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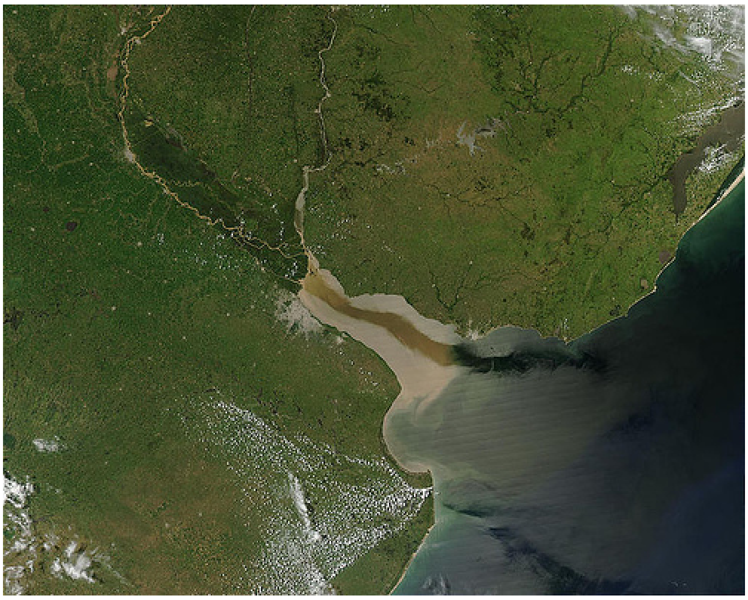
Impacts of freshwater flow on catch rates of estuarine fisheries resources in New South Wales

by
J.P. Gillson, J.P. Scandol and I.M. Suthers



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Fisheries research activities in the NSW Department of Primary Industries are based at various centres throughout the state.

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The major role of the research is to provide information upon which relevant fisheries management policies and strategies are developed, monitored and assessed in terms of the Department's obligations under the NSW *Fisheries Management Act*, 1994.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

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EXECUTIVE SUMMARY

Impacts of freshwater flow on catch rates of estuarine fisheries resources in New South Wales

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OBJECTIVES:

(a) Examine the relationships between drought declaration, rainfall, river discharge and the catch rates of estuarine-dependent fish.

(b) Investigate aspects of the freshwater flow regime that were most important in determining the catch rates of estuarine-dependent fish.

EXECUTIVE SUMMARY:

Conflicts have arisen over the allocation of freshwater for environmental and human needs in eastern Australia. The freshwater flow requirements of estuarine fisheries remain poorly understood. An improved understanding of the role of freshwater in maintaining estuarine fisheries production is essential to appreciate the impacts of climate change and environmental flow regulations.

Nine estuaries in NSW with distinct freshwater inputs (three estuaries each with high, medium and low riverine inflow) and varying degrees of freshwater regulation were selected to investigate the impacts of freshwater flow on fisheries production. The estuaries were the lower reaches of the Clarence River, the Hunter River, the Hawkesbury River, Camden Haven River, Wallis Lake, Port Stephens and Myall Lakes, Tuggerah Lakes, Lake Illawarra, and St. Georges Basin. All estuaries were officially “drought declared” at various times during the study period from 1997 to 2007. Monthly gill netting catch rates (termed catch per unit effort, CPUE) were used to infer the abundance of five commercially important estuarine-dependent fisheries species: bream (*Acanthropagrus australis/Acanthropagrus butcheri)*, dusky flathead (*Platycephalus fuscus*), luderick (*Girella tricuspidata*), sand whiting (*Sillago ciliata*) and sea mullet (*Mugil cephalus*).

Drought declaration was associated with reductions in monthly aggregated CPUE in all examined estuaries, except Tuggerah Lakes and Lake Illawarra, which have low riverine inflow. Impacts of drought on fisheries production are likely to be dependant upon the level of freshwater input into an estuary. Monthly CPUE for all examined species, except bream, increased during times of high freshwater flow and decreased during periods of drought declaration. These relationships may be driven by changes in catchability resulting from alterations in habitat availability due to fluctuations in salinity and turbidity. Bream may respond negatively to high freshwater flows due to the seaward displacement of preferred habitat. Alterations to freshwater flow were also linked to the recruitment success of estuarine-dependent fish, as indicated by relationships (positive and negative) between CPUE and freshwater flow lagged by a period equalling the appropriate age when dusky flathead (3 years), luderick (4 years), sand whiting (3 years) and sea mullet (3 years) recruit to the fishery.

Minimum and maximum monthly flows were important determinants of fisheries CPUE. Freshwater flow *per se* may not be as important in determining fisheries production as extremes in the hydrological continuum. Extreme flow events may enhance fisheries production by resulting in increased catchability due to stimulating migration and schooling into areas where fish are more readily caught. Seasonal flows were the most important aspect of the flow regime that best explained fisheries CPUE. Ensuring the delivery of flows in proximity to spawning periods may be particularly important for maintaining estuarine fisheries production.

While riverine enhancement of estuarine fisheries production seems clear, the exact mechanisms through which this occurs are not. Estuarine fisheries production may be influenced by variation in freshwater flow via changes in recruitment and catchability. Further research is required to provide an improved understanding of how freshwater flow produces such a marked influence on estuarine fish communities.

1. INTRODUCTION

1.1. Background

Estuaries are of major economic, social and environmental value (Costanza *et al*. 1997). They are highly productive ecosystems (Schelske and Odum 1961), which make a significant contribution to the global carbon balance (Smith and Hollibaugh 1993). Many organisms are dependent upon estuaries during part of their lifecycle. Estuaries may constitute important spawning areas, nursery grounds, feeding habitats and migration routes for many species of fish (Potter *et al*. 1990, Blaber 1997, McLusky and Elliot 2004). Increasing pressure from human activities and environmental change threatens their ecological health (Lotze *et al*. 2006). The importance of estuaries is increasingly recognised and is strongly emphasized in policy, planning and legislation throughout the world (Cochrane 2000, Ormerod 2003, Koehn 2004).

Seasonal and interannual changes in community composition can occur in estuaries with shifts in the relative abundance of marine and freshwater fish due to variation in freshwater flow (Tzeng and Wang 1993, Ter Morshuizen *et al*. 1996, Potter and Hyndes 1999, Kanandjembo *et al*. 2001). Freshwater flow can be regarded as a "master variable" (Power *et al*. 1995) influencing estuarine geomorphology and water physicochemistry (Reddering 1988, Grimes and Kingsford 1996, Eyre 1998, Roy *et al*. 2001). Numerous studies have emphasised that freshwater flow has a pivotal role in determining estuarine fisheries production (e.g., Schlacher and Wooldridge 1996, Livingston 1997, Grimes 2001, Lloret *et al*. 2004, Robins *et al*. 2005, Meynecke *et al*. 2006). Fisheries-flow relationships have been reported for more than 45 estuarine or near-coastal fishery species worldwide (Table 1). Despite consistent links between freshwater flow and estuarine fish communities, underlying causal mechanisms remain poorly understood (Livingston *et al*. 1997). Various mechanisms have been proposed: (i) physical changes in habitat availability (Kimmerer 2002, Gillanders and Kingsford 2002); (ii) increased catchability due to migration and schooling (Loneragan and Bunn 1999); (iii) trophic cascades resulting from nutrient enrichment increasing primary and secondary production (Copeland 1966, Aleem 1972, Livingston *et al*. 1997, Tsai *et al*. 1998, Loneragan and Bunn 1999, Salen-Picard *et al*. 2002); and (iv) alterations to fish population dynamics during the first year of life (Quiñones and Montes 2001, Salen-Picard *et al*. 2002, Halliday *et al*. 2008, Ferguson *et al*. 2008).

The ecological health of estuaries depends upon a sufficient amount of freshwater flow (Whitfield and Wooldridge 1994). There is still a false perception that freshwater is 'lost' when it enters estuaries or coastal systems (Loneragan and Bunn 1999, Gillanders and Kingsford 2002, Whitfield 2005). Particular concern has been expressed about the impacts of reduced freshwater flow into Australian estuaries (McPhail and Young 1992, Zann 1996, Pierson *et al*. 2002, Robins *et al*. 2005, Scheltinga *et al*. 2006). Under drought conditions, freshwater flow can cease into estuaries causing the mouth to close, thus preventing marine-estuarine interactions (Cooper 1994). Droughts may have deleterious effects on estuarine biota (Copeland 1966). Freshwater-deprived estuaries can become "arms" of the sea with high axial salinity and poor water quality (Gasith and Resh 1999, Mackay and Cyprus 2001, Scharler and Baird 2005). Nevertheless, there is no available information on the impacts of drought on estuarine fisheries production in NSW.

This project examined the impacts of freshwater flow on fisheries landings using effort-adjusted data from gill netting to infer the abundance of five commercially important estuarine-dependent fisheries species in NSW. Accordingly, the objectives were to: (i) examine the relationships between drought declaration, rainfall, river discharge and the catch rates of estuarine-dependent fish from 1997 to 2007; and (ii) investigate aspects of the freshwater flow regime that were most important in determining the catch rates of estuarine-dependent fish.

Table 1. Examples of significant relationships between freshwater flow (or rainfall) and estuarine fisheries production.

Species	**Location**	**Relationship**	**Reference**
Banana prawns (*Penaeus merguiensis*)	Gulf of Carpentaria, Australia	Positive	Vance *et al*. 1985, 1998
School prawn (*Metapenaeus macleayi*)	Hunter and Clarence Rivers, Australia	Positive	Ruello 1973, Glaister 1978
Brown shrimp (*Penaeus aztecus*)	Texas, USA	Positive	Powell *et al*. 2002
White shrimp (*Penaeus sertiferus*)	Texas, USA	Positive	Powell *et al*. 2002
Shrimp (*Litopenaeus styllrostris*)	Gulf of California, Mexico	Positive	Galindo-Bect *et al*. 2000
Pink shrimp (*Penaeus duorarum*)	Gulf of Mexico, USA	Positive	Browder 1985, Browder *et al*. 2002
Lobster (*Homarus americanus*)	Gulf of St. Lawrence, Canada	Positive	Sutcliffe 1973
Blue crab (*Callinectes sapidus*)	Florida and Texas, USA	Positive and Negative	Powell *et al*. 2002
Common octopus (*Octopus vulgaris*)	Gulf of Cádiz, Spain	Negative	Sobrino *et al*. 2002
Oyster (*Crassostrea virginica*)	Apalachicola Bay, Gulf of Mexico	Positive	Livingston *et al*. 2000
Anchovy (*Engraulis encrasicolus*)	North-western Mediterranean	Positive	Lloret *et al*. 2004
Australian bass (*Macquaria novemaculeata*)	Hawkesbury River , Australia	Positive	Growns and James 2005
Barramundi (*Lates calcarifer*)	Fitzroy River estuary, Australia	Positive	Robins *et al*. 2005
Common sole (*Solea solea*)	Gulf of Lions, Mediterranean	Positive	Salen-Picard *et al*. 2002
Herring (*Clupea pallasi*)	Strait of Georgia, Canada	Positive	Beamish *et al*. 1994
Horse mackerel (*Trachurus mediterraneus*)	Black Sea	Positive	Daskalov 1999
North east Artic cod (*Gadus morhua*)	Norwegian coast	Positive	Skreslet 1976
Black drum (*Pogonias cromis*)	Texas, USA	Positive and Negative	Powell *et al*. 2002
Red drum (*Scianeops ocellatus*)	Texas, USA	Positive and Negative	Powell *et al*. 2002
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
Sprat (*Sprattus sprattus*)	Black Sea	Positive	Daskalov 1999
Spotted sea trout (*Cynoscion nebulous*)	Texas, USA	Positive and Negative	Powell *et al*. 2002
Whiting (*Merlangius merlangus*)	Black Sea	Positive	Daskalov 1999
Various commercial species	North-western Mediterranean	Positive	Lloret *et al*. 2001
Various commercial species	Mississippi river, Gulf of Mexico	Positive	Grimes 2001
Various finfish and crustaceans	Queensland, Australia	Positive	Loneragan and Bunn 1999

1.2. Need

Not only is Australia one of the driest continents in the world, it also has greater variability in precipitation and river discharge than any other country apart from South Africa (Finlayson and McMahon 1988, Kuhnel *et al.* 1990, Finlayson and McMahon 1991). This relatively extreme hydrological nature is an important feature of Australian rivers (Puckridge *et al*. 1998, McMahon and Finlayson 2003), creating temporally and spatially variable aquatic ecosystems (Ward 1998). Investigations in NSW could provide 'strong-signals' from which to isolate causal mechanisms due to the aseasonal and relatively stochastic nature of freshwater flow. Understanding fisheries-flow relationships is essential to appreciate the impacts of environmental flow regulations and climate change on estuarine fisheries. Without adequate research, the socio-economic implications of altering estuarine freshwater inflow could become apparent, potentially instigating the need for reform to fisheries policy and planning (Loneragan and Bunn 1999, Montagna *et al*. 2002, Robins *et al*. 2005).

Anthropogenic modification of freshwater flow is widely accepted to be a major cause of deteriorating conditions in many Australian river and floodplain ecosystems (Walker 1985, Kingsford 2000, Bunn and Arthington 2002). The NSW government implemented the *Water Management Act* (2000) to promote environmental flow allocations for the conservation of freshwater dependent ecosystems. This project was initiated in response to increasing demands for an improved understanding of the freshwater flow requirements of NSW estuarine fisheries. Quantitative information on the role of freshwater in maintaining estuarine fisheries production is urgently required to devise effective management strategies. Research is needed to identify aspects of the flow regime that may enhance fisheries production.

Climate change is expected to alter the hydrological cycle (Loaiciga *et al*. 1996), with associated impacts on riverine-estuarine interactions (Liu 2000). Particular concern has been expressed about the effects of climate change and increasing human population size on freshwater flow and any subsequent effects on water resources (Carpenter *et al*. 1992, Postel *et al*. 1996, Vörösmarty *et al*. 2000, Nijssen *et al*. 2001, Oki and Kanae 2006). An improved knowledge of freshwater flow as a driver of estuarine fisheries production will assist population modellers and therefore fisheries managers in sustaining fisheries harvests.

Estuarine fish communities could be highly responsive to the flood-drought cycle in NSW. Flooding can result in mass mortalities of estuarine biota due to acidification degrading habitat quality and reduced dissolved oxygen levels causing asphyxiation (Sammut *et al*. 1995, Corfield 2000, Johnston *et al*. 2003). Droughts in the terrestrial realm are likely to be reflected by droughts in aquatic systems due to lower rainfall. Under drought conditions, estuarine fish communities may be at greater risk from fishing pressure due to reduced population size. There is, however, no available information on whether drought results in estuarine freshwater deprivation and reductions in fisheries production in NSW (Figure 1).

Accurate historical information on freshwater flowing into estuaries is not readily available in NSW. Freshwater flow can be measured by river gauges, derived from proxies (e.g., rainfall-run-off and river height) and estimated by hydrological modelling (e.g., the Integrated Quality and Quantity Model, IQQM). In addition to examining fisheries-flow relationships, an important component of this project is to identify alternative hydrological variables (e.g., drought declaration and rainfall) that could be used as surrogate measures of estuarine freshwater inflow. The findings of this project could have implications for management and conservation efforts, highlighting species of fish that could be susceptible to hydrological change and identifying 'drought sensitive' estuaries.

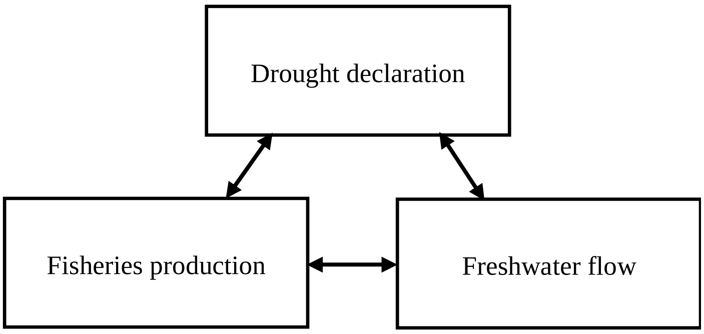


Figure 1. Identification of potential relationships between drought declaration, freshwater flow, and fisheries production is required to provide quantitative information on environmental flow allocations for NSW estuaries.

2. METHODS

Data were collated from a variety of sources, selected for critical times according to the life cycle of estuarine-dependent fisheries species and formatted accordingly (Table 2). The analysis aimed to determine whether there was evidence of relationships between the catch rates of commercially important species of estuarine-dependent fish and freshwater flow, and if so, which of the proposed theoretical mechanisms were most consistently supported from the correlative analyses. Considered hypotheses were based on information from existing literature (Table 3). Conceptual models were formulated to elucidate critical life history periods when freshwater flow may have the most pronounced impacts on fisheries production. Hydrological variables were selected if existing literature deemed them to be successful indicators of fisheries landings (e.g., Grimes 2001, Gillanders and Kingsford 2002, Robins *et al*. 2005). Freshwater flows from monthly, annual (June to June) and seasonal time series were examined. Seasons were selected to correspond with spawning period because this time interval is postulated to be a key determinant of interannual survival variability (Cushing 1982, Houde 1987). For this purpose, seasons were defined as: winter (June – August), spring (September – November), summer (December – February) and autumn (March – May). The summer period incorporated data from the December of the previous year. Monthly aggregated CPUE data in nine different estuaries were examined under drought declared and undeclared scenarios. Relationships between species-specific catch rates, drought declaration, rainfall and freshwater flow were investigated in the Clarence River and Hunter River estuaries.

2.1. Study areas

Nine estuaries along the NSW coastline were selected to evaluate the impacts of freshwater flow on estuarine fisheries production (Figure 2). The selection process was structured to obtain a suite of estuaries that were open to commercial fishing from differing localities with distinct freshwater inputs (three estuaries each with high, medium and low flow) and varying degrees of freshwater regulation (Table 4). Estuaries entering the Pacific Ocean included (i); the lower reaches of the Clarence River and Lake Wooloweyah, (ii); the Hunter River, (iii); the Hawkesbury River, (iv); Camden Haven River, (v); Wallis Lake, (vi); Port Stephens and Myall Lakes, (vii); Tuggerah Lakes, (viii); Lake Illawarra, and (ix); St. Georges Basin.

Clarence River

The Clarence River system on the north coast of NSW contains the largest coastal river in southeastern Australia. The river rises near the McPherson Ranges and flows ~400 km, before reaching a riverine barrier estuary in the town of Yamba. The major tributaries delivering freshwater into the estuary are the Mann, Nymboida and Orara Rivers. Mangroves stands (7.65 km^2), seagrass beds (0.82 km^2) and saltmarsh plains (2.90 km^2) are present in the estuary (Williams *et al*. 2006). Freshwater flow has been moderately regulated, with a small weir for power generation and a storage dam for regional water supply. Commercial finfish production in the Clarence River estuary was the highest estuarine production in NSW, with 10 886 tonnes harvested between July 1997 and July 2007 representing 22.5% of the total NSW estuarine catch (NSW DPI catch records). 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.

Table 2. Rainfall, freshwater flow and fisheries data sources and formats.

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

NSW DPI ComCatch = New South Wales Department of Primary Industries Commercial Catch and effort database; NSW DPI Drought 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.

Table 3. Hypothesised mechanisms connecting freshwater flow and estuarine finfish communities.

Hypothesis	**Reference**
Fish actively seek optimum habitat conditions when they arise and trace land-based cues back to an estuary by following olfactory concentration gradients that result from changes in freshwater flow.	Whitfield 1994, Whitfield and Harrison 1996, Grange *et al*. 2000
Altered spatial distribution of fish due to changes in habitat availability (i.e., connected, reduced or expanded habitat) resulting from variation in freshwater flow. Fish opportunistically exploit flow-driven changes to habitat quality and quantity (e.g., favourable nursery habitats) resulting in faster growth rates and greater survival.	Kimmerer 2002, Gillanders and Kingsford 2002, Robins *et al*. 2005, Halliday and Robins 2007
Changes in freshwater flow triggers the migration of mature fish to the lower reaches of an estuary in preparation for seasonal spawning. Altered flow conditions may create “windows of opportunity” to undertake spawning movements. The stimulus could be flow rates, salinity, dissolved oxygen, water temperature or turbidity.	Whitfield and Wooldridge 1994, Robins *et al*. 2005, Halliday and Robins 2007
Catch rates of fish altered by variation in freshwater flow due to behavioural responses. Higher flows may result in increased catchability due to restricting the distribution or stimulating movement into areas where fish are more likely to be caught.	Loneragan and Bunn 1999
Freshwater delivers nutrients into an estuary stimulating increased primary and secondary production, which is then propagated up the foodweb to fish via a trophic cascade. Flow-driven changes to food availability may effect fish growth, survival and reproductive output.	Copeland 1966, Aleem 1972, Livingston *et al*. 1997, Tsai *et al*. 1997, Loneragan and Bunn 1999, Salen-Picard *et al*. 2002
Variation in freshwater flow affects the transport of fish eggs and larvae. Extreme flow events may flush eggs and larvae from an estuary into coastal waters (i.e., a negative effect owing to advection). Alternatively, lower flows may retain eggs and larvae in nursery habitats (i.e., a positive effect owing to retention).	Kimmerer *et al*. 2001, North and Houde 2003
Alterations to fish population dynamics during the first year of life (i.e., cohort or year-class strength effects) resulting from flow-driven changes to water physicochemistry and food availability.	Rose and Summers 1992, Quiñones and Montes 2001, Salen-Picard *et al*. 2002, Balston 2005

Hunter River

The Hunter River system on the central coast contains one of the largest rivers in NSW. The river rises in the Mount Royal Range and flows 300 km through the Hunter Valley, before reaching a riverine barrier estuary 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 has been extensively regulated, with several major dams and reservoirs (e.g., Chichester, Glenbawn, Glennies Creek and Grahamtown) in the north of the catchment. Commercial finfish production in the Hunter River estuary was the seventh highest in NSW estuaries, with 1675 tonnes harvested between July 1997 and July 2007 representing 3.5% of the total NSW estuarine catch (NSW DPI catch records).

Hawkesbury River

The Hawkesbury River system on the central coast of NSW flows ~145 km, before reaching a drowned river valley estuary 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 (0.38 km^2) and saltmarsh plains (2.4 km^2) (Williams *et al.* 2006). Freshwater flow is highly modified, with several major dams (e.g., Nepean, Avon, Cordeaux and Warragamba) in the catchment. Commercial finfish production in the Hawkesbury River estuary was the forth highest in NSW estuaries, with 4,001 tonnes harvested between July 1997 and July 2007 representing 8.3% of the total NSW estuarine catch (NSW DPI catch records).

Camden Haven River

The Camden Haven River on the north coast of NSW rises in the Great Dividing Range and flows ~40 km, before reaching a riverine barrier estuary in the town of North Haven. The estuary consists of two saline coastal lagoons, which are Queens Lake and Watson Taylor Lake. The major tributaries are Black, Upsalls, McLeods and Gills creeks. Flow regulation is relatively minor, with no large dams in the catchment. There are mangrove stands (1.40 km^2), seagrass beds (10.25 km^2), and saltmarsh plains (0.77 km^2) in the estuary (Williams *et al.* 2006). Commercial finfish production in the Camden Haven River estuary was 1,531 tonnes between July 1997 and July 2007, which represents 3.16% of the total NSW estuarine catch (NSW DPI catch records). Since May 2002, commercial fishing has been closed and a recreational fishing haven declared downstream of Dunbogan Bridge and North Haven Bridge.

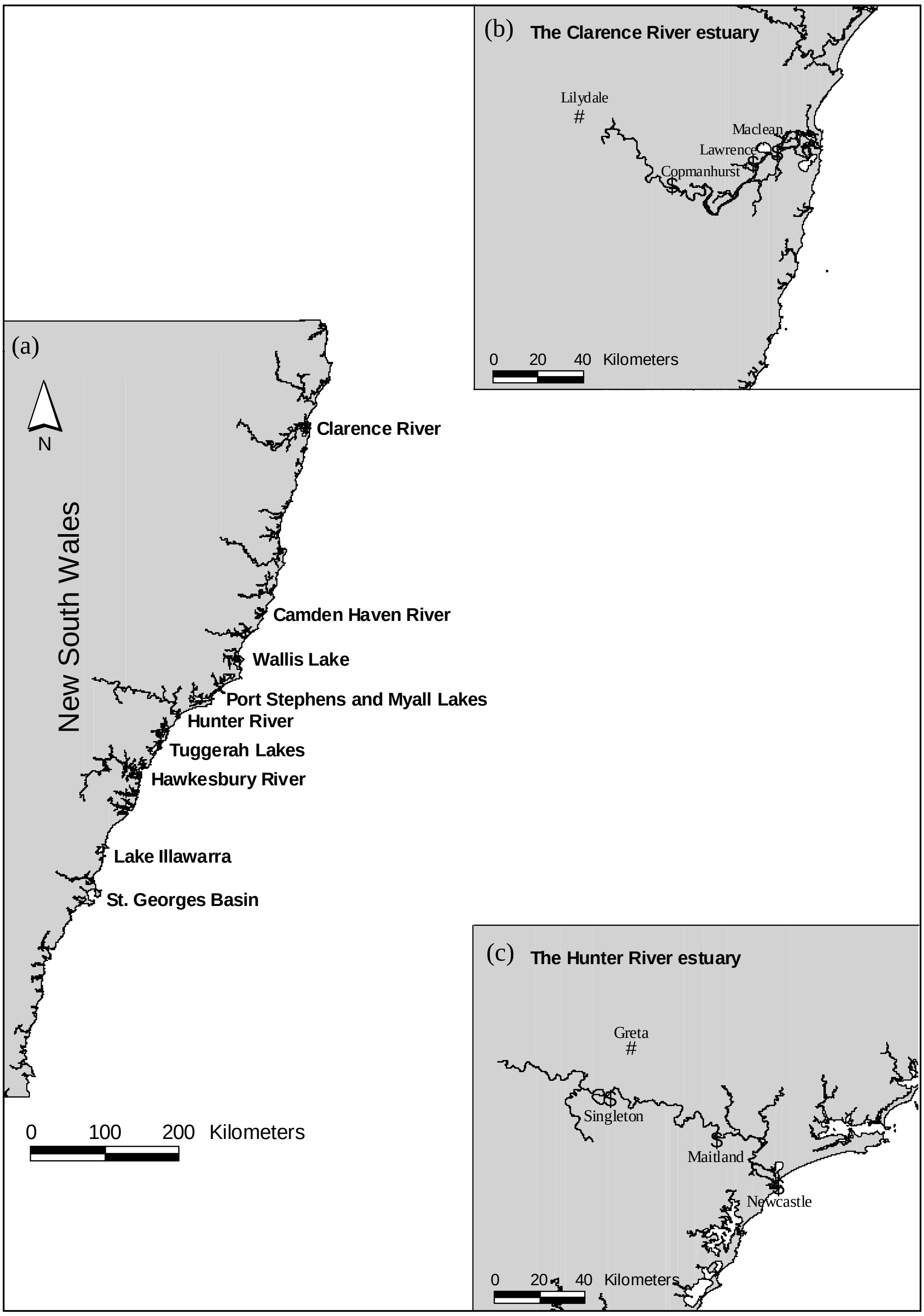


Figure 2. Location of nine estuaries selected to investigate the impacts of freshwater flow on estuarine fisheries production in NSW. Monthly aggregated CPUE data from nine different estuaries were examined under drought declared and undeclared scenarios (a). Rainfall ($) and freshwater flow (#) gauging stations are shown in relation to the estuarine reaches of the Clarence (b) and Hunter River (c) systems.

Table 4. Estuaries selected to investigate the impacts of freshwater flow on estuarine fisheries production in NSW.

Estuary name	**Latitude and longitude**	**Bioregion**	**Estuary type**	**Water area (km^2)**	**Catchment area (km^2)**	**Flow type**	**Flow regulation**
The Clarence River	29°25’37.20” S, 153°22’19.20” E	Northern	Barrier river	89	22400	High	Moderate
The Hunter River	32°54’54.00” S, 151°48’03.59” E	Central	Barrier river	29	22000	High	High
The Hawkesbury River	33°34’10.20” S, 151°18’32.40” E	Central	Drowned river valley	100	21500	High	High
Camden Haven River	31°38’09.59” S, 152°50’13.20” E	Northern	Barrier river	28	720	Medium	Low
Wallis Lake	32°10’26.40” S, 152°30’39.59” E	Central	Barrier lagoon	85	1420	Medium	Low
Port Stephens and Myall Lakes	32°42’29.00” S, 152°11’45.59” E	Central	Drowned river valley	289	6610	Medium	Low
Tuggerah Lakes	33°20’42.00” S, 151°30’14.40” E	Central	Barrier lagoon	70	760	Low	High
Lake Illawarra	34°32’38.40” S, 150°52’26.40” E	Central	Barrier lagoon	36	270	Low	Moderate
St. Georges Basin	35°11’06.00” S, 150°35’38.40” E	Central	Barrier lagoon	39	390	Low	Low

Data from West et al. 1985. Bioregion refers to defined latitudinal estuarine regions in NSW (Pease 1999). Estuary type describes the geomorphological classification (Roy et al. 2001, Saintilan 2004). Flow type is a comparative theoretical measure of freshwater flow. Flow regulation refers to the amount of regulation and extraction of freshwater within the catchment.

Wallis Lake

The Wallis Lake estuary on the central coast of NSW is a complex saline barrier lagoon system. Freshwater is mainly delivered into the estuary from the Coolongolook, Wang Wauk, Wollamba and Wallingat Rivers. The shallow (≤ 3m) well-mixed estuary can become hypersaline during dry periods. Flow regulation is relatively minor, with no major dams in the catchment. The estuary has the largest seagrass area in NSW (33.20 km^2) and considerable saltmarsh plains (5.29 km^2) (Williams *et al*. 2006). Commercial finfish production in Wallis Lake was third highest in NSW estuaries, with 4595 tonnes harvested between July 1997 and July 2007 representing 9.5% of the total NSW estuarine catch (NSW DPI catch records).

Karuah River, Port Stephens and Myall Lakes System

The Port Stephens and Myall Lakes estuary on the central coast of NSW lies at the confluence of the Karuah and Myall Rivers. The Karuah River enters a drowned river valley estuary, which flows into Port Stephens and Myall Lakes, along with the freshwater dominated Myall River estuary. There are mangrove stands (9.46 km^2), seagrass beds (11.14 km^2) and saltmarsh plains (5.03 km^2) in the estuary (Williams *et al*. 2006). Commercial finfish production in Port Stephens and Myall Lakes was the second highest in NSW estuaries, with 5,809 tonnes harvested between July 1997 and July 2007 representing 12% of the total NSW estuarine catch (NSW DPI catch records).

Tuggerah Lakes

The Tuggerah Lakes estuary on the central coast of NSW consists of three inter-connected saline lagoons which are Lake Munmorah, Budgewoi Lake and Tuggerah Lake. The major tributaries flowing into the estuary are the Wyong River, the Ourimbah Creek and the Wallarah Creek. The shallow (≤ 1.9 m) well-mixed barrier lagoon estuary is poorly flushed with a small tidal range (0.1m – 1.0m). The catchment has been extensively modified, with water pumped from the Wyong and Ourimbah Rivers to a series of storage reservoirs in the Mardi dam. Seagrass beds (17.61 km^2) and saltmarsh plains (0.11km^2) are present in the estuary (Williams *et al*. 2006). Commercial finfish production in Tuggerah Lakes was the fifth highest in NSW estuaries, with 3119 tonnes harvested between July 1997 and July 2007 representing 6.5% of the total NSW estuarine catch (NSW DPI catch records).

Lake Illawarra

The Lake Illawarra region on the south coast of NSW consists of a shallow (≤ 3m) well-mixed but poorly flushed saline barrier lagoon estuary with a limited tidal range (0.03m – 0.1m). Freshwater is mainly delivered into the estuary from Macquarie Rivulet. Without adequate freshwater flow, the estuary mouth can become periodically closed resulting highly saline conditions (Pocock *et al*. 2003). Freshwater is moderately regulated, with several small dams and weirs (e.g., Macquarie Rivulet farm and Mullet Creek) in the catchment. There are considerable seagrass beds (7.96 km^2) and moderate saltmarsh plains (0.32km^2) in the estuary (Williams *et al*. 2006). Commercial finfish production in Lake Illawarra was the sixth highest in NSW estuaries, with 1783 tonnes of finfish harvested between July 1997 and July 2007 representing 4% of the total NSW estuarine catch (NSW DPI catch records).

St. Georges Basin

St. Georges Basin on the south coast of NSW contains a shallow barrier lagoon estuary. The major tributary flowing into the estuary is Wandandian Creek. Flow regulation in relatively minor, with no major dams in the catchment. Mangrove forests (0.28 km^2), seagrass beds (3.17 km^2) and saltmarsh plains (0.15 km^2) are present in the estuary (Williams *et al*. 2006). The estuary supported an important commercial fishery, with 554 tonnes of estuarine finfish harvested between July 1997 and April 2002 (NSW DPI catch records). Since May 2002, St. Georges Basin has been closed to commercial fishing and declared a recreational fishing haven.

2.2. Fisheries catch 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) from gill netting. This passive gear provided a size specific measure of fisheries catch (≥ 80mm mesh size) from which to assess the impacts of freshwater flow on fisheries production, and presented the most consistent method from which an index of abundance could be inferred. Fisheries landings were standardised for fishing effort by dividing the monthly catch of each species from gill netting by the number of fisher days that were submitted as gill netting in a month for all fishers (Tanner and Liggins 2000). Five estuarine-dependent finfish species were selected for analysis: bream (a mixture of yellowfin and black bream (*Acanthropagrus australis/Acanthropagrus butcheri*)), dusky flathead (*Platycephalus fuscus*), luderick (*Girella tricuspidata*), sand whiting (*Sillago ciliata*) and sea mullet (*Mugil cephalus*). Yellowfin bream and black bream are reported as a single species group in NSW DPI commercial catch records. Distinguishing between these two species by visual examination can be very difficult and this is further complicated by hybridization due to interbreeding (Scandol *et al*. 2008). In NSW, yellowfin bream represent the significant majority (~95%) of commercial estuarine landings with black bream only found south of Myall Lakes. These species were selected because they make the dominant contribution to the total commercial and recreational harvest in NSW estuaries (Gray *et al*. 2000). CPUE for all examined species was aggregated into monthly and annual (July to June inclusive) totals to investigate the impacts of freshwater flow on fisheries production.

2.3. Hydrological data

Monthly drought declaration maps were obtained from NSW DPI from June 1992 to June 2007. Periods of drought declaration were examined for an area surrounding each estuary, and formatted into a categorical variable with “0” and “1” representing the absence or presence of drought declaration, respectively.

Total monthly rainfall (mm) was collated from the Bureau of Meteorology (BoM) from June 1992 to June 2007. Rainfall data from gauging stations in the upper, middle and lower reaches of the catchment were summed to calculate total monthly rainfall. Stations were in Copmanhurst, Lawrence and Maclean for the Clarence River system and Singleton, Maitland and in Newcastle for the Hunter River system (Table 5).

Monthly freshwater flow data were extracted from the Pinneena 9.1 database of the New South Wales Department of Water and Energy (NSW DWE). This extensive hydrological archive provided gauged freshwater flow data for the Clarence River at Lilydale (29°18’12.59” S, 152°24’20.16” E) and the Hunter River at Greta (32°23'43.44” S, 151°14’56.40” E) from June 1992 to June 2007. A variety of flow variables were selected: (i); total, minimum, mean and maximum river discharge, (ii); maximum river discharge as a percentage of total river discharge (hereafter referred to as % Maximum monthly flow); (iii); and total seasonal river discharge as a percentage of total annual river discharge. Variables were categorized 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 as variable $^{L\text{-}x}$). Temporal trends in freshwater flow were examined to identify potential flood events. Once total monthly flow exceeded 1.0 million ML in the Clarence River and 0.20 million ML in the Hunter River a flood event was declared. A categorical variable was then formulated with “0” and “1” representing the absence or presence of a flood event, respectively.

Table 5. Rainfall gauging stations in the Clarence and Hunter River systems.

Catchment reach	Station name	Latitude and Longitude
Clarence River upper	Copmanhurst	29°35’10.00” S, 152°46’33.24” E
Clarence River middle	Lawrence	29°29’48.12” S, 153°06’15.00” E
Clarence River lower	Maclean	29°27’07.56” S, 153°12’02.52” E
Hunter River upper	Singleton	32°35’30.48” S, 151°10’27.48” E
Hunter River middle	Maitland	32°44’34.00” S, 151°34’06.00” E
Hunter River lower	Newcastle	32°55’06.06” S, 151°47’54.59” E

2.4. Data analysis

Prior to analysis, a $\log_{10}$ transformation was applied to fisheries, rainfall and freshwater flow variables to normalize variances. All transformed variables were normally distributed (Lilliefors test) with no evidence of heteroscedasticity (standardised quantile plots).

Univariate analyses were performed to examine relationships between fisheries CPUE and hydrological variables. Initial exploratory analysis was undertaken with linear regression techniques and corrected with Bonferroni inequality adjustment (Sokal and Rolf 1995). A one-way analysis of variance (ANOVA) was used to compare freshwater flow and fisheries CPUE under drought declared and undeclared scenarios. The same technique was used to compare fisheries CPUE during six months of relatively low (February – July 2006) and high (February – July 1999) freshwater flow. Forward stepwise multiple regression analysis was undertaken to identify hydrological variables that explained the highest proportion of variability in fisheries 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 is the CPUE (bream, dusky flathead, luderick, sand whiting or sea mullet), x the covariates that represent environmental factors (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 states how U_t responds to a change in x_t (current month change in x_t). The β_i weights can be positive or negative. Only significant β_i coefficients were considered ($P < 0.05$). The simplest regression models with the best predictive success were retained from the Clarence River estuary and tested on the Hunter River estuary to examine the consistency of results. 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. RESULTS

3.1. Temporal trends in freshwater flow

Total monthly rainfall and freshwater flow were positively correlated in the Clarence and Hunter River systems from 1997 to 2007 (Appendix 1). The correlation between total monthly rainfall and freshwater flow was better for the relatively unregulated Clarence River ($r^2 = 0.331$, $n = 121$, $P < 0.0001$) than the highly regulated Hunter River ($r^2 = 0.259$, $n = 121$, $P < 0.0001$). There were distinct seasonal and inter-annual trends in freshwater flow (Figure 3). Most freshwater flow in the Clarence River system occurred during the summer-autumn period (71%), corresponding with summer-autumn rainfall ($r^2 = 0.630$, $P < 0.01$, $n = 11$). This seasonal periodicity was confirmed by ANOVA, with a significant difference between high flows in the summer-autumn period and low flows in the winter-spring period ($F = 5.46$, $df = 10$, $P < 0.05$). Freshwater flow in the Hunter River system was relatively aseasonal, with no significant difference between flows occurring in summer-autumn months (53%) and in winter-spring months (47%). There were sustained summer-autumn and winter-spring peak flows in both river systems from 1999 to 2001. Relatively low summer-autumn and winter-spring flows occurred from 2002 to 2005 compared to proceeding and succeeding years. Mean annual flow in the Clarence River system was 1.94 million ML, with minimum and maximum annual flows of 0.26 million ML and 6.72 million ML respectively. The highest annual flows were in 2001 and lowest in 2002. There was a significant decrease in total monthly freshwater flow by 10% in the Hunter River system from 1997 to 2007 ($r^2 = 0.098$, $P < 0.0001$, $n = 121$). Mean annual flow was 0.47 million ML, with minimum and maximum annual flows of 0.05 million ML and 1.7 million ML respectively. The highest flows were in 2007 and lowest in 2006.

Total monthly freshwater flow was significantly lower ($P < 0.0001$) in both rivers during periods of drought declaration from 1997 to 2007 (Figure 4). The nine-month period from September 2002 to May 2003 was characterised by a prolonged drought, with flow magnitudes that were frequently below the long-term (10 year) monthly means and often less than 49% and 84% of what the Clarence and Hunter River estuaries usually receive in freshwater flow respectively.

3.2. Relationships between estuarine fisheries catch rates and drought declaration

There were significant differences in monthly aggregated CPUE in all nine examined estuaries under drought declared and undeclared scenarios from 1997 to 2007 (Figure 5). Monthly aggregated CPUE was significantly lower and exhibited less variability around the median during periods of drought declaration in the Clarence River, the Hunter River, the Hawkesbury River, Camden Haven River, Wallis Lake, Port Stephens and Myall Lakes, and St. Georges Basin (all $P < 0.05$). Contrasting relationships were identified in Tuggerah Lakes and Lake Illawarra, with significantly higher monthly aggregated CPUE during periods of drought declaration ($P < 0.05$). Monthly aggregated CPUE demonstrated considerable deviation from the long-term (10 year) monthly mean during drought declared scenarios (Figure 6). Negative deviation ranged from a minimum of -18% in the Hunter River estuary to a maximum of -34% in the Camden Haven River estuary, while positive deviation ranged from a minimum of +9% in the Tuggerah Lakes to a maximum of +22% in the Lake Illawarra.

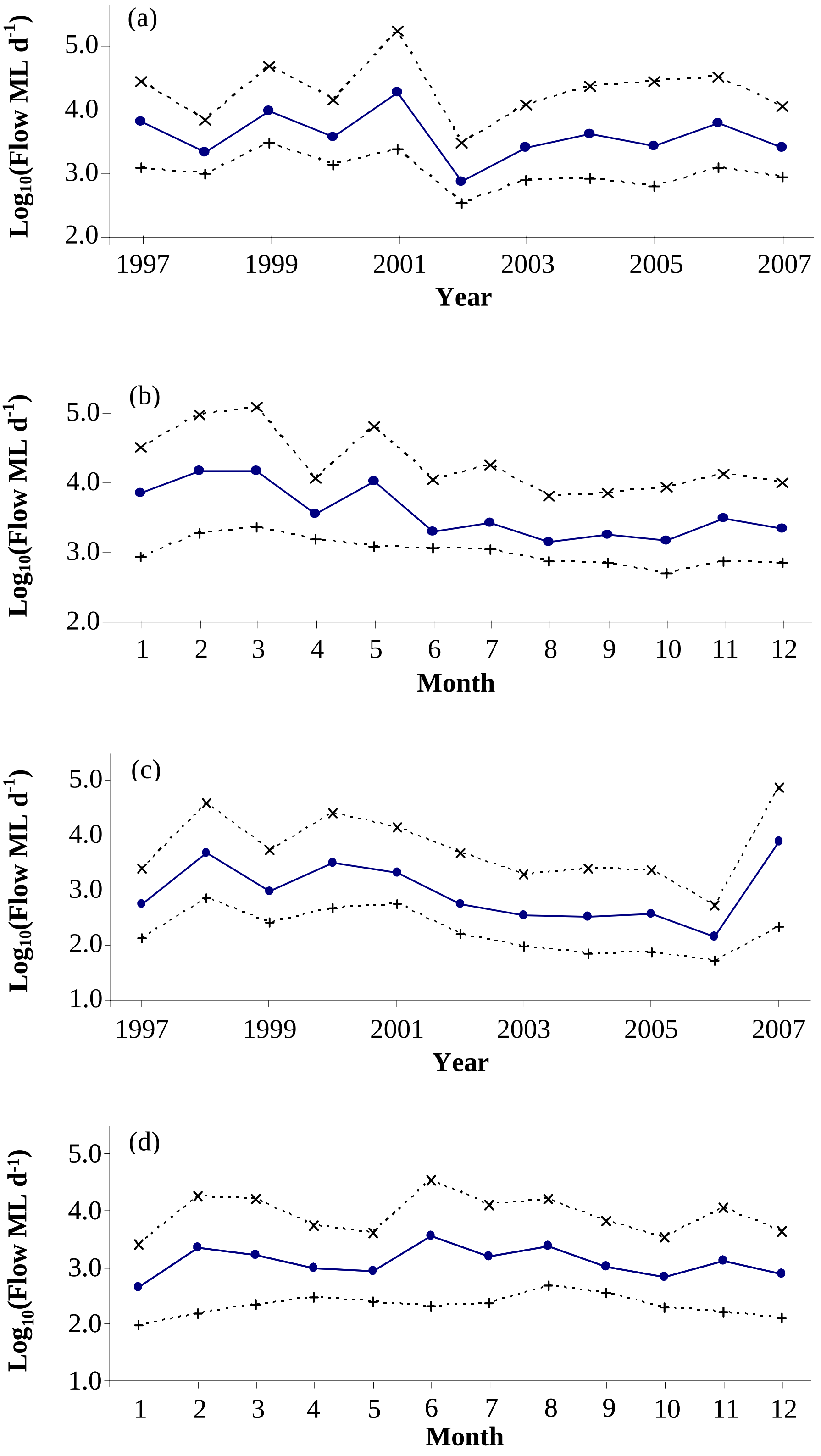


Figure 3. Temporal trends in freshwater flow for the Clarence (a and b) and the Hunter River systems (c and d) from 1997 to 2007. Minimum (- - -+- - -), mean (——●——) and maximum (- - -×- - -) flow.

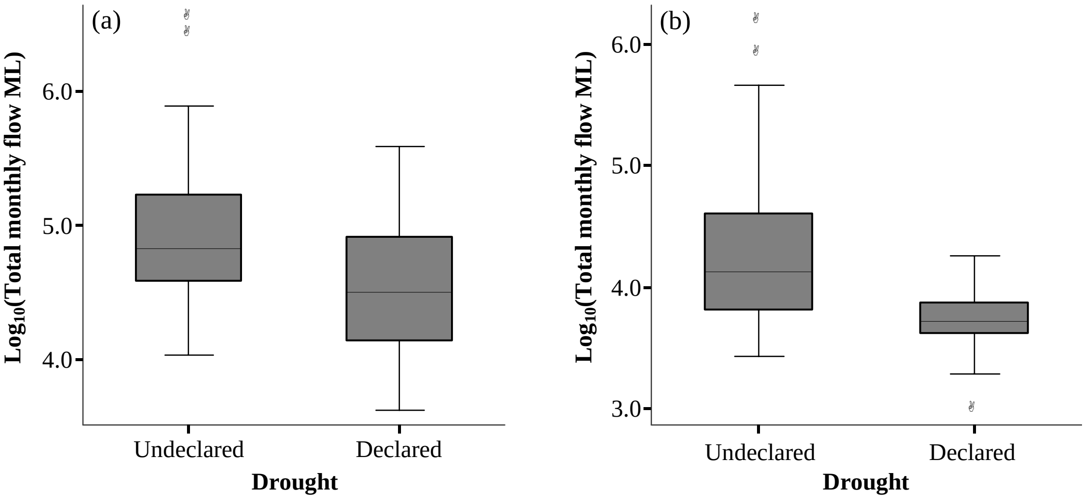


Figure 4. Box plots illustrating significant differences in total monthly freshwater flow for the Clarence (a) and Hunter (b) River systems under drought declared and undeclared scenarios from 1997 to 2007 (one-way ANOVA, $\alpha = 0.05$, Median S.D. ±). ANOVA details are (a); $F = 13.96$, $df = 120$, $P < 0.0001$, and (b); $F = 18.92$, $df = 120$, $P < 0.0001$. Periods of drought declaration consisted of 38 out of a total 121 analysed months in the Clarence River catchment and 31/121 months in the Hunter River catchment.

Species-specific differences in monthly CPUE under drought declared and undeclared scenarios were identified from 1997 to 2007 (Figure 7). Monthly CPUE was significantly lower for dusky flathead, luderick and sea mullet during periods of drought declaration in the Clarence River estuary (all $P < 0.05$). Similar relationships were identified in the Hunter River estuary with significantly lower monthly CPUE for dusky flathead, luderick, sand whiting and sea mullet under an equivalent scenario (all $P < 0.05$). During periods of drought declaration, there was considerable deviation from the long-term monthly mean CPUE of luderick (-37%) and dusky flathead (-46%) in the Clarence and Hunter River estuaries respectively (Figure 8). Bream were the only species that demonstrated significantly higher monthly CPUE (+20%) and higher variability around the median during periods of drought declaration ($P < 0.05$).

3.3. Relationships between estuarine fisheries catch rates and freshwater flow

There were numerous significant relationships between hydrological variables and estuarine fisheries CPUE in the Clarence and Hunter River estuaries from 1997 to 2007 (Appendix 2 and 3). Forward stepwise multiple regression indicated that the best predictors of variation in monthly fisheries CPUE were drought declaration, minimum monthly flow and maximum monthly flow. Other hydrological variables were relatively less important in explaining fisheries CPUE. Non-significant ($P > 0.05$) or statistically inadequate regression models (autocorrelation or non-normal residuals) relating fisheries CPUE and freshwater flow did not account for observed relationships. After considering the variation in CPUE accounted for by month, freshwater flow explained from 2.1% to 17.1% of the variation in the residuals for the CPUE and month relationship (all $P < 0.05$). Freshwater flow and residuals were significantly correlated, which means that after removing temporal effects CPUE was higher during months of higher flow.

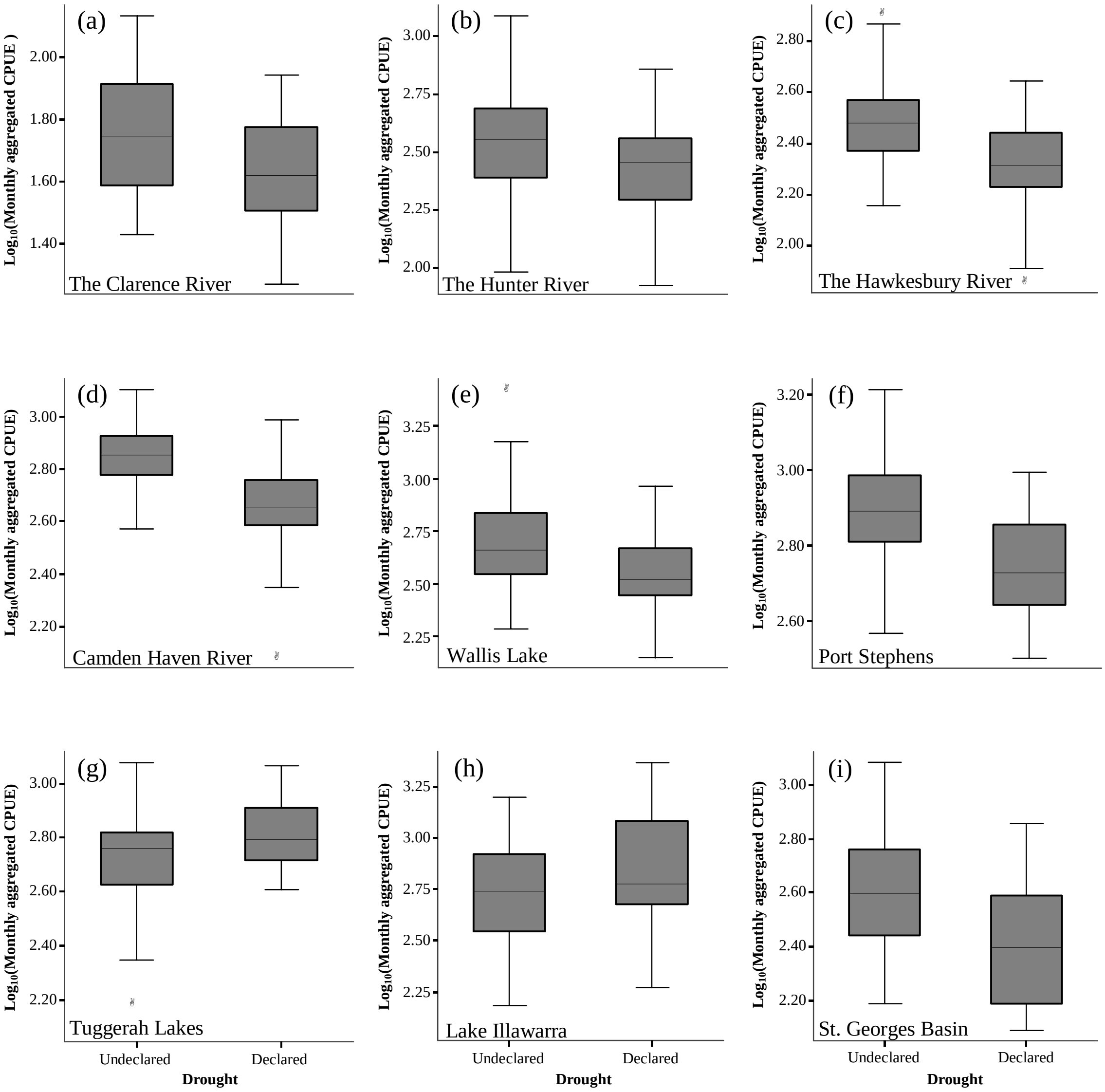


Figure 5. Box plots illustrating significant differences in monthly aggregated CPUE for nine estuaries in NSW under drought declared and undeclared scenarios from 1997 to 2007 (one-way ANOVA, α = 0.05, Median S.D. ±). ANOVA details are (a); the Clarence River; F = 11.63, df = 120, P = 0.001, (b) the Hunter River; F = 5.66, df = 120, P = 0.019, (c) the Hawkesbury River; F = 28.74, df = 120, $P < 0.0001$, (d) Camden Haven River; F = 63.35, df = 120, $P < 0.0001$, (e) Wallis Lake; F = 16.95, df = 120, $P < 0.0001$, (f) Port Stephens and Myall Lakes; F = 37.65, df = 120, $P < 0.0001$, (g) Tuggerah Lakes; F = 4.44, df = 120, P = 0.037, (h) Lake Illawarra; F = 6.61, df = 120, P = 0.011, and (i); St. Georges Basin; F = 5.24, df = 57, P = 0.026. Monthly periods of drought declaration for the Clarence River were 38 months out of a total 121 months analysed, the Hunter River 31/121, the Hawkesbury River 29/121, Camden Haven River 30/121, Wallis Lake 32/121, Port Stephens and Myall Lakes 34/121, Tuggerah Lakes 29/121, Lake Illawarra 35/121 and St. Georges Basin 8/58. Monthly aggregated CPUE refers to the summed total CPUE for all species examined.

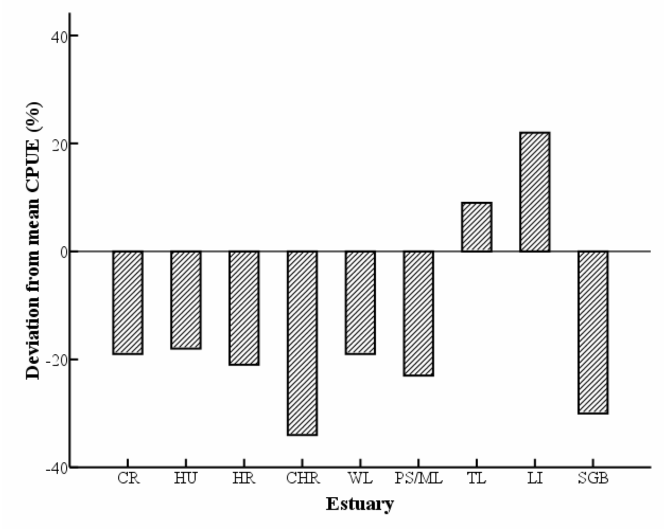


Figure 6. Deviation (%) from mean monthly aggregated CPUE for all five species combined (i.e., bream, dusky flathead, luderick, sand whiting and sea mullet) during periods of drought declaration. Calculation was as follows: (drought declared mean monthly CPUE/ long-term mean monthly CPUE × 100) – 100. Estuaries include the Clarence River (CR), the Hunter River (HU), the Hawkesbury River (HR), Camden Haven River (CHR), Wallis Lake (WL), Port Stephens and Myall Lakes (PS/ML), Tuggerah Lakes (TL), Lake Illawarra (LI) and St. Georges Basin (SGB) estuaries. All estuaries demonstrated significantly different (*P* < 0.05) monthly aggregated CPUE during periods of drought declaration.

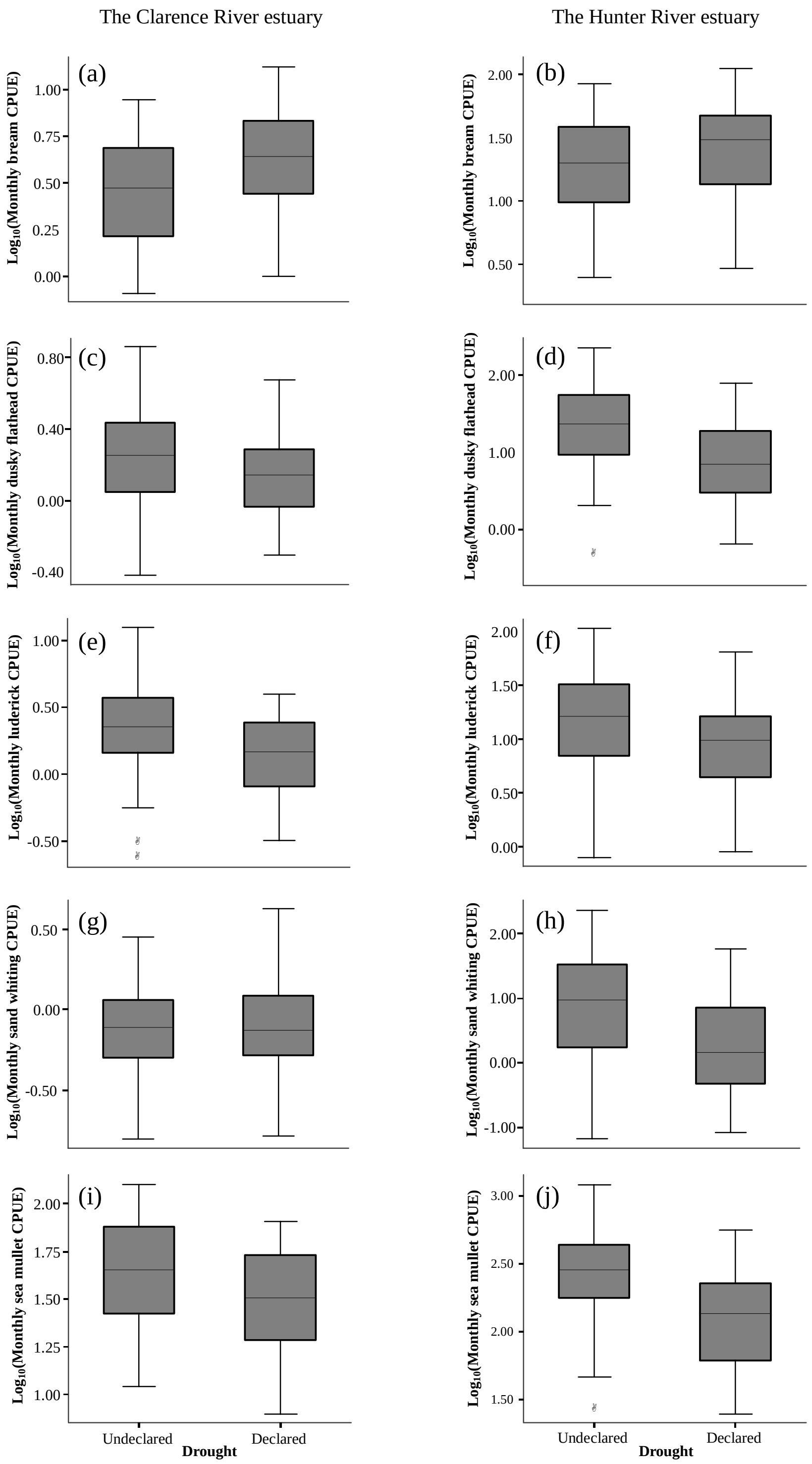


Figure 7. Box plots illustrating species-specific differences in monthly CPUE for the Clarence (a, c, e, g, and i) and Hunter River estuaries (b, d, f, h and j) under drought declared and undeclared scenarios from 1997 to 2007 (one-way ANOVA, all P values < 0.05, Median S.D. ±). ANOVA details are (a) bream CPUE; *F* = 7.66, *df* = 120, *P* = 0.007, (b) bream CPUE; *F* = 6.86, *df* = 120, *P* = 0.041, (c) dusky flathead CPUE; *F* = 4.84, *df* = 120, *P* = 0.030, (d) dusky flathead CPUE; *F* = 4.33, *df* = 120, *P* < 0.0001, (e) luderick CPUE; *F* = 12.50, *df* = 120, *P* = 0.001, (f) luderick CPUE; *F* = 9.36, *df* = 120, *P* = 0.048, (g) sand whiting CPUE; *F* = 1.93, *df* = 120, *P* = 0.661, (h) sand whiting CPUE; *F* = 7.08, *df* = 120, *P* < 0.0001, (i) sea mullet CPUE; *F* = 8.49, *df* = 120, *P* = 0.004, and (j) sea mullet CPUE; *F* = 8.33, *df* = 120, *P* < 0.0001. All species, except sand whiting in the Clarence River estuary, demonstrated significantly different (*P* < 0.05) monthly CPUE during periods of drought declaration.

3.3.1. Bream

The Clarence River estuary

Monthly CPUE of bream was positively correlated with drought declaration and % maximum monthly flow, and negatively correlated with total monthly rainfall, total monthly flow, minimum monthly flow, mean monthly flow and maximum monthly flow (Appendix 4). Stepwise multiple regression identified five alternative models that explained between 15% to 36% of the variation in monthly CPUE of bream (Table 6). The simplest model that contained a hydrological variable was year, season and drought declaration. Annual CPUE of bream was positively correlated with minimum winter flow and % total summer flow (Figure 9).

The Hunter River estuary

There was a positive correlation between monthly CPUE of bream and drought declaration ($P <$ 0.05). No other significant correlations between CPUE of bream and monthly or annual flow variables were identified. Stepwise multiple regression indicated that drought declaration as the best predictor of monthly CPUE of bream (Table 6). Annual CPUE of bream was positively correlated with % total summer flow and % total autumn flow $^{L-4}$ (Figure 9).

3.3.2. Dusky flathead

The Clarence River estuary

Monthly CPUE of dusky flathead was negatively correlated with drought declaration ($P < 0.05$). There were no other significant correlations between monthly CPUE of dusky flathead and hydrological variables. Stepwise multiple regression identified alternative two models that explained from 10% to 16% of the variation in monthly CPUE of dusky flathead (Table 6). The simplest model containing a hydrological variable was season and drought declaration. There was a positive correlation between annual CPUE of dusky flathead and total annual rainfall (Appendix 5). Several significant correlations between annual CPUE of dusky flathead and seasonal flow variables were identified (all $P < 0.05$). Annual CPUE of dusky flathead was positively correlated with maximum spring flow, and negatively correlated with % total summer flow and % total autumn flow $^{L-1}$ (Figure 10). Other positive correlations between annual CPUE of dusky flathead and total spring flow, % total spring flow, minimum spring flow and mean spring flow maximum spring flow produced relatively lower r^2 values (Appendix 6).

The Hunter River estuary

The monthly CPUE of dusky flathead was positively correlated with total monthly flow, minimum monthly flow and mean monthly flow, and negatively correlated with drought declaration (Appendix 5). Stepwise multiple regression analysis provided two alternative models that explained between 15% and 21% of the variation in monthly CPUE of dusky flathead (Table 6). The simplest predictive model contained minimum monthly flow. There was a positive correlation between annual dusky flathead CPUE and minimum annual flow ($P < 0.05$). Annual CPUE of dusky flathead was positively correlated with total annual flow $^{L-3}$, minimum annual flow $^{L-3}$, mean annual flow $^{L-3}$ and maximum annual flow $^{L-3}$ (all $P < 0.05$). There were several significant correlations between annual CPUE of dusky flathead and seasonal flow variables (all $P < 0.05$). The highest proportion of variability in annual CPUE of dusky flathead was explained by positive correlations with maximum winter flow and minimum spring flow $^{L-3}$ (Figure 10). There were also positive correlations between annual CPUE of dusky flathead and total winter flow, minimum winter flow, mean winter flow, minimum spring flow $^{L-3}$ and total spring flow $^{L-3}$ (Appendix 6 and 7).

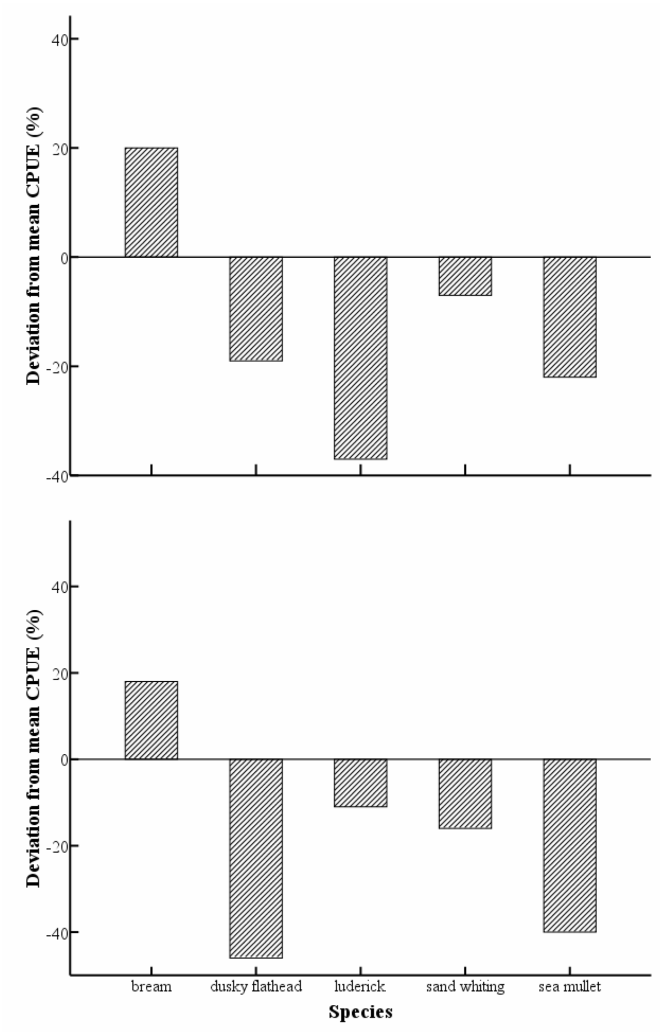


Figure 8. Species-specific deviation (%) from mean monthly CPUE during periods of drought declaration in the Clarence River (a) and Hunter River (b) estuaries. Calculation was as follows: (drought declared mean monthly CPUE / long-term mean monthly CPUE × 100) – 100. Species include bream, dusky flathead, luderick, sand whiting and sea mullet. All species, except sand whiting in the Clarence River estuary, demonstrated significantly different ($P < 0.05$) monthly aggregated CPUE during periods of drought declaration.

Table 6. Significant stepwise multiple regression models for fisheries CPUE and hydrological variables and temporal components for the Clarence and Hunter River estuaries.

Species	**Estuary**	**Model**	r^2	***n***	***P***
Bream	The Clarence River	Year	0.151	121	< 0.0001
Bream	The Clarence River	Year, season	0.232	121	< 0.0001
Bream	The Clarence River	Year, season, drought declaration	0.294	121	< 0.0001
Bream	The Clarence River	Year, season, drought declaration, Log_{10}(Total monthly rainfall mm)	0.339	121	< 0.0001
Bream	The Clarence River	Year, season, drought declaration, Log_{10}(Total monthly rainfall mm), % Maximum monthly flow	0.363	121	< 0.0001
Dusky flathead	The Clarence River	Season	0.100	121	< 0.0001
Dusky flathead	The Clarence River	Season, drought declaration	0.158	121	< 0.0001
Luderick	The Clarence River	% Maximum monthly flow	0.166	121	< 0.0001
Luderick	The Clarence River	% Maximum monthly flow, Log_{10}(Maximum monthly flow ML d^{-1})	0.341	121	< 0.0001
Luderick	The Clarence River	% Maximum monthly flow, Log_{10}(Maximum monthly flow ML d^{-1}), season	0.442	121	< 0.0001
Luderick	The Clarence River	% Maximum monthly flow, Log_{10}(Maximum monthly flow ML d^{-1}), season, year	0.499	121	< 0.0001
Luderick	The Clarence River	% Maximum monthly flow, Log_{10}(Maximum monthly flow ML d^{-1}), season, year, Log_{10}(Total monthly rainfall mm)	0.567	121	< 0.0001
Sand whiting	The Clarence River	Season	0.155	121	< 0.0001
Sea mullet	The Clarence River	Season	0.327	121	< 0.0001
Sea mullet	The Clarence River	Season, Log_{10}(Minimum monthly flow ML d^{-1})	0.384	121	< 0.0001
Sea mullet	The Clarence River	Season, Log_{10}(Minimum monthly flow ML d^{-1}), Log_{10}(Total monthly rainfall mm)	0.408	121	< 0.0001
Aggregated	The Clarence River	Season	0.361	121	< 0.0001
Aggregated	The Clarence River	Season, Log_{10}(Minimum monthly flow ML d^{-1})	0.460	121	< 0.0001
Bream	The Hunter River	Drought declaration	0.021	121	0.007
Dusky flathead	The Hunter River	Log_{10}(Minimum monthly flow ML d^{-1})	0.147	121	< 0.0001
Dusky flathead	The Hunter River	Log_{10}(Minimum monthly flow ML d^{-1}), Drought declaration	0.208	121	0.002
Luderick	The Hunter River	Drought declaration	0.079	121	0.015
Luderick	The Hunter River	Drought declaration, season	0.012	121	0.001
Luderick	The Hunter River	Drought declaration, season, month	0.162	121	< 0.0001
Sand whiting	The Hunter River	Season	0.136	121	< 0.0001
Sand whiting	The Hunter River	Season, drought declaration	0.269	121	< 0.0001
Sand whiting	The Hunter River	Season, drought declaration, year	0.318	121	< 0.0001
Sand whiting	The Hunter River	Season, drought declaration, year, Log_{10}(Maximum monthly flow ML d^{-1})	0.364	121	< 0.0001
Sea mullet	The Hunter River	Drought declaration	0.160	121	< 0.0001
Sea mullet	The Hunter River	Drought declaration, season	0.218	121	< 0.0001
Aggregated	The Hunter River	Drought declaration	0.063	121	0.003
Aggregated	The Hunter River	Drought declaration, season	0.099	121	0.001

Aggregated refers to the summed total monthly CPUE for all species examined.

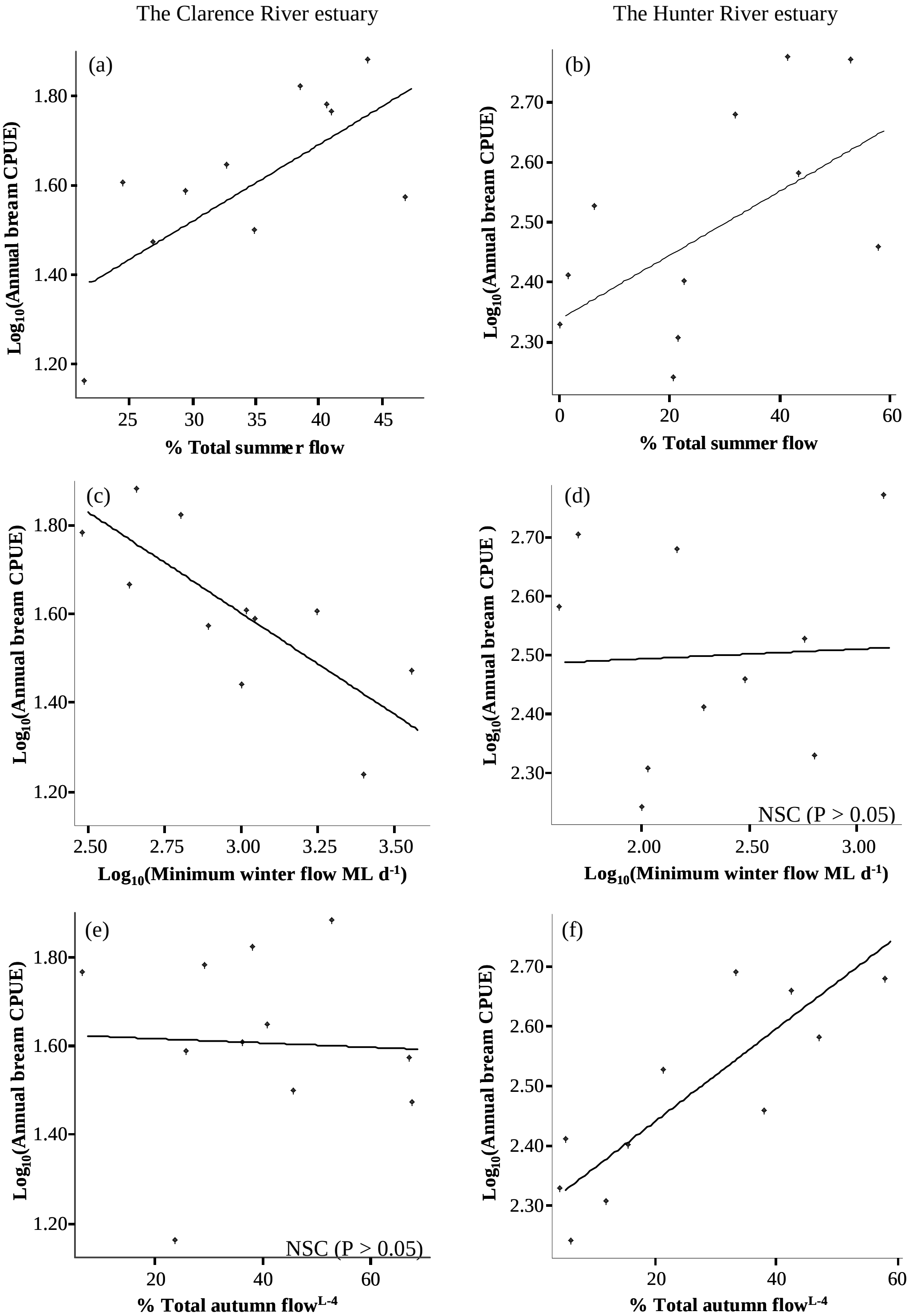
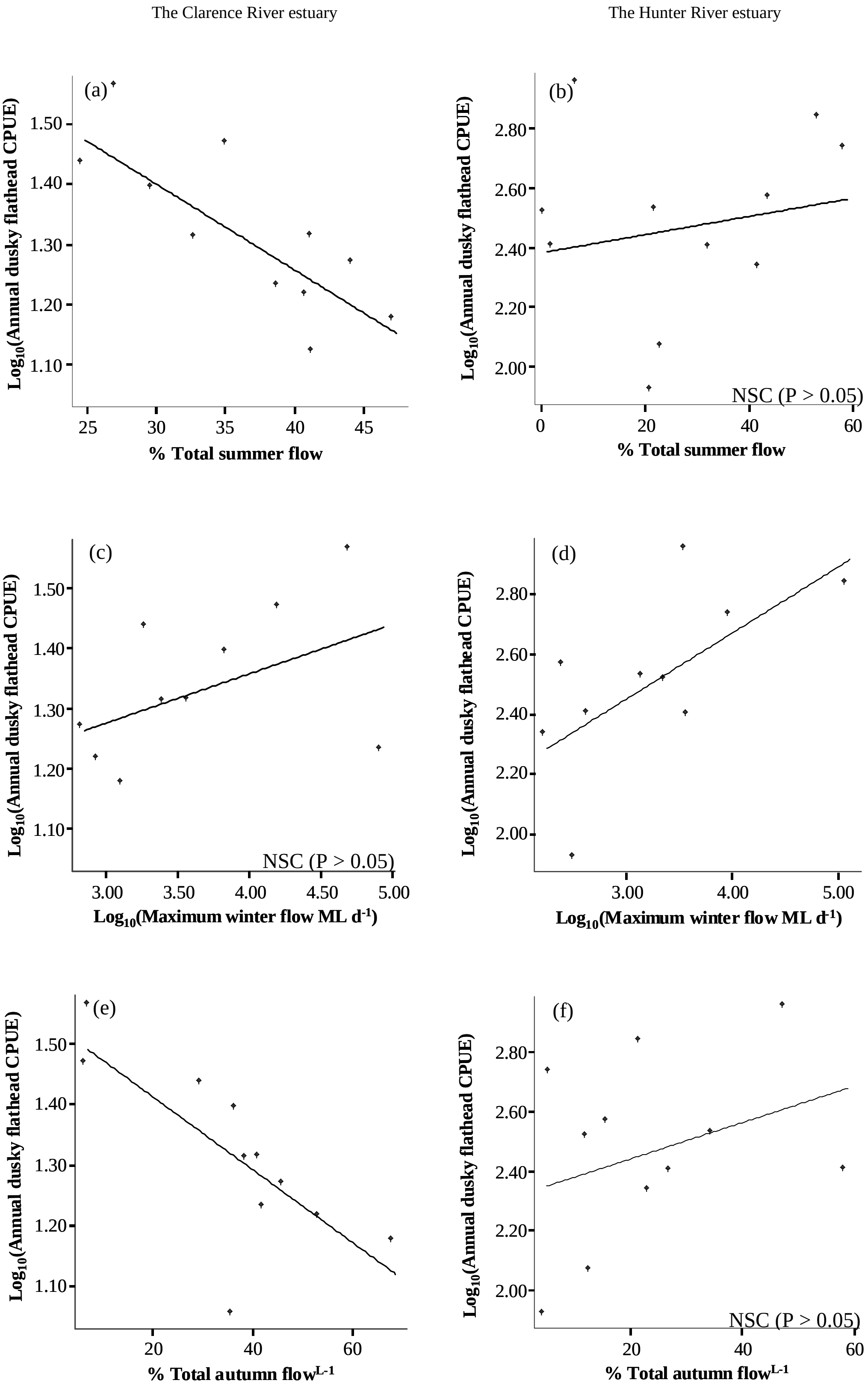


Figure 9. Relationships between the annual CPUE of bream and seasonal flow variables in the Clarence (a, c, e and g) and Hunter River (b, d, f and h) estuaries. Regression details are (a); r^2 = 0.443, P = 0.008, n = 11, (b); r^2 = 0.260, P = 0.042, (c); r^2 = 0.506, P = 0.015, n = 11, (d); r^2 = -0.123, P = 0.908, n = 11, (e) r^2 = -0.086, P = 0.659, n = 11, and (f); r^2 = 0.554, P = 0.005, n = 11. Non-independent residuals (Durban-Watson test) did not account for observed relationships. % Total summer flow refers to total summer flow as a percentage of total annual flow. % Total autumn flow refers to total autumn flow as a percentage of annual flow. Minimum winter flow indicates the lowest flows during winter. A lag period of four years is represented by $^{L-4}$. NSC (P > 0.05) symbolises non-significant correlations.


The Clarence River estuary
The Hunter River estuary
(a)
(b)
(c)
(d)
(e)
(f)
Log10(Annual dusky flathead CPUE)
1.50
1.40
1.30
1.20
1.10
2.80
2.60
2.40
2.20
2.00
25
30
35
40
45
0
20
40
60
% Total summer flow
NSC (P > 0.05)
3.00
3.50
4.00
4.50
5.00
Log10(Maximum winter flow ML d-1)
% Total autumn flowL-1

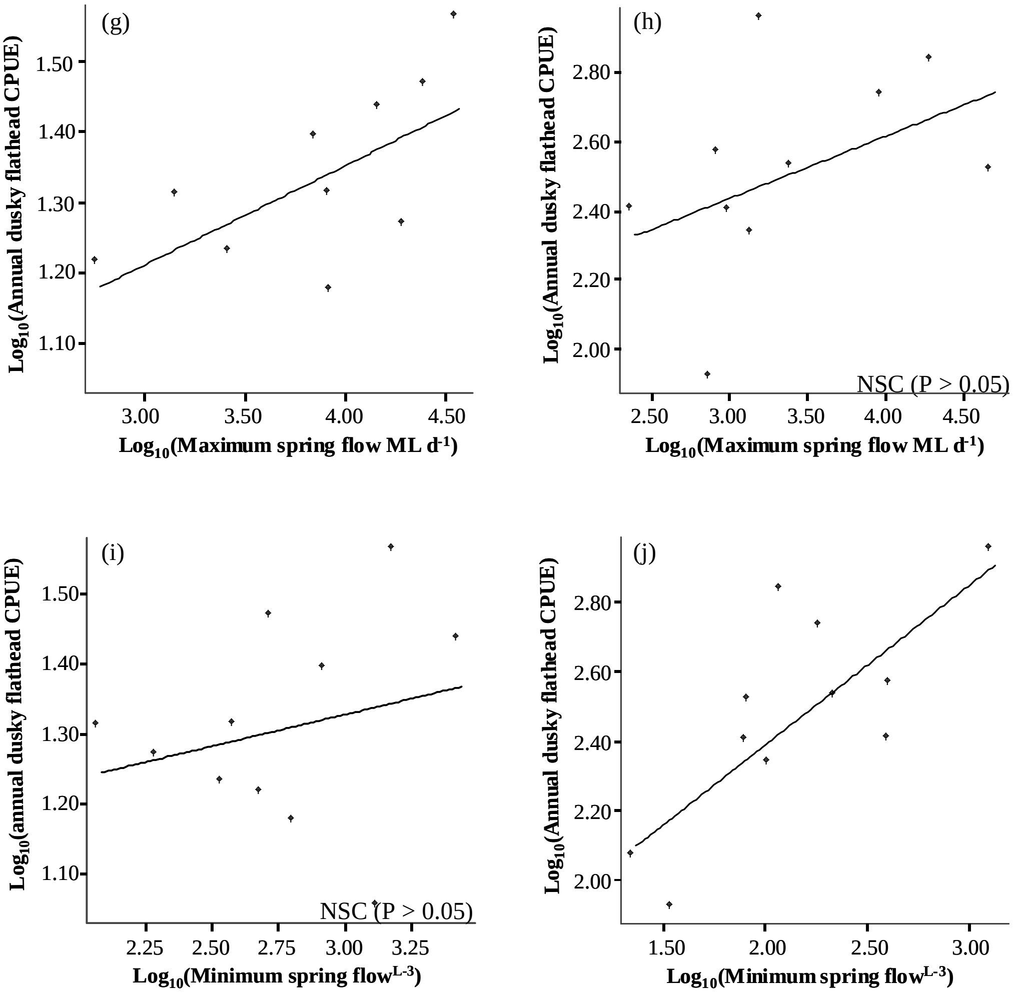


Figure 10. Relationships between the annual CPUE of dusky flathead and seasonal flow variables in the Clarence (a, c, e, g and i) and Hunter River (b, d, f, h and j) estuaries. Regression details are (a); r^2 = 0.433, P = 0.016, n = 11, (b); r^2 = -0.067, P = 0.557, n = 11, (c); r^2 = 0.129, P = 0.165, n = 11, (d); r^2 = 0.367, P = 0.037, n = 11, (e); r^2 = 0.351, P = 0.032, n = 11, (f); r^2 = 0.016, P = 0.308, n = 11, (g); r^2 = 0.444, P = 0.043, n = 11, (h); r^2 = 0.094, P = 0.202, n = 11, (i); r^2 = 0.011, P = 0.761, n = 11, and (j); r^2 = 0.523, P = 0.007, n = 11. There was no evidence of non-independent residuals (Durban-Watson test). Minimum spring flow indicates the lowest flow during spring. Maximum winter and spring flows indicate the highest flows during that time period. % Total summer flow refers to total summer flow as a percentage of total annual flow. % Total autumn flow refers to total autumn flow as a percentage of total annual flow. A lag period of one and three years is represented by $^{L-1}$ and $^{L-3}$, respectively. NSC (P > 0.05) symbolises non-significant correlations.

3.3.3. Luderick

The Clarence River estuary

Monthly CPUE of luderick was positively correlated with total monthly rainfall, minimum monthly flow and % maximum monthly flow, and negatively correlated with drought declaration (Appendix 8). Multiple regression identified five alternative models that explained from 17% to 57% of the variation in monthly CPUE of luderick (Table 6). The best predictor of monthly CPUE of luderick was % maximum monthly flow. There were positive correlations between annual CPUE of luderick and total annual rainfall, total annual flow and minimum annual flow (Appendix 9). The highest proportion of variability in annual CPUE of luderick was explained by a positive correlation with minimum winter flow (Figure 11).

The Hunter River estuary

The monthly CPUE of luderick was positively correlated with total monthly rainfall and % maximum monthly flow, and negatively correlated with drought declaration (Appendix 8). Stepwise multiple regression identified three alternative models that explained between 8% to 16% of the variation in monthly CPUE of luderick (Table 6). The primary factor that best predicted monthly CPUE of luderick was drought declaration. There were no significant correlations between luderick CPUE and annual flow variables. Annual CPUE of luderick was negatively correlated with total spring flow $^{L-4}$, % total spring flow $^{L-4}$ and maximum spring flow $^{L-4}$ (Appendix 9). The highest proportion of variability in annual CPUE of luderick was explained by a negative correlation with % total winter flow (Figure 11).

3.3.4. Sand whiting

The Clarence River estuary

There were no significant correlations between monthly CPUE of sand whiting and hydrological variables. Stepwise multiple regression identified season as the best predictor of monthly CPUE of sand whiting (Table 6). There were positive correlations between annual CPUE of sand whiting and total annual flow $^{L-3}$, minimum annual flow $^{L-3}$, mean annual flow $^{L-3}$ and maximum annual flow $^{L-3}$ (Figure 12).

The Hunter River estuary

Monthly CPUE of sand whiting was positively correlated with total monthly flow, minimum monthly flow, mean monthly flow and maximum monthly flow, and negatively correlated with drought declaration (Appendix 10). Stepwise multiple regression identified four alternative models that explained from 14% to 36% of the variation in monthly CPUE of sand whiting (Table 6). The best predictors of monthly CPUE of sand whiting were season and drought declaration. There were positive correlations between annual sand whiting CPUE and total annual flow $^{L-3}$, minimum annual flow $^{L-3}$, mean annual flow $^{L-3}$ and maximum annual flow $^{L-3}$ (Figure 12).

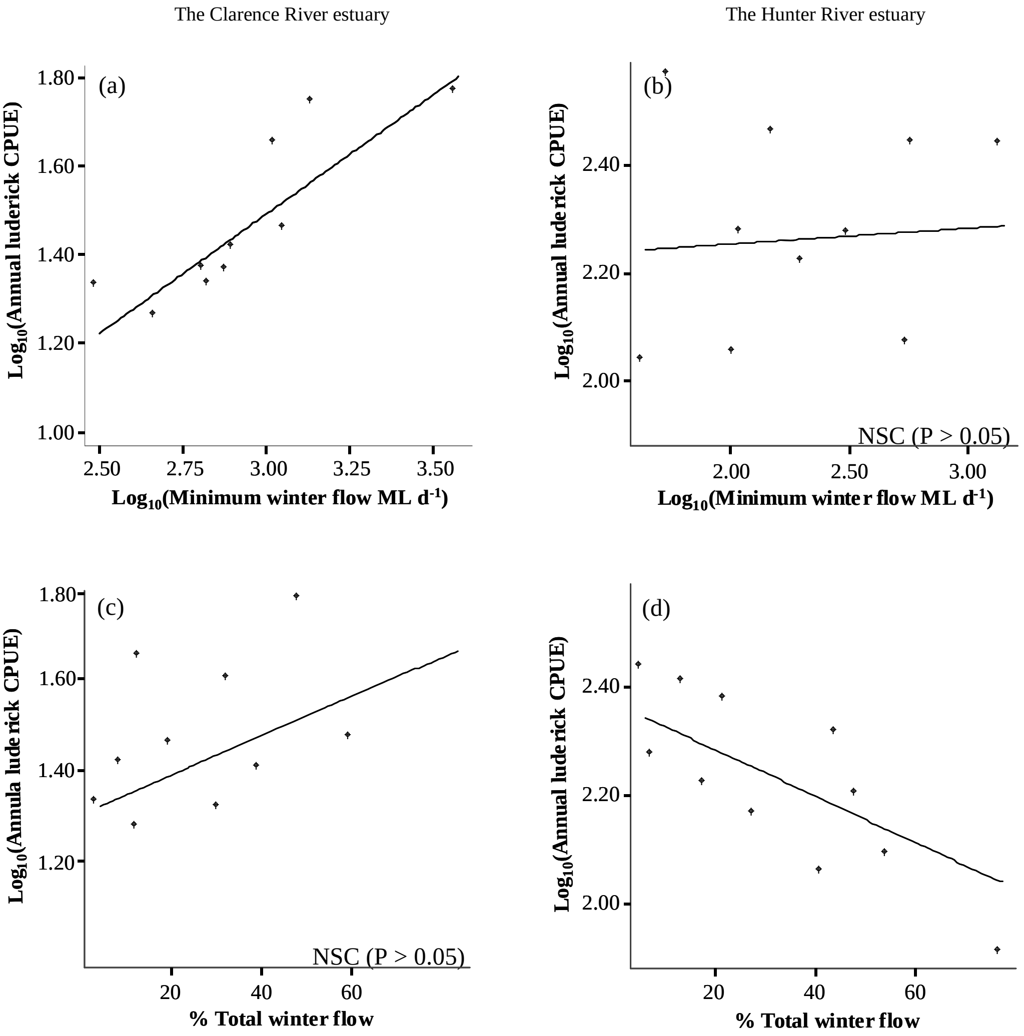
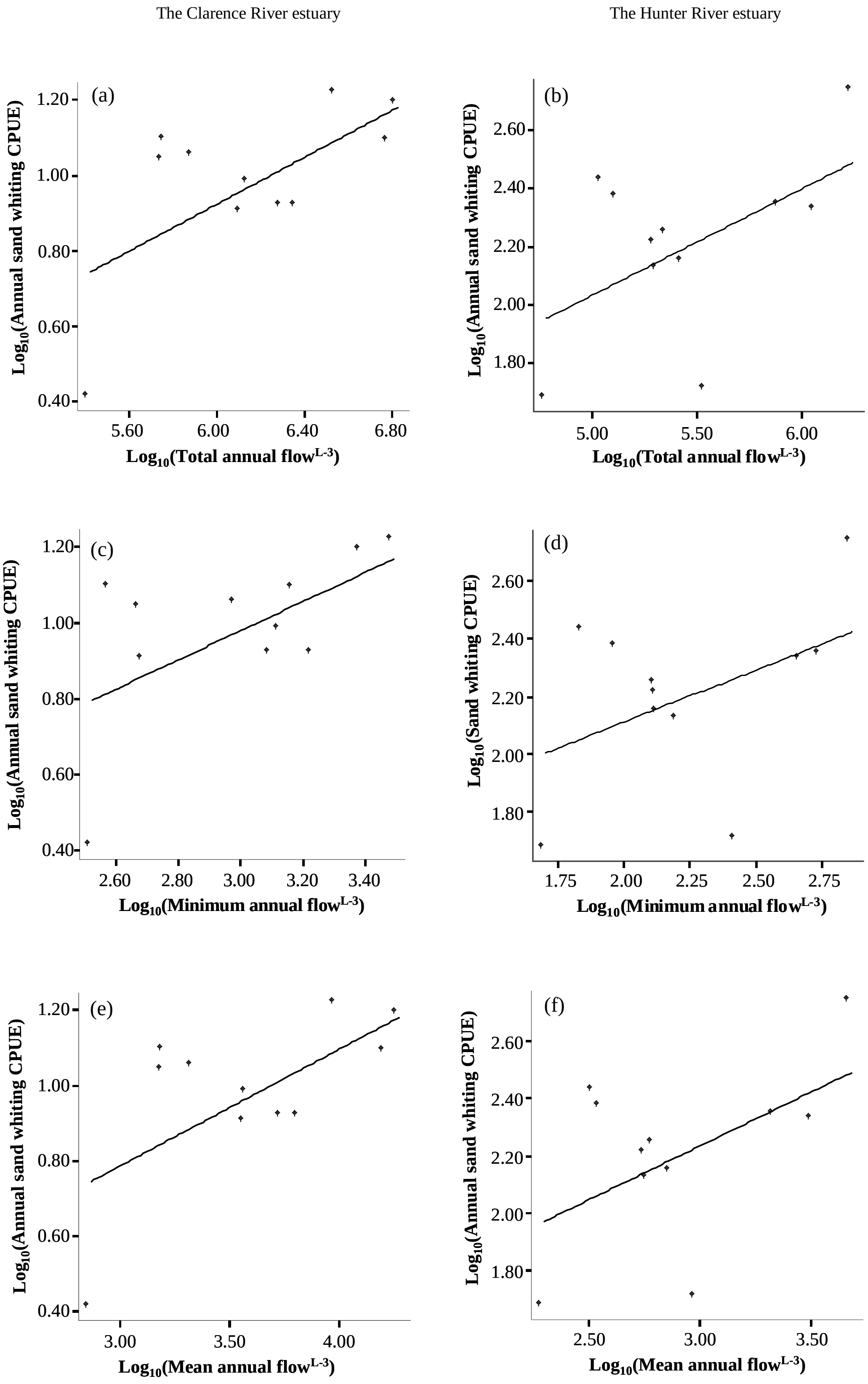


Figure 11. Relationships between the annual CPUE of luderick and winter flows in the Clarence (a and c) and Hunter (b and d) River estuaries. Regression details are (a) $r^2 = 0.700$, $P = 0.002$, $n = 11$, (b); $r^2 = -0.120$, $P = 0.855$, $n = 11$, (c); $r^2 = 0.240$, $P = 0.060$, $n = 11$, and (d); $r^2 = 0.622$, $P = 0.007$, $n = 11$. Non-independent residuals (Durban-Watson test) did not account for the observed relationships. Minimum winter flow indicates the lowest flows during winter. % Total winter flow refers to total winter flow as a percentage of total annual flow. NSC ($P > 0.05$) symbolises non-significant correlations.


The Clarence River estuary
The Hunter River estuary
(a)
Log10(Annual sand whiting CPUE)
1.20
1.00
0.80
0.60
0.40
5.60
6.00
6.40
6.80
Log10(Total annual flowL-3)
(b)
Log10(Annual sand whiting CPUE)
2.60
2.40
2.20
2.00
1.80
5.00
5.50
6.00
Log10(Total annual flowL-3)
(c)
Log10(Annual sand whiting CPUE)
1.20
1.00
0.80
0.60
0.40
2.60
2.80
3.00
3.20
3.40
Log10(Minimum annual flowL-3)
(d)
Log10(Sand whiting CPUE)
2.60
2.40
2.20
2.00
1.80
1.75
2.00
2.25
2.50
2.75
Log10(Minimum annual flowL-3)
(e)
Log10(Annual sand whiting CPUE)
1.20
1.00
0.80
0.60
0.40
3.00
3.50
4.00
Log10(Mean annual flowL-3)
(f)
Log10(Annual sand whiting CPUE)
2.60
2.40
2.20
2.00
1.80
2.50
3.00
3.50
Log10(Mean annual flowL-3)

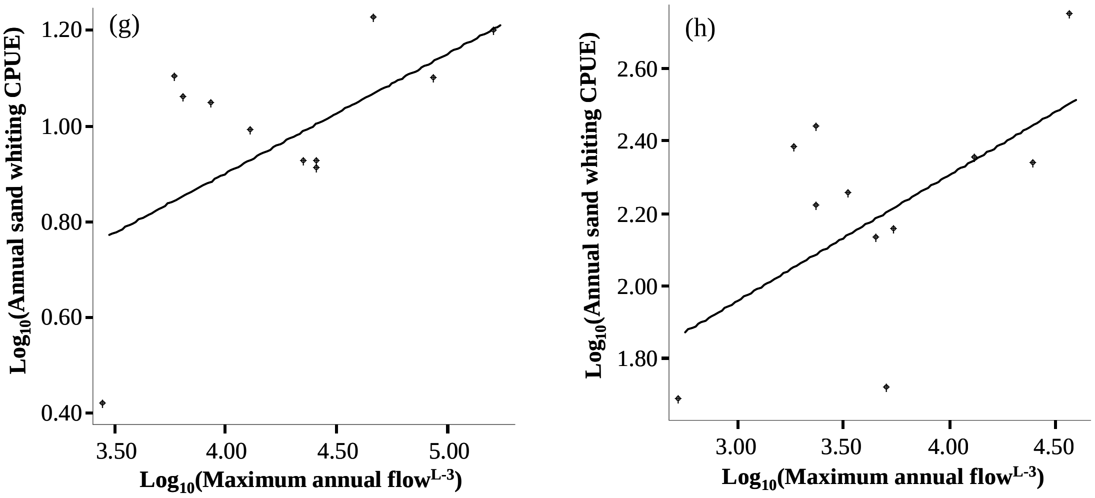


Figure 12. Significant relationships between the annual CPUE of sand whiting and annual flow variables with a three-year lag in the Clarence (a, c, e, and g) and Hunter River (b, d, f and h) estuaries. Regression details are (a) r^2 = 0.340, P = 0.035, n = 11, (b); r^2 = 0.322, P = 0.040, n = 11, (c); r^2 = 0.346, P = 0.047, n = 11, (d); r^2 = 0.222, P = 0.048, n = 11, (e); r^2 = 0.336, P = 0.036, n = 11, (f); r^2 = 0.195, P = 0.045, n = 11, (g); r^2 = 0.301, P = 0.047, n = 11, and (h); r^2 = 0.290, P = 0.042, n = 11. There was no evidence of non-independent residuals (Durban-Watson test). Maximum and minimum annual flow refers to the highest and lowest flows during a year, respectively. A lag period of three years is represented by $^{L-3}$.

3.3.5. Sea mullet

The Clarence River estuary

The monthly CPUE of sea mullet was positively correlated with total monthly flow, minimum monthly flow, mean monthly flow, maximum monthly flow and % maximum monthly flow, and negatively correlated with drought declaration (Appendix 11). Stepwise multiple regression identified three alternative models that explained between 33% and 41% of the variation in monthly CPUE of sea mullet (Table 6). Season was the primary factor that explained the highest proportion of variability in monthly CPUE of sea mullet, with minimum monthly flow added to a second model. Annual CPUE of sea mullet was negatively correlated with maximum autumn flow $^{L-1}$ (Figure 13).

The Hunter River estuary

Monthly CPUE of sea mullet was negatively correlated with drought declaration ($P < 0.0001$). No other significant correlations between CPUE of monthly sea mullet and hydrological variables were detected. Stepwise multiple regression identified two alternative models that explained between 16% and 22% of the variation in monthly CPUE of sea mullet (Table 6). The simplest model that best predicted monthly CPUE of sea mullet contained drought declaration. There was a positive correlation between annual CPUE of sea mullet and % maximum annual flow (Appendix 11). The highest proportion of variability in annual CPUE of sea mullet was explained by positive correlations with total winter flow and % total autumn flow $^{L-3}$ (Figure 13).

3.3.6. Species-aggregated CPUE

The Clarence River estuary

Aggregated monthly CPUE was positively correlated with total monthly flow, minimum monthly flow, mean monthly flow and maximum monthly flow, and negatively correlated with drought declaration (Appendix 12). Stepwise multiple regression identified two alternative models that explained between 36% and 46% of the variation in monthly aggregated CPUE (Table 6). The simplest predictive model containing a hydrological variable was season and minimum monthly flow.

The Hunter River estuary

Monthly aggregated CPUE was positively correlated with total monthly rainfall, total monthly flow, mean monthly flow, maximum monthly flow and % maximum monthly flow, and negatively correlated with drought declaration (Appendix 13). Stepwise multiple regression identified two alternative models that explained between 6% and 10% of the variation in monthly aggregated CPUE (Table 6). The best explanatory variable of monthly aggregated CPUE was drought declaration, with season added to a second model.

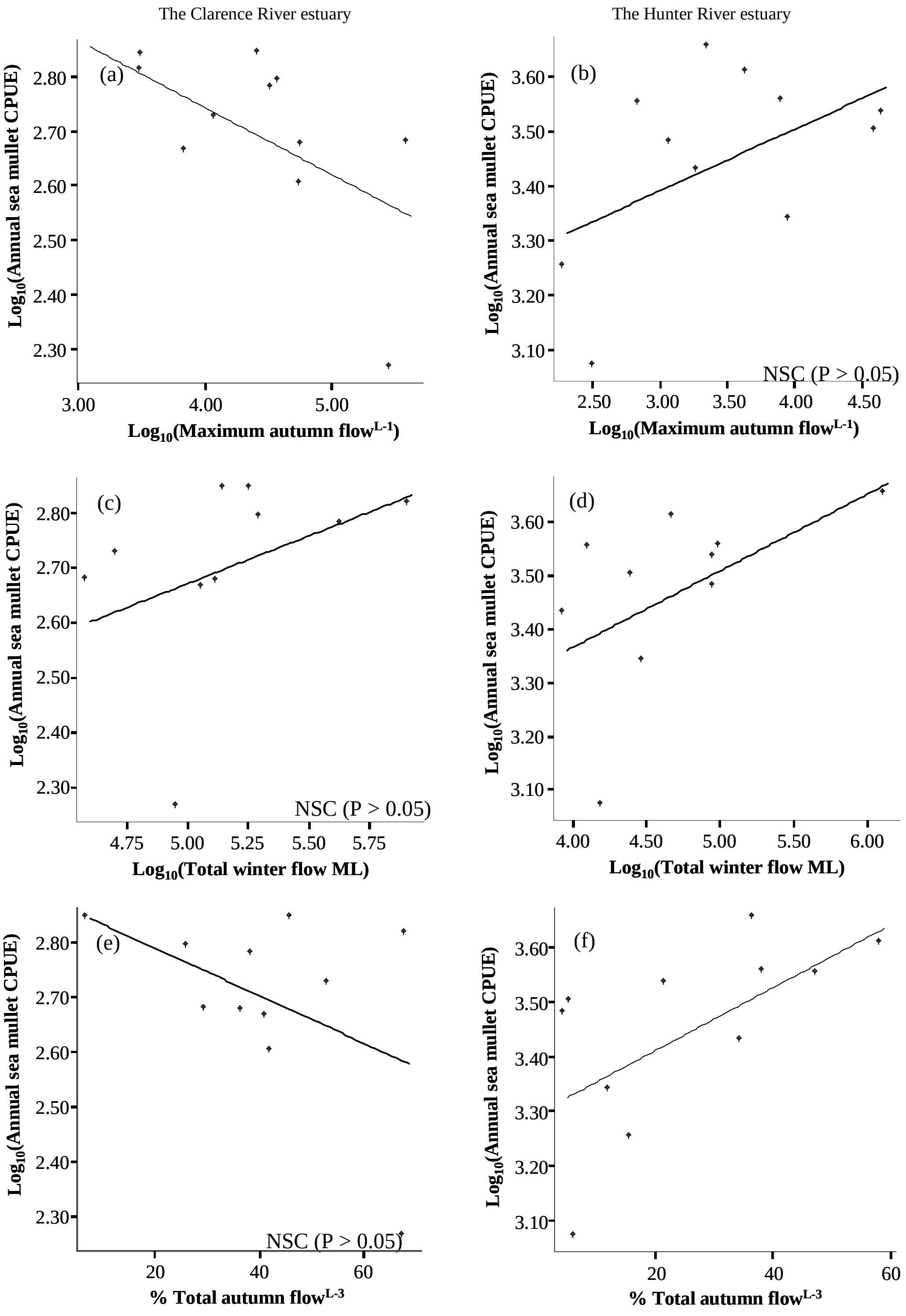


Figure 13. Significant relationships between the annual CPUE of sea mullet and seasonal flow variables in the Clarence (a, c and e) and Hunter (b, d and f) River estuaries. Regression details are (a); $r^2 = 0.312$, $P = 0.043$, $n = 11$, (b); $r^2 = 0.180$, $P = 0.108$, $n = 11$, (c); $r^2 = 0.150$, $P = 0.149$, $n = 11$, (d); $r^2 = 0.201$, $P = 0.032$, $n = 11$, (e); $r^2 = 0.057$, $P = 0.249$, $n = 11$, and (f); 0.374, $P = 0.042$, $n = 11$. There was no evidence of non-independent residuals (Durban-Watson test). Maximum autumn flow indicates the highest flows during autumn. % Total autumn flow refers to total autumn flow as a percentage of total annual flow. A lag period of one and three years is represented by $^{L-1}$ and $^{L-3}$, respectively. NSC ($P > 0.05$) symbolises non-significant correlations.

4. DISCUSSION

Our analysis of comprehensive commercial fisheries and hydrological datasets, obtained from nine estuaries with distinct riverine inputs, has enabled a detailed assessment of the impacts of freshwater flow on estuarine fisheries production in NSW. Fisheries-flow relationships were species, season and estuary specific. Riverine enhancement of fisheries production (see also Loneragan and Bunn 1999, Grimes 2001, Lloret *et al*. 2004, Robins *et al*. 2005) was supported by the results of our analyses, with increased CPUE in months with high freshwater flow. Freshwater flow has a proximate influence on numerous physicochemical attributes in estuaries such as salinity, dissolved oxygen, water temperature, nutrient inputs and sediment delivery (Reddering 1988, Justic *et al*. 1993, Forbes and Cyprus 1993, Baird and Heymans 1996, Eyre 1998). Results from our analyses suggest a hydrological-driven mechanism for estuarine fisheries production via effects on recruitment and catchability. Monthly fisheries-flow relationships yielded relatively low r^2 values. Once seasonality had been factored into the analyses, freshwater flow explained a higher proportion of the variability in fisheries CPUE (from 19 to 70%). Seasonal freshwater flows were the most important aspect of the flow regime that best explained estuarine fisheries production.

Relationships between rainfall, freshwater flow and fisheries CPUE were consistently better (higher r^2 values) for the less regulated Clarence River than the highly regulated Hunter River (Appendix 1 – 3). Total monthly rainfall had significant relationships (positive and negative) with the monthly CPUE of 3/5 fish species in the Clarence River and 0/5 fish species in the Hunter River (Table 6). Furthermore, results from stepwise multiple regression were comparatively better for the Clarence River than the Hunter River estuary. There were also stronger positive relationships between freshwater flow and monthly aggregated CPUE in the Clarence River than the Hunter River estuary (Appendix 13). Together, these results suggest that the strength of fisheries-flow relationships within an estuary may be influenced by the degree of freshwater regulation within the catchment. Freshwater regulation may dampen hydrological extremes, decouple fisheries-flow relationships and hinder the identification of important aspects of the flow regime for maintaining estuarine fisheries production. Some of the variability underlying relationships between estuarine fisheries production and freshwater flow may be related to factors such as bioregion (Pease 1999), estuary type (Roy *et al*. 2001, Saintilan 2004), the degree of freshwater regulation within the catchment (Drinkwater and Frank 1994) and the ecology/life history of individual species (Halliday and Robins 2007).

4.1. Impacts of drought declaration on estuarine fisheries production

The declaration of a drought-affected area was associated with significant reductions in monthly aggregated CPUE in all examined estuaries, except Tuggerah Lakes (+9%) and Lake Illawarra (+22%). Drought-associated reductions in fisheries production were most pronounced in the Camden Haven River (-34%) and St. Georges Basin (-30%) estuaries. These results highlight potential differences in the impacts of drought on estuarine fisheries production in urbanised catchments with differing freshwater inputs. Freshwater flow into Tuggerah Lakes and Lake Illawarra is relatively low compared to other estuaries examined. Drought-induced low flows may result in higher estuarine fisheries production in freshwater deprived systems due to increased catchability resulting from short-term improvements in water quality. Alternatively, drought-induced low flows in river-dominated estuaries may result in lower fisheries production due to decreased catchability resulting from unfavourable water quality characteristics forcing the emigration of estuarine-dependent fishery species into coastal waters.

Species-specific reductions in monthly CPUE were evident for dusky flathead, luderick, sand whiting and sea mullet during periods of drought declaration. Drought is an immediate proximate stressor that deteriorates estuarine water quality and affects biogeochemical processes that underlie ecosystem functioning (Copeland 1966, Attrill and Power 2000, Humphries and Baldwin 2003).

Little is known about the mechanisms underlying population responses to drought (Matthews and Marsh-Matthews 2003). Drought-induced low flows may decrease catchability by stimulating the migration of estuarine-dependent fish to more benign refugia due to alterations in water quality. Reductions in estuarine freshwater inflow can result in unfavourable water quality characteristics that force the emigration of estuarine-dependent fish (Whitfield and Harrison 2003).

Bream were the only species with significantly higher monthly CPUE during periods of drought declaration. The reasons for this are not clear, but are likely to reflect differences in life history strategies. Hereafter, we consider that yellowfin bream make the most significant contribution to our CPUE data in the Clarence and Hunter River estuaries. Not only do yellowfin bream represent the significant majority (~95%) of commercial estuarine landings for this species group in NSW, but also black bream are only found in estuarine waters south of Myall Lakes (Scandol *et al*. 2008). Furthermore, hybridization between black and yellowfin bream is proportionally lower (85% yellowfin bream alleles) in northern NSW estuaries (Roberts *et al*. in press). Yellowfin bream complete their whole life cycle 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). We hypothesise that drought-induced low flows result in the increased catchability of yellowfin bream owing to higher-salinity waters stimulating increased downstream migration. A variety of mechanisms have been proposed for impacts of drought on estuarine biota elsewhere:

- Deterioration of water quality leading to population declines (Attrill and Power 2000).
- Migrational response to more suitable refugia owing to habitat loss (Magoulick and Kobza 2003).
- Food web limitation as a consequence of reduced nutrient inputs (Bennett *et al*. 1995).
- Altered community structure resulting from changes in interspecific competition (Lake 2003).

4.2. Impacts of freshwater flow on the catchability of estuarine fish species

Commercial gillnet CPUE increased with freshwater flow for all species, except bream. Higher freshwater flows may result in increased catchability due to restricting the distribution or stimulating the movement of fish into areas where they are more readily caught (Loneragan and Bunn 1999). Range alterations occur primarily due to freshwater flow changing salinity and turbidity, which creates physiological stress and stimulates the movement of estuarine-dependent fish to more benign conditions (Cyprus and Blaber 1987, Sheaves 1996, Kanandjembo *et al*. 2001). Episodic flow events may force the emigration of estuarine-dependent fish into higher-salinity waters (Whitfield and Harrison 2003). Anecdotal evidence from commercial estuarine fishers suggests that sea mullet may undertake seaward migrations during periods of high freshwater flow, thereby increasing their catchability by passive fishing gear, such as gillnets.

Riverine inputs affect estuarine habitat dynamics and food availability (Bebars and Lessarre 1983, Whitfield and Wooldridge 1994, Livingston *et al.* 1997, Jung and Houde 2003). Negative relationships between the monthly CPUE of bream and freshwater flow could result from alterations in habitat quality and quantity. Yellowfin bream may respond negatively to increased freshwater flow as a result of the seaward displacement of habitat and population centres. Similar responses have been reported for black bream with considerable numbers leaving the Hopkins River estuary in Victoria for sheltered coastal habitats when 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 apparently return to the natal estuary once the rate of freshwater discharge declines (Chaplin *et al.*1998).

Catchability may be related to the seasonality of the fishery, and therefore freshwater flows before or during the main fishing season will potentially have the most pronounced effects. Most catches of dusky flathead occur in winter (Gray *et al*. 2000). Positive relationships between the annual CPUE of dusky flathead and winter flows in the Hunter River estuary may, therefore, be explained by fishing season. Accordingly, our results suggest that freshwater flow may have a pronounced influence on the catchability of estuarine fisheries species due to stimulating migration and schooling into areas where estuarine-dependent fish are more likely to be caught. Higher freshwater flows may result in the increased movement of estuarine-dependent fish owing to lowered salinity. The following mechanism underlying connections between freshwater flow and catchability has been proposed:

- Altered spatial distribution due to migration and schooling resulting from flow-driven changes in habitat availability (Loneragan and Bunn 1999, Kimmerer 2002, Robins *et al*. 2005, Halliday and Robins 2007).

4.3. Impacts of freshwater flow on the spawning movements of estuarine fish species

Aquatic species may have evolved life history strategies primarily in direct response to natural flow regimes (Bunn and Artington 2002). In our study, the best correlations (highest r^2 values) between fisheries CPUE and freshwater flow coincided with spawning periods. Riverine inputs may influence factors that make estuaries suitable spawning areas, feeding habitats and migration routes. Yellowfin bream undertake annual seaward migrations to spawn in coastal surf zones near the mouths of estuaries (Pollock 1982a, 1982b, 1984), typically during winter (Kailola *et al*. 1993). The negative relationship between the annual CPUE of bream and minimum winter flow could, therefore, reflect decreased catchability as a consequence of freshwater flow triggering the seaward spawning migration. Yellowfin bream may move downstream to spawn with a winter freshwater flush, when freshwater rains promote suitable hydrological conditions within an estuary.

The annual CPUE of dusky flathead was positively correlated with maximum spring flow and negatively correlated with percentage total summer flow. Dusky flathead spawn in the lower reaches of estuaries and nearshore coastal waters, typically during summer (Pease *et al*. 1981, Kailola *et al*. 1993). High spring flows may result in increased catchability by triggering the pre-spawning migration, while high summer flows may result in decreased catchability by flushing mature fish into coastal waters.

Minimum winter flow explained 70% of the variation in the annual CPUE of luderick in the Clarence River estuary. Luderick spawn in coastal surf zones near the mouths of estuaries, typically during winter (Kailola *et al*. 1993). Minimum winter flows may result in increased catchability by triggering the downstream spawning migration of luderick.

Mature sea mullet undertake extensive northerly migrations to spawn in coastal waters typically during winter (Kailola *et al*. 1993). Thus, the positive relationship between the annual CPUE of sea mullet and total winter flow in the Hunter River estuary could reflect increased catchability resulting from freshwater flow triggering the spawning migration. Accordingly, our analyses suggest that seasonal flows may have a pronounced influence on estuarine-dependent fishery species by creating windows of opportunity to undertake spawning migrations when optimum conditions arise. Seasonal changes in flow conditions may trigger the spawning migration of mature fish to the lower reaches of an estuary. The stimulus could be seasonal flow-driven changes in salinity, dissolved oxygen, water temperature and turbidity. The following mechanism has been proposed to underlie connections between freshwater flow and the migration of estuarine-dependent fish species:

- Movement triggered by favourable water quality characteristics such as seasonal shifts in salinity, turbidity, dissolved oxygen and water temperature (Whitfield and Wooldridge 1994, Bjorgo *et al*. 2000, Hashemi and Maes 2005).

4.4. Impacts of freshwater flow on the recruitment of estuarine fish species

Effects of freshwater flow on recruitment were suggested when significant correlations between fisheries CPUE and freshwater flow were lagged by a period equalling the appropriate age when a species recruits to the fishery. Variation in freshwater flow can have pronounced impacts on the early life history stages of estuarine-dependent fish (Lloret *et al*. 2001, Quiñones and Montes 2001, Salen-Picard *et al*. 2002, North and Houde 2003, Staunton-Smith *et al*. 2004, Halliday *et al*. 2008). Since yellowfin bream take approximately 4 years to attain sexual maturity (24 cm fork length) in central NSW (Pease *et al*. 1981, Gray *et al*. 2000), the positive relationship between the annual CPUE of bream and percentage total autumn flow with a four-year lag in the Hunter River estuary may indicate a recruitment effect. High autumn flows may improve the survival of yellowfin bream larvae, resulting in an increase in CPUE four years later.

Dusky flathead attain sexually maturity at approximately 3 years or a total length of 32 cm (male) and 38 cm (female) in central NSW (Kailola *et al*. 1993). This corresponds with the observed positive relationships between annual CPUE of dusky flathead and spring flow variables with a three-year lag in the Hunter River estuary. Further relationships between fisheries CPUE and lagged flow variables were identified for luderick (4 year lag), sand whiting (3 year lag) and sea mullet (3 year lag). Together, our results suggest that freshwater flow may have an influence on the recruitment of estuarine-dependent fish. A variety of alternative mechanisms underlying connections between freshwater flow and the recruitment of estuarine fisheries species have been proposed elsewhere. They include:

- Increased nutrient inputs stimulate primary and secondary production, which is mediated via a trophic cascade to fish occupying higher levels in the food chain (Aleem 1972, Bebars and Lessarre 1983, Livingston *et al*. 1997, Loneragan and Bunn 1999, Kimmerer *et al*. 2001, Salen-Picard *et al*. 2002). Elevated food resources may lead to faster growth rates, improved survival and subsequently greater catches (Grimes and Kingsford 1996, Daskalov 1999, Quiñones and Montes 2001, Robins *et al*. 2005, Halliday and Robins 2007, Halliday *et al*. 2008).
- Modification of habitat quality and quantity altering density-dependant mortality (Stevens and Miller 1983).
- Advection (negative effect) or retention (positive effect) of eggs and larvae in nursery habitats (Kimmerer *et al*. 2001).
- Increased predation (negative effect) of young-of the-year (Kimmerer *et al*. 2001).

4.5. Important aspects of the flow regime for maintaining estuarine fisheries production

Minimum and maximum monthly flows explained the highest proportion of variability in fisheries CPUE. Freshwater flow *per se* may not be as important in determining estuarine fisheries production as extremes in the hydrological continuum (Figure 14). Episodic flow events may maintain and enhance biological productivity in estuaries (Cooper 1989, Martin *et al*. 1992, Livingston 1997, Whitfield 2005). Higher minimum flows may stimulate a migrational response due to lowered salinity, while higher maximum flows may stimulate schooling into the lower reaches of an estuary due to flushing. Once the magnitude of freshwater inflow reaches a minimum threshold, it could enhance fisheries production by resulting in increased catchability due to lower salinity water stimulating migration and schooling into areas where estuarine-dependent fish are more readily caught.

Seasonal flows were the most important aspect of the flow regime that determined fisheries CPUE. Results from our analyses were synonymous with other studies that have suggested maintaining seasonal flows may be as important as maintaining the magnitude of flow to determine fisheries production in Australian estuaries (Loneragan and Bunn 1999, Robins *et al*. 2005, Halliday and Robins 2007). High flow events during critical reproductive periods may result in increased catchability due to estuarine-dependent fish species migrating and schooling in preparation for seasonal spawning.

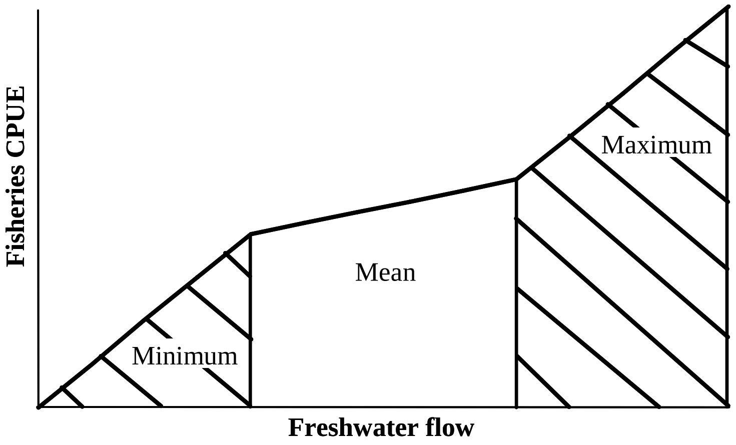


Figure 14. Extremes in the hydrological continuum could be important determinates of estuarine fisheries production. Higher minimum and maximum flows may result in increased catchability due to migration and schooling into areas where estuarine-dependent fish are more readily caught. Minimum flows could trigger fish to migrate downstream due to lowered salinity. Maximum flows may flush schooling fish into the lower reaches of the estuary.

5. CONCLUSIONS

Overall, the results of our analyses suggest that estuarine-dependent fish species are influenced by variation in freshwater flow in ways that affect fisheries production via changes in recruitment and catchability. The impacts of drought on fisheries CPUE are likely to be dependant upon the degree of freshwater input and hydrological characteristics of an estuary. High freshwater flows may result in increased fisheries production due to lower salinity waters stimulating migration and schooling into areas where estuarine-dependent fish are more readily caught. Freshwater flow may regulate physical and biological factors that influence recruitment and survival variability. If the true effects of freshwater flow on estuarine fisheries production are to be identified, future work should consider the influence of riverine inputs during critical reproductive periods. With climatic warming and greater hydrological extremes predicted to continue in Australia (Hughes 2003), improved knowledge of the freshwater flow requirements of estuarine fauna is essential for the development of effective management strategies. It is crucial to understand the role of freshwater flow in determining fisheries production, and consider the wider implications of altered flow regimes on estuarine biodiversity. Although riverine enhancement of estuarine fisheries production was clear in NSW, underlying casual mechanisms were not. Further research is required to provide an increased understanding of how freshwater flow produces such a marked influence on species of estuarine-dependent fish.

6. POSSIBLE LINES OF ADDITIONAL RESEARCH

- Improve quantitative data on freshwater flowing into NSW estuaries. Concentrate on relatively unregulated systems (e.g., the Clarence River) to get the best signal in fisheries-flow relationships.

- Determine causal mechanisms underling connections between estuarine fisheries production and freshwater flow by unravelling physical aspects of flow from nutrient delivery aspects.

- Establish whether catch rates in estuarine fisheries are driven by changes in water physicochemistry (e.g., salinity, turbidity and temperature) linked to variation in freshwater flow.

- Use sonic tagging data to track the migration patterns of commercially important species of estuarine-dependent fish during episodic flow events.

- Provide quantitative information on the minimum freshwater flow requirements of estuarine fisheries and identify important aspects of the flow regime such as the magnitude, frequency, seasonal timing, predictability, duration and rate of change of flow conditions (as per Lytle and Poff 2004).

- Elucidate whether the impacts of drought on fisheries production depend upon the degree of freshwater input and hydrological characteristics of an estuary.

- Perform a multivariate analysis on a suite of estuarine geomorphologies with distinct freshwater inputs and varying degrees of freshwater regulation.

- Confirm a hydrological-driven mechanism for the population dynamics of estuarine-dependent fish using the results of other fishing gears or independent surveys.

- Commence further biological research on the life history of commercially important fishery species to elucidate potential fisheries-flow hypotheses, such as connections between summer flow and the spawning period of dusky flathead.

- Undertake simulation modelling to probabilistically explore potential changes in fisheries production under differing freshwater flow scenarios.

- Use otolith micro-chemistry and elemental analysis to assess patterns of freshwater usage by key species of estuarine-dependent fish in relation to annual and seasonal flows.

- Assess relationships between freshwater flow and recruitment by undertaking otolith aging of key species and looking for relationships between annual flow variables and stronger or weaker than average year classes.

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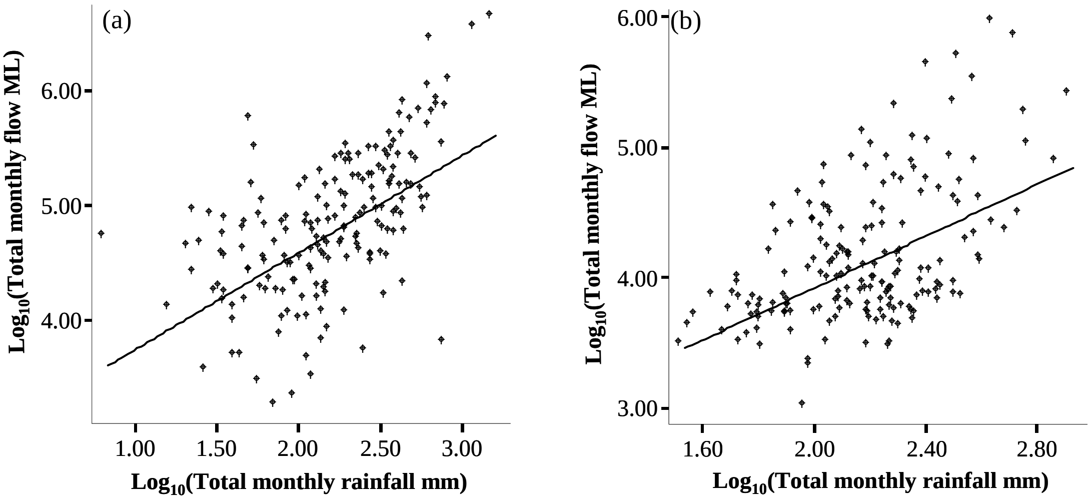
8. APPENDICES



Appendix 1. Significant relationships between total monthly rainfall and freshwater flow in the Clarence (a) and Hunter (b) River systems. Regression details are (a); $r^2 = 0.331$, $P = < 0.0001$, $n = 121$, (b); $r^2 = 0.259$, $P = < 0.0001$, $n = 121$. Non-independent residuals (Durban-Watson test) did not account for relationships between total monthly rainfall and freshwater flow.

Appendix 2. Statistically significant linear regressions for the association between fisheries CPUE and hydrological variables in the Clarence River estuary.

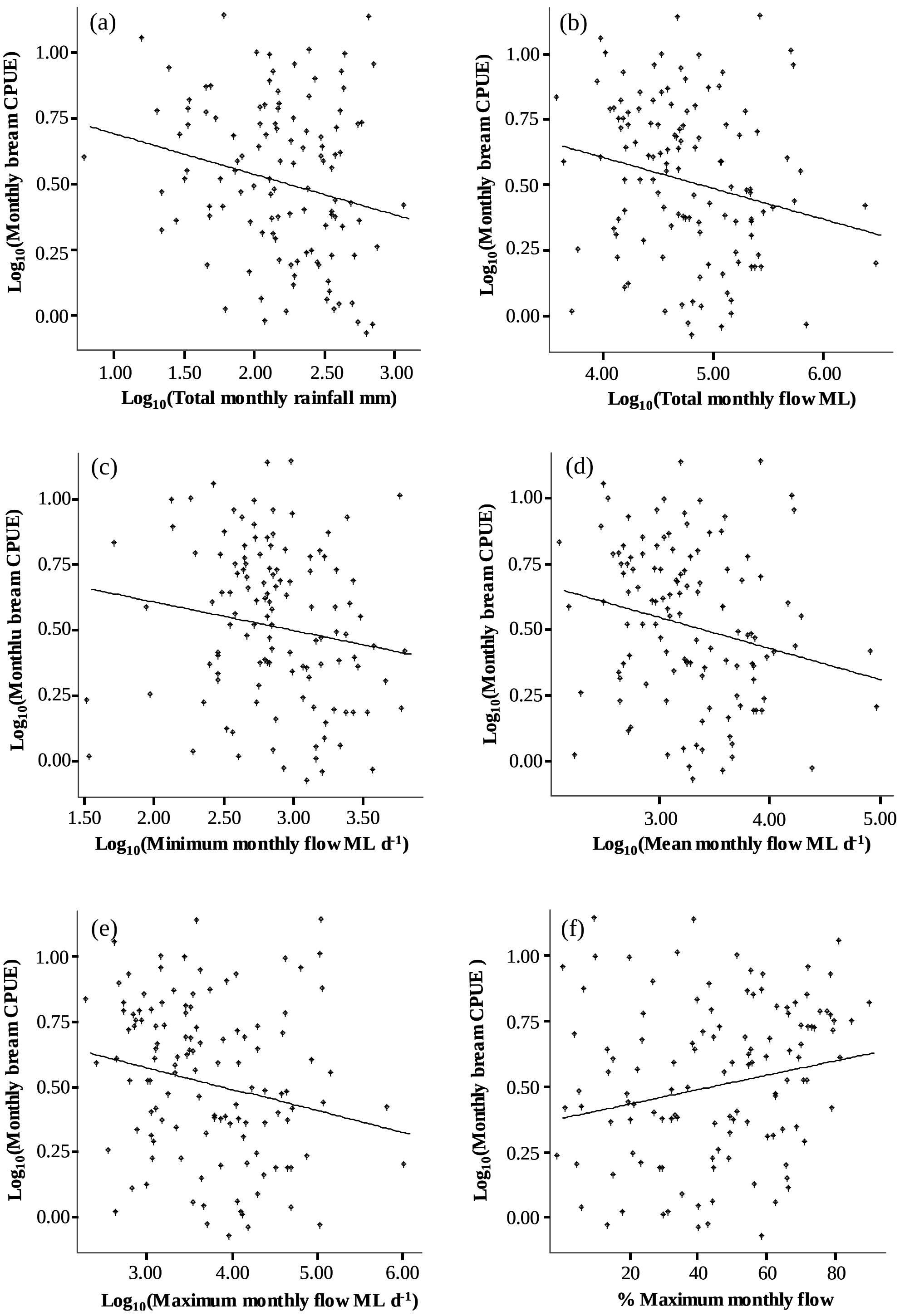
Fisheries measure	Hydrological variable (x)	Regression equation	r^2	*n*	*P*
Log$_{10}$(Monthly bream CPUE)	Log$_{10}$(Total monthly rainfall mm)	$y = 0.85 - 0.15x$	0.040	121	0.017
Log$_{10}$(Monthly bream CPUE)	Log$_{10}$(Total monthly flow ML)	$y = 1.07 - 0.12x$	0.038	121	0.018
Log$_{10}$(Monthly bream CPUE)	Log$_{10}$(Minimum monthly flow ML)	$y = 0.82 - 0.16x$	0.041	121	0.021
Log$_{10}$(Monthly bream CPUE)	Log$_{10}$(Mean monthly flow ML d^{-1})	$y = 0.90 - 0.12x$	0.039	121	0.017
Log$_{10}$(Monthly bream CPUE)	Log$_{10}$(Maximum monthly flow ML d^{-1})	$y = 0.82 - 0.08x$	0.037	121	0.019
Log$_{10}$(Monthly bream CPUE)	% Maximum monthly flow	$y = 0.38 + 0.27x$	0.037	121	0.019
Log$_{10}$(Annual bream CPUE)	% Total summer flow	$y = -0.50 + 1.37x$	0.443	11	0.008
Log$_{10}$(Annual bream CPUE)	Minimum winter flow	$y = 2.97 - 0.46x$	0.506	11	0.015
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Total annual rainfall mm)	$y = -0.60 + 0.56x$	0.430	11	0.028
Log$_{10}$(Annual dusky flathead CPUE)	% Total summer flow	$y = 1.83 - 0.01x$	0.433	11	0.016
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Total spring flow ML)	$y = 0.27 + 0.20x$	0.411	11	0.021
Log$_{10}$(Annual dusky flathead CPUE)	% Total spring flow	$y = 1.23 + 0.01x$	0.252	11	0.039
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Minimum spring flow ML d^{-1})	$y = 0.81 + 0.19x$	0.322	11	0.041
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Mean spring flow ML d^{-1})	$y = 0.67 + 0.20x$	0.411	11	0.021
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Maximum spring flow ML d^{-1})	$y = 0.79 + 0.14x$	0.444	11	0.043
Log$_{10}$(Annual dusky flathead CPUE)	% Total autumn flow $^{L-1}$	$y = 1.53 - 0.01x$	0.351	11	0.032
Log$_{10}$(Monthly luderick CPUE)	Log$_{10}$(Total monthly rainfall mm)	$y = 0.85 + 0.24x$	0.092	121	0.001
Log$_{10}$(Monthly luderick CPUE)	Log$_{10}$(Minimum monthly flow ML d^{-1})	$y = -0.48 + 0.27x$	0.113	121	< 0.0001
Log$_{10}$(Monthly luderick CPUE)	% Maximum monthly flow	$y = 0.02 + 0.60 x$	0.157	121	< 0.0001
Log$_{10}$(Annual luderick CPUE)	Log$_{10}$(Total annual rainfall mm)	$y = -1.36 + 0.81x$	0.325	11	0.039
Log$_{10}$(Annual luderick CPUE)	Log$_{10}$(Total annual flow ML)	$y = -0.90 + 0.38x$	0.380	11	0.026
Log$_{10}$(Annual luderick CPUE)	Log$_{10}$(Minimum annual flow ML d^{-1})	$y = -0.33 + 0.58x$	0.407	11	0.021
Log$_{10}$(Annual luderick CPUE)	Log$_{10}$(Minimum winter flow ML d^{-1})	$y = -0.12 + 0.54x$	0.700	11	0.002
Log$_{10}$(Annual sand whiting CPUE)	Log$_{10}$(Total annual flow $^{L-3}$)	$y = -0.94 + 0.31x$	0.340	11	0.035
Log$_{10}$(Annual sand whiting CPUE)	Log$_{10}$(Minimum annual flow $^{L-3}$)	$y = -0.18 + 0.39x$	0.346	11	0.047
Log$_{10}$(Annual sand whiting CPUE)	Log$_{10}$(Mean annual flow $^{L-3}$)	$y = -0.14 + 0.31x$	0.336	11	0.036
Log$_{10}$(Annual sand whiting CPUE)	Log$_{10}$(Maximum annual flow $^{L-3}$)	$y = -0.10 + 0.25x$	0.301	11	0.047
Log$_{10}$(Monthly sea mullet CPUE)	Log$_{10}$(Total monthly flow ML)	$y = 0.60 + 0.21x$	0.150	121	< 0.0001
Log$_{10}$(Monthly sea mullet CPUE)	Log$_{10}$(Minimum monthly flow ML d^{-1})	$y = 0.91 + 0.24x$	0.151	121	< 0.0001
Log$_{10}$(Monthly sea mullet CPUE)	Log$_{10}$(Mean monthly flow ML d^{-1})	$y = 0.90 + 0.21x$	0.114	121	< 0.0001
Log$_{10}$(Monthly sea mullet CPUE)	Log$_{10}$(Maximum monthly flow ML d^{-1})	$y = 1.10 + 0.13x$	0.125	121	< 0.0001
Log$_{10}$(Monthly sea mullet CPUE)	% Maximum monthly flow	$y = 1.73 + 0.29x$	0.023	121	0.011
Log$_{10}$(Annual sea mullet CPUE)	Log$_{10}$(Maximum autumn flow $^{L-1}$)	$y = 3.24 - 0.12x$	0.312	11	0.043
Log$_{10}$(Monthly aggregated CPUE)	Log$_{10}$(Total monthly flow ML)	$y = 0.97 + 0.15x$	0.171	121	< 0.0001
Log$_{10}$(Monthly aggregated CPUE)	Log$_{10}$(Minimum monthly flow ML d^{-1})	$y = 1.13 + 0.20x$	0.184	121	< 0.0001
Log$_{10}$(Monthly aggregated CPUE)	Log$_{10}$(Mean monthly flow ML d^{-1})	$y = 1.20 + 0.15x$	0.123	121	< 0.0001
Log$_{10}$(Monthly aggregated CPUE)	Log$_{10}$(Maximum monthly flow ML d^{-1})	$y = 1.35 + 0.09x$	0.171	121	< 0.0001

Monthly aggregated CPUE refers to the summed total monthly CPUE for all species combined.

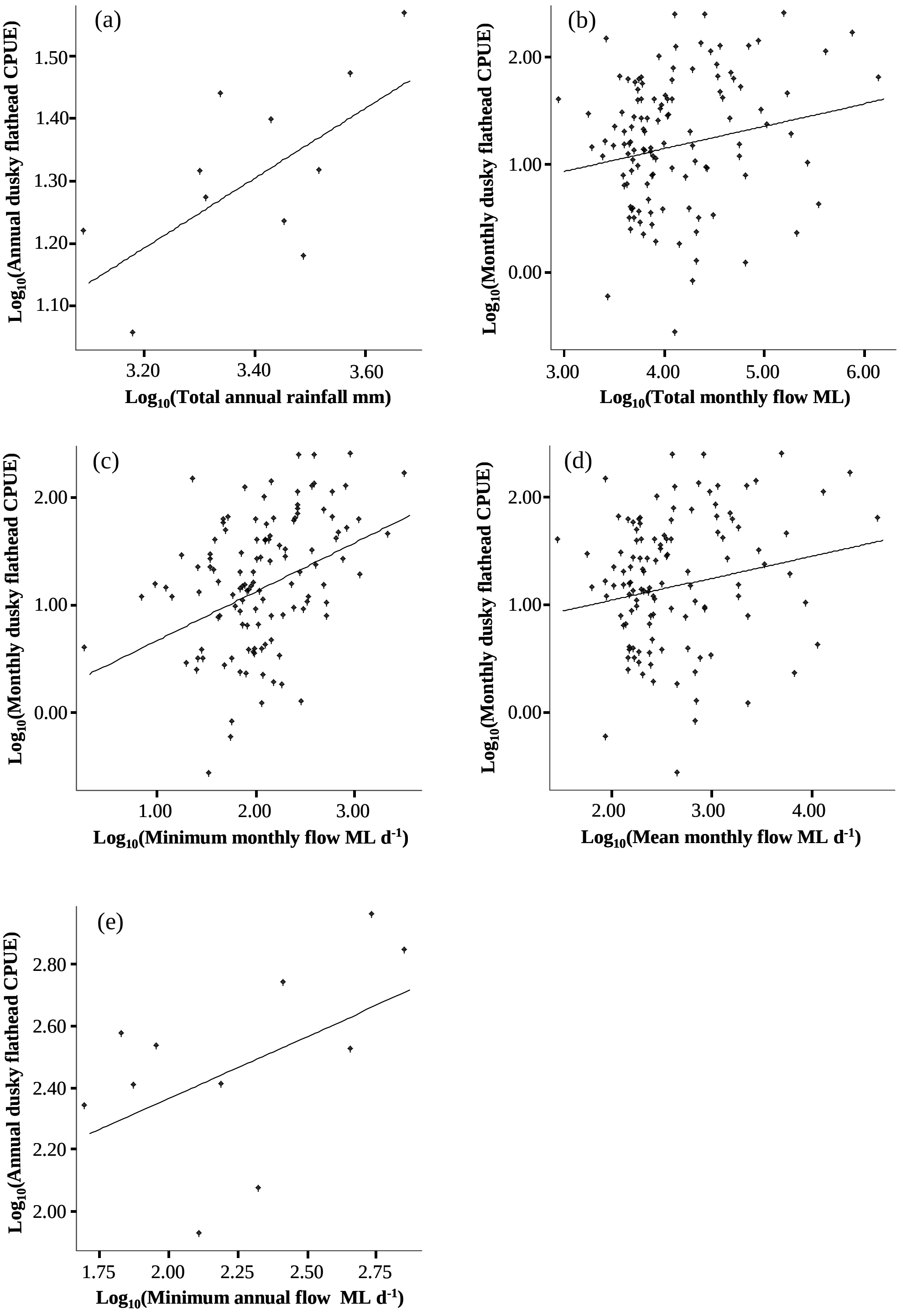
Appendix 3. Statistically significant linear regressions for the association between fisheries CPUE and hydrological variables in the Hunter River estuary.

Fisheries measure	**Hydrological variable (x)**	**Regression equation**	r^2	***n***	***P***
Log$_{10}$(Annual bream CPUE)	% Total summer flow	y = 2.34 + 0.01x	0.260	11	0.042
Log$_{10}$(Annual bream CPUE)	% Total autumn flow^{L-4}	y = 2.29 + 0.01x	0.554	11	0.005
Log$_{10}$(Monthly dusky flathead CPUE)	Log$_{10}$(Total monthly flow ML)	y = 0.31 + 0.21x	0.033	121	0.027
Log$_{10}$(Monthly dusky flathead CPUE)	Log$_{10}$(Minimum monthly flow ML d^{-1})	y = 0.22 + 0.45x	0.147	121	< 0.0001
Log$_{10}$(Monthly dusky flathead CPUE)	Log$_{10}$(Mean monthly flow ML d^{-1})	y = 0.64 + 0.20x	0.030	121	0.032
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Minimum annual flow ML d^{-1})	y = 1.56 + 0.40x	0.180	11	0.023
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Total winter flow ML)	y = 1.07 + 0.31x	0.361	11	0.039
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Minimum winter flow ML d^{-1})	y = 1.68 + 0.36x	0.361	11	0.045
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Mean winter flow ML d^{-1})	y = 1.67 + 0.31x	0.284	11	0.039
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Maximum winter flow ML d^{-1})	y = 1.79 + 0.22x	0.367	11	0.037
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Total annual flow $^{L-3}$)	y = -0.26 + 0.50x	0.473	11	0.012
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Minimum annual flow $^{L-3}$)	y = 1.24 + 0.54x	0.388	11	0.024
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Mean annual flow $^{L-3}$)	y = 0.99 + 0.51x	0.441	11	0.015
Log$_{10}$(Annual dusky flathead CPUE)	Log$_{10}$(Maximum annual flow $^{L-3}$)	y = 0.93 + 0.42x	0.455	11	0.014
Log$_{10}$(Annual dusky flathead CPUE)	Total spring flow $^{L-3}$	y = 0.88 + 0.33x	0.298	11	0.048
Log$_{10}$(Annual dusky flathead CPUE)	Minimum spring flow $^{L-3}$	y = 1.47 + 0.46x	0.523	11	0.007
Log$_{10}$(Monthly luderick CPUE)	Log$_{10}$(Total monthly rainfall mm)	y = 1.57 + 0.25x	0.025	121	0.041
Log$_{10}$(Monthly luderick CPUE)	% Maximum monthly flow	y = 1.15 + 0.80x	0.027	121	0.043
Log$_{10}$(Annual luderick CPUE)	% Total winter flow	y = 2.37 – 0.00x	0.622	11	0.007
Log$_{10}$(Annual luderick CPUE)	Total spring flow $^{L-4}$	y = 3.52 – 0.26x	0.403	11	0.021
Log$_{10}$(Annual luderick CPUE)	% Total spring flow $^{L-4}$	y = 2.50 – 0.01x	0.343	11	0.034
Log$_{10}$(Annual luderick CPUE)	Maximum spring flow $^{L-4}$	y = 3.06 – 0.22x	0.321	11	0.004
Log$_{10}$(Monthly sand whiting CPUE)	Log$_{10}$(Total monthly flow ML)	y = -0.79 + 0.35x	0.045	121	0.013
Log$_{10}$(Monthly sand whiting CPUE)	Log$_{10}$(Minimum monthly flow ML d^{-1})	y = -0.15 + 0.38x	0.046	121	0.014
Log$_{10}$(Monthly sand whiting CPUE)	Log$_{10}$(Mean monthly flow ML d^{-1})	y = -0.26 + 0.34x	0.044	121	0.015
Log$_{10}$(Monthly sand whiting CPUE)	Log$_{10}$(Maximum monthly flow ML d^{-1})	y = -0.07 + 0.23x	0.037	121	0.022
Log$_{10}$(Annual sand whiting CPUE)	Log$_{10}$(Total annual flow $^{L-3}$)	y = 0.20 + 0.37x	0.322	11	0.040
Log$_{10}$(Annual sand whiting CPUE)	Log$_{10}$(Minimum annual flow $^{L-3}$)	y = 1.38 + 0.36x	0.222	11	0.048
Log$_{10}$(Annual sand whiting CPUE)	Log$_{10}$(Mean annual flow $^{L-3}$)	y = 1.11 + 0.38x	0.195	11	0.045
Log$_{10}$(Annual sand whiting CPUE)	Log$_{10}$(Maximum annual flow $^{L-3}$)	y = 0.91 + 0.35x	0.290	11	0.042
Log$_{10}$(Annual sea mullet CPUE)	% Maximum annual flow	y = 2.11 + 2.82x	0.263	11	0.041
Log$_{10}$(Annual sea mullet CPUE)	Log$_{10}$(Total winter flow ML)	y = 2.79 + 0.14x	0.201	11	0.032
Log$_{10}$(Annual sea mullet CPUE)	% Total autumn flow $^{L-3}$	y = 3.30 + 0.01x	0.374	11	0.042
Log$_{10}$(Monthly aggregated CPUE)	Log$_{10}$(Total monthly rainfall mm)	y = 2.29 + 0.10x	0.031	121	0.031
Log$_{10}$(Monthly aggregated CPUE)	Log$_{10}$(Total monthly flow ML)	y = 2.28 + 0.06x	0.015	121	0.023
Log$_{10}$(Monthly aggregated CPUE)	Log$_{10}$(Mean monthly flow ML d^{-1})	y = 2.36 + 0.06x	0.015	121	0.045
Log$_{10}$(Monthly aggregated CPUE)	Log$_{10}$(Maximum monthly flow ML d^{-1})	y = 2.37 + 0.05x	0.020	121	0.043
Log$_{10}$(Monthly aggregated CPUE)	% Maximum monthly flow	y = 2.48 + 0.29x	0.016	121	0.040

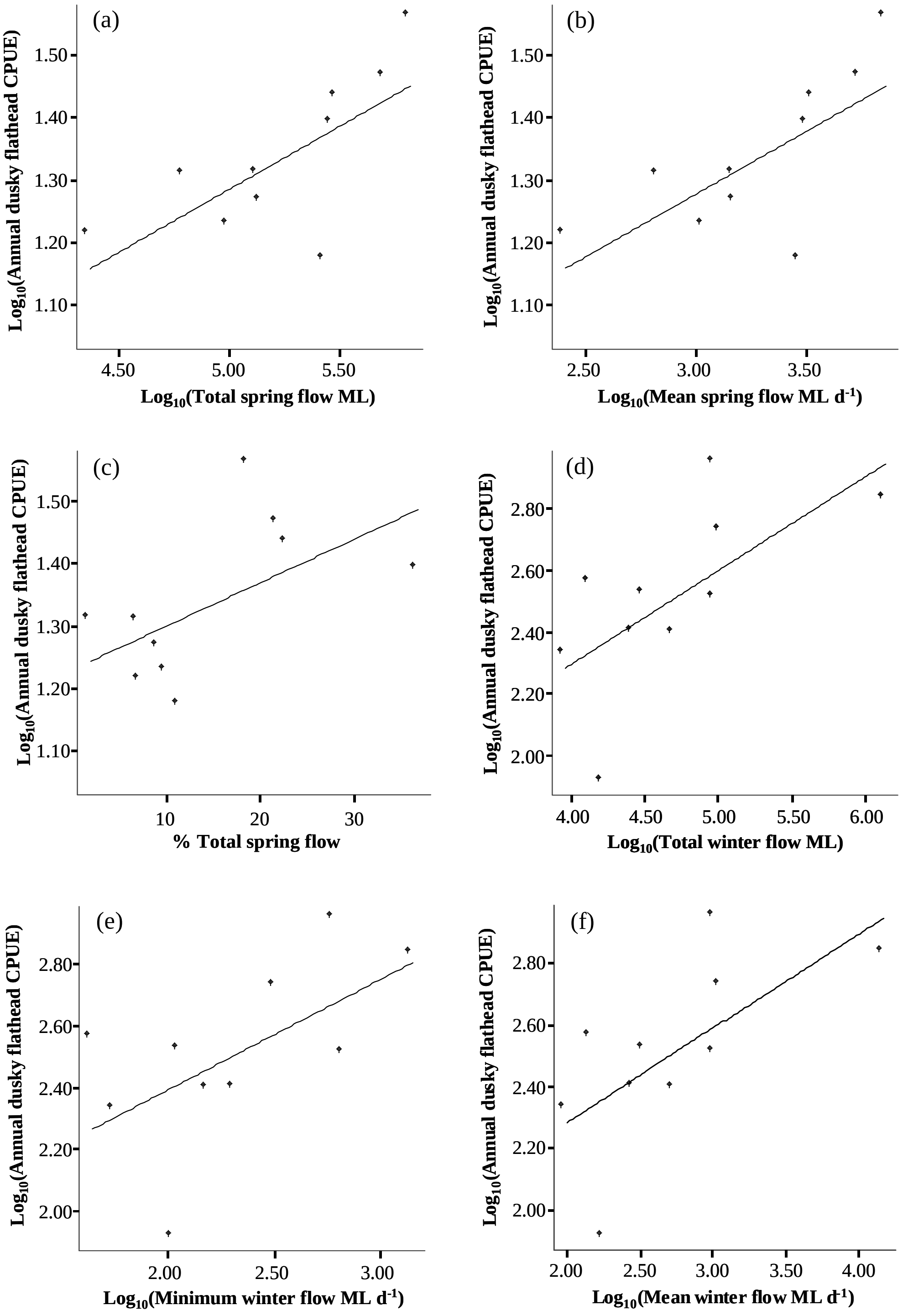
Monthly aggregated CPUE refers to the summed total monthly CPUE for all species combined.



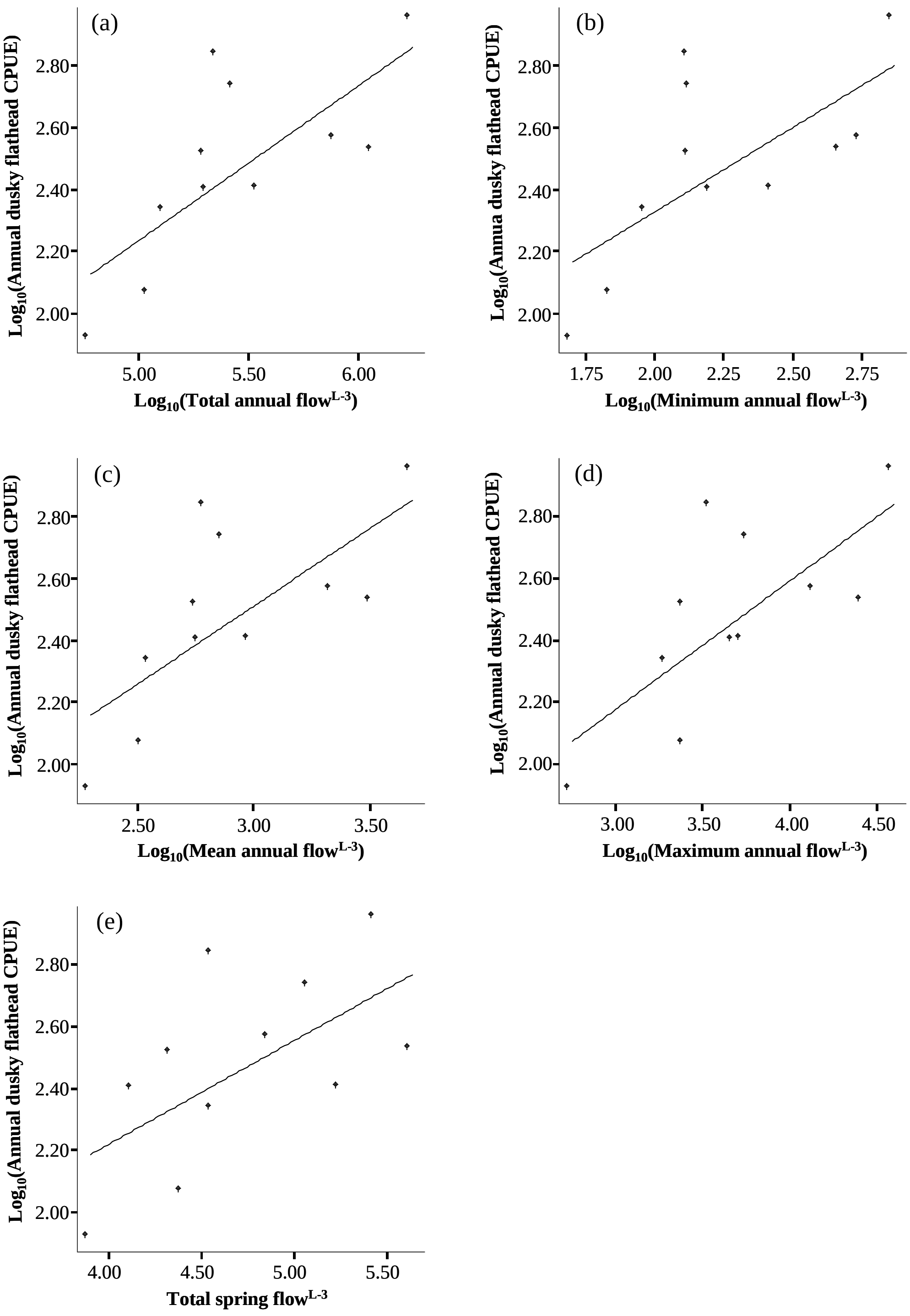
Appendix 4. Significant relationships between the monthly CPUE of bream and rainfall and freshwater flow in the Clarence River estuary. Regression details are (a); r^2 = 0.040, P = 0.017, n = 121, (b); r^2 = 0.038, P = 0.018, n = 121, (c); r^2 = 0.041, P = 0.021, n = 121, (d); r^2 = 0.039, P = 0.017, n = 121, (e); r^2 = 0.037, P = 0.019, n = 121, and (f); r^2 = 0.037, P = 0.019, n = 121. Non-independent residuals (Durban-Watson test) did not account for observed relationships. Minimum monthly flow refers to the lowest flows during a month. Maximum monthly flow indicates the highest flows during a month. % Maximum monthly flow represents maximum flow as a percentage of total flow for that month.



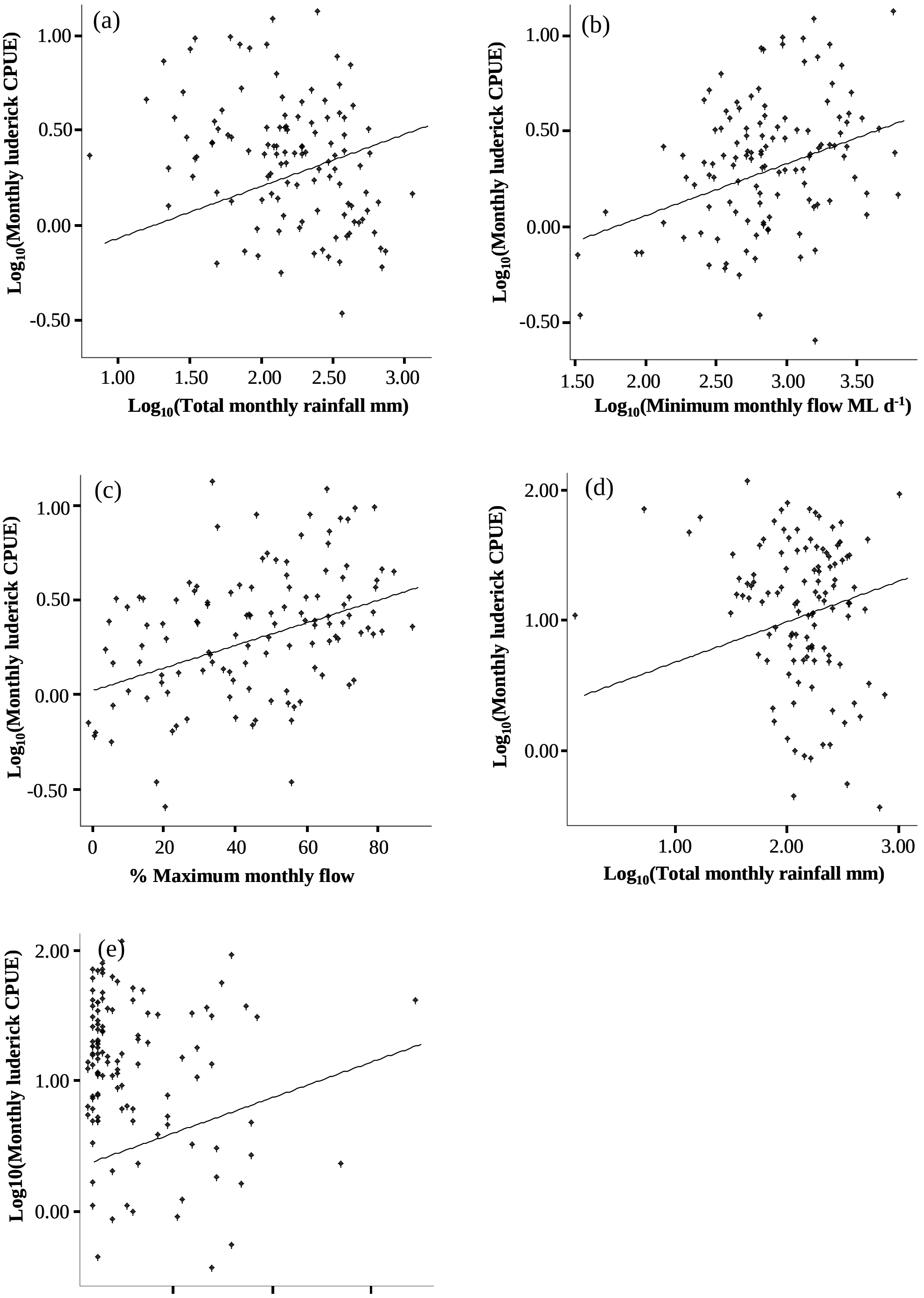
Appendix 5. Significant relationships between the CPUE of dusky flathead and rainfall and freshwater flow in the Clarence (a) and Hunter River estuaries (b, c, d and e). Regression details are (a); $r^2 = 0.430$, $P = 0.028$, $n = 11$, (b); $r^2 = 0.033$, $P = 0.027$, $n = 121$, (c); $r^2 = 0.147$, $P < 0.0001$, $n = 121$, (d); $r^2 = 0.030$, $P = 0.032$, $n = 121$, and (e); $r^2 = 0.180$, $P = 0.023$, $n = 11$. There was no evidence of non-independent residuals (Durban-Watson test). Minimum monthly flow and minimum annual flow refer to the lowest flows during that time period.



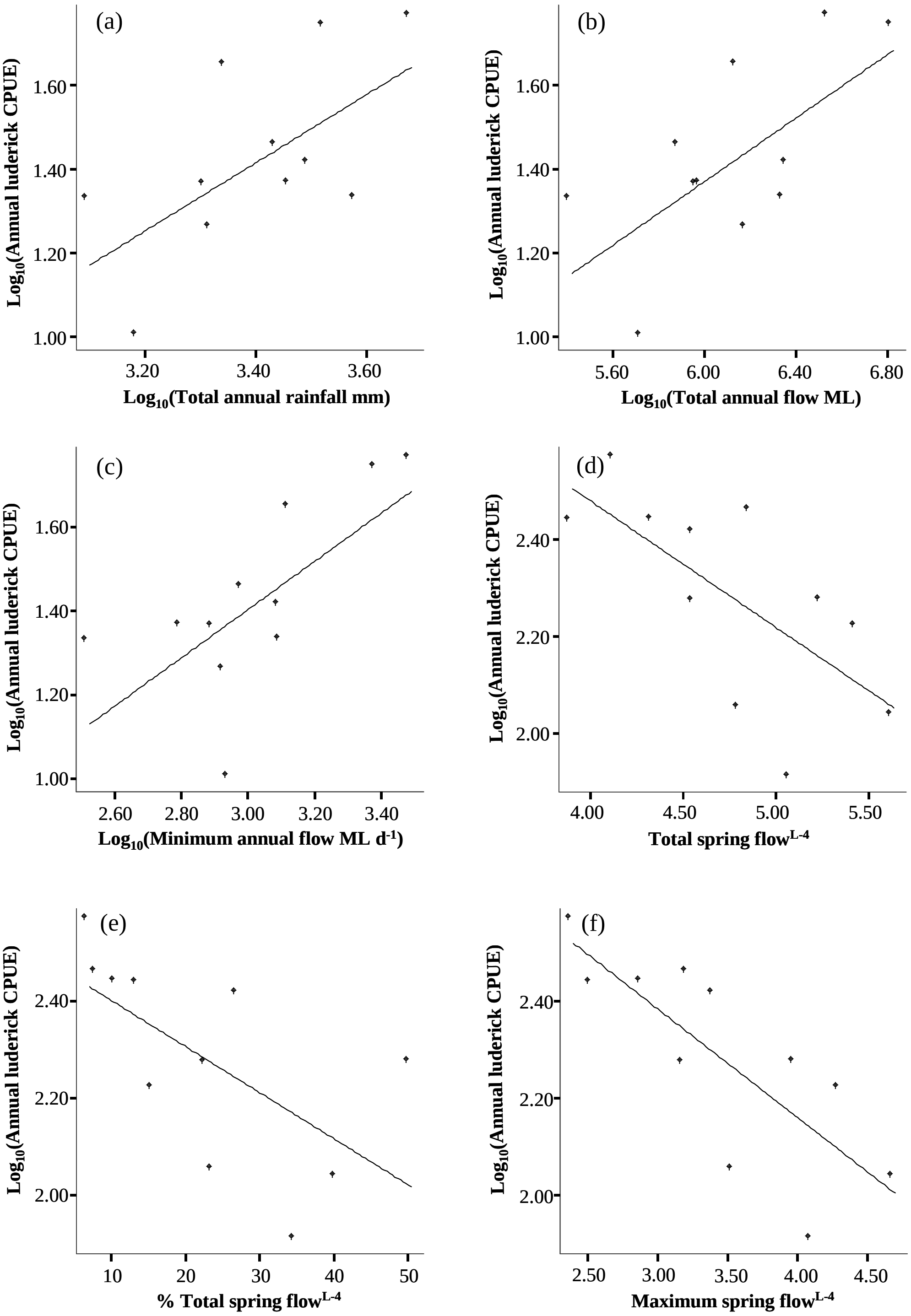
Appendix 6. Significant relationships between the annual CPUE of dusky flathead and seasonal flow variables in the Clarence (a, b and c) and Hunter River estuaries (d, e and f). Regression details are (a); $r^2 = 0.411$, $P = 0.021$, $n = 11$, (b); $r^2 = 0.411$, $P = 0.021$, $n = 11$, (c); $r^2 = 0.252$, $P = 0.039$, $n = 11$, (d); $r^2 = 0.361$, $P = 0.039$, $n = 11$, (e); $r^2 = 0.361$, $P = 0.045$, $n = 11$, and (f); $r^2 = 0.284$, $P = 0.039$, $n = 11$. Non-independent residuals (Durban-Watson test) did not account for observed relationships. % Total spring flow refers to total spring flow as a percentage of total annual flow. Minimum winter flow indicates the lowest flows during winter.



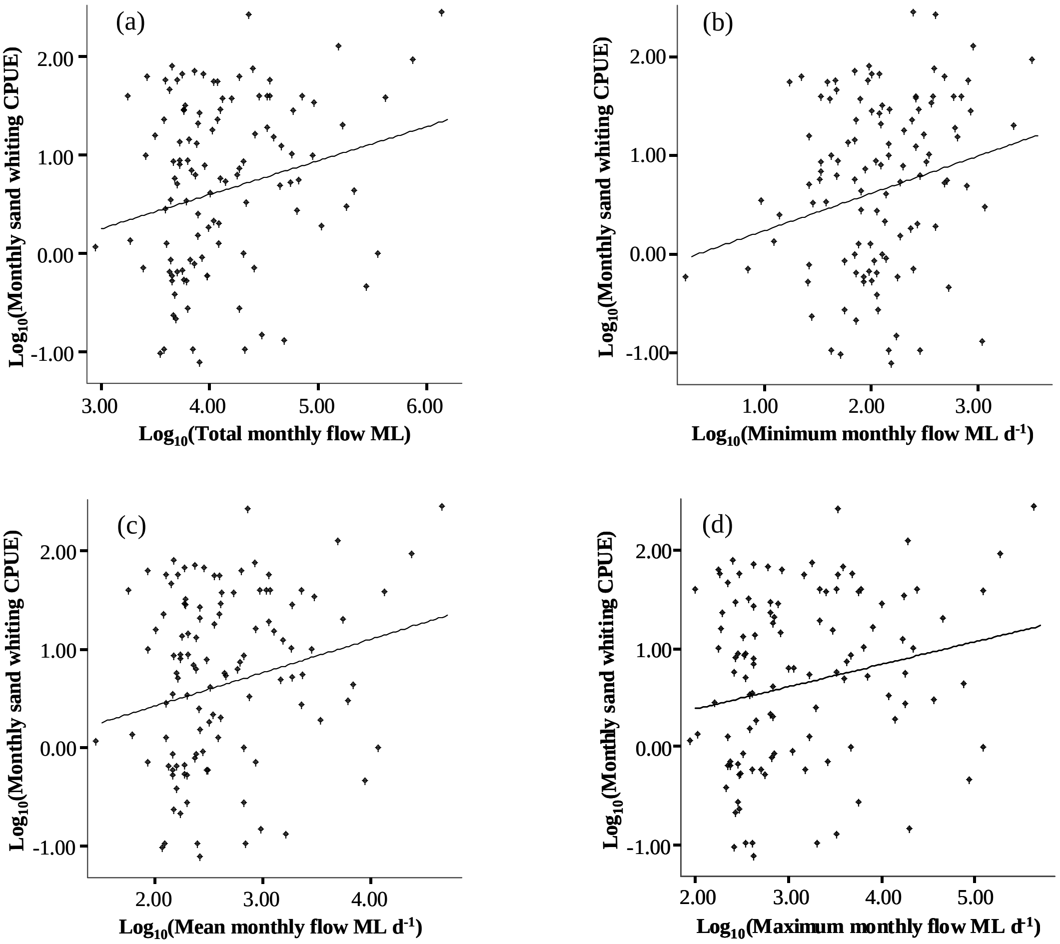
Appendix 7. Significant relationships between the annual CPUE of dusky flathead and freshwater flow variables with a three-year lag in the Hunter River estuary. Regression details are (a); $r^2 = 0.473$, $P = 0.012$, $n = 11$, (b); $r^2 = 0.388$, $P = 0.024$, $n = 11$, (c); $r^2 = 0.441$, $P = 0.015$, $n = 11$, (d); $r^2 = 0.455$, $P = 0.014$, $n = 11$, and (e); $r^2 = 0.298$, $P = 0.048$, $n = 11$. There was no evidence of non-independent residuals (Durban-Watson test). Minimum annual flow refers to the lowest flows during a year. Maximum annual flow indicates the highest flows during a year. A lag period of three years is represented by $^{L\text{-}3}$.



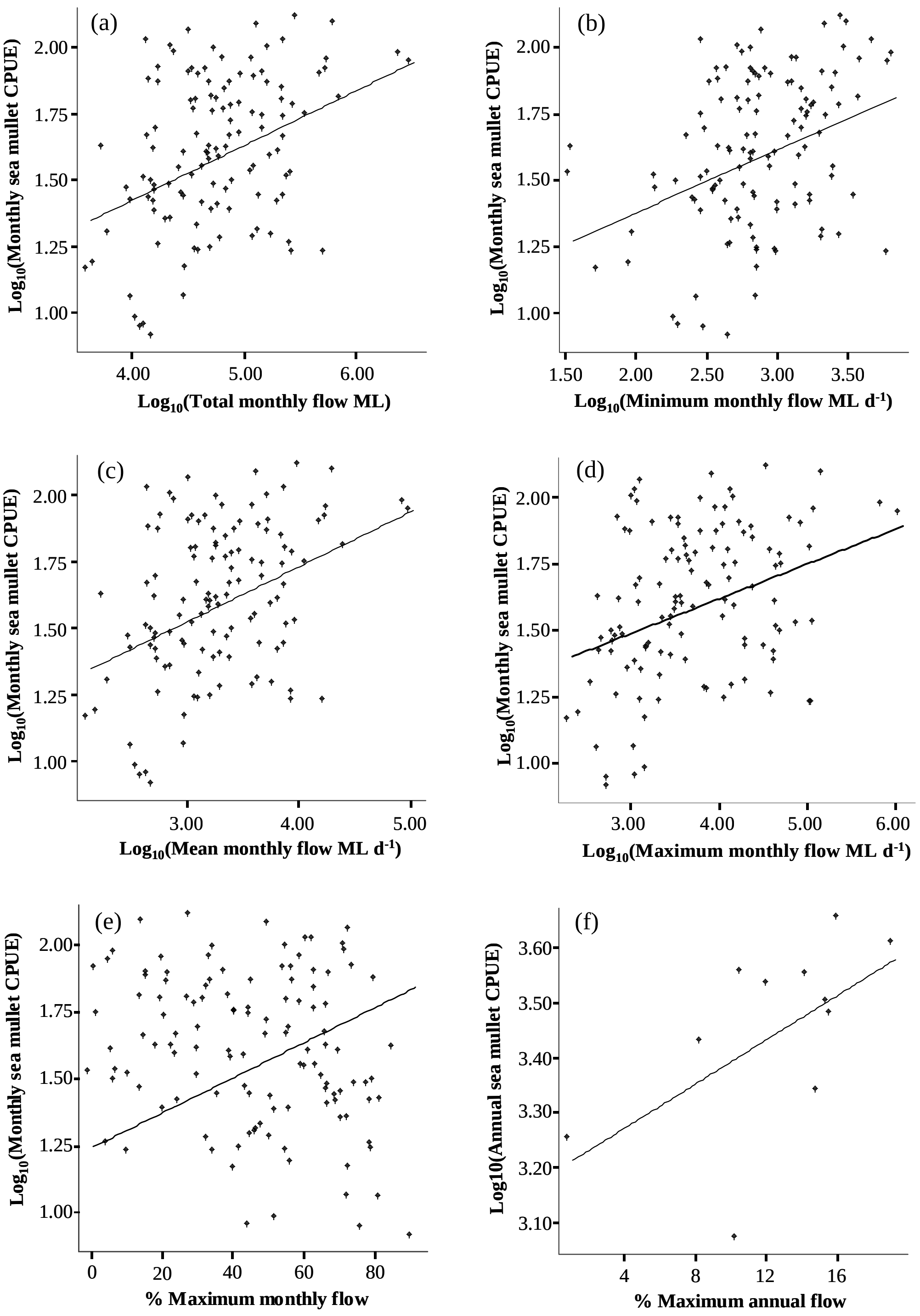
Appendix 8. Significant relationships between the monthly CPUE of luderick and rainfall and freshwater flow in the Clarence (a, b and c) and Hunter River (d and e) estuaries. Regression details are (a); $r^2 = 0.092$, $P = 0.001$, $n = 121$, (b); $r^2 = 0.113$, $P = < 0.0001$, $n = 121$, (c); $r^2 = 0.157$, $P = < 0.0001$, $n = 121$, (d); $r^2 = 0.025$, $P = 0.041$, $n = 121$, and (e); $r^2 = 0.027$, $P = 0.043$, $n = 121$. Non-independent residuals (Durban-Watson test) did not account for observed relationships. Minimum monthly flow refers to the lowest flows during a month. % Maximum monthly flow represents maximum flow as a percentage of total flow during that month.



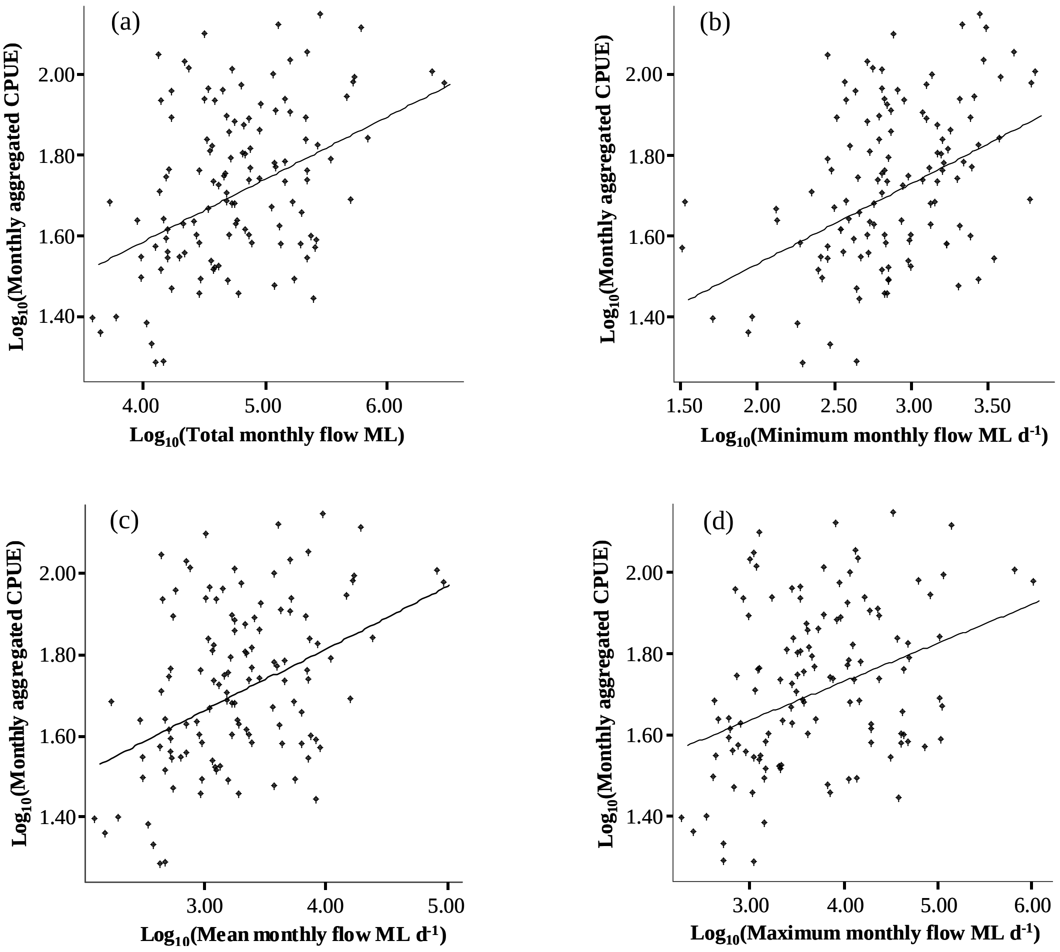
Appendix 9. Significant relationships between the annual CPUE of luderick and rainfall and freshwater flow variables in the Clarence (a, b and c) and Hunter River (d, e and f) estuaries. Regression details are (a); r^2 = 0.325, P = 0.039, n = 11, (b); r^2 = 0.380, P = 0.026, n = 11, (c); r^2 = 0.407, P = 0.021, n = 11, (d); r^2 = 0.403, P = 0.021, n = 11, (e); r^2 = 0.343, P = 0.034, n = 11, and (f); r^2 = 0.321, P = 0.004, n = 11. There was no evidence of non-independent residuals (Durban-Watson test). Minimum annual flow refers to the lowest flows during a year. Maximum spring flow indicates the highest flows during spring. % Total spring flow refers to total spring flow as a percentage of total annual flow. A lag period of four years is represented by $^{L-4}$.



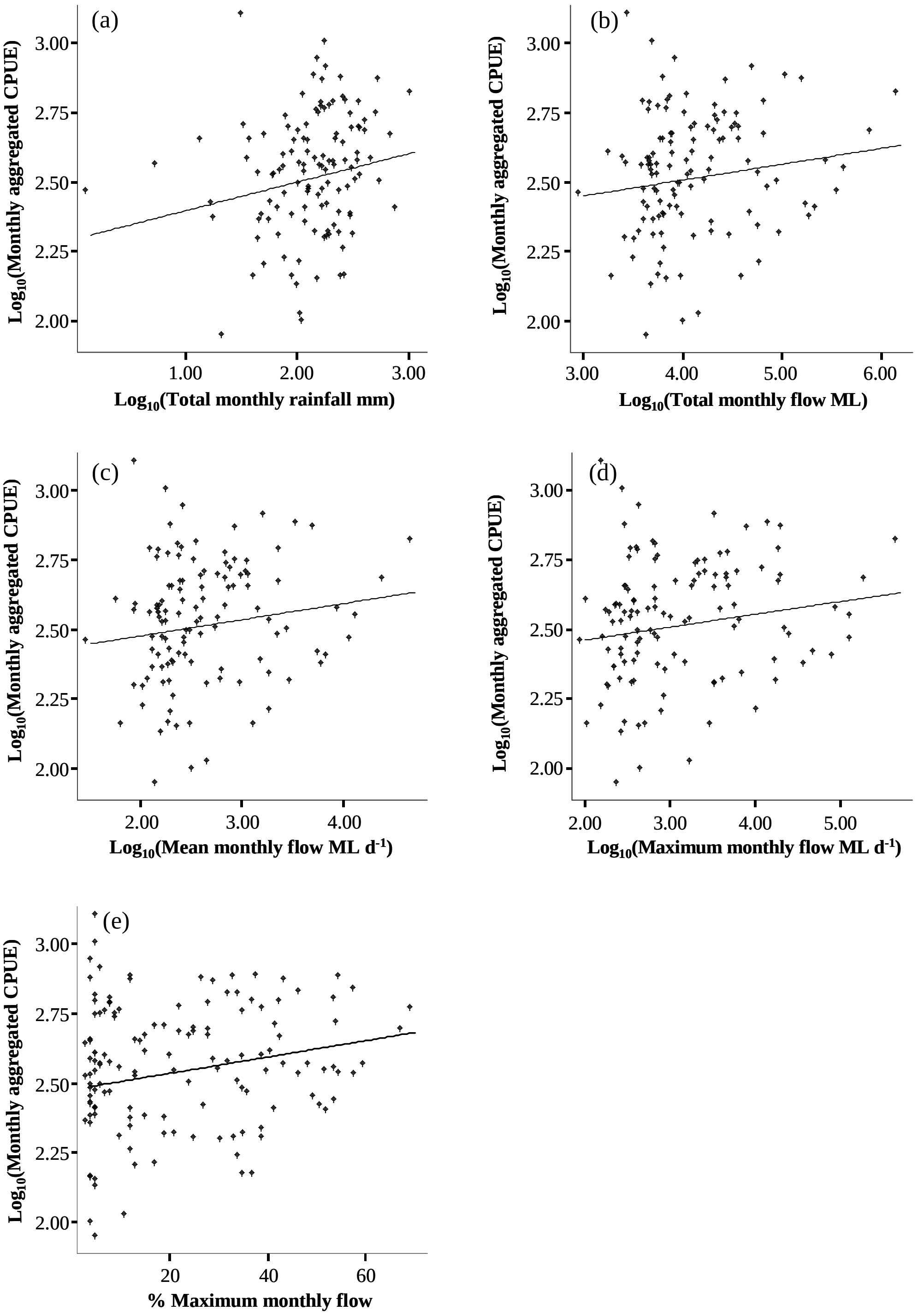
Appendix 10. Significant relationships between the monthly CPUE of sand whiting and freshwater flow variables in the Hunter River estuary. Regression details are (a); $r^2 = 0.045$, $P = 0.013$, $n = 121$, (b); $r^2 = 0.046$, $P = 0.014$, $n = 121$, (c); $r^2 = 0.044$, $P = 0.015$, $n = 121$, and (d); $r^2 = 0.037$, $P = 0.022$, $n = 121$. Non-independent residuals (Durban-Watson test) did not account for observed relationships. Minimum monthly flow refers to the lowest flows during a month. Maximum monthly flow indicates the highest flows during a month.



Appendix 11. Significant relationships between the CPUE of sea mullet and freshwater flow variables in the Clarence (a, b, c, d and e) and Hunter River (f) estuaries. Regression details are (a); $r^2 = 0.150$, $P < 0.0001$, $n = 121$, (b); $r^2 = 0.151$, $P < 0.0001$, $n = 121$, (c); $r^2 = 0.114$, $P < 0.0001$, $n = 121$, (d); $r^2 = 0.125$, $P < 0.0001$, $n = 121$, (e); $r^2 = 0.023$, $P = 0.011$, $n = 121$, and (f); $r^2 = 0.263$, $P = 0.041$, $n = 11$. There was no evidence of non-independent residuals (Durban-Watson test). Minimum monthly flow refers to the lowest flows during a month. Maximum monthly flow indicates the highest flows during a month. % Maximum monthly and % Maximum annual flow represent maximum flow and as percentage of total flow for that month or year, respectively.



Appendix 12. Significant relationships between monthly aggregated CPUE and freshwater flow in the Clarence River estuary. Regression details are (a); $r^2 = 0.171$, $P < 0.0001$, $n = 121$, (b); $r^2 = 0.184$, $P < 0.0001$, $n = 121$, (c); $r^2 = 0.123$, $P < 0.0001$, $n = 121$, and (d); $r^2 = 0.171$, $P < 0.0001$, $n = 121$. Non-independent residuals (Durban-Watson test) did not account for observed relationships. Monthly aggregated CPUE refers to the summed total monthly CPUE for all species combined. Minimum monthly flow represents the lowest flows during a month. Maximum monthly flow indicates the highest flows during a month.



Appendix 13. Significant relationships between monthly aggregated CPUE and freshwater flow in the Hunter River estuary. Regression details are (a); r^2 = 0.031, *P* = 0.031, *n* = 121, (b); r^2 = 0.015, *P* = 0.023, *n* = 121, (c); r^2 = 0.015, *P* = 0.045, *n* = 121, (d); r^2 = 0.020, *P* = 0.043, *n* = 121, and (e); r^2 = 0.016, *P* = 0.040, *n* = 121. There was no evidence of non-independent residuals (Durban-Watson test). Monthly aggregated CPUE refers to the summed total monthly CPUE for all species combined. Maximum monthly flow indicates the highest flows during a month. % Maximum monthly flow represents maximum flow as a percentage of total flow during a month.

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