Freshwater Flow and Commercial Fisheries Production in Estuarine and Coastal Systems

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Abstract

Freshwater flow profoundly influences fisheries production in estuarine and coastal systems. Although connections between freshwater flow and fisheries production are well established, underlying mechanisms remain poorly understood. Investigating relationships between freshwater flow and fisheries production is essential to ensure that the interests of commercial fishers are represented in debates over environmental flows. This thesis examines the impacts of freshwater flow on the production and profitability of estuarine and coastal fisheries. Chapter 1 outlines relationships between freshwater flow and fisheries production in estuarine and coastal systems. Chapter 2 presents a literature review which indicates that freshwater flow influences fisheries production by regulating habitat availability, trophic interactions and fishers' harvesting behaviour. Chapter 3 examines relationships between hydrological variation and the commercial catch rates of five estuarine-associated fish species from nine estuaries in New South Wales (NSW), eastern Australia. Freshwater enhancement of fisheries production was evident, with increased catch rates in months with higher flow. Freshwater flow *per se*, however, was not as important in influencing catch rates as episodic flow events. Chapter 4 explores the impacts of episodic flow events on estuarine and coastal fisheries by examining multivariate patterns in landings, effort and revenue between periods of flood and drought. Results indicate that flood and drought events influence the bio-economic productivity of commercial fisheries by modifying landings composition, fishers' harvesting behaviour and revenue generation. Chapter 5 presents a multi-species, multi-method bio-economic analysis that was used to evaluate the economic performance of fishers' harvesting strategies between non-drought and drought conditions. Projections from the model indicate that droughts redistribute revenue and profit among fishing methods, modifying the economic performance of commercial fisheries. Although diversified harvesting behaviour increased revenue generation, this marginal economic benefit was compromised by higher costs which lowered profitability. Results indicate that the commercial fishing sector is a drought-affected industry in coastal NSW. Chapter 6 summarises the findings of the research presented in this thesis and suggests directions for future work. The research described here provides empirical evidence that freshwater flow regulates the availability of fisheries resources, fishers' harvesting behaviour and the economic performance of commercial fisheries in estuarine and coastal systems.

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I love a sunburnt country,

A land of sweeping plains,

Of ragged mountain ranges,

Of droughts and flooding rains.

I love her far horizons,

I love her jewel-sea,

Her beauty and her terror –

The wide brown land for me

Excerpt from “My Country” by Dorothea Mackellar (1904)

Preface

This dissertation consists of four stand-alone manuscripts (Chapters 2 to 5) that have either been published in peer-reviewed journals or recently submitted for publication. Each of these chapters is self-contained and subsequently some repetition occurs among them. A single reference list formatted in the Harvard style of referencing has been provided at the end of the dissertation to prevent unnecessary duplication. This thesis is a compilation of my own work, with guidance from my supervisors Iain Suthers and James Scandol. I conceptualised the research design described here with the assistance of my supervisors. I also conducted all data analysis and wrote and illustrated the manuscripts. The contributions of co-authors are detailed below.

Chapter 2: **Jonathan Gillson**. Freshwater flow and fisheries production in estuarine and coastal systems: where a drop of rain is not lost. Published in *Reviews in Fisheries Science* (2011) 19: 168-186.

Chapter 3: **Jonathan Gillson**, James Scandol and Iain Suthers. Estuarine gillnet fishery catch rates decline during drought in eastern Australia. Published in *Fisheries Research* (2009) 99: 26-37.

James Scandol and Iain Suthers gave conceptual advice, analytical guidance and intellectual input into the data analysis. Both co-authors proof-read and edited the final manuscript.

Chapter 4: **Jonathan Gillson**, James Scandol and Iain Suthers. Effects of flood and drought events on multi-species, multi-method estuarine and coastal fisheries in eastern Australia. In Press in *Fisheries Management and Ecology*. Accepted for publication on the 19th June, 2011.

James Scandol and Iain Suthers gave conceptual advice, analytical guidance and intellectual input into the data analysis. Both co-authors proof-read and edited the final manuscript.

Chapter 5: **Jonathan Gillson** and James Scandol. Spreading the economic risk: harvesting strategies of multi-method inshore fisheries during drought in eastern Australia. Submitted for publication in *Fisheries Research* on the 15th of December, 2010.

James Scandol gave conceptual advice, analytical guidance and intellectual input into the data analysis. He also proof-read and edited the final manuscript.

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To my family, this would have been impossible without each of you. Mum, thank you for your unrivalled strength and support that continues to inspire me everyday. Dad, thank you for your unfaltering composure and humour that helped me during toughest parts of this candidature. Stephen, thank you for your incessant patience and understanding that encouraged me to pursue my research interest. My sincere gratitude goes to Matthew Crabb and James Hall for their unwavering encouragement, reassurance and friendship. I will always be indebted to my childhood friends who relentlessly encouraged me to chase my dreams, especially Lawrence Raven and Matthew Egan for your continued support in my somewhat incomprehensible passion.

Abstract

Freshwater flow has profound effects on fisheries production in estuarine and coastal systems. Although connections between freshwater flow and fisheries production are well established, underlying mechanisms remain poorly understood. Investigating relationships between freshwater flow and the production of estuarine and coastal fisheries is a research priority aimed at ensuring that the interests of commercial fishers are duly represented in decision-making processes associated with the allocation of environmental flows. This thesis examines the role of freshwater flow in influencing fisheries production and profitability in estuarine and coastal systems.

Chapter 1 outlines relationships between freshwater flow and fisheries production in estuarine and coastal systems throughout the world. Chapter 2 presents a review of the ecological and socio-economic impacts of freshwater flow on estuarine and coastal fisheries, with particular emphasis on regional examples from eastern Australia and southern Africa. This chapter reveals that freshwater flow influences fisheries production by regulating habitat availability, trophic interactions and fishers' harvesting behaviour. Subsequent chapters examine how freshwater flow impacts fisheries production using a suite of estuarine and coastal fisheries along the New South Wales (NSW) coastline in eastern Australia.

Chapter 3 examines relationships between hydrological variation and the commercial catch-per-unit-effort (CPUE) of five estuarine-associated fish species in nine permanently open estuaries between 1997 and 2007. Freshwater enhancement of

fisheries production was evident, with increased CPUE in months with higher flow. Seasonal flows were consistently the most important aspect of the flow regime that explained the highest proportion of variation in CPUE. Freshwater flow *per se*, however, was not as important in influencing CPUE as episodic flow events.

Chapter 4 explores the impacts of episodic flow events on inshore fisheries by examining multivariate patterns in commercial fisheries landings, effort and revenue from three adjacent estuarine and coastal systems between nine-month periods of flood and drought. Flood and drought events were associated with shifts in the species composition of landings that were reciprocated between estuarine and coastal systems. Species that dominated estuarine landings during drought subsequently dominated coastal landings during flood. Estuarine migrant species (e.g. school prawn *Metapenaeus macleayi*) primarily contributed to landings during flood, while marine estuarine-opportunist species (e.g. yellowfin bream *Acanthopagrus australis*) primarily contributed to landings during drought. Significant differences in landings and revenue between flood and drought were attributed to a mixed-signal of ecological response and fishers' harvesting behaviour. Results indicate that flood and drought events influence the bio-economic productivity of commercial fisheries by modifying the species composition of landings, fishers' harvesting behaviour and revenue generation.

Chapter 5 presents a multi-species, multi-method bio-economic analysis that was used to evaluate the economic performance of fishers' harvesting strategies between non-drought and drought conditions in three adjacent estuarine and coastal systems.

Sensitivity analyses were used to evaluate the robustness of revenue and profit outputs under alternative economic scenarios. Projections from the model indicate that droughts redistribute revenue and profit among fishing methods, modifying the economic performance of commercial fishing businesses. Reductions in revenue and profit were most pronounced for businesses that operated ocean prawn trawls and estuary prawn trawls during drought. Although diversified harvesting behaviour increased revenue generation, this marginal economic benefit was compromised by higher costs associated with increased diversification which appeared to lower profitability. Fishers would benefit from diversifying their employment outside the commercial fishing industry to maintain net incomes during drought. Results indicate that the commercial fishing sector is a drought-affected industry in coastal NSW.

Chapter 6 summarises the findings of the research presented in this thesis and suggests directions for future work. The research presented here demonstrates that freshwater flow regulates the availability of fisheries resources, modifies fishers' harvesting behaviour and influences the economic performance of commercial fisheries in estuarine and coastal systems.

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General Introduction

1.1. Background on freshwater flow and fisheries production

Freshwater flow has profound effects on the production of estuarine and coastal fisheries (Beamish et al. 1994; Grimes 2001; Erzini 2005). Commercial landings of fish, crustaceans and molluscs have been related to variation in freshwater flow in temperate, tropical and subtropical regions (Quiñones and Montes 2001; Lloret et al. 2004; Möller et al. 2009). Relationships between freshwater flow and the landings of estuarine and coastal fishery species can be positive, negative or inconsistent among regions (Figure 1–1). For example, positive relationships between freshwater flow and landings of fish and invertebrates were reported in northern Australia (Loneragan and Bunn 1999). Negative relationships between freshwater flow and landings of poenskop (*Cymatoceps nasutus*) were identified on the east coast of southern Africa (Lamberth et al. 2009); and positive and negative relationships between freshwater flow and landings of banana prawns (*Peneaus merguiensis*) were documented in two different coastal regions in northern Australia (Vance et al. 1985). Mechanisms underlying relationships between freshwater flow and commercial landings are multifaceted. This introductory chapter outlines environmental, ecological and socio-economic processes that drive these relationships over varying temporal and spatial scales.

Aquatic species have evolved life history strategies in direct response to natural flow regimes (Bunn and Arthington 2002). Natural variation in freshwater flow strongly influences the growth, survival and recruitment of fish and invertebrates that exhibit varying degrees of estuarine dependency (North and Houde 2003; Staunton-Smith et al. 2004; Purtlebaugh and Allen 2010). Freshwater flow regulates the offshore extent of riverine plume fronts, thereby influencing the abundance and distribution of juvenile marine fish in estuarine nursery grounds (Grimes and Kingsford 1996; Le Pape et al. 2003; Vinagre et al. 2009). For example, high flows positively influence the recruitment and survival of juvenile sole (*Solea solea*) by increasing the availability of estuarine nursery grounds in the Bay of Biscay, France (Le Pape et al. 2003). Riverine plume fronts increase offshore concentrations of land-based cues that stimulate juvenile marine fish to migrate from coastal spawning grounds towards estuaries (James et al. 2007; Vinagre et al. 2007; Vinagre et al. 2009).

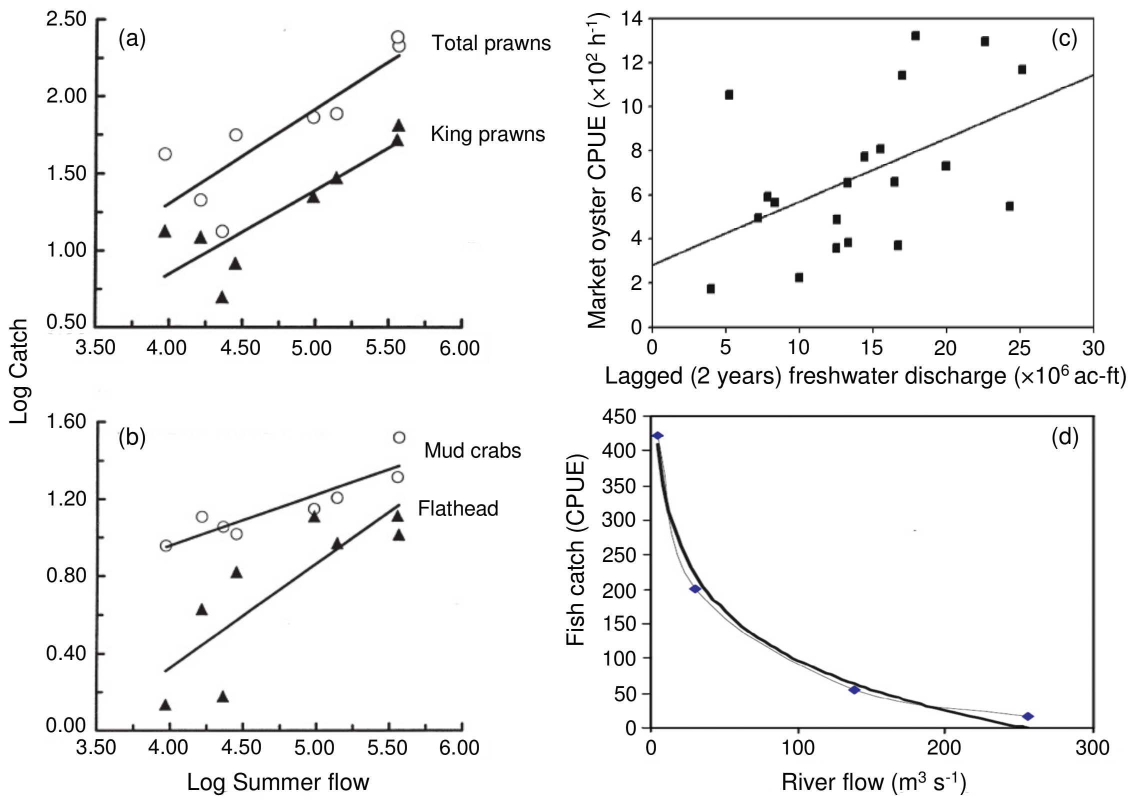


Figure 1-1: Examples of relationships between freshwater flow and landings of fish and invertebrates in estuarine and coastal systems. Subfigures a and b illustrate positive relationships between $\log_{10}$ summer flow and catches of prawns, mud crabs and flathead in the Logan River system in northern Australia from 1988 to 1995 (data from Loneragan and Bunn 1999); subfigure c shows a positive relationship between lagged (2 years) freshwater flow and mean annual oyster catch-per-unit-effort (CPUE) in Galveston Bay in North America from 1985 to 2004 (data from Buzan et al. 2009); and subfigure d illustrates a negative relationship between freshwater flow and the catch-per-unit-effort (CPUE) of fish in the Thukela estuary in southern Africa (data from Whitfield and Harrison 2003).

Natural fluxes in the flow regime influence the catchability of fish and invertebrates by restricting their distribution or stimulating movement into areas where they are more likely to be caught (Loneragan and Bunn 1999). In eastern Australia, for example, high flows result in the increased catchability of school prawns (*Metapenaeus macleayi*) due to reductions in salinity enhancing emigration rates from estuarine to coastal systems (Racek 1959; Ruello 1973; Glaister 1978). Seasonal pulses of freshwater proximate to reproductive periods have marked impacts on the catchability of estuarine-associated fish. For instance, increased freshwater flow into the Princess Charlotte Bay of eastern Australia results in increased catchability of barramundi (*Lates calcarifer*) by stimulating mature males to migrate towards estuarine spawning grounds at the beginning of the wet season (Balston 2009). Both the timing and magnitude of freshwater flow influence the migration patterns of fish and invertebrates in estuarine and coastal systems (Drinkwater and Frank 1994).

Despite consistent links between freshwater flow and the production of estuarine and coastal fisheries, underlying mechanisms remain poorly understood. Freshwater flow regulates the physical, chemical and biological properties of estuarine and coastal systems (Skreslet 1986). Consequently, one of the major difficulties in isolating mechanisms underlying relationships between freshwater flow and fisheries production is that river discharge affects a myriad of environmental factors (e.g. sediment delivery, salinity regimes and water temperature) that impact the life-histories of fish and invertebrates. Nevertheless, the complex effects of freshwater flow on fish and invertebrates in estuarine and coastal systems can be broadly divided into two categories, effects on habitat availability and trophic interactions.

1.1.1. Habitat availability

Freshwater flow directly impacts fisheries production by regulating the availability of habitat for fish and invertebrates in estuarine and coastal systems (Loneragan and Bunn 1999; Kimmerer 2002a; Whitfield and Harrison 2003). Seasonal and interannual variation in freshwater flow influences the distribution and abundance of fish and invertebrates by modifying rates of sediment delivery, salinity regimes, turbidity levels and water temperature (Jassby et al. 1995; Wingate and Secor 2008; Vivier and Cyrus 2009).

Temporal and spatial variation in freshwater flow controls the duration and frequency that an estuary mouth is open or closed by modifying rates of sediment delivery (Reddering and Rust 1990; Eyre 1998). The status of an estuary mouth determines whether fish and invertebrates can migrate between estuarine and coastal systems (Whitfield and Kok 1992; Vorwerk et al. 2003; Vivier and Cyrus 2009). Permanently open estuaries maintain a constant connection with the sea, thus enabling fish and invertebrates migrations between estuarine and coastal systems (Kok and Whitfield 1986; Potter et al. 1990; Whitfield 1994a). Estuary mouth closure, however, inhibits species exchange resulting in the decreased abundance of marine taxa, recruitment limitation and a loss of estuarine nursery function (Wooldridge 1991; Harrison and Whitfield 1995; Young and Potter 2002). Alterations to freshwater flow can affect community composition by modifying the periodicity that Intermittently Closed and Open Lakes and Lagoons (ICOLLs) are connected to the ocean in eastern Australia (Roy et al. 2001; Jones and West 2005; Haines et al. 2006).

Freshwater flow strongly influences the species composition of fish and invertebrate communities by altering salinity regimes in estuarine and coastal systems (Jassby et al. 1995; Hurst et al. 2004; Costa et al. 2007). One of the most essential adaptations of fish and invertebrates that enter estuaries is the ability to adjust to changes in salinity (Panikkar 1960). Salinity strongly influences habitat selection, with species actively seeking optimum habitat conditions to minimise osmoregulatory costs and maximise growth rates (Edeline et al. 2005; Cardona 2006; Shen et al. 2009). Differences in the salinity tolerance of individual species are often attributed to the divergent responses of fish and invertebrates to variation in freshwater flow (Drinkwater and Frank 1994; Gillanders and Kingsford 2002; Whitfield 2005). Freshwater encroachment onto the continental shelf lowers salinity, expands estuarine conditions offshore and permits euryhaline species to increase their distribution into coastal waters (Able 2005). Marine stenohaline species respond to increased freshwater flow by emigrating from estuarine into coastal systems due to lower salinity forcing the seaward displacement of habitat (Kimmerer 2002a; Whitfield and Harrison 2003; James et al. 2007).

Freshwater flow can modify the distribution and abundance of marine fish by altering turbidity levels in estuarine and coastal systems (Cyrus and Blaber 1992; Blaber et al. 1995; Grange et al. 2000). Turbidity has a profound effect on the early-life history stages of marine fish (Blaber and Blaber 1980; Whitfield 1994a; Harris et al. 2001). For example, detailed studies in KwaZulu-Natal estuaries on the east coast of southern Africa have demonstrated that juvenile marine fish can be divided into categories depending on the turbidity tolerance of individual species (Cyrus and Blaber 1987a;

1987b). Cyrus and Blaber (1987c) identified that 16 out of 20 species studied exhibited an affinity for turbid waters. Offshore turbidity gradients influence the feeding rates of fish, predation pressure and larval immigration into estuarine nursery grounds (Blaber and Blaber 1980; Hecht and van der Lingen 1992; Utne-Palm 2002).

Fisheries production is strongly influenced by freshwater flow altering the temperature of estuarine and coastal waters (Vance et al. 1985; Mantua et al. 1997; Albaret et al. 2004). For example, the combination of winter water temperature and freshwater flow were the most important environmental factors explaining the distribution and abundance of anadromous and coastal spawning species in the nursery grounds of Chesapeake Bay in North America (Wingate and Secor 2008). Temperature is an ecological resource that controls the metabolic rate and physiology of fish (Magnuson et al. 1979). Fish can be assigned a thermal niche according to the temperature tolerance of individual species (Magnuson and Destasio 1996). Habitat selection by juvenile marine fish is dependent on the availability of optimal thermal habitats in estuarine and coastal systems (Attrill and Power 2002; 2004).

1.1.2. Trophic interactions

Freshwater flow can indirectly impact fisheries production via a trophic cascade. Natural variation in freshwater flow regulates fisheries production by altering the delivery of terrestrially-derived nutrients and organic matter into estuarine and coastal systems (Darnaude 2005). Nutrient-enriched freshwater stimulates increased phytoplankton and zooplankton production thereby enhancing the recruitment, growth and survival of fish and invertebrates through upward trophic transfer (Darnaude et al. 2004; Hoffman et al. 2007; Kostecki et al. 2010).

Estuarine and coastal food web structure is highly sensitive to variation in freshwater flow (Darnaude 2005). Seasonal and interannual variation in freshwater flow determines the origin of carbon assimilated into pelagic and benthic food webs (Wissel and Fry 2005; Vorwerk and Froneman 2009; Vinagre et al. 2011). Relationships between nutrient-enriched freshwater and fisheries production are most noticeable in oligotrophic or semi-enclosed coastal regions that receive limited nutrient supplies from oceanic currents and upwelling events (e.g. the Mediterranean Sea: Darnaude et al. 2004; the Gulf of Mexico: Wissel and Fry 2005; and the South China Sea: Qiu et al. 2010).

1.2. Episodic flow events and fisheries production

Connections between freshwater flow and fisheries production are best illustrated by the ecological impacts of episodic flow events in estuarine and coastal systems. Flood and drought events are pulse disturbances that maintain biological productivity by modifying species richness and diversity due to changes in physicochemical conditions (Flint 1985; Martin et al. 1992; Dolbeth et al. 2008). Although connections between freshwater flow and fisheries production are well established (Caddy and Bakun 1995), limited information is available on the impacts of flood and drought events on estuarine and coastal fisheries.

Flood events can temporary reduce fish abundance and diversity in estuaries. For example, freshwater flooding into southern African estuaries reduces fish abundance and diversity by forcing marine taxa to emigrate from estuarine into coastal systems due to rapid declines in salinity (Marais 1983; Ter Morshuizen et al. 1996; Whitfield and Harrison 2003). Severe floods create a physical barrier to the recruitment of marine taxa by lowering salinity, reducing available nursery habitat and forcing the seaward dispersion of larvae (Loneragan and Bunn 1999; Strydom et al. 2002; Whitfield and Harrison 2003). Flood generated mass mortalities of fish and invertebrates result from the creation of unfavourable water quality characteristics. For instance, a major flash flood into the Sundays River Estuary in southern Africa caused extensive mortalities of marine migrant and estuarine resident species due to suspended sediment clogging gills, low salinities creating osmoregulatory stress and reduced dissolved oxygen levels causing asphyxiation (Whitfield and Paterson 1995).

Drought events can have deleterious effects on estuarine biota (Copeland 1966). Drought-induced high salinities result in a loss of freshwater species, declines in estuarine-dependent species and the establishment of marine straggler species in the lower reaches of estuaries (Vivier and Cyrus 2002; Baptista et al. 2010). Reductions in the delivery of nutrient-enriched freshwater into estuaries can lead to recruitment failure in marine fish. For example, a five-year drought in the San Francisco Bay estuary resulted in reductions in the recruitment success of stripped bass (*Morone saxatilis*) due to larval starvation arising from pelagic food web limitation (Bennett et al. 1995). The production of estuarine resident and juvenile marine fish exported between estuarine and coastal systems can be significantly reduced during drought (Dolbeth et al. 2008). These alterations to biological productivity are likely to have major impacts on estuarine and coastal fisheries.

1.3. The need to understand fisheries/flow relationships

Estuarine and coastal systems are becoming increasingly degraded by human activities (Lotze et al. 2006). One human activity that is compromising the goods and services provided by estuarine and coastal systems is the modification of freshwater flow (Kennish 2002). Anthropogenic modification of freshwater flow disrupts the structure and function of estuarine and coastal systems by forcing physicochemical processes to deviate from natural successionary patterns (Sklar and Browder 1998; Gillanders and Kingsford 2002; Sheaves et al. 2007). Protecting natural variation in freshwater flow is essential to maintain the structure and function of estuarine and coastal systems (Schlacher and Wooldridge 1996; Sklar and Browder 1998; Young and Potter 2002). Nevertheless, there is still a false perception that freshwater is 'lost' when it enters estuarine or coastal systems (Gillanders and Kingsford 2002). Understanding the role of freshwater flow in determining fisheries production is essential to ensure that the interests of commercial fishers are duly represented in decision-making processes associated with the allocation of environmental flows. Examining relationships between freshwater flow and the catch rates of commercially harvested species is an important avenue of investigation that will provide an improved understanding of the impacts of river regulation, freshwater extraction and climate change on estuarine and coastal fisheries.

Knowledge regarding the impacts of freshwater flow on fisheries production is greater in estuarine than coastal systems. Many marine studies considering the impacts of freshwater flow on fish and invertebrates have focused on estuarine-dependent species (Browder 1985; Galindo-Bect et al. 2000; Powell et al. 2002). Consequently, limited information is available on the impacts of freshwater flow on commercially harvested open-sea species that do not depend on estuaries during their life-cycle (Grimes 2001; Erzini 2005; Lamberth et al. 2009). Considerable attention has also been devoted to the ecological impacts of variable flows on fish and invertebrates. In contrast, the socio-economic impacts of variable flows on multi-species, multi-method fisheries that operate in estuarine and coastal systems have received relatively little attention. Fisheries scientists and managers must recognise that freshwater flow has ecological and socio-economic impacts on estuarine and coastal fisheries. One issue that requires consideration is the influence of freshwater flow on the availability of fisheries resources and the operational characteristics of commercial fisheries in estuarine and coastal systems (Figure 1–2).

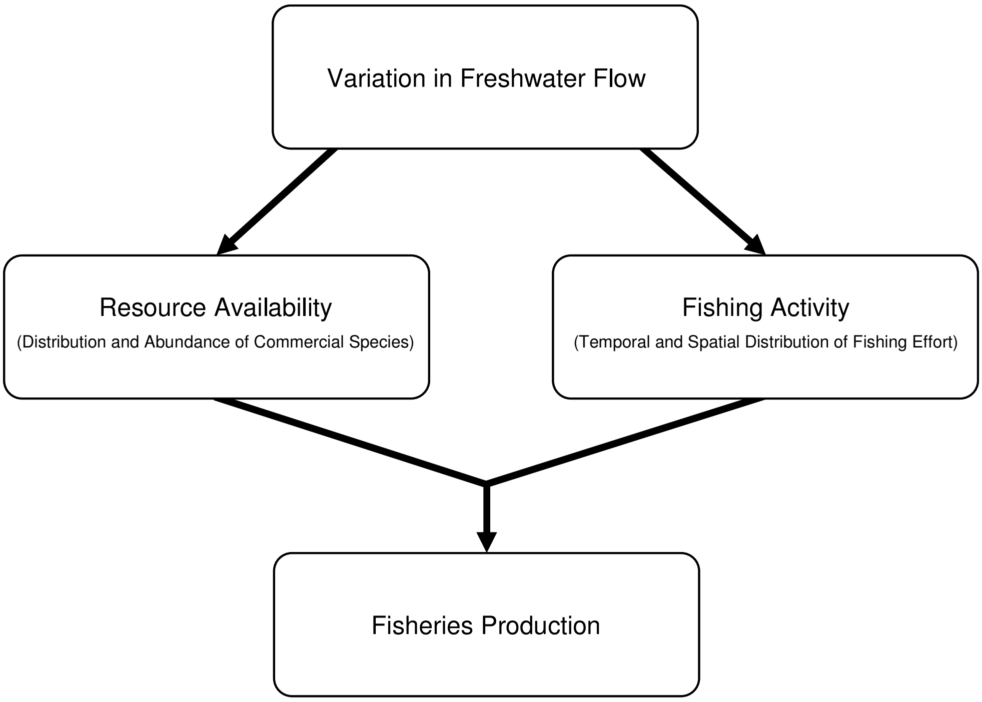


Figure 1-2: A conceptual view of the influence of freshwater flow on the production of estuarine and coastal fisheries.

1.4. Management of freshwater flow into estuarine and coastal systems

Conflicts over the allocation of freshwater for human and ecosystem needs are increasingly emerging throughout the world (Poff et al. 2003). Management agencies concerned with allocating freshwater to maintain the ecological integrity of aquatic systems are faced with a complex dilemma. Human appropriation of freshwater for municipal, industrial and agricultural uses has long taken precedence over the needs of aquatic ecosystems (Baron et al. 2002). There is an inherent trade-off between allocating freshwater to meet the demands of a growing human population while conserving the goods and services provided by aquatic ecosystems (Jackson et al. 2001). One of the many concerns associated with allocating freshwater to aquatic ecosystems is the combined impacts of human population growth and climate change on the future availability of freshwater resources (Vörösmarty et al. 2000).

Estuarine and coastal systems require a sufficient volume of freshwater to maintain biogeochemical processes (Skreslet 1986), but this remains to be quantified in many regions of the world. A global review of the impacts of changes in freshwater flow on estuarine and coastal systems has been conducted by Gillanders and Kingsford (2002). These authors concluded that, in some areas of the world, freshwater entitlements exceed the available water supply yet few proposals for regulating quantities are scrutinised in terms of possible environmental impacts on estuarine and coastal systems. Knowledge regarding the freshwater requirements of estuarine and coastal systems is far from complete (Montagna et al. 2002). A substantial research effort is required to gain a better understanding of the impacts of modifying natural variation in freshwater flow on estuarine and coastal fisheries.

Regulation of freshwater flow is widely considered to be a major cause of deteriorating environmental conditions in many rivers throughout the world (Bunn and Arthington 2002). Recognition that environmental flows need to be allocated to maintain the structure and function of freshwater dependent ecosystems is increasing emerging in policy, planning and legislation (Tharme 2003; Arthington et al. 2006; Poff et al. 2010). Methods to determine the freshwater requirements of estuarine and coastal systems have been proposed in Australia. A two-stage approach that includes a “preliminary evaluation phase” followed by a “detailed investigative phase” has been proposed by Peirson et al. (2002). Although this approach has a sound rationale to determine the freshwater requirements of estuarine and coastal systems at a broad-scale, it provides limited guidance on identifying flows needed to maintain fisheries production. An improved understanding of the freshwater requirements of estuarine and coastal systems will only emerge as we gain a better appreciation of ecologically-important aspects of the flow regime (Gippel 2001; Scheltinga et al. 2006). Research that integrates life-history information will assist in understanding the freshwater requirements of estuarine and coastal fisheries (Robins et al. 2005).

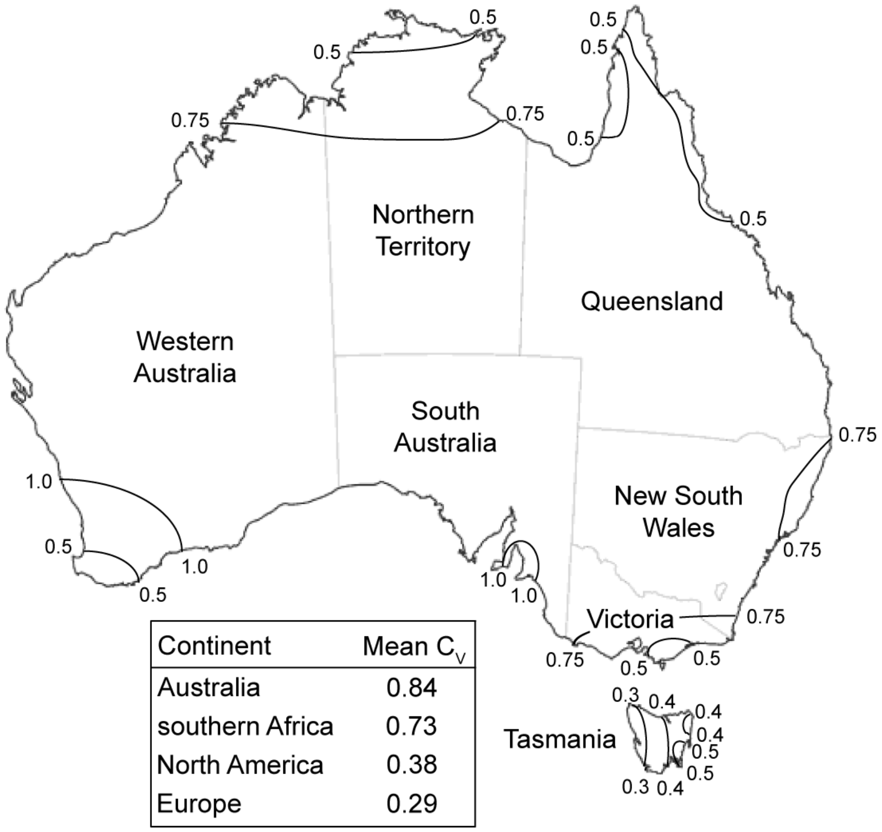
1.5. Nature of freshwater flows in eastern Australia

Australia is the driest inhabited continent in the world, with low annual rainfall and high evaporation rates (Fleming 1995). This continent is a land of extreme droughts and flooding rains. Rivers in Australia exhibit extreme hydrological conditions characterised by the most variable flows in the world (Finlayson and McMahon 1988). Annual variation in freshwater flow from Australian rivers ($C_V = 0.84$) is considerably higher than North American ($C_V = 0.38$), European ($C_V = 0.29$) and Asian ($C_V = 0.33$) Rivers (Figure 1–3). This high variability in freshwater flow can be partially attributed to the exposure of the Australian continent to the El Niño Southern Oscillation (ENSO) (Kuhnel et al. 1990). The ENSO is a driving force of climatic systems in the Southern Hemisphere (Allan et al. 1996), which strongly influences rainfall and freshwater flow in eastern Australia (Chiew et al. 1998). Variation in the ENSO drives sporadic rainfall and stochastic flow events in this region (Power et al. 1999). Other environmental factors that influence rainfall and freshwater flow in this region include sea surface temperature oscillations in the Central Pacific and the Indian Ocean (Power et al. 1999;

Ashok et al. 2003). Coastal rivers in eastern Australia experience prolonged periods of drought that are punctuated by sporadic flood events due to extreme variations in rainfall (Erskine and Warner 1998). Freshwater is primarily delivered into estuarine and coastal systems in this region by episodic flow events (Eyre 1998).

Australian rivers are becoming increasingly regulated due to growing human demand for freshwater resources (Arthington and Pusey 2003). River regulation in Australia has replaced natural variability in flow regime with artificial flow cycles that have human-imposed trajectories (McMahon and Finlayson 2003). In eastern Australia, freshwater resources are highly developed in some areas (e.g. the Murray-Darling Basin: Reid and Brooks 2000) and are being planned for development in others (e.g. the Clarence River catchment). Concern has been expressed about the impacts of modified flow regimes on estuarine and coastal fisheries in Australia (Walker 1985; Loneragan and Bunn 1999; Robins et al. 2005). Nevertheless, limited information is available on the impacts of modified flow regimes on estuarine and coastal fisheries in this region.

Another major concern is the impacts of climate change on freshwater resources and the associated implications for estuarine and coastal fisheries (Kennish 2002). Climate change is predicted to modify the hydrological cycle with associated changes in rainfall, evaporation, surface runoff, groundwater and freshwater flow (Zestser and Loaiciga 1993; Loaiciga et al. 1996; Milly et al. 2005). Climatic projections indicate that reductions in rainfall and warmer temperatures will decrease the availability of freshwater resources in eastern Australia (Kundzewicz et al. 2007). Greater hydrological extremes are expected to increase the frequency and severity of flood and drought events in this region (Meehl et al. 2007). Alterations to freshwater flow resulting from climate change are likely to be exacerbated by increased human population growth increasing demand for freshwater (Vörösmarty et al. 2000).



Continent	Mean C_V
Australia	0.84
southern Africa	0.73
North America	0.38
Europe	0.29

Figure 1-3: Coefficient of variation (C_V) for annual freshwater flow in Australian coastal rivers. Note that the table below the illustration shows the mean C_V for annual freshwater flow in several regions of the world. (Modified from Finlayson and McMahon 1988).

1.6. Estuarine and coastal fisheries in New South Wales

Diverse multi-species, multi-method fisheries operate along the New South Wales (NSW) coastline in eastern Australia. Commercial fisheries target penaeid prawns

(*Metapenaeus macleayi*, *Melicertus plebejus, Metapenaeus bennettae*), finfish (*Acanthopagrus australis, Platycephalus fuscus, Mugil cephalus*), sharks (*Carcharhinus* spp.) and crabs (*Portunus pelagicus, Scylla serrata, Ranina ranina*) with a gross value of ~AU$82 million per annum (ABARE 2009). These species are primarily harvested by five major commercial fisheries (Table 1–1, and Figure 1–4): the Estuary General fishery (EG), Estuary Prawn Trawl fishery (EPT), Ocean Hauling fishery (OH), Ocean Trawl fishery (OT) and the Ocean Trap and Line fishery (OT&L). Other commercial fisheries that were not considered in this thesis include the Abalone fishery and the Lobster fishery. Fishers can possess endorsements to operate multiple fishing methods in multiple fisheries. A short description of each fishery considered in this thesis is provided below.

Table 1-1: Summary of the five major commercial fisheries in NSW.

Fishery	Fishing method	Fishing businesses	Capital investment range (AU$000's)
Estuary General	Gillnets	199	10 – 100
	Hauling net		
	Prawn set pocket net		
	Crab pot		
	Eel trap		
	Bait net		
	Handline		
	Fish trap		
	Bullringing		
Estuary Prawn Trawl	Estuarine prawn trawl	69	30 – 150
Ocean Hauling	Hauling net	24	20 – 150
	Purse seine net		
	Bait net		
Ocean Trawl	Ocean prawn trawl	112	70 – 850
	Fish trawl		
Ocean Trap and Line	Fish trap	101	50 – 250
	Handline		

Fishing businesses represents the mean monthly number of fishing businesses between July 1997 and June 2007. Capital investment range indicates the minimum and maximum amount of money (AU $000's) fishing businesses invest in fishing assets. Information on the capital investment range was obtained from economic assessments undertaken by Dominion Consulting Pty Ltd for the 1999 2000 fiscal period (Dominion Consulting Pty Ltd 2001, 2002a, 2002b, 2004, 2006).

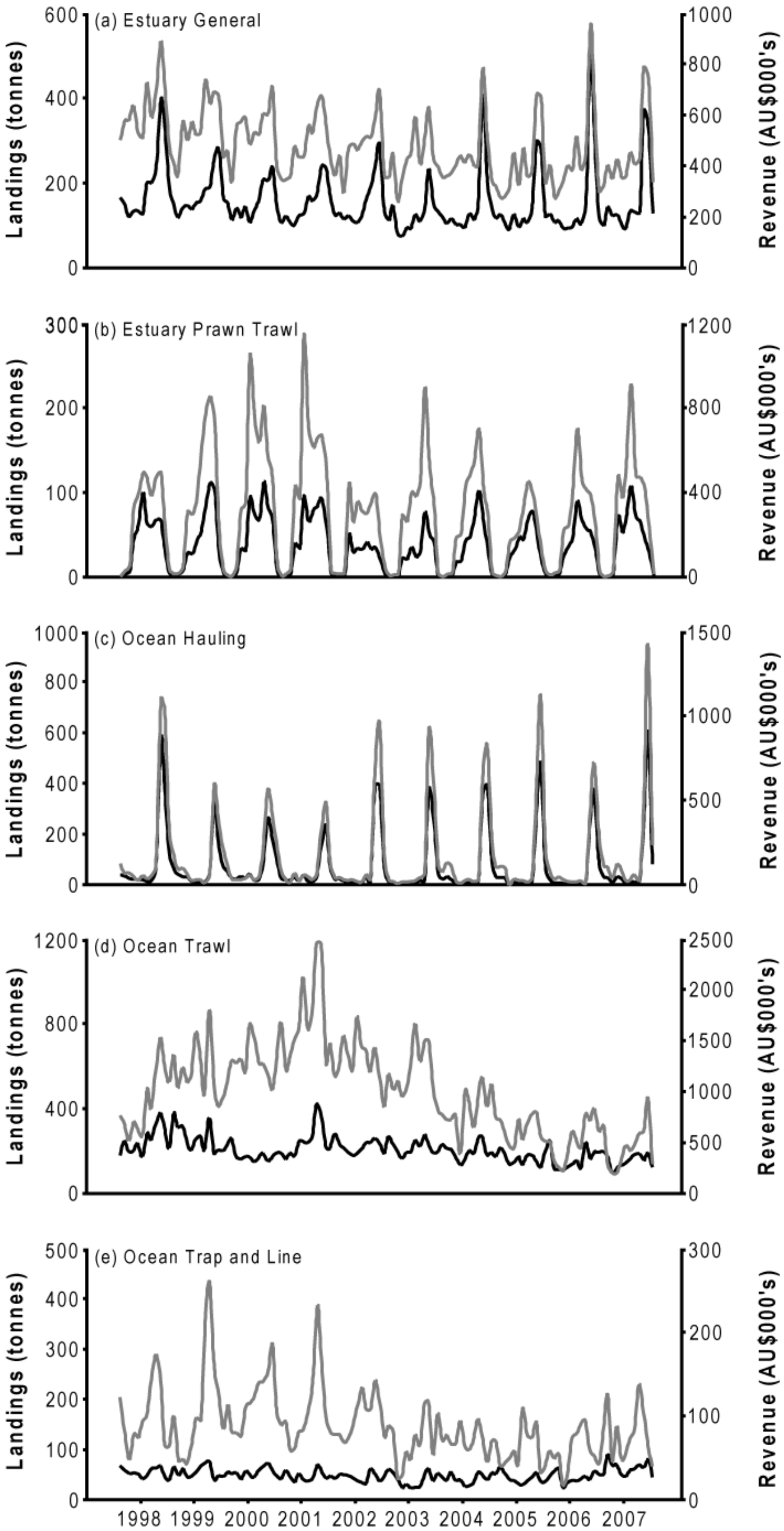


Figure 1-4: Temporal trends in landings (black line) and revenue (grey line) for the Estuary General (a), Estuary Prawn Trawl (b), Ocean Hauling (c), Ocean Trawl (d) and Ocean Trap and Line (e) fisheries from July 1997 to June 2007. Note that revenue has been inflation–adjusted using the Sydney food Consumer Price Index (CPI) relative to June 2007 ($CPI_{June2007}$ = 1).

1.6.1. Estuary General fishery (EG)

The Estuary General fishery is a diverse multi-method fishery that provides endorsements for fishers to operate 17 different fishing methods (including crab pots, handlines and hauling nets) in the estuarine waters of NSW (I&I NSW 2010a). These fishing methods are used to target a variety of different fish and invertebrate species (e.g. *Platycephalus fuscus, Mugil cephalus* and *Scylla serrata*). The EG fishery is comprised of a diverse range of owners (~615 licensed fishing businesses in 2009 (I&I NSW 2010a)), many with endorsements in other commercial fisheries, particularly the Estuary Prawn Trawl fishery. Average capital investment in this fishery ranges from ~AU$10 000 to AU$100 000 (Dominion Consulting Pty Ltd 2001). Mean landings from the EG fishery between 1997 and 2007 was 110 tonnes per month, with a monthly value of ~AU$350 000 at Sydney Fish Market prices (I&I NSW Catch Records 2010).

1.6.2. Estuary Prawn Trawl fishery (EPT)

The Estuary Prawn Trawl fishery is a single-method fishery that provides endorsements for fishers to operate otter trawl nets in the estuarine waters of NSW. These trawling nets are used to target penaeid prawns (e.g. *Metapenaeus macleayi* and *Penaeus plebejus*). A diverse range of fishing businesses operate in the EPT fishery (~180 licensed businesses in 2009 (I&I NSW 2010b)), many with endorsements in other commercial fisheries, particularly Estuary General fishery. Average capital investment in this fishery is ~AU$80 000, with a range from AU$30 000 to AU$150 000 (Dominion Consulting Pty Ltd 2002a). Mean landings from the EPT fishery between 1997 and 2007 was 37 tonnes per month valued at ~AU$260 000 per month at Sydney Fish Market prices (I&I NSW Catch Records 2010).

1.6.3. Ocean Hauling fishery (OH)

The Ocean Hauling fishery is a multi-method fishery that provides endorsements for fishers to operate 5 different netting methods (including hauling nets, purse seine nets and bullringing nets) in ocean waters off the coast of NSW. These netting methods are used to target a variety of different fish species (e.g. *Mugil cephalus*, *Scomber australasicus* and *Trachurus novaezelandiae*) from beaches and ocean waters within 3 nautical miles of the coast (I&I NSW 2010c). The OH fishery was comprised of ~285 licensed fishing businesses in 2009 (I&I NSW 2010c). Average capital investment in this fishery ranges from ~AU$20 000 to AU$150 000 (Dominion Consulting Pty Ltd 2002b). Mean landings from the OH fishery between 1997 and 2007 was 72 tonnes per month, with a monthly value of ~AU$150 000 at Sydney Fish Market prices (I&I NSW Catch Records 2010).

1.6.4. Ocean Trawl fishery (OT)

The Ocean Trawl fishery is a dual-method fishery that provides endorsements for fishers to operate prawn trawls and fish trawls in ocean waters off the coast of NSW. Although both fishing sectors use a demersal trawl net, they have different operational characteristics and target different species (NSW Department of Primary Industries 2004). Ocean prawn trawls target penaeid prawns (e.g. *Penaeus plebejus* and

Metapenaeus macleayi), while ocean fish trawls target teleost fish (e.g. *Pseudocaranx georgianus* and *Platycephalus richardsoni*). Given that trawling gear is unselective and operates over a wide geographic area, a large number of non-target fish and invertebrates are captured by ocean trawlers. More than 300 fish species and 80 invertebrates species have been recorded in ocean trawl catches, with ~40% of species being unmarketable (NSW Department of Primary Industries 2004). Vessels used in the OT fishery range from 9 to 27 meters in length, with single or twin diesel main engines of 60 to 400 kilowatts. Replacement vessels are restricted to 20 meters maximum length and a maximum engine power of 300 kilowatts (NSW Department of Primary Industries 2004). Many fishing businesses operate in the OT fishery (~240 licensed businesses in 2009 (I&I NSW 2010d)). Average capital investment in this fishery ranges from ~AU$70 000 to AU$850 000 (Dominion Consulting Pty Ltd 2004). Mean landings from the OT fishery between 1997 and 2007 was 64 tonnes per month valued at ~AU$820 000 per month at Sydney Fish Market prices (I&I NSW Catch Records 2010).

1.6.5. Ocean Trap and Line fishery (OT&L)

The Ocean Trap and Line fishery is a multi-method fishery that provides endorsements for fishers to operate fish traps and fishing lines in ocean waters off the coast of NSW. These fishing methods are used to target a variety of pelagic and demersal species (e.g. *Sarda australis*, *Acanthopagrus australis* and *Seriola lalandi*). The OT&L fishery was comprised of ~365 licensed fishing businesses in 2009 (I&I NSW 2010e). Average capital investment in this fishery ranges from ~AU$50 000 to AU$250 000 (Dominion

Consulting Pty Ltd 2006). Mean landings from the Ocean Trap and Line Fishery between 1997 and 2007 was 12 tonnes per month, with a monthly value of ~AU$60 000 at Sydney Fish Market prices (I&I NSW Catch Records 2010).

1.6.6. Recreational fishery

Although the impacts of freshwater flow on recreational fisheries were not considered in this thesis, the recreational fishing industry is extremely valuable from a social and economic perspective in NSW (ABARE 2009). The recreational fishery is a diverse multi-method fishery that enables members of the public to use any of 18 different fishing methods (including lines, pots/traps, nets, spears and hand collecting, though angling is by far the most common method) in the freshwater, estuarine and coastal systems of NSW (Henry and Lyle 2003). These fishing methods are used to target a variety of different fish and invertebrate species (e.g. *Platycephalus fuscus*, *Acanthopagrus australis*, *Sillago ciliata*) for non-commercial uses primarily in estuarine and coastal waters. Participation in recreational fishing is relatively high in NSW, with ~17% of the public participating in recreational fishing at least once in the 12 months prior to May 2000 (Henry and Lyle 2003). Approximately 200 000 households owned recreational fishing vessels in NSW at a value of ~AU$790 million in the 12 months prior to May 2000. Vessels used in the recreational fishery range from 3 to 25 meters in length. The recreational fishery was comprised of approximately one million fishers harvesting ~7000 tonnes of fish and invertebrates with direct expenditure on fishing activities estimated at AU$555 million between May 2000 and April 2001 (Henry and Lyle 2003; Campbell and Murphy 2005).

1.7. Research aims

The research undertaken for this thesis aimed to provide an improved understanding of the impacts of freshwater flow on the production and profitability of estuarine and coastal fisheries. Investigations in NSW could provide "strong-signals" from which to isolate mechanisms underlying relationships between freshwater flow and fisheries production because rivers in this region exhibit highly variable flows. Another rationale behind this research was that the NSW Government implemented the *Water Management* Act (2000) to *inter alia* promote the allocation of environmental flows for the conservation of freshwater dependent ecosystems. This research was initiated in response to demands from fisheries and water resource managers for an improved understanding of relationships between freshwater flow and the production of estuarine and coastal fisheries in NSW (Chessman and Jones 2001). This work addressed two broad goals: firstly, to investigate the relationship between freshwater flow and fisheries production and secondly, to evaluate the impacts of freshwater flow on the dynamics of estuarine and coastal fisheries.

More specifically the aims of the research presented here are to:

1) Examine relationships between hydrological variation and commercial catch-per-unit-effort (CPUE) in nine permanently open estuaries with differing geomorphologies, distinct freshwater inputs and varying degrees of river regulation;

2) Explore multivariate patterns in species landings, methods of fishing effort and revenue per species in multi-method, multi-species estuarine and coastal fisheries between periods of flood and drought;

3) Evaluate the economic impacts of drought events on commercial fishing businesses that operate in adjacent estuarine and coastal systems.

1.8. Study areas

A suite of estuarine and coastal fisheries along the NSW coastline were selected to investigate the influence of freshwater flow on fisheries production. Nine estuaries with differing geomorphologies, distinct freshwater inputs and varying degrees of river regulation were selected to examine relationships between hydrological variation and fisheries CPUE (Aim 1). Three adjacent estuarine and coastal fisheries were subsequently selected to examine the impacts of flood and drought events on multi-method, multi-species inshore fisheries (Aims 2 and 3). These estuarine and coastal fisheries administered by I&I NSW were selected for investigation because they provide the dominant contribution (32%) to commercial harvest in NSW (I&I NSW Catch Records 2010), and the neighbouring river systems exhibit highly variable annual flows with a coefficient of variation (Cv) of more than 75% (Finlayson and McMahon 1988). A short description of each major river system and the associated estuarine and coastal fisheries considered in this dissertation is provided below.

1.8.1. Clarence River

The Clarence River is the largest coastal river system in south-eastern Australia with a catchment of ~22 400 km^2 (Roy et al. 2001), and a mean annual discharge of ~2.0 million ML (NSW Department of Water and Energy 2010). This river rises near the McPherson Ranges and flows ~394 km, before reaching a barrier estuary with an area of 89 km^2 in the town of Yamba. The major tributaries delivering freshwater into the estuary are the Mann, Nymboida and Orara Rivers. Mangroves stands (7.7 km^2), seagrass beds (0.8 km^2) and saltmarsh plains (2.9 km^2) are present in the estuary (Williams et al. 2006). Freshwater flow in the Clarence River has been moderately regulated, with a small weir for power generation and a storage dam for regional water supply. Sections of the Clarence River estuary (e.g. the Middle Wall, Oyster Channel Bridge and the Entrance of Saltwater Inlet) were closed to commercial fishing and declared a Recreational Fishing Haven in September 2002. The adjacent coastal fishery (coastal zone 2) extends ~30 km onto the continental shelf and ~0.5° north and south of the Clarence River. Mean landings from the Clarence River estuary and coastal zone 2 between 1997 and 2007 was 149 tonnes per month, with a monthly value of ~AU$523 000 at Sydney Fish Market prices (I&I NSW Catch Records 2010).

1.8.2. Hunter River

The Hunter River system on the central coast of NSW has a catchment of ~22 000 km^2 (Roy et al. 2001), and a mean annual discharge of ~0.5 million ML (NSW Department of Water and Energy 2010). The river rises in the Mount Royal Range and flows 300 km through the Hunter Valley, before reaching a barrier estuary with an area of 29 km^2 in the town of Newcastle. The major tributaries include the Paterson and Williams Rivers. The estuary has the second largest mangrove forest (15 km^2) and third largest saltmarsh plain (5 km^2) in NSW but virtually no major sea grass beds (Williams et al. 2006). Freshwater flow is highly regulated, with several major dams and reservoirs (e.g. Chichester, Glenbawn, Glennies Creek and Grahamtown) in the north of the catchment. The adjacent coastal fishery (coastal zone 5) extends ~30 km onto the continental shelf and ~0.5° north and south of the Hunter River. Mean landings from the Hunter River estuary and coastal zone 5 between 1997 and 2007 was 79 tonnes per month valued at ~AU$168 000 per month at Sydney Fish Market prices (I&I NSW Catch Records 2010).

1.8.3. Hawkesbury River

The Hawkesbury River system on the central coast of NSW has a catchment of ~21 500 km^2 (Roy et al. 2001), and a mean annual discharge of ~0.7 million ML (Sydney Catchment Authority 2010). This river flows ~145 km, before reaching a drowned valley estuary with an area of 100 km^2 in the town of Picton. Freshwater is mainly delivered into the estuary from the MacDonald, Colo and Grose Rivers. The estuary has extensive mangrove stands (11 km^2), seagrass beds (0.4 km^2) and saltmarsh plains (2.4 km^2) (Williams et al. 2006). Freshwater flow has been extensively regulated, with several major dams (e.g. Nepean, Avon, Cordeaux and Warragamba) throughout the catchment. The adjacent coastal fishery (coastal zone 6) extends ~30 km onto the continental shelf and ~0.5° north and south of the Hawkesbury River. Mean landings from the Hawkesbury River estuary and coastal zone 6 between 1997 and 2007 was 62 tonnes per month, with a monthly value of ~AU$114 000 at Sydney Fish Market prices (I&I NSW Catch Records 2010).

1.9. Main data sources used in this research

1.9.1. Fisheries data

Monthly commercial fisheries catch, effort and market price data were compiled from the Industry and Investment New South Wales (I&I NSW) ComCatch database between July 1997 and June 2007. Fisheries data was made available for this research in a format that protects the privacy of individual fishers while providing detailed information on monthly landings per species (kilograms per month), effort per fishing method (days fished per month) and mean market price per species (AU$ per month) from Sydney Fish Market.

Fishing cost data was derived from economic assessments undertaken by Dominion Consulting Pty Ltd (2001; 2002a; 2002b; 2004; 2006) for the 1999-2000 fiscal period. These data consisted of monthly costs per fishing business for each fishery. Monthly changes in the prices of major inputs into the fisheries (e.g. labour and fuel) were obtained from the Australian Bureau of Statistics (ABS) for quarterly periods between July 1997 and June 2007 (www.abs.gov.au/AUSSTATS).

1.9.2. Hydrological data

Monthly drought declaration maps between July 1992 and June 2007 were obtained from I&I NSW (2010). I&I NSW assess climatic and agricultural factors to officially declare the drought-affected status of an area in NSW (www.dpi.nsw.gov.au/drought). Drought-affected areas were based on Rural Lands Protection Board Districts.

Monthly rainfall from July 1992 to June 2007 was collated from the Bureau of Meteorology (BoM). Rainfall data from gauging stations in the upper, middle and lower reaches of the catchment were summed to calculate total monthly rainfall for each river system examined. Monthly freshwater flow data July 1992 to June 2007 were extracted from the Pineena 9.1 database of the New South Wales Department of Water and Energy (NSW DWE) and obtained from the Sydney Catchment Authority (SCA). When accurate historical information on freshwater flow could not be obtained, alternative hydrological variables (e.g. drought declaration and rainfall) were used as surrogate measures of freshwater flowing into estuarine and coastal systems.

1.10. Chapter summary

The subsequent chapters of this dissertation present four studies (Chapters 2 to 5) that examine the impacts of freshwater flow on fisheries production and profitability in estuarine and coastal systems. A synthesis of the bio-economic impacts of freshwater flow on estuarine and coastal fisheries has not been presented in the scientific literature. Consequently, Chapter 2 presents a synopsis of the ecological and socio-economic impacts of freshwater flow on estuarine and coastal fisheries, with particular emphasis on regional examples from eastern Australia and southern Africa. This chapter identifies areas of research priority by performing a quantitative review of published articles that examine the impacts of freshwater flow on fishery-related topics in estuarine and coastal systems. This work has been published in *Reviews in Fisheries Science* (Gillson 2011).

Studies that comparatively examine the impacts of freshwater flow on fisheries catch rates from a range of estuaries with distinct hydrological characteristics have not been conducted. Chapter 3 therefore examines relationships between hydrological variation and the commercial catch rates of five estuarine-associated fish species from nine permanently open estuaries in NSW between 1997 and 2007. These estuaries have differing geomorphologies, distinct freshwater inputs and varying degrees of river regulation. This work has been published in *Fisheries Research* (Gillson et al. 2009).

Limited information is available on the impacts of episodic flow events on estuarine and coastal fisheries. Hence, chapter 4 explores the impacts of episodic flow events on multi-method, multi-species estuarine and coastal fisheries in NSW. Multivariate patterns in commercial fisheries landings, effort and revenue from three adjacent estuarine and coastal systems were examined between nine-month periods of flood and drought. This work is in the process of being published in *Fisheries Management and Ecology* (Gillson et al. In Press).

Studies that explicitly perform quantitative research on the economic impacts of variable flows on estuarine and coastal fisheries remain elusive. Chapter 5 therefore presents a multi-species, multi-method bio-economic analysis that was used to evaluate the economic performance of fishers' harvesting strategies between non-drought and drought conditions in three adjacent estuarine and coastal systems in NSW. Sensitivity analyses were used to evaluate the robustness of profit outputs under alternative cost and revenue scenarios. This work has been submitted for publication in *Fisheries Research*.

Chapter 6 summarises the findings of the research presented here, and suggests directions for future work to improve our understanding of how freshwater flow affects commercial fisheries production in estuarine and coastal systems.

Freshwater flow and fisheries production in estuarine and coastal systems: where a drop of rain is not lost

Jonathan Gillson. Published in *Reviews in Fisheries Science* (2011) 19: 168-186.

Abstract

This review presents a synopsis of the impacts of freshwater flow on fisheries production in estuarine and coastal systems, with particular emphasis on regional examples from eastern Australia and southern Africa. Freshwater flow regulates environmental factors that determine habitat availability, trophic interactions and fishers' harvesting behaviour in estuarine and coastal systems. Seasonal and interannual variation in freshwater flow influences the distribution and abundance of fish and invertebrates through changes in growth, survival and recruitment. Episodic flood and drought events have the most pronounced impacts on fisheries production due to rapid changes in physicochemical conditions modifying species richness and diversity. Many documented reductions in fisheries production have been attributed to river regulation modifying natural variation in freshwater flow. Protecting natural flow regimes is likely to be an effective management strategy to maintain the production of estuarine and coastal fisheries. Understanding the freshwater requirements of estuarine and coastal fisheries will become increasingly important as climate change modifies the hydrological cycle and human population growth increases demand for water resources. One of the main challenges for scientists seeking to explore relationships between freshwater flow and fisheries production is to understand how variable flows influence resource availability, fishing activity and the economic performance of commercial fisheries in estuarine and coastal systems.

Keywords: Freshwater flow; Fisheries production; River regulation; Climate change

2.1. Introduction

Not a single drop of water received from rain should be allowed to escape into the sea without being utilised for human benefit — Parākramābāhu, the Great Sinhalese King of Sri Lanka, 1153-1186

Most fisheries production worldwide is associated with three nutrient enrichment processes: coastal upwelling, tidal mixing and land-based runoff including major river outflow (Caddy and Bakun 1994). Natural variation in freshwater flowing from rivers strongly influences the production of fish, crustaceans and molluscs in estuarine and coastal fisheries (Beamish et al. 1994; Grimes 2001; Erzini 2005). Despite consistent links between freshwater flow and the production of estuarine and coastal fisheries, underlying mechanisms remain poorly understood. Proposed mechanisms include: (1) improved growth and survival due to nutrient enrichment increasing primary and secondary production (Darnaude 2005); (2) alterations to abundance resulting from salinity fluctuations modifying habitat availability (Kimmerer 2002a); (3) changes to migration and schooling altering catchability (Loneragan and Bunn 1999); (4) increased estuarine immigration owing to changes in offshore olfactory concentration gradients from riverine plume fronts (Whitfield 1994a); and (5) recruitment variability arising from alterations to water physicochemistry (North and Houde 2003). These mechanisms are interrelated, operating over different temporal and spatial scales, and therefore no single characteristic of freshwater flow is likely to be solely responsible for influencing fisheries production in estuarine and coastal systems.

Freshwater flow is critical landscape process that has profound effects on the physical, chemical and biological properties of estuarine and coastal systems (Skreslet 1986). Seasonal and interannual variation in freshwater flow is essential for maintaining the structure and function of estuarine and coastal systems (Schlacher and Wooldridge 1996; Sklar and Browder 1998; Young and Potter 2002). Nevertheless, there is still a false perception that freshwater is 'lost' when it enters estuarine or coastal systems (Gillanders and Kingsford 2002). Growing demand for freshwater resources has necessitated the construction of large dams and inter-basin transfer schemes often with little regard for impacts on estuarine and coastal fisheries (Walker 1985; Loneragan and Bunn 1999; Erzini 2005). When river regulation has modified natural variation in the flow regime, major declines in the production of estuarine and coastal fisheries have followed (Drinkwater and Frank 1994). Modified flow regimes have diminished the abundance of fish and invertebrates in estuarine and coastal systems, which has forced commercial fishers to exploit stocks further offshore (Roberts 2007).

A comprehensive literature search identified more than 800 published articles examining the impacts of freshwater flow (or rainfall) on fishery-related topics in estuarine and coastal systems (Figure 2–1). Most of these articles (82%) focused on the ecological impacts of variation in freshwater flow on fish and invertebrates. In contrast, the economic impacts of variable flows on commercial fisheries have received relatively little attention. The aim of this review is to present a synopsis of the ecological and socio-economic impacts of freshwater flow on estuarine and coastal fisheries. Examples from temperate, tropical and subtropical regions are used to illustrate connections between freshwater flow and the life histories of fish and invertebrates in estuarine and coastal systems. Regional examples from eastern Australia and southern Africa have been given particular emphasis because rivers in these areas exhibit the most variable flows in the world (Figure 2–2), which provides an ideal opportunity to extrapolate the impacts of freshwater flow on the production of estuarine and coastal fisheries.

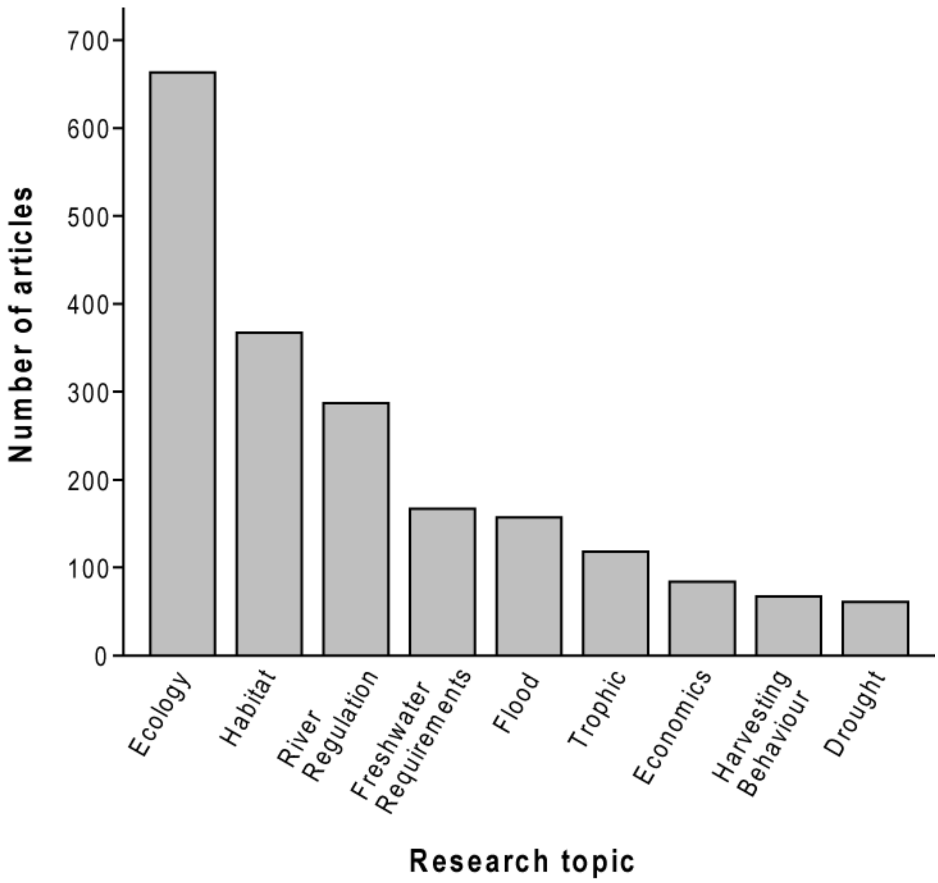


Figure 2-1: A summary of published articles examining the impacts of freshwater flow (or rainfall) on fishery-related research topics in estuarine and coastal systems from 1910 to 2010. A comprehensive search of 5 scientific databases (CSA Illumina, Geobase, ISI Web of Science, Scopus and OvidSP) identified 823 peer-reviewed articles that used the following key-words and search logic: freshwater flow OR rain* AND fish* AND estuar* AND coast*. Synonyms used in the literature search were 'precipitation' OR 'freshwater inflow' OR 'freshwater outflow' OR 'freshwater input' OR 'freshwater output' OR 'freshwater runoff' OR 'freshwater discharge' OR 'river discharge' OR 'river flow' OR 'river inflow' OR 'river outflow' OR 'river input' OR 'river output' OR 'river runoff' OR 'riverine flow' OR 'riverine inflow' OR 'riverine outflow' OR 'riverine input' OR 'riverine output' OR 'riverine runoff' OR 'riverine discharge' OR 'streamflow' OR 'stream flow' OR 'stream discharge' OR 'stream inflow' OR 'stream outflow' OR 'stream input' OR 'stream output' OR 'stream runoff' OR 'stream discharge' OR 'fluvial flow' OR 'fluvial flow' OR 'fluvial discharge' OR 'fluvial inflow' OR 'fluvial outflow' OR 'fluvial input' OR 'fluvial output' OR 'fluvial runoff' OR 'fluvial discharge'.

2.2. Nature of freshwater flows

Freshwater flow regimes are often related to latitude (Finlayson and McMahon 1988; Kench 1999; Poff et al. 2006). Rivers at high latitudes exhibit relatively consistent flows but seasonal peaks typically follow melting of snow or glaciers (Walker 1985). Snowmelt from mountainous regions triggers peak flows in spring or summer in some areas of the world (e.g. Canada: Smith 2000), but snowmelt is not an important factor influencing flows in most Australian and southern African rivers (Finlayson and McMahon 1988). Flows at mid and low latitudes are relatively stochastic and less predictable (Walker 1985; Puckridge et al. 1998; Thoms and Sheldon 2000). Rivers in Australia and southern Africa exhibit extreme hydrological conditions characterised by the most variable flows in the world (Peel et al. 2004). Annual variation in freshwater flow from Australian (C_V = 0.84) and southern African (C_V = 0.73) rivers exceeds the world average (C_V = 0.40) by a factor of more than ×1.8 (Finlayson and McMahon 1988). Sporadic rainfall events generate stochastic river flows in these regions (Dettinger and Diaz 2000). In eastern Australia, rivers are influenced by alternating flood and drought dominated regimes (Erskine and Warner 1998), with freshwater primarily delivered into estuarine and coastal systems by episodic flow events (Eyre 1998).

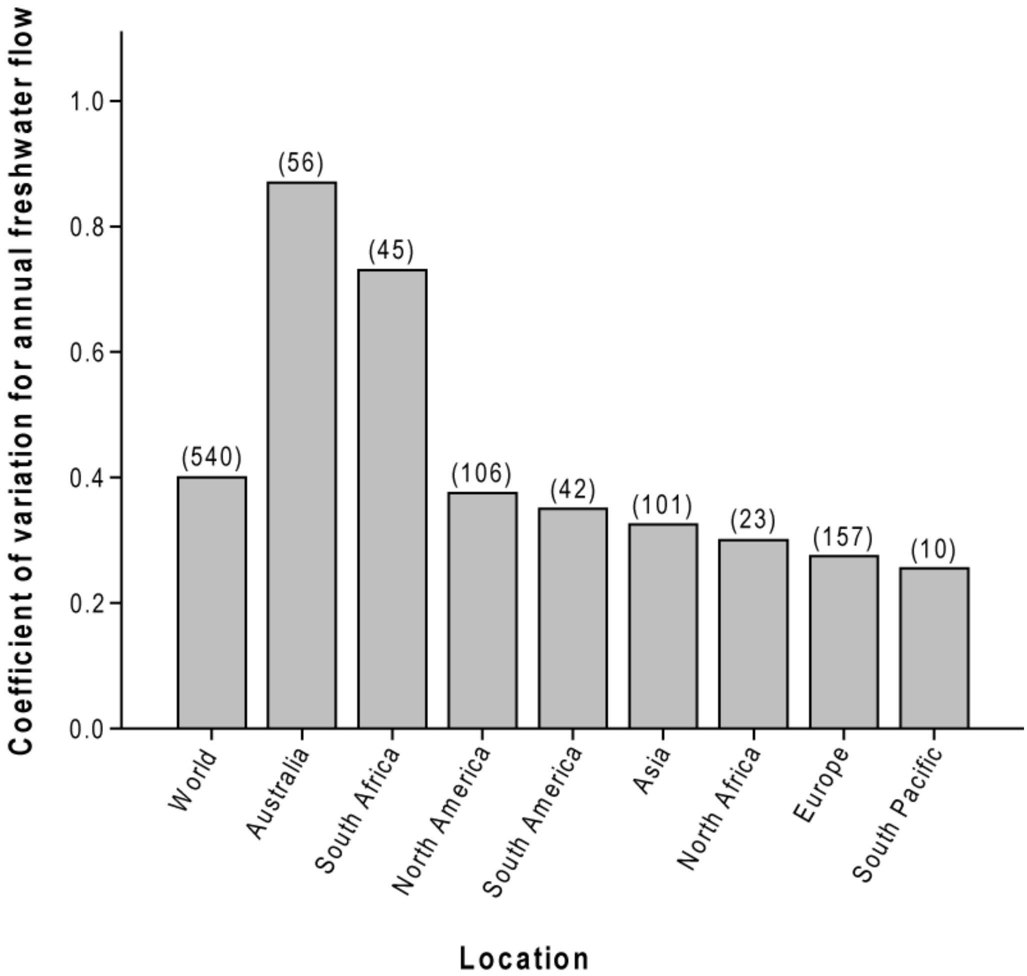


Figure 2-2: A global comparison of the coefficient of variation for annual freshwater flow in river catchments greater than 1000 km^2. The number of river systems examined in each location is shown in parentheses above each bar. (Modified from Finlayson and McMahon 1988).

Climatic variability influences the quantity of freshwater entering estuarine and coastal systems by altering rainfall and evaporation rates. Teleconnection patterns are atmospheric circulation systems that influence climatic conditions over vast geographic areas (Barnston and Livezey 1987). One of the most prominent teleconnection patterns is the North Atlantic Oscillation (NAO) in the Northern Hemisphere (Rogers 1984; Hurrell 1995; Hurrell et al. 2003). The NAO is a driving force of climatic systems that strongly influences rainfall, air temperature and river flow

(Hurrell and Van Loon 1997; McHugh and Rogers 2001; Rîmbu et al. 2002). Another prominent teleconnection pattern is the El Niño Southern Oscillation (ENSO), which exerts a profound influence on rainfall, air temperature and river flow in the Southern Hemisphere (Kuhnel et al. 1990; Molles and Dahm 1990; Allan et al. 1996). Rainfall in Australia and southern Africa are also related to sea surface temperature oscillations in the Central Pacific (Power et al. 1999; Reason and Rouault 2002) and the Indian Ocean (Landman and Mason 1999; Ashok et al. 2003).

Once freshwater enters estuarine and coastal systems, its influence on environmental conditions depends on tidal regimes, wind direction and strength, estuary mouth topography and the nature of ocean currents. Freshwater flow influences a myriad of environmental factors in estuarine and coastal systems including: estuary channel dimensions (Reddering 1988), the status of an estuary mouth (Roy et al. 2001), the offshore extent of riverine plume fronts (Grimes and Kingsford 1996), tidal mixing (Hunter et al. 2010), water temperature (Attrill and Power 2002), salinity regimes (Kurup et al. 1998), dissolved oxygen concentrations (Somville and De Pauw 1982), nutrient inputs (Qu and Kroeze 2010), sediment delivery (Eyre 1998), turbidity levels (Laheta and Stramski 2010), stratification (Schumann and Pearce 1997) and the residence time of pollutants (Baird and Heymans 1996).

2.3. Anthropogenic modification of freshwater flow

Relatively few modern-day rivers have retained their natural flow regime (Poff et al. 1997). River headwaters have been diverted, middle reaches dammed and floodplains developed (Boon 1992). Concern has been expressed about the impacts of modifying the delivery of freshwater flow into estuarine and coastal systems (Benson 1981; Whitfield and Wooldridge 1994; Sklar and Browder 1998). River regulation disrupts the structure and function of estuarine and coastal systems by forcing physicochemical processes to deviate from natural successionary patterns (Sklar and Browder 1998; Gillanders and Kingsford 2002; Sheaves et al. 2007). Anthropogenic modification of freshwater flow alters sediment delivery (Eyre 1998), erosion processes (Roy 1984), riverine plume fronts (Grimes and Kingsford 1996), nutrient inputs (Sin et al. 1999), salinity regimes (Sklar and Browder 1998) and dissolved oxygen concentrations (Serafy et al. 1997). These alterations to physicochemical processes can have deleterious effects on fish and invertebrates by degrading habitat and restructuring food webs in estuarine and coastal systems (Pollard and Hannan 1994; Baird and Heymans 1996; Adams et al. 2009).

Aquatic species have evolved life history strategies in direct response to natural flow regimes (Bunn and Arthington 2002). Modification of freshwater flow impacts the distribution, abundance and species composition of fish and invertebrates in estuarine and coastal systems (Drinkwater and Frank 1994). Impacts are most pronounced for anadromous and catadromous species that require longitudinal and lateral connectivity between marine and freshwater habitats to migrate into spawning grounds. On the Pacific coast of North America, for example, more than 75% of the original 2500 km of spawning and rearing habitat for chinook salmon (*Oncorhynchus tshawytscha*) has been eliminated due to the construction of an extensive network of hydroelectric dams in the Columbia River basin (Dauble and Geist 2000). In south-eastern Australia, stream impoundments have obstructed nearly half of the aquatic habitat for migratory fish in coastal drainages (Harris 1984). Habitat destruction due to modified flow regimes can remove environmental cues required for migration (Zale and Adornato 1996), lower species diversity (Plumstead 1990) and create inimical conditions for native biota favouring the colonisation of exotic species (Bunn and Arthington 2002). Protecting natural flow regimes in rivers is an essential requirement for the conservation of estuarine and coastal systems (Sklar and Browder 1998; Grange et al. 2000; Whitfield and Taylor 2009).

Commercial fisheries are under increasing threat from river regulation modifying the delivery of freshwater into estuarine and coastal systems. Numerous examples of the major, irreversible impacts of river regulation on commercial fisheries exist worldwide (e.g. the Mediterranean Sea: Aleem 1972; the Gulf of Mexico: Sklar and Browder 1998; and the Caribbean Sea: Baisre and Arboleya 2006). A striking example of the consequences of modifying the delivery of freshwater into estuarine and coastal systems has been provided by the construction of the Aswan High Dam in the Mediterranean Nile delta (Bebars and Lasserre 1983). After the construction of the High Aswan Dam in 1969, freshwater flow from the Nile River decreased by 90% resulting in a loss of primary production and a consequent ~80% reduction in Egyptian fishery landings in the Mediterranean coastal region. Declines in commercial landings were primarily from economically valuable sardine (Wadie 1982) and prawn (Bishara 1984) fisheries. The collapse of the Egyptian fishery off the Nile delta lasted for ~25 years, but since the mid-1980s the fishery has been restored by increased nitrogen and phosphorus loading from anthropogenic inputs of agricultural fertiliser and sewage effluent (Nixon 2004; Ockowski et al. 2009). Today, Egyptian fishery landings off the Nile delta are more than three times the pre-dam levels due to anthropogenic nutrient enrichment of the oligotrophic Mediterranean coastal region (Ockowski et al. 2009).

2.4. Relationships between freshwater flow and fisheries production

Commercially harvested fish and invertebrates that exhibit varying degrees of estuarine dependency are influenced by variation in freshwater flow. Relationships between freshwater flow and the landings of more than 80 estuarine or coastal fishery species have been reported worldwide (examples shown in Table 2–1). Commercial landings of fish, crustaceans and molluscs have been related to variation in freshwater flow in temperate, tropical and sub-tropical regions. Relationships between freshwater flow and landings can be positive, negative or inconsistent among regions for the same species (Figure 2–3). For example, positive relationships between freshwater flow and landings of fish and invertebrates were reported in tropical northern Australia (Loneragan and Bunn 1999). Negative relationships between freshwater flow and landings of Róbalo (*Eleginops maclovinus*) were documented in subtropical central-south Chile (Quiñones and Montes 2001); and positive and negative relationships between freshwater flow and landings of dusky flathead (*Platycephalus fuscus*) were identified in temperate eastern Australia (Gillson et al. 2009; see Chapter 3). Some of the variability underlying relationships between freshwater flow and landings of fish and invertebrates may be related to factors such as geographic location (Gillanders and Kingsford 2002), estuarine geomorphology (Saintilan 2004), degree of river regulation within the surrounding catchment (Drinkwater and Frank 1994) and the life history of individual species (Robins et al. 2005).

Table 2-1: Examples of relationships between freshwater flow (or rainfall) and landings of fish and invertebrates in estuarine and coastal systems.

Species	Location	Relationship	Reference
Banana prawn (*Penaeus merguiensis*)	Gulf of Carpentaria, Australia	Positive and negative	Vance et al. 1985; 1998
Blue shrimp (*Litopenaeus stylirostris*)	Gulf of California, Mexico	Positive	Galindo-Bect et al. 2000
School prawn (*Metapenaeus macleayi*)	Clarence and Hunter Rivers, Australia	Positive	Ruello 1973; Glaister 1978
Pink shrimp (*Farfantepenaeus paulensis*)	Patos Lagoon, Brazil	Negative	Möller et al. 2009
White shrimp (*Litopenaeus occidentalis)*	Buenaventura, Colombia	Positive	Díaz-Ochoa and Quiñones 2008
Blue crab (*Callinectes sapidus*)	Apalachicola Bay, North America	Positive	Wilber 1994
Harbour crab (*Liocarcinus depurator)*	North-western Mediterranean	Positive	Lloret et al. 2001
Mud crab (*Scylla serrata*)	Logan River, Australia	Positive	Loneragan and Bunn 1999
American lobster (*Homarus americanus*)	Gulf of St. Lawrence, Canada	Positive	Sutcliffe 1973
Common octopus (*Octopus vulgaris*)	Gulf of Cadiz, Spain	Negative	Sobrino et al. 2002
Eastern oyster (*Crassostrea virginica*)	Apalachicola Bay, North America	Positive and negative	Wilber 1992
Anchovy (*Engraulis encrasicolus*)	North-western Mediterranean	Positive	Lloret et al. 2004
Barramundi (*Lates calcarifer*)	Fitzroy River, Australia	Positive	Robins et al. 2005
Black drum (*Pogonias cromis*)	Galveston Bay, North America	Positive and negative	Powell et al. 2002
Common sole (*Solea solea*)	Gulf of Lions, Mediterranean	Positive	Salen-Picard et al. 2002
Halibut (*Hippoglossus hippoglossus*)	Gulf of St. Lawrence, Canada	Positive	Sutcliffe 1973
Herring (*Clupea pallasi*)	Strait of Georgia, Canada	Positive	Beamish et al. 1994
Róbalo (*Eleginops maclovinus*)	Central-south Chile	Negative	Quiñones and Montes 2001
Salmon (*Oncorhynchus spp.*)	Strait of Georgia, Canada	Positive	Beamish et al. 1994
Sardine (*Sardina pilchardus*)	North-western Mediterranean	Positive	Lloret et al. 2004
Sea mullet (*Mugil cephalus*)	New South Wales, Australia	Positive	Gillson et al. 2009
Slinger (*Chrysoblephus puniceus*)	KwaZulu-Natal, South Africa	Positive	Lamberth et al. 2009

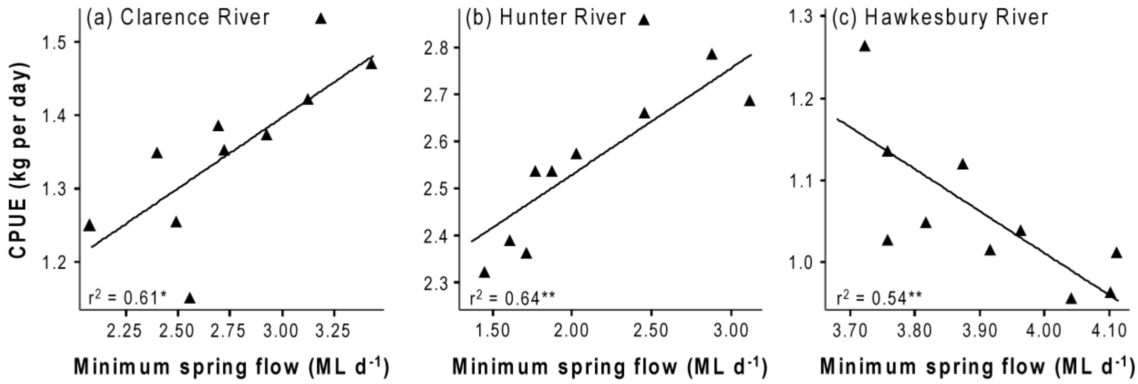


Figure 2-3: Relationships between $\log_{10}$ catch per unit effort for dusky flathead and minimum spring flow in the Clarence (a), Hunter (b) and Hawkesbury (c) River estuaries of eastern Australia. *$P < 0.05$; ** $P < 0.01$; $n = 10$. Minimum flow indicates the lowest spring flows. (Modified from Gillson et al. 2009, see Chapter 3).

Freshwater flow has profound effects on the early-life history stages of marine fish. For example, seasonal variation in freshwater flow influences the abundance, growth and mortality of age-0 red drum (*Sciaenops ocellatus*), pinfish (*Lagodon rhomboides*), sand seatrout (*Cynoscion arenarius*) and spot (*Leiostomus xanthurus*) in the Suwannee River estuary, North America (Purtlebaugh and Allen 2010). Natural variation in freshwater flow regulates recruitment by modifying the distribution, growth and mortality of juvenile marine fish (Kimmerer et al. 2001; North and Houde 2003; Staunton-Smith et al. 2004). Riverine plume fronts that extend offshore are sites of intense biological activity that favourably influence the recruitment and survival of juvenile marine fish (Grimes and Kingsford 1996). Off the Bay of Biscay, for example, the spatial extent of the riverine plume front influences the production of juvenile sole (*Solea solea*) by determining the availability of estuarine nursery grounds (Le Pape et al. 2003). Large riverine plume fronts increase offshore concentrations of land-based cues that stimulate juvenile marine fish to migrate from coastal spawning grounds towards estuaries (James et al. 2007; Vinagre et al. 2007; Vinagre et al. 2009).

Seasonal and interannual variation in freshwater flow influences the growth rates of fish and invertebrates. For example, high flows enhance the growth of barramundi (*Lates calcarifer*) in eastern Australia (Robins et al. 2006), and reduce the growth of Gulf menhaden (*Brevoortia patronus*) in North America (Deegan 1990). Freshwater flow influences growth rates by modifying food availability, salinity regimes and water temperature in estuarine and coastal systems (Loneragan and Bunn 1999; Robins et al. 2005; Shoji et al. 2006). Positive relationships between freshwater flow and the growth rates of school prawns (*Metapenaeus macleayi*) were attributed to increased food availability and decreased salinity in the Hunter River estuary on the east coast of Australia (Ruello 1973). Experimental studies have shown that the food-unlimited growth rates of penaeid prawns function most efficiently within relatively narrow temperature-salinity ranges (O'Brien 1994; Kumlu et al. 2000; Su et al. 2010). Under laboratory conditions, for instance, banana prawns (*Penaeus merguiensis*) grow fastest at temperatures between 20-31°C and in salinities between 20-30‰ (Staples and Heales 1991). Freshwater flow has a particularly pronounced effect on the growth of sessile mollusc species. Negative relationships between freshwater flow and the growth rates of eastern oysters (*Crassostrea virginica*) result from suboptimal low salinities (mean ≤ 17ppt) in Apalachicola Bay on the east coast of North America (Wilber 1994; Livingston et al. 2000; Wang et al. 2008).

Natural fluxes in the flow regime influence the catchability of fish and invertebrates by restricting their distribution or stimulating movement into areas where they are more likely to be caught (Loneragan and Bunn 1999). Freshwater effects on catchability are most noticeable for short-lived schooling species such as penaeid prawns. For example, high flows result in the increased catchability of school prawns due to reductions in salinity enhancing emigration rates from estuarine to coastal systems in eastern Australia (Racek 1959; Ruello 1973; Glaister 1978). Freshwater flow also has a pivotal role in determining the catchability of longer-lived, migratory fish species. For instance, freshwater flow alters the catchability of sea mullet (*Mugil cephalus*) in estuaries by stimulating migration and schooling due to salinity fluctuations altering habitat availability in eastern Australia (Gillson et al. 2009, see Chapter 3). Seasonal pulses of freshwater proximate to reproductive periods influence catchability by stimulating spawning migrations in estuarine-dependent fish. For example, increased freshwater flow into the Princess Charlotte Bay of eastern Australia results in increased catchability of barramundi by stimulating mature males to migrate towards estuarine spawning grounds at the beginning of the wet season (Balston 2009).

Freshwater flow has a controlling influence on fisheries production by regulating habitat availability, trophic interactions and fishers' harvesting behaviour in estuarine and coastal systems (Figure 2–4). Seasonal and interannual variation in freshwater flow modifies environmental conditions, stimulating a biological response and forcing commercial fishers to alter their fishing activity in estuarine and coastal systems.

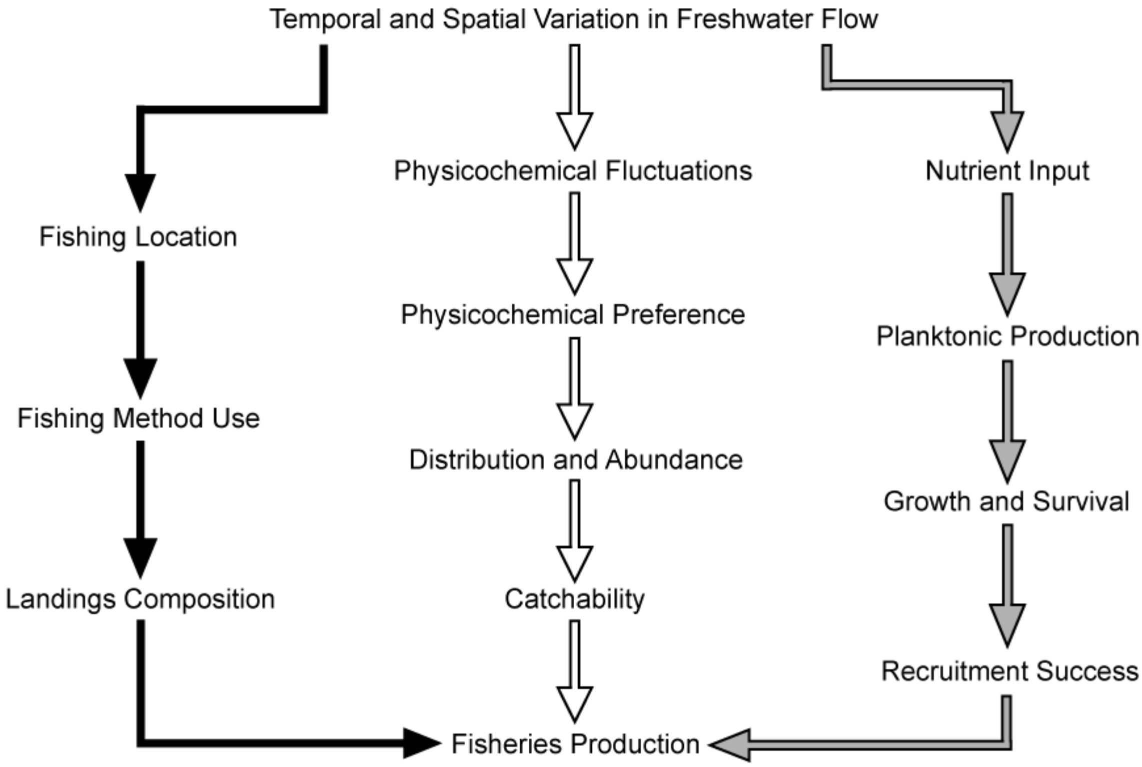


Figure 2-4: A conceptual model illustrating the controlling influence of freshwater flow on the production of estuarine and coastal fisheries. Note that freshwater flow influences fisheries production by regulating habitat availability (white arrows), trophic interactions (grey arrows) and fishers' harvesting behaviour (black arrows) in estuarine and coastal systems.

2.4.1. Habitat availability

Natural variation in freshwater flow directly impacts fisheries production by regulating environmental factors that determine habitat availability for fish and invertebrates. Biotic effects stem from four main environmental factors forced by variation in freshwater flow: modified rates of sediment delivery; salinity fluctuations; turbidity changes; and thermal alteration.

Temporal and spatial variation in freshwater flow controls the duration and frequency that an estuary mouth is open or closed by modifying rates of sediment delivery (Reddering and Rust 1990; Eyre 1998). The status of an estuary mouth influences the distribution, abundance and species composition of fish and invertebrate communities (Whitfield and Kok 1992; Vorwerk et al. 2003; Vivier and Cyrus 2009). Permanently open estuaries maintain a constant connection with the sea, thus enabling fish and invertebrate migrations between estuarine and coastal systems (Kok and Whitfield 1986; Potter et al. 1990; Whitfield 1994a). Temporary mouth closure, however, inhibits species exchange resulting in the decreased abundance of marine taxa, recruitment limitation and a loss of estuarine nursery function (Wooldridge 1991; Harrison and Whitfield 1995; Young and Potter 2002). Prolonged mouth closure can result in extensive fish mortalities due to changes in salinity creating osmoregulatory stress. For example, prolonged closure of the Bot Estuary in southern Africa resulted in the mortality of more than 7000 fish from 9 species due to salinities lower than 3‰ producing oligohaline conditions (Bennett 1985). Similarly, prolonged closure of the Seekoei Estuary in southern Africa resulted in the mortality of more than 6000 fish from 11 species due to salinities higher than 95‰ producing hypersaline conditions (Whitfield 1989).

Freshwater flow has a profound effect on community composition in estuarine and coastal systems by altering the distribution and abundance of marine, estuarine and freshwater species due to changes in salinity (Jassby et al. 1995; Hurst et al. 2004; Costa et al. 2007). One of the most essential adaptations of organisms that enter estuaries is the ability to adjust to changes in salinity (Panikkar 1960). Salinity strongly influences habitat selection, with species actively seeking optimum habitat conditions to minimise osmoregulatory costs and maximise growth rates (Edeline et al. 2005;

Cardona 2006; Shen et al. 2009). Differences in the salinity tolerance of euryhaline and stenohaline species are often attributed to the divergent responses of estuarine and coastal biota to variation in freshwater flow. Freshwater encroachment onto the continental shelf lowers salinity, expands estuarine conditions offshore and permits euryhaline species to increase their distribution into coastal waters (Able 2005). Marine stenohaline species respond to increased freshwater flow by emigrating from estuarine into coastal systems due to lower salinity forcing the seaward displacement of habitat (Kimmerer 2002a; Whitfield and Harrison 2003; James et al. 2007). The influence of freshwater flow on salinity is particularly important for early-life history stages of fish in estuarine nursery grounds (Kimmerer et al. 2001; North and Houde 2003; Bolle et al. 2009). For example, freshwater flow influences the distribution of black bream (*Acanthopagrus butcheri*) eggs and larvae by altering salt-wedge position and halocline depth in the Glenelg and Hopkins estuaries on the east coast of Australia (Nicholson et al. 2008). A combination of intermediate flows (> ~3000 ML d^{-1}) and strong vertical salinity stratification have also been shown to favourably influence the recruitment of black bream by increasing the availability of spawning habitat in Gippsland Lakes, eastern Australia (Jenkins et al. 2010).

Freshwater flow can modify the distribution and abundance of marine fish by altering turbidity levels in estuarine and coastal systems (Cyrus and Blaber 1992; Blaber et al. 1995; Grange et al. 2000). Turbidity has a profound effect on the early-life history stages of marine fish (Blaber and Blaber 1980; Whitfield 1994; Harris et al. 2001). Detailed studies in KwaZulu-Natal estuaries on the east coast of southern Africa have demonstrated that juvenile marine fish can be divided into categories depending on the turbidity tolerance of individual species (Cyrus and Blaber 1987a; 1987b). Cyrus and Blaber (1987c) identified that 16 out of 20 species studied exhibited an affinity for turbid waters. Offshore turbidity gradients influence the feeding rates of fish, predation pressure and larval immigration into estuaries (Blaber and Blaber 1980; Hecht and van der Lingen 1992; Utne-Palm 2002). Annual changes in freshwater flow into Chesapeake Bay on the east coast of North America control the survival and recruitment of anadromous fish by modifying the co-occurrence of larvae and predators in the high turbidity refuge (North and Houde 2003). Rapid increases in turbidity due to sudden influxes of freshwater can impair estuarine nursery function leading to increased larval mortality and decreased prey availability (Gonzalez-Ortegon et al. 2010).

Fisheries production is strongly influenced by freshwater flow altering water temperature in estuarine and coastal systems. For example, high flows and warm sea surface temperatures enhance salmon production in the North Pacific Ocean (Mantua et al. 1997). Temperature is an ecological resource that controls the metabolic rate and physiology of fish (Magnuson et al. 1979). Fish can be assigned a thermal niche according to the temperature tolerance of individual species (Magnuson and Destasio 1996). Habitat selection by juvenile marine fish is dependent on the availability of optimal thermal habitats in estuarine and coastal systems (Attrill and Power 2002; 2004). Freshwater flow and water temperature synergistically impact fish community structure. For instance, winter water temperature and freshwater flow were the most important environmental factors explaining the distribution and abundance of anadromous and coastal spawning species in the nursery grounds of Chesapeake Bay, North America (Wingate and Secor 2008).

One of the major difficulties in isolating mechanisms underlying relationships between freshwater flow and fisheries production is that river flow impacts a myriad of environmental factors that determine the habitat characteristics of estuarine and coastal systems. In central Mozambique, for example, positive relationships between Zambezi River flow and landings of white shrimp (*Penaeus indicus*) were attributed to lower salinities increasing available habitat for recruitment, elevated turbidity providing refuge from predators and floodwaters increasing larval dispersal in estuarine nursery grounds (Gammelsrød 1992). Another difficulty is that the direction of the relationship between freshwater flow and fisheries production can be attributed to differences in the physicochemical tolerance of individual species. For instance, the catch rates of 30 out a total of 45 fish species were related to differences in turbidity and salinity tolerance in the Emberly estuary in northern Australia (Cyrus and Blaber 1992).

2.4.2. Trophic interactions

Freshwater flow can also indirectly impact fisheries production via a trophic cascade. Natural variation in freshwater flow regulates fisheries production by altering the delivery of terrestrially-derived nutrients and organic matter into estuarine and coastal systems (Darnaude 2005). Nutrient-enriched freshwater stimulates increased primary and secondary production (Mallin et al. 1993; Sin et al. 1999; Scharler and Baird 2005), which is then propagated through the food web to species occupying higher trophic levels (Livingston et al. 1997; Salen-Picard et al. 2002; Connolly et al. 2009). Pulses of freshwater and associated nutrient inputs elevate phytoplankton and zooplankton abundance enhancing the recruitment, growth and survival of fish and invertebrates (Quiñones and Montes 2001; Hoffman et al. 2007; Kostecki et al. 2010).

Estuarine and coastal food web structure is highly sensitive to variation in freshwater flow (Darnaude 2005). Seasonal and interannual variation in freshwater flow determines the origin of carbon assimilated into pelagic and benthic food webs (Canuel et al. 1995; Vorwerk and Froneman 2009; Vinagre et al. 2011). Relationships between nutrient-enriched freshwater and fisheries production depend on how reliant a food web is on river flow to supply nutrients and organic matter. A trophic-driven mechanism for fisheries production is particularly important in oligotrophic or semi-enclosed coastal regions that receive limited nutrient supplies from oceanic currents and upwelling events (e.g. the Mediterranean Sea: Darnaude et al. 2004; the Gulf of Mexico: Wissel and Fry 2005; and the South China Sea: Qui et al. 2010). Nutrient-enriched freshwater, however, may not always have such an important role in determining fisheries production. Kimmerer (2002a) demonstrated that variation in the abundance and survival of organisms at higher trophic levels in the San Francisco estuary resulted from freshwater flow altering habitat availability rather than trophic dynamics. Upward trophic transfer was an unlikely mechanism in this estuary given that the positive flow responses of taxa in higher trophic levels (e.g. fish and shrimp) were largely uncoupled from the inconsistent flow responses of taxa in lower trophic levels (e.g. phytoplankton and zooplankton).

Stable isotope analysis has provided insight into how nutrient-enriched freshwater contributes to the energetic requirements of commercially harvested fish and invertebrates. Darnaude et al. (2004) used stable isotope analysis to link flow-related increases in polychaete abundance to the increased growth and survival of sole, confirming previously reported claims of relationships between freshwater flow and fisheries production in the oligotrophic northwest Mediterranean basin (Salen-Picard et al. 2002). We can expect that the increased use of stable isotopes will improve our understanding of how nutrient-enriched freshwater influences fisheries production, particularly in the estuarine and coastal systems of eastern Australia and southern Africa that experience highly variable flow regimes.

2.4.3. Harvesting behaviour

Freshwater flow can indirectly impact fisheries production by altering the harvesting behaviour of commercial fishers in estuarine and coastal systems. Off the east coast of Australia, for example, commercial fishers respond to variable flows by modifying their harvesting behaviour to opportunistically exploit alterations to the catchability of fishery species (Gillson et al. In Press, see Chapter 4). Adjustments to harvesting behaviour enable fishers' to exploit the increased catchability of estuarine migrant species (e.g. school prawn) during periods of flood and marine estuarine-opportunist species (e.g. blue swimmer crab, *Portunus pelagicus*) during periods of drought.

Fisheries scientists must recognise that relationships between freshwater flow and fisheries production represent a signal that is a mixture of ecological response and fishers' harvesting behaviour. Fishing activity in estuarine and coastal systems is influenced by variation in freshwater flow (Loneragan and Bunn 1999; Moses et al. 2002; Lamberth et al. 2009). When freshwater flow alters the availability of fisheries resources, commercial fishers respond by modifying their harvesting behaviour to minimise fishing effort and maximise catch rates. Nevertheless, relatively few of the identified articles (8%) referred to the impacts of freshwater flow on fishing activity. More information on how variable flows influence fishers' harvesting behaviour is required to better understand the impacts of freshwater flow on fisheries production.

2.5. Episodic flow events

Freshwater flow *per se* may not be as important in determining fisheries production as episodic flow events (Gillson et al. 2009, see Chapter 3). Floods and droughts are episodic flow events that maintain and enhance biological productivity in estuarine and coastal systems (Flint 1985; Martin et al. 1992; Dolbeth et al. 2008). Along the eastern Australia coastline, for example, fish communities and dependent fisheries are affected by the flood-drought cycle (Loneragan and Bunn 1999; Robins et al. 2005; Ives et al. 2009). Estuarine migrant species primarily contribute to landings during flood, while marine estuarine-opportunist species primarily contribute to landings during drought (Figure 2–5). Flood and drought events modify the species composition of landings by altering rates of estuarine immigration and emigration due to changes in salinity altering habitat availability.

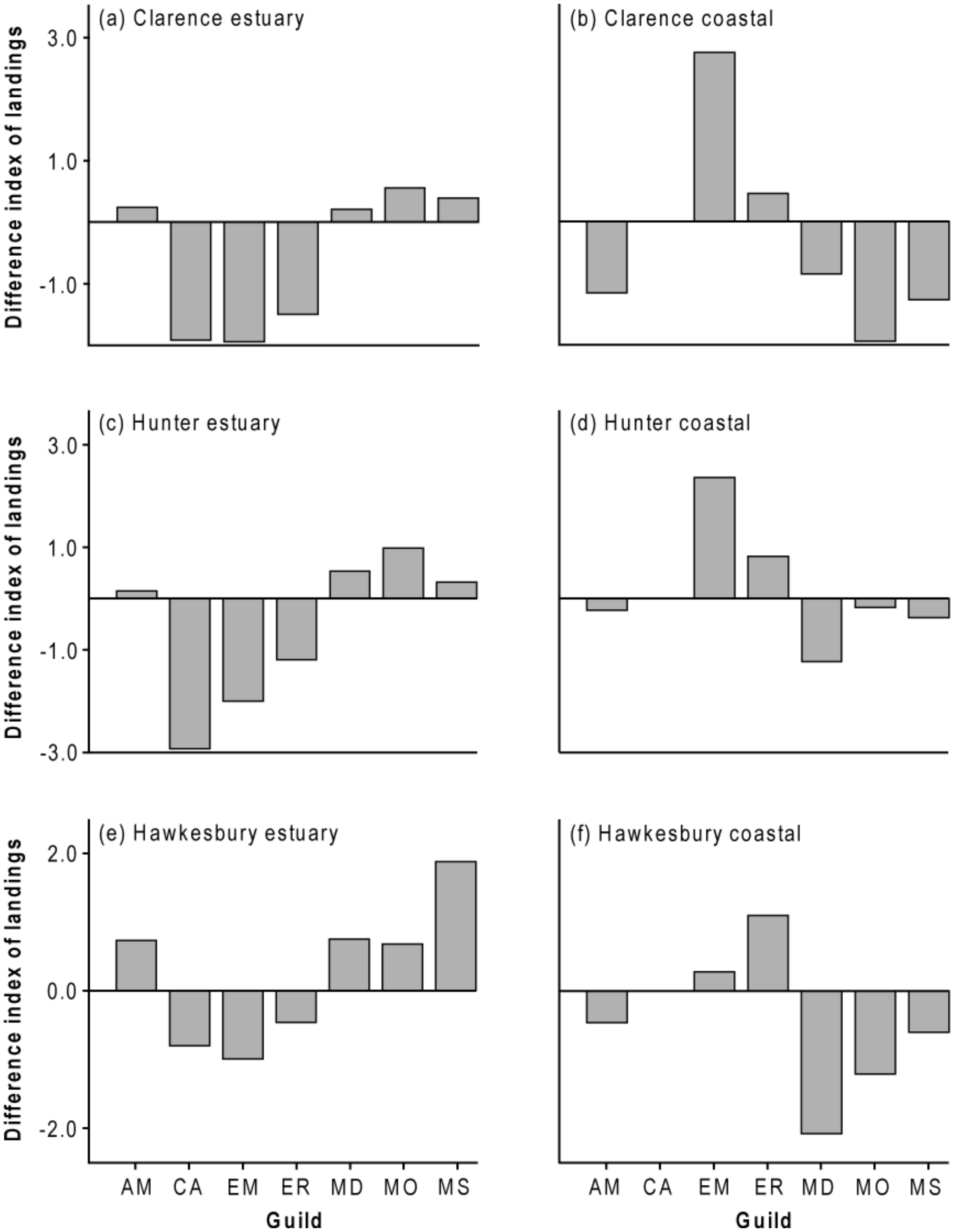


Figure 2-5: Difference index of landings per guild (kg of each guild per month) between flood and drought events in the estuarine and coastal fisheries associated with the Clarence, Hunter and Hawkesbury Rivers of eastern Australia. Results based on fourth-root transformed data. Estuarine use guilds consisted of Amphidromous (AM); Catadromous (CA); Estuarine Migrant (EM); Estuarine Resident (ER); Marine estuarine Dependent (MD); Marine estuarine-Opportunist (MO); and Marine Straggler (MS). Note that a positive difference in landings per guild represents a drought period, while a negative difference in landings per guild represents a flood period. (Modified from Gillson et al. In Press, see Chapter 4).

Flood events temporary reduce species abundance and diversity in estuaries. Excessive delivery of freshwater into southern African estuaries can decrease fish abundance by forcing marine taxa to emigrate from estuarine into coastal systems due to rapid declines in salinity (Marais 1983; Ter Morshuizen et al. 1996; Whitfield and Harrison 2003). Floods create a physical barrier to the recruitment of marine taxa by lowering salinity, reducing available nursery habitat and forcing the seaward dispersion of larvae (Loneragan and Bunn 1999; Strydom et al. 2002; Whitfield and Harrison 2003). Estuarine food web structure can be disrupted by floodwaters altering the availability of pelagic and benthic food resources (Vinagre et al. 2011). Severe floods carrying large quantities of suspended sediment can be lethal to estuarine biota. For example, a major flash flood into the Sundays River Estuary on the east coast of southern Africa resulted in extensive mortalities of marine migrant and estuarine resident species due to suspended sediment clogging gills, low salinities creating osmoregulatory stress and reduced dissolved oxygen levels causing asphyxiation (Whitfield and Paterson 1995). Post-flood reductions in abundance are most pronounced for sessile bivalve species that cannot actively avoid suspended sediment clogging feeding structures (Cardoso et al. 2008). Flood generated mass mortalities of fish result from the production of unfavourable water quality characteristics in estuarine and coastal systems. An excellent example has been provided by severe flood events that caused widespread mortalities of fish in the Richmond, Clarence and Mcleay River estuaries in eastern Australia (Dawson 2002; Eyre et al. 2006; Kroon and Ludwig 2010). Floodwaters reduced dissolved oxygen concentrations to lethal limits for fish (≤ 1mg/L) by flushing decomposing organic matter and acidified water from the surrounding floodplains into these estuaries (Walsh et al. 2004).

Drought events can have deleterious impacts on estuarine biota (Copeland 1966). Under drought conditions, estuaries can become “arms” of the sea with high salinity and poor water quality (Scharler and Baird 2005). Drought-induced high salinities result in a loss of freshwater species, declines in estuarine-dependent species and the establishment of marine straggler species in the lower reaches of estuaries (Vivier and Cyrus 2002; Baptista et al. 2010). Reductions in the delivery of nutrient-enriched freshwater into estuaries can lead to recruitment failure in marine fish. For example, a five-year drought in the San Francisco Bay estuary resulted in reductions in the recruitment success of stripped bass (*Morone saxatilis*) due to larval starvation arising from pelagic food web limitation (Bennett et al. 1995). The production of larval fish exported between estuarine and coastal systems can be significantly reduced during drought (Dolbeth et al. 2008). These alterations to biological productivity can have major impacts on estuarine fisheries. In eastern Australia, for example, the catch rates of estuarine gillnet fisheries decrease by 18–34% during drought (Gillson et al. 2009, see Chapter 3). In contrast, droughts increase oyster production by elevating growth rates in Apalachicola Bay on the east coast of North America (Livingston et al. 1997).

2.6. Economic impacts of variable flows on estuarine and coastal fisheries

Information on the economic impacts of variable flows on estuarine and coastal fisheries remains elusive. Only a small proportion of the identified articles (10%) alluded to the economic impacts of variable flows on estuarine and coastal fisheries, many without explicitly performing quantitative research (e.g. All 2006; Cardoso et al. 2008). Reduced flows due to droughts can lower the economic performance of commercial fisheries operating in estuarine and coastal systems. Revenue generation from commercial fishing businesses in estuarine and coastal fisheries decreased between 8–36% during periods of drought in eastern Australia (Gillson and Scandol Under Review, see Chapter 5). Businesses that operated ocean prawn trawls and estuary prawn trawls primarily contributed to significant reductions in revenue (Figure 2–6). Diversifying harvesting behaviour to target a broad-range of species partially compensated for these reductions in revenue. Commercial fishers, however, would also benefit from augmenting income from enterprises unrelated to fishing during drought. A lack of information on the economic impacts of variable flows on commercial fisheries has hindered the representation of estuarine and coastal systems in water allocation proposals. Identifying fishing sectors that are economically sensitive to variation in freshwater flow will improve understanding of the freshwater requirements of estuarine and coastal fisheries.

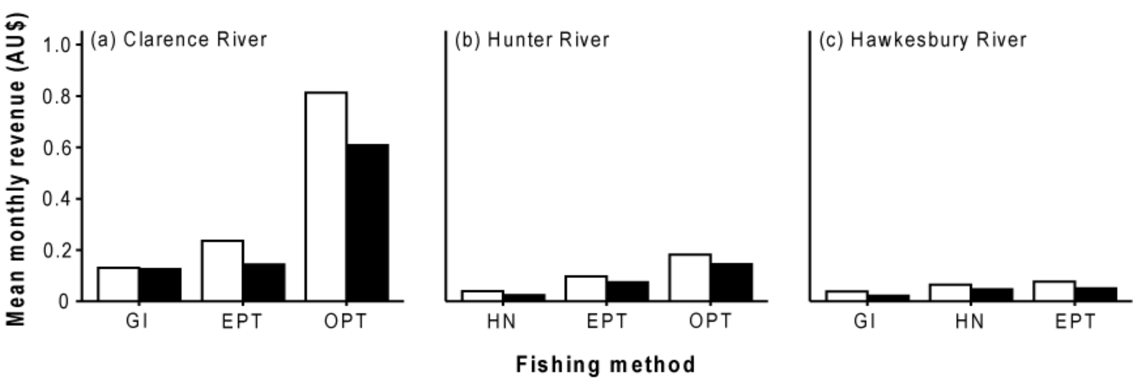


Figure 2-6: Mean revenue per month (AU$ millions) from the three most financially productive fishing methods during non-drought (white bars) and drought (black bars) conditions in the estuarine and coastal fisheries associated with the Clarence, Hunter and Hawkesbury Rivers of eastern Australia. Fishing method abbreviations are Estuary Prawn Trawl (EPT), Gillnetting (GI), Hauling Net (HN) and Ocean Prawn Trawl (OPT). (Modified from Gillson and Scandol Under Review, see Chapter 5).

2.7. Freshwater requirements of estuarine and coastal fisheries

Conflicts over the allocation of freshwater for human and ecosystem needs are increasingly emerging throughout the world (Poff et al. 2003), particularly in areas of agricultural and ecological importance (Falkenmark 2003). For example, management strategies concerned with allocating freshwater to maintain agricultural production and conserve biodiversity remain highly disputed in the Murray-Darling Basin in eastern Australia (Kingsford et al. 2011). Fortunately, there is increasing recognition that estuarine and coastal systems require a sufficient volume of freshwater to maintain biogeochemical processes (Benson 1981; Sklar and Browder 1998; Powell et al. 2002), but this remains to be quantified in many regions of the world. Knowledge regarding the freshwater requirements of estuarine and coastal systems is far from complete (Gillanders and Kingsford 2002). Information on the freshwater requirements of estuarine and coastal systems is essential to ensure that the interests of commercial fishers are duly represented in decision-making processes associated with the allocation of environmental flows. Recognition that freshwater flow strongly influences fisheries production in estuarine and coastal systems is increasingly emerging in policy, planning and legislation (Montagna et al. 2002).

Methods to determine the freshwater requirements of estuarine and coastal systems have been developed in southern Africa. In the Mtata estuary on the east coast of southern Africa, for example, mean winter flows < 4 m^3 s^{-1} favour the colonisation of estuarine biota by promoting natural seasonal flow patterns, establishing a longitudinal salinity gradient and reducing sediment loads (Adams et al. 2002).

Simulation models have explored changes to estuarine nursery function under alternative flow scenarios. Annual flows into the Great Brak estuary on the west coast of southern Africa can be halved to 17.35 × 10^{-6} m^3 with no discernable effect on fish recruitment but a sharp decline in estuarine immigration resulted thereafter (Quinn et al. 1999). Reduced flows are expected to decrease landings of commercially-important species that currently dominate fisheries harvest. For example, a 44% reduction in freshwater flow from the Thukela River is predicted to decrease commercial landings of slinger (*Chrysoblephus puniceus*) and squaretail kob (*Argyrosomus thorpei*) by 36% and 28% respectively in the Thukela Banks linefishery in KwaZulu-Natal (Lamberth et al. 2009).

A variety of techniques have been presented to manage the delivery of freshwater into estuarine and coastal systems in North America: the optimisation of biological productivity under specified environmental conditions in Texas (Powell et al. 2002); abstraction limits to a percentage of flow at the time of withdrawal in Florida (Flannery et al. 2002); the establishment of salinity gradient ≥ 2 psu to maximise estuarine habitat in California (Kimmerer 2002b); and pulsed freshwater events to maximise oyster production in the Gulf of Mexico (La Peyre et al. 2009).

Less is known about the freshwater requirements of estuarine and coastal systems in Australia. Protecting natural variation in the flow regime is likely to be the most reliable management strategy to maintain fisheries production (Loneragan and Bunn 1999; Robins et al. 2005; Gillson et al. 2009). Seasonal variation in freshwater flow is the most important aspect of the flow regime that influences the production of estuarine and coastal fisheries. For example, summer flows explained the highest proportion (69–80%) of variation in fish and invertebrate landings from the Logan River and Moreton Bay fishery in northern Australia (Loneragan and Bunn 1999). Seasonal pulses of freshwater are particularly important for juvenile fish inhabiting estuarine nursery grounds. For instance, high flows during spring and summer positively influence the recruitment of juvenile barramundi and king threadfin (*Polydactylus macrochir*) in eastern Australia (Staunton-Smith et al. 2004; Halliday et al. 2008).

Ensuring the delivery of freshwater into estuarine and coastal systems is essential to minimise the combined impacts of drought and human water extraction on fish and invertebrates (Whitfield and Bruton 1989; Vivier and Cyrus 2002; Vivier et al. 2010). Identifying the freshwater requirements of estuarine and coastal fisheries is likely to be more difficult in highly regulated catchments, where variability in the flow regime is managed for human requirements. River regulation can dampen hydrological extremes, decouple fisheries–flow relationships and hinder the identification of important aspects of the flow regime for maintaining fisheries production (Gillson et al. 2009, see Chapter 3). Since many regulated rivers flow across jurisdictional boundaries (Kingsford et al. 1998), the management of freshwater resources over large geographic areas is problematic. Gaining political and managerial consensus in international transboundary rivers has proven difficult (Bernauer 2002). Nevertheless, protecting the goods and services provided by estuarine and coastal ecosystems requires the implementation of integrated water resource management (Jewitt 2002).

An improved understanding of the freshwater requirements of estuarine and coastal fisheries is essential to appreciate the impacts of climate change on fisheries production.

2.8. Freshwater flow and fisheries production in a changing climate

Climate change is predicted to have major impacts on fisheries production (Brander 2007), potentially influencing the economies of many developing nations worldwide (Allison et al. 2009). Regional climatic variability is responsible for recent changes in the production of estuarine and coastal fisheries due to alterations in fish distribution and abundance (Roessig et al. 2004; Lehodey et al. 2006; Jennings and Brander 2010). Future changes in climate are expected to spatially redistribute fisheries landings in estuarine and coastal systems (Cheung et al. 2010). Many marine studies predicting the impacts of climate change on fish communities have focused on the effects of warmer temperature (e.g. Perry et al. 2005; Fogarty et al. 2008; Jennings and Brander 2010). In contrast, possible changes to fish communities under alternative freshwater flow scenarios have received relatively little attention.

Increased climatic variability is projected to modify the hydrological cycle with associated changes in rainfall, evaporation, surface runoff, groundwater and freshwater flow (Zestser and Loaiciga 1993; Loaiciga et al. 1996; Milly et al. 2005). Reductions in rainfall and warmer temperatures are expected to decrease freshwater resources in eastern Australia and southern Africa (Kundzewicz et al. 2007). Greater hydrological extremes are predicted to increase the frequency and intensity of flood and drought events in these regions (Meehl et al. 2007). Alterations to freshwater flow resulting from climate change could be exacerbated by human population growth increasing demand for water resources (Vörösmarty et al. 2000). It is likely that the impacts of future changes in rainfall and freshwater flow on fisheries production will vary between geographic regions. For example, increased monsoonal rainfall is projected to elevate fish production in northern China (Qiu et al. 2010), whereas decreased freshwater flow is projected to reduce penaeid prawn production in eastern Australia (Ives et al. 2009).

Future changes in freshwater flow will modify primary and secondary production by altering the delivery of nutrients and organic matter into estuarine and coastal systems (Mallin et al. 1993; Rabalais et al. 1996; Struyf et al. 2004). These changes to primary and secondary production are expected to modify the productivity of commercial fisheries (Kennedy 1990; Lehodey et al. 2006; Jennings and Brander 2010). Estuarine and coastal systems will be mainly impacted by changes to the delivery of nutrient-enriched freshwater through the exacerbation of current stresses such as eutrophication and hypoxia (Vitousek et al. 1997; Cloern 2001; Rabalais et al. 2009). For example, climate predictions indicate a 20% increase in freshwater flow entering the Gulf of Mexico, which is expected to negatively impact coastal biota due to elevated nutrient loads increasing primary production and expanding the oxygen-depleted area (Justić et al. 1996). Eutrophication and hypoxia are arguably the biggest threats to estuarine and coastal fisheries due to the creation of dead zones with limited biological productivity (Diaz and Rosenberg 2008).

Alterations to freshwater flow and rising sea levels are likely to modify habitat availability for fish and invertebrates in estuarine and coastal systems (Kennedy 1990). Increased ocean volume and decreased flows could increase habitat for marine species by expanding saline habitats inland (Cheung et al. 2009). In contrast, upstream saline intrusion could decrease habitat for freshwater species that inhabit lakes and rivers (Ficke et al. 2007). Decreased flows are expected to negatively impact the recruitment of marine fish in estuaries. In eastern Australia, for example, lower flows are expected to reduce the survival of black bream eggs and larvae in estuaries by increasing salinity stratification and hypoxic low-oxygen conditions during the spawning period (Nicholson et al. 2008). Reductions in the extent of riverine plume fronts will decrease offshore concentrations of land-based cues that stimulate larval immigration towards estuarine nursery grounds (Vinagre et al. 2009). Lower flows could modify the phenological activities of estuarine-dependent fish by altering synchrony between the delivery of freshwater flow and recurring life cycle events. Impacts would be most pronounced for anadromous species that require seasonal flows to provide offshore environmental cues for migration towards riverine spawning grounds. For example, the upstream migration of Atlantic salmon (*Salmo salar*) into rivers has been delayed by low flows during hot dry summers in the South West of England (Solomon and Sambrook 2004).

It is unclear exactly how future increases in flood events will impact fisheries production in estuarine and coastal systems. Although climate projections indicate that flooding will increase in frequency and intensity in the future (Meehl et al. 2007), the impacts of more frequent and intense flood events on estuarine and coastal systems have not been predicted in detail. Evidence from recent studies indicates that increased flood occurrence could reduce species abundance and diversity by disrupting food web structure and reducing the availability of high salinity habitat in estuarine and coastal systems (Whitfield and Harrison 2003; Cardoso et al. 2008; Vinagre et al. 2011). In contrast, the impacts of drought events on estuarine and coastal fisheries have been predicted with greater confidence. More frequent droughts are likely to modify the structure and function of estuarine and coastal systems. In the Tagus estuary on the western coast of Portugal, for example, the increased frequency of droughts is expected to modify food web structure, decrease the availability of nursery habitats and diminish resilience to disturbance events (Vinagre et al. 2011). Changes to ecological processes arising from droughts are likely to negatively impact the productivity of estuarine and coastal fisheries. For instance, future reductions in freshwater flow due to droughts are predicted to decrease commercial landings of penaeid prawns on the east coast of Australia (Ives et al. 2009).

Predicting the impacts of future changes in freshwater flow on estuarine and coastal fisheries is essential to inform long-term policy debate and strategic management issues. It is necessary to identify management strategies that will ensure the sustainability of estuarine and coastal fisheries under circumstances of increased flow variability. Sustainable management of estuarine and coastal fisheries could be achieved by adjusting quotas to relieve fishing pressure on species that are sensitive to variation in freshwater flow associated with climate change. More detailed hydrological projections are required to predict the impacts of future changes in freshwater flow on the productivity of estuarine and coastal fisheries with greater certainty.

2.9. Conclusions

Freshwater flow impacts fisheries production by regulating environmental factors that determine habitat availability, trophic interactions and fishers' harvesting behaviour in estuarine and coastal systems. Seasonal and interannual variation in freshwater flow influences the distribution and abundance of fish and invertebrates through changes in growth, survival and recruitment. Flood and drought events have the most pronounced impacts on fisheries production due to rapid changes in physicochemical conditions modifying species richness and diversity. Our current understanding of the impacts of freshwater flow on fisheries production has been limited by an inability to separate the effects of physical aspects of freshwater flow from nutrient delivery aspects. An improved understanding will only emerge as we gain a better appreciation of the effects of variable flows on habitat availability and trophic dynamics. Research emphasis has now shifted to a more holistic approach due to the realisation that freshwater flow influences a myriad of environmental factors that impact the life histories of fish and invertebrates in estuarine and coastal systems.

Estuarine and coastal fisheries are under increasing threat from river regulation modifying natural flow regimes. Protecting natural flow regimes is likely to be the most effective management strategy to maintain the production of estuarine and coastal fisheries. Information on the socio-economic impacts of variable flows on commercial fisheries is required to resolve some of the outstanding problems in determining the freshwater requirements of estuarine and coastal systems. Understanding the freshwater requirements of estuarine and coastal fisheries will become increasingly important as climate change modifies the hydrological cycle and human population growth increases demand for water resources. Fisheries scientists and mangers must therefore continue to emphasise the important role of freshwater flow in maintaining the production of estuarine and coastal fisheries. Only then will the interests of commercial fishers in estuarine and coastal systems be duly represented in decision-making processes associated with the allocation of environmental flows.

One of the main challenges for scientists seeking to explore relationships between freshwater flow and fisheries production is to understand how variable flows influence resource availability, fishing activity and the economic performance of commercial fisheries in estuarine and coastal systems. Three areas of priority for future research are suggested: investigating connections between seasonal flows and the timing of recurring life cycle events in estuarine-associated fish (see Chapter 3); examining relationships between freshwater flow and fishing activity (see Chapter 4); and developing bio-economic models to predict the effects of variable flows on commercial fisheries under alternative climate scenarios (see Chapter 5).

2.10. Acknowledgements

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Estuarine gillnet fishery catch rates decline during drought in eastern Australia

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Abstract

Commercial catch-per-unit-effort (CPUE) data from nine estuaries were related to hydrological variations in eastern Australia. Relationships between drought declaration, rainfall, freshwater flow and fisheries catch rates were assessed from 1997 to 2007. Estuaries varied from 0.5 to 2.0 × 10^6 ML of mean freshwater inflow per annum. Monthly CPUE data from gillnetting was used to infer the abundance of yellowfin bream (*Acanthropagrus australis)*, dusky flathead (*Platycephalus fuscus*), luderick (*Girella tricuspidata*), sand whiting (*Sillago ciliata*) and sea mullet (*Mugil cephalus*). CPUE for all species examined, except yellowfin bream, increased in proportion to freshwater flow and decreased during periods of drought. Freshwater flow may affect CPUE by stimulating migration and schooling due to salinity fluctuations altering habitat availability. Minimum and maximum flows were important determinants of CPUE. Freshwater flow *per se* may not be as important in influencing CPUE as extremes in the hydrological continuum. Seasonal flows were consistently the most important aspect of the flow regime that explained the highest proportion of variability in CPUE. Seasonal freshwater pulses proximate to critical reproductive periods may influence catchability by triggering seaward spawning migrations in estuarine-associated fish.

Keywords: Estuarine-associated fish; Drought; Freshwater flow; Catchability; River regulation

3.1. Introduction

Freshwater flow is a critical landscape process that regulates the physical, chemical and biological properties of estuaries (Wolanski 2007). Natural variability in freshwater flow, through its effects on environmental conditions in estuaries, has a pivotal role in determining fisheries production (Grimes 2001). Despite consistent links between freshwater flow and estuarine fish communities, the underlying causal mechanisms remain poorly understood. Several mechanisms have been proposed: (1) alterations to abundance and survival resulting from physical changes in habitat availability (Kimmerer 2002a); (2) changes to migration and schooling altering catchability (Loneragan and Bunn 1999); (3) improved growth and survival due to nutrient enrichment increasing primary and secondary production (Darnaude et al. 2004); (4) increased immigration into estuaries owing to changes in olfactory concentration gradients (Whitfield 1994a); and (5) recruitment variability arising from alterations in water physicochemistry (North and Houde 2003). These mechanisms are not, however, mutually exclusive and operate over differing temporal and spatial scales.

Estuaries require a sufficient volume of freshwater to maintain biogeochemical processes (Skreslet 1986). Nevertheless, there is still a false perception that freshwater is ‘lost’ when it enters estuaries or coastal systems (Gillanders and Kingsford 2002). Without adequate freshwater flow, estuaries can become “arms” of the sea with high salinity and poor water quality (Scharler and Baird 2005). Concern has been expressed about the ecological effects of reduced freshwater flow into estuaries (Benson 1981). Reductions in freshwater flow can have major impacts on estuarine fish communities

(Drinkwater and Frank 1994). Under drought conditions, freshwater flow can cease into estuaries causing sedimentation at the mouth, thus creating a physical barrier at the estuary-coastal interface (Cooper 1994). Although droughts can have deleterious effects on estuarine biota (Copeland 1966), limited information is available on the impacts of drought on estuarine fisheries production.

Comparative examination of the effects of freshwater flow on fisheries catch rates from a range of eastern Australian estuaries with distinct hydrological characteristics has received little attention. Eastern Australia has an extreme hydrological nature (Finlayson and McMahon 1988), with climatic shifts driving sporadic rainfall and unpredictable flow events (Power et al. 1999). Coastal rivers in this region are influenced by alternating flood and drought dominated regimes (Erskine and Warner 1998).

Here, we analysed relationships between hydrological variation and fisheries catch rates from nine permanently open estuaries in eastern Australia. Our objectives were to determine the influence of hydrological variation on fisheries landings by using effort-adjusted data from gillnetting to infer the abundance of five commercially-important species of estuarine-associated fish. We aimed to: (i) examine relationships between drought declaration, rainfall, freshwater flow and fisheries catch rates from 1997 to 2007; and (ii) investigate aspects of the freshwater flow regime that were most important in determining fisheries catch rates.

3.2. Methods

Freshwater flow data from monthly, annual (July to June) and seasonal time series were examined (Table 3–1). Seasons were selected to correspond with the spawning period of individual species because this time interval is postulated to be a key determinant of interannual variability in survival (Houde 1987). For this purpose, austral seasons were defined as: winter (June–August), spring (September–November), summer (December–February) and autumn (March–May). Note that the summer period incorporated data from the December of the previous year. Monthly CPUE data in nine estuaries were examined during drought declared and undeclared periods. Relationships between drought declaration, rainfall, freshwater flow and species-specific catch rates were investigated in the Clarence, Hunter and Hawkesbury River estuaries. A lack of freshwater flow data prohibited the examination of relationships between freshwater flow and species-specific catch rates in the remaining six estuaries.

Table 3-1: Rainfall, freshwater flow and fisheries data sources and formats.

Variable	Source	Format	Period
Commercial catch	NSW DPI ComCatch	Monthly landings (kg) and catch per unit effort (CPUE)	1997–2007
Drought declaration	NSW DPI Drought declaration maps	Monthly drought declaration maps	1992–2007
Rainfall	BoM	Monthly, seasonal and annual rainfall	1992–2007
Freshwater flow	NSW DWE/SCA	Monthly, seasonal and annual river flow	1992–2007

NSW DPI ComCatch = New South Wales Department of Primary Industries Commercial Catch and effort database; NSW DPI Drought declaration maps = New South Wales Department of Primary Industries drought situation maps; BoM = Bureau of Meteorology; NSW DWE = New South Wales Department of Water and Energy Pinneena 9.1 database; SCA = Sydney Catchment Authority.

3.2.1. Study areas

Nine estuaries along the Eastern Australian coastline were selected to evaluate the impacts of freshwater flow on fisheries catch rates (Figure 3–1). The selection process was structured to obtain a suite of permanently open estuaries with differing geomorphologies, distinct freshwater inputs (three estuaries each with high, medium and low flow) and varying degrees of freshwater regulation (Table 3–2). Estuaries entering the Tasman Sea included: (1) the lower reaches of the Clarence River and adjoining Lake Wooloweyah; (2) Hunter River; (3) Hawkesbury River; (4) Camden Haven River; (5) Wallis Lake; (6) Port Stephens and adjoining Myall Lakes; (7) Tuggerah Lakes; (8) Lake Illawarra; and (9) St. Georges Basin. A detailed description of the geomorphological classification and physicochemical characteristics of the estuaries is provided in Pease (1999), Roy et al. (2001) and Saintilan (2004).

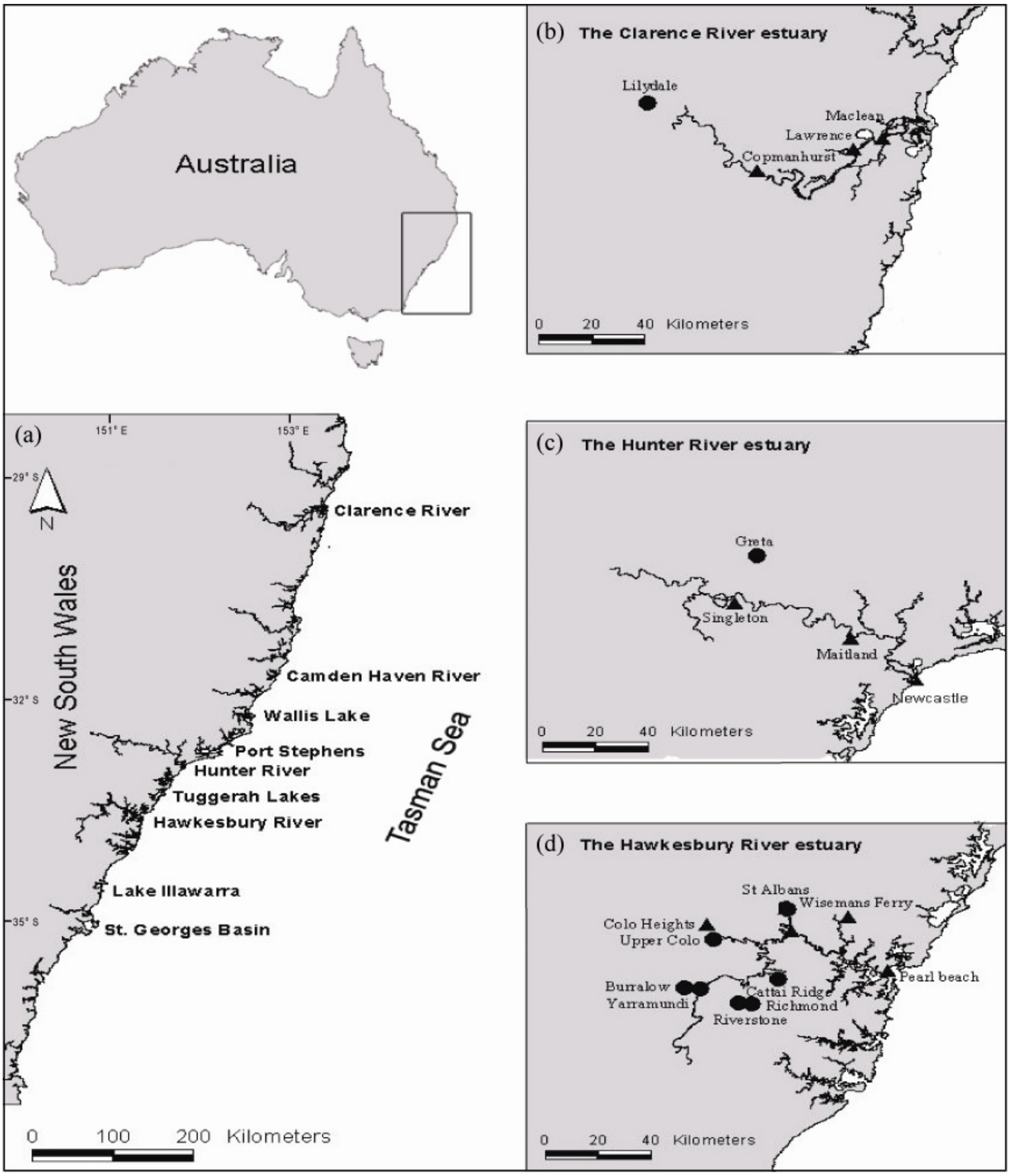

Figure 3-1: Location of nine estuaries selected to investigate the impacts of freshwater flow on estuarine fisheries catch rates in eastern Australia (a). Rainfall [▲] and freshwater flow [●] gauging stations shown in relation to the estuarine reaches of the Clarence (b), Hunter (c) and Hawkesbury (d) River systems.

Table 3-2: Estuaries selected to investigate the impacts of freshwater flow on fisheries catch rates in eastern Australia.

Estuary name	Latitude and longitude	Bioregion	Estuary type	Water area (km^2)	Catchment area (km^2)	Flow type	Flow regulation	Finfish production (t)
Clarence River	29°25’37.20” S, 153°22’19.20” E	Northern	Barrier river	89	22400	High	Moderate	10870
Hunter River	32°54’54.00” S, 151°48’03.59” E	Central	Barrier river	29	22000	High	High	1669
Hawkesbury River	33°34’10.20” S, 151°18’32.40” E	Central	Drowned river valley	100	21500	High	High	3997
Camden Haven River	31°38’09.59” S, 152°50’13.20” E	Northern	Barrier river	28	720	Medium	Low	1526
Wallis Lake	32°10’26.40” S, 152°30’39.59” E	Central	Barrier lagoon	85	1420	Medium	Low	4577
Port Stephens and Myall Lakes	32°42’29.00” S, 152°11’45.59” E	Central	Drowned river valley	289	6610	Medium	Low	5794
Tuggerah Lakes	33°20’42.00” S, 151°30’14.40” E	Central	Barrier lagoon	70	760	Low	High	3109
Lake Illawarra	34°32’38.40” S, 150°52’26.40” E	Central	Barrier lagoon	36	270	Low	Moderate	1778
St. Georges Basin	35°11’06.00” S, 150°35’38.40” E	Central	Barrier lagoon	39	390	Low	Low	554

Bioregion refers to defined latitudinal estuarine regions (Pease 1999). Estuary type describes the geomorphological classification (Roy et al. 2001; Saintilan 2004). Water area (km^2) denotes the area of water comprising the estuary from the downstream estuarine limit to the upper limit of tidal influence (West et al. 1985). Flow type is a comparative measure of freshwater flow devised from estimates of rainfall, catchment area and groundwater runoff to define threshold categories of flow for each river system (i.e. high, medium and low). Flow regulation symbolises the amount of regulation and extraction of freshwater within a catchment. Finfish production represents the summed total harvest of bream, dusky flathead, luderick, sand whiting and sea mullet in tonnes (t) from July 1997 to June 2007 for all estuaries examined, except St. Georges Basin. Commercial fishing ceased and a recreational fishing haven was declared in St. Georges Basin in May 2002.

3.2.2. Fisheries data

Monthly commercial fisheries catch and effort data were compiled from the New South Wales Department of Primary Industries (NSW DPI) ComCatch database from July 1997 to June 2007. Fisheries parameters consisted of landings (kg) and catch-per-unit-effort (CPUE, kg per day) from gillnetting. This passive gear provided a size specific measure of fisheries catch (≥ 80 mm mesh size) from which to assess the impacts of freshwater flow on CPUE, and presented the most consistent method available from which an index of abundance could be inferred. Estuarine fishers deploy gillnets throughout the upper limits of tidal influence. Fisheries landings were standardised for fishing effort by dividing the monthly or annual catch of each species from gillnetting by the total number of days fished with gillnetting in that month or year. Five species of estuarine-associated finfish were selected for analysis: yellowfin bream (*Acanthropagrus australis*), dusky flathead (*Platycephalus fuscus*), luderick (*Girella tricuspidata*), sand whiting (*Sillago ciliata*) and sea mullet (*Mugil cephalus*). Yellowfin bream and black bream (*Acanthropagrus butcheri*) hybridise in eastern Australia (Roberts et al. 2009), and therefore are reported as a single species group in NSW DPI commercial catch records. Hereafter, we consider that yellowfin bream make the most significant contribution to our CPUE data. Yellowfin bream represent the majority (~95%) of commercial estuarine landings for this species group in New South Wales, with black bream only found in estuarine waters south of Myall Lakes. These five species of estuarine-associated fish were selected because they make the dominant contribution to commercial and recreational harvest. When the five species studied were examined in combination, gillnet catch data for all five species were summed and then divided by total gillnet effort data (on either a monthly or annual timescale) to investigate the impacts of freshwater flow on multi-species catch rates.

3.2.3. Hydrological data

Monthly drought declaration maps from July 1992 to June 2007 were obtained from NSW DPI. NSW DPI assesses climatic and agricultural factors to officially declare the drought-affected status of an area (www.dpi.nsw.gov.au/drought). Drought-affected areas were based on Rural Lands Protection Board districts, with the following estuaries co-located within the same district: the Hunter River and Tuggerah Lakes, and Wallis Lake and Port Stephens and Myall Lakes. Periods of drought declaration were examined for an area surrounding each estuary and formatted into a dichotomous variable with “0” and “1” representing the absence or presence of drought declaration, respectively.

Monthly rainfall from July 1992 to June 2007 was collated from the Bureau of Meteorology (BoM). Rainfall data from gauging stations in the upper, middle and lower reaches of the catchment were summed to calculate monthly rainfall. Gauging stations were located in Copmanhurst, Lawrence and Maclean for the Clarence River system; Singleton, Maitland and in Newcastle for the Hunter River system; and Colo Heights, St. Albans, Wisemans Ferry and Pearl beach for the Hawkesbury River system.

Monthly freshwater flow data were extracted from the Pinneena 9.1 database of the New South Wales Department of Water and Energy (NSW DWE) for the Clarence and

Hunter Rivers; and obtained from the Sydney Catchment Authority (SCA) for the Hawkesbury River. Gauged freshwater flow data was provided for the Clarence River at Lilydale (~10 km upstream of the estuarine reaches); the Hunter River at Greta (~15 km upstream of the estuarine reaches); and the Hawkesbury River at Yarramundi, Burralow, Richmond, Cattai Ridge, Upper Colo, St. Albans and Riverstone (all < 9 km upstream of the estuarine reaches) from July 1992 to June 2007. Several flow variables were selected to measure monthly, annual and seasonal variability in the flow regime: (i) total, minimum, mean and maximum river discharge; and (ii) total seasonal river discharge as a percentage of total annual river discharge (referred to as % total seasonal flow). Variables were categorised for their impacts on: (i) catchability (i.e. a relatively short-term response with no lags, coinciding with the seasonality of the fishery); and (ii) recruitment (i.e. a delayed response with lags equalling the appropriate age when a cohort recruits to the fishery). Lags of up to five years were considered for all examined species (indicated by the notation L – x).

3.2.4. Data analysis

Fisheries, rainfall and freshwater flow variables were $\log_{10}$ transformed to normalise variances. Transformed variables were normally distributed (Lilliefors' test) with no evidence of heteroscedasticity (standardised quantile plots).

Univariate analyses were performed to examine relationships between hydrological variables and CPUE. Initial exploratory analysis was undertaken with linear regression techniques and corrected with Bonferroni inequality adjustment (Sokal and Rohlf

1995). A one-way analysis of variance (ANOVA) was used to compare rainfall, freshwater flow and CPUE during drought declared and undeclared periods. The ANOVA models applied to each estuary in section 3.3.2. consisted of one fixed factor (drought) and two levels (declared and undeclared). Interactions between drought and estuary were not considered. Forward stepwise multiple regression analysis was used in section 3.3.3. to identify hydrological variables that explained the highest proportion of variability in CPUE. The general equation used to predict CPUE from environmental variables was:

$$U_t = f(x_t) = \sum_{i=0}^{n} \beta_i x_{i,t} + e_t$$

Where U_t is the CPUE (yellowfin bream, dusky flathead, luderick, sand whiting or sea mullet) at time $t, x_{i,t}$ the covariates that represent environmental factor i (drought declaration, rainfall or freshwater flow), t the unit of time (month, year and season), n the number of covariates, β_i the coefficient for covariate i and e_t is the residual term for observation t. The environmental factors were either continuous variables such as rainfall and freshwater flow, or categorical variables associated with multi-level factors such as drought declaration or season. Coefficient β_i is a weight that indicates how U_t responds to a change in $x_{i,t}$. Only significant β_i coefficients were considered ($P < 0.05$). Regression models were checked for statistical adequacy by examining the normality (Lilliefors' test), independence (Durbin-Watson test) and heteroscedasticity (standardised quantile plots) of the residuals.

3.3. Results

3.3.1. Temporal trends in freshwater flow

Monthly rainfall and freshwater flow were positively correlated in the Clarence ($r^2 = 0.331$, $P < 0.0001$, $n = 120$), Hunter ($r^2 = 0.259$, $P < 0.0001$, $n = 120$) and Hawkesbury ($r^2 = 0.316$, $P < 0.0001$, $n = 120$) River systems from 1997 to 2007. There were distinct seasonal and inter-annual trends in freshwater flow (Figure 3–2). Most freshwater flow in the Clarence River corresponded with summer ($r^2 = 0.571$, $P < 0.05$, $n = 10$) and autumn ($r^2 = 0.422$, $P < 0.05$, $n = 10$) rainfall. This seasonal periodicity was confirmed by ANOVA, with a significant difference between high flows in summer and autumn periods and low flows in winter and spring periods ($P < 0.05$). Freshwater flow in the Hunter and Hawkesbury Rivers was relatively aseasonal with no significant difference between flows in winter, spring, summer or autumn. Sustained summer and autumn peak flows occurred in all river systems from 1999 to 2001. Relatively low summer and autumn flows occurred from 2003 and 2005.

Annual variability in freshwater flow was significantly higher in the Clarence River compared to the Hunter and Hawkesbury Rivers from 1997 to 2007 (ANOVA, $P < 0.05$). Mean annual flow in the Clarence River was 2.00 million ML with minimum and maximum annual flows of 0.50 million ML and 6.96 million ML, respectively. Highest annual flows occurred in 2001 and the lowest in 2002. Mean annual flow in the Hunter River was 0.50 million ML with minimum and maximum annual flows of 0.09 million ML and 1.67 million ML, respectively. Total monthly flow decreased by 10% from 1997 to 2007 ($r^2 = 0.098$, $P < 0.0001$, $n = 120$). Highest annual flows occurred in 2007 and the lowest in 2005. Mean annual flow in the Hawkesbury River was 0.70 million ML with minimum and maximum annual flows of 0.25 million ML and 1.76 million ML, respectively. Highest annual flows were in 1998 and the lowest in 2002.

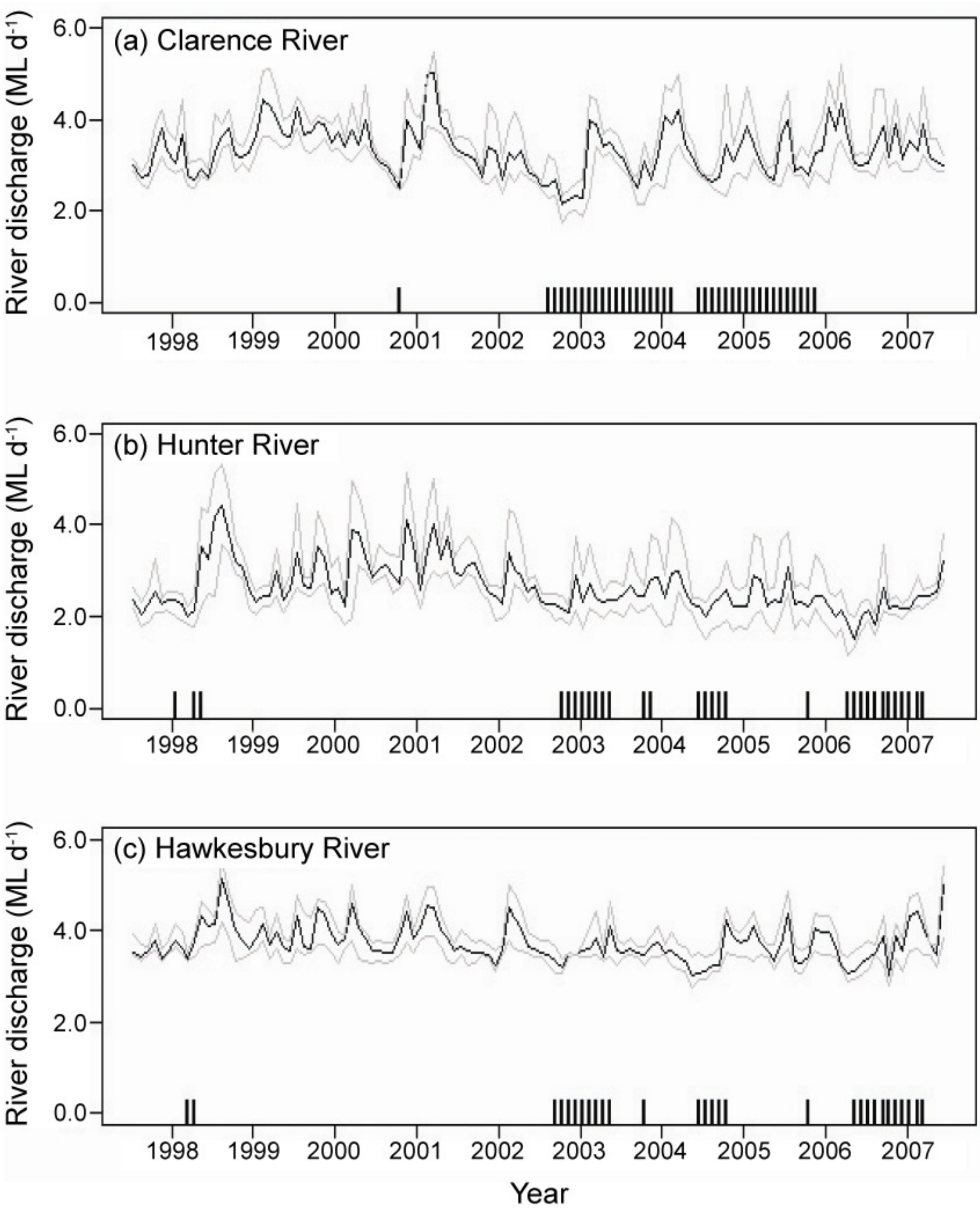

Figure 3-2: Temporal trends in freshwater flow for the Clarence (a), Hunter (b) and Hawkesbury (c) River systems from July 1997 to June 2007. Log_{10} monthly minimum (lower grey line), mean (middle black line) and maximum (upper grey line) flow. Vertical black lines indicate periods of drought declaration.

Monthly rainfall was significantly lower in the Clarence ($F = 7.36$, $df = 119$, $P < 0.001$), Hunter ($F = 12.81$, $df = 119$, $P < 0.001$) and Hawkesbury ($F = 12.54$, $df = 119$, $P < 0.001$) Rivers during periods of drought declaration from 1997 to 2007. Total monthly freshwater flow also exhibited significant reductions in the Clarence ($F = 13.96$, $df = 119$, $P < 0.0001$), Hunter ($F = 18.92$, $df = 119$, $P < 0.0001$) and Hawkesbury ($F = 21.16$, $df = 119$, $P < 0.0001$) Rivers during periods of drought declaration. The nine-month period from September 2002 to May 2003 was characterised by prolonged drought, with flow magnitudes that were frequently below the long-term (10 year) monthly means and considerably less than the Clarence (–49%), Hunter (–84%) and Hawkesbury (–65%) River estuaries usually receive.

3.3.2. Relationships between drought declaration and CPUE

Monthly CPUE was significantly different in all nine estuaries during drought declared and undeclared periods from 1997 to 2007 (Figure 3–3). Not only was monthly CPUE lower during periods of drought but CPUE also exhibited less variability around the median in the Clarence River, Hunter River, Hawkesbury River, Camden Haven River, Wallis Lake, Port Stevens and Myall Lakes, and St. Georges Basin ($P < 0.05$). Contrasting relationships were identified in Tuggerah Lakes and Lake Illawarra, with significantly higher monthly CPUE during periods of drought ($P < 0.05$). There was considerable deviation from the long-term (10 year) monthly mean CPUE during periods of drought. Negative deviation ranged from a minimum of –11% in the Hunter River to a maximum of –34% in the Camden Haven River, while positive deviation ranged from a minimum of +9% in Tuggerah Lakes to a maximum of +22% in Lake Illawara.

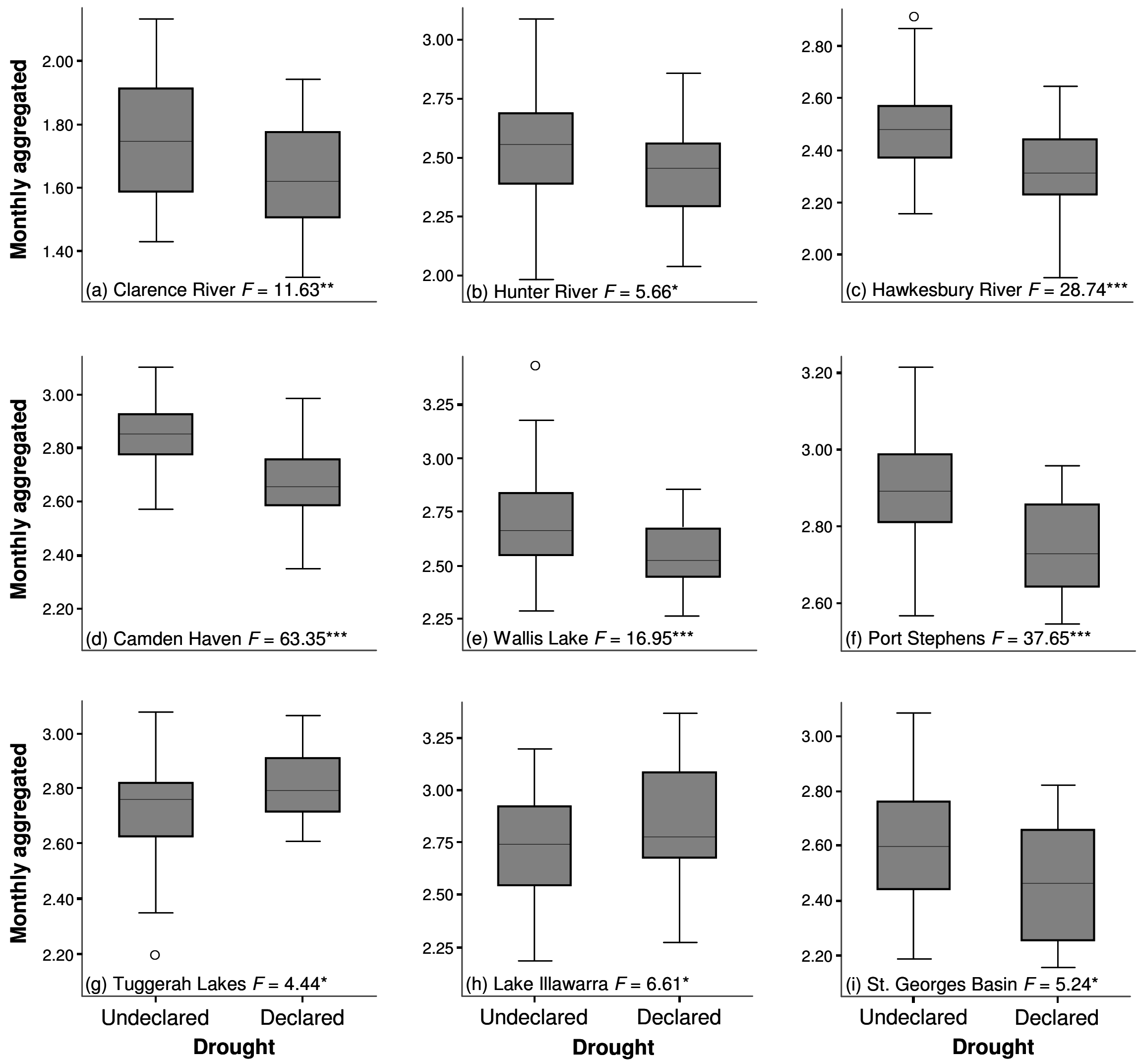

Figure 3-3: Box and whisker plots illustrating significant differences in $\log_{10}$ monthly aggregated CPUE for nine estuaries in eastern Australia during drought declared and undeclared periods from 1997 to 2007 (one-way ANOVA; *P < 0.05; **P < 0.01; ***P < 0.001; df = 119; minimum, 25% quartile, median, 75% quartile and maximum ranges). Monthly aggregated refers to the ∑ Catch / ∑ Effort for all species combined (bream, dusky flathead, luderick, sand whiting and sea mullet). Monthly periods of drought declaration for the Clarence River were 38 months out of a total 120 months analysed, Hunter River 31/120, Hawkesbury River 29/120, Camden Haven 30/120, Wallis Lake 32/120, Port Stephens and Myall Lakes 32/120, Tuggerah Lakes 31/120, Lake Illawarra 35/120 and St. Georges Basin 8/58.

Species-specific differences in monthly CPUE were identified during drought declared and undeclared periods from 1997 to 2007 (Figure 3–4). CPUE was significantly lower for dusky flathead, luderick and sea mullet during periods of drought in the Clarence River ($P < 0.05$). Similar relationships were identified in the Hunter River with significantly lower monthly CPUE for dusky flathead, luderick, sand whiting and sea mullet under an equivalent scenario ($P < 0.05$). Monthly CPUE of sea mullet was significantly lower in the Hawkesbury River during periods of drought ($P < 0.05$). Yellowfin bream was the only species that demonstrated higher monthly CPUE (+20%) and higher variability around the median during periods of drought in the Clarence and Hunter Rivers ($P < 0.05$).

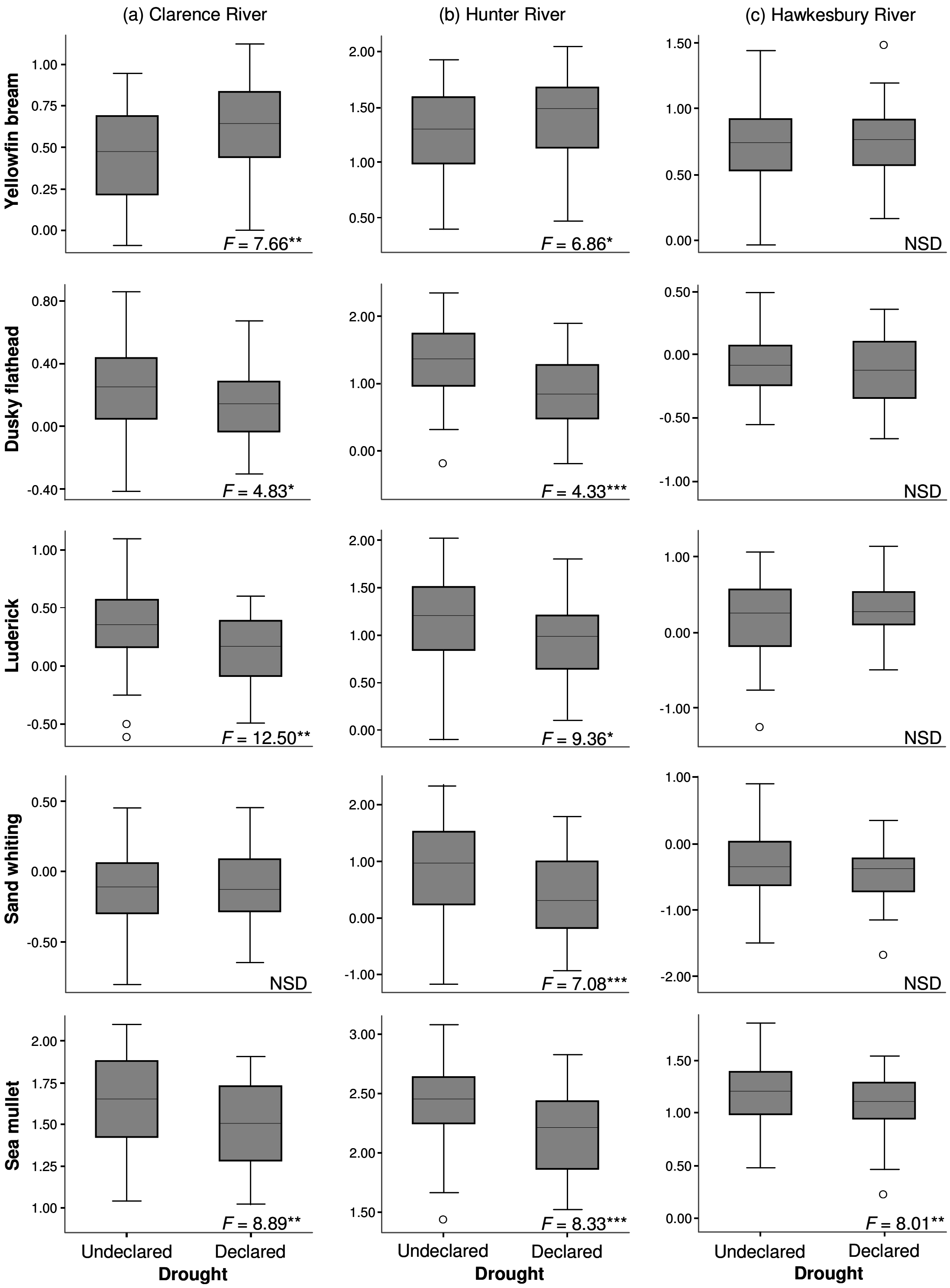

Figure 3-4: Box and whisker plots illustrating species-specific differences in $\log_{10}$ monthly CPUE for the Clarence (a), Hunter (b) and Hawkesbury (c) River estuaries during drought declared and undeclared periods from 1997 to 2007 (one-way ANOVA; *P < 0.05; **P < 0.01; ***P < 0.001; df = 119; minimum, 25% quartile, median, 75% quartile and maximum ranges). Monthly periods of drought declaration for the Clarence River were 38 months out of a total 120 months analysed, Hunter River 31/120 and Hawkesbury River 29/120. NSD indicates no significant difference (P > 0.05) between monthly CPUE during drought declared and undeclared periods.

3.3.3. Relationships between freshwater flow and CPUE

Numerous significant relationships between CPUE and hydrological variables were identified in the Clarence, Hunter and Hawkesbury River estuaries from 1997 to 2007 (see Figure 3–5, and Tables 3–3 to 3–5). Forward stepwise multiple regression indicated that the best predictors of variation in monthly CPUE were drought declaration, monthly rainfall, minimum monthly flow and maximum monthly flow (Table 3–4). Other hydrological variables were relatively less important in explaining variation in monthly CPUE. Non-significant ($P > 0.05$) or statistically inadequate regression models (autocorrelation or non-normal residuals) relating monthly CPUE and freshwater flow did not account for observed relationships. After considering the variation in CPUE accounted for by month, freshwater flow explained from 2% to 17% of the variation in the residuals for the CPUE and month relationship ($P < 0.05$). Freshwater flow and residuals were significantly correlated, indicating that, even after removing temporal effects CPUE was higher during months of higher flow.

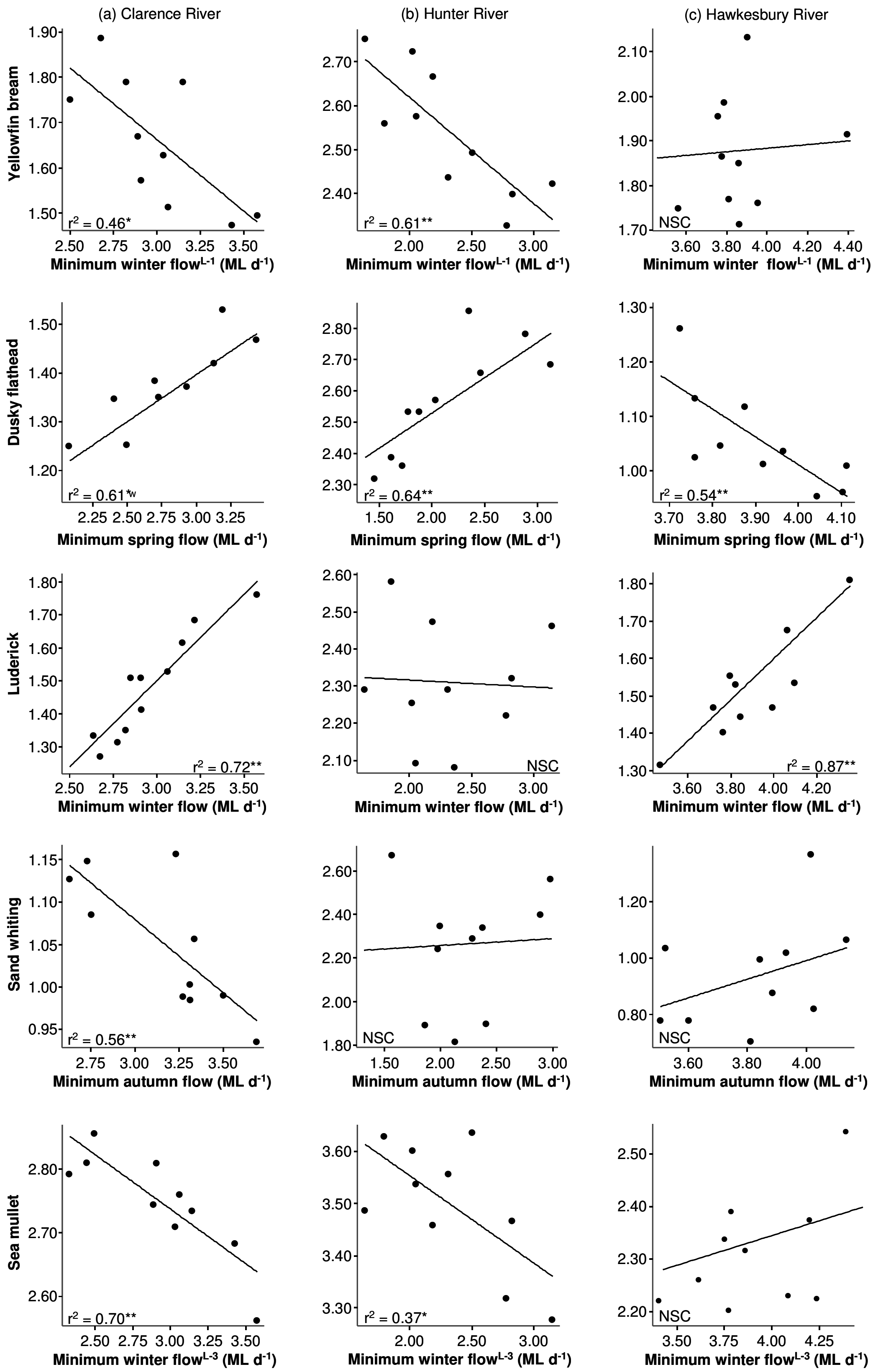

Figure 3-5: Examples of relationships between $\log_{10}$ annual CPUE and minimum seasonal flow variables in the Clarence (a), Hunter (b) and Hawkesbury (c) River estuaries. *P < 0.05; **P < 0.01; n = 10. Minimum flow indicates the lowest flow per season. A lag period of one and three years is represented by L – 1 and L – 3, respectively. NSC indicates non-significant correlations (P > 0.05).

Table 3-3: Statistically significant linear regressions (r^2) for the association between monthly CPUE and monthly hydrological variables in the Clarence (CR), Hunter (HU) and Hawkesbury (HK) River estuaries.

Estuary	Species	Rainfall	Total flow	Min. flow	Mean flow	Max. flow
CR	Bream	–0.040*	–0.038*	–0.041*	–0.039*	–0.037*
HU	Bream	–	–	–	–	–
HK	Bream	–0.050**	–0.029*	–0.052**	–0.049**	–0.042*
CR	Dusky flathead	–	–	–	–	–
HU	Dusky flathead	–	0.033*	0.147***	–	–
HK	Dusky flathead	–	–	–	–	–
CR	Luderick	0.092**	–	0.113***	–	–
HU	Luderick	0.025*	–	–	–	–
HK	Luderick	0.060**	–	0.028*	0.021*	0.024*
CR	Sand whiting	–	–	–	–	–
HU	Sand whiting	–	0.045*	0.046*	0.044*	0.037*
HK	Sand whiting	–	–	–	–	–
CR	Sea mullet	0.108***	0.150***	0.151***	0.114***	0.125***
HU	Sea mullet	–	–	–	–	–
HK	Sea mullet	0.035*	0.098**	0.118***	0.028*	0.037*
CR	All species	0.046*	0.171***	0.184***	0.123***	0.171***
HU	All species	0.031*	0.015*	0.129***	0.015*	0.020*
HK	All species	0.044*	0.029*	0.142***	0.051**	0.065**

Regression details provided for $\log_{10}$ transformed data; n = 120. Non-independent residuals (Durbin-Watson test) did not account for observed relationships between monthly fisheries CPUE and hydrological variables. All species refers to the ∑ Catch / ∑ Effort for bream, dusky flathead, luderick, sand whiting and sea mullet combined. Min. and max. flow represents the lowest and highest flows per month, respectively. Note that one megalitre/day^{-1} equals ~0.0116 $m^3 s^{-1}$.

*P < 0.05.
**P < 0.01.
***P < 0.001.

Table 3-4: Significant stepwise multiple regression models for monthly fisheries CPUE and hydrological variables and temporal components for the Clarence (CR), Hunter (HU) and Hawkesbury (HK) River estuaries.

Estuary	Species	Model	r^2
CR	Bream	Year + season + drought + rainfall (mm)	0.344***
HU	Bream	Drought	0.021**
HK	Bream	Min. flow (ML d^{-1}) + drought	0.245***
CR	Dusky flathead	Season + drought	0.158***
HU	Dusky flathead	Min. flow (ML d^{-1}) + drought	0.208***
CR	Luderick	Rainfall (mm) + min. flow (ML d^{-1}) + season	0.321***
HU	Luderick	Drought + season + month	0.162***
HK	Luderick	Season + month + rainfall (mm)	0.209***
CR	Sand whiting	Season	0.155***
HU	Sand whiting	Season + drought + year + max. flow (ML d^{-1})	0.364***
HK	Sand whiting	Season + year + min. flow (ML d^{-1})	0.123*
CR	Sea mullet	Season + min. flow (ML d^{-1}) + rainfall (mm)	0.408***
HU	Sea mullet	Drought + season	0.218***
HK	Sea mullet	Min. flow (ML d^{-1}) + total flow (ML) + year	0.192***
CR	All species	Season + min. flow (ML d^{-1})	0.460***
HU	All species	Min. flow (ML d^{-1}) + season	0.183***
HK	All species	Min. flow (ML d^{-1}) + drought	0.258***

Models with the highest correlation coefficients presented for $\log_{10}$ transformed data; n = 120. Fisheries and hydrological variables were from monthly time series. Interaction terms between hydrological variables were not fitted. All species refers to the ∑ Catch / ∑ Effort for all species combined (bream, dusky flathead, luderick, sand whiting and sea mullet). Min. and max. flow indicates the lowest and highest flows per month, respectively. Drought denotes the drought declared status for an area surrounding each estuary. Season represents winter, spring, summer and autumn.

*P < 0.05.
**P < 0.01.
***P < 0.001.

3.3.3.1. Yellowfin bream

Monthly CPUE of yellowfin bream was negatively correlated with monthly rainfall, total monthly flow, minimum monthly flow, mean monthly flow and maximum monthly flow in the Clarence and Hawkesbury Rivers (Table 3–3). Stepwise multiple regression identified five alternative models that explained from 2% to 34% of the variation in the monthly CPUE of bream (Table 3–4). The most parsimonious models that contained a hydrological variable were year, season and drought declaration in the Clarence River ($r^2 = 0.302$, $P < 0.001$, $n = 120$); drought declaration in the Hunter River ($r^2 = 0.021$, $P < 0.01$, $n = 120$) and minimum flow in the Hawkesbury River ($r^2 = 0.197$, $P < 0.001$, $n = 120$). Annual CPUE of yellowfin bream was positively correlated with % total winter flow in the Clarence, Hunter and Hawkesbury Rivers (Table 3–5). Negative correlations between the annual CPUE of yellowfin bream and minimum winter flow L – 1 were identified in the Clarence and Hunter Rivers (Figure 3–5).

3.3.3.2. Dusky flathead

Monthly CPUE of dusky flathead was positively correlated with total monthly flow and minimum monthly flow in the Hunter River (Table 3–3). No significant correlations between the monthly CPUE of dusky flathead and flow variables were identified in the Clarence and Hawkesbury Rivers. Stepwise multiple regression provided three alternative models that explained between 16% and 21% of the variation in the monthly CPUE of dusky flathead (Table 3–4). Hydrological factors that explained the highest proportion of variability in the monthly CPUE of dusky flathead were drought declaration (r^2 = 0.058, $P < 0.001$, n = 120) and minimum flow (r^2 = 0.147, $P < 0.001$, n = 120) in the Clarence and Hunter Rivers, respectively. No significant relationships between the monthly CPUE of dusky flathead and hydrological variables were identified in the Hawkesbury River. Annual CPUE of dusky flathead was positively correlated with minimum annual flow in the Clarence (r^2 = 0.591, $P < 0.01$, n = 10), Hunter (r^2 = 0.532, $P < 0.01$, n = 10) and Hawkesbury (r^2 = 0.637, $P < 0.01$, n = 10) Rivers. Positive correlations between the annual CPUE of dusky flathead and total spring rainfall, total spring flow, minimum spring flow, mean spring flow and maximum spring flow were identified in the Clarence and Hunter Rivers (Table 3–5). Negative correlations between the annual CPUE of dusky flathead and total spring rainfall, total spring flow, minimum spring flow, mean spring flow and maximum spring flow were evident in the Hawkesbury River (Table 3–5). Annual CPUE of dusky flathead was negatively correlated with total spring flow L – 3, mean spring flow L – 3 and minimum spring flow L – 3 in the Clarence River ($P < 0.05$).

3.3.3.3. Luderick

Monthly CPUE of luderick was positively correlated with monthly rainfall, minimum monthly flow, mean monthly flow and maximum monthly flow (Table 3–3). Stepwise multiple regression identified six alternative models that explained from 16% to 32% of the variation in the monthly CPUE of luderick (Table 3–4). Primary factors that explained the highest proportion of variability in the monthly CPUE of luderick were rainfall in the Clarence River (r^2 = 0.202, $P < 0.001$, n = 120); drought declaration in the Hunter River (r^2 = 0.091, $P < 0.001$, n = 120); and season, month and rainfall in the

Hawkesbury River (r^2 = 0.209, $P < 0.001$, n = 120). Annual CPUE of luderick was positively correlated with total annual rainfall, total annual flow, mean annual flow and maximum annual flow in the Hawkesbury River (all $P < 0.05$). Positive correlations between the annual CPUE of luderick and minimum winter flow were identified in the Clarence and Hawkesbury Rivers (Figure 3–5). There was a negative correlation between the annual CPUE of luderick and % total winter flow in the Hunter River (Table 3–5).

3.3.3.4. Sand whiting

Monthly CPUE of sand whiting was positively correlated with total monthly flow, minimum monthly flow, mean monthly flow and maximum monthly flow in the Hunter River (Table 3–3). No significant correlations between the monthly CPUE of sand whiting and hydrological variables were identified in the Clarence and Hawkesbury Rivers. Stepwise multiple regression provided five alternative models that explained between 12% and 36% of the variation in the monthly CPUE of sand whiting (Table 3–4). The most parsimonious models that contained the fewest number of parameters that were significantly different from zero included season in the Clarence River (r^2 = 0.155, $P < 0.001$, n = 120); season and drought declaration in the Hunter River (r^2 = 0.267, $P < 0.001$, n = 120); and season, year and minimum flow in the Hawkesbury River (r^2 = 0.123, $P < 0.005$, n = 120). Annual CPUE of sand whiting was negatively correlated with total autumn rainfall, total autumn flow, minimum autumn flow, maximum autumn flow, total spring flow L – 3, minimum spring flow L – 3, mean spring flow L – 3 and maximum spring flow L – 3 in the Clarence River (Table 3–5).

3.3.3.5. Sea mullet

Monthly CPUE of sea mullet was positively correlated with monthly rainfall, total monthly flow, minimum monthly flow, mean monthly flow and maximum monthly flow in the Clarence and Hawkesbury Rivers (Table 3–3). Stepwise multiple regression identified six alternative models that explained from 12% to 41% of the variation in the monthly CPUE of sea mullet (Table 3–4). The most parsimonious models were season and minimum flow in the Clarence River (r^2 = 0.364, $P < 0.001$, n = 120); drought declaration in the Hunter River (r^2 = 0.163, $P < 0.001$, n = 120); and minimum flow in the Hawkesbury River (r^2 = 0.118, $P < 0.001$, n = 120). Annual CPUE of sea mullet was negatively correlated with total winter flow L – 3, minimum winter flow L – 3, mean winter flow L – 3 and maximum winter flow L – 3 in the Clarence and Hunter Rivers.

3.3.3.6. Monthly CPUE summed for all species

Monthly CPUE summed for all species was positively correlated with monthly rainfall, total monthly flow, minimum monthly flow, mean monthly flow and maximum monthly flow (Table 3–3). Stepwise multiple regression provided three alternative models that explained between 18% and 46% of the variation in monthly CPUE summed for all species (Table 3–4). The most parsimonious models were season and minimum flow in the Clarence River (r^2 = 0.460, $P < 0.001$, n = 120); minimum flow in the Hunter River (r^2 = 0.123, $P < 0.001$, n = 120); and minimum flow in the Hawkesbury River (r^2 = 0.162, $P < 0.001$, n = 120). No significant correlations between CPUE summed for all species and annual or seasonal hydrological variables were identified (Table 3–5).

Table 3-5: Statistically significant linear regressions (r^2) for the association between annual CPUE and seasonal hydrological variables in the Clarence (CR), Hunter (HU) and Hawkesbury (HK) River estuaries.

Estuary	Species	Season	Rainfall	% flow	Total flow	Min. flow	Mean flow	Max. flow
CR	Bream	Winter	–	0.513*	–	–0.457* (L – 1)	–	–
HU	Bream	Winter	–	0.478*	–	–0.614** (L – 1)	–	–
HK	Bream	Winter	–	0.499*	–	–	–	–
CR	Dusky flathead	Spring	0.593**	–	0.503*	0.608**	0.305*	0.487*
	Dusky flathead	Spring	–	–	–0.446** (L – 3)	–0.362* (L – 3)	–0.447* (L–3)	–
HU	Dusky flathead	Spring	0.343*	–	0.812***	0.636**	0.801***	0.718**
HK	Dusky flathead	Spring	–0.422*	–	–0.580**	–0.543**	–0.507*	–0.325*
CR	Luderick	Winter	–	–	–	0.865**	–	–
HU	Luderick	Winter	–	–0.352*	–	–	–	–
HK	Luderick	Winter	–	–	–	0.721**	–	–
CR	Sand whiting	Autumn	–0.613**	–	–0.481*	–0.555**	–	–0.472*
	Sand whiting	Spring	–	–	–0.456* (L – 3)	–0.334* (L – 3)	–0.455* (L – 3)	–0.532** (L–3)
HU	Sand whiting	Autumn	–	–	–	–	–	–
HK	Sand whiting	Autumn	–	–	–	–	–	–
CR	Sea mullet	Winter	–	–	–0.752** (L – 3)	–0.695** (L–3)	–0.715** (L–3)	–0.753** (L–3)
HU	Sea mullet	Winter	–	–	–0.408* (L – 3)	–0.370* (L–3)	–0.282* (L–3)	–0.409* (L–3)
HK	Sea mullet	Winter	–	–	–	–	–	–

Regression details provided for $\log_{10}$ transformed data; n = 10. Non-independent residuals (Durbin-Watson test) did not account for observed relationships between annual fisheries CPUE and seasonal hydrological variables. Min. and max. flow represents the lowest and highest flows per season, respectively. % flow refers to total seasonal flow as a percentage of total annual flow. A lag period of one and three years is indicated by (L – 1) and (L – 3), respectively. Note that one megalitre/day^{-1} equals ~0.0116 $m^3 s^{-1}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

3.4. Discussion

Commercial fisheries and hydrological datasets from nine estuaries with a range of freshwater inputs revealed the effects of river flow on fisheries CPUE. Catch rate/flow relationships were species, season and estuary specific. Freshwater enhancement of fisheries production was evident (see also Loneragan and Bunn 1999; Grimes 2001; Robins et al. 2005), with increased CPUE in months with higher flow. Monthly fisheries-flow relationships were often highly significant ($P < 0.01$), but yielded relatively low correlation coefficients. Once seasonality in river discharge was factored into linear regression analysis, freshwater flow explained a higher proportion (28–87%) of variability in annual CPUE (Table 3–5). Some of the variability underlying relationships between freshwater flow and CPUE may be related to factors such as bioregion (Pease 1999), estuary type (Saintilan 2004), degree of freshwater regulation within the catchment (Drinkwater and Frank 1994) and the life history of individual species (Robins et al. 2005).

Anthropogenic modification of freshwater flow often forces estuarine processes to deviate from natural successionary patterns (Whitfield 2005). Our results suggest that river regulation dampens hydrological extremes, decouples fisheries-flow relationships and hinders identification of important aspects of the flow regime that affect CPUE. Correlation coefficients (r^2) between rainfall, freshwater flow and CPUE were consistently higher for the less regulated Clarence River than the highly regulated Hunter or Hawkesbury Rivers (Tables 3–3 to 3–5). Significant relationships between the annual CPUE of dusky flathead and spring flow variables in the Hawkesbury River produced contrasting regression slopes compared to the Clarence and Hunter Rivers (Figure 3–5). Divergent fisheries-flow relationships may be attributed to freshwater regulation altering connections between the delivery of seasonal flows and the timing of recurring lifecycle events in estuarine-associated fish (Drinkwater and Frank 1994). Dusky flathead spawn in estuaries and coastal waters, during spring and summer (Kailola et al. 1993). Freshwater regulation may alter synchronisation between spring flows and the reproductive movements of dusky flathead in the Hawkesbury River. Fisheries and environmental attributes have a similar ordination in these river systems (Pease 1999). Thus, differences in river geomorphology were unlikely to account for observed disparity in fisheries-flow relationships. Determining the freshwater flow requirements of estuarine fisheries is likely to be more difficult in highly regulated river systems, where variability in the flow regime is managed for human requirements.

3.4.1. Impacts of drought on CPUE

Drought declaration in catchments associated with the river-dominated estuaries corresponded with lower rainfall, freshwater flow and estuarine fisheries CPUE. Significant reductions in monthly CPUE summed for all species during periods of drought were identified in all examined estuaries, except Tuggerah Lakes and Lake Illawarra. Drought may lower fisheries production by reducing food availability (Bennett et al. 1995), deteriorating water quality (Attrill and Power 2000), forcing seaward migration of estuarine residents (Dolbeth et al. 2008), or by increasing predation pressure from marine species (Martinho et al. 2007). Tuggerah Lakes and

Lake Illawarra are shallow (≤ 3m) poorly flushed coastal barrier lagoons with a limited tidal range (0.1m–1.0m) and relatively low freshwater inputs. Hydrodynamics are largely controlled by runoff from highly urbanised catchments in these estuaries (Scanes et al. 2007). Drought may result in higher fisheries catch rates in freshwater deprived estuaries due to increased catchability resulting from short-term improvements in water quality. Lower rainfall reduces runoff limiting concentrations of land-based pollutants leached into running waters (Niemczynowicz 1999). Drought-induced low flows may lower fisheries catch rates in river-dominated estuaries owing to unfavourable water quality characteristics forcing the emigration of estuarine-associated fish into coastal waters. Reductions in freshwater flow can alter the abundance and distribution of estuarine fish communities by increasing salinity and decreasing concentrations of dissolved oxygen (Sklar and Browder 1998). Fish actively avoid drought associated conditions by using behavioural adaptations to limit physiological costs associated with unfavourable water quality characteristics (Magoulick and Kobza 2003).

Species-specific reductions in monthly CPUE were evident for dusky flathead, luderick, sand whiting and sea mullet during periods of drought. Sea mullet dominated estuarine finfish harvest (≥ 65%) providing the greatest contribution to significant differences in monthly aggregated CPUE between drought declared and undeclared periods. Yellowfin bream was the only species with significantly higher monthly CPUE during periods of drought. Yellowfin bream complete their lifecycle within estuarine and inshore coastal waters (Blaber and Blaber 1980), predominately inhabiting marine and brackish regions but can also penetrate the inter-tidal freshwater reaches of coastal rivers (West and King 1996). Drought may result in the increased catchability of yellowfin bream owing to higher-salinity estuarine waters stimulating seaward migration into lower-salinity coastal waters. Other environmental factors associated with reduced freshwater flow may also stimulate seaward migration in yellowfin bream during drought. These environmental factors may include higher river water temperatures, elevated turbidity, increased exposure to solar radiation in shallow water areas and the depletion of riverine/estuarine food resources (Cyrus and Blaber 1992; Bennett et al. 1995; Zagarese and Williamson 2001). Estuarine fishers suggest that yellowfin bream migrate downstream into the estuary mouth during periods of low flow, thereby increasing their catchability by passive fishing gears, such as gillnets.

3.4.2. Impacts of freshwater flow on CPUE

High freshwater flow results in increased catchability by restricting distribution or stimulating movement into areas where estuarine-associated fish are more readily caught (Loneragan and Bunn 1999). Comparison of positive slope values with stepwise multiple regression suggested that the catch rates of sea mullet were highly responsive to flow variability (Tables 3–3 and 3–4). Salinity strongly influences habitat selection by sea mullet with individuals actively seeking optimum habitat conditions to minimise osmoregulatory costs and maximise growth rates (Cardona 2000; Chang et al. 2004; Cardona 2006). Freshwater flow may have a marked influence on the catch rates of sea mullet due to salinity fluctuations stimulating migration into preferred habitat.

Increased freshwater flow lowers salinity altering habitat availability for estuarine-associated fish (Jassby et al. 1995). Yellowfin bream may respond negatively to high flows due to the seaward displacement of preferred habitat. Yellowfin bream and black bream are not conspecific, and have markedly different life-history characteristics (Roberts et al. 2009). Nevertheless, similar responses have been reported for black bream in southeastern Australia, where considerable numbers of fish left the Hopkins River in Victoria for sheltered coastal habitats after the salt wedge was flushed seaward by heavy freshwater discharge (Sherwood and Backhouse 1982). Black bream can be flushed out to sea during extreme flow events but return to the natal estuary once the rate of freshwater discharge declines (Chaplin et al. 1998). Freshwater flow may regulate fisheries catch rates by altering the spatial distribution of estuarine-associated fish due to salinity fluctuations stimulating migration and schooling.

Minimum and maximum flows were important correlates of CPUE (Table 3–3). Freshwater flow *per se* may not be as important in influencing estuarine fisheries production as episodic flow events. Episodic flow events are natural perturbations that maintain biological productivity in estuaries (Whitfield 2005). Protecting natural fluxes in the flow regime may represent the most reliable management strategy to maintain fisheries production in Australian estuaries. Management of environmental flows has evolved from solely concentrating on the protection of minimum flows to recognition of the importance of episodic flow events for maintaining the structure and function of aquatic ecosystems (Sparks and Spink 1998).

Aquatic species have evolved life history strategies in direct response to natural flow regimes (Bunn and Arthington 2002). Our analyses indicated that the highest correlation coefficients (r^2) between freshwater flow and CPUE coincided with spawning periods. High seasonal flows may trigger spawning migrations in estuarine-associated fish (Stevens and Miller 1983). Yellowfin bream undertake annual migrations to spawn in coastal surf zones near the mouths of estuaries, typically during winter (Pollock 1982a; Pollock 1982b; Kailola et al. 1993). Annual CPUE of yellowfin bream was positively correlated with percentage total winter flow. Minimum winter flow explained a substantial proportion of the variation in the annual CPUE of luderick in the Clarence (87%) and Hawkesbury Rivers (72%). Luderick spawn in coastal surf zones from August to December in central and northern New South Wales (Kailola et al. 1993). The protracted spawning period of luderick corresponds with late winter, spring and early summer. High winter flow rates may result in increased catchability by triggering the seaward spawning migration of yellowfin bream and luderick.

Dusky flathead spawn in the lower reaches of estuaries and nearshore coastal waters, typically during spring and summer (Kailola et al. 1993). Positive relationships between the annual CPUE of dusky flathead and spring flow variables could, therefore, reflect increased catchability due to high flows inducing the pre-spawning migration. Sand whiting aggregate to spawn in the lower reaches of estuaries and nearshore coastal waters, typically during summer and autumn (Morton 1985; Burchmore et al. 1988). Annual CPUE of sand whiting was negatively correlated with autumn flows in the Clarence River. Accordingly, our results suggest that seasonal freshwater pulses create windows of opportunity for estuarine-associated fish to undertake spawning migrations when suitable hydrological conditions arise. Reproductive movements may be synchronised with seasonal environmental cues such as changes in freshwater flow, water temperature, salinity, turbidity and dissolved oxygen (Bjorgo et al. 2000; Dahl et al. 2004; Nicholson et al. 2008).

Relationships between freshwater flow and CPUE lagged by age at first maturity indicated a possible recruitment effect. Sexual maturity for dusky flathead, sand whiting and sea mullet occurs after approximately three years (Morton 1985; Burchmore et al. 1988; Kailola et al. 1993), which coincides with negative relationships between annual CPUE and seasonal flow variables with a three-year lag in the Clarence River. Freshwater flow can enhance recruitment by increasing offshore concentrations of land-based cues that stimulate fish larvae to immigrate into estuarine nursery grounds (Vinagre et al. 2007). The results presented here, however, suggest that recruitment effects were unlikely to result from olfactory cues increasing estuarine immigration. High freshwater flows lower salinity creating a barrier to recruitment, reducing available nursery habitat and limiting the immigration of marine larvae (Loneragan and Bunn 1999; Strydom et al. 2002; Shoji et al. 2006). Negative relationships between CPUE and lagged flows may result from lower salinity reducing estuarine immigration and forcing the larvae of marine-estuarine opportunists (e.g. dusky flathead and sand whiting) to find temporary refuge in the sea. Another possible mechanism for estuarine migrant species (e.g. sea mullet) is that high freshwater flows flush larvae out of estuaries into adjacent coastal waters. Increased freshwater flow may create unfavourable habitat conditions that force the seaward dispersion of larvae and result in subsequent reductions in CPUE.

The results from this study suggest that freshwater flow influences the catchability of estuarine-associated fish by stimulating migration and schooling due to salinity fluctuations altering habitat availability (Loneragan and Bunn 1999). Correlative analyses undertaken in this study were insufficient to make inferences about possible food chain effects. Freshwater flow can influence fish abundance by altering nutrient delivery and trophic conditions within an estuary (Livingston et al. 1997). However, it has been alleged that freshwater flow is more likely to determine the abundance of estuarine organisms by altering habitat availability rather than trophic dynamics (Kimmerer 2002a). There was no evidence to suggest that high freshwater flow stimulated larval immigration into estuaries. Negative relationships between CPUE and lagged flows may be attributed to lower salinity reducing available habitat and forcing the seaward dispersion of larvae.

3.5. Conclusions

Estuarine-associated fish are influenced by variation in freshwater flow in ways that affect CPUE via changes in recruitment and catchability. Freshwater flow may regulate fisheries catch rates by stimulating migration and schooling due to salinity fluctuations altering the availability of habitat. If the true effects of freshwater flow on estuarine fish communities are to be identified, future work should examine the influence of flows during critical reproductive periods. With climatic warming and greater hydrological extremes predicted in Australia (Hughes 2003), improved knowledge of the freshwater flow requirements of estuarine fisheries is important to devise effective management strategies. Understanding how interactions between hydrology and salinity produce such a marked effect on estuarine-associated fish is essential when considering the wider implications of altered flow regimes on estuarine fisheries.

3.6. Acknowledgements

Special thanks must go to the New South Wales Department of Primary Industries (NSW DPI) and the University of New South Wales (UNSW) Ecology and Evolution Research Centre (E&ERC) for funding this project. This study would not have been possible without the submission of monthly catch returns and the continued support of commercial estuarine fishers in New South Wales. Thanks to the Commonwealth Bureau of Meteorology, the New South Wales Department of Water and Energy and the Sydney Catchment Authority for permission to analyse relevant data. We are grateful to Bruce Pease and Douglas Rotherham for constructive comments on the development of the original study, which was published by NSW DPI in October 2008. The authors would also like to thank two anonymous reviewers for their comments which greatly improved this manuscript.

Effects of flood and drought events on multi-species, multi-method estuarine and coastal fisheries in eastern Australia

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Abstract

Coastal fish and fisheries are highly responsive to the flood-drought cycle. Multivariate patterns in commercial fisheries landings, effort and revenue from three adjacent estuarine and coastal systems were examined in eastern Australia between nine-month periods of flood (September 2000 to May 2001) and drought (September 2002 to May 2003). Patterns in species landings, methods of fishing effort and revenue per species were significantly different between flood and drought. Spearman's rank correlations between Bray-Curtis similarity matrices for landings, effort and revenue indicated that patterns in fisheries metrics represented a mixed-signal of ecological response and fishers' harvesting behaviour. Flood and drought events were associated with shifts in the species composition of landings that were reciprocated between estuarine and coastal systems. Estuarine migrant species (e.g. school prawn *Metapenaeus macleayi*) primarily contributed to landings during flood, while marine estuarine-opportunist species (e.g. yellowfin bream *Acanthopagrus australis*) primarily contributed to landings during drought. Flood and drought events redistributed fisheries resources between estuarine and coastal systems, modifying the bio-economic productivity of commercial fisheries. Results indicated that flood and drought events influence commercial fisheries by modifying the species composition of landings, fishers' harvesting behaviour and revenue generation.

Keywords: Commercial fisheries; Episodic flows; Harvesting behaviour; Landings composition; Revenue generation

4.1. Introduction

Understanding connections between freshwater flow and coastal fish communities is an important issue in fisheries ecology (Gillanders and Kingsford 2002). Freshwater flow is a critical landscape process that regulates the physical, chemical and biological properties of coastal marine ecosystems (Skreslet 1986). Natural variability in freshwater flow strongly influences the distribution and abundance of fish communities by altering habitat availability and trophic dynamics in estuarine and coastal systems (Kimmerer 2002a; Darnaude et al. 2004; Lamberth et al. 2009). Seasonal and interannual shifts in the composition of fish communities can occur due to natural fluxes in the flow regime modifying the distribution and abundance of marine, estuarine and freshwater species (Hurst et al. 2004; Costa et al. 2007; Baptista et al. 2010). Alterations to freshwater flow have a marked influence on coastal fish communities and any dependent fisheries (Drinkwater and Frank 1994).

Freshwater flow has a pivotal role in determining fisheries production due to effects on environmental conditions in estuarine and coastal systems (Loneragan and Bunn 1999; Grimes 2001; Lloret et al. 2004). Freshwater enhancement of fisheries production operates via several interrelated mechanisms: (1) increased growth and survival due to nutrient enrichment increasing primary and secondary production (Darnaude et al. 2004); (2) alterations to abundance resulting from salinity fluctuations modifying habitat availability (Kimmerer 2002a); (3) changes to migration and schooling altering catchability (Loneragan and Bunn 1999); and (4) improved recruitment due to increased offshore concentrations of land-based cues stimulating fish larvae to immigrate into estuarine nursery grounds (Vinagre et al. 2007). Despite well established connections between freshwater flow and fisheries production (Caddy and Bakun 1995), the effects of flood and drought events on multi-species and multi-method fisheries in estuarine and coastal systems have received little attention.

Flood and drought events are pulse disturbances that maintain biological productivity in estuaries (Flint 1985; Martin et al. 1992; Dolbeth et al. 2008). Episodic flow events are important determinants of estuarine fisheries production in eastern Australia (Gillson et al. 2009). Nevertheless, the effects of flood and drought events on the availability of fisheries resources and the dynamics of commercial fisheries in eastern Australia remain unclear. Eastern Australia experiences relatively extreme hydrological conditions (Finlayson and McMahon 1988), with climatic variability driving sporadic rainfall and stochastic flow events (Power et al. 1999). Coastal rivers in this region are influenced by alternating flood and drought dominated regimes (Erskine and Warner 1998), with freshwater primarily delivered into estuaries by episodic flow events (Eyre 1998).

Environmental fluctuations influence fish population dynamics by modifying ecological processes, which in turn produces cascading effects on fishing activity and the economic productivity of commercial fisheries that operate in estuarine and coastal systems (Pauly et al. 2002; Link and Tol 2006; Rouyer et al. 2008). An improved understanding of interactions between environmental variation, the availability of fisheries resources and the operational characteristics of commercial fisheries is essential for the development of an ecosystem-based approach to fisheries management (Hall and Mainprize 2004). We could expect that flood and drought events impact the species composition of commercial landings, fishers' harvesting behaviour and the economic performance of estuarine and coastal fisheries in eastern Australia. We test this prediction using the following hypotheses. Firstly, changes in the species composition of landings between flood and drought will result from differences in the life history characteristics and habitat preference of individual species. Estuarine migrant species will dominate coastal landings during flood, while marine estuarine-opportunist species will dominate estuarine landings during drought. Secondly, fishers' will modify their harvesting behaviour between flood and drought primarily to exploit alterations in species landings. Thirdly, revenue generation will fluctuate between flood and drought primarily due to variation in landings rather than the market price per species.

This study conducted a multivariate analysis of commercial fisheries metrics from three adjacent estuarine and coastal systems in eastern Australia between periods of flood and drought. This research represented a multivariate extension of a previous study that focused on the impacts of drought on the catch rates of a single-method gillnet fishery (Gillson et al. 2009). The objectives of this study were to: (i) examine multivariate patterns in the species composition of landings and revenue between flood and drought; and (ii) investigate multivariate patterns in the effort composition of fishing methods between flood and drought.

4.2. Methods

4.2.1. Study areas

Three adjacent estuarine and coastal systems along the eastern Australian coastline were selected to evaluate the impacts of flood and drought events on multi-species, multi-method fisheries (Figure 4–1). Estuarine fisheries were located in the permanently open lower reaches of the Clarence, Hunter and Hawkesbury River systems. Adjacent coastal fisheries extended ~30 km onto the continental shelf and ~0.5° north and south of each river system (i.e. coastal zones 2, 5 and 6). The spatial extent of coastal fisheries was based on reporting zones used by the Industry and Investment New South Wales (I&I NSW) and its predecessors the New South Wales Department of Primary Industries (NSW DPI). These estuarine and coastal fisheries administered by I&I NSW were selected for investigation because they provide the dominant contribution to commercial harvest in NSW (Table 4–1), and the neighbouring river systems exhibit highly variable annual flows with a coefficient of variation (C_v) of more than 75% (Finlayson and McMahon 1988). Annual variation in freshwater flow from eastern Australian rivers exceeds the world average by a factor of more than 1.8 (Peel *et al.* 2001). The El Niño-Southern Oscillation (ENSO) generates sporadic rainfall and unpredictable flow events in this region (Power *et al.* 1999). Coastal rivers in eastern Australia can experience prolonged periods of drought that are punctuated by sporadic flood events (Erskine and Warner 1998).

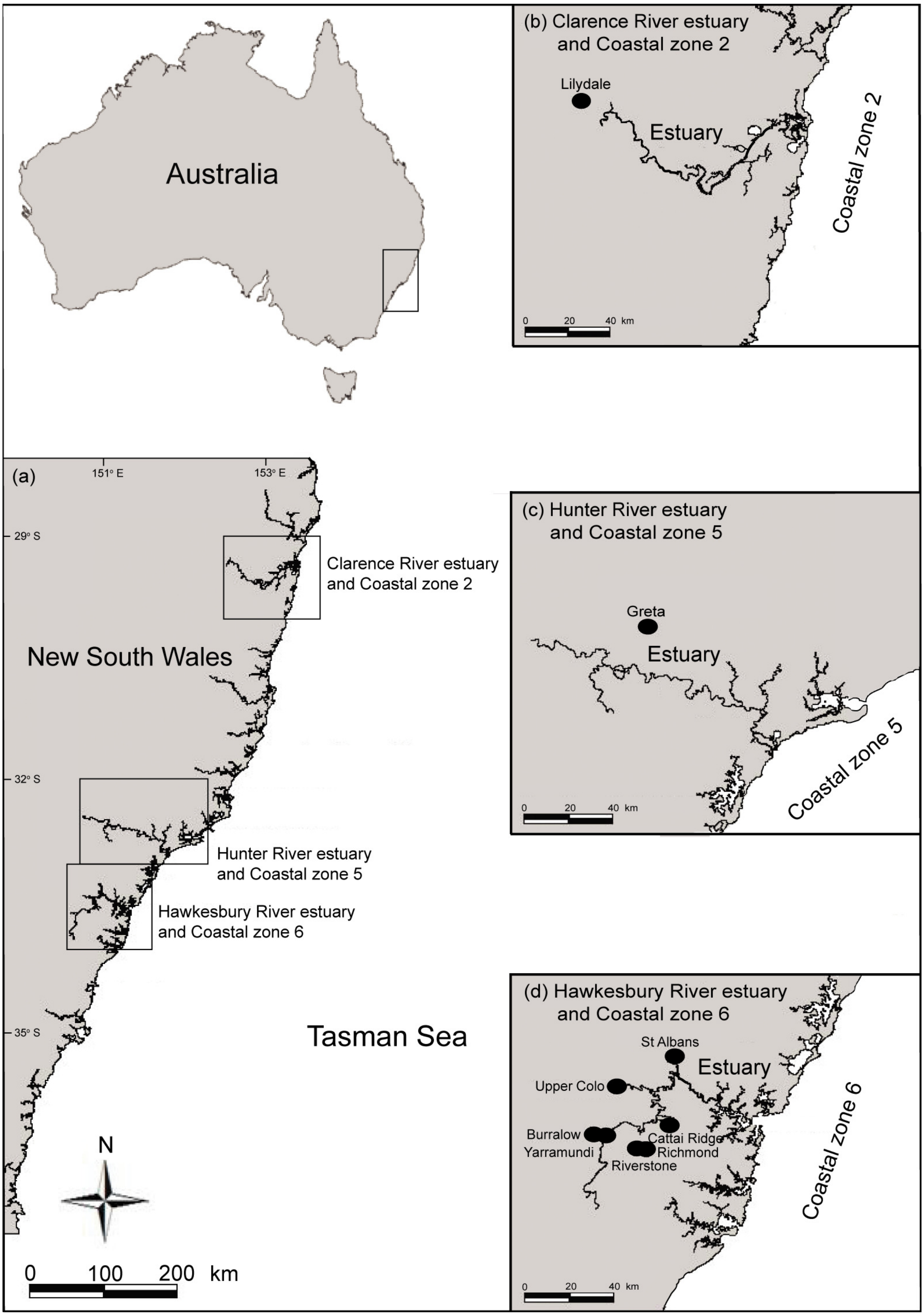

Figure 4-1: Location of three adjacent estuarine and coastal systems selected to investigate the impacts of flood and drought events on multi-species and multi-method fisheries in eastern Australia (a). Freshwater flow [●] gauging stations shown in relation to the estuarine and coastal reaches of the Clarence (b), Hunter (c) and Hawkesbury (d) River systems.

Table 4-1: Systems selected to investigate the effects of flood and drought events on multi-species and multi-method fisheries in eastern Australia.

System	Latitude and longitude	Bioregion	Catchment area (km^2)	Mean flow ($ML\ d^{-1}$/month)	River regulation	Mean landings (tonnes/month)	Percent of fisheries harvest	Mean effort (days/month)	Mean revenue (AU$000/month)
Clarence	29°25’37.20” S, 153°22’19.20” E	Northern	22400	181946	Moderate	149	16	1160	522.9
Hunter	32°54’54.00” S, 151°48’03.59” E	Central	22000	53608	High	79	9	444	167.9
Hawkesbury	33°34’10.20” S, 151°18’32.40” E	Central	21500	65353	High	62	7	478	113.9

Bioregion refers to defined latitudinal estuarine regions (Pease 1999). Mean flow ($ML\ d^{-1}$/month) represents mean monthly freshwater flow in $ML\ d^{-1}$ between 1997 and 2007 (note that 1 $ML\ d^{-1}$ equals ~0.0116 $m^3\ s^{-1}$). River regulation describes the amount of freshwater regulation and extraction within a catchment. Mean landings (tonnes/month), percent of fisheries harvest, mean effort (days/month) and mean revenue (AU$000/month) indicates mean landings in tonnes per month, the percentage contribution to commercial fisheries harvest from all fisheries per month, mean effort in days per month and mean revenue in AU$000's per month respectively between 1997 and 2007.

4.2.2. Hydrological data

Nine-month periods of flood (September 2000 to May 2001) and drought (September 2002 to May 2003) were identified in the Clarence, Hunter and Hawkesbury River catchments. These periods of flood and drought were defined by the Australian Bureau of Meteorology (Australian Bureau of Meteorology 2010, www.bom.gov.au/weather). Monthly freshwater flow data from September 2000 to May 2001 and September 2002 to May 2003 were extracted from the Pinneena 9.1 database of the New South Wales Department of Water and Energy (NSW DWE) for the Clarence and Hunter Rivers; and obtained from the Sydney Catchment Authority (SCA) for the Hawkesbury River. Gauged freshwater flow data was provided for the Clarence River at Lilydale; the Hunter River at Greta; and the Hawkesbury River at Yarramundi, Burralow, Richmond, Cattai Ridge, Upper Colo, St. Albans and Riverstone. Freshwater flow data included spring to autumn periods in temporally adjacent flood and drought phases.

4.2.3. Fisheries data

Monthly commercial fisheries landings, effort and Sydney Fish Market price data were compiled from the I&I NSW ComCatch database from September 2000 to May 2001 and September 2002 to May 2003. Fisheries metrics included landings (kg per month), effort (days fished per month) and revenue (AU$ per month) for 27 species groups and 16 fishing methods that contributed > 95% of commercial harvest from the five fisheries described in Chapter 1 between July 1997 and June 2007 (Tables 4–2 and 4–3). Life history information (e.g. reproductive characteristics, migration patterns and physiological adaptations) and habitat use (e.g. riverine, estuarine and marine) were considered before assigning individual species into one of seven estuarine use guilds: (1) Amphidromous (AM; species that migrate between freshwater and marine habitats but not for reproductive purposes); (2) Catadromous (CA; species that primarily inhabit freshwater habitats but migrate out to sea to spawn); (3) Estuarine Migrant (EM; species that have larval stages of their life cycle completed outside an estuary); (4) Estuarine Resident (ER; species capable of completing their entire life cycle within an estuary); (5) Marine estuarine Dependent (MD; species that depend on sheltered estuarine habitats as juveniles); (6) Marine estuarine-Opportunist (MO; species that opportunistically enter estuaries in substantial numbers but use nearshore marine waters as alternative habitat); and (7) Marine Straggler (MS; species that spawn at sea and typically enter the lower reaches of estuaries in low numbers when salinities are ~35. These species are often stenohaline and primarily inhabit coastal marine waters). A detailed description of the approach used to categorise species into estuarine use guilds has been presented in Elliot et al. (2007). Fisheries metrics were summed into monthly totals for individual species, guilds and fishing methods during periods of flood and drought. Difference indexes of landings per guild and revenue per guild were calculated by subtracting mean landings and revenue from each guild between periods of flood and drought.

Revenue per guild was calculated as:

$$R_{g,t} = \sum_{s=1}^{n_g} C_{s,t} \cdot \overline{P}_{s,t}$$

Where $R_{g,t}$ is revenue for guild g in month t (Australian dollars), n_g is the number of species in guild g, $C_{s,t}$ is the landings of species s in month t (kilograms) and $\overline{P}_{s,t}$ is the mean market price per kilogram of species s in month t from Sydney Fish Market.

Table 4-2: Summary of selected species groups used to examine the impacts of flood and drought events on estuarine and coastal fisheries.

Estuarine use guild	Species group	Mean landings (tonnes/month)	Mean revenue (AU$000/month)
AM	Catfish (*Siluriformes* spp.)	1.5	2.8
CA	River eels (*Anguilla* spp.)	3.9	12.6
EM	Eastern king prawn (*Melicertus plebejus*)	36.2	716.5
EM	School prawn (*Metapenaeus macleayi*)	43.1	299.2
EM	Sea mullet (*Mugil cephalus*)	112.5	198.6
EM	Giant mud crab (*Scylla serrata*)	2.1	34.8
EM	Estuary squid (*Uroteuthis* spp.)	2.5	5.5
EM	Silver scat (*Selenotoca multifasciatus*)	1.0	1.4
ER	Trumpeter whiting (*Sillago maculata*)	1.5	5.9
MD	Goldspot mullet (*Liza argentea*)	1.7	2.0
MD	River garfish (*Hyporhamphus regularis ardelio*)	0.4	1.5
MO	Yellowfin bream (*Acanthopagrus australis*)	10.4	89.5
MO	Sand whiting (*Sillago ciliata*)	4.2	43.2
MO	Silver trevally (*Pseudocaranx georgianus*)	13.0	34.1
MO	Mulloway (*Argyrosomus japonicus*)	3.3	24.7
MO	Sand mullet (*Myxus elongatus*)	17.8	21.8
MO	Blue swimmer crab (*Portunus pelagicus*)	2.2	13.5
MO	Dusky flathead (*Platycephalus fuscus*)	2.0	10.2
MO	Tailor (*Pomatomus saltatrix*)	1.6	8.4
MO	Largehead hairtail (*Trichiurus lepturus*)	0.9	8.0
MO	Yellowtail scad (*Trachurus novaezelandiae*)	4.2	7.0
MO	Luderick (*Girella tricuspidata*)	5.6	6.7
MO	Sandy sprat (*Hyperlophus vittatus*)	1.7	5.6
MO	Silver biddy (*Gerres subfasciatus*)	1.5	4.0
MS	Blue spotted flathead (*Platycephalus caeruleopunctatus*)	7.8	25.6
MS	Whaler sharks (*Carcharhinus* spp.)	4.8	14.9
MS	Australian sardine (*Sardinops neopilchardus*)	3.5	11.9

Estuarine use guilds consisted of Amphidromous (AM); Catadromous (CA); Estuarine Migrant (EM); Estuarine Resident (ER); Marine estuarine Dependent (MD); Marine estuarine-Opportunist (MO); and Marine Straggler (MS). Mean landings (tonnes/month) and mean revenue (AU$000/month) indicates mean landings in tonnes per month and mean revenue in AU$000's per month respectively between 1997 and 2007.

Table 4-3: Summary of selected fishing methods used to examine the impacts of flood and drought events on estuarine and coastal fisheries.

System	Fishing method	Gear type	Mean landings (tonnes/month)	Mean effort (days/month)	Mean revenue (AU$000/month)
Estuarine	Estuary prawn trawl	Active	37.1	854	255.7
Estuarine	Gillnets	Passive	61.4	711	155.7
Estuarine	Hauling net	Active	32.1	276	85
Estuarine	Prawn set pocket net	Passive	4.7	69	34.6
Estuarine	Crab pot	Passive	2.3	89	33.8
Estuarine	Eel trap	Passive	3.8	127	12.3
Estuarine	Bait net	Active	3.4	12	8.9
Estuarine	Handline	Active	1.1	72	8.6
Estuarine	Fish trap	Passive	0.8	51	6.1
Estuarine	Bullringing	Active	0.5	10	1.9
Coastal	Ocean prawn trawl	Active	49.5	779	772.7
Coastal	Hauling net	Active	62.6	244	123.9
Coastal	Fish trawl	Active	14.8	196	44.6
Coastal	Fish trap	Passive	6.7	337	31.0
Coastal	Handline	Active	5.7	355	27.1
Coastal	Purse seine net	Active	5.7	17	15.7
Coastal	Bait net	Active	3.2	7	9.6

Gear type indicates whether fishing equipment is active or passive. Mean landings (tonnes/month), mean effort (days/month) and mean revenue (AU$000/month) indicates mean landings in tonnes per month, mean effort in days per month and mean revenue in AU$000's per month respectively between 1997 and 2007.

4.2.4. Data analysis

Freshwater flow data was $\log_{10}$ transformed to normalise variances. Transformed freshwater flow data was normally distributed (Lillefor's test) with no evidence of heteroscedasticity (standardised quantile plots). A one-way analysis of variance (ANOVA) was used to compare freshwater flow between flood and drought.

Multivariate techniques were adopted to examine variation in landings, effort and revenue between flood and drought using the PERMANOVA+ add-on package for PRIMER v6 (Clarke and Gorley 2006; Anderson et al. 2008). Separate analyses were undertaken for estuarine and coastal systems to determine whether multivariate patterns in landings, effort and revenue between flood and drought were consistent among the distinct fisheries. Bray-Curtis similarity matrices were constructed from forth-root transformed data to reduce the weighting of frequently landed species and regularly used fishing methods whilst preserving information about relative contribution. Spearman's rank correlation coefficients (ρ) between Bray-Curtis similarity matrices for landings, effort and revenue were calculated using RELATE tests performed with 4999 permutations. Non-metric multidimensional scaling (MDS) ordination plots, based upon Bray-Curtis similarity matrices, were used to visualise multivariate patterns in landings, effort and revenue between flood and drought. A one-way permutational multivariate analysis of variance (PERMANOVA) was performed to test the statistical significance of visualised differences identified in MDS ordination plots of landings, effort and revenue between flood and drought (Anderson et al. 2008). PERMANOVA models consisted of one fixed factor (flow condition) with two levels (flood and drought). *P*-values for PERMANOVA models were calculated using 4999 unrestricted permutations of raw data (Manly 1997). As a statistically significant result from PERMANOVA could indicate that the groups differ in their location and/or dispersion in multivariate space, a permutational analysis of multivariate dispersions (PERMDISP) was used as a post-hoc test to compare heterogeneity in the multivariate dispersion of landings, effort and revenue between flood and drought. PERMDISP is a multivariate analogue of the Levene's test that assesses multivariate dispersion by comparing distances from observed vectors to their group centroid using 4999 permutations of residuals to calculate *P*-values (Anderson et al. 2008). A similarity percentage contribution analysis (SIMPER) was performed to identify species, guilds and methods that primarily contributed to average Bray–Curtis dissimilarities between flood and drought (Clarke and Gorley 2006).

4.3. Results

4.3.1. Freshwater flow

Freshwater flow was significantly different in the Clarence, Hunter and Hawkesbury Rivers between flood and drought events (Figure 4–2). Flow magnitudes were considerably higher than the long-term (10 year) monthly means in Clarence (+472%), Hunter (+243%) and Hawkesbury (+165%) Rivers during flood. Drought conditions were characterised by flow magnitudes that were below the long-term (10 year) monthly means in the Clarence (–49%), Hunter (–84%) and Hawkesbury (–65%) Rivers.

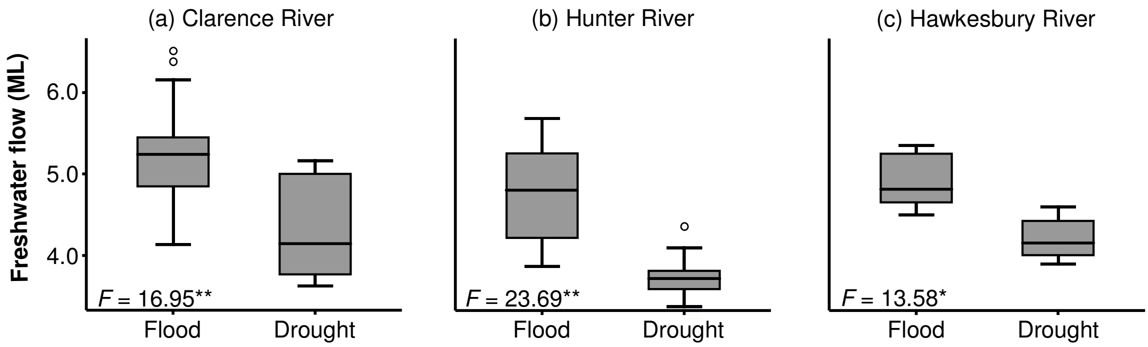

Figure 4-2: Box and whisker plots illustrating significant differences in $\log_{10}$ freshwater flow for the Clarence (a), Hunter (b) and Hawkesbury (c) River systems between flood and drought events (one-way ANOVA; *P < 0.01; **P < 0.001; d.f. = 17; minimum, 25% quartile, median, 75% quartile and maximum ranges). Note that 1 ML d^{-1} equals ~0.0116 $m^3 s^{-1}$.

4.3.2. Landings per guild

MDS ordination plots revealed detectable contrasts in estuarine and coastal landings per guild between flood and drought (Figure 4–3), which were statistically significant (Tables 4–4 and 4–5). Heterogeneity in landings per guild between flood and drought arose from differences in the location of groups in multivariate space (PERMDISP,

$P \geq 0.05$). Average dissimilarity in landings per guild between flood and drought was relatively high in the Clarence (16.9%), Hunter (12.7%) and Hawkesbury (10.3%) River estuaries. The SIMPER analysis revealed that estuarine migrant, estuarine resident and catadromous guilds primarily contributed to estuarine landings during flood. Marine estuarine-opportunist, marine estuarine dependent and marine straggler guilds primarily contributed to estuarine landings during drought. Average dissimilarity in landings per guild between flood and drought was relatively low in the Clarence (7.9%), Hunter (6.2%) and Hawkesbury (4.6%) coastal systems. Marine estuarine-opportunist, marine straggler and marine estuarine dependent guilds primarily contributed to coastal landings during flood. Estuarine migrant and estuarine resident guilds primarily contributed to coastal landings during drought.

Differences in landings per guild between flood and drought were reciprocated in estuarine and coastal systems (Figure 4–4). Guilds that dominated estuarine landings during flood subsequently dominated coastal landings during drought. Estuarine migrant and estuarine resident guilds primarily contributed to estuarine landings during flood and coastal landings during drought. Marine estuarine dependent, marine estuarine-opportunist and marine straggler guilds primarily contributed to estuarine landings during drought and coastal landings during flood.

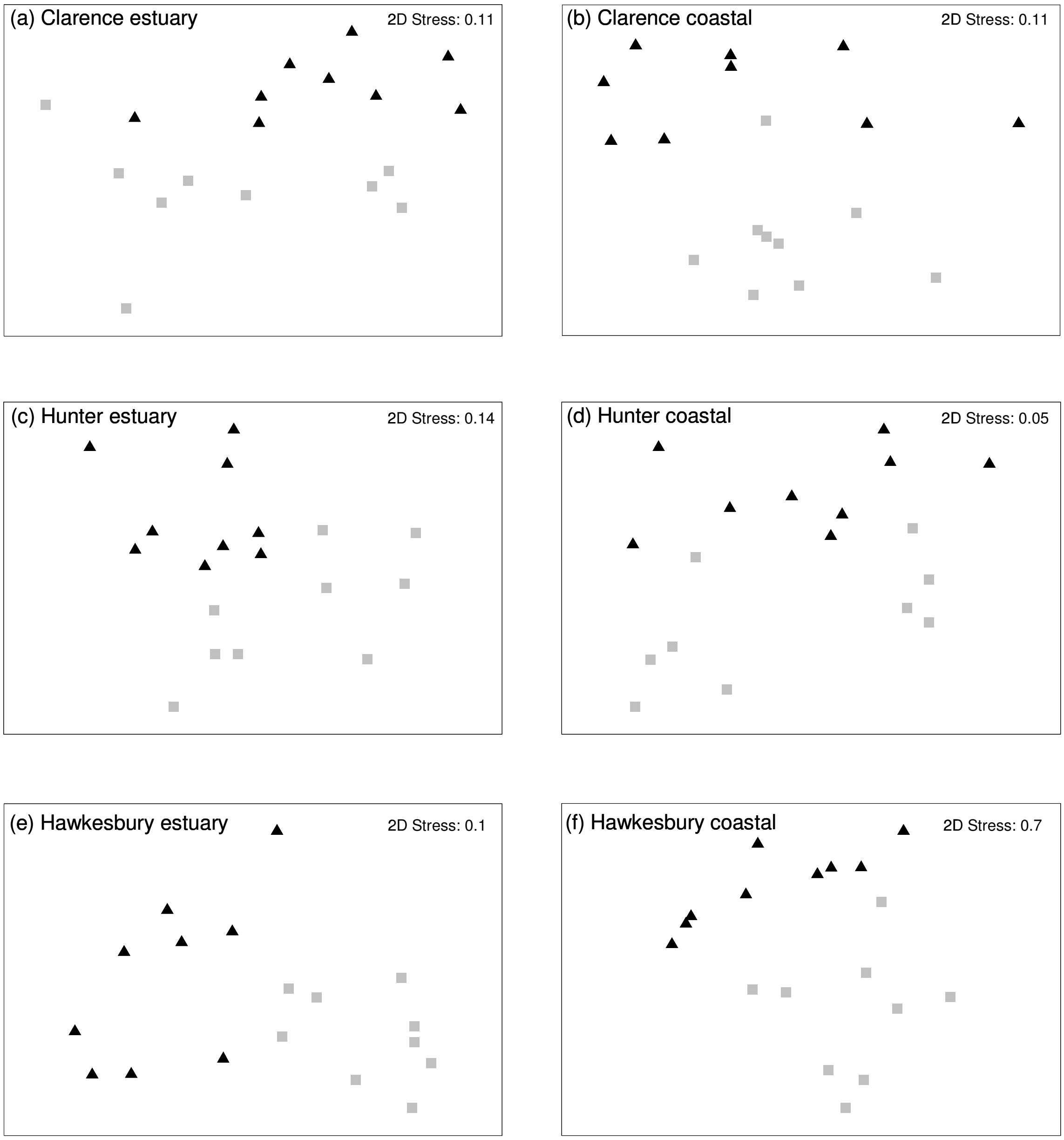

Figure 4-3: Examples of MDS ordination plots revealing detectable contrasts in landings per guild (kg of each guild per month) between flood (▲) and drought (■) for three adjacent estuarine and coastal systems in eastern Australia. Each point represents a month of flood or drought. See Table 4–2 for details of estuarine use guilds.

Table 4-4: PERMANOVA of landings per species, landings per guild, fishing effort, revenue per species and revenue per guild between flood and drought events in the Clarence (CR), Hunter (HU) and Hawkesbury (HK) River estuaries.

Estuary	Fisheries metric	d.f.	MS	Pseudo-F	P(perm)
CR	Landings per species	1	502.53	5.4644	0.0006
HU	Landings per species	1	1119.50	3.4592	0.0050
HK	Landings per species	1	358.79	2.6866	0.0178
CR	Landings per guild	1	200.12	16.1150	0.0006
HU	Landings per guild	1	715.87	8.0284	0.0002
HK	Landings per guild	1	279.75	4.2633	0.0182
CR	Fishing effort	1	180.68	5.7611	0.0002
HU	Fishing effort	1	1013.20	3.7310	0.0354
HK	Fishing effort	1	125.97	2.8487	0.0216
CR	Revenue per species	1	483.25	4.9525	0.0004
HU	Revenue per species	1	1067.50	3.2008	0.0106
HK	Revenue per species	1	282.17	3.4171	0.0038
CR	Revenue per guild	1	1175.90	7.2485	0.0008
HU	Revenue per guild	1	122.12	3.3717	0.0270
HK	Revenue per guild	1	219.34	2.7927	0.0434

Landings per species (kg of each species per month), landings per guild (kg of each guild per month), fishing effort (days fished per month), revenue per species (AU$ for each species per month) and revenue per guild (AU$ for each guild per month) were from 27 species groups, 7 estuarine use functional guilds and 10 fishing methods that contributed ≥ 95% of estuarine fisheries harvest between 1997 and 2007. PERMANOVA models were tested with 4999 random permutations of raw data.

Table 4-5: PERMANOVA of landings per species, landings per guild, fishing effort, revenue per species and revenue per guild between flood and drought events in the Clarence (CRC), Hunter (HUC) and Hawkesbury (HKC) coastal regions.

Coastal region	Fisheries metric	d.f.	MS	Pseudo-F	P(perm)
CRC	Landings per species	1	926.95	7.4754	0.0002
HUC	Landings per species	1	1068.10	3.3721	0.0310
HKC	Landings per species	1	1107.90	4.4476	0.0044
CRC	Landings per guild	1	128.49	11.8320	0.0004
HUC	Landings per guild	1	116.43	8.0506	0.0006
HKC	Landings per guild	1	60.59	4.4188	0.0326
CRC	Fishing effort	1	143.60	9.1841	0.0010
HUC	Fishing effort	1	190.20	3.0537	0.0482
HKC	Fishing effort	1	66.83	3.9147	0.0292
CRC	Revenue per species	1	839.87	8.2163	0.0002
HUC	Revenue per species	1	535.81	2.8592	0.0270
HKC	Revenue per species	1	1211.30	4.2372	0.0060
CRC	Revenue per guild	1	373.00	20.4820	0.0002
HUC	Revenue per guild	1	65.93	10.0350	0.0008
HKC	Revenue per guild	1	410.16	6.4192	0.0018

Landings per species (kg of each species per month), landings per guild (kg of each guild per month), fishing effort (days fished per month), revenue per species (AU$ for each species per month) and revenue per guild (AU$ for each guild per month) were from 27 species groups, 7 estuarine use functional guilds and 6 fishing methods that contributed ≥ 95% of coastal fisheries harvest between 1997 and 2007. PERMANOVA models were tested with 4999 random permutations of raw data.

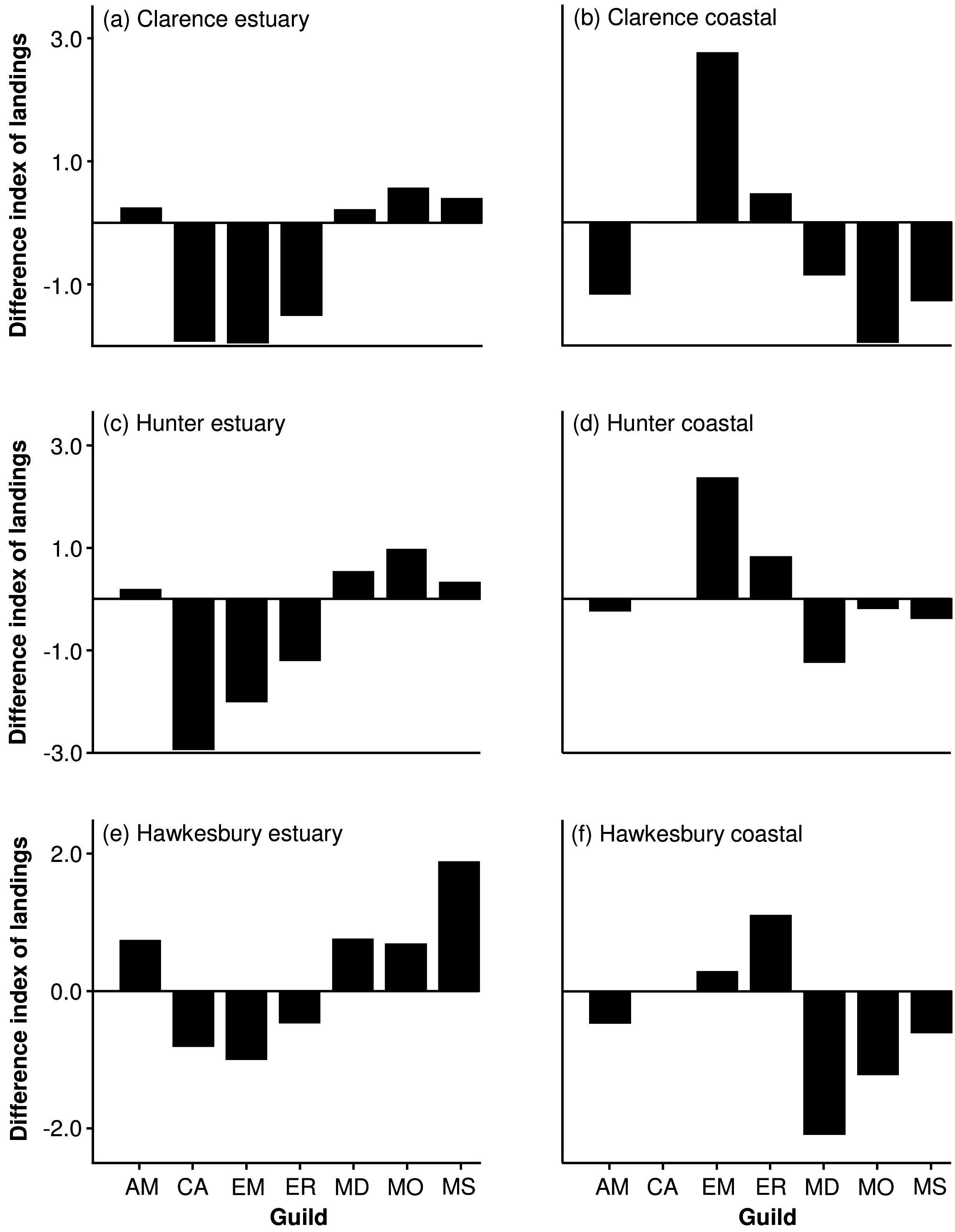

Figure 4-4: Difference index of landings per guild (kg of each guild per month) between flood and drought calculated using fourth-root transformed data. See Table 4–2 for details of estuarine use guilds. Note that a positive difference in landings per guild represents a drought period, while a negative difference in landings per guild represents a flood period.

4.3.3. Landings per species

Estuarine and coastal landings per species were significantly different between flood and drought (Tables 4–4 and 4–5), with heterogeneity arising from differences in group location (PERMDISP, $P \geq 0.05$). Average dissimilarity in landings per species between flood and drought was relatively high in the Clarence (27.8%), Hunter (25.6%) and Hawkesbury (20.0%) River estuaries. The SIMPER analysis identified that school prawn (*Metapenaeus macleayi*), sea mullet (*Mugil cephalus*) and river eels (*Anguilla* spp.) provided the greatest contribution to estuarine landings during flood. Yellowfin bream (*Acanthopagrus australis*), blue swimmer crab (*Portunus pelagicus*) and whaler sharks (*Carcharhinus* spp.) provided the greatest contribution to estuarine landings during drought. Average dissimilarity in landings per species between flood and drought was relatively low in the Clarence (20.1%), Hunter (16.3%) and Hawkesbury (15.4%) coastal systems. School prawn, sea mullet and blue swimmer crab provided the greatest contribution to coastal landings during flood. Yellowfin bream (*Acanthopagrus australis*), silver biddy (*Gerres subfasciatus*) and yellowtail scad (*Trachurus novaezelandiae*) provided the greatest contribution to coastal landings during drought.

4.3.4. Fishing effort

Detectable contrasts in estuarine and coastal fishing effort were evident between flood and drought (Tables 4–4 and 4–5). Heterogeneity in fishing effort between flood and drought arose from differences in the location of groups (PERMDISP, $P \geq 0.05$). Average dissimilarity in fishing effort between flood and drought was relatively high in the Clarence (23.9%), Hunter (19.0%) and Hawkesbury (14.0%) River estuaries. The SIMPER analysis showed that prawn trawls, prawn set pocket nets and eel traps were primarily used in estuarine systems during flood. Handlines, hauling nets and crab pots were primarily used in estuarine systems during drought. Average dissimilarity in fishing effort between flood and drought was relatively low in the Clarence (9.6%), Hunter (8.3%) and Hawkesbury (6.4%) coastal systems. Fish traps, fish trawls and prawn trawls were primarily used in coastal systems during flood. Handlines, hauling nets and purse seine nets were primarily used in coastal systems during drought.

4.3.5. Revenue per guild

Estuarine and coastal revenue per guild was significantly different between flood and drought (Tables 4–4 and 4–5), with heterogeneity arising from differences in group location (PERMDISP, $P \geq 0.05$). Average dissimilarity in revenue per guild was relatively high in the Clarence (22.0%), Hunter (13.24%) and Hawkesbury (9.3%) River estuaries. The SIMPER analysis revealed that estuarine migrant, estuarine resident and catadromous guilds dominated estuarine fisheries revenue during flood. Marine estuarine-opportunist, marine estuarine dependent and marine straggler guilds dominated estuarine fisheries revenue during drought. Average dissimilarity in revenue per guild was relatively low in the Clarence (13.5%), Hunter (9.2%) and Hawkesbury (4.9%) coastal systems. Marine estuarine-opportunist, marine straggler and marine estuarine dependent guilds dominated coastal fisheries revenue during flood. Estuarine migrant and estuarine resident guilds dominated coastal fisheries revenue during drought.

Differences in revenue per guild were reciprocated in estuarine and coastal systems (Figure 4–5). Guilds that dominated estuarine fisheries revenue during drought subsequently dominated coastal fisheries revenue during flood. Estuarine migrant and estuarine resident guilds primarily contributed to estuarine fisheries revenue during flood and coastal fisheries revenue during drought. Marine estuarine dependent, marine estuarine-opportunist and marine straggler guilds primarily contributed to estuarine fisheries revenue during drought and coastal fisheries revenue during flood.

4.3.6. Revenue per species

Significant differences in estuarine and coastal revenue per species were evident between flood and drought (Tables 4–4 and 4–5), which resulted from differences in the location of groups (PERMDISP, $P \geq 0.05$). Average dissimilarity in revenue per species was relatively high in the Clarence (27.8%), Hunter (27.2%) and Hawkesbury (20.8%) River estuaries. School prawn, sea mullet and river eels primarily contributed to estuarine fisheries revenue during flood. Yellowfin bream, blue swimmer crab and whaler sharks primarily contributed to estuarine fisheries revenue during drought. Average dissimilarity in revenue per species was relatively low in the Clarence (18.6%), Hunter (16.5%) and Hawkesbury (14.3%) coastal systems. School prawn, sea mullet and blue swimmer crab primarily contributed to coastal fisheries revenue during flood. Yellowfin bream, silver biddy and yellowtail scad primarily contributed to coastal fisheries revenue during drought. Mean market price per species was significantly different between flood and drought (Pseudo-$F_{1,\ 17}$ = 6.0202, P(perm) = 0.0016). Average dissimilarity in mean market value between flood and drought was 3.8%.

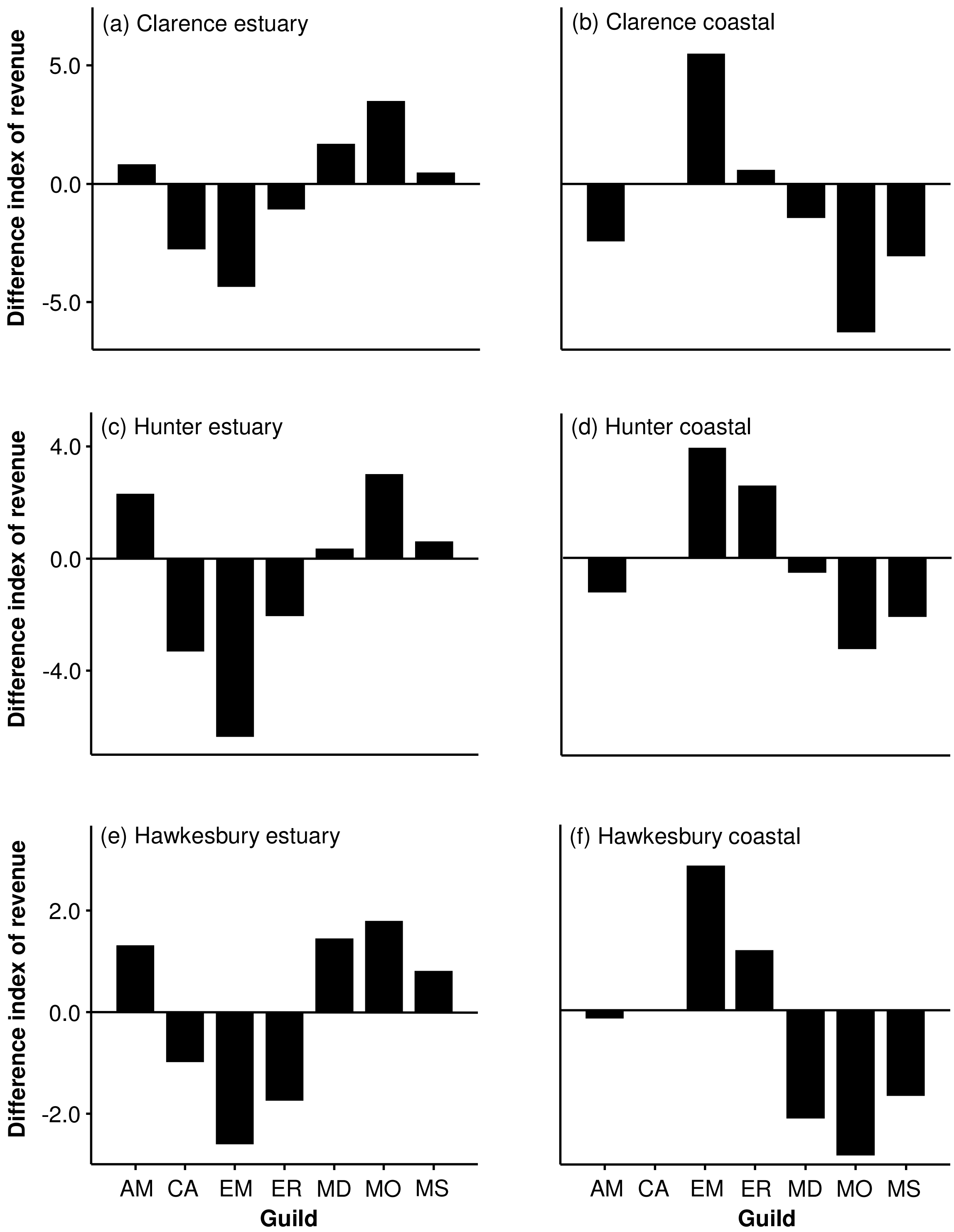

Figure 4-5: Difference index of revenue per guild (AU$ for each guild per month) between flood and drought calculated using fourth-root transformed data. See Table 4–2 for details of estuarine use guilds. Note that a positive difference in revenue per guild represents a drought period, while a negative difference in revenue per guild represents a flood period.

4.4. Discussion

Examination of commercial fisheries metrics from three adjacent estuarine and coastal systems revealed the effects of flood and drought events on multi-species, multi-method fisheries. Significant differences in landings, effort and revenue between flood and drought were species, guild and system specific. These differences were caused by heterogeneity in the multivariate location of groups between flood and drought (PERMDISP, $P \geq 0.05$ for all fisheries metrics examined). Similarities in the multivariate patterns of landings and revenue between flood and drought were attributed to limited variation in market price. Variation in the market price per species was relatively small ($C_V = 0.14$) compared to landings per species ($C_V = 0.57$) over a ten-year period between 1997 and 2007. Correlations between Bray-Curtis similarity matrices for landings, effort and revenue indicated that multivariate patterns in fisheries metrics represented a signal of ecological response and a function of fishers' harvesting behaviour. Natural variation in freshwater flow modifies the species composition of landings, the temporal and spatial distribution of fishing effort and ultimately the economic performance of commercial fisheries that operate in estuarine and coastal systems (Loneragan and Bunn 1999; Robins et al. 2005; Lamberth et al. 2009).

The extent that our analysis experienced temporal pseudo-replication (*sensu* Hurlbert 1984) depends upon the degree of interdependence between the flood and drought events in the three locations examined. As the flood and drought events did not occur at the same time for each location, the three locations are not true replicates of an event. This difficulty of finding truly replicated systems is a common issue in analyses of fisheries data (Millar and Anderson 2004). An alternative strategy to avoid pseudo-replication could involve the employment of univariate mixed effects models using an extended time series of hydrological data with increased numbers of flood and drought events. Nevertheless, there are two issues of more importance to the outcomes of this study. Firstly, some of the variability underlying multivariate patterns in fisheries metrics between flood and drought may be related to factors such as bioregion (Pease 1999), estuarine geomorphology (Saintilan 2004), recruitment success (Bennett et al. 1995), fishers' harvesting behaviour (Salas and Gaertner 2004), socio-economics (Charles 1989) and the degree of river regulation within the catchment (Drinkwater and Frank 1994). Secondly, the multivariate patterns identified here are more important than the reported statistical significance. These patterns provide a heuristic model for future studies in alternative systems where some of the statistical constraints experienced here may be less pronounced.

River regulation dampens hydrological extremes and decouples fisheries-flow relationships in eastern Australia (Gillson et al. 2009). Our results suggest that river regulation reduces multivariate dispersion in landings, effort and revenue between flood and drought. Pseudo-F values obtained from PERMANOVA of landings, effort and revenue between flood and drought were consistently higher for the less regulated Clarence River than the highly regulated Hunter or Hawkesbury Rivers. Deviation in pseudo-F values may result from river regulation altering connections between the delivery of freshwater flow and the migration patterns of commercially-important species (Drinkwater and Frank 1994). The effects of flood and drought events on fisheries resources are likely to be more clearly manifested in estuarine and coastal systems that receive freshwater from rivers with a relatively low degree of regulation and high variability in freshwater flow.

4.4.1. Landings composition between flood and drought

Flood and drought events were associated with shifts in the species composition of landings. Estuarine migrant species (e.g. school prawn and sea mullet) primarily contributed to landings during flood, while marine estuarine-opportunist species (e.g. yellowfin bream and blue swimmer crab) primarily contributed to landings during drought. Freshwater flow influences the distribution and abundance of fish and invertebrates due to salinity fluctuations altering habitat availability (Jassby et al. 1995; Kimmerer 2002a; Barletta et al. 2005). Differences in the salinity tolerance of euryhaline and stenohaline species may be attributed to observed disparity in the responses of coastal biota to flood and drought (Cognetti and Maltagliati 2000). The school prawn is a euryhaline species that responds to flood events and resultant reductions in salinity by emigrating from estuarine to coastal systems (Ruello 1973; Glaister 1978; Dall et al. 1990). Floodwaters reduce salinity on the continental shelf, expanding the offshore estuary and permitting euryhaline species to increase their distribution into coastal habitats (Able 2005). Droughts can induce seaward migration in euryhaline species due to increased salinity creating hypersaline conditions, thereby reducing the extent of available habitat for fish and invertebrates in estuaries (Dolbeth et al. 2008). Marine stenohaline species are transient components of estuarine communities due to stenotopic environmental requirements (Whitfield 1994b). Floods result in the decreased estuarine abundance of marine stenohaline species due to lower salinity forcing the seaward displacement of preferred habitat (Marais 1983; Ter Morshuizen et al. 1996; Whitfield and Harrison 2003). Droughts, alternatively, may create windows of opportunity for marine stenohaline species to enter estuaries due to increased salinity (Nordlie 2003). Silver biddy is a marine stenohaline species that may immigrate into estuaries during drought due to increased salinity expanding available habitat.

Floodwaters can flush estuarine resident species out of estuaries into coastal systems (Strydom et al. 2002). Nevertheless, our results indicated that estuarine resident species (e.g. trumpeter whiting *Sillago maculata* Quoy and Gaimard) primarily contributed to coastal landings during drought. Trumpeter whiting may retreat to coastal systems during drought, and therefore this species may have been more appropriately described as an estuarine migrant. Support for downstream displacement by flooding was provided for catadromous species (e.g. anguillid eels) which primarily contributed to estuarine landings during flood. Anguillid eels can be washed out of rivers into estuaries by flood events (Tsukamoto and Arai 2001).

Resistance and resilience of aquatic biota to flood and drought events may be facilitated by movement to refugia (Lake 2007). Aquatic organisms possess chemosensory organs that enable detection and orientation toward suitable ambient conditions (Weissburg 2000). Fish dispersal and migration is strongly influenced by freshwater flow altering estuarine salinity regimes (Garcia et al. 2003; Garcia et al. 2004; Sosa-López et al. 2007). We observed that flood and drought events altered landings composition by modifying species exchange between estuarine and coastal systems. Flood and drought events may result in shifts in the species composition of landings by modifying rates of estuarine immigration and emigration due to salinity fluctuations altering habitat availability. Temporal and spatial variation in freshwater flow modifies salinity regimes forcing the composition of coastal fish communities to oscillate through a continuum of successionary states (Garcia et al. 2001; Whitfield 2005; Love et al. 2009).

4.4.2. Species-specific landings between flood and drought

Significant differences in estuarine and coastal landings between flood and drought were likely to result from alterations in catchability. Freshwater flow influences the catchability of fish and invertebrates by modifying their distribution due to changes in salinity and/or turbidity (Loneragan and Bunn 1999). School prawns primarily contributed to estuarine and coastal landings during flood. Flood events result in the increased catchability of school prawns due to reductions in salinity enhancing emigration rates from estuarine to coastal systems (Racek 1959; Ruello 1973; Glaister 1978). Freshwater flow also has a marked influence on the catchability of sea mullet due to changes in salinity stimulating migration and schooling into preferred habitat (Gillson et al. 2009). Salinity strongly influences habitat selection by sea mullet, with individuals locating optimum salinity conditions to minimise osmoregulatory costs and maximise growth rates (Cardona 2000; Chang et al. 2004; Cardona 2006). Sea mullet dominated fisheries harvest (≥ 35%) providing the greatest contribution to significant differences in estuarine and coastal landings between flood and drought. River eels primarily contributed to estuarine landings during flood. High flows stimulate seaward migration in river eels, thereby increasing their catchability in estuaries (Chen et al. 1994; Miyai et al. 2004; Tsukamoto 2009).

Increased freshwater flow forces the emigration of blue swimmer crab from estuarine to coastal systems (Potter et al. 1983). Blue swimmer crab primarily contributed to estuarine landings during drought and coastal landings during flood. Salinity exerts a profound influence on the spatial distribution of blue swimmer crab, with individuals preferring salinities > 20 (Potter et al. 1983, Potter and de Lestang 2000, de Lestang et al. 2003). Differences in estuarine and coastal landings of blue swimmer crab between flood and drought may result from alterations in catchability due to individuals shifting their spatial distribution to seek optimal salinities. Yellowfin bream primarily contributed to coastal landings during drought. Drought results in the increased catchability of yellowfin bream due to increased estuarine salinity stimulating downstream migration into coastal habitats (Gillson et al. 2009).

Another possible mechanism underlying differences in species-specific landings between flood and drought is alterations to the catchability of fish and invertebrates that result from changes in turbidity (Loneragan and Bunn 1999, North and Houde 2003, Robins et al. 2005). Changes in turbidity strongly influence the catchability of fish and invertebrates by modifying their distribution and abundance due to alterations in habitat availability (Cyrus and Blaber 1987, Cyrus and Blaber 1992, Grange et al. 2000). In our study, silver biddy primarily contributed to estuarine and coastal landings during drought. Drought events may result in the increased catchability of silver biddy due to higher salinity and/or lower turbidity increasing habitat availability in estuarine and coastal systems. Flood and drought events, therefore, may alter the catchability of coastal species by stimulating migration and schooling due to changes in salinity and/or turbidity altering habitat availability.

4.4.3. Fishers' harvesting behaviour between flood and drought

Fishers employ dynamic fishing strategies as an adaptive response to alterations in resource abundance and environmental conditions (Salas and Gaertner 2004). We observed that fishers' modified their harvesting behaviour between flood and drought events. Prawn trawls and prawn set pocket nets were primarily used during flood, which resulted in increased landings of school prawns. The mass movement of school prawns from estuarine to coastal systems after flooding noticeably increases the susceptibility of this species to fishing effort (Glaister 1978). Commercial fishers recognise that increased freshwater flow results in increased landings of penaeid prawns due to extensive practical experience. Prawn trawls dominated fishing effort (≥ 35%) providing the greatest contribution to significant differences in harvesting behaviour between flood and drought. Eel traps were primarily used during flood, which accounts for increased estuarine landings of river eels. Handlines, hauling nets and crab pots were primarily used in estuaries during drought which can be attributed to fishers targeting the increased catchability of yellowfin bream, blue swimmer crab and whaler sharks. Flood and drought events may prompt fishers' to adjust their harvesting behaviour by altering fishing method use. Handlines, hauling nets and purse seine nets were primarily used in coastal systems during drought which explains increased coastal landings of yellowfin bream, silver biddy and yellowtail scad. Accordingly, these results suggest that fishers' modify harvesting behaviour to exploit alterations to the catchability of coastal species that arise during flood and drought.

4.4.4. Revenue between flood and drought

Environmental fluctuations influence the economic productivity of commercial fisheries by modifying the availability of fisheries resources (Grafton et al. 2006). Significant differences in fisheries revenue between flood and drought were primarily attributed to variation in landings rather than market price. Landings of high-value estuarine migrant species (e.g. school prawn) primarily contributed to revenue during flood, while landings of low-value marine estuarine-opportunist species (e.g. silver biddy) primarily contributed to revenue during drought. Flood and drought events may regulate fisheries revenue by modifying the landed composition of coastal fish communities due to alterations in catchability arising from migration and schooling. Fish migration has an important role in exporting productivity between estuarine and coastal systems (Deegan 1993), with associated economic impacts on commercial fisheries (Bjørndal et al. 2004). School prawns dominated fisheries revenue (≥ 31%) providing the greatest contribution to significant differences in revenue generation between flood and drought. Flood and drought events, therefore, may influence the economic performance of commercial fisheries by modifying revenue generation due to changes in the species composition of landings.

Results from this study indicate that flood and drought events redistributed fisheries resources between estuarine and coastal systems, modifying the bio-economic productivity of commercial fisheries. Flood and drought events may influence the bio-economic productivity of commercial fisheries by modifying the species composition of landings, fishers' harvesting behaviour and revenue generation. Coastal species that exhibit varying degrees of estuarine dependency are influenced by variation in freshwater flow (Lamberth et al. 2009). Differences in landings and revenue between flood and drought were most discernible for estuarine migrant (e.g. school prawn and sea mullet) and marine-estuarine opportunist (e.g. yellowfin bream and blue swimmer crab) species. With increased climatic variability and greater hydrological extremes predicted in many regions of the world (Alley et al. 2003), improved knowledge of the effects of flood and drought events on multi-species and multi-method fisheries is essential to devise effective management strategies. Future research would be most profitably directed on examining how individual fishers, rather than the industry in aggregate, modify their harvesting behaviour during flood and drought events. Understanding variation in the harvesting behaviour of individual fishers during flood and drought would provide insight into patterns of fishing method use that will make fishing businesses more robust to climate change.

4.5. Acknowledgements

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Spreading the economic risk: harvesting strategies of multi-method inshore fisheries during drought in eastern Australia

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Abstract

Droughts will increase in frequency and severity with climate change, modifying the economic viability of inshore fisheries in regions of hydrological extreme. Variation in the revenue and profit of different fishing methods between non-drought and drought conditions was examined for commercial fishing businesses in three adjacent estuarine and coastal systems in eastern Australia from 1997 to 2007. Mean monthly revenue decreased from 8% to 36% between non-drought and drought. Decreased mean monthly revenue was primarily attributed to reduced revenue generation from ocean prawn trawling (≥ 20%) and estuary prawn trawling (≥ 34%) during drought. Fishing method diversity (measured by the Shannon index) and mean monthly revenue were positively related. However, estimated reductions in mean monthly profit under alternative cost scenarios ranged from 5% to 95% between non-drought and drought. Reduced mean monthly profit was primarily attributed to losses from ocean prawn trawling (≥ 15%) and estuary prawn trawling (≥ 30%) during drought. In contrast to revenue, mean monthly profit and fishing method diversity were negatively related. Although diversified harvesting behaviour increased revenue generation, this marginal economic benefit was compromised by higher costs associated with increased diversification which lowered profitability. Results indicated that the commercial fishing sector is a drought-affected industry in coastal New South Wales.

Keywords: Economic risk; Climatic variability; Drought; Commercial fisheries

5.1. Introduction

Understanding connections between climatic variability and fisheries production is an important avenue of investigation (Brander 2007). Climatic variability strongly influences the production of estuarine and coastal fisheries by modifying the spatial distribution, abundance and species composition of fish communities (Roessig et al. 2004; Lehodey et al. 2006; Brander 2010). Many studies have focused on climatic effects on commercially-important fish species such as horse mackerel (*Trachurus murphyi*), tuna (*Thunnus albacares*) and cod (*Gadus morhua*) (Klyashtorin 1998; Lehodey et al. 2003; Fogarty et al. 2008). Concern has, however, also been expressed about the economic impacts of climate change on estuarine and coastal fisheries (Lyne et al. 2003; Hannesson 2007; Allison et al. 2009). Information on the economic impacts of climate change on estuarine and coastal fisheries is required to inform long-term policy debate and strategic management options (Johnson and Welch 2010).

Climatic variability has a pivotal role in determining the quantity of freshwater entering coastal marine ecosystems (Gillanders and Kingsford 2002). Natural variation in freshwater flow influences fisheries production by regulating habitat availability and affecting trophic dynamics in estuarine and coastal systems (Grimes 2001; Robins et al. 2005; Lamberth et al. 2009). Freshwater flow *per se*, however, may not be as important in determining the production of estuarine and coastal fisheries as extreme hydrological events (Gillson et al. 2009). Floods and droughts are extreme hydrological events that regulate biological productivity in estuarine and coastal systems (Flint 1985; Martin et al. 1992; Dolbeth et al. 2008). Despite well established connections between freshwater flow and fisheries production (Caddy and Bakun 1995), the economic impacts of drought on estuarine and coastal fisheries have received little attention.

Diverse multi-species and multi-method fisheries operate along the eastern Australian coastline. Commercial fisheries target penaeid prawns (*Metapenaeus macleayi*, *Melicertus plebejus, Metapenaeus bennettae*), finfish (*Acantopagrus australis, Platycephalus fuscus, Mugil cephalus*), sharks (*Carcharhinus* spp.) and crabs (*Portunus pelagicus, Scylla serrata, Ranina ranina*) with a gross value of ~AU$350 million per annum (ABARE 2009). Coastal fish communities and dependent fisheries are affected by flood and drought events in this region (Loneragan and Bunn 1999; Robins et al. 2005; Ives et al. 2009). Nevertheless, the impacts of drought on the economic performance of estuarine and coastal fisheries in eastern Australia remain unclear. Eastern Australia experiences relatively extreme hydrological conditions (Finlayson and McMahon 1988), with climatic variability driving sporadic rainfall and stochastic freshwater flow events (Chiew et al. 1998). Coastal rivers in this region are influenced by alternating flood and drought dominated regimes (Erskine and Warner 1998). Climatic projections indicate that extreme fluctuations in rainfall will increase the frequency and severity of floods and droughts in eastern Australia (Hennessy et al. 2007). One of the many concerns associated with climate change is the impacts of reduced freshwater flow on estuarine and coastal fisheries (Loneragan and Bunn 1999; Robins et al. 2005; Ives et al. 2009). Reductions in freshwater flow resulting from climate change could be exacerbated by human population growth increasing demand for water resources (Vörösmarty et al. 2000).

This study examined the economic impacts of droughts on commercial fishing businesses that operate in three adjacent estuarine and coastal fisheries in eastern Australia. The aims of this study were to: (i) examine the revenue, costs and profits of different multi-method fishing strategies during non-drought and drought, and (ii) test the hypothesis that diversified harvesting behaviour increased revenue and profit during non-drought and drought.

5.2. Methods

5.2.1. Study Areas

Three adjacent estuarine and coastal systems along the eastern Australian coastline were selected to investigate the economic impacts of droughts on commercial fishing businesses (Figure 5–1). Estuarine fisheries were located in the permanently open lower reaches of the Clarence, Hunter and Hawkesbury Rivers. Adjacent coastal fisheries extended ~30 km onto the continental shelf and ~0.5° north and south of each river system. The spatial extent of coastal fisheries were based on reporting zones used by the Industry and Investment New South Wales (coastal zones 2, 5 and 6, (I&I NSW)). These estuarine and coastal fisheries administered by I&I NSW (hereafter referred to as the Clarence, Hunter and Hawkesbury systems) were selected for investigation because they provide the dominant contribution to commercial fisheries harvest in New South Wales (Table 5–1).

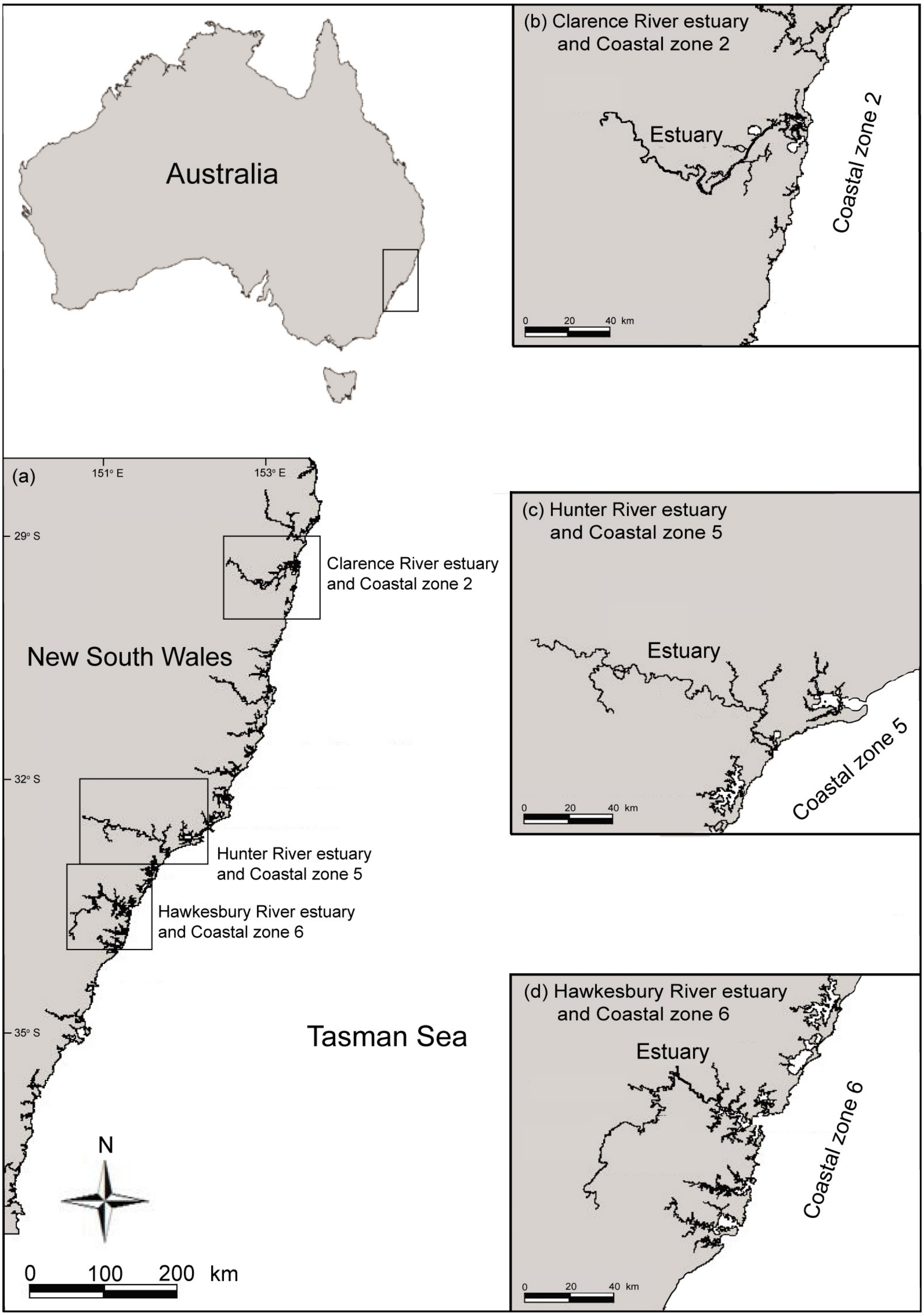

Figure 5-1: Location of three adjacent estuarine and coastal systems selected to investigate the economic impacts of droughts on commercial fishing businesses in eastern Australia (a). Estuarine and coastal reaches shown in relation to the Clarence (b), Hunter (c) and Hawkesbury (d) Rivers.

Table 5-1: Systems selected to investigate the economic impacts of drought events on commercial fishing businesses that operate in adjacent estuarine and coastal fisheries in eastern Australia.

System	Latitude and longitude	Bioregion	Fishing businesses	Mean landings (tonnes/month)	Percent of fisheries harvest	Mean effort (days/month)	Mean revenue (AU$000/month)	Months of drought
Clarence	29°25’37.20” S, 153°22’19.20” E	Northern	191	149	16	1160	522.9	38
Hunter	32°54’54.00” S, 151°48’03.59” E	Central	91	79	9	444	167.9	31
Hawkesbury	33°34’10.20” S, 151°18’32.40” E	Central	86	62	7	478	113.9	29

Bioregion refers to defined latitudinal estuarine regions (Pease 1999). Fishing businesses represent the mean number of fishing businesses operating per month. Mean landings (tonnes/month), percent of fisheries harvest, mean effort (days/month) and mean revenue (AU$000/month) indicates mean landings in tonnes per month, the percentage contribution to monthly commercial fisheries harvest in NSW, mean effort in days per month and mean revenue in AU$000's per month respectively between July 1997 and June 2007. Months of drought describes the number of drought declared months in the respective catchment out of a total of 120 months.

5.2.2. *Hydrological data*

Reductions in rainfall and freshwater flow have been documented in the Clarence, Hunter and Hawkesbury Rivers during drought (Gillson et al. 2009). This study used the governmental declaration of drought-affected areas in the respective catchments to indicate decreased rainfall and freshwater flow in the coastal rivers examined. Monthly drought declaration maps from July 1997 to June 2007 were obtained from I&I NSW (2010). I&I NSW assesses climatic and agricultural factors to officially declare the drought-affected status of an area (www.dpi.nsw.gov.au/drought). Drought-affected areas were based on Rural Lands Protection Board Districts, and no rivers considered were co-located within the same district. Periods of drought declaration were examined for an area surrounding each coastal river and formatted into a dichotomous variable with “0” and “1” representing the absence or presence of drought declaration, respectively.

5.2.3. *Fisheries data*

Monthly commercial fisheries catch, effort and Sydney Fish Market price data were compiled from the I&I NSW ComCatch database between July 1997 and June 2007. Fisheries metrics for individual fishing businesses included landings (kilograms per month), effort (days fished per month), revenue (AU$ per month) and profit (AU$ per month) from 27 species groups and 16 fishing methods that contributed > 95% of commercial harvest from the five fisheries described in Chapter 1 between July 1997 and June 2007 (Tables 5–2 and 5–3). Landings and effort per fishing method were aggregated into monthly totals for individual businesses.

A "fishing business" represented a separate and identifiable financial entity (New South Wales *Fisheries Management* Act 1994). Fishing businesses can possess endorsements to operate multiple-methods in multiple fisheries and business owners (usually the fishers) utilise endorsements as they see fit. Fishing methods from five commercial fisheries in NSW were considered: Estuary General fishery (multi-method), Estuary Prawn Trawl fishery (single-method), Ocean Hauling fishery (multi-method), Ocean Trawl fishery (dual-method) and the Ocean Trap and Line fishery (multi-method). Endorsements in the Abalone and Lobster fisheries were not considered in this study because there is an ambiguous linkage of fishing businesses between these fisheries and other major commercial fisheries in NSW. Although some overlap exists between fishers that operate in the Lobster fishery and Ocean Trap and Line fishery, different identifiers are used for fishing businesses in the catch records so relating these operations at the scale of fishing businesses is very error prone.

Table 5-2: Selected species used to investigate the economic impacts of drought events on commercial fishing businesses that operate in adjacent estuarine and coastal fisheries in eastern Australia.

Species	Mean landings (tonnes/month)	Mean revenue (AU$000/month)
Eastern king prawn (*Melicertus plebejus*)	36.2	716.5
School prawn (*Metapenaeus macleayi*)	43.1	299.2
Sea mullet (*Mugil cephalus*)	112.5	198.6
Yellowfin bream (*Acanthopagrus australis*)	10.4	89.5
Sand whiting (*Sillago ciliata*)	4.2	43.2
Giant mud crab (*Scylla serrata*)	2.1	34.8
Silver trevally (*Pseudocaranx georgianus*)	13.0	34.1
Blue spotted flathead (*Platycephalus caeruleopunctatus*)	7.8	25.6
Mulloway (*Argyrosomus japonicus*)	3.3	24.7
Sand mullet (*Myxus elongatus*)	17.8	21.8
Whaler sharks (*Carcharhinus* spp.)	4.8	14.9
Blue swimmer crab (*Portunus pelagicus*)	2.2	13.5
River eels (*Anguilla* spp.)	3.9	12.6
Australian sardine (*Sardinops neopilchardus*)	3.5	11.9
Dusky flathead (*Platycephalus fuscus*)	2.0	10.2
Tailor (*Pomatomus saltatrix*)	1.6	8.4
Largehead hairtail (*Trichiurus lepturus*)	0.9	8.0
Yellowtail scad (*Trachurus novaezelandiae*)	4.2	7.0
Luderick (*Girella tricuspidata*)	5.6	6.7
Trumpeter whiting (*Sillago maculata*)	1.5	5.9
Sandy sprat (*Hyperlophus vittatus*)	1.7	5.6
Estuary squid (*Uroteuthis* spp.)	2.5	5.5
Silver biddy (*Gerres subfasciatus*)	1.5	4.0
Catfish (*Siluriformes* spp.)	1.5	2.8
Goldspot mullet (*Liza argentea*)	1.7	2.0
River garfish (*Hyporhamphus regularis ardelio*)	0.4	1.5
Silver scat (*Selenotoca multifasciatus*)	1.0	1.4

Mean landings (tonnes/month) and revenue (AU$000/month) refer to mean landings in tonnes per month and mean revenue in AU$000’s per month respectively for the three systems examined between July 1997 and June 2007. Landings and revenue information presented for species that provided the dominant contribution (≥ 95%) to commercial harvest in NSW.

Table 5-3: Selected fishing methods used to investigate the economic impacts of drought events on commercial fishing businesses that operate in adjacent estuarine and coastal fisheries in eastern Australia.

System	Fishing method	Method abbreviation	Fishery	Gear	Mean landings (tonnes/ month)	Mean effort (days/ month)	Mean revenue (AU$000/ month)
Estuarine	Estuary prawn trawl	EP	EPT	Active	37.1	854	255.7
Estuarine	Gillnets	GI	EG	Passive	61.4	711	155.7
Estuarine	Hauling net	HN	EG	Active	32.1	276	85.0
Estuarine	Prawn set pocket net	PN	EG	Passive	4.7	69	34.6
Estuarine	Crab pot	CP	EG	Passive	2.3	89	33.8
Estuarine	Eel trap	EE	EG	Passive	3.8	127	12.3
Estuarine	Bait net	BN	EG	Active	3.4	12	8.9
Estuarine	Handline	LI	EG	Active	1.1	72	8.6
Estuarine	Fish trap	FT	EG	Passive	0.8	51	6.1
Estuarine	Bullringing	BU	EG	Active	0.5	10	1.9
Coastal	Ocean prawn trawl	OP	OT	Active	49.5	779	772.7
Coastal	Hauling net	HN	OH	Active	62.6	244	123.9
Coastal	Fish trawl	FW	OT	Active	14.8	196	44.6
Coastal	Fish trap	FT	OT&L	Passive	6.7	337	31.0
Coastal	Handline	LI	OT&L	Active	5.7	355	27.1
Coastal	Purse seine net	PS	OH	Active	5.7	17	15.7
Coastal	Bait net	BN	OH	Active	3.2	7	9.6

Fishery represents Estuary General (EG), Estuary Prawn Trawl (EPT), Ocean Hauling (OH), Ocean Trawl (OT) and Ocean Trap and Line (OT&L). Gear indicates whether fishing equipment is active or passive. Mean landings (tonnes/month), effort (days/month) and revenue (AU$000/month) refer to mean landings in tonnes per month, mean effort in days per month and mean revenue in AU$000's per month respectively for the three systems examined between July 1997 and June 2007. Landings, effort and revenue information presented for fishing methods that provided the dominant contribution (≥ 95%) to commercial harvest in NSW.

5.2.4. Revenue

Revenue was calculated as:

$$R_{m,b,t} = \sum_{s} C_{m,b,s,t} \cdot \bar{P}_{s,t}$$

Where $R_{m,b,t}$ is revenue for fishing method *m* from business *b* in month *t* (Australian dollars), $C_{m,b,s,t}$, is the landings of species *s* for fishing method *m* from business *b* in month *t* (kilograms) and $\bar{P}_{s,t}$ is the mean market price per kilogram of species *s* in month *t* from Sydney Fish Market.

Nominal revenue per method was adjusted for inflation using the Sydney food Consumer Price Index (CPI) relative to June 2007 ($CPI_{June2007} = 1$) to give revenue per method. The Sydney food CPI was obtained from the Australian Bureau of Statistics (ABS) for quarterly periods between July 1997 and June 2007 (www.abs.gov.au/AUSSTATS).

5.2.5. Costs

A cost model containing parameterised assumptions of cost variability was developed to examine profits associated with fishing activity. Information on the mean monthly cost of fishing was available, but not the variability of these costs experienced across the fleet. The cost model was further complicated by the constraint that mean monthly cost was only available by fishery. Therefore, the costs associated with different methods within a fishery could not be differentiated. For single-method fisheries the cost calculation was straightforward, but for multiple-method fisheries the cost calculation required assumptions about how the costs accrued within a fishery and a business.

Costs for individual businesses were partitioned into fixed-monthly costs (including sunk costs; i.e. retrospective costs that have already been incurred and cannot be recovered) and variable-monthly costs. Fixed-monthly costs were considered to be independent of fishing effort, while variable-monthly costs were assumed to be a linear function of fishing effort. Fixed costs were incurred on a monthly or annual basis such as licences, registration fees, insurance, governmental costs, equipment and maintenance. Variable costs were dependent on the amount of fishing effort undertaken, and in this study consisted of labour and fuel costs. Information on fixed and variable costs per business from each fishery were derived from economic assessments undertaken by Dominion Consulting Pty Ltd (2001; 2002a; 2002b; 2004; 2006) for the 1999-2000 fiscal period (Table 5–4). Nominal fixed and variable cost proportions were inflation-adjusted using the Fuel Price Index (FPI) and Labour Price Index (LPI) from the ABS relative to June 2000 ($FPI_{June2000}$ and $LPI_{June2000} = 1$).

Table 5-4: Mean monthly costs per fishing business (AU$) for the 1999-2000 fiscal period.

Fishery	Fixed cost	Variable cost	Total cost
Estuary General	1900	4600	6500
Estuary Prawn Trawl	4500	4900	9400
Ocean Hauling	3200	6200	9400
Ocean Trawl	8600	9000	17600
Ocean Trap and Line	3900	5700	9600

Mean monthly costs per fishing business were obtained from economic assessments undertaken by Dominion Consulting Pty Ltd for the 1999-2000 fiscal period (Dominion Consulting Pty Ltd 2001, 2002a, 2002b, 2004, 2006). Values presented to the nearest AU$100.

Total costs were calculated using:

$$TC'_{b,t} = \max_{m(f)}[FC_{m(f),t}] + \max_{m(f)}[VC_{m(f),t} \cdot E_{m,b,t}]$$

Where $TC'_{b,t}$ is total cost for business *b* in month *t* (Australian dollars), max[$FC_{m(f),t}$] is the maximum fixed cost for fishery *f* (over methods *m* within *f*) in month *t* (Australian dollars), max[$VC_{m(f),t}$] is the maximum variable cost for fishery *f* (over method *m* within *f*) in month *t* (Australian dollars). $E_{m,b,t}$ is the fishing effort for method *m* from business *b* in month *t*.

The assumption that monthly fixed and variable costs were capped at the maximum for a particular business was used to represent the reduced costs of deploying multiple gears within a month. This assumption also prevented costs from becoming unrealistically high in multi-method fisheries. For example, if a business operated low cost methods such as crab pots and high cost methods such as ocean prawn trawling, only the costs associated with ocean prawn trawling were included. Monthly total costs per business were standardised (using a z-transformation) to a distribution with a specified mean and standard deviation. The mean was that of the average monthly costs from Dominion Consulting Pty Ltd (2001; 2002a; 2002b; 2004; 2006). The standard deviation of costs across businesses in a month was modelled by assuming a specific coefficient of variation (C_V) of either 25%, 50% or 75% (hereafter referred to as cost-variability scenarios). This standardisation prevented the standard deviation of the raw costs experienced by businesses becoming unrealistically large.

5.2.6. Profit

Profit was calculated as:

$$\pi_{b,t} = \sum_{m}(R_{m,b,t}) - (TC'_{b,t})$$

Where $\pi_{b,t}$ is the profit for business *b* in month *t* (Australian dollars), $R_{m,b,t}$ is revenue for fishing method *m* from business *b* in month *t* (Australian dollars) and $TC'_{b,t}$ is total cost for business *b* in month *t* (Australian dollars).

In accordance with the nominal cost adjustment, nominal revenue was inflation-adjusted using the Sydney food CPI relative to June 2000 ($CPI_{June2000}$ = 1) before calculating monthly profit per method. Profits under alternative cost-variability scenarios were examined to determine the effects of increased cost-variability on profit.

5.2.7. Sensitivity analyses

Sensitivity analyses were performed to examine the robustness of profit outputs by altering key parameter values. Firstly, mean monthly market price per species was increased by 20%, 40% and 60% to determine effects on profit. Preliminary examination of percentage differences in the mean market price of eastern king prawn (*Melicertus plebejus*), school prawn (*Metapenaeus macleayi*), sea mullet (*Mugil cephalus*) and yellowfin bream (*Acanthopagrus australis*) revealed that prices from the Sydney Fish Market were 5% to 50% lower than the Professional Fishermen's Association. Secondly, costs were decreased by 20%, 40% and 60% to examine effects on profit. Finally, fixed costs incurred by non-operational (i.e. latent) businesses during drought were summed with total costs to estimate effects on profit. Fewer businesses operated during drought in the Clarence (32%), Hunter (20%) and Hawkesbury (33%) systems.

5.2.8. Data analysis

A preliminary investigation of mean monthly revenue per method revealed that revenue generation decreased when businesses operated beyond a certain number of methods (Figure 5–2). The number of methods required to saturate revenue generation was five or less in the Clarence system and two or less in the Hunter and

Hawkesbury systems. Based on these findings, numbers of methods were categorised into two distinct groups for each system: less than five methods or more than five methods for the Clarence system; and less than two methods or more than two methods for the Hunter and Hawkesbury Systems. One-tailed Fisher's exact tests were then employed to compare proportional differences in the number of businesses that operated different numbers of methods during non-drought and drought. Fisher's exact tests evaluated the presence of non-random associations between numbers of methods used by businesses during non-drought and drought.

Mean monthly revenue (or profit; this notation indicates that the same analysis was repeated for revenue and profit) during non-drought and drought was standardised by dividing the sum of monthly revenue (or profit) by the number of non-drought and drought months in each river. This standardisation procedure prevented differences in mean monthly revenue (or profit) being a result of an unbalanced number of non-drought and drought months. Differences between mean monthly revenue and costs during non-drought and drought were examined using box and whisker plots. Profits under alternative cost-variability scenarios were compared to baseline profit values during non-drought. A similar approach was used to examine profit under the alternative economic scenarios within the sensitivity analyses.

Mean revenue (or profit), when businesses operated two or more fishing methods per month (hereafter referred to as multiple-method months), was calculated to determine the contribution of different fishing methods to revenue (or profit) during non-drought and drought. Single-method months were excluded from these calculations given that this study was interested in the incremental benefit of fishing method diversity within a month, rather than revenue and profit *per se*. We employed the Shannon index to measure fishing method diversity during multiple-method months. A modified form of the Shannon index was calculated using relative monthly effort per method from individual businesses rather than the usual application of relative species abundance.

The modified form of the Shannon index used was:

$$H'_{b,t} = -\sum_{m} E_{m,b,t} \ln(E_{m,b,t})$$

Where $H'_{b,t}$ is the modified Shannon index value for business *b* in month *t* and $E_{m,b,t}$ is the fishing effort for method *m* from business *b* in month *t*.

Mean monthly values for revenue (or profit) and the Shannon index were calculated from all businesses. Ordinary least squares regression was adopted to examine the relationship between mean monthly revenue (or profit), the Shannon index and drought declaration. Regression models consisted of two covariates, one fixed factor (hydrological condition) with two levels (non-drought and drought) and one continuous covariate (mean Shannon index, $\bar{H}'_t$). Mean monthly revenue was $\log_{10}$ transformed to stabilise variances. After transformation, mean monthly revenue was normally distributed (Lilliefors' test) with no evidence of heteroscedasticity (standardised quantile plots). Log transformations were not applied to mean monthly profit as these were not required.

5.3. Results

5.3.1. Harvesting behaviour

Numbers of businesses that operated different fishing methods between non-drought and drought exhibited considerable variation in the Clarence, Hunter and Hawkesbury systems. A significant difference in the proportional number of businesses that operated one to five methods compared to five or more methods between non-drought and drought was evident in the Clarence system (One tailed Fisher's exact test, $P < 0.05$). This difference was characterised by an 11% increase in the number of businesses that operated fewer methods (1–5) during drought compared to non-drought in the Clarence system. In the Hunter and Hawkesbury systems, there were significant differences in numbers of businesses that operated one to two methods compared to two or more methods between non-drought and drought (One tailed Fisher's exact test, $P < 0.05$). In contrast to the Clarence system, more businesses operated one to two methods during drought compared to non-drought in the Hunter (10%) and Hawkesbury (8%) systems.

5.3.2. Revenue among fishing methods

Mean monthly revenue was significantly lower during drought compared to non-drought in the Clarence (27%), Hunter (8%) and Hawkesbury (36%) systems (Figure 5–2). Cumulative mean monthly revenue increased in proportion to the number of fishing methods used during non-drought and drought, however, the marginal benefit of using more methods declined in all systems. Rates of revenue generation decreased after businesses operated five or more methods in the Clarence system. Similar results were identified for the Hunter and Hawkesbury systems, with diminishing returns when businesses operated two or more methods. Fishing methods that primarily contributed to decreased mean monthly revenue between non-drought and drought were ocean prawn trawling (≥ 20%) and estuary prawn trawling (≥ 34%). Methods that provided a relatively smaller contribution to decreased mean monthly revenue between non-drought and drought were gillnets (≥ 15%) and hauling nets (≥ 16%).

5.3.3. Revenue and fishing method diversity

Regression models revealed significant positive relationships between mean monthly revenue and the Shannon index during non-drought and drought (Figure 5–3). Interaction terms between the Shannon index and drought declaration were non-significant ($P \geq 0.05$). The fixed effect regression models identified positive coefficients for the relationship between mean monthly revenue and the Shannon index, and negative coefficients for the relationship between mean monthly revenue and drought declaration (Table 5–5).

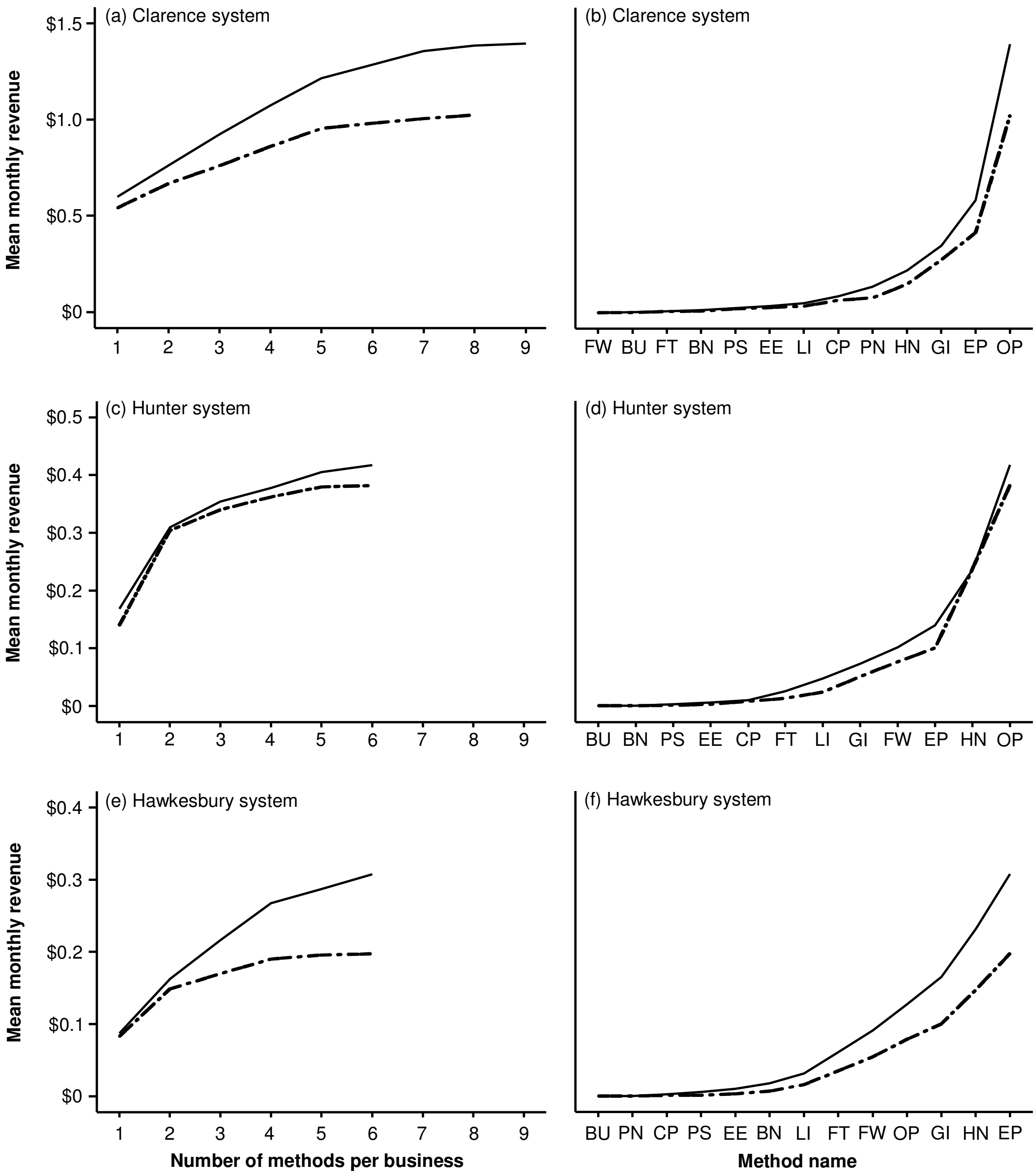

Figure 5-2: Cumulative mean revenue per month in millions of Australian dollars generated from different fishing methods during non-drought (solid line) and drought (dotted line) conditions for the Clarence, Hunter and Hawkesbury systems from July 1997 to June 2007. See Table 5–3 for details of fishing method abbreviations. Revenue is standardised by the number of drought declared months in each river system.

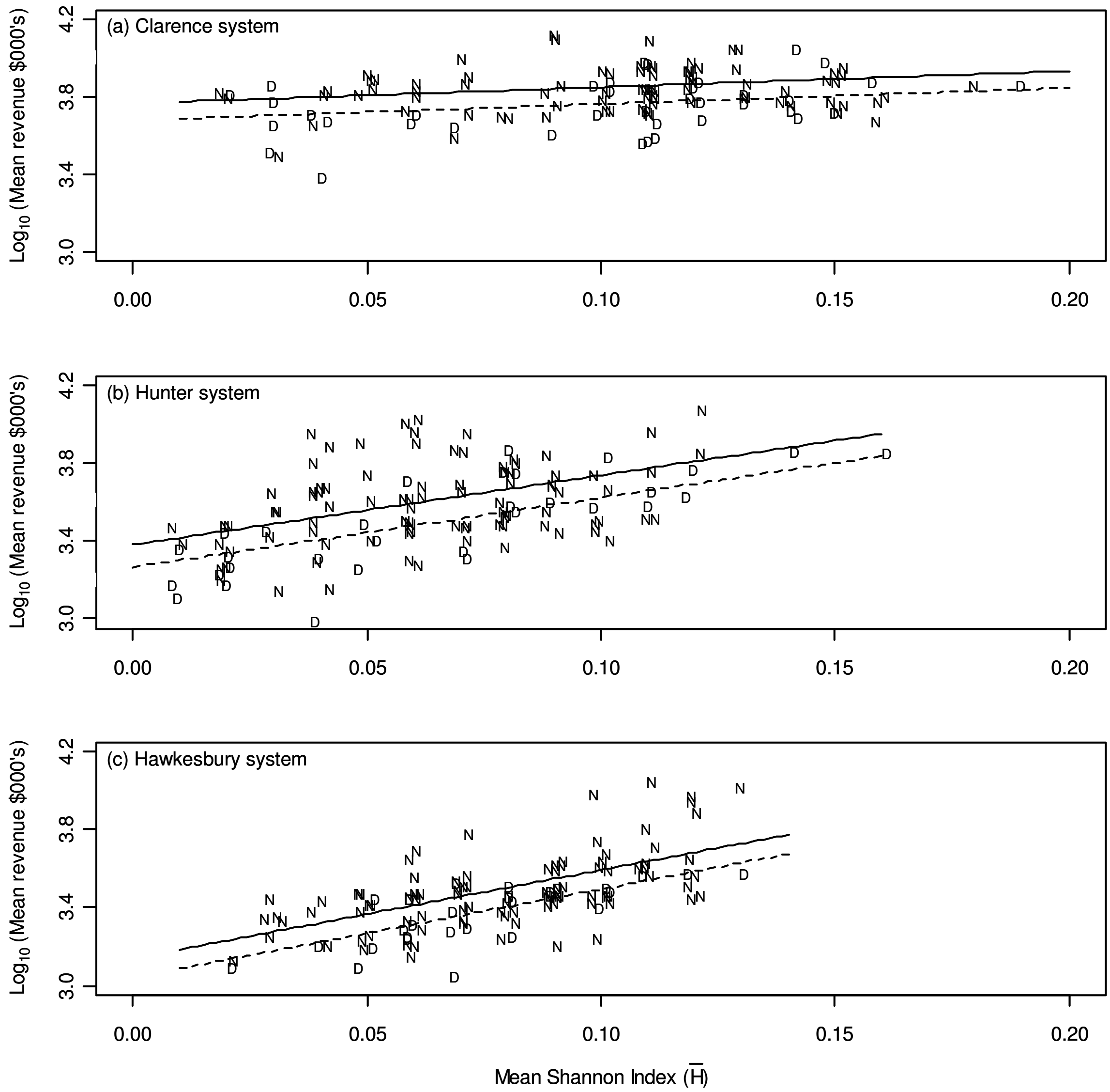

Figure 5-3: Regression models predicting mean monthly revenue per business from the mean monthly Shannon index during non-drought (solid line) and drought (dotted line) conditions for the Clarence, Hunter and Hawkesbury systems (statistics for the regression models presented in Table 5–5). Note that data points associated with non-drought (N) and drought (D) periods have been jittered on linear plots to improve clarity.

Table 5-5: Fitted coefficients for model terms that incorporated $R_t \sim \overline{H}'_t + D_t$ for the Clarence (CR), Hunter (HU) and Hawkesbury (HK) systems.

System	Term	Estimate of coefficient	SE	P(t)
CR	Intercept	3.77	0.03	< 0.001
	$\overline{H}'_t$	0.83	0.28	< 0.01
	D_t	–0.09	0.02	< 0.001
	$\overline{H}'_t \times D_t$	0.76	0.56	**> 0.05**
HU	Intercept	3.38	0.04	< 0.001
	$\overline{H}'_t$	3.57	0.54	< 0.001
	D_t	–0.11	0.04	< 0.01
	$\overline{H}'_t \times D_t$	2.01	1.09	**> 0.05**
HK	Intercept	3.14	0.04	< 0.001
	$\overline{H}'_t$	4.53	0.51	< 0.001
	D_t	–0.10	0.03	< 0.01
	$\overline{H}'_t \times D_t$	0.07	1.26	**> 0.05**

Coefficient details provided for $\log_{10}$ transformed data from multiple-method months; n = 120; $\alpha < 0.05$. R_t, $\overline{H}'_t$ and D_t refer to the mean revenue in month *t*, mean Shannon index in month *t* and drought declaration in month *t*, respectively. Non-significant model terms (P > 0.05) shown in bold.

5.3.4. Profit under cost-variability scenarios

Mean monthly revenue and costs were markedly different during non-drought and drought (Figure 5–4). Not only were estimated costs considerably higher than revenue (~4×), but estimated costs also exhibited more variability around the mean. Mean monthly losses under alternative cost-variability scenarios were higher during drought (Figure 5–5). Costs with a 75% coefficient of variation were attributed to increased losses in both the Clarence and Hawkesbury systems.

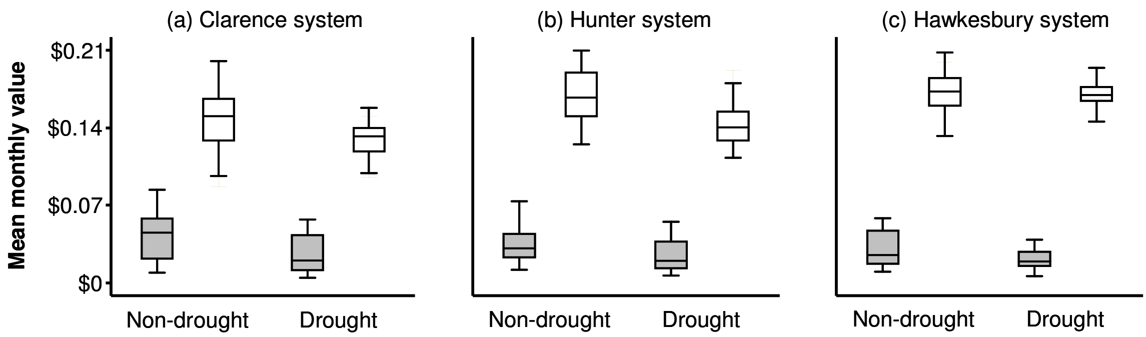

Figure 5-4: Box and whisker plots illustrating differences between mean monthly revenue (grey) and costs (white) in thousands of Australian dollars during non-drought and drought conditions for the Clarence, Hunter and Hawkesbury systems.

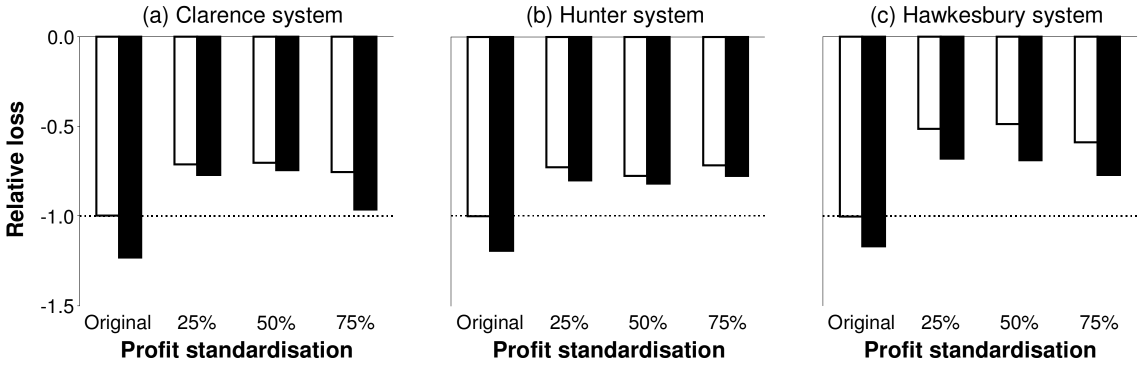

Figure 5-5: Sensitivity analyses indicating the effects of variability in monthly costs on profit during non-drought (white) and drought (black) conditions for the Clarence, Hunter and Hawkesbury systems. Subfigures illustrate the relative loss as the coefficient of variation of cost increases from the non-drought baseline (dotted line). Costs have been standardised by mean costs per fishing business with a fixed 25%, 50% and 75% coefficient of variation.

5.3.5. Profit under economic scenarios

Profit exhibited considerable variation under alternative economic scenarios (Figure 5–6). Increased market price of seafood and decreased costs were associated with decreased losses during non-drought and drought. The addition of fixed costs incurred by latent businesses increased losses during drought in the Clarence (43%), Hunter (40%) and Hawkesbury (46%) systems.

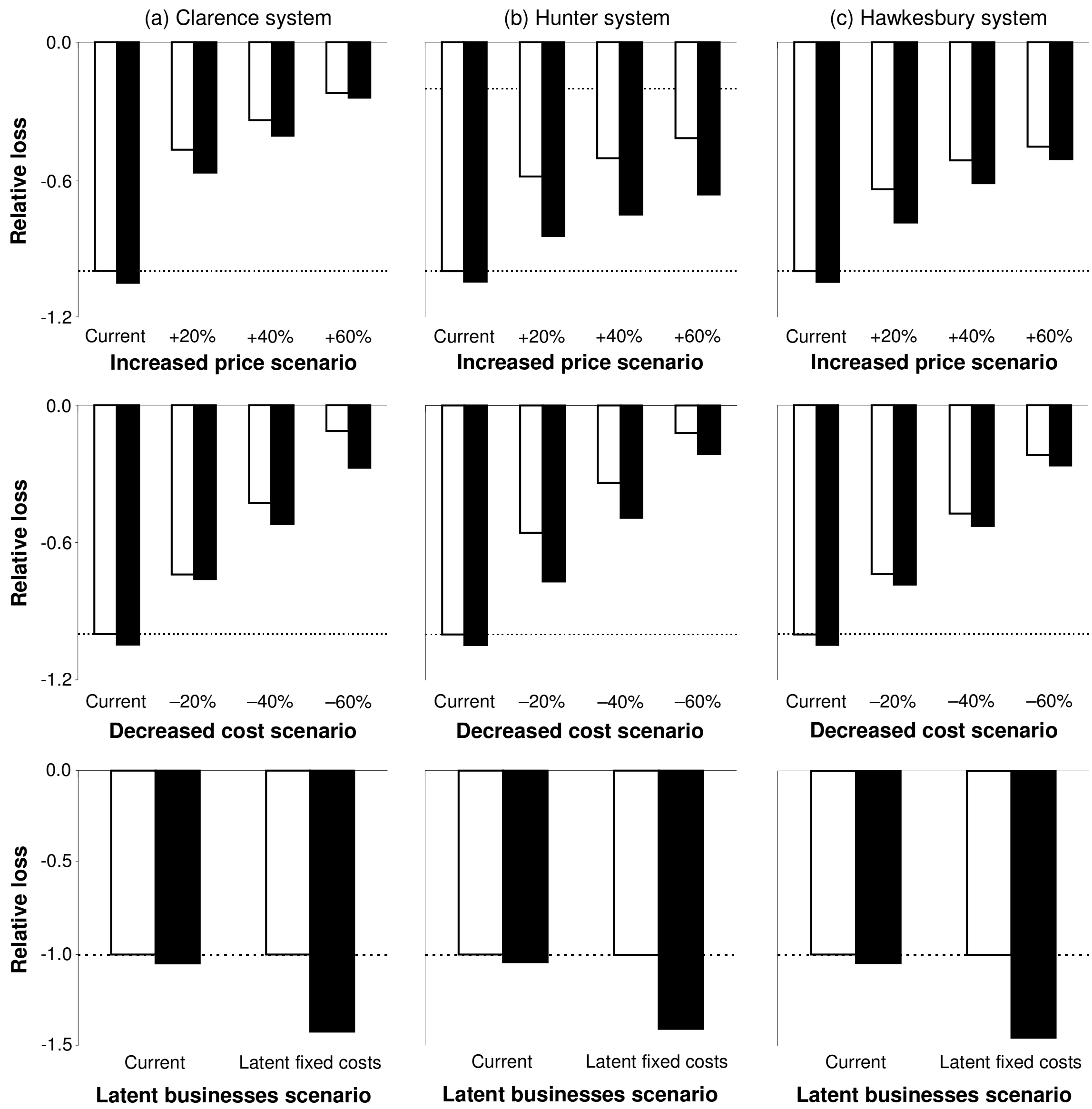

Figure 5-6: Sensitivity analyses indicating the effects of increased market price of seafood, decreased costs and the addition of fixed costs incurred by drought latent businesses on profit during non-drought (white) and drought (black) conditions for the Clarence, Hunter and Hawkesbury systems. Subfigures illustrate relative loss due to changes in market price, costs and fixed costs incurred by drought latent businesses from the non-drought baseline (dotted line). Results presented for a mean monthly cost coefficient of variation of 50%.

5.3.6. Profit and fishing method diversity

Regression models revealed significant negative relationships between mean monthly profit and the Shannon index during non-drought and drought (Figure 5–7). Increased cost-variability was associated with increased coefficients for the significant negative relationship between mean monthly profit and the Shannon index (Table 5–6). Significant interaction terms between the Shannon index and drought declaration ($\bar{H}'_t \times D_t$) were identified for regression models that incorporated mean monthly profit with a 50% (β_1 = 19.98, P = 0.04, df = 116) and 75% (β_1 = -50.15, P < 0.01, df = 116) coefficient of variation of costs in the Clarence system. The fixed effect regression models revealed significant negative coefficients for the relationship between profit and the Shannon index during non-drought and drought.

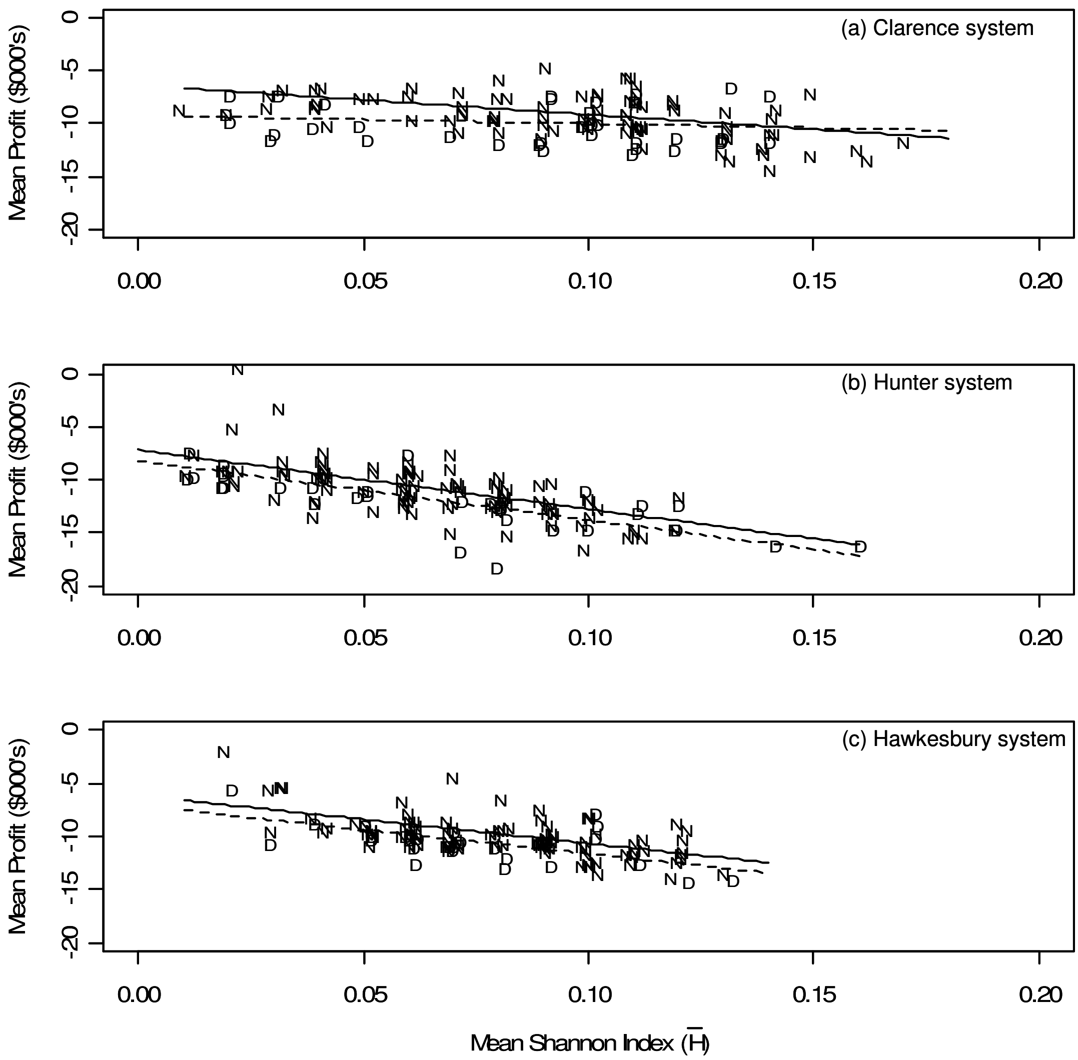

Figure 5-7: Regression models predicting mean monthly profit per business from the mean monthly Shannon index during non-drought (solid line) and drought (dotted line) conditions for the Clarence, Hunter and Hawkesbury systems (statistics for the regression models presented in Table 5–6). Results presented for a mean monthly cost coefficient of variation of 50%. Note that data points associated with non-drought (N) and drought (D) periods have been jittered on linear plots to improve clarity.

Table 5-6: Fitted coefficients for model terms that incorporated $\pi_t \sim \bar{H}'_t + D_t$ for the Clarence (CR), Hunter (HU) and Hawkesbury (HK) systems.

System	C_V model	Term	Estimate of coefficient	SE	P(t)
CR	25%	Intercept	−6.73	0.62	< 0.001
		$\bar{H}'_t$	−21.71	6.06	< 0.001
		D_t	−3.60	1.03	< 0.001
		$\bar{H}'_t \times D_t$	15.90	10.52	**> 0.05**
	50%	Intercept	−5.61	0.57	< 0.001
		$\bar{H}'_t$	−27.75	5.56	< 0.001
		D_t	−2.86	0.95	< 0.01
		$\bar{H}'_t \times D_t$	19.98	9.65	< 0.05
	75%	Intercept	−4.77	1.05	< 0.001
		$\bar{H}'_t$	−10.39	10.28	< 0.01
		D_t	−2.62	1.75	< 0.01
		$\bar{H}'_t \times D_t$	−50.15	17.83	< 0.05
HU	25%	Intercept	−8.50	0.40	< 0.001
		$\bar{H}'_t$	−33.74	5.40	< 0.001
		D_t	−2.43	0.38	< 0.01
		$\bar{H}'_t \times D_t$	15.06	10.83	**> 0.05**
	50%	Intercept	−7.19	0.41	< 0.001
		$\bar{H}'_t$	−55.72	5.64	< 0.001
		D_t	−2.02	0.40	< 0.05
		$\bar{H}'_t \times D_t$	16.44	11.30	**> 0.05**
	75%	Intercept	−4.63	1.09	< 0.001
		$\bar{H}'_t$	−89.92	14.87	< 0.001
		D_t	−2.54	1.06	< 0.01
		$\bar{H}'_t \times D_t$	6.01	30.07	**> 0.05**
HK	25%	Intercept	−7.58	0.40	< 0.001
		$\bar{H}'_t$	−24.43	4.67	< 0.001
		D_t	−2.85	0.28	< 0.01
		$\bar{H}'_t \times D_t$	−6.85	11.07	**> 0.05**
	50%	Intercept	−6.13	0.47	< 0.001
		$\bar{H}'_t$	−45.22	5.50	< 0.001
		D_t	−2.98	0.33	< 0.01
		$\bar{H}'_t \times D_t$	5.59	13.06	**> 0.05**
	75%	Intercept	−2.36	1.32	< 0.01
		$\bar{H}'_t$	−122.20	15.60	< 0.001
		D_t	−2.60	0.94	< 0.01
		$\bar{H}'_t \times D_t$	−9.21	37.04	**> 0.05**

Coefficient details provided for untransformed data from multiple-method months; n = 120; α < 0.05. C_V model indicates the alternative cost-variability scenarios examined. π_t, $\bar{H}'_t$ and D_t refer to the estimated mean profit in month *t*, mean Shannon index in month *t* and drought declaration in month *t*, respectively. Non-significant model terms (P > 0.05) shown in bold.

5.4. Discussion

Examination of fishery-dependant data from commercial fishing businesses revealed a range of patterns in the economic impacts of drought on multi-method inshore fisheries. Results from this study indicate that reductions in freshwater flow due to drought or increased human water extraction are likely to have negative economic impacts on fishing businesses that operate in the estuarine and coastal systems of eastern Australia. Climate change is predicted to increase the frequency and severity of droughts in this region (Hennessy et al. 2007), which will place additional demands on freshwater resources (Kundzewicz et al. 2007). Understanding the patterns in revenues and costs associated with fishing under such conditions has provided insight into the types of fishing businesses that will be more robust to climate change.

Differences in revenue and profit between non-drought and drought were business, method and system specific. Droughts were associated with reductions in the revenue and profit of commercial fishing businesses. Businesses that operated ocean prawn trawls and estuary prawn trawls primarily contributed to significant reductions in revenue and profit during drought. Relationships between revenue (or profit) and fishing method diversity were highly significant ($P < 0.01$), but yielded coefficients of opposite sign (Tables 5–5 and 5–6). Once costs were included into the analyses, the positive revenue-diversity relationship shifted to a negative profit-diversity relationship. This result indicated that fishers altered their harvesting behaviour and operated less profitable methods during drought. Some of the variability underlying differences in revenue and profit between non-drought and drought may be related to factors such as bioregion (Pease 1999), estuarine geomorphology (Saintilan 2004), degree of river regulation within the catchment (Drinkwater and Frank 1994) and the life history of individual species (Robins et al. 2005).

Relatively fewer businesses operated during drought suggesting that fishers temporally sourced income from employment unrelated to commercial fishing. Fishers often engage in alternative employment when income falls below the opportunity cost of fishing (Gordon 1991). A substantial proportion of the businesses examined (20%) supplement income from enterprises (e.g. agriculture, construction and tourism) outside the fishing industry (Dominion Consulting Pty Ltd 2001; 2002a; 2002b; 2004; 2006). Fishers' entry and exit strategies from the fishing industry depend on their economic situation (Opaluch and Bockstael 1984). This sustainable livelihoods approach allows fishers to supplement income from activities unrelated to fishing during periods of resource uncertainty (Allison and Horemans 2006). Income augmentation from employment unrelated to fishing represented an efficient strategy for businesses to economically endure droughts and remain in the fishing industry for the long-term.

Harvesting strategies are driven primarily by the economic outcomes of previous fishing activities (Link and Tol 2006). Alterations to fishing activity were evident between non-drought and drought. Businesses that operated ocean prawn trawling and estuary prawn trawling altered their harvesting behaviour to generate revenue from fish trawls and gillnets during drought. Commercial fishers' in New South Wales modify their harvesting behaviour to opportunistically exploit alterations to the catchability of fishery species that arise during drought (Gillson et al. In Press). Adjustments to harvesting behaviour permit fishers' to target the increased catchability of marine estuarine-opportunist species such as yellowfin bream (*Acanthopagrus australis*) and silver biddy (*Gerres subfasciatus*) during drought.

This study incorporated various assumptions regarding the operational characteristics of fishing businesses. Firstly, determining the costs of businesses that operated in multiple fisheries with multiple-methods was problematic. This issue was resolved by considering maximum costs per business within a fishery and examining alternative cost-variability scenarios. Secondly, the cost model adopted a labour cost function dependent on fishing effort. Fishers' labour costs, however, can fluctuate as a function of income (Charles 1989). This may have inhibited the analyses given that no information on the relationship between fishers' labour costs and income existed. In many cases, the costs may have been lower (and profits higher) due to fishers paying themselves less during low revenue periods. Thirdly, the analyses focused on the economic characteristics of fishing businesses. Harvesting behaviour, however, represents a dynamic combination of socio-economic factors (Salas and Gaertner 2004). Information on social patterns of harvesting behaviour may have improved our understanding of business responses to drought not explained by economics. Fishers often forgo income for lifestyle and autonomy (Dominion Consulting Pty Ltd 2001; 2002a; 2002b; 2004; 2006). Fourthly, fishing behaviour can be associated with other demographic and socio-economic factors (e.g. age, educational status and housing tenure) not considered in this study. These additional dimensions to the characteristics of commercial fishing operations could generate contrasting results to those presented here. Despite the various assumptions, this study provided a relative indication of the economic impacts of drought on commercial fishing businesses and revealed the economic role of fishing method diversity under circumstances of climatic variability.

5.4.1. Revenue between non-drought and drought conditions

Mean monthly revenue was significantly lower during drought (Figure 5–2). Ocean prawn trawling and estuary prawn trawling exhibited the most pronounced reductions in revenue. This result was not surprising given that positive relationships between freshwater flow and commercial landings of penaeid prawns have been reported in eastern Australia (Loneragan and Bunn 1999; Robins et al. 2005; Ives et al. 2009). Increased freshwater flow results in the increased catchability of penaeid prawns due to reductions in salinity enhancing emigration rates from estuarine to coastal systems (Racek 1959; Ruello 1973; Glaister 1978). Reductions in revenue from ocean prawn trawling and estuary prawn trawling during drought resulted from decreased landings of penaeid prawns rather than market price fluctuations. Variation in the market price of eastern king prawns and school prawns was relatively low ($C_V \geq 19\%$) compared to landings ($C_V \geq 55\%$) from prawn trawlers. Future reductions in freshwater flow due to droughts are projected to decrease commercial landings of penaeid prawns in eastern Australia (Ives et al. 2009). Results from this study indicated that decreased landings of penaeid prawns during drought reduced revenue generation from fishing businesses that operated ocean prawn trawling and estuary prawn trawling.

Gillnets and hauling nets provided a relatively smaller contribution to decreased revenue during drought. Sea mullet dominated revenue generation from gillnets (≥ 45%) and hauling nets (≥ 65%) providing the greatest contribution to decreased revenue from these methods during drought. Positive relationships between freshwater flow and landings of sea mullet have been reported in eastern Australia (Gillson et al. 2009). Increased freshwater flow results in the increased catchability of sea mullet due to reduced salinity stimulating migration and schooling into alternative habitat. Decreased landings of sea mullet during drought primarily reduced revenue generation from fishing businesses that operated gillnets and hauling nets.

Decreased revenue during drought can to some extent be compensated by diversifying harvesting behaviour to increase revenue generation (Figure 5–3). Businesses that harvested with multiple fishing methods possessed an inherent flexibility to generate revenue from a range of species. Diverse harvesting strategies represent a form of economic resilience for fishers during periods of resource uncertainty (Hilborn et al. 2001). Commercial fishers recognise that diverse harvesting strategies increase revenue generation due to extensive practical experience. A bet-hedging component to harvesting strategies was indicated by high Shannon index values. Fishers may employ bet-hedging harvesting strategies to minimise fishing effort and maximise revenue generation. Detection of diminishing returns indicated that diverse harvesting strategies only maximised revenue generation to a degree. Rates of revenue generation decreased when businesses operated beyond a certain number of methods. The number of methods required to saturate revenue generation was five or less in the Clarence system and two or less in the Hunter and Hawkesbury systems.

5.4.2. Profit between non-drought and drought conditions

Many businesses exhibited losses due to costs frequently exceeding revenue (Figure 5–4). Businesses were not expected to generate large profits given that the estuary general, estuary prawn trawl and the ocean trap and line fisheries frequently operate at an economic loss (Dominion Consulting Pty Ltd 2001; 2002a; 2002b; 2004; 2006). Modelled estimates of losses under alternative cost-variability scenarios were consistently greater (≥ 5%) during drought (Figure 5–5). Increased cost-variability was generally associated with decreased mean losses. It should be noted that the cost component of this analysis required more assumptions than the revenue component therefore the conclusions drawn from the latter are more qualified. Furthermore, the cost data were not originally collected for the purposes to which they were applied here. Nevertheless, examination of costs and profits associated with fishing activity was fundamentally important to this analysis as presentation of the revenue results in isolation could have lead to a misinterpretation of the value of method diversification in these fisheries.

A full sensitivity analysis of the key assumptions in the cost model has been provided. Sensitivity analyses indicated that increased market prices of seafood and decreased costs reduced losses during non-drought and drought (Figure 5–6). Businesses on average, moved to profit when market prices and costs were increased or decreased, respectively, by ≥ 80%. Once fixed costs incurred by latent businesses were factored into profit models, losses increased considerably (≥ 40%) during drought. This result highlighted the importance of incorporating fixed costs incurred by latent fishing businesses into profit models to provide a better understanding of the economic impacts of drought on commercial fisheries.

Diversified harvesting behaviour appeared to decrease profitability due to businesses incurring higher costs with increased fishing method diversity (Figure 5–7). Harvesting strategies represent an economic trade-off between revenue generation and the cost of fishing activities (Sampson 1991). Businesses that operated multiple fishing methods employed an economic risk-reduction strategy that may have been compromised by higher costs. A bet-hedging component to harvesting strategies was indicated by high Shannon index values. Fishers may adopt bet-hedging harvesting strategies to minimise costs and maximise revenue. Increased cost variance was associated with decreasingly negative coefficients for the relationship between profit and fishing method diversity (Table 5–6). Significant interaction terms between the Shannon index and drought declaration revealed that interpretation of the relationship between profit and drought changed with fishing method diversity in the Clarence system. This result indicated that freshwater flows, method diversification and economic factors all need to be considered to better understand the impact of climate change on the economic performance of commercial fisheries.

5.5. Conclusions

Droughts redistributed revenue and probably profit among fishing methods, modifying the economic performance of commercial fishing businesses operating in estuarine and coastal fisheries in NSW. Reductions in revenue and profit were most pronounced for businesses that operated ocean prawn trawls and estuary prawn trawls during drought. Modelled estimates of profit were dependent on costs incurred by businesses that operated in multiple fisheries. Although diversification of harvesting behaviour can function as a risk-reduction strategy for fishers during periods of resource uncertainty (Hilborn et al. 2001), this phenomenon was only marginally evident for commercial fishing businesses in eastern Australia. Diversified harvesting behaviour increased revenue generation, but this marginal economic benefit was compromised by higher costs associated with increased diversification which lowered profitability.

If drought conditions are so severe and protracted that they are considered beyond the bounds of normal risk management, then the Australian Federal Government may declare an area as experiencing “drought exceptional circumstances” (White and O'Meagher 1995; White and Karssies 1999; Botterill 2003). Declaration of drought exceptional circumstances qualifies agricultural producers in these areas to apply for financial assistance from the federal, state and/or territory government. Commercial fisheries, however, are rarely eligible for such assistance given that businesses cannot readily demonstrate that drought results in an economic downturn. The findings presented here indicate that the commercial fishing sector is a drought-affected industry in coastal NSW.

Fishers in NSW would benefit from diversifying their employment outside the commercial fishing industry to maintain net incomes during drought. Alterations to the economic performance of commercial fishing businesses during drought have important implications for the management of multi-method inshore fisheries in a changing climate. However, a more complete understanding of the coupled socio-economic impacts of drought on commercial fishing businesses is essential when considering the wider implications of climate change on estuarine and coastal fisheries.

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General Discussion

6.1. Summary of research findings

Freshwater flow has a profound effect on fisheries production in estuarine and coastal systems (Grimes 2001; Erzini 2005; Möller et al. 2009). Despite well established connections between freshwater flow and fisheries production (Caddy and Bakun 1995), underlying mechanisms remain poorly understood. The research presented in this thesis examined the impacts of freshwater flow on the production and profitability of estuarine and coastal fisheries. This thesis provides empirical evidence that freshwater flow impacts fisheries production by regulating the availability of fisheries resources, modifying fishers' harvesting behaviour and influencing the economic performance of commercial fisheries in estuarine and coastal systems.

Initially the research process began by reviewing the ecological and socio-economic impacts of freshwater flow on estuarine and coastal fisheries, with particular emphasis on regional examples from eastern Australia and southern Africa. Chapter 2 indicates that freshwater flow affects fisheries production by regulating environmental factors that determine habitat availability, trophic interactions and fishers' harvesting behaviour in estuarine and coastal systems. This chapter reveals that information on the socio-economic impacts of variable flows on commercial fisheries is required to resolve some of the outstanding problems in determining the freshwater requirements of estuarine and coastal systems.

Chapter 3 examined relationships between hydrological variation and the commercial catch-per-unit-effort (CPUE) of five estuarine-associated fish species in nine permanently open estuaries between 1997 and 2007. Findings from this chapter indicate a surprising number of relationships between freshwater flow and CPUE. Freshwater enhancement of fisheries production was evident, with increased CPUE in months with higher flow for all but one species. Minimum and maximum flows were important determinants of CPUE. Freshwater flow *per se* was not as important in determining CPUE as episodic flow events. Episodic flow events are pulse disturbances that maintain and enhance biological productivity in estuarine and coastal systems (Flint 1985; Martin et al. 1992; Dolbeth et al. 2008). Seasonal flows were consistently the most important aspect of the flow regime that explained the highest proportion of variation in CPUE. Seasonal freshwater pulses proximate to reproductive periods may influence catchability by triggering seaward spawning migrations in estuarine-associated fish (Loneragan and Bunn 1999; Robins et al. 2005; Balston 2009). Results indicate that freshwater flow influenced CPUE through changes in the recruitment and catchability of estuarine-associated fish. Freshwater flow may affect CPUE by stimulating migration and schooling in estuarine-associated fish due to salinity fluctuations altering the availability of habitat (Stevens and Miller 1983; Loneragan and Bunn 1999; Robins et al. 2005).

Chapter 4 used the insights gained from the previous chapter to explore the impacts of episodic flow events on estuarine and coastal fisheries. Multivariate patterns in commercial fisheries landings, effort and revenue from three adjacent estuarine and coastal systems were examined between nine-month periods of flood and drought. Flood and drought events were associated with shifts in the species composition of landings that were reciprocated between estuarine and coastal systems. Species that dominated estuarine landings during drought subsequently dominated coastal landings during flood. Estuarine migrant species (e.g. school prawn *Metapenaeus macleayi*) primarily contributed to landings during flood, while marine estuarine-opportunist species (e.g. yellowfin bream *Acanthopagrus australis*) primarily contributed to landings during drought. Significant differences in landings and revenue between flood and drought were attributed to a mixed-signal of ecological response and fishers' harvesting behaviour. Results indicate that flood and drought events influence the bio-economic productivity of commercial fisheries by modifying the species composition of landings, fishers' harvesting behaviour and revenue generation.

The economic impacts of drought events on estuarine and coastal fisheries were further investigated in Chapter 5. A multi-species, multi-method bio-economic analysis was performed to evaluate the economic performance of fishers' harvesting strategies between non-drought and drought conditions in three adjacent estuarine and coastal systems. Sensitivity analyses were used to evaluate the robustness of profit outputs under alternative cost and revenue scenarios. Projections from the model indicate that droughts redistribute revenue and profit among fishing methods, modifying the economic performance of commercial fishing businesses. Reductions in revenue and profit were most pronounced for businesses that operated ocean prawn trawls and estuary prawn trawls during drought. This result was not surprising given that increased freshwater flow enhances valuable penaeid prawn production in eastern Australia (Loneragan and Bunn 1999; Robins et al. 2005; Ives et al. 2009). Although diversified harvesting behaviour can function as a risk-reduction strategy for fishers during periods of resource uncertainty (Hilborn et al. 2001), this phenomenon was only marginally evident for commercial fishing businesses in NSW. Diversified harvesting behaviour increased revenue generation, but this marginal economic benefit was compromised by higher costs associated with increased diversification which lowered profitability. Fishers would benefit from diversifying their employment outside the commercial fishing industry to maintain net incomes during drought. Results indicate that the commercial fishing sector is a drought-affected industry in coastal NSW.

Findings from this thesis have extended our understanding of the impacts of freshwater flow on estuarine and coastal fisheries from a primarily ecological perspective to incorporate a socio-economic component. Freshwater flow influences the availability of fisheries resources by modifying the distribution and abundance of fish and invertebrates, which in turn produces cascading effects on fishers' harvesting behaviour and the economic performance of commercial fisheries in estuarine and coastal systems (Grimes 2001; Erzini 2005; Lamberth et al. 2009). One of the key findings from this thesis is that reductions in freshwater flow due to droughts significantly reduce the production and income of estuarine and coastal fisheries in NSW. This finding provides empirical support for the previously anecdotal claim by commercial fishers in NSW that a "drought on land is a drought in the sea." Commercial fishers' that diversified their harvesting behaviour during drought experienced increased losses of income due to businesses incurring higher costs with increased fishing method diversity. The Australian Governments may therefore want to reconsider the eligibility of commercial fishing businesses for financial assistance once an area surrounding an estuarine or coastal fishery has been declared as experiencing drought exceptional circumstances.

Commercially harvested fish and invertebrates that exhibit varying degrees of estuarine dependency are influenced by variation in freshwater flow (Grimes 2001; Erzini 2005; Lamberth et al. 2009). Significant positive relationships between monthly freshwater flow and CPUE for four out of five fish species were identified in Chapter 3. These findings have important implications for water resource managers — they demonstrate that freshwater is not 'lost' when it enters estuarine or coastal systems but plays an important role in the bio-economic processes that constitute commercial fisheries. Ensuring the delivery of freshwater into estuarine and coastal systems is essential to minimise the impacts of drought, river regulation and human water extraction on fish and invertebrates (Whitfield and Bruton 1989; Sklar and Browder 1998; Gillanders and Kingsford 2002). Results from this thesis indicate that changes in freshwater flow have the most pronounced impacts on species (e.g. school prawn and sea mullet) that dominate commercial fisheries harvest. Protecting natural variation in freshwater flow is likely to be the most reliable management strategy to maintain the production of estuarine and coastal fisheries (Loneragan and Bunn 1999; Robins et al. 2005; Baisre and Arboleya 2006).

Anthropogenic modification of freshwater flow is one of many concerns expressed about the impacts of human activities and environmental change on estuarine and coastal systems. Other concerns include the overexploitation of fisheries resources (Cooke and Cowx 2006), changing land use practices (Harris 2001), coastal erosion (Mazda et al. 2002), nutrient enrichment (Rabalais et al. 2009), pollution (Howarth 2008), acidification (Sammut et al. 1995), species invasions (Preisler et al. 2009), and climate change (Harley et al. 2006).

Management strategies concerned with allocating freshwater with the objective of maintaining the ecological integrity of estuarine and coastal systems are faced with a complex dilemma. Appropriation of freshwater for municipal, industrial and agricultural uses has long taken precedence over the needs of aquatic ecosystems (Baron et al. 2002). Controversy continues to surround the decision-making processes of water resource managers, particularly where the needs of aquatic ecosystems compete directly with more established freshwater uses for agriculture and industry (Bouwer 2000). A continuing challenge faced by decision-makers is to manage the trade-offs associated with allocating freshwater to different users (Loucks 2000). Comparing the economic value that could be obtained from allocating one litre of freshwater to different users is regarded as an essential selection criterion for decision-makers by Ward (2007). Under these criteria, estuarine and coastal fisheries are unlikely to be well represented for allocations of freshwater, which will instead be provided in greater quantities to more economically productive users such as agriculture and industry. Integrated water resource management strategies implement a diverse range of tools to evaluate ecological and societal needs for freshwater (Falkenmark 2003). Frameworks for the equitable allocation of freshwater are shifting towards solutions that do not focus solely on economic criteria but also incorporate social, ecological and ethical perspectives (Wallace et al. 2003).

Ecological and societal needs for freshwater must be addressed collectively with all interested parties working together for a mutually acceptable future (Baron et al. 2002). However, most projects concerned with allocating freshwater to aquatic ecosystems require the co-operation of many organisations that are not likely to have the sustainability and profitability of estuarine and coastal fisheries as their highest priority. Fisheries scientists and managers must therefore continue to emphasise the important role of freshwater flow in maintaining the productivity of estuarine and coastal fisheries. Only then will the interests of estuarine and coastal fisheries be duly represented in decision-making processes associated with the allocation of freshwater. Managing the delivery of freshwater into estuarine and coastal systems is not an easy task given that there is limited information on reference states in these highly dynamic environments. One issue that requires consideration is whether the benefits of allocating freshwater to maximise fisheries production will be offset by resultant increases commercial and recreational fishing pressure. Both freshwater resources and fisheries resources must be simultaneously managed to meet societal expectations for the protection and restoration of estuarine and coastal systems.

6.2. Future research directions

Although the work completed for this dissertation demonstrates that freshwater flow impacts the production and profitability of estuarine and coastal fisheries, further research is needed to explore the generality of these findings for other species and systems. The research presented here provides a heuristic model for studies that wish to examine the impacts of freshwater flow on the production and profitability of estuarine and coastal fisheries in the future. I urge future studies to comparatively analyse relationships between freshwater flow and fisheries production in a range of estuarine and coastal systems with differing geomorphologies, distinct freshwater inputs and varying degrees of river regulation. Comparative studies are needed to provide an improved understanding of the mechanisms underlying relationships between freshwater flow and fisheries production.

One important avenue of investigation not considered in this thesis is to examine the impacts of freshwater flow on recreational fisheries that operate in estuarine and coastal systems. Positive relationships between freshwater flow and catches of Australian bass (*Macquaria novemaculeata*) from recreational fishing competitions have been reported in the Hawkesbury River on the east coast of Australia (Growns and James 2005). Studies such as these are required to provide a more unified understanding of the impacts of freshwater flow on fisheries resources in estuarine and coastal systems. In future, studies could examine relationships between freshwater flow, recreational landings and the harvesting behaviour of anglers.

A lack of freshwater flow data precluded the examination of relationships between freshwater flow and fisheries production in a greater range of estuarine and coastal systems. An important recommendation therefore would not be for more fisheries data, but rather for more freshwater flow data. Accurate historical information on freshwater flowing into estuarine and coastal systems is not readily available in NSW. Freshwater flow can be measured by river gauges, derived from proxies (e.g. rainfall and river height) and estimated using hydrological modelling (e.g. the Integrated Quantity and Quality Model, IQQM). An important component of future studies is to identify alternative hydrological variables (e.g. rainfall, groundwater discharge and river height) that can be used as surrogate measures of freshwater flow. If direct measurements of hydrological variables do not exist, freshwater flow could be estimated indirectly using satellite remote sensing imagery (e.g. All 2006).

6.2.1. Ecological research

A number of profitable directions can be pursued by studies concerned with ecological mechanisms underlying relationships between freshwater flow and fisheries production. One potential criticism of the research presented here is the isolated use of fishery-dependent data. Studies need to use a combination of fishery-dependent and fishery-independent data to examine potential ecological mechanisms. Fishery-independent data from appropriately designed field surveys minimises potential biases associated with data from commercial fishers (e.g. spatio-temporal changes in fishing activity). Our results identified that the highest correlation coefficients (r^2) between freshwater flow and CPUE coincided with the spawning periods of estuarine-associated fish (Chapter 3). Acoustic telemetry could be used to confirm whether seasonal pulses of freshwater trigger seaward spawning migrations in estuarine-associated fish. Results from Chapter 4 suggested that flood and drought events modify species exchange between estuarine and coastal systems. Another important avenue of investigation could also include examining the migration patterns of fish in estuarine and coastal systems during periods of flood and drought using otolith chemistry analysis. Investigating differences in the chemical composition (e.g. Mg, Mn, Sr and Ba concentrations) of fish otoliths has enabled identification of the movements of snapper (*Pagarus auratus*) between estuarine and coastal systems in eastern Australia (Gillanders 2002).

One of the main challenges for studies is to unravel the effects of variable flows on habitat availability and trophic dynamics. Manipulative experiments that systematically alter freshwater flow have been suggested to identify potential ecological mechanisms (e.g. Bunn and Arthington 2002), but this is not a practical solution due to the improbable likelihood of gaining stakeholder consensus for such an approach. Studies need to use a combination of techniques to separate the effects of freshwater flow on habitat availability and trophic dynamics. Firstly, studies could examine relationships between freshwater flow, salinity (as a proxy of habitat availability) and the catch rates of fish and invertebrates (e.g. Jassby et al. 1995). Secondly, stable isotope analysis could be employed as a complementary technique to measure the contribution of nutrient-enriched freshwater to benthic and pelagic food webs (e.g. Darnaude 2005). An important issue that requires consideration is how reliant a food web is on freshwater flow to supply terrestrially-derived nutrients and organic matter. Future studies could comparatively assess the origin of carbon assimilated into food webs from a range of estuarine and coastal systems that receive heterogeneous supplies of nutrients from riverine inputs, oceanic currents and upwelling events using stable isotope analysis. Another area of potential research is determining whether droughts facilitate freshwater enhancement of fisheries production by allowing nutrients and organic matter to accumulate in terrestrial soils before being leached into estuarine and coastal systems by heavy rainfall.

Freshwater flow can influence the early-life history stages of estuarine-dependent fish (Kimmerer et al. 2001; Le Pape et al. 2003; Purtlebaugh and Allen 2010). Although Chapter 3 identified relationships between freshwater flow and the CPUE of estuarine-associated fish lagged by age at first maturity, this provided limited information on possible recruitment effects. In future, studies could investigate the effects of freshwater flow on recruitment by examining relationships between seasonal flows and the year-class strength of juvenile fish in estuarine nursery grounds using otolith ageing techniques. Similar methods have been successfully used to identify positive relationships between seasonal flows and the recruitment of juvenile barramundi (*Lates calcarifer*) and king threadfin (*Polydactylus macrochir*) in the Fitzroy River estuary in eastern Australia (Staunton-Smith et al. 2004; Halliday et al. 2008).

6.2.2. Investigating fishers' harvesting behaviour

Results from Chapter 4 revealed the importance of fishers' harvesting behaviour in driving relationships between freshwater flow and fisheries production. One problem with using commercial CPUE as an index of fisheries production is that changes in fishers' harvesting behaviour can maintain catch rates even when fish abundance is low (Arreguín-Sánchez 1996; Salthaug and Aanes 2003; Ellis and Wang 2007). Some factors that are known to influence catch rates independently of fish abundance are changes in the efficiency of a fishing fleet, fishers' knowledge, species targeting practices, fish behaviour and environmental conditions (Maunder et al. 2006). Studies therefore should place more emphasis on understanding the influence of freshwater flow on the temporal and spatial distribution of fishing effort in estuarine and coastal systems. Some caution, however, should be exercised when interpreting relationships between freshwater flow and fishing effort in multi-method fisheries. Comparisons among fishing methods are often difficult to make due to the inherent complexities in obtaining accurate measurements of fishing effort (Shepherd 2003). Nevertheless, significant differences in fishers' harvesting behaviour between flood and drought events were identified by examining multivariate patterns in fishing effort (Chapter 4). Univariate analysis of fishing effort also enabled identification of significant differences in fishers' harvesting behaviour between non-drought and drought conditions (Chapter 5). One hypothesis that requires further investigation is that variation in freshwater flow prompts commercial fishers' to adjust their harvesting behaviour to exploit changes in the catchability of fish and invertebrates. Our analyses could be extended to test this hypothesis by examining relationships between freshwater flow, species' catchability and the allocation of effort among fishing methods.

6.2.3. Socio-economic considerations

The bio-economic analysis presented in Chapter 5 could be improved in a number of areas. Firstly, a diminishing labour cost function that depends on revenue generation could be incorporated into cost models. Secondly, supply and demand functions could be generated to provide fishers with more power over prices, such as holding (freezing) stock for periods of lower catch and higher product prices. Thirdly, given that many fishing businesses were operating at an economic loss, some benefit could be gained from assessing the appropriate number of operators within each fishery during periods of flood and drought. Finally, some estuarine and coastal fisheries may not fit the conventional economic paradigm given that profitability is not always the primary driver of fishing activity. In NSW, for example, commercial fishers often forgo income for lifestyle and autonomy (Dominion Consulting Pty Ltd 2001; 2002a; 2002b; 2004; 2006). Information on social patterns of harvesting behaviour may have improved our understanding of fisher responses to drought not explained by economics. Future studies should not focus solely on the economic impacts of variable flows on commercial fisheries, but adopt a more holistic approach by incorporating social patterns of harvesting behaviour into analyses of fisheries data.

Chapter 5 indicated that fishers in NSW would benefit from diversifying their employment outside the commercial fishing industry to maintain net incomes during drought. However, enterprises outside the commercial fishing industry that generate a steady stream of income for commercial fishers during drought remain largely unexplored. Studies could identify alternative employment opportunities that maximise income generation for commercial fishers during drought. These studies would provide important information for risk management strategies concerned with maximising the profitability of estuarine and coastal fisheries during periods of economic uncertainty.

6.2.4. Fisheries modelling

Predictions of the bio-economic impacts of climate change on estuarine and coastal fisheries are required by managers and policy makers to develop mitigation and adaptation strategies (Adger et al. 2005; Allison et al. 2009; Brander 2010). Simulation models could be developed to explore management strategies that minimise the bio-economic impacts of future changes in freshwater flow on estuarine and coastal fisheries. Modelling represents an appropriate technique to analyse the effectiveness of different management strategies in maintaining the production and profitability of estuarine and coastal fisheries under alternative freshwater flow scenarios. Freshwater flow scenarios could be based on regional estimates from the scientific literature or modelled projections for individual river systems. Sensitivity analyses would need to be performed to examine the key assumptions in the simulation models. Similar modelling techniques have been successfully used to examine the effectiveness of management strategies in mitigating the impacts of climate change on penaeid prawn fisheries in eastern Australia (Ives et al. 2009).

6.3. Conclusions

Examination of commercial fisheries and hydrological datasets from a range of estuarine and coastal systems revealed the impacts of freshwater flow on the production and profitability of estuarine and coastal fisheries. The research presented here demonstrates that freshwater flow regulates the availability of fisheries resources, modifies fishers' harvesting behaviour and influences the economic performance of commercial fisheries in estuarine and coastal systems. Flood and drought events have the most pronounced impacts on estuarine and coastal fisheries in eastern Australia due to extreme variability in freshwater flow modifying the species composition of landings, commercial fishing activity and revenue generation.

Understanding the impacts of freshwater flow on the production and profitability of estuarine and coastal fisheries is a multifaceted problem. Many abiotic and biotic processes generate uncertainty in fisheries bio-economics over different temporal and spatial scales (Seijo and Caddy 2000). Despite ongoing uncertainty in fisheries bio-economics, the analyses in this dissertation should be useful to those concerned with the management of fisheries and water resources. Even if stakeholders do not accept all of the conclusions from these analyses, the work still provides valuable background and insight that should inform debate and future policies.

Conflicts over the management of freshwater resources are increasingly emerging throughout the world (Poff et al. 2003). If climate change modifies the frequency and intensity of rainfall, it is likely that significant changes to estuarine and coastal fisheries will occur. Although knowledge regarding the freshwater requirements of estuarine and coastal systems is far from complete (Montagna et al. 2002), we understand enough about these systems to minimise the impacts of river regulation and human water extraction on populations of fish and invertebrates. An improved understanding of the freshwater requirements of estuarine and coastal systems will only emerge once studies embrace a more comprehensive approach by considering the ecological and socio-economic impacts of variable flows. This approach will provide fisheries and water resource managers with a better understanding of the consequences of altering the delivery of freshwater into estuarine and coastal systems.

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