**** | **.56**** | .11 | .13 |
| Wallis Lake | **.35** | **.36** | 0 | 0 |
| Tweed | **.69**** | **.67**** | .25 | **.42** |

Table 13. Example of Pearson correlations between annual mud crab CPUE, mean catchment rainfall and SST lagged by two years for fiscal years 1984/1985-1996/1997 (a) and 1997/1998-2007/2008 (b). Significant r values are indicated in bold (* P<0.05).

a.

| **System** | **Annual CPUE-SST** | **Annual CPUE-SST 2-yr lag** | **Annual CPUE-rainfall** | **Annual CPUE-rainfall 2-yr lag** |
|---|---|---|---|---|
| Clarence | -.56 | -.47 | -.27 | .23 |
| Hastings/CH | .31 | .19 | .28 | .38 |
| Hawkesbury | .17 | -.19 | .43 | .20 |
| Hunter | .46 | .0 | .38 | **.67*** |
| Macleay | -.19 | .62 | -.36 | .27 |
| Nambucca, Bellinger | .0 | .14 | .47 | -.57 |
| Port Stephens, Karuah River | .29 | .34 | .52 | .23 |
| Wallis Lake | -.59 | -.56 | -.38 | -.53 |
| Tweed | .31 | .0 | .28 | .0 |

b.

| System | Annual CPUE-SST | Annual CPUE-SST 2-yr lag | Annual CPUE-rainfall | Annual CPUE-rainfall 2-yr lag |
|---|---|---|---|---|
| Clarence | .14 | .0 | .51 | .18 |
| Hastings | .20 | .51 | .44 | .0 |
| Hawkesbury | .49 | .41 | .37 | .18 |
| Hunter | .0 | .48 | .45 | .18 |
| Macleay | -.49 | -.19 | -.40 | .37 |
| Nambucca, Bellinger | .25 | -.61 | -.51 | .0 |
| Port Stephens, Karuah River | .12 | .0 | .34 | **.77*** |
| Wallis Lake | -.57 | -.23 | .19 | -.52 |
| Tweed | .54 | .0 | .12 | .0 |

### 5.3.3 Regression and Forward Stepwise Multiple Regression Analyses

Analyses using forward regression and multiple regression for monthly and seasonal data configurations revealed significant $r^2$ values for most of the selected river systems. The best explanatory factor for mud crab CPUE was temperature, either in combination with SOI, or mean rainfall and SST. These environmental drivers explained most of the monthly mud crab CPUE variability. When catchment rainfall was added as a second variable in the linear models, the $r^2$ values increased and were between 0.5-0.7 for some river systems. As fishing usually did not occur over winter months, this was an expected outcome. When SST lagged by two years for different seasons was put into a regression on its own with mean mud crab CPUE, the best explanatory factor was mean summer SST or mean spring SST (Table 14).

It is important to note that mean catchment rainfall had the best $r^2$ values with two-year lagged mud crab CPUE. A pattern was identified that particularly occurred in the 1985-1997 data set, where a positive relationship between mean autumn SST and mud crab CPUE was identified. The same was true for two-year lagged mean catchment rainfall/flow and mud crab CPUE. Either summer or spring temperatures appeared to have increased catches, with rainfall during the same seasons also increasing catches with a two-year lag. A trend that was predominantly evident within the Clarence and the Hunter River systems (Table 14 and Figure 15).

Table 14. Example of significant relationships between seasonal kg/day and sea surface temperature in New South Wales for mud crab catches between 1997 and 2008. Significant r values are indicated in bold (* $P<0.05$, ** $P<0.01$).

| System | $r^2$ values for monthly SST | $r^2$ values for seasonal SST with 2yr lag |
|---|---|---|
| Camden | .45 | .29 (summer) |
| Clarence | .44 | .54 (spring) |
| Hastings | .28 | NSC |
| Hawkesbury | NSC | NSC |
| Hunter | NSC | .37 (summer) |
| Macleay | .25 | NSC |
| Nambucca | .13 | .41 (summer) |

| System | $r^2$ values for monthly SST | $r^2$ values for seasonal SST with 2yr lag |
|---|---|---|
| Port Stephens | .27 | NSC |
| Wallis Lake | .15 | NSC |
| Tweed | .42 | .32 (summer) |

Table 15. Example of significant $r^2$ values between seasonal log transformed New South Wales mud crab CPUE and log transformed sea surface temperature or rainfall for the fiscal years 1984/1985-1996/1997. CR – Clarence, CH – Camden Haven, Mac - Macleay, TW – Tweed, PS – Port Stephens, HU – Hunter, HK - Hawkesbury.

| System | Climatic parameter | $r^2$ | P-value | $r^2$ 2yrlag | P-value |
|---|---|---|---|---|---|
| CR | MeanAutumnSST | .439 | .01 | NSC | NSC |
| CR | MeanSummerRainfall | NSC | NSC | .227 | .04 |
| CH | MeanAutumnSST | .352 | .02 | NSC | NSC |
| CH | MeanSummerRainfall | NSC | NSC | .337 | .02 |
| Mac | MeanSpringSST | .448 | .01 | NSC | NSC |
| TW | MeanSpringSST | NSC | NSC | .285 | .04 |
| TW | MeanSummerRainfall | .342 | .02 | NSC | NSC |
| PS | MeanSummerSST | .393 | .01 | NSC | NSC |
| PS | MeanSummerRainfall | NSC | NSC | .522 | .00 |
| HU | MeanSummerSST | .403 | .01 | NSC | NSC |
| HU | MeanSpringRainfall | NSC | NSC | .716 | .00 |
| HK | MeanSummerSST | NSC | NSC | .335 | .02 |

When the total fiscal data from all selected river systems were entered into regression analyses, the maximum SOI values provided a significant $r^2$ of 0.30, i.e. explaining 30% of the mud crab CPUE variability between 1984/1985 and1996/1997. The strength of the relationship between mud crab CPUE and maximum SOI values is similar to Northern Territory and Queensland but slightly weaker. However, this relationship was not found for the 1997/1998 to 2007/2008 data set due to management control. When mud crab CPUE from both data sets were presented in one graph, the changes in CPUE with the changes of logbooks (1997) and the implementation of closure zones (2001/2002) were reflected in the mud crab CPUE trend over the years. In 2004/2005 the CPUE reached a low of less than 3kg/day, a rate that was clearly too low to make mud crab fishing economically viable.

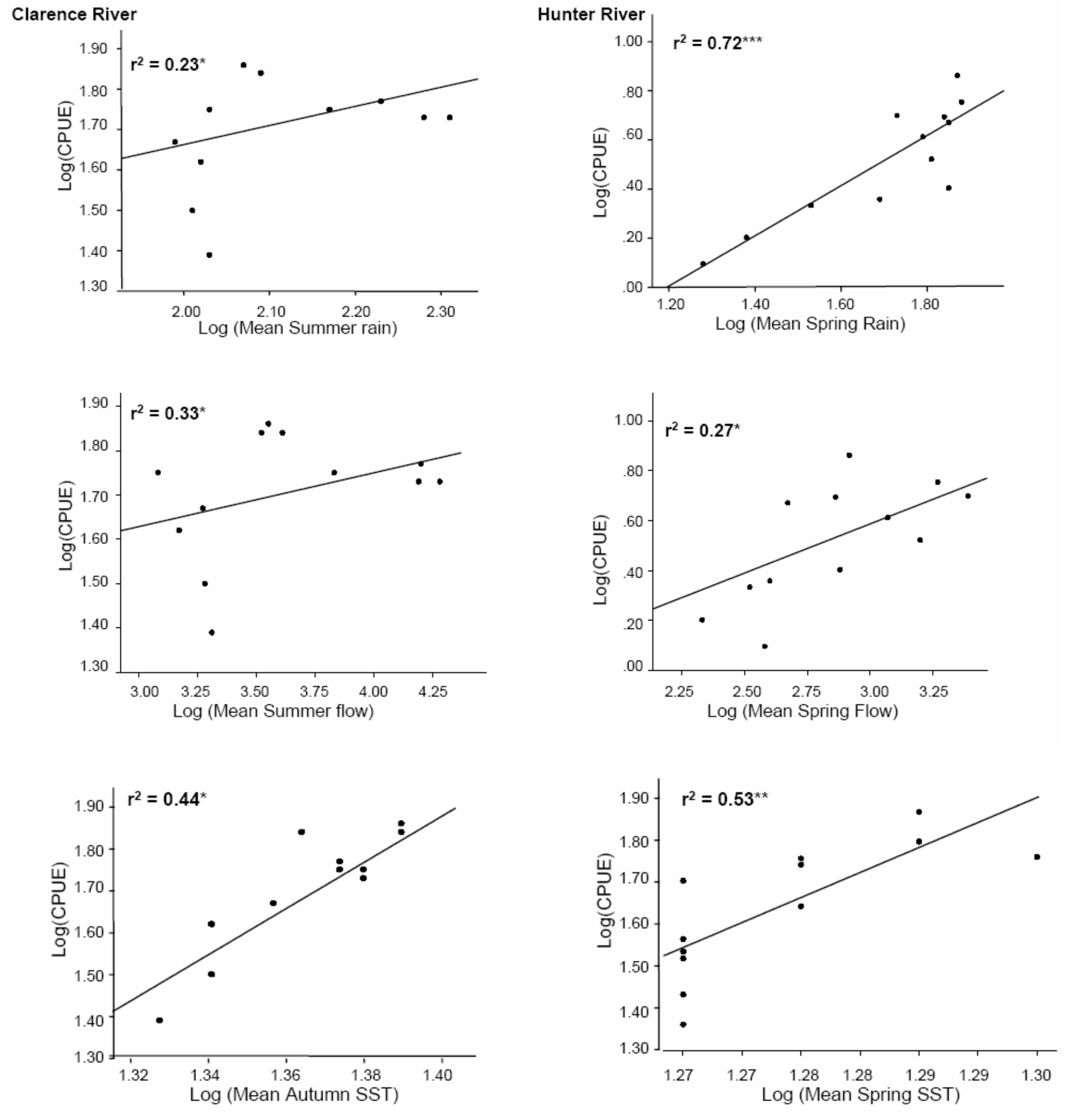


Figure 22. Linear relationships between log-transformed mud crab CPUE, mean temperature, mean catchment rainfall and mean flow for different seasons for the Clarence (left) and Hunter River (right) systems.

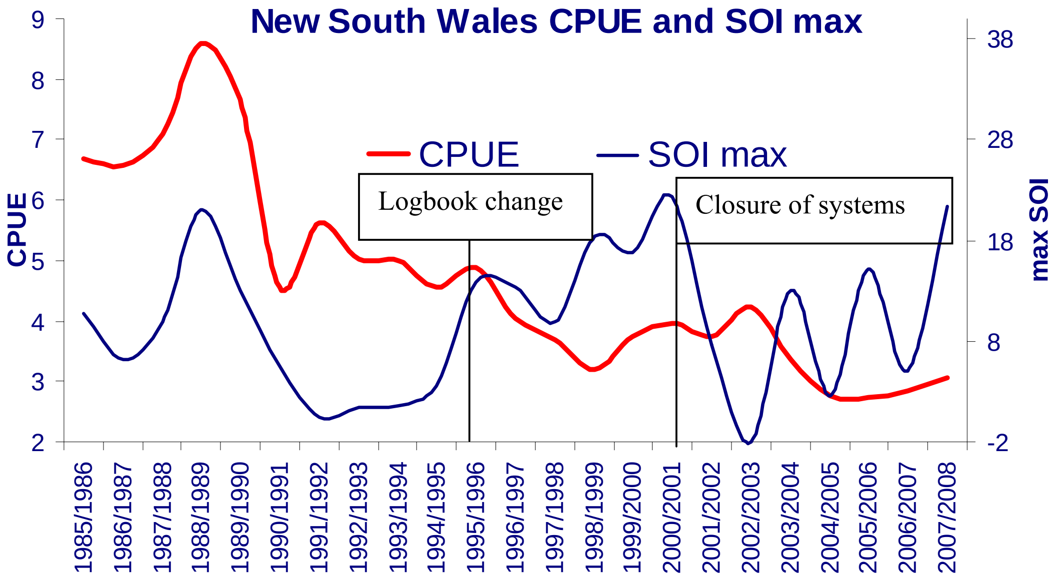


Figure 23. NSW CPUE and SOI maximum values between 1988 and 2008. Similar to the Northern Territory and Queensland, the relationship between kg/day of mud crab catch and SOI max is significant with an $r^2 = 0.30$ for the record time period 1984/1985 to 1996/1997.

### 5.3.4 Meta-Analyses

The overview of mud crab catch between the selected river systems revealed that higher catches occurred in the Tweed, Karuah and Clarence River catchments. An nMDS using mud crab catch, kg/day, mean rainfall and mean temperature separated the data into two major groups: the Central and North Bioregions. As previously defined by Pease (1999) (and expanded by Saintilan, 2004), the Hunter and Hawkesbury fell within the Central Bioregion, and the other selected river systems were part of the North Bioregion. The differentiation within the data set is mainly driven by temperature, with cooler temperatures in the Central Bioregion and slightly warmer temperatures in the Northern Bioregion. Total catch as indicated by the size of the circles in the nMDS plot (Figure 24) were also significantly different between Central and Northern Bioregions.

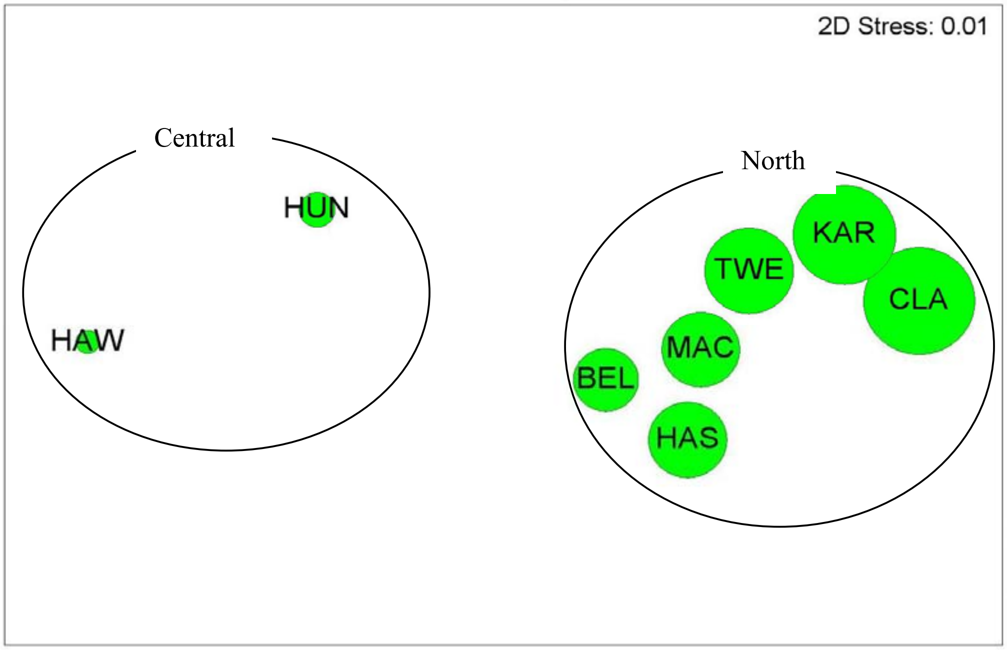


Figure 24. nMDS plot displaying eight of the nine selected river systems (excluding Wallis Lake as there was no flow or catchment rainfall data available) for New South Wales mud crab catch analyses. The size of the circles indicates the size of the total catch. The plot is based on standardised average catch, CPUE, SST and rainfall between 1997 and 2008 and transformed using Euclidean distance. HAW = Hawkesbury, HUN = Hunter, BEL = Bellinger, HAS = Hastings, MAC = Macleay, TWE = Tweed, KAR = Karuah, CLA = Clarence

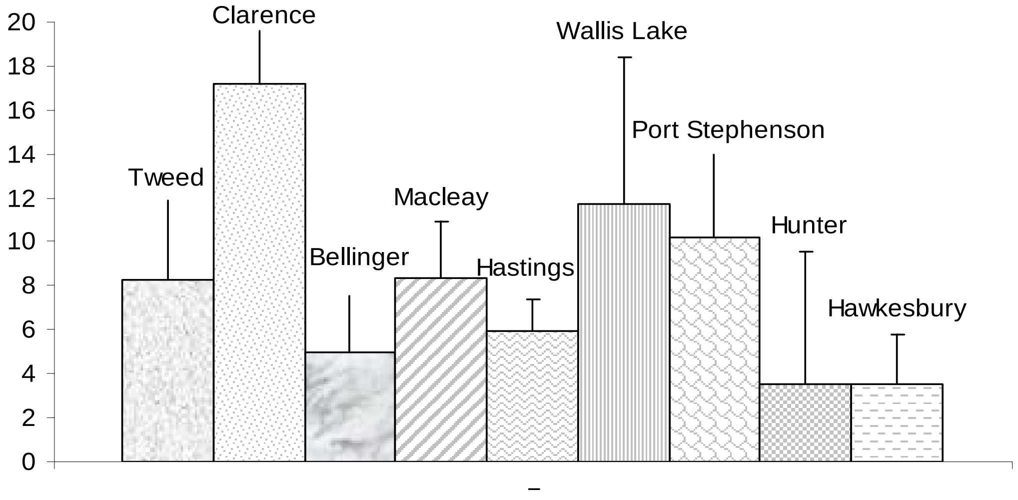


Figure 25. Mean mud crab catch in tonnes for 9 selected systems in New South Wales based on catch data ranging from 1984/1985 to 2007/2008. The error bar is indicating the variability of annual catch data.

An nMDS plot displaying the selected river systems for New South Wales mud crab catches using standardised average catch, CPUE, SST, rainfall and the monthly correlation between CPUE and temperature between 1997 and 2008, revealed three different groups. The size of the circles indicates the strength of the monthly Pearson correlation between sea surface temperature and mud crab CPUE: the Hunter and Hawkesbury with relative low catches but medium to high correlations between mud crab CPUE and SST (see Table 12), the Clarence, Tweed, Karuah/Port Stephens and Hastings with high catches and strong correlations between mud crab CPUE and SST, and the Bellinger and Macleay systems with relative small correlations between CPUE and SST. Pearson r was highest for Northern Bioregion river systems that had the highest catches. The analyses showed that regions with high catches generally had stronger relationships with environmental drivers than systems with low catches, in which case the influence of effort on the catch was higher.

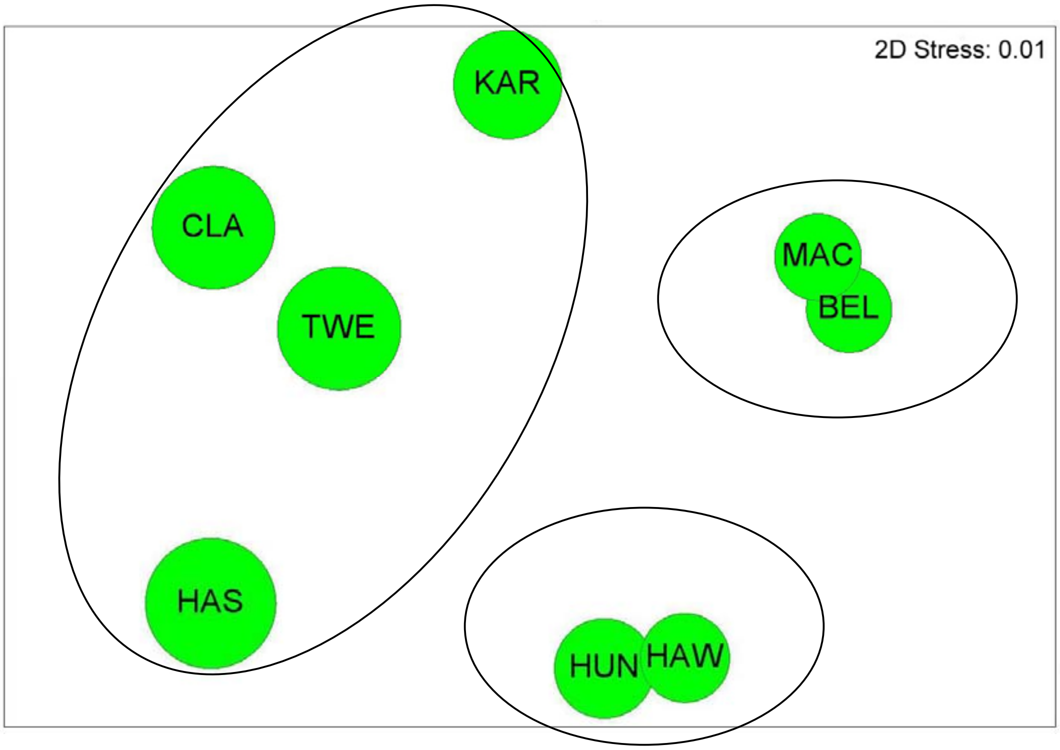


Figure 26. nMDS plot displaying eight of the nine selected river systems (excluding Wallis Lake) for New South Wales mud crab catch analyses. The size of the circles indicates the strength of the monthly Pearson correlation between sea surface temperature and mud crab CPUE. The plot is based on standardised average catch, CPUE, SST and rainfall between 1997 and 2008 and transformed using Euclidean distance. HAW = Hawkesbury, HUN = Hunter, BEL = Bellinger, HAS = Hastings, MAC = Macleay, TWE = Tweed, KAR = Karuah, CLA = Clarence

### 5.3.5 Discussion

The overall trend showed that temperature (indicated by sea surface temperature) was the most important driver of mud crab catches in New South Wales. In particular, high temperatures in the summer, autumn and spring were related to high catches, and high average rainfall in the summer was related to high mud crab catches two years after the event. The life cycle of mud crabs in New South Wales correlates strongly with seasonal changes. During the winter months the mud crabs become less active and reduce their foraging activities, and thus catchability. Therefore, catches over the winter month were low. Subsequently, the strong positive relationship between monthly catch and temperature was expected – the higher the temperatures in the summer, the higher the growth rate and activity of mud crabs. Increased rainfall is relevant for mud crab recruitment and is associated with enhanced survival of juvenile mud crabs. The estimated time lag that it takes a mud crab to recruit to the fishery is approximately two years.

The relationship between catch and maximum SOI values for NSW was less significant than for the Northern Territory and Queensland, and was only found for the period 1984/1985 to 1996/1997. The SOI effects are weakened in the southern parts of Australia and the application of the Indian Ocean Dipole (Ummenhofer *et al.*, 2009) to indicate drought events may be a better environmental variable. However, the influence of management restructure and reporting on the catch data were expected to be higher in New South Wales and therefore the relationships with environmental drivers lower. Changes to regulations and closure of fishing grounds influenced mud crab catches but are difficult to incorporate in the catch data analyses. Other external considerations, such as the construction of dams and river system alteration (factors which can have negative impacts on the abundance of mud crabs), also influence catch rates over time. Similar findings have been reported for the catch rate/flow relationships from other fishery species in NSW (Gillson *et al*., 2009). In addition, the use of fiscal years for annual time configuration may have had an influence on the analyses.

As shown by the meta-analyses, the river systems separated into at least two distinct groups. These groupings were mainly driven by temperature and total catch, reflecting the oceanographic discontinuity around Port Macquarie. If data on mud crab catch were to be combined for all of New South Wales, a separation into Central and Northern Bioregions would be meaningful and likely provide the best results. It is suggested that management efforts should also be applied separately to these distinctive regions.

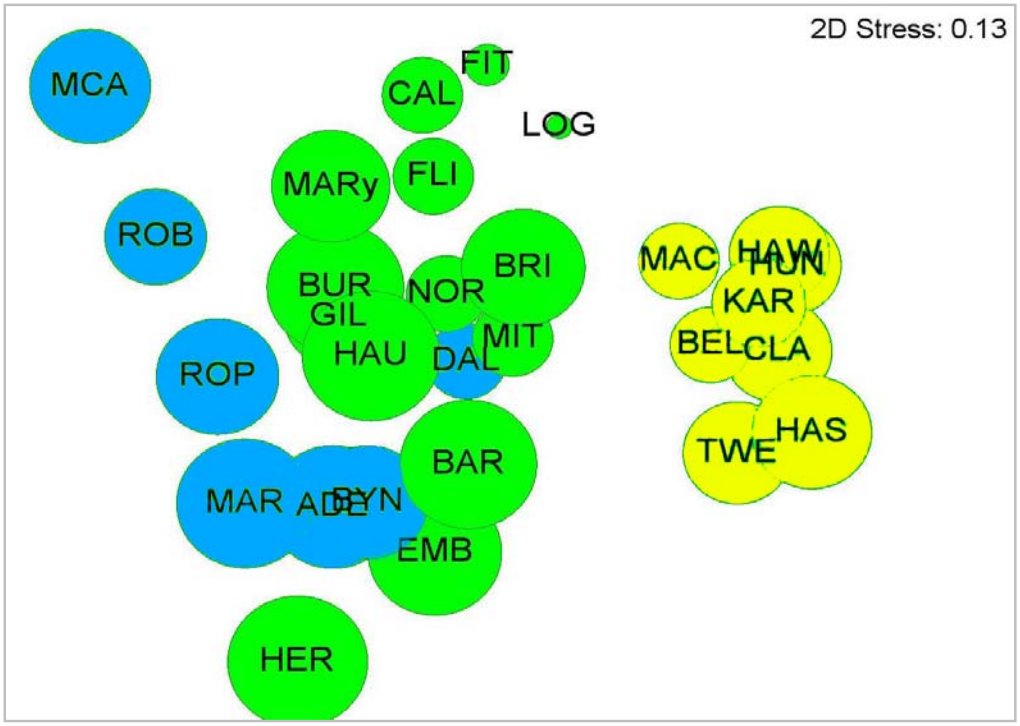
The results from the regression analyses suggested the following possible general linear model for New South Wales annual mud crab catches: annual CPUE = Log (mean Summer SST) + (mean summer rainfall two years prior to catch). To improve the model the total catchment size could be included and, if available, flow volume would be a better predictor than catchment rainfall.

## 5.4 Comparison of analysed data from the Northern Territory, Queensland and New South Wales

Northern river systems with high rainfall generally had higher catches, and there was a strong relationship between rainfall and mud crab CPUE. Conversely, river systems at the southern end showed lower mud crab catches and either had a higher dependence on temperature than rainfall, or both factors were equally important. A nMDS using total catch, average CPUE, SST, rainfall and the correlation values between mud crab CPUE and SST and/or rainfall for the analysed time series for each state showed that the correlation with SST became more significant towards the southern distribution limit of mud crabs, and that rainfall was more significant at the northern Australian distribution of mud crabs (Figure 27a/b).

When flow and mud crab CPUE time-series were analysed for relationships, a four- to seven-year SOI cycle was evident for most selected river systems (see also Appendix 7). Analysis of the rainfall and flow data with mud crab catch data also indicated that extreme rainfall/flow events over many weeks had a long term negative impact on catch whereas flooding at the end of the wet season may be positively related to catch 2-3 years after the event. Spectral analysis revealed significant peaks every four to seven years, coinciding with the SOI cycle. Given the relationship with SOI values throughout the data sets a four- to seven-year cycle of high catches would support the model that predicts highest catches when there is high average rainfall and temperature. A 15-20 year cycle with the Pacific Ocean Dipole (PDO) would also be expected. Bayliss *et al*. (2008) found significant relationships between flow and PDO using long-term data sets. Unfortunately the data sets for mud crab catches were not long enough to provide time-series analyses of time intervals of that scale.

a.



b.

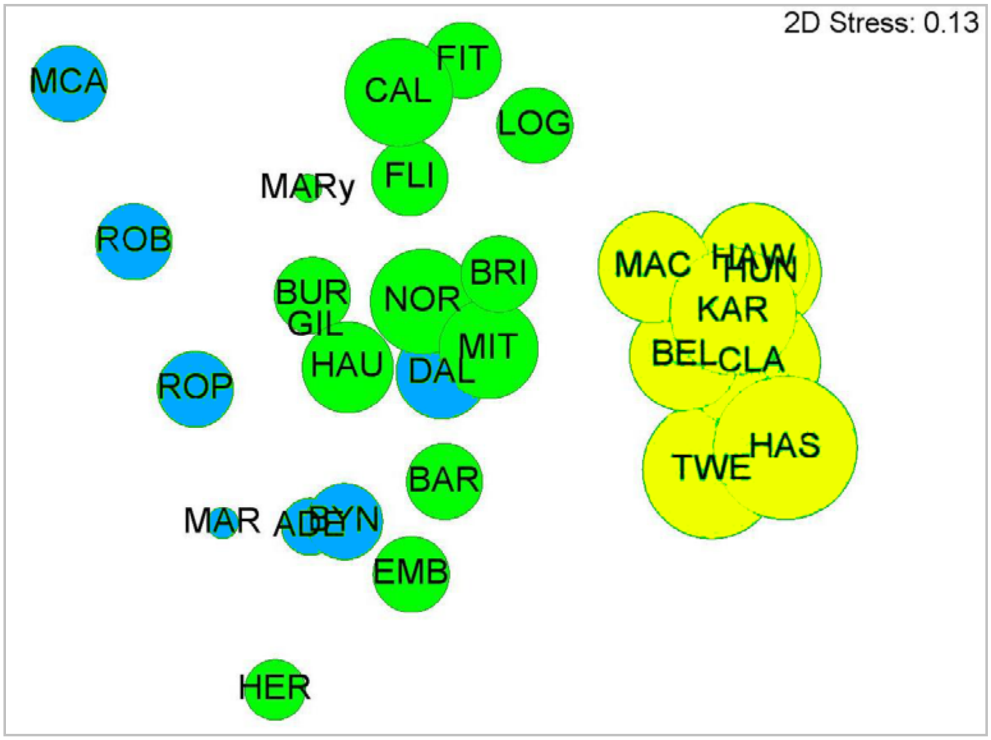


Figure 27 a and b. nMDS plot displaying all of the selected river systems for Australian mud crab catch analyses (excluding Wallis Lake in New South Wales). The size of the circles indicates the strength of the correlation between rainfall (Figure 27a) and sea surface temperature (Figure 27b). The plot is based on standardised average catch, CPUE, SST and rainfall for the relevant time periods from each state (NT in blue, Qld. in green and NSW in yellow) and transformed using Euclidean distance. HAW = Hawkesbury, HUN = Hunter, BEL = Bellinger, HAS = Hastings, MAC = Macleay, TWE = Tweed, KAR = Karuah, CLA = Clarence, Coleman/Mitchel River, NOR - Normanby, FLI - Flinders, Norman, EMB - Embley, GIL - Gilbert, MIT - Mitchell, Coleman rivers, FIT - Fitzroy, Raglan rivers, CAL - Calliope, Boyne, HER - Herbert, Tully, BAR - Barratta, Houghton, BUR - Burdekin, BAR - Barron, BRI - Brisbane, Albert, Logan, Nerang, Coomera, MARy - Burrum, Mary, MCA – McArthur, ROB – Robinson/Wearyan, ROP – Roper, ADE – Adelaide, BYN – Bynoe Harbour, DAL – Daly, MAR – Mary.

## 5.5 Western Australia Mud Crab Catches and Environmental Drivers

### 5.5.1 State-Specific Background Information

Commercial fishing for mud crabs in Western Australia commenced in 2003 and has continued through to 2008. Fishing generally occurs between March and November, with May to September fished consistently each year (fishers avoid the summer months because of extreme heat). The minimum size limit of mud crabs in Western Australia is 150 mm CW for *S. serrata* and 120 mm CW for *S. olivacea*. Mud crab fishers usually operate from a mother ship using small dinghies to fish estuaries; however, other fishing licenses provide the main income. The value of the catch is between $14-33/kg, but long travel distances from remote areas often make the Western Australia mud crab fishery less economically viable. Live products are supplied to domestic markets in Broome, Derby and Perth.

Catch was relatively low between 2003 and 2005 (ranging between 0.3-1.1t); however, it increased significantly in 2006 to about 9 t (Figure 28). This was primarily due to substantial increases in effort (i.e. effort increased from 1790 potlifts in 2005 to 20,504 in 2006) and numbers of days fished (i.e. average increased from 62 in 2005 to 204 in 2006). CPUE increased between 2003 and 2005 with greater knowledge of the fishery, but remained fairly constant between 2005 and 2006. Catch declined in 2007 to 5.3 t with a marked reduction in potlifts (decreasing to 6.1 t) and approximately half the number of days fished (Figure 29). However, CPUE increased to a high level of 0.48 t/day.

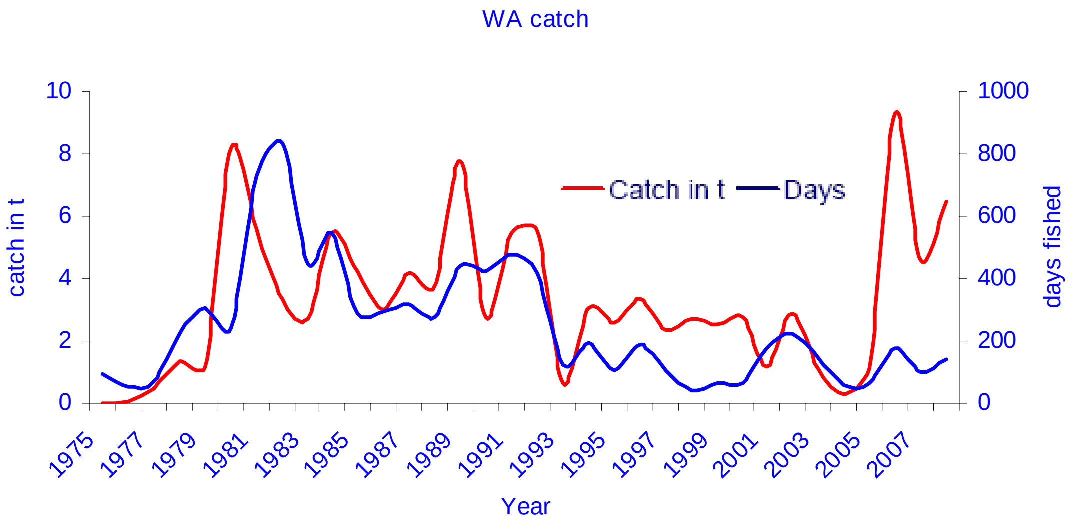


Figure 28. Western Australia mud crab catch in tonnes and fishing days for the years 1975 to 2008 (including recreational catch data).

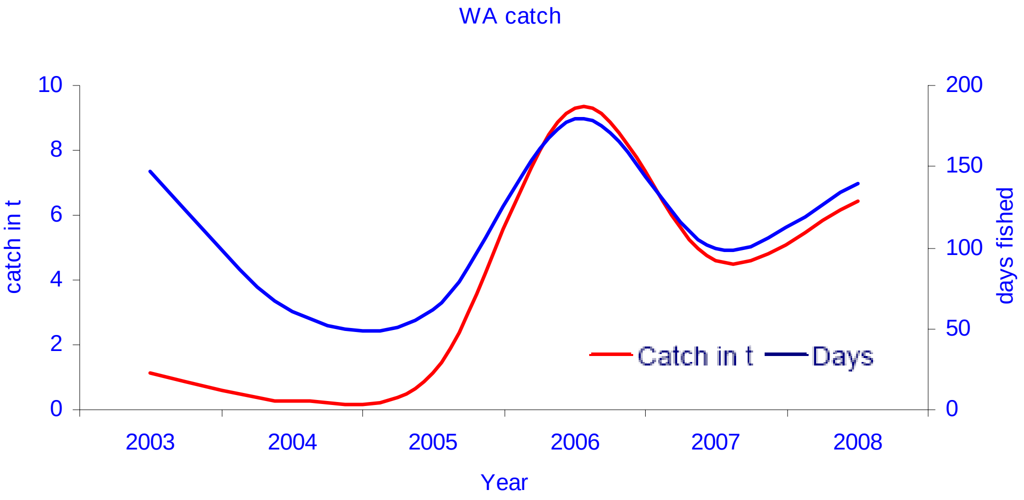


Figure 29. Western Australia mud crab catch in tonnes and fishing days for the years 2003 to 2008.

Mud crab catch data for Western Australia were sparse and also consisted of two different species (*S. serrata and S. olivacea*). The commercial mud crab fishery is currently a small developing fishery with a total annual catch between 3-7 t per year for the last decade. It is concentrated around York Sound, King Sound, Cambridge Gulf and Admiralty Gulf.

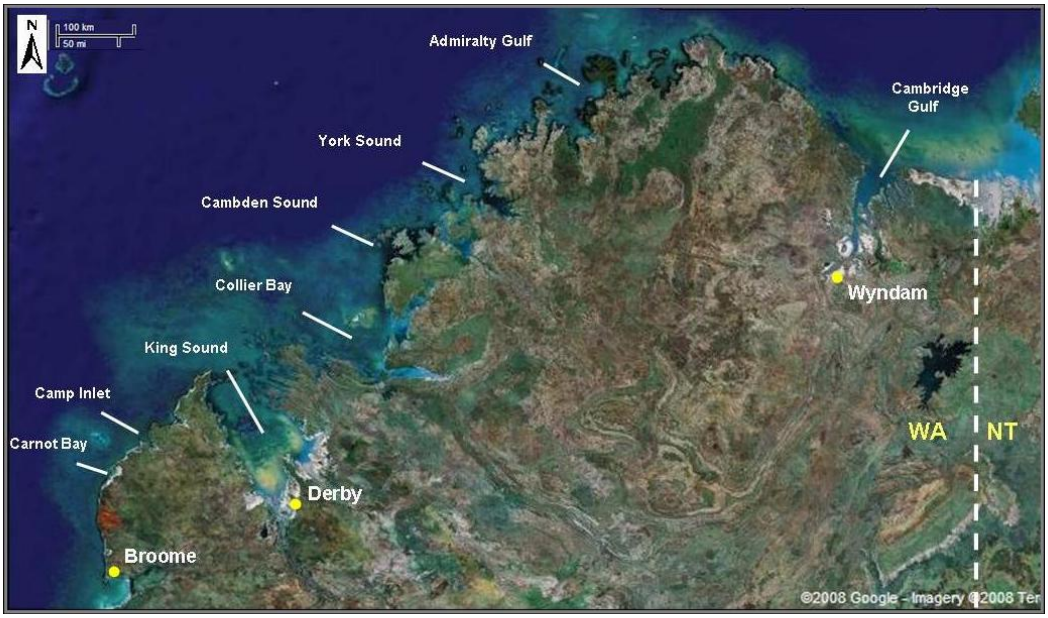


Figure 30. Map showing the main fishing regions for Western Australia's developing mud crab fishery. King Sound had the highest catch records.

Most of commercial crabbing occurred in King Sound. Indeed crabs from this area constituted almost all of the catch in 2007. Fishing in these waters has occurred every year since the fishery commenced, whereas fishing has been relatively sporadic in other areas. Another important area (in terms of number of years fished) has been Admiralty Gulf; however, catches at this location have been relatively low. In contrast, relatively large catches were taken in 2006 and 2008 in Cambridge Gulf, but no fishing occurred in other years. King Sound was fished significantly for 3 years - 2006, 2007 and 2008, although catches and CPUE have declined.

The data set was analysed on a qualitative basis using log books and notes from fishers in relation to significant weather events. It was concluded that the data set is not consistent enough, nor was the catch high enough, to allow meaningful statistical analyses; however, anecdotal information has helped to develop a better picture of the effects of environmental factors on mud crab catches in all relevant states of Australia.

### 5.5.2 Reports from fishers

Anecdotal reports from fishers in Western Australia mainly were derived from notes on the record sheets showed that lower catches were evident when temperatures were low (around 19°C). Fishers also reported that during full moon and big tides catches were low due to difficulties in accessing creeks. It was also noted that during rain event catches were good but during strong freshwater runoff catches were low. Such reports from fishers are helpful to develop a better picture of environmental effects. In particular notes about mud crab abundance in conjunction with weather patterns and temperature as well as a detailed location can assist to develop meaningful statistical models. The reports from Western Australia fishers were similar to those from other jurisdictions.

# 6. Discussion

## 6.1 General Discussion

Fisher from all jurisdictions reported that more than average freshwater runoff over weeks during summer month was enhancing mud crab catch rates but flooding peaks reduced catch rates. Catch rates also dropped when water temperatures felt below 20°C and when water temperatures exceeded 35°C. The statistical analyses and modelling presented in this report confirmed these findings. Rainfall and temperature were important potential environmental drivers affecting mud crab catch throughout Australia. Furthermore, the Southern Oscillation Index (SOI) was identified as an influential factor for mud crab catches in particular in northern Australia. Between 30 and 40% of the catch variability were explained by La Niña phases which are associated with increased rainfall and higher temperatures over large parts of northern Australia. Similar, in Queensland the majority of river systems showed a strong positive relationship with SOI or average catchment rainfall for annual data time configurations, however, some systems had no relationship with any of the selected environmental drivers. Temperature was found to be a less important driver for mud crab catches in northern Australia but explaining between 30-50% of catch variability in NSW. The trend identified throughout the jurisdictions can be explained by the increasing importance of temperature towards the southern distribution limit of mud crabs and freshwater flow (rainfall) being a limiting factor in Northern Australia at critical development phases of mud crabs. Temperature enhances growth rates of mud crabs and overall productivity and freshwater flow (rainfall) provides preferable habitat conditions and nutrients into the lower estuary.

## 6.2 Benefits

A conceptual model to assess the relationship between physical environmental drivers and mud crab catches was established and an overview of the mud crab fishery status throughout Australia was provided. We have undertaken a literature review on mud crab studies to investigate the potential effects of environmental factors on mud crab biology and highlight gaps in current knowledge. This study has also defined regional characteristics of systems and established groups based on catch, temperature, rainfall and the relationship between catch and these two environmental factors. The groups generally fall within biogeographic regions that should allow ecosystem orientated management of each state/territory fishery.

This information, together with the results from the statistical analyses of mud crab catch data and environmental drivers, greatly improved the understanding of mud crab catch variability in Australia. The research provides an effective tool for predicting future mud crab catches depending on latitude within a two- to three-year timeframe, as well as the basis for a mud crab fishery model that includes environmental factors. The influence of major physical environmental factors such as freshwater runoff and temperature on Australian mud crab catches can now be quantified and explains at least one third of the catch variation.

## 6.3 Further Development

This work identified gaps in our knowledge of mud crab biology and mud crab fisheries. Information (such as abundance, mortality and year class strength of mud crabs) was required to complete the model proposed in this study. Even if fishing mortality is known, the natural mortality may be much higher under extreme environmental conditions.

Independent abundance estimates of mud crabs for the most productive river systems would enhance and build on the outcomes of this project. Collection of independent mud crab abundance data, particularly for Queensland, are necessary to assess population strength and refine some of the findings from this research. In some cases, like the Fitzroy River system, fisheries catch data provide very poor information on mud crab abundance which might be caused by over reporting.

More field studies to examine the linkages between specific environmental drivers and their influence on the mud crab life cycle are needed. There is little evidence of cause and effect which is an issue with most ecological/climatological modelling. This includes the definition of activity and spawning trigger values, such as tide, temperature and salinity, for a number of Australian mud crab populations from various biogeographic regions. Such information would greatly improve the predictive capacity of our model. Furthermore, information on growth rate, mortality and survival for a process-based ecosystem fisheries model are required to allow for regional catch prediction. Previous attempts to model stock size of mud crabs have assumed no regional differences. The functionality of ecosystems clearly suggests that local recruitment failure is a common event in marine environments (Bay *et al.*, 2008). Generalised, jurisdiction based fisheries models can not provide a reliable estimate of the mud crab population development. Future studies on mud crab catch data may include other environmental variables when they become broadly available, such as currents and salinity. Adjustments to the data can also be made by using catch relative to catchment size and by incorporating biogeographic information such as mangrove area.

## 6.3 Planned Outcomes

The first objective was to determine the links between selected environmental factors and mud crab (*Scylla serrata*) catches in representative areas within the species’ range in Australia. This was achieved by selecting river systems with the highest mud crab catches from all relevant jurisdictions and a statistical analysis of mud crab catch data from these systems with SOI values, SST, flow and rainfall data. The second objective was to document possible time lags between environmental phenomena and mud crab catches. The determination of the links between selected environmental factors and mud crab (*Scylla serrata*) catches in representative areas within the species' (Australian) range allowed the documentation of time lags between environmental phenomena and mud crab catches by selecting time lags that were biological meaningful and had the highest correlation with environmental drivers. The third objective was to develop predictive models for Australian mud crab fisheries based on the information gathered from Objectives 1 and 2. Valuable models explaining mud crab catch variability were generated using regression models based on the relationships between mud crab catch and environmental variables such as temperature and rainfall. These models were presented in this report (for further details and data access contact the principle author).

The project identified the environmental factors driving mud crab catches in several major estuarine systems along the Australian coastline. This knowledge can be used to facilitate the production of more comprehensive and accurate predictive models for the mud crab fishery. Furthermore, the research discovered great variability between river systems and a need to manage these systems based on their environmental settings that are best described as biogeographic regions. These outputs are likely to make a difference for fisheries manager who have to plan for large number of river systems.

The commercial mud crab fishing industry is the primary beneficiary of the information and tools developed through this work. Other stakeholders (including the general public) also benefit from the knowledge that the commercial mud crab fishery aims operating in accordance with best practice. The information has broader application for the mud crab fishery across Australia and the nation wide management of this resource.

## 7. Conclusion

As hypothesised, SOI including rainfall was the most important explanatory environmental factors for mud crab catches in the Northern Territory, while seasonally de-trended temperature was the most significant driver for mud crab catches in New South Wales. Positive maximum SOI values indicating monsoonal activities over most parts of Northern Australia and La Niña phases were significantly positively correlated with mud crab catches in the Northern Territory and Queensland and to some extent in New South Wales. The strength of the relationship varies with the river system in focus and weakens when catch is not continuous over time or influenced by non-environmental factors. The analyses revealed differences between river systems and showed distinct grouping for the Northern Territory, Queensland and New South Wales.

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## Appendix 1: Intellectual Property

There is no intellectual property arising from this research project.

All results, findings and developed methods have already been communicated to the mud crab industry and management. All information belongs in the public domain.

## Appendix 2: List of staff engaged in the project

| Staff | Association |
|---|---|
| Dr Jan-Olaf Meynecke | Griffith University, Australian Rivers Institute |
| Dr Mark Grubert | NT Fisheries, Department of Resources |
| Prof Joe Lee | Griffith University, Australian Rivers Institute |
| Dr Ian Brown | DEEDI, Southern Fisheries Centre |
| Dr Steven Montgomery | NSW Department of Primary Industry |
| Dr Neil Gribble | DEEDI, Northern Fisheries Centre |
| Dr Danielle Johnston | WA Fisheries and Marine Research Laboratories |
| Chris Errity | NT Fisheries, Department of Resources |
| Jordyn de Boer | Griffith University |
| Julie Hunter | Griffith University |
| Jonathan Gillson | University of New South Wales |

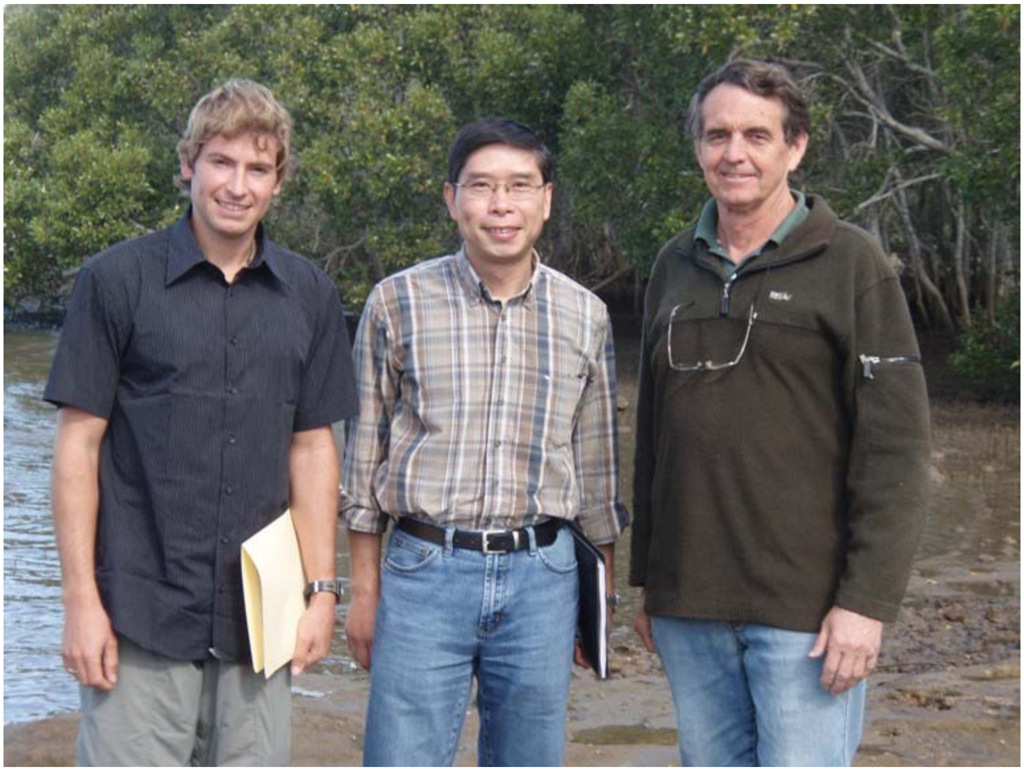


Figure 31. Start-up meeting at Southern Fisheries Centre in Deception Bay in August 2008 from left to right: Dr Jan-Olaf Meynecke, Prof Joe Lee and Dr Ian Brown.

Figure 32. Meeting at NT Fisheries in Darwin in October 2008 from left to right: Chris Calogera (C-Aid Consultants), Doug Neville, Dr Mark Grubert, Dr Jan-Olaf Meynecke

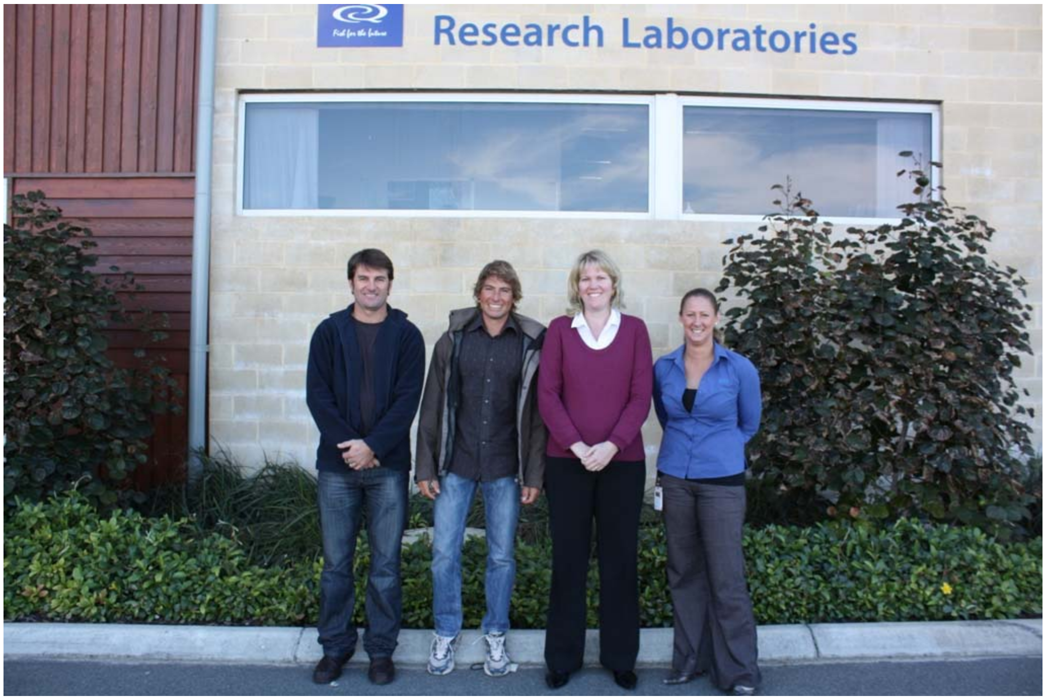
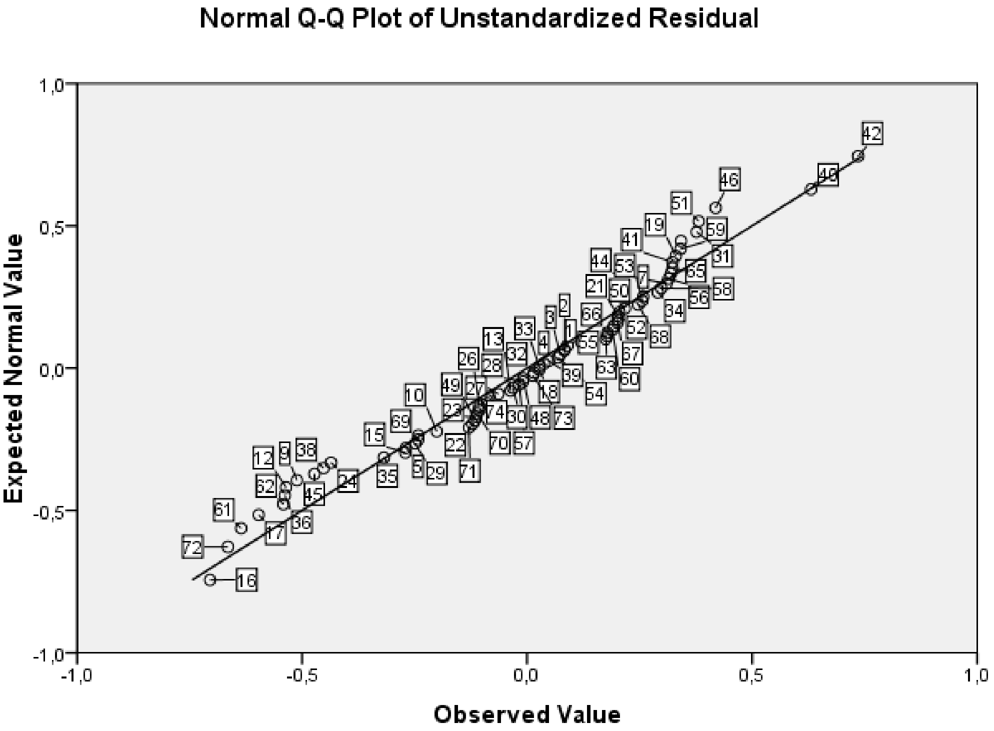


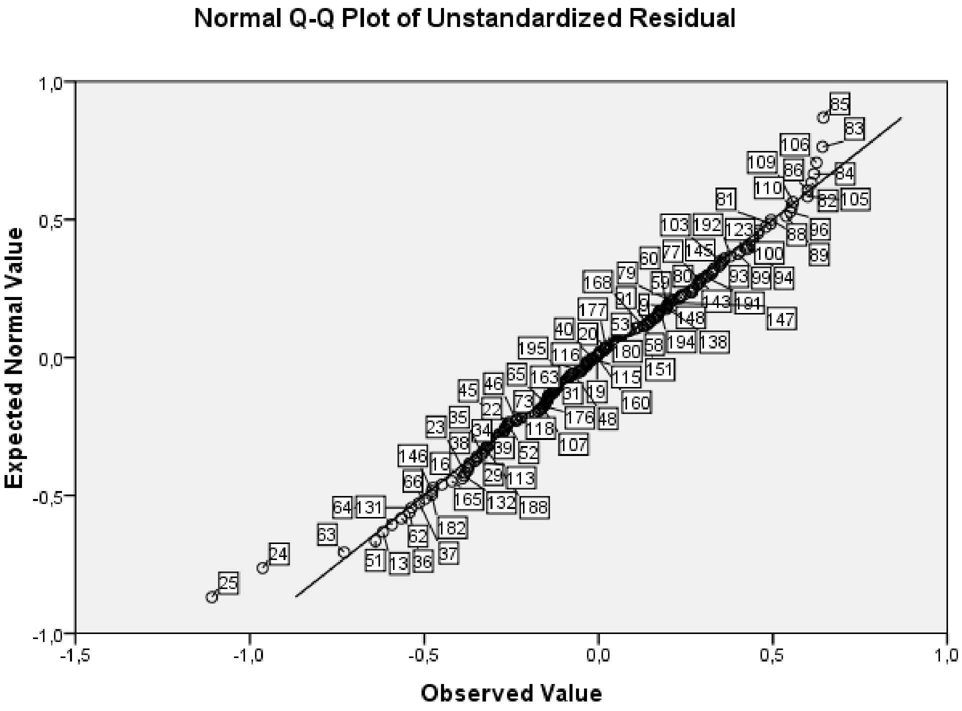
Figure 33. Meeting at WA Fisheries in Perth in July 2009 from left to right: Dave Harris, Dr Jan-Olaf Meynecke, Dr Danielle Johnson, Brooke Hay

## Appendix 3: Fitting of unstandardised residuals (expected against observed values) for selected river systems in the Northern Territory. Residuals can be used to adjust catch for effort. Plots indicated the linear or non-linear character of the relationship.

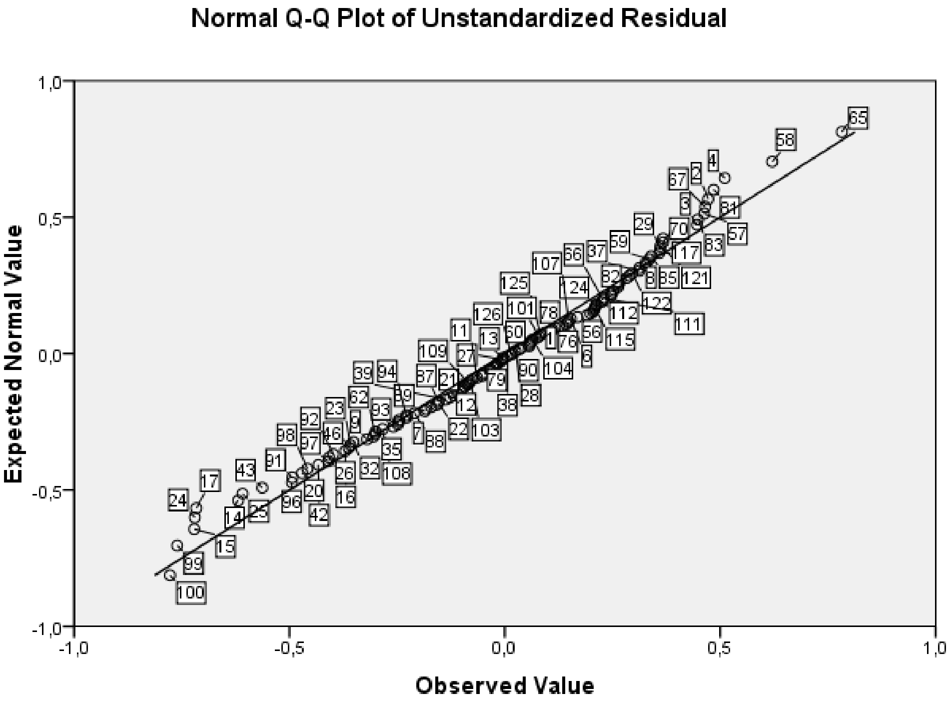
Daly River



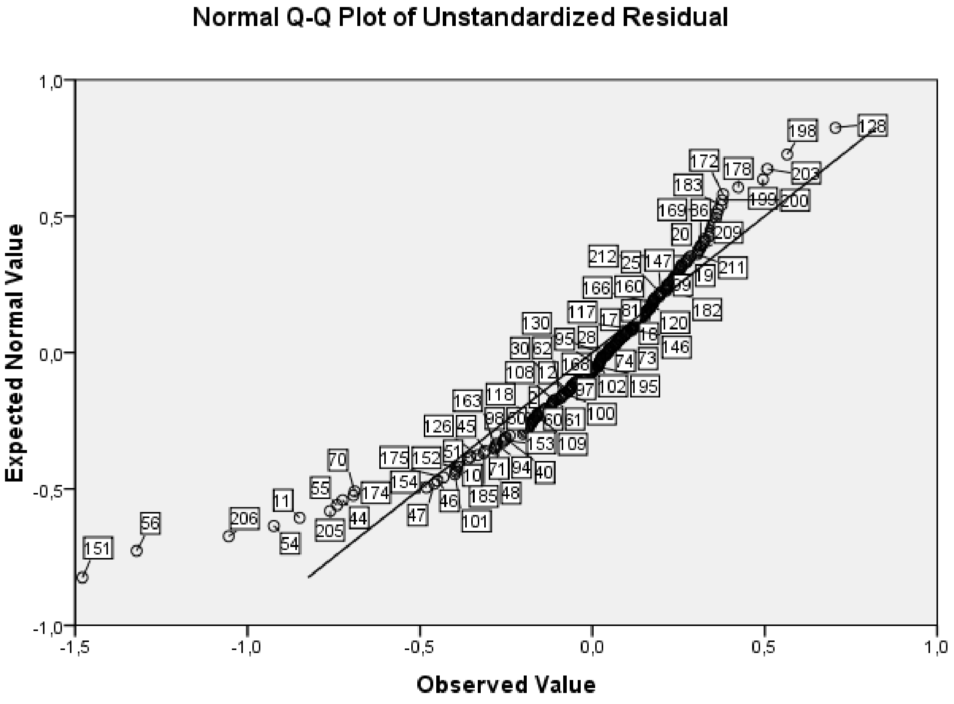
Bynoe Harbour



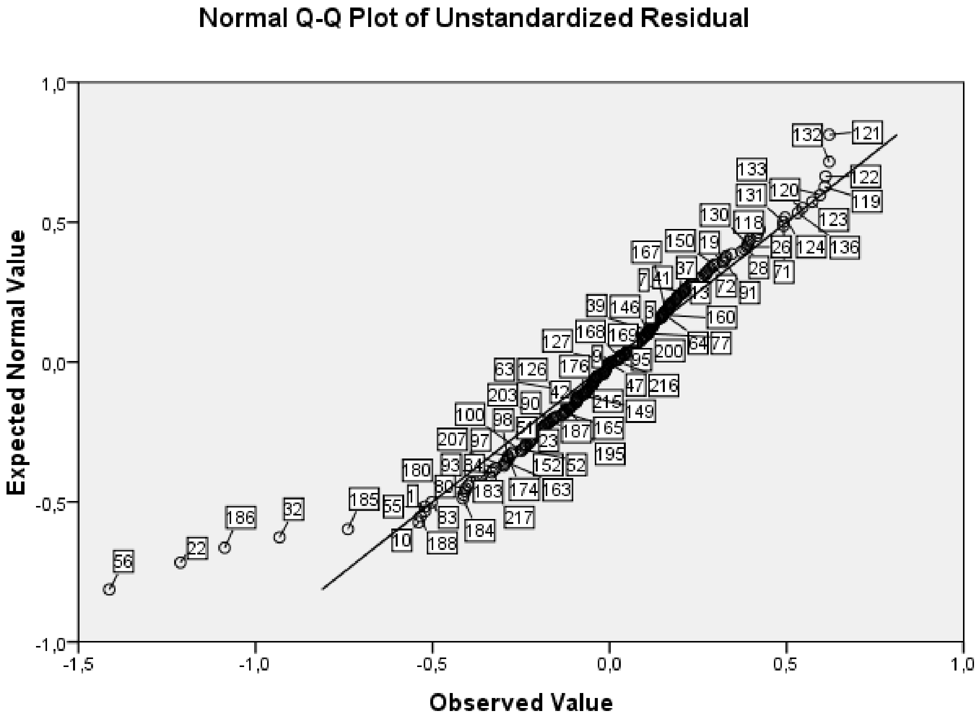
Mary River



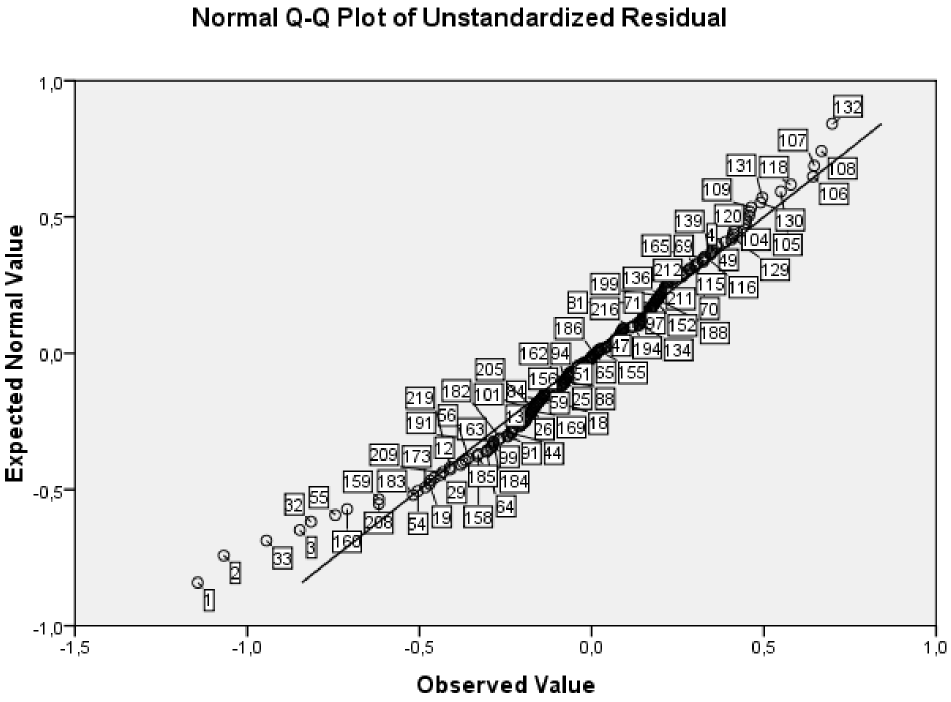
McArthur



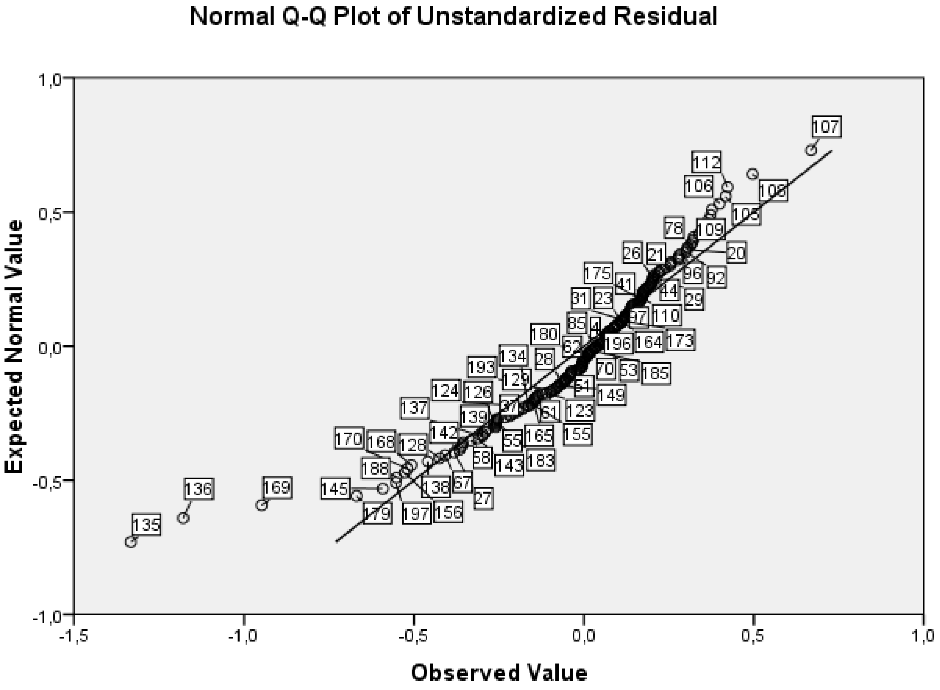
Robinson



Adelaide



Roper



# Appendix 4: List of the selected 46 river or catchment systems for this study for statistical analyses showing ID of mud crab catch record and gauge station. WA systems are not included.

| River systems | State | Catch record identification system | Stream gauge stations |
|---|---|---|---|
| Roper River | Northern Territory | LIMMEN BIGHT PORT ROPER ROPER RIVER ROPER RIVER FLATS, Grids: 1434, 1435 | 903176, 903146, 903250, 903102 |
| Mary River | | POINT STUART, TOMMYCUT CREEK MARY RIVER SAMPAN CREEK, Grids: 1231 | N.A. |
| McArthur | | CROOKED RIVER DUGONG CREEK SHARKER POINT CARRINGTON CHANNEL PORT MCARTHUR MCARTHUR RIVER DAVIES CHANNEL BORROLOOLA GEORGES CHANNEL VICTORIA BAY DAVID ISLET, Grids: 1636, 1536 | 907142, 907229, 907132, 907121 |
| Adelaide River | | TAA/ADAMS BAY ADELAIDE RIVER CHAMBERS BAY, FRIGHT POINT, ADAM BAY, SALTWATER ARM, POINT STEPHENS LEADERS CREEK ADAM BAY/SALTWATER ARM, Grids: 1231 | 817240, 817005 |
| Byone Harbour | | BYNOE HARBOUR GUNN POINT TURNBULL BAY INDIAN ISLAND MILNE INLET PORT PATERSON RAFT POINT PHOENIX INLET ANNIE RIVER CHARLOTTE RIVER, Grids: 1230 | N.A. |
| Robinson River and Wearyan | | FAT FELLOWS CREEK ROBINSON RIVER WOLLOGORANG, Wearyan, Grids: 1637, 1636, 1537 | 908122, 908133 |
| Daily River | | ANSON BAY DALY RIVER PERON ISLAND, Grids: 1330, 1331 | 814041, 814042, 814152, 814001, 814067, 814063 |
| North Pine River | Queensland | W37 | N.A. |
| Brisbane River | | W37 | 143026A |
| Albert River | | W38 | 145196A, 145105B |
| Logan River | | W38 | 145014A |
| Coomera River | | W38 | 146010A |
| Nerang River | | W38 | 146002B |
| Raglan River | | R30 | none |
| Fitzroy River | | R30, R29 | 130002B and A |
| Calliope River | | S30 | 132001A |
| Boyne River | | S30 | 136318A, 136317A |
| Herbert River | | I19 | 116001E |
| Tully River | | I19 | 113006A |
| Murray River | | I19 | 401201A, 614065 |
| Burrum River | | V33 | 137303A |
| Mary River | | V33, V34 | 138013B, G8180059, G8180058 |
| Tinana Creek | | V33, V34 | N.A. |

| | | | |
|---|---|---|---|
| Barratta Creek | | K21 | N.A. |
| Houghton River | | K21 | N.A. |
| Burdekin | | L22 | 120008B, 120015A |
| Flinders River | | AD17, AD18, AC18 | 915003A |
| Norman River | | AD 17, AD18, AC18 | 916001B |
| Normanby River | | E11 | 105101A |
| Marrett River | | E11 | N.A. |
| Embley River | | AB8 | 924001A |
| Gilbert River | | AC16 | 917001D |
| Middle Creek | | AC16 | N.A. |
| Mitchell River | | AB13 | 919014A, 919009A |
| Coleman River | | AB13 | 920003A |
| Barron River | | H16 | 110001D, 110020A |
| Wallis Lake | New South Wales | Wallis Lake | 209401, 209006 |
| Tweed River | | Tweed Cobaki Broadwater Terranora | 201432 |
| Port Stephenson, Myall River | | Port Stephens/ Myall Lakes, Myall River, Tea Garden | 209460 |
| Nambucca River | | Nambucca River Macksville | 205416 |
| Macleay River, Spencers Creek | | Macleay River, Spencers Creek, Trial Bay | 206456, 206406 |
| Clarence, Maclean, Yamba, Wooloweyah | | Clarence R Iluka Maclean Yamba Wooloweyah | 204410, 204406 |
| Camden, Haven River | | Camden Haven R, Queens Lake, Watson Taylors Lake, | 207428, 207425 |
| Hastings River | | Hastings River | Port Macquarie Offshore, 207401 |
| Hunter River | | Hunter River | |
| Hawkesbury River | | Hawkesbury River, Broken Bay, Brisbane Water, Pitt | |

## Appendix 5: Northern Territory mud crab research field trip to three major river systems in the Gulf Country: Roper River, McArthur and Wearyan.

Summary of interviews of commercial crabbers

**Roper River** – Summary of interview with Tam and Paul

Tam is a Vietnamese crabber who has been in the area for 4 years with 120 pots. He is fishing at the Roper River for mud crabs with his brothers. The crabbing mainly takes place on the flats at the mouth of the Roper River. Tam states that very high temperatures are a problem as the crabs don't survive in the pots and 40 degrees seems a threshold.

He believes that crabs stay in the same area for 6-7 month and that if crabs are not caught in April, they would still be there in August.

2009 was a good year and started off with very high catches in April. Double to last year with the lowest catch in 2009 being the highest in 2008. In average he landed 10 trays a week (40-50 crabs each that is 500 crabs a week that is 16000 crabs a season).
Tam agrees that a good previous wet season results in high catches in the following dry season.

Paul is a barramundi fisher who has been fishing in the Roper River for almost 30 years. He used to hold a crab license in the early days. He used to catch the crabs upstream in the mangroves but there are very little crabs now. In general the crabs start moving upstream in the dry season. He believes that crabs would not stay in the same area for a long time.

Consequences for this study: The relationship between a good wet season being followed by a dry season with high catches has been confirmed. It seems the first catches after the wet season might be artificially high in weight due to heavier crabs but not necessarily high in numbers of crabs. An exclusion of high catches for analyses for the first month might be meaningful in some cases.

**McArthur River** – Summary of interview with Tian and Greg

Tian is a Cambodian crabber who has been crabbing in the McArthur River system for 17 years. He considers high temperatures a problem with crabs dying in the pots, when exposed during low tide. Therefore, catches usually drop with very high temperatures. He also stated that a good wet season means a good catch in the following dry season. A good catch trend generally last for a few years (3-4 years) before it drops again.

Tian observed that males leave an area at the end of the dry season to search for females and that females leave the area after mating and do not return.

An extreme flood event in 2004 killed large seagrass beds near Sharker Point and Tian assumes that the following drop of catches 2-3 years after the event was related to the massive seagrass die off.

Greg has been a crabber for a few years. Not intensively fishing but knows the area quite well. Catches in the Rosie Creek. He agreed to the comments made by Tian.

Consequences for the study: Major flood events can kill seagrass and would have a long term negative effect on the recruitment of mud crabs. Hence, there should be a negative lagged effect of major flooding events. High temperatures might temporarily effect the catch negative but this might be difficult to detect in a monthly catch data resolution. The positive between good wet season and good catches in the dry season has been confirmed.

**Wearyan River** - Summary of interview with Neil

Neil has been a crabber in the Wearyan and around the coastline to Sharker Point for 16 years. He also fishes in the following creeks: Fat Fellow Creek, Davos Creek, Middle Creek, Twin Sister Creek, Blackfellas Creek, Salt Creek, Les Creek, First Creek and Boundary Creek to Sharker Point. Neil noticed seagrass dieback from a cylone in 2004 that might have caused a reduction in catches until 2006/2007. Neil catches crabs throughout the wet season and he has no problem with high temperatures since he catches most of his crabs in deeper waters and not on the flats. He finds that good average rainfall brings in general more crabs. Neil believes that crabs remain in one area for 6-7 month.

Consequences for the study: The findings from other crabbers were confirmed. Little effect of temperature would be expected when crabbing in deeper water over the wet season.

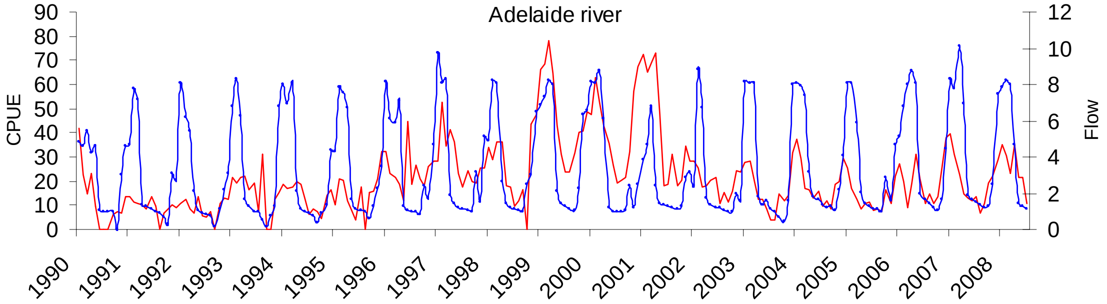
## Appendix 6: Metadata information

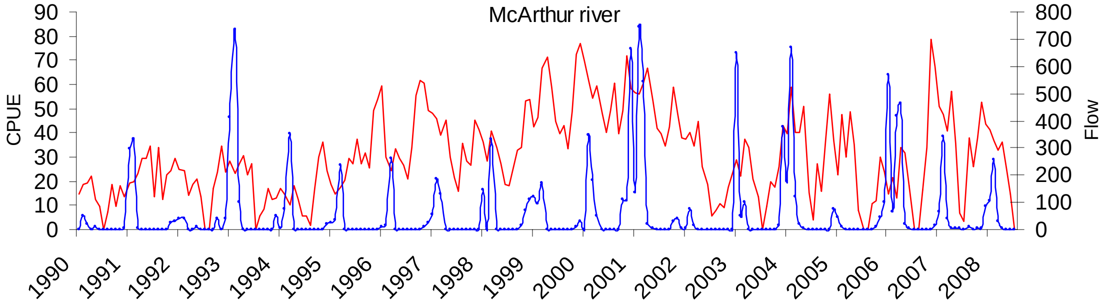
| Type | Resolution | Last updated | Custodian | Jurisdiction | Format | Abstract |
|---|---|---|---|---|---|---|
| Mud Crab catch data NT | monthly, river system | 2008 | NT Fisheries | Northern Territory | Excel | Mud crab catch data for pots for the Northern Territory from 1990 to 2008. Providing information on monthly catch per area and grid code, monthly fishing days, pots and potlifts |
| Mud Crab catch data Qld. | monthly, grid based | 2008 | Qld. Fisheries | Queensland | Excel | Mud crab catch data for pots for Queensland from 1988 to 2008. Providing monthly catch in kg per grid code, monthly fishing days, monthly number of boats and GVP as well as Longitude and Latitude for each grid |
| Mud Crab catch data NSW | monthly, river system | 2008 | NSW Fisheries | New South Wales | MS Access | Mud crab catch data for pots and traps for NSW from 1984/1985 to 2007/2008 fiscal year. Providing information on monthly catch in kg, fishing days, area of catch and boats |
| Mud crab catch data WA | monthly, grid based | 2009 | WA Fisheries | Western Australia | Excel | Mud crab catch data for pots, traps and nets for WA from 1975 to 2009. Providing information on monthly catch in kg, grid fished, area fished, days and hours fished and number of boats. |
| Freshwater Flow NT | daily, inconsistent | 2008 | DNR | Northern Territory | Excel | Freshwater flow data from NT gauge stations. Providing daily records on selected gauge stations. Data often covering only short periods of time or with gaps. |
| Freshwater Flow Qld | daily, inconsistent | 2008 | DNR | Queensland | Excel | Freshwater flow data from Qld. gauge stations. Providing daily records on selected gauge stations. Data often covering only short periods of time or with gaps. |
| Freshwater Flow NSW | daily, inconsistent | 2008 | DNR | New South Wales | Excel | Freshwater flow data from NSW gauge stations. Providing daily records on selected gauge stations. Data often covering only short periods of time or with gaps. |
| Rainfall | daily, 5km grids | 2008 | BOM | Australia | ASCII file | Daily rainfall data in 5km grids for Australia from 1981 to 2008. Data based on selected weather |

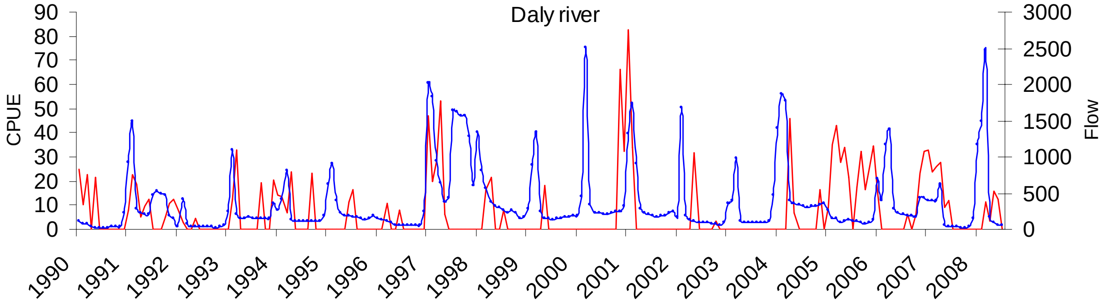
| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | stations and interpolated. |
| SST | monthly, 4km grids | 2008 | NOAA | Australia | ASCII file | Sea surface temperature is accessed from NASA (http://poet.jpl.nasa.gov) satellites from AVHRR Pathfinder Version 5 providing a 4 km resolution for monthly, daytime SST with the highest quality category. For 2008 SST monthly data MODIS Aqua data with a 4km resolution was used. |
| SOI | monthly | 2008 | BOM | Australia | ASCII file | Monthly values for the Southern Oscillation index from 1985 to 2008 |
| MJO | monthly | 2008 | BOM | Australia | ASCII file | Monthly values for the MJO for phase 2, 5 and 6. Providing information on longitudinal position of the centre of the oscillation (phase) and the number of days in each phase |
| Rivers basins | ranging from 1:10 000 to 1:250 000 | 2004 | Geoscience Australia | Australia | shp-file | Australia's River Basins 1997 provides the extent of major hydrologic basins. The data has been derived from topographic maps at scales ranging from 1:10 000 to 1:250 000. These basins are the primary building block for the collection of national hydrologic data and the assessment of water resources. |

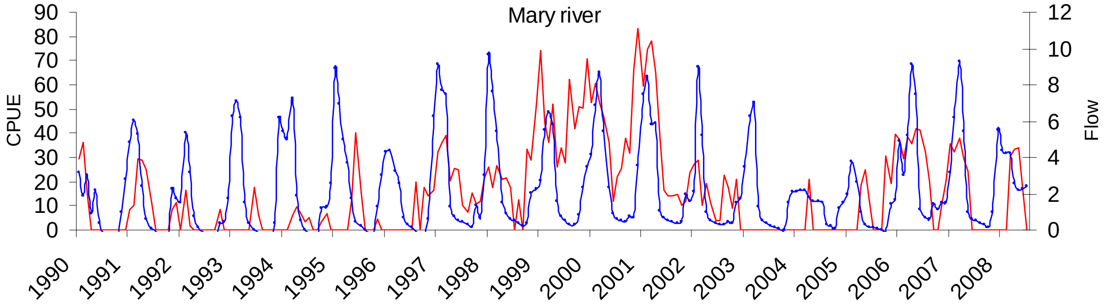
## Appendix 7: Time series between CPUE and rainfall/flow for selected river systems and catchments in the Northern Territory, Queensland and New South Wales. The flow/rainfall for the Northern Territory has been lagged by 6 month to adjust for the reduced catch in the wet season due to restricted access. Flow is shown in blue and CPUE in red over time.

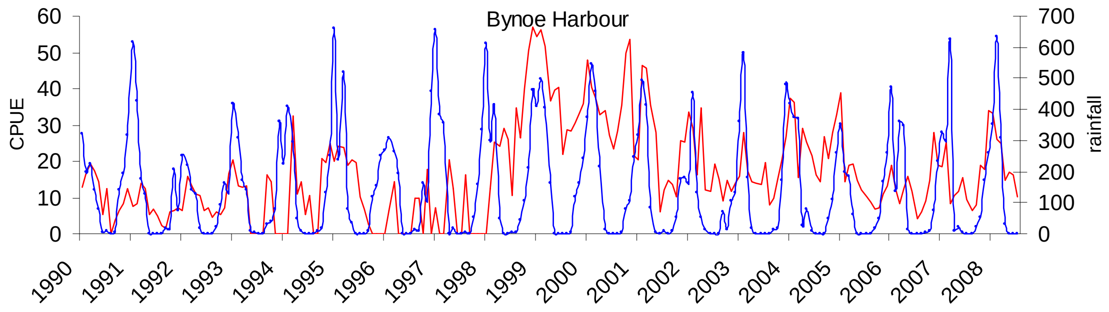
*Northern Territory systems*

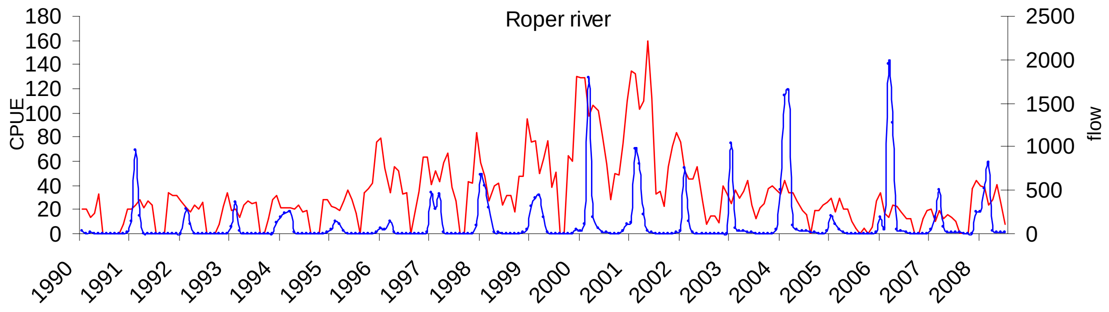


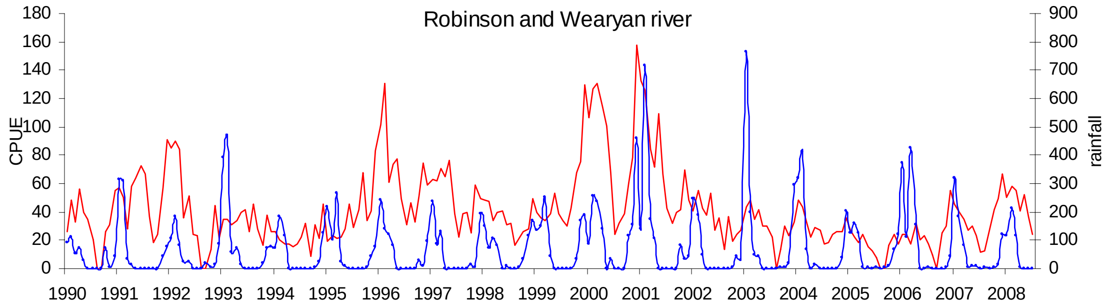




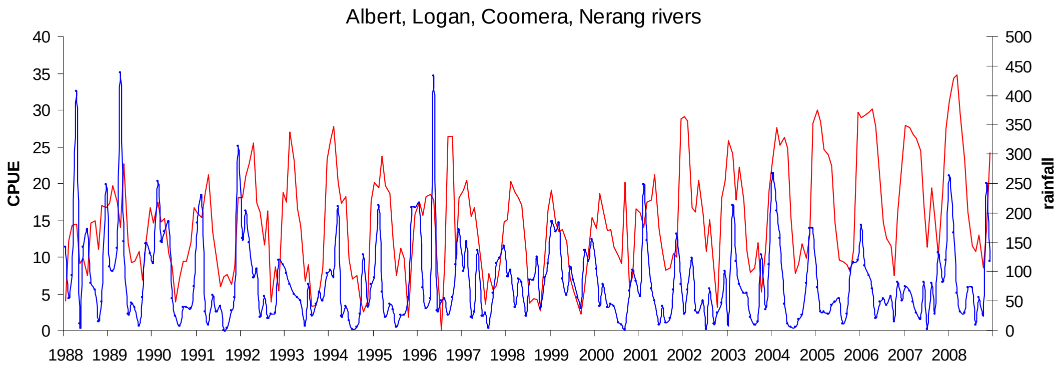


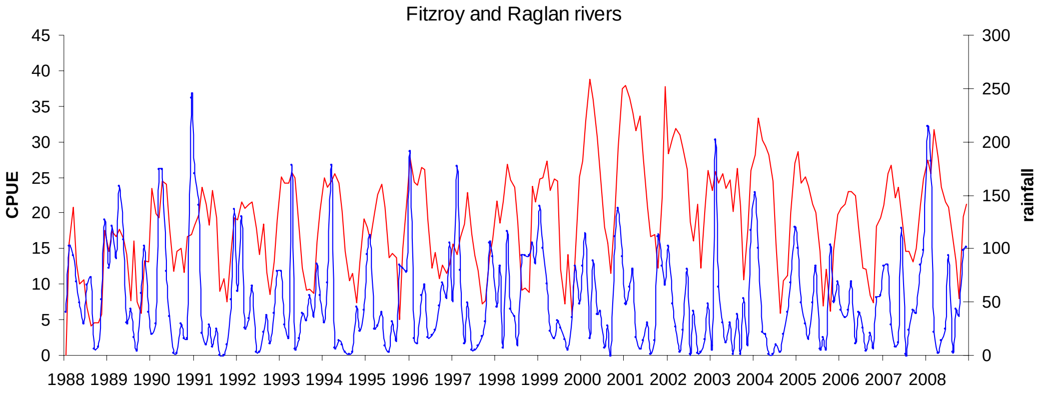


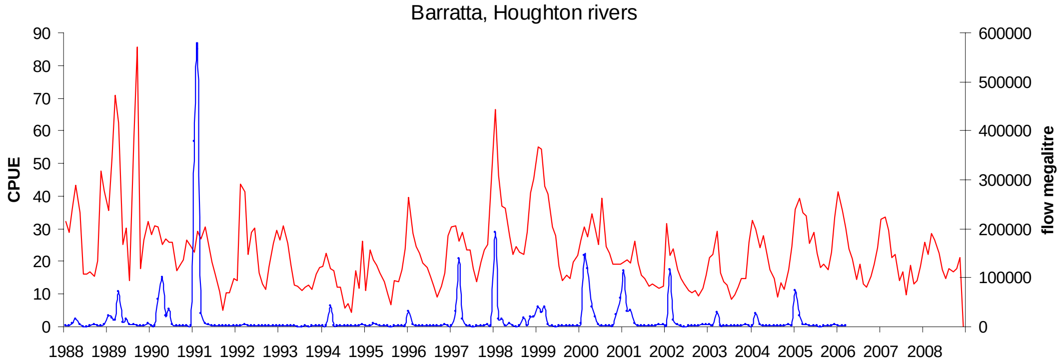


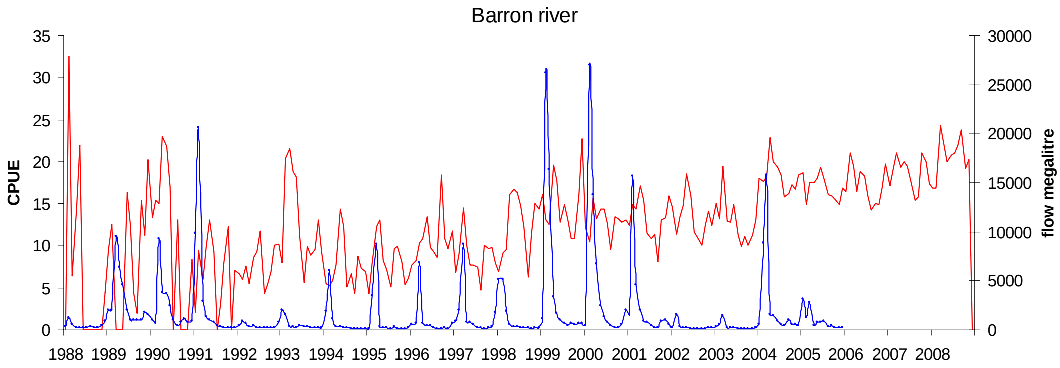


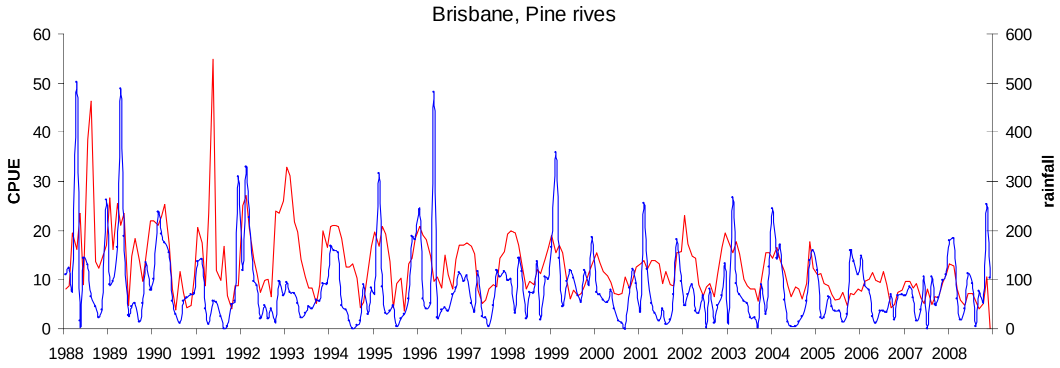
## *Queensland systems*

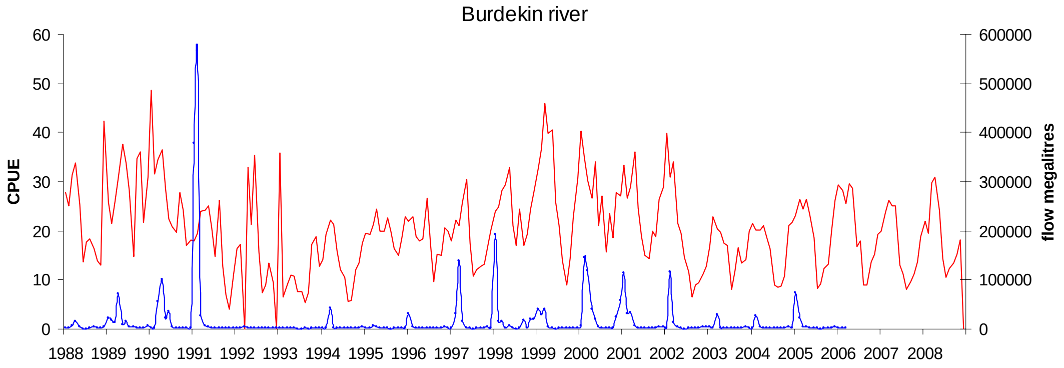



Fitzroy and Raglan rivers
CPUE
0
5
10
15
20
25
30
35
40
45
rainfall
0
50
100
150
200
250
300
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008


Barratta, Houghton rivers
CPUE
0
10
20
30
40
50
60
70
80
90
flow megalitre
0
100000
200000
300000
400000
500000
600000
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008


Barron river
CPUE
0
5
10
15
20
25
30
35
flow megalitre
0
5000
10000
15000
20000
25000
30000
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008


Brisbane, Pine rives
CPUE
0
10
20
30
40
50
60
rainfall
0
100
200
300
400
500
600
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008


Burdekin river
CPUE
flow megalitres
0
10
20
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40
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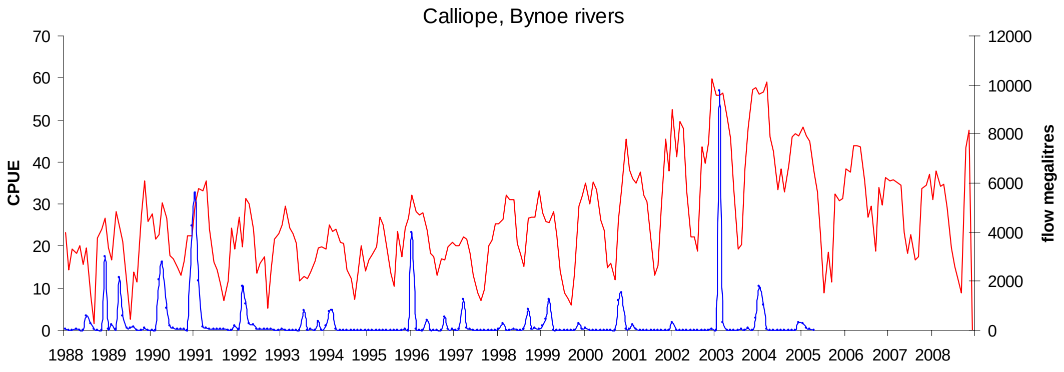
60
0
100000
200000
300000
400000
500000
600000
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008


Calliope, Bynoe rivers
CPUE
flow megalitres
0
10
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40
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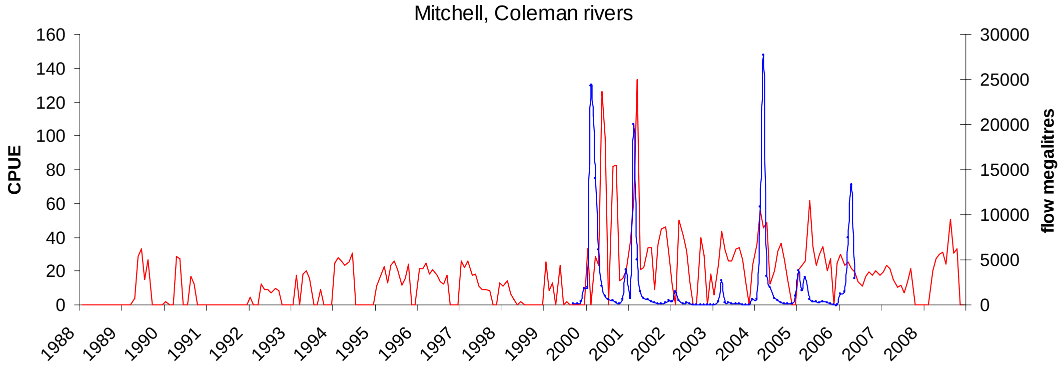
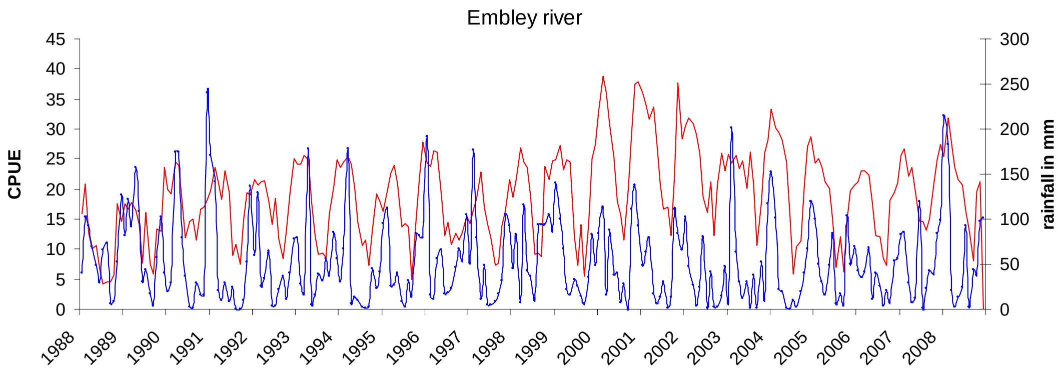
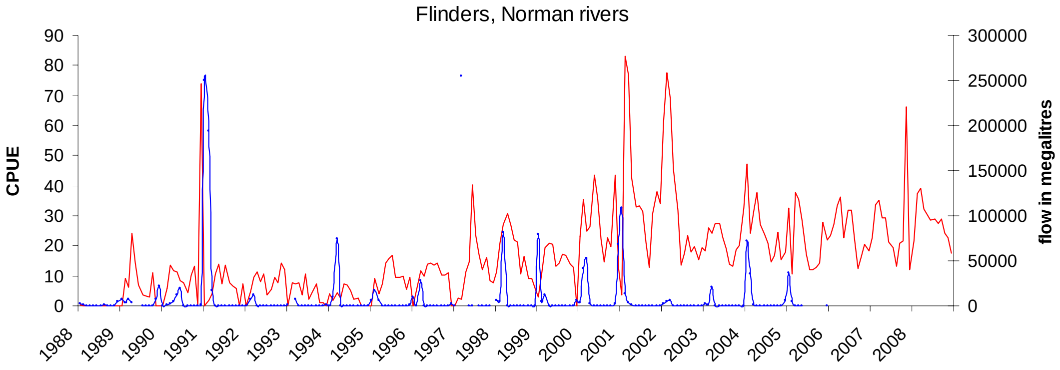
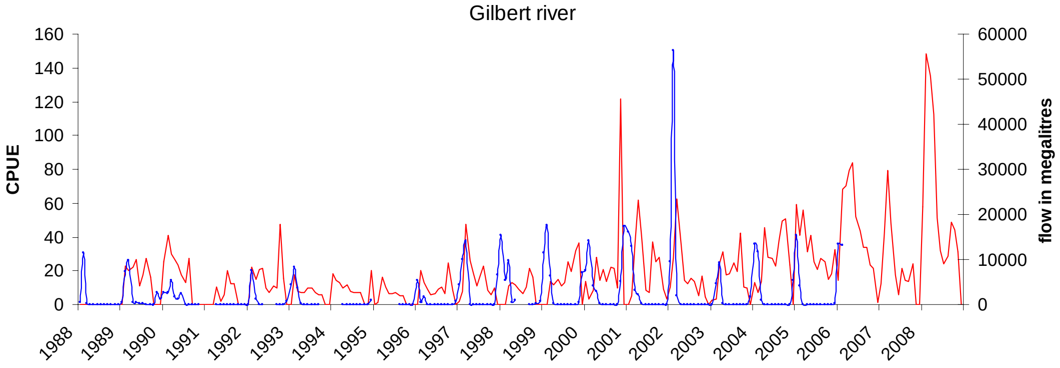
60
70
0
2000
4000
6000
8000
10000
12000
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008


Mitchell, Coleman rivers
CPUE
flow megalitres
0
20
40
60
80
100
120
140
160
0
5000
10000
15000
20000
25000
30000
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008


Embley river
CPUE
rainfall in mm
0
5
10
15
20
25
30
35
40
45
0
50
100
150
200
250
300
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008


Flinders, Norman rivers
CPUE
0
10
20
30
40
50
60
70
80
90
flow in megalitres
0
50000
100000
150000
200000
250000
300000
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008


Gilbert river
CPUE
0
20
40
60
80
100
120
140
160
flow in megalitres
0
10000
20000
30000
40000
50000
60000
1988
1989
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1996
1997
1998
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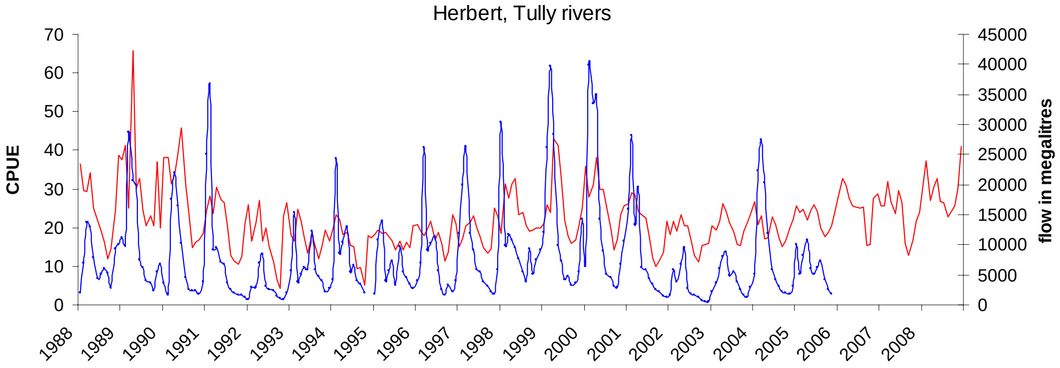
2000
2001
2002
2003
2004
2005
2006
2007
2008


Herbert, Tully rivers
CPUE
0
10
20
30
40
50
60
70
flow in megalitres
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
1988
1989
1990
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1993
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2000
2001
2002
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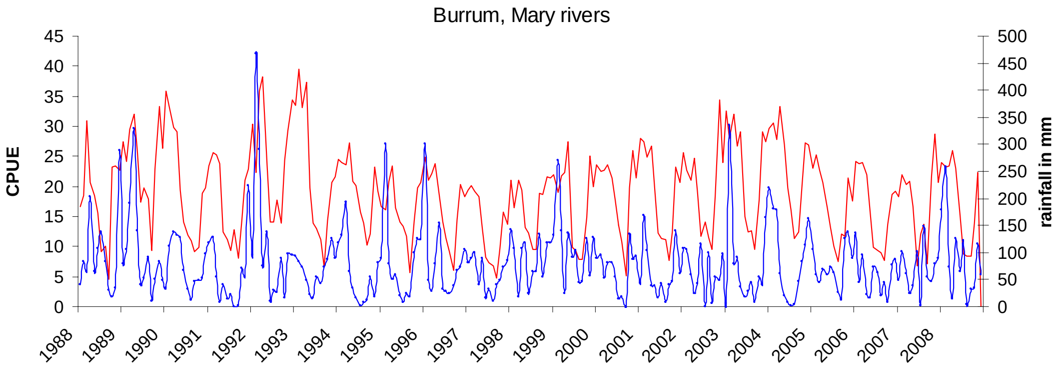
2004
2005
2006
2007
2008


Burrum, Mary rivers
CPUE
0
5
10
15
20
25
30
35
40
45
rainfall in mm
0
50
100
150
200
250
300
350
400
450
500
1988
1989
1990
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1992
1993
1994
1995
1996
1997
1998
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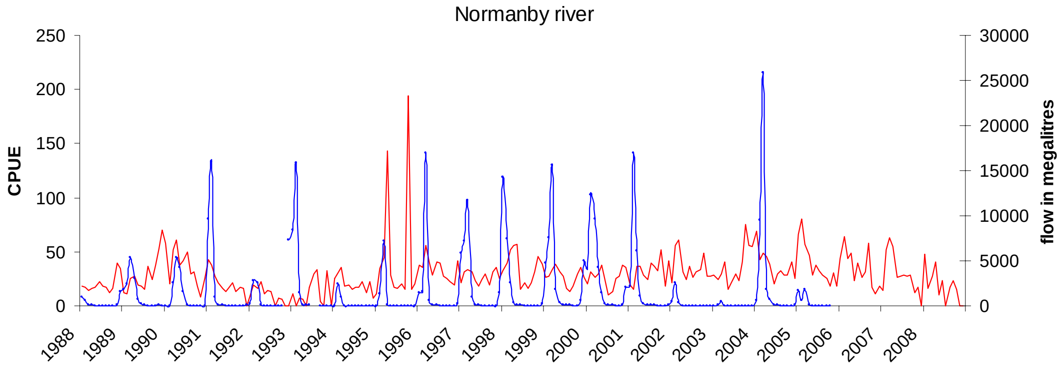
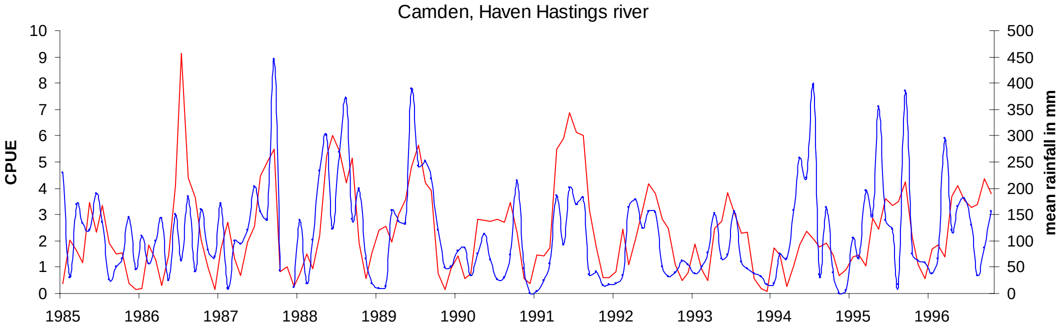
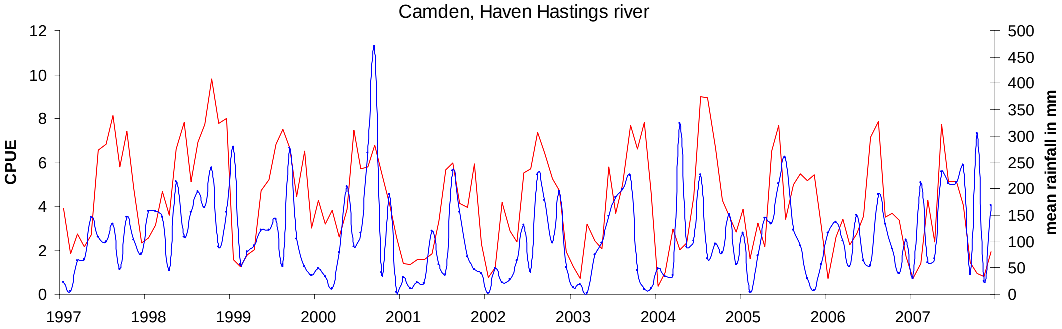
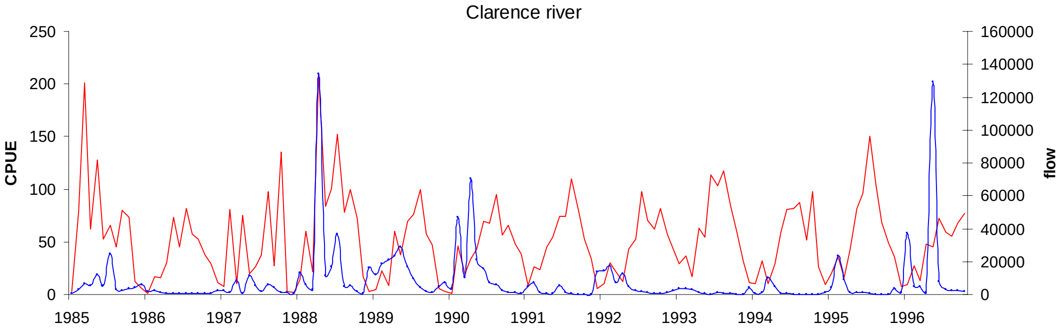
2001
2002
2003
2004
2005
2006
2007
2008

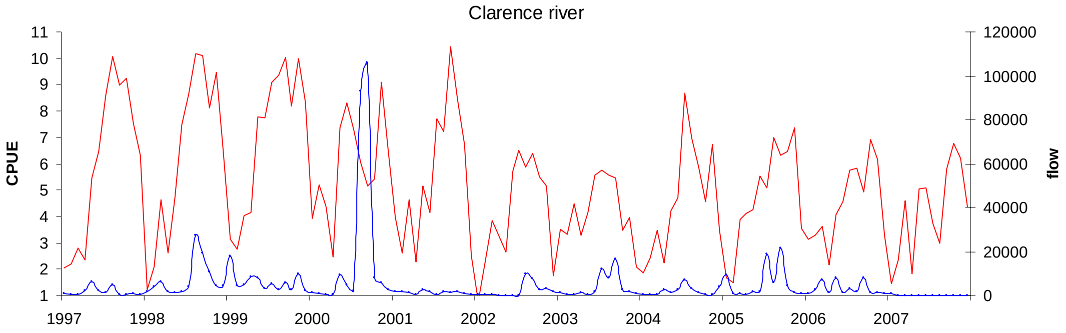


## *New South Wales systems*








Clarence river
CPUE
flow
11
10
9
8
7
6
5
4
3
2
1
120000
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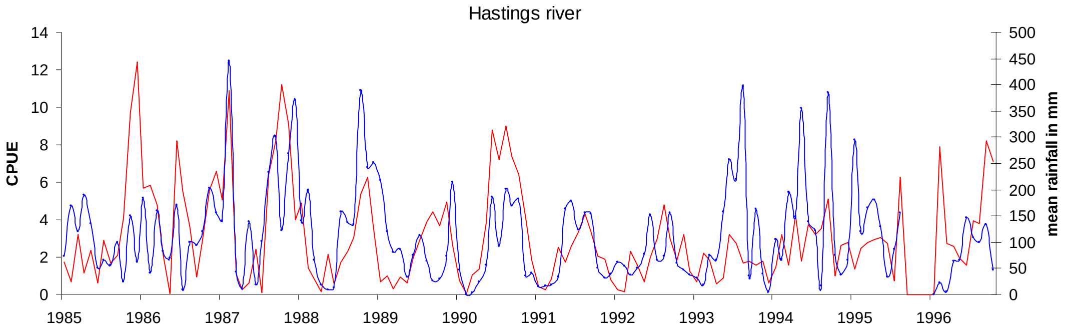
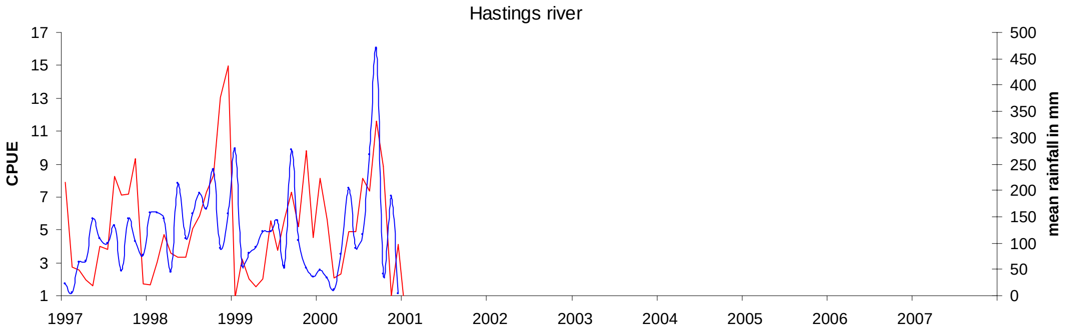
60000
40000
20000
0
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007


Hastings river
CPUE
mean rainfall in mm
14
12
10
8
6
4
2
0
500
450
400
350
300
250
200
150
100
50
0
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996


Hastings river
CPUE
mean rainfall in mm
17
15
13
11
9
7
5
3
1
500
450
400
350
300
250
200
150
100
50
0
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
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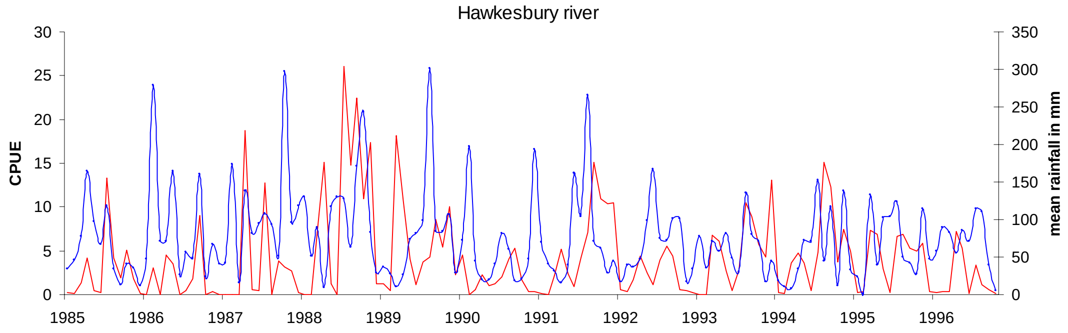
Hawkesbury river
CPUE
mean rainfall in mm
0
5
10
15
20
25
30
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200
250
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350
1985
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1989
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1995
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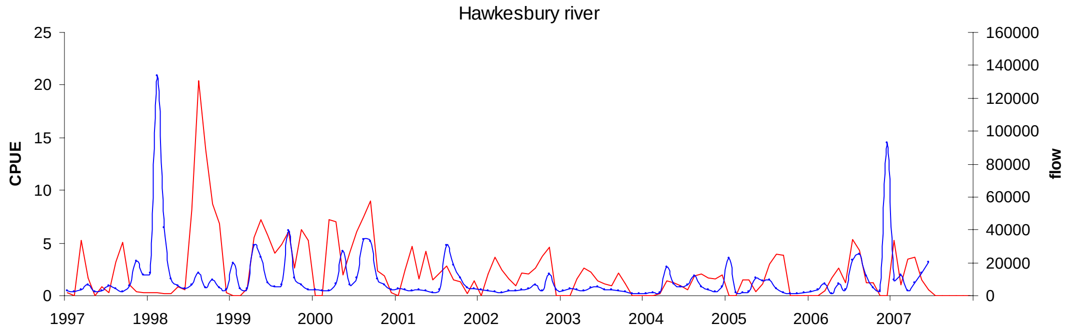
Hawkesbury river
CPUE
flow
0
5
10
15
20
25
0
20000
40000
60000
80000
100000
120000
140000
160000
1997
1998
1999
2000
2001
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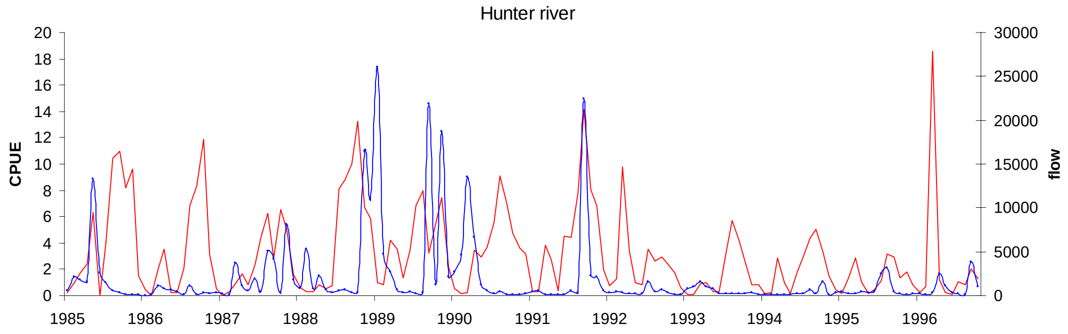
2003
2004
2005
2006
2007


Hunter river
CPUE
flow
0
2
4
6
8
10
12
14
16
18
20
0
5000
10000
15000
20000
25000
30000
1985
1986
1987
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1995
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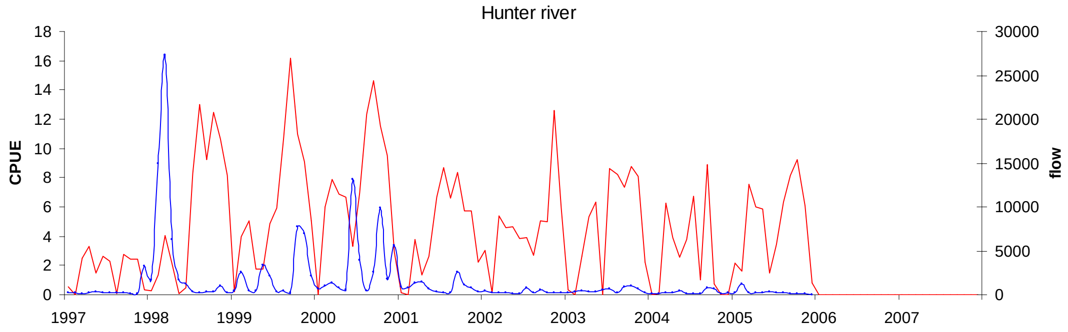
Hunter river
CPUE
flow
0
2
4
6
8
10
12
14
16
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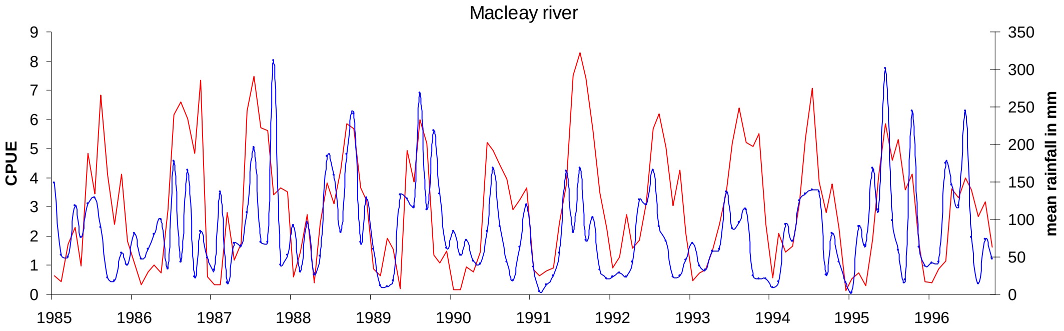
10000
15000
20000
25000
30000
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007


Macleay river
CPUE
mean rainfall in mm
0
1
2
3
4
5
6
7
8
9
0
50
100
150
200
250
300
350
1985
1986
1987
1988
1989
1990
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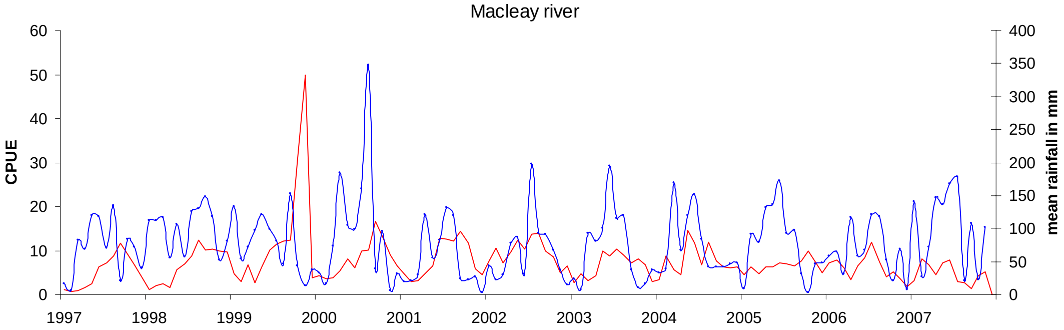
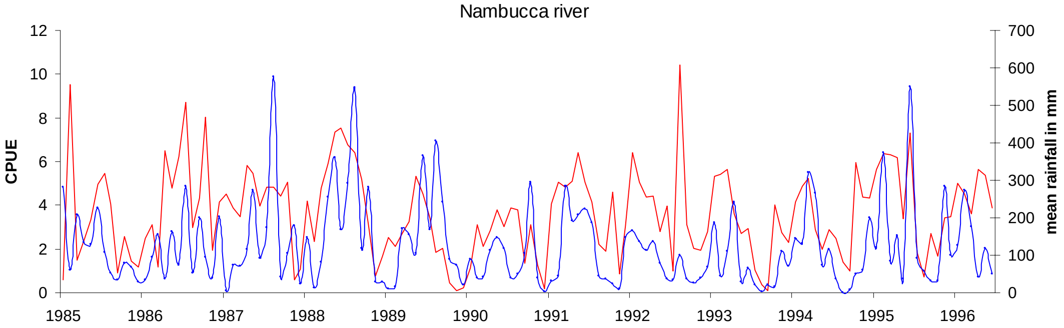
1993
1994
1995
1996


Macleay river
CPUE
mean rainfall in mm
0
10
20
30
40
50
60
0
50
100
150
200
250
300
350
400
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007


Nambucca river
CPUE
mean rainfall in mm
0
2
4
6
8
10
12
0
100
200
300
400
500
600
700
1985
1986
1987
1988
1989
1990
1991
1992
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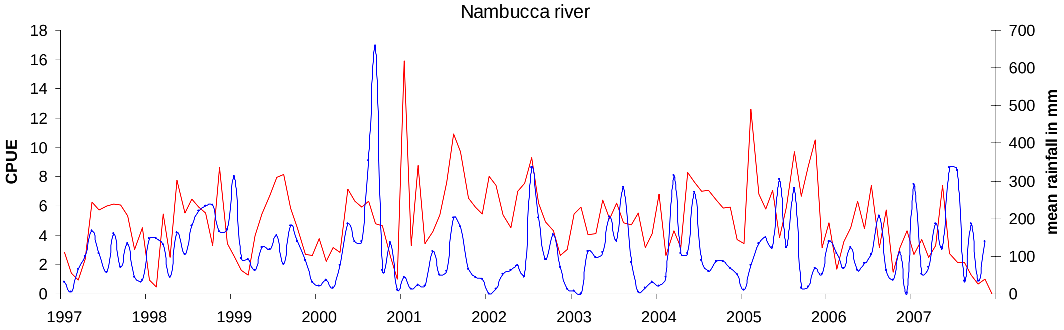
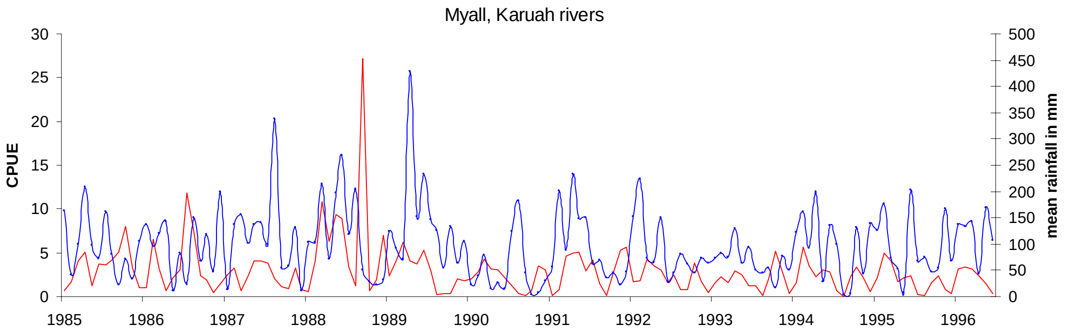
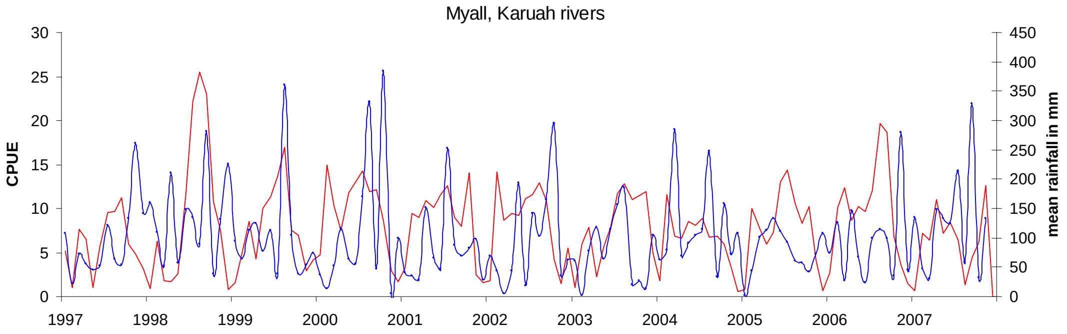
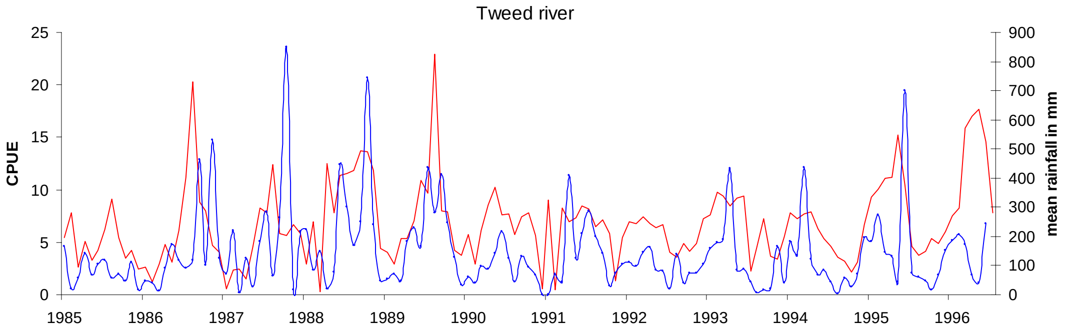
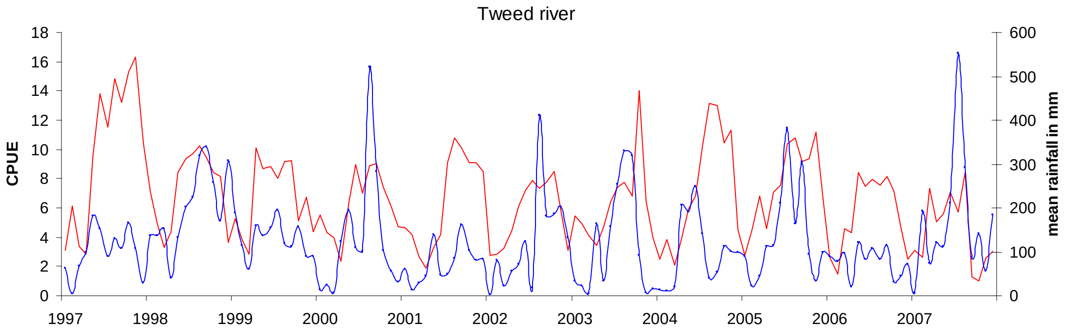
1994
1995
1996

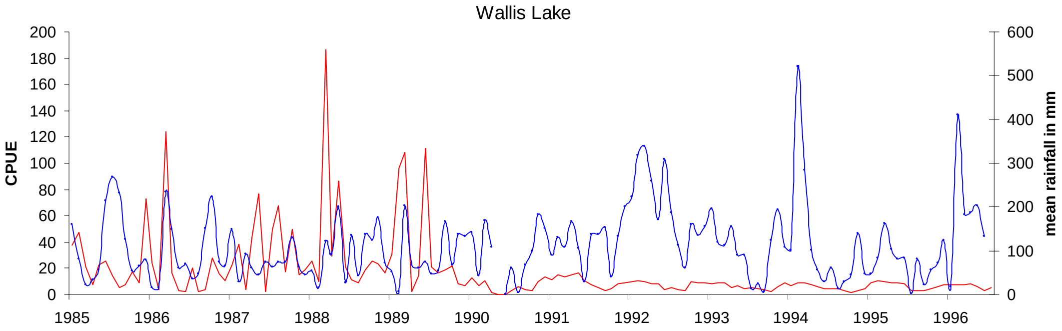

Nambucca river
CPUE
mean rainfall in mm
0
2
4
6
8
10
12
14
16
18
0
100
200
300
400
500
600
700
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

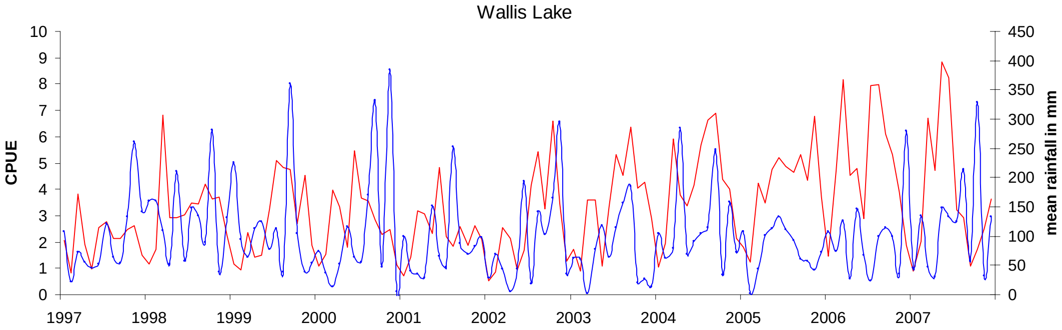

Myall, Karuah rivers
CPUE
0
5
10
15
20
25
30
mean rainfall in mm
0
50
100
150
200
250
300
350
400
450
500
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996


Myall, Karuah rivers
CPUE
0
5
10
15
20
25
30
mean rainfall in mm
0
50
100
150
200
250
300
350
400
450
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007


Tweed river
CPUE
0
5
10
15
20
25
mean rainfall in mm
0
100
200
300
400
500
600
700
800
900
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996


Tweed river
CPUE
0
2
4
6
8
10
12
14
16
18
mean rainfall in mm
0
100
200
300
400
500
600
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007


Wallis Lake
CPUE
0
20
40
60
80
100
120
140
160
180
200
mean rainfall in mm
0
100
200
300
400
500
600
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996


Wallis Lake
CPUE
0
1
2
3
4
5
6
7
8
9
10
mean rainfall in mm
0
50
100
150
200
250
300
350
400
450
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007