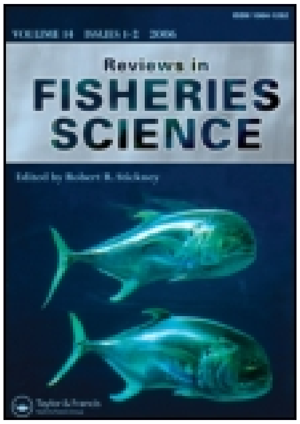

Reviews in Fisheries Science
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/brfs20

Freshwater Flow and Fisheries Production in Estuarine and Coastal Systems: Where a Drop of Rain Is Not Lost

Jonathan Gillson [a]

[a] Fisheries and Marine Environmental Research Facility, School of Biological, Earth and Environmental Sciences, University of New South Wales, NSW, Australia

Available online: 05 Apr 2011

To cite this article: Jonathan Gillson (2011): Freshwater Flow and Fisheries Production in Estuarine and Coastal Systems: Where a Drop of Rain Is Not Lost, Reviews in Fisheries Science, 19:3, 168-186

To link to this article: http://dx.doi.org/10.1080/10641262.2011.560690

Reviews in Fisheries Science, 19(3):168–186, 2011

ISSN: 1064-1262 print / 1547-6553 online
DOI: 10.1080/10641262.2011.560690

Taylor & Francis
Taylor & Francis Group

Freshwater Flow and Fisheries Production in Estuarine and Coastal Systems: Where a Drop of Rain Is Not Lost

JONATHAN GILLSON

Fisheries and Marine Environmental Research Facility, School of Biological, Earth and Environmental Sciences, University of New South Wales, NSW, Australia

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

Keywords freshwater flow, fisheries production, river regulation, climate change

INTRODUCTION

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

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

Address correspondence to Jonathan Gillson, Fisheries and Marine Environmental Research Facility, School of Biological, Earth and Environmental Sciences, University of New South Wales, Kensington, Sydney, NSW 2052, Australia. E-mail: jonathan.gillson@unsw.edu.au

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

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

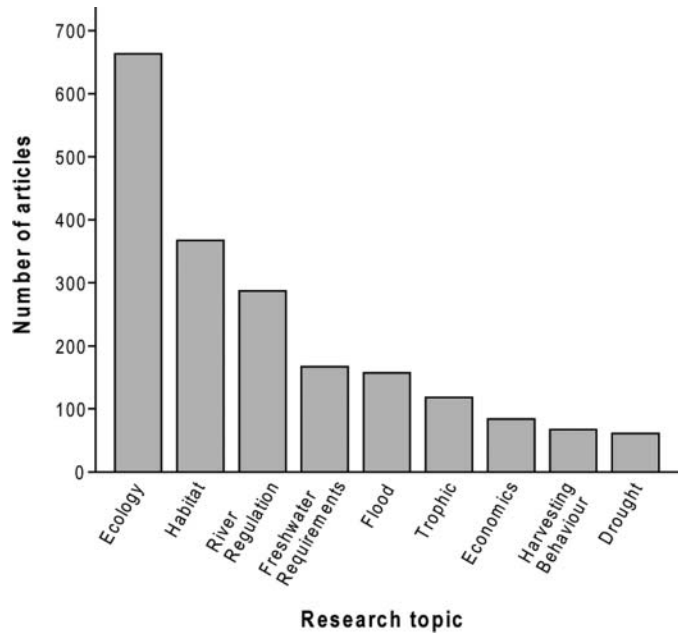

Figure 1 A summary of published articles examining the impacts of freshwater flow (or rainfall) on fishery-related research topics in estuarine and coastal systems from 1910 to 2010. A comprehensive search of 5 scientific databases (CSA Illumina, Geobase, ISI Web of Science, Scopus, and OvidSP) identified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

NATURE OF FRESHWATER FLOWS

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

Climatic variability influences the quantity of freshwater entering estuarine and coastal systems by altering rainfall and evaporation rates. Teleconnection patterns are atmospheric circulation systems that influence climatic conditions over vast geographic areas (Barnston and Livezey, 1987). One of the most prominent teleconnection patterns is the North Atlantic Oscillation (NAO) in the Northern Hemisphere (Rogers, 1984; Hurrell, 1995; Hurrell et al., 2003). The NAO is a driving force of climatic systems that strongly influences rainfall, air temperature, and river flow (Hurrell and Van Loon, 1997; McHugh and Rogers, 2001; Rîmbu et al., 2002). Another

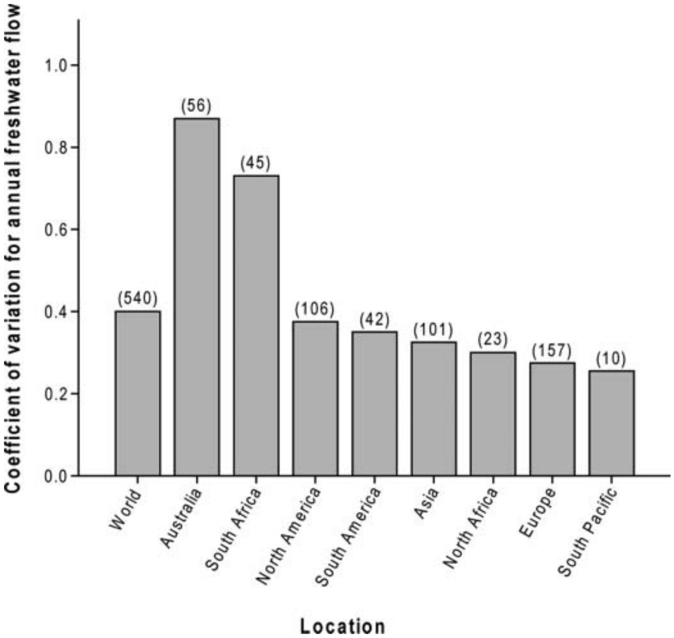

Figure 2 A global comparison of the coefficient of variation for annual freshwater flow in river catchments greater than 1,000 km^2. The number of river systems examined in each location is shown in parentheses above each bar (modified from Finlayson and McMahon, 1988).

prominent teleconnection pattern is the El Niño Southern Oscillation (ENSO), which exerts a profound influence on rainfall, air temperature, and river flow in the southern hemisphere (Kuhnel et al., 1990; Molles and Dahm, 1990; Allan et al., 1996). Rainfall in Australia and southern Africa are also related to sea surface temperature oscillations in the central pacific (Power et al., 1999; Reason and Rouault, 2002) and the Indian Ocean (Landman and Mason, 1999; Ashok et al., 2003).

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

ANTHROPOGENIC MODIFICATION OF FRESHWATER FLOW

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

Aquatic species have evolved life history strategies in direct response to natural flow regimes (Bunn and Arthington, 2002). Modification of freshwater flow impacts the distribution, abundance, and species composition of fish and invertebrates in estuarine and coastal systems (Drinkwater and Frank, 1994). Impacts are most pronounced for anadromous species that require longitudinal and lateral connectivity between marine and freshwater habitats to migrate into riverine spawning grounds. On the Pacific coast of North America, for example, more than 75% of the original 2,500 km of spawning and rearing habitat for chinook salmon (*Oncorhynchus tshawytscha*) has been eliminated due to the construction of an extensive network of hydroelectric dams in the Columbia River basin (Dauble and Geist, 2000). In southeastern Australia, stream impoundments have obstructed almost half of the aquatic habitat for migratory fish in coastal drainages (Harris, 1984). Habitat destruction due to modified flow regimes can remove environmental cues required for migration (Zale and Adornato, 1996), lower species diversity (Plumstead, 1990), and create inimical conditions for native biota favoring the colonization of exotic species (Bunn and Arthington, 2002). Protecting natural flow regimes is an essential requirement for the conservation of estuarine and coastal systems (Sklar and Browder, 1998; Grange et al., 2000; Whitfield and Taylor, 2009).

Commercial fisheries are under increasing threat from river regulation modifying the delivery of freshwater into estuarine and coastal systems. Numerous examples of the major, irreversible impacts of river regulation on commercial fisheries exist worldwide (e.g., the Mediterranean Sea—Aleem, 1972; the Gulf of Mexico—Sklar and Browder, 1998; and the Caribbean Sea—Baisre and Arboleya, 2006). A striking example of the consequences of modifying the delivery of freshwater into estuarine and coastal systems has been provided by the construction of the Aswan High Dam in the Mediterranean Nile delta (Bebars and Lasserre, 1983). After the construction of the High Aswan Dam in 1969, freshwater flow from the Nile River decreased by 90%, resulting in a loss of primary production and a consequent ∼80% reduction in Egyptian fishery landings in the Mediterranean coastal region. Declines in landings were primarily from economically valuable sardine (Wadie, 1982) and prawn (Bishara, 1984) fisheries.

RELATIONSHIPS BETWEEN FRESHWATER FLOW AND FISHERIES PRODUCTION

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

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

Seasonal and interannual variation in freshwater flow influences the growth rates of fish and invertebrates. For example, high flows enhance the growth of barramundi (*Lates calcarifer*) in eastern Australia (Robins et al., 2006) and reduce the growth of Gulf menhaden (*Brevoortia patronus*) in North

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

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

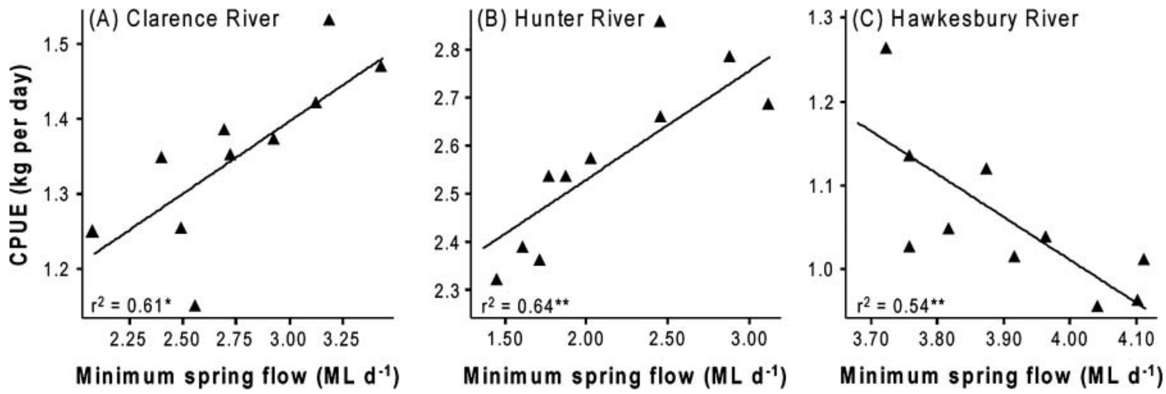

Figure 3 Relationships between $\log_{10}$ catch per unit effort for dusky flathead and minimum spring flow in the (A) Clarence, (B) Hunter, and (C) Hawkesbury River estuaries of eastern Australia. $^{*}P < 0.05$; $^{**}P < 0.01$; $n = 10$. Minimum flow indicates the lowest spring flows (modified from Gillson et al., 2009).

America (Deegan, 1990). Freshwater flow influences growth rates by modifying food availability, salinity regimes, and water temperature in estuarine and coastal systems (Loneragan and Bunn, 1999; Robins et al., 2005; Shoji et al., 2006). Positive relationships between freshwater flow and the growth rates of school prawns (*Metapenaeus macleayi*) were attributed to increased food availability and decreased salinity in the Hunter River estuary on the east coast of Australia (Ruello, 1973). Experimental studies have shown that the food-unlimited growth rates of penaeid prawns function most efficiently within relatively narrow temperature-salinity ranges (O'Brien, 1994; Kumlu et al., 2000; Su et al., 2010). Under laboratory conditions, for instance, banana prawns (*Penaeus merguiensis*) grow fastest at temperatures between 20–31°C and in salinities between 20–30‰ (Staples and Heales, 1991). Freshwater flow has a particularly pronounced effect on the growth of sessile mollusc species. Negative relationships between freshwater flow and the growth rates of eastern oysters (*Crassostrea virginica*) result from suboptimal low salinities (mean ≤17 ppt) in North America (Wilber, 1992; Livingston et al., 2000; Wang et al., 2008).

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

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

Habitat Availability

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

Temporal and spatial variation in freshwater flow controls the duration and frequency that an estuary mouth is open or closed by modifying rates of sediment delivery (Reddering and Rust, 1990; Eyre, 1998). The status of an estuary mouth influences the distribution, abundance, and species composition of fish and invertebrate communities (Whitfield and Kok, 1992; Vorwerk et al., 2003; Vivier and Cyrus, 2009). Permanently open estuaries maintain a constant connection with the sea, thus enabling fish and invertebrate migrations between estuarine and coastal systems (Kok and Whitfield, 1986; Potter et al., 1990; Whitfield, 1994). Temporary mouth closure, however, inhibits species exchange, resulting in the decreased abundance of marine taxa, recruitment limitation, and a loss of estuarine nursery function (Wooldridge, 1991; Harrison and Whitfield, 1995; Young and Potter, 2002). Prolonged mouth closure can result in extensive fish mortalities due to changes in salinity creating osmoregulatory stress. For example, prolonged closure of the Bot estuary in southern Africa resulted in the mortality of more than 7,000 fish from 9 species due to salinities lower than 3‰ producing

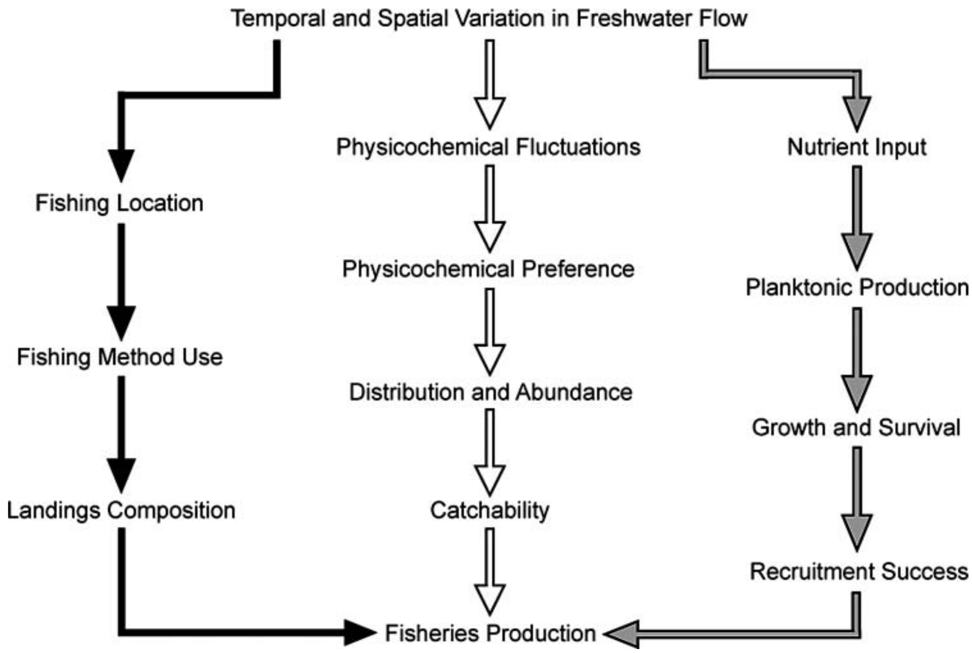

Figure 4 A conceptual model illustrating the controlling influence of freshwater flow on the production of estuarine and coastal fisheries. Note that freshwater flow influences fisheries production by regulating habitat availability (white arrows), trophic interactions (gray arrows), and fishers' harvesting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

oligohaline conditions (Bennett, 1985). Similarly, prolonged closure of the Seekoei estuary in southern Africa resulted in the mortality of more than 6,000 fish from 11 species due to salinities higher than 95‰ producing hypersaline conditions (Whitfield, 1989).

Freshwater flow has a profound effect on community composition in estuarine and coastal systems by altering the distribution and abundance of marine, estuarine, and freshwater species due to changes in salinity (Jassby et al., 1995; Hurst et al., 2004; Costa et al., 2007). One of the most essential adaptations of organisms that enter estuaries is the ability to adjust to changes in salinity (Panikkar, 1960). Salinity strongly influences habitat selection, with species actively seeking optimum habitat conditions to minimize osmoregulatory costs and maximize growth rates (Edeline et al., 2005; Cardona, 2006; Shen et al., 2009). Differences in the salinity tolerance of euryhaline and stenohaline species are often attributed to the divergent responses of estuarine and coastal biota to variation in freshwater flow. Freshwater encroachment onto the continental shelf lowers salinity, expands estuarine conditions offshore, and permits euryhaine species to increase their distribution into coastal waters (Able, 2005). Marine stenohaline species respond to increased freshwater flow by emigrating from estuarine into coastal systems due to lower salinity forcing the seaward displacement of habitat (Kimmerer, 2002a; Whitfield and Harrison, 2003; James et al., 2007). The influence of freshwater flow on salinity is particularly important for early life history stages of fish in estuarine nursery grounds (Kimmerer et al., 2001; North and Houde, 2003; Bolle et al., 2009). For example, freshwater flow influences the distribution of black bream (*Acanthopagrus butcheri*) eggs and larvae by altering the salt-wedge position and halocline depth in the Glenelg and Hopkins estuaries on the east coast of Australia (Nicholson et al., 2008). A combination of intermediate flows ($>\sim$3,000 ML d^{-1}) and strong vertical salinity stratification has also been shown to favorably influence the recruitment of black bream by increasing the availability of spawning habitat in Gippsland Lakes, eastern Australia (Jenkins et al., 2010).

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

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

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

Trophic Interactions

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

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

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

Harvesting Behavior

Freshwater flow can indirectly impact fisheries production by altering the harvesting behavior of commercial fishers in estuarine and coastal systems. Off the east coast of Australia, for example, commercial fishers respond to variable flows by modifying their harvesting behavior to opportunistically exploit alterations to the catchability of fishery species (Gillson et al., 2010b). Adjustments to harvesting behavior enable fishers' to exploit the increased catchability of estuarine migrant species (e.g., school prawn) during periods of flood and marine estuarine-opportunist species (e.g., blue swimmer crab, *Portunus pelagicus*) during periods of drought. Fisheries scientists must recognize that relationships between freshwater flow and fisheries production represent a signal that is a mixture of ecological response and fishers' harvesting behavior. Fishing activity in estuarine and coastal systems is influenced by variation in freshwater flow (Loneragan and Bunn, 1999; Moses et al., 2002; Lamberth et al. 2009). When freshwater flow alters the availability of fisheries resources, commercial fishers respond by modifying their harvesting behavior to minimize fishing effort and maximize catch rates. Nevertheless, relatively few of the identified articles (8%) referred to the impacts of freshwater flow on fishing activity. More information on how variable flows influence fishers' harvesting behavior is required to better understand the impacts of freshwater flow on fisheries production.

EPISODIC FLOW EVENTS

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

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

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

ECONOMIC IMPACTS OF VARIABLE FLOWS ON ESTUARINE AND COASTAL FISHERIES

Information on the economic impacts of variable flows on estuarine and coastal fisheries remains elusive. Only a small proportion of the identified articles (10%) alluded to the economic impacts of variable flows on estuarine and coastal fisheries, many without explicitly performing quantitative research (e.g., All, 2006; Cardoso et al., 2008). Reduced flows due to droughts can lower the economic performance of commercial fisheries operating in estuarine and coastal systems. Revenue generation from commercial fishing businesses in estuarine and coastal fisheries decreased between 8–36% during periods of drought in eastern Australia (Gillson and Scandol, 2010a). Businesses that operated ocean prawn trawls and estuarine prawn trawls primarily contributed to significant reductions in revenue (Figure 6). Diversifying harvesting behavior to target a broad range of species partially compensated for these reductions in revenue. Commercial fishers, however, would also benefit from

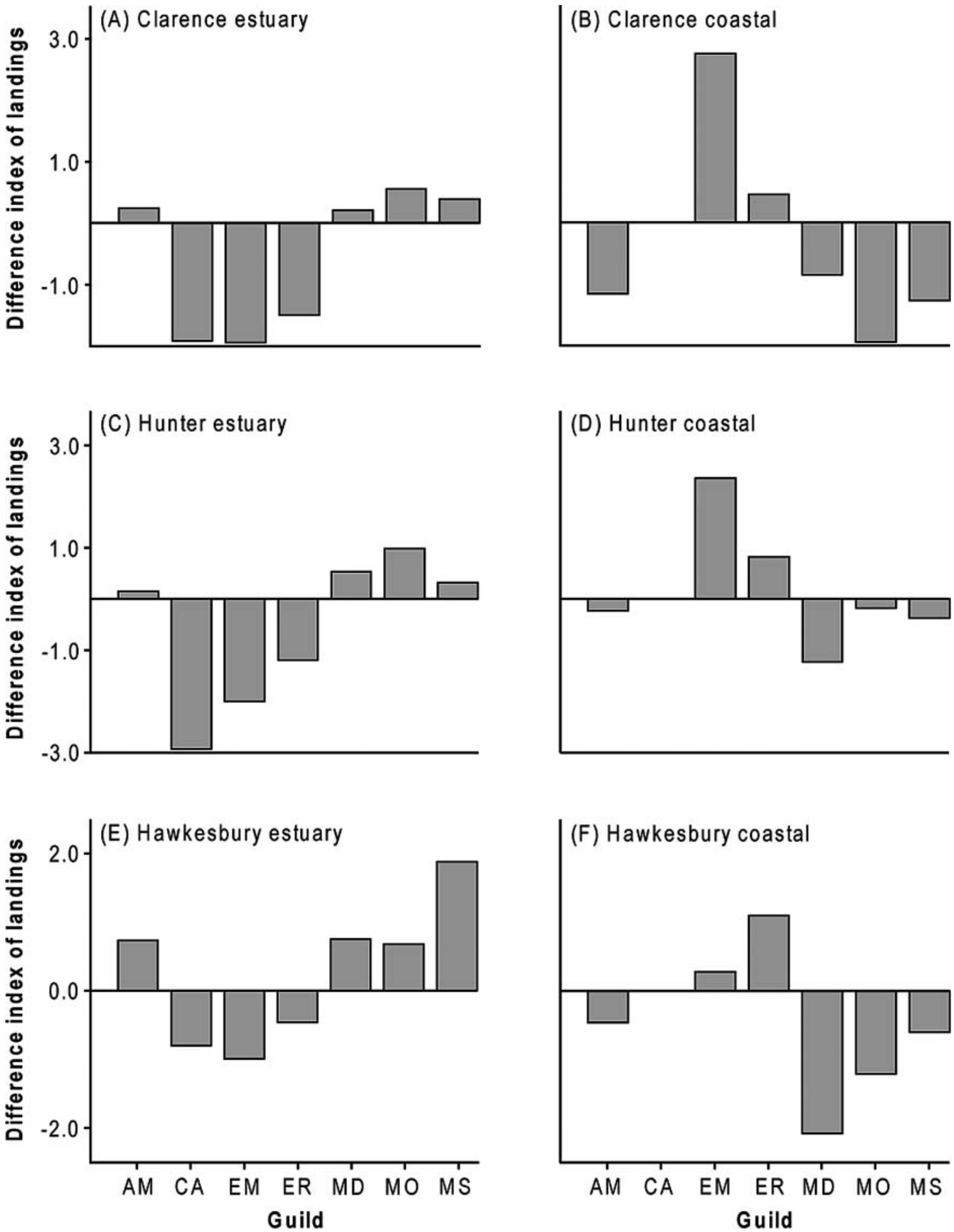

Figure 5 Difference index of landings per guild (kg of each guild per month) between flood and drought events in the estuarine and coastal fisheries associated with the Clarence, Hunter, and Hawkesbury Rivers of eastern Australia. Results based on fourth-root transformed data. Estuarine use guilds consisted of Amphidromous (AM), Catadromous (CA), Estuarine Migrant (EM), Estuarine Resident (ER), Marine estuarine Dependent (MD), Marine estuarine-Opportunist (MO), and Marine Straggler (MS) (modified from Gillson et al., 2010b).

augmenting income from enterprises unrelated to fishing during drought. A lack of information on the economic impacts of variable flows on commercial fisheries has hindered the representation of estuarine and coastal systems in water allocation proposals. Identifying fishing sectors that are economically sensitive to variation in freshwater flow will improve understanding of the freshwater requirements of estuarine and coastal fisheries.

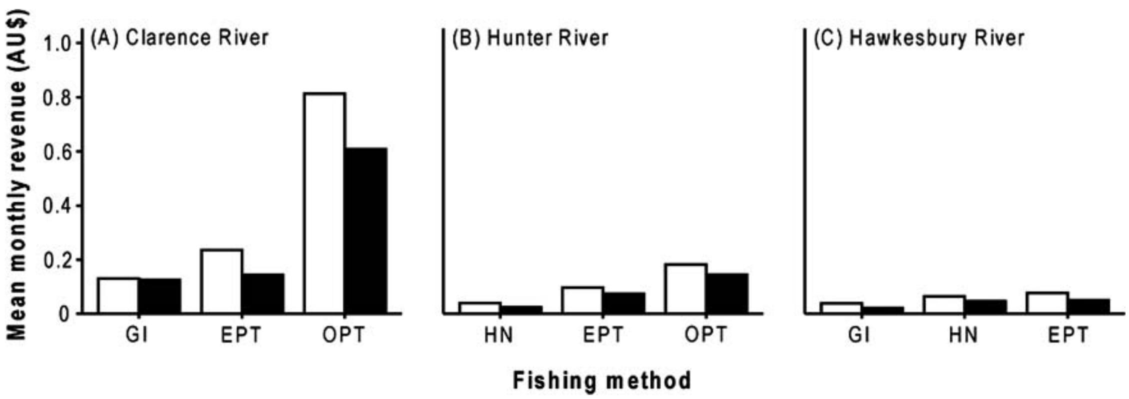

Figure 6 Mean revenue per month (AU$ millions) from the three most financially productive fishing methods during non-drought (white bars) and drought (black bars) conditions in the estuarine and coastal fisheries associated with the Clarence, Hunter, and Hawkesbury Rivers of eastern Australia. Fishing method abbreviations are Estuarine Prawn Trawl (EPT), Gillnetting (GI), Hauling Net (HN), and Ocean Prawn Trawl (OPT) (modified from Gillson and Scandol, 2010a).

FRESHWATER REQUIREMENTS OF ESTUARINE AND COASTAL FISHERIES

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

Methods to determine the freshwater requirements of estuarine and coastal systems have been developed in southern Africa. In the Mtata estuary on the east coast of southern Africa, for example, mean winter flows < 4 m^3 s^{-1} favor the colonization of estuarine biota by promoting natural seasonal flow patterns, establishing a longitudinal salinity gradient, and reducing sediment loads (Adams et al., 2002). Simulation models have explored changes to estuarine nursery function under alternative flow scenarios. Annual flows into the Great Brak estuary on the west coast of southern Africa can be halved to 17.35×10^{-6} m^3 with no discernable effect on fish recruitment, but a sharp decline in estuarine immigration resulted thereafter (Quinn et al., 1999). Reduced flows are expected to decrease landings of commercially important species that currently dominate fisheries harvest. For example, a 44% reduction in freshwater flow from the Thukela River is predicted to decrease commercial landings of slinger (*Chrysoblephus puniceus*) and squaretail kob (*Argyrosomus thorpei*) by 36% and 28%, respectively, in the Thukela Bank linefishery in KwaZuluNatal (Lamberth et al., 2009).

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

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

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

FRESHWATER FLOW AND FISHERIES PRODUCTION IN A CHANGING CLIMATE

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

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

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

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

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

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

CONCLUSIONS

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

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

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

ACKNOWLEDGMENTS

Thanks to the University of New South Wales Evolution and Ecology Research Centre for providing funding for this project. The author is grateful to Iain Suthers and James Scandol for providing constructive comments on the development of this manuscript.

REFERENCES

Able, K. W. A re-examination of fish estuarine dependence: Evidence for connectivity between estuarine and ocean habitats. *Estuar. Coast. Shelf Sci.*, **64:** 5–17 (2005).

Adams, A. J., R. K. Wolfe, and C. A. Layman. Preliminary examination of how human-driven freshwater flow alteration affects trophic ecology of juvenile snook (*Centropomus undecimalis*) in estuarine creeks. *Estuaries Coast*, **32:** 819–828 (2009).

Adams, J. B., G. C. Bate, T. D. Harrison, P. Huizinga, S. Taljaard, L. van Niekerk, E. E. Plumstead, A. K. Whitfield, and T. H. Wooldridge. A method to assess the freshwater inflow requirements of estuaries and application to the Mtata Estuary, South Africa. *Estuaries Coast*, **25:** 1382–1393 (2002).

Aleem, A. A. Effect of river outflow management on marine life. *Mar. Biol.*, **15:** 200–208 (1972).

All, J. D. Colorado River floods, droughts, and shrimp fishing in the upper Gulf of California, Mexico. *Environ. Manag.*, **37:** 111–125 (2006).

Allan, R., J. Lindesay, and D. Parker. *El Nino Southern Oscillation and Climatic Variability*. Collingwood, Australia: CSIRO Publishing (1996).

Allison, E. H., A. L. Perry, M.-C. Badjeck, W. N. Adger, K. Brown, D. Conway, A. S. Halls, G. M. Pilling, J. D. Reynolds, N. L. Andrew, and N. K. Dulvy. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish.*, **10:** 173–196 (2009).

Ashok, K., Z. Guan, and T. Yamagat. Influence of the Indian Ocean dipole on the Australian winter rainfall. *Geophys. Res. Lett.*, **30:** 1821 (2003).

Attrill, M. J., and M. Power. Climatic influence on a marine fish assemblage. *Nature*, **417:** 275–278 (2002).

Attrill, M. J., and M. Power. Partitioning of temperature resources amongst an estuarine fish assemblage. *Estuar. Coast. Shelf Sci.*, **61:** 725–738 (2004).

Baird, D., and J. J. Heymans. Assessment of ecosystem changes in response to freshwater inflow of the Kromme River Estuary, St Francis Bay, South Africa: A network analysis approach. *Water SA*, **22:** 307–318 (1996).

Baisre, J. A., and Z. Arboleya. Going against the flow: Effects of river damming in Cuban fisheries. *Fish Res.*, **81:** 283–292 (2006).

Balston, J. Short-term climate variability and the commercial barramundi (*Lates calcarifer*) fishery of north-east Queensland, Australia. *Mar. Freshw. Res.*, **60:** 912–923 (2009).

Baptista, J., F. Martinho, M. Dolbeth, I. Viegas, H. Cabral, and M. Pardal. Effects of freshwater flow on the fish assemblage of the Mondego estuary (Portugal): Comparison between drought and non-drought years. *Mar. Freshw. Res.*, **61:** 490–501 (2010).

Barnston, A. G., and R. E. Livezey. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Weather Rev.*, **115:** 1083–1126 (1987).

Beamish, R. J., C. E. M. Neville, B. L. Thomson, P. J. Harrison, and M. St. John. A relationship between Fraser River discharge and interannual production of Pacific salmon (*Oncorhynchus* spp.) and Pacific herring (*Clupea pallasi*) in the Strait of Georgia. *Can. J. Fish Aquat. Sci.*, **51:** 2843–2855 (1994).

Bebars, M. I., and G. Lasserre. Analysis of the Egyptian marine and lagoon fisheries from 1962–1976, in relation to the construction of the Aswan Dam (completed in 1969). *Oceanol. Acta.*, **6:** 417–426 (1983).

Bennett, B. A. A mass mortality of fish associated with low salinity conditions in the Bot River estuary. *Trans. R. Soc. S. Afr.*, **45:** 437–448 (1985).

Bennett, W. A., D. J. Ostrach, and D. E. Hinton. Larval striped bass condition in a drought-stricken estuary: Evaluating pelagic food-web limitation. *Ecol. Appl.*, **5:** 680–692 (1995).

Benson, N. G. The freshwater-inflow-to-estuaries issue. *Fish*, **6:** 8–10 (1981).

Bernauer, T. Explaining success and failure in international river management. *Aquat. Sci. Res. Acr. Boun.*, **64:** 1–19 (2002).

Bishara, N. F. The problem of prawn fisheries in Egypt. *Archiv für Hydrobiol.*, **101:** 577–586 (1984).

Blaber, S. J. M., and T. G. Blaber. Factors affecting the distribution of juvenile estuarine and inshore fish. *J. Fish Biol.*, **17:** 143–162 (1980).

Blaber, S. J. M., D. T. Brewer, and J. P. Salini. Fish communities and the nursery role of the shallow inshore waters of a tropical bay in the gulf of Carpentaria, Australia. *Estuar. Coast. Shelf Sci.*, **40:** 177–193 (1995).

Bolle, L. J., M. Dickey-Collas, J. K. L. Van Beek, P. L. A. Erftemeijer, J. I. J. Witte, H. W. Van der Veer, and A. D. Rijnsdorp. Variability in transport of fish eggs and larvae. III. Effects of hydrodynamics and larval behaviour on recruitment in plaice. *Mar. Ecol. Prog. Ser.*, **390:** 195–211 (2009).

Boon, P. J. Essential elements in the case for river conservation. **In:** *River Conservation and Management* (Boon P. J., P. Calow, and G. E. Petts, Eds.). Chichester, John Wiley (1992).

Brander, K. M. Global fish production and climate change. *P. Natl. Acad. Sci. Biol.*, **104:** 19709–19714 (2007).

Bunn, S. E., and A. H. Arthington. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ. Manag.*, **30:** 492–507 (2002).

Caddy, J. F., and A. Bakun. A tentative classification of coastal marine ecosystems based on dominant processes on nutrient supply. *Ocean Coast. Manag.*, **23:** 201–211 (1994).

Canuel, E. A., J. E. Cloern, D. B. Ringelberg, J. B. Guckert, and G. H. Rau. Molecular and isotopic tracers used to examine sources of organic matter and its incorporation into the food webs of San Francisco Bay. *Limnol. Oceanogr.*, **40:** 67–81 (1995).

Cardona, L. Habitat selection by grey mullets (Osteichthyes: Mugilidae) in Mediterranean estuaries: The role of salinity. *Sci Mar.*, **70:** 443–455 (2006).

Cardoso, P. G., D. Raffaelli, A. I. Lillebøa, T. Verdelhosa, and M. A. Pardala. The impact of extreme flooding events and anthropogenic stressors on the macrobenthic communities' dynamics. *Estuar. Coast. Shelf Sci.*, **76:** 553–565 (2008).

Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson, and D. Pauly. Projecting global marine biodiversity impacts under climate change scenarios. *Fish Fish.*, **10:** 235–251 (2009).

Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Change Biol.*, **16:** 24–35 (2010).

Cloern, J. E. Our evolving conceptual model of the coastal eutrophication problem. *Mar. Ecol. Prog. Ser.,* **210:** 223–253 (2001).

Connolly, R. M., T. A. Schlacher, and T. F. Gaston. Stable isotope evidence for trophic subsidy of coastal benthic fisheries by river discharge plumes off small estuaries. *Mar. Biol. Res.,* **5:** 164–171 (2009).

Copeland, B. J. Effects of decreased river flow on estuarine ecology. *Water Pollut. Control Fed.*, **38:** 1831–1839 (1966).

Costa, M. J., R. Vasconcelos, J. L. Costa, and H. N. Cabral. River flow influence on the fish community of the Tagus estuary (Portugal). *Hydrobiologia*, **587:** 113–123 (2007).

Cyrus, D. P., and S. J. M. Blaber. The influence of turbidity on juvenile fishes in estuaries. Part 1. Field studies at Lake St. Lucia on the southeastern coast of Africa. *J. Exp. Mar. Biol. Ecol.*, **109:** 53–70 (1987a).

Cyrus, D. P., and S. J. M. Blaber. The influence of turbidity on juvenile marine fishes in estuaries. Part 2. Laboratory studies, comparisons with field data and conclusions. *J. Exp. Mar. Biol. Ecol.*, **109:** 71–91 (1987b).

Cyrus, D. P., and S. J. M. Blaber. The influence of turbidity on juvenile marine fish in the estuaries of Natal, South africa. *Cont. Shelf Res.*, **7:** 1411–1416 (1987c).

Cyrus, D. P., and S. J. M. Blaber. Turbidity and salinity in a tropical northern Australian estuary and their influence on fish distribution. *Estuar. Coast. Shelf Sci.*, **35:** 545–563 (1992).

Darnaude, A. M. Fish ecology and terrestrial carbon use in coastal areas: Implications for marine fish production. *J. Anim. Ecol.*, **74:** 864–876 (2005).

Darnaude, A. M., C. Salen-Picard, N. V. C. Polunin, and M. L. Harmelin-Vivien. Trophodynamic linkage between river runoff and coastal fishery yield elucidated by stable isotope data in the Gulf of Lions (NW Mediterranean). *Oecologia*, **138:** 325–332 (2004).

Dauble, D. D., and D. R. Geist. Comparison of mainstem spawning habitats for two populations of fall chinook salmon in the Columbia River basin. *Regul River Res. Manag.*, **16:** 345–361 (2000).

Dawson, K. Fish kill events and habitat losses of the Richmond River, NSW Australia: An overview. *J. Coast. Res.*, **36:** 216–221 (2002).

Deegan, L. A. Effects of estuarine environmental conditions on population dynamics of young-of-the-year gulf menhaden. *Mar. Ecol. Prog. Ser.*, **68:** 195–205 (1990).

Dettinger, M. D., and H. F. Diaz. Global characteristics of stream flow seasonality and variability. *J, Hydrometeor.*, **1:** 289–310 (2000).

Diaz, R. J., and R. Rosenberg. Spreading dead zones and consequences for marine ecosystems. *Science*, **321:** 926–929 (2008).

Díaz-Ochoa, J. A., and R. A. Quiñones. Relationship of precipitation, freshwater input, and sea level height with the abundance of the white shrimp (*Litopenaeus occidentalis*; Street, 1871) off Buenaventura, eastern tropical Pacific. *Fish Res.*, **92:** 148–161 (2008).

Dolbeth, M., F. Martinho, I. Viegas, H. Cabral, and M. A. Pardal. Estuarine production of resident and nursery fish species: Conditioning by drought events? *Estuar. Coast. Shelf Sci.*, **78:** 51–60 (2008).

Drinkwater, K. F., and K. T. Frank. Effects of river regulation and diversion on marine fish and invertebrates. *Aquat. Conserv.*, **4:** 135–151 (1994).

Edeline, E., S. Dufour, and P. Elie. Role of glass eel salinity preference in the control of habitat selection and growth plasticity in *Anguilla anguilla*. *Mar. Ecol. Prog. Ser.*, **304:** 191–199 (2005).

Erskine, W. D., and R. F. Warner. Further assessment of flood- and drought-dominated regimes in south-eastern Australia. *Aust. Geogr.*, **29:** 257–261 (1998).

Erzini, K. Trends in NE Atlantic landings (southern Portugal): Identifying the relative importance of fisheries and environmental variables. *Fish Oceanogr.*, **14:** 195–209 (2005).

Eyre, B. Transport, retention and transformation of material in Australian estuaries. *Estuar. Coast*, **21:** 540–551 (1998).

Eyre, B. D., G. Kerr, and L. A. Sullivan. Deoxygenation potential of the Richmond River estuary floodplain, northern NSW, Australia. *River Res. Appl.*, **22:** 981–992 (2006).

Falkenmark, M. Freshwater as shared between society and ecosystems: From divided approaches to integrated challenges. *Philos. Trans. R. Soc. B*, **358:** 2037–2049 (2003).

Ficke, A. D., C. A. Myrick, and L. J. Hansen. Potential impacts of global climate change on freshwater fisheries. *Rev. Fish Biol. Fish*, **17:** 581–613 (2007).

Finlayson, B. L., and T. A. McMahon. Australia vs the world: A comparative analysis of streamflow characteristics. **In:** *Fluvial Geomorphology of Australia* (Warner R. F. S., Ed.). Sydney: Academic Press (1988).

Flannery, M. S., E. B. Peebles, and R. T. Montgomery. A percent-of-flow approach for managing reductions of freshwater inflows from unimpounded rivers to southwest Florida estuaries. *Estuar. Coast*, **25:** 1318–1332 (2002).

Flint, R. W. Long-term estuarine variability and associated biological response. *Estuar. Coast*, **8:** 158–169 (1985).

Fogarty, M., L. Incze, K. Hayhoe, D. Mountain, and J. Manning. Potential climate change impacts on Atlantic cod (*Gadus morhua*) off the northeastern USA. *Mitig. Adapt. Strat. Glob. Chan.*, **13:** 453–466 (2008).

Galindo-Bect, M. S., E. P. Glenn, H. M. Page, K. Fitzsimmons, L. Galindo-Bect, J. M. Hernandez-Ayon, R. L. Petty, J. Garcia-Hernandez, and D. Moore. Penaeid shrimp landings in the upper Gulf of California in relation to Colorado river freshwater discharge. *Fish Bull.*, **98:** 222–225 (2000).

Gammelsrød, T. Variation in shrimp abundance on the Sofala Bank, Mozambique, and its relation to the Zambezi river runoff. *Estuar. Coast. Shelf Sci.*, **35:** 91–103 (1992).

Gillanders, B. M., and M. J. Kingsford. Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanogr. Mar. Bio.*, **40:** 233–309 (2002).

Gillson, J., and J. Scandol. Spreading the economic risk: Harvesting strategies of multi method inshore fisheries during drought in eastern Australia. *Fish Res*., under review (2010a).

Gillson, J., J. Scandol, and I. Suthers. Effects of flood and drought events on multi-species and multi-method coastal fisheries in eastern Australia. *Fish Manag. Ecol.,* under review (2010b).

Gillson, J., J. Scandol, and I. Suthers. Estuarine gillnet fishery catch rates decline during drought in eastern Australia. *Fish Res.*, **99:** 26–37 (2009).

Glaister, J. P. The impact of river discharge on distribution and production of the school prawn *Metapenaeus macleayi* (Haswell) (Crustacea: Penaeidae) in the Clarence River Region, northern New South Wales. *Aust. J. Mar. Freshw. Res.*, **29:** 311–323 (1978).

Gonzalez-Ortegon, E., M. D. Subida, J. A. Cuesta, A. M. Arias, C. Fernandez-Delgado, and P. Drake. The impact of extreme turbidity events on the nursery function of a temperate European estuary with regulated freshwater inflow. *Estuar. Coast. Shelf Sci.*, **87:** 311–324 (2010).

Grange, N., A. K. Whitfield, C. J. De Villiers, and B. R. Allanson. The response of two South African east coast estuaries to altered river flow regimes. *Aquat. Conserv.*, **10:** 155–177 (2000).

Grimes, C. B. Fishery production and the Mississippi River discharge. *Fish,* **26:** 17–26 (2001).

Grimes, C. B., and M. J. Kingsford. How do riverine plumes of differing sizes influence fish larvae: Do they enhance recruitment? *Mar. Freshw. Res.*, **47:** 191–208 (1996).

Halliday, I. A., J. B. Robins, D. G. Mayer, J. Staunton-Smith, and M. J. Sellin. Effects of freshwater flow on the year-class strength of a non-diadromous estuarine finfish, king threadfin (*Polydactylus macrochir*), in a dry-tropical estuary. *Mar. Freshw. Res.*, **59:** 157–164 (2008).

Harris, J. H. Impoundment of coastal drainages of south-eastern Australia, and a review of its relevance to fish migrations. *Aust. Zool.*, **21:** 235–250 (1984).

Harris, S. A., D. P. Cyrus, and L. E. Beckley. Horizontal trends in larval fish diversity and abundance along an ocean-estuarine gradient on the northern KwaZulu-Natal coast, South Africa. *Estuar. Coast. Shelf Sci.*, **53:** 221–235 (2001).

Harrison, T. D., and A. K. Whitfield. Fish community structure in three temporarily open/closed estuaries on the Natal coast. *Ichthy Bull. Smith Instit Ichthy.,* **64:** 1–80 (1995).

Hecht, T., and C. D. van der Lingen. Turbidity-induced changes in feeding strategies of fish in estuaries. *S. Afr. J. Zool.*, **27:** 95–107 (1992).

Hoffman, J. C., D. A. Bronk, and J. E. Olney. Tracking nursery habitat use in the York River Estuary, Virginia, by young American

Shad using stable isotopes. *Trans. Am. Fish Soc.*, **136:** 1285–1297 (2007).

Hunter, E. J., R. J. Chant, J. L. Wilkin, and J. Kohut. High-frequency forcing and subtidal response of the Hudson River plume. *J. Geophys. Res.*, **115:** 1–16 (2010).

Hurrell, J. W. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science*, **269:** 676–679 (1995).

Hurrell, J. W., and H. Van Loon. Decadal variations in climate associated with the North Atlantic Oscillation. *Clim. Change.,* **36:** 301–326 (1997).

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck. An overview of the North Atlantic Oscillation. *Geophys. Monogr.* **134:** 1–35 (2003).

Hurst, T. P., K. A. McKown, and D. O. Conover. Interannual and long-term variation in the nearshore fish community of the mesohaline Hudson River estuary. *Estuar. Coast*, **27:** 659–669 (2004).

Ives, M. C., J. P. Scandol, S. S. Montgomery, and I. M. Suthers. Modelling the possible effects of climate change on an Australian multi-fleet prawn fishery. *Mar. Freshw. Res.*, **60:** 1211–1222 (2009).

James, N. C., P. D. Cowley, A. K. Whitfield, and S. J. Lamberth. Fish communities in temporally open/closed estuaries from warm-and cool-temperate regions of South Africa: A review. *Rev. Fish Biol. Fish*, **17:** 565–580 (2007).

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. Isohaline position as a habitat indicator for estuarine populations. *Ecol. Appl.*, **5:** 272–289 (1995).

Jenkins, G. P., S. D. Conron, and A. K. Morison. Highly variable recruitment in an estuarine fish is determined by salinity stratification and freshwater flow: Implications of a changing climate. *Mar. Ecol. Prog. Ser.* **417:** 249–261 (2010).

Jennings, S., and K. Brander. Predicting the effects of climate change on marine communities and the consequences for fisheries. *J. Mar. Sys.*, **79:** 418–426 (2010).

Jewitt, G. Can integrated water resources management sustain the provision of ecosystem goods and services? *Phys. Chem. Earth*, **27:** 887–895 (2002).

Justic, D., N. N. Rabalais, and R. E. Turner. Effects of climate change on hypoxia in coastal waters: A doubled CO_2 scenario for the northern Gulf of Mexico. *Limnol. Oceanogr.*, **41:** 992–1003 (1996).

Kench, P. S. Geomorphology of Australian estuaries: Review and prospect. *Aust. J. Ecol.*, **24:** 367–380 (1999).

Kennedy, V. S. Anticipated effects of climate changes on estuarine and coastal fishes. *Fish*, **15:** 16–24 (1990).

Kimmerer, W. J. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Mar. Ecol. Prog. Ser.*, **243:** 39–55 (2002a).

Kimmerer, W. J. Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. *Estuar. Coast*, **25:** 1275–1290 (2002b).

Kimmerer, W. J., J. H. Cowan, Jr., L. W. Miller, and K. A. Rose. Analysis of an estuarine striped bass population: Effects of environmental conditions during early life. *Estuar. Coast*, **24:** 557–575 (2001).

Kingsford, R. T., H. C. Biggs, and S. R. Pollard. Strategic adaptive management in freshwater protected areas and their rivers. *Biol Conserv.,* **144:** 1194–1203 (2011).

Kingsford, R. T., R. J. Boulton, and J. T. Puckridge. Challenges in managing dryland rivers crossing political boundaries: Lessons from Cooper creek and the Paroo River, central Australia. *Mar. Freshw. Ecosyst.*, **8:** 361–378 (1998).

Kok, H. M., and A. K. Whitfield. The influence of open and closed mouth phases on the marine fish fauna of the Swartvlei estuary. *S. Afr. J. Zool.,* **21:** 309–315 (1986).

Kostecki, C., F. Le Loc'h, J.-M. Roussel, N. Desroy, D. Huteau, P. Riera, H. Le Bris and O. Le Pape. Dynamics of an estuarine nursery ground: The spatio-temporal relationship between the river flow and the food web of the juvenile common sole (*Solea solea*, L.) as revealed by stable isotopes analysis. *J. Sea Res.*, **64:** 54–60 (2010).

Kroon, F. J., and J. A. Ludwig. Response and recovery of fish and invertebrate assemblages following flooding in five tributaries of a sub-tropical river. *Mar. Freshw. Res.*, **61:** 86–96 (2010).

Kuhnel, I., T. A. McMahon, B. L. Finlayson, A. Haines, P. H. Whetton, and T. T. Gibson. Climatic influences on streamflow variability: A comparison between southeastern Australia and southeastern United States of America. *Water Res. Res.*, **26:** 2483–2496 (1990).

Kumlu, M., O. T. Eroldogan, and M. Aktas. Effects of temperature and salinity on larval growth, survival and development of *Penaeus semisulcatus*. *Aquaculture* **188:** 167–173 (2000).

Kundzewicz, Z. W., L. J. Mata, N. W. Arnell, P. Döll, P. Kabat, B. Jiménez, K. A. Miller, and T. Oki. Freshwater resources and their management, pp. 173–210. **In:** *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, Eds.). Cambridge, UK: Cambridge University Press (2007).

Kurup, G. R., D. P. Hamilton, and J. C. Patterson. Modelling the effect of seasonal flow variations on the position of salt wedge in a microtidal estuary. *Estuar. Coast. Shelf Sci.*, **47:** 191–208 (1998).

La Peyre, M. K., B. Gossman, and J. F. La Peyre. Defining optimal freshwater flow for oyster production: Effects of freshet rate and magnitude of change and duration on eastern oysters and *Perkinsus marinus* infection. *Estuar. Coast*, **32:** 522–534 (2009).

Laheta, F., and D. Stramski. MODIS imagery of turbid plumes in San Diego coastal waters during rainstorm events. *Remote Sens. Environ.*, **114:** 332–344 (2010).

Lamberth, S. J., L. Drapeau, and G. M. Branch. The effects of altered freshwater inflows on catch rates of non-estuarine-dependent fish in a multispecies nearshore linefishery. *Estuar. Coast. Shelf Sci.*, **84:** 527–538 (2009).

Landman, W. A., and S. J. Mason. Change in the association between Indian Ocean sea-surface temperatures and summer rainfall over South Africa and Namibia. *Int. J. Climato.*, **19:** 1477–1492 (1999).

Le Pape, O., F. Chauvet, Y. Désaunay, and D. Guérault. Relationship between interannual variations of the river plume and the extent of nursery grounds for the common sole (*Solea solea*, L.) in Vilaine Bay. Effects on recruitment variability. *J. Sea. Res.*, **50:** 177–185 (2003).

Lehodey, P., J. Alheit, M. Barange, T. Baumgartner, G. Beaugrand, K. Drinkwater, J.-M. Fromentin, S. R. Hare, G. Ottersen, R. I. Perry, C. Roy, C. D. van der Lingen, and F. Werner. Climate variability, fish, and fisheries. *J. Clim.*, **19:** 5009–5030 (2006).

Livingston, R. J., F. G. Lewis, G. C. Woodsum, X.-F. Niu, B. Galperin, W. Huang, J. D. Christensen, M. E. Monaco, T. A. Battista, C. J. Klein, R. L. Howell, and G. L. Ray. Modelling oyster population response to variation in freshwater input. *Estuar. Coast. Shelf Sci.*, **50:** 655–672 (2000).

Livingston, R. J., X.-F. Niu, F. G. Lewis, and G. C. Woodsum. Freshwater input to a Gulf Estuary: Long-term control of trophic organization. *Ecol. Appl.*, **7:** 277–299 (1997).

Lloret, J., J. Lleonart, I. Sole, and J.-M. Fromentin. Fluctuations of landings and environmental conditions in the north-western Mediterranean Sea. *Fish Oceanogr.*, **10:** 33–50 (2001).

Lloret, J., I. Palomera, J. Salat, and I. Sole. Impact of freshwater input and wind on landings of anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) in shelf waters surrounding the Ebre (Ebro) River delta (north-western Mediterranean). *Fish Oceanogr.*, **13:** 102–110 (2004).

Loaiciga, H. A., J. B. Valdes, R. Vogel, J. Garvey, and H. Schwarz. Global warming and the hydrological cycle. *J. Hydrol.*, **174:** 83–127 (1996).

Loneragan, N. R., and S. E. Bunn. River flows and estuarine ecosystems: Implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. *Aust. J. Ecol.*, **24:** 431–440 (1999).

Magnuson, J. J., and B. T. Destasio. Thermal niche of fishes and global warming. **In:** *Global Warming: Implications for Freshwater and Marine Fish* (Wood, C. M., and D. G. McDonald, Eds.). Cambridge: Cambridge University Press (1996).

Magnuson, J. J., L. B. Crowder, and P. A. Medvick. Temperature as an ecological resource. *Am. Zool.*, **19:** 331–343 (1979).

Mallin, M. A., H. W. Paerl, J. Rudek, and P. W. Bates. Regulation of estuarine primary production by watershed rainfall and river flow. *Mar. Ecol. Prog. Ser.*, **93:** 199–203 (1993).

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Meteorol. Soc.,* **78:** 1069–1079 (1997).

Marais, J. F. K. Fish abundance and distribution in the Gamtoos Estuary with notes on the effect of floods. *S. Afr. J. Zool.*, **18:** 103–109 (1983).

Martin, T. J., D. P. Cyrus, and A. T. Forbes. Episodic events: The effects of cyclonic flushing on the ichthyoplankton of St Lucia estuary on the southeast coast of Africa. *Neth. J. Sea. Res.*, **30:** 273–278 (1992).

McHugh, M. J., and J. C. Rogers. North Atlantic Oscillation influence on precipitation variability around the southeast African convergence zone. *J. Clim.,* **14:** 3631–3642 (2001).

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.-C. Zhao. Global climate projections. **In:** *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds.). Cambridge, UK and New York: Cambridge University Press (2007).

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia. Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, **438:** 347–350 (2005).

Möller, O. O., J. P. Castello, and A. C. Vaz. The effect of river discharge and winds on the interannual variability of the pink shrimp *Farfantepenaeus paulensis* production in Patos lagoon. *Estuar. Coast*, **32:** 787–796 (2009).

Molles, M. C., Jr., and C. N. Dahm. A perspective on El Nino and La Nina: Global implications for stream ecology. *J. North Am Benthol. Soc.*, **9:** 68–76 (1990).

Montagna, P. A., M. Alber, P. Doering, and M. S. Connor. Freshwater inflow: Science, policy, management. *Estuar. Coast*, **25:** 1243–1245 (2002).

Moses, B. S., O. M. Udoidiong, and A. O. Okon. A statistical survey of the artisanal fisheries of south-eastern Nigeria and the influence of hydroclimatic factors on catch and resource productivity. *Fish Res.*, **57:** 267–278 (2002).

Nicholson, G., G. P. Jenkins, J. Sherwood, and A. Longmore. Physical environmental conditions, spawning and early-life stages of an estuarine fish: Climate change implications for recruitment in intermittently open estuaries. *Mar. Freshw. Res.*, **59:** 735–749 (2008).

North, E. W., and E. D. Houde. Linking ETM physics, zooplankton prey and fish early-life histories to striped bass *Moore saxatilis* and white perch *M. americana* recruitment. *Mar. Ecol. Prog. Ser.*, **260:** 219–236 (2003).

O'Brien, C. J. The effects of temperature and salinity on growth and survival of juvenile tiger prawns *Penaeus esculentus* (Haswell). *J. Exp. Mar. Biol. Ecol.*, **183:** 133–145 (1994).

Panikkar, N. K. Physiological aspects of adaptation to estuarine conditions. *Aust. Fishery Council Proc.*, **32:** 168–175 (1960).

Peel, M. C., T. A. McMahon, and B. L. Finlayson. Continental differences in the variability of annual runoff-update and reassessment. *J. Hydrol.*, **295:** 185–197 (2004).

Perry, A. L., P. J. Low, J. R. Ellis, and J. D. Reynolds. Climate change and distribution shifts in marine fishes. *Science*, **308:** 1912–1915 (2005).

Plumstead, E. E. Changes in ichthyofaunal diversity and abundance within the Mbashe Estuary, Transkei, following construction of a river barrage. *S. Afr. J. Mar. Sci.*, **9:** 399–407 (1990).

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. The natural flow regime. *Bioscience*, **47:** 769–784 (1997).

Poff, N. L., J. D. Allan, M. A. Palmer, D. D. Hart, B. D. Richter, A. H. Arthington, K. H. Rogers, J. L. Meyer, and J. A. Stanford. River flows and water wars: Emerging science for environmental decision making. *Front Ecol. Env.*, **1:** 298–306 (2003).

Poff, N. L., J. D. Olden, D. M. Pepin, and B. P. Bledsoe. Placing global stream flow variability in geographic and geomorphic contexts. *River Res. Appl.*, **22:** 149–166 (2006).

Pollard, D. A., and J. C. Hannan. The ecological effects of structural flood mitigation works on fish habitats and fish communities in the lower Clarence River system of south-eastern Australia. *Estuar. Coast*, **17:** 427–461 (1994).

Potter, I. C., L. E. Beckley, A. K. Whitfield, and R. C. J. Lenanton. Comparisons between the roles played by estuaries in the life cycles of fishes in temperate Western Australia and southern Africa. *Environ. Biol. Fishes*, **28:** 143–178 (1990).

Powell, G. L., J. Matsumoto, and D. A. Brock. Methods for determining minimum freshwater inflow needs of Texas Bays and estuaries. *Estuar. Coast*, **25:** 1262–1274 (2002).

Power, S., T. Casey, C. Folland, A. Colman, and V. Mehta. Inter-decadal modulation of the impact of ENSO in Australia. *Climate Dynam.*, **15:** 319–324 (1999).

Puckridge, J. T., F. Sheldon, K. F. Walker, and A. J. Boulton. Flow variability and the ecology of large rivers. *Mar. Freshw. Res.,* **49:** 55–72 (1998).

Purtlebaugh, C. H., and M. S. Allen. Relative abundance, growth, and mortality of five age-0 estuarine fishes in relation to discharge of the Suwannee River, Florida. *Trans. Am. Fish Soc.*, **139:** 1233–1246 (2010).

Qiu, Y., Z. Lin, and Y. Wang. Responses of fish production to fishing and climate variability in the northern South China Sea. *Prog. Oceanogr.*, **85:** 197–212 (2010).

Qu, H. J., and C. Kroeze. Past and future trends in nutrients export by rivers to the coastal waters of China. *Sci. Total Environ.*, **408:** 2075–2086 (2010).

Quinn, N. W., C. M. Breen, A. K. Whitfield, and J. W. Hearne. An index for the management of South African estuaries for juvenile fish recruitment from the marine environment. *Fish Manag. Ecol.*, **6:** 421–436 (1999).

Quiñones, R. A., and R. M. Montes. Relationship between freshwater input to the coastal zone and the historical landings of the benthic/demersal fish *Eleginops maclovinus* in central-south Chile. *Fish Oceanogr.*, **10:** 311–328 (2001).

Rabalais, N. N., R. E. Turner, D. Justic, Q. Dortch, W. J. Wiseman, and B. K. Sen Gupta. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuar. Coast.,* **19:** 386–407 (1996).

Rabalais, N. N., R. E. Turner, R. J. Díaz, and D. Justic. Global change and eutrophication of coastal waters. *ICES J. Mar. Sci.,* **66:** 1528–1537 (2009).

Racek, A. A. Prawn investigations in eastern Australia. *Res. Bull. NSW Fish. Station*, **6:** 1–57 (1959).

Reason, C. J. C., and M. Rouault. ENSO-like decadal variability and South African rainfall. *Geophys. Res. Lett.*, **29:** 1638 (2002).

Reddering, J. S. V. Prediction of the effects of reduced river discharge on the estuaries of the southeastern Cape Province, South Africa. *S. Afr. J. Sci.*, **84:** 726–730 (1988).

Reddering, J. S. V., and I. C. Rust. Historical changes and sedimentary characteristics of southern African estuaries. *S. Afr. J. Sci.*, **86:** 425–428 (1990).

Rîmbu, N., C. Boroneant, C. Buta, and M. Dima. Decadal variability of the Danube river flow in the lower basin and its relation with the North Atlantic Oscillation. *Int. J. Climato.,* **22:** 1169–1179 (2002).

Roberts, C. M. *The Unnatural History of the Sea*. Washington DC: Island Press (2007).

Robins, J., D. Mayer, J. Staunton-Smith, I. Halliday, B. Sawynok, and M. Sellin. Variable growth rates of the tropical estuarine fish barramundi *Lates calcarifer* (Bloch) under different freshwater flow conditions. *J. Fish Biol.*, **69:** 379–391 (2006).

Robins, J. B., I. A. Halliday, J. Staunton-Smith, D. G. Mayer, and M. J. Sellin. Freshwater-flow requirements of estuarine fisheries in tropical Australia: A review of the state of knowledge and application of a suggested approach. *Mar. Freshw. Res.*, **56:** 343–360 (2005).

Roessig, J. M., C. M. Woodley, J. J. J. Cech, and L. J. Hansen. Effects of global climate change on marine and estuarine fish and fisheries. *Rev. Fish Biol. Fish*, **14:** 251–275 (2004).

Rogers, J. C. The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Mon. Weather Rev.*, **112:** 1999–2015 (1984).

Roy, P. S. *New South Wales Estuaries: Their Origin and Evolution. Coastal Geomorphology in Australia*. Sydney: Academic Press (1984).

Roy, P. S., R. J. Williams, A. R. Jones, I. Yassini, P. J. Gibbs, B. Coates, R. J. West, P. R. Scanes, J. P. Hudson, and S. Nichol. Structure and function of south-east Australian estuaries. *Estuar. Coast. Shelf Sci.*, **53:** 351–384 (2001).

Ruello, N. V. The influence of rainfall on the distribution and abundance of school prawn *Metapenaeus macleayi* (Haswell) in the Hunter River region, Australia. *Mar. Biol.*, **23:** 221–228 (1973).

Saintilan, N. Relationships between estuarine geomorphology, wetland extent and fish landings in New South Wales. *Estuar. Coast. Shelf Sci.*, **61:** 591–601 (2004).

Salen-Picard, C., A. M. Darnaude, D. Arlhac, and M. L. Harmelin-Vivien. Fluctuations of macrobenthic populations: A link between climate-driven run-off and sole fishery yields in the Gulf of Lions. *Oecologia*, **133:** 380–388 (2002).

Schlacher, T. A., and T. H. Wooldridge. Ecological responses to reductions in freshwater supply and quality in South Africa's estuaries: Lessons for management and conservation. *J. Coast. Conserv.,* **2:** 115–130 (1996).

Scharler, U. M., and D. Baird. A comparison of selected ecosystem attributes of three South African estuaries with differing freshwater inflow regimes, using network analysis. *J. Mar. Sys.*, **56:** 283–308 (2005).

Schumann, E. H., and M. W. Pearce. Freshwater inflow and estuarine variability in the Gamtoos estuary, South Africa. *Estuar. Coast*, **20:** 124–133 (1997).

Serafy, J. E., K. C. Linderman, T. E. Hopkins, and J. S. Ault. Effects of freshwater canal discharge on fish assemblages in a subtropical bay: Field and laboratory observations. *Mar. Ecol. Prog. Ser.*, **160:** 161–172 (1997).

Sheaves, M., R. Johnston, B. Molony, and G. Shepard. The effect of impoundments on the structure and function of fish fauna in a highly regulated dry tropics estuary. *Estuar. Coast,* **30:** 507–517 (2007).

Shen, K. N., C. W. Chang, Y. Iizuka, and W. N. Tzeng. Facultative habitat selection in Pacific tarpon *Megalops cyprinoides* as revealed by otolith Sr:Ca ratios. *Mar. Ecol. Prog. Ser.*, **387:** 255–263 (2009).

Shoji, J., T. Ohta, and M. Tanaka. Effects of river flow on larval growth and survival of Japanese seaperch *Lateolabrax japonicus* (Pisces) in the Chikugo River estuary, upper Ariake Bay. *J. Fish Biol.,* **69:** 1662–1674 (2006).

Sin, Y., R. L. Wetzel, and I. C. Anderson. Spatial and temporal characteristics of nutrient and phytoplankton dynamics in the York river estuary, Virginia: Analyses of long-term data. *Estuar. Coast*, **22:** 260–275 (1999).

Sklar, F. H., and J. A. Browder. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. *Environ. Manag.*, **22:** 547–562 (1998).

Skreslet, S. *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. Berlin: Springer-Verlag (1986).

Smith, B. D. Trends in wild adult steelhead (*Oncorhynchus mykiss*) abundance for snowmelt-driven watersheds of British Columbia in relation to freshwater discharge. *Can. J. Fish Aquat. Sci.*, **57:** 285–297 (2000).

Sobrino, I., L. Silva, J. M. Bellido, and F. Raminos. Rainfall, river discharges and sea temperature as factors affecting abundance of two coastal benthic cephalopod species in the Gulf of Cádiz (SW Spain). *Bull. Mar. Sci.*, **71:** 851–865 (2002).

Solomon, D. J., and H. T. Sambrook. Effects of hot dry summers on the loss of Atlantic salmon, *Salmo salar*, from estuaries in South West England. *Fish Manag. Ecol.*, **11:** 353–363 (2004).

Somville, M., and N. De Pauw. Influence of temperature and river discharge on water quality of the western scheldt estuary. *Water Res.*, **16:** 1349–1356 (1982).

Staples, D. J., and D. S. Heales. Temperature and salinity optima for growth and survival of juvenile banana prawns *Penaeus merguiensis*. *J. Exp. Mar. Biol. Ecol.*, **154:** 251–274 (1991).

Staunton-Smith, J., J. B. Robins, D. G. Mayer, M. J. Sellin, and I. A. Halliday. Does the quantity and timing of fresh water flowing into a dry tropical estuary affect year-class strength of barramundi (*Lates calcarifer*)? *Mar. Freshw. Res.*, **55:** 787–797 (2004).

Struyf, E., S. Van Damme, and P. Meire. Possible effects of climate change on estuarine nutrient fluxes: A case study in the highly nutrified Schelde estuary (Belgium, the Netherlands). *Estuar. Coast. Shelf Sci.,* **60:** 649–661 (2004).

Strydom, N. A., A. K. Whitfield, and A. W. Paterson. Influence of altered freshwater flow regimes on abundance of larval and juvenile *Gilchristella aestuaria* (Pisces: Clupeidae) in the upper reaches of two South African estuaries. *Mar. Freshw. Res.,* **53:** 431–438 (2002).

Su, Y., S. Ma, and C. Feng. Effects of salinity fluctuation on the growth and energy budget of juvenile *Litopenaeus vannamei* at different temperatures. *J. Crustac. Biol.*, **30:** 430–434 (2010).

Sutcliffe, W. H. J. Correlations between seasonal river discharge and local landings of American lobster (*Homarus americanus*) and Atlantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence. *J. Fish Res. Board Can.*, **30:** 856–859 (1973).

Ter Morshuizen, L. D., A. K. Whitfield, and A. W. Paterson. Influence of freshwater flow regime on fish assemblages in the Great Fish River and estuary. *S. Afr. J. Aquat. Sci.*, **22:** 52–61 (1996).

Thoms, C., and F. Sheldon. Water resource development and hydrological change in a large dryland river: The Barwon–Darling River, Australia. *J. Hydro.,* **228:**10–21 (2000).

Utne-Palm, A. C. Visual feeding of fish in a turbid environment: Physical and behavioural aspects. *Mar. Freshw. Behav. Physiol.*, **35:** 111–128 (2002).

Vance, D. J., M. D. E. Haywood, D. S. Heales, R. A. Kenyon, and N. R. Loneragan. Seasonal and annual variation in the abundance of postlarval and juvenile banana prawns *Penaeus merguiensis* and environmental variation in two estuaries in tropical northeastern Australia: A six year study. *Mar. Ecol. Prog. Ser.*, **163:** 21–36 (1998).

Vance, D. J., D. J. Staples, and J. D. Kerr. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguiensis*) in the Gulf of Carpentaria, Australia. *J. Cons. Intl. L'Explor. Mer.*, **42:** 83–97 (1985).

Vinagre, C., M. J. Costa, and H. N. Cabral. Impact of climate and hydrodynamics on sole larval immigration towards the Tagus estuary, Portugal. *Estuar. Coast. Shelf Sci.*, **75:** 516–524 (2007).

Vinagre, C., J. Salgado, H. N. Cabral, and M. J. Costa. Food web structure and habitat connectivity in fish estuarine nurseries-impact of river flow. *Estuar. Coast*, in press.

Vinagre, C., F. D. Santos, H. N. Cabral, and M. J. Costa. Impact of climate and hydrology on juvenile fish recruitment towards estuarine nursery grounds in the context of climate change. *Estuar. Coast. Shelf Sci.*, **85:** 479–486 (2009).

Vitousek, P. M., J. D. Aber, R. W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger, and D. G. Tilman. Human alteration of the global nitrogen cycle: Sources and consequences. *Ecol. Appl.,* **7:** 737–750 (1997).

Vivier, L., and D. P. Cyrus. Ichthyofauna of the sub-tropical Nhlabane estuary, KwaZulu-Natal: Drought-related changes in the fish community during extended mouth closure. *Mar. Freshw. Res.*, **53:** 457–464 (2002).

Vivier, L., and D. P. Cyrus. Alternative nursery habitat for estuarine associated marine fish during prolonged closure of the St Lucia estuary, South Africa. *Estuar. Coast. Shelf Sci.*, **85:** 118–125 (2009).

Vivier, L., D. P. Cyrus, and H. L. Jerling. Fish community structure of the St Lucia estuarine system under prolonged drought conditions and its potential for recovery after mouth breaching. *Estuar. Coast. Shelf Sci.*, **86:** 568–579 (2010).

Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers. Global water resources: Vulnerability from climate change and population growth. *Science*, **289:** 284–288 (2000).

Vorwerk, P. D., and P. W. Froneman. The importance of estuarine-derived carbon for the nearshore marine environment: Studies on two contrasting South African estuaries. *Afr. J. Aquat. Sci.*, **34:** 137–146 (2009).

Vorwerk, P. D., A. K. Whitfield, P. D. Cowley, and A. W. Paterson. The influence of selected environmental variables on fish assemblage structure in a range of southeast African estuaries. *Environ. Biol. Fishes*, **66:** 237–247 (2003).

Wadie, W. F. Observations on the catch of the most important fishes along the Egyptian continental shelf in the South Eastern part of the Mediterranean Sea. *Bull. Instit. Oceanogr. Fish*, **8:** 212–227 (1982).

Walker, K. F. A review of the ecological effects of river regulation in Australia. *Hydrobiologia*, **125:**111–129 (1985).

Walsh, S., C. Copeland, and M. Westlake. Major fish kills in the northern rivers of NSW in 2001: Causes, impacts & responses. Fisheries Final Report Series. Australia: NSW Department of Primary Industries (2004).

Wang, H., W. Huang, M. A. Harwell, L. Edmiston, E. Johnson, P. Hsieh, K. Milla, J. Christensen, J. Stewart, and X. Liu. Modeling oyster growth rate by coupling oyster population and hydrodynamic models for Apalachicola Bay, Florida, USA. *Ecol. Model*, **211:** 77–89 (2008).

Whitfield, A. K. Paradise lagoon or paradise lost? *Ichthos*, **22:** 2–3 (1989).

Whitfield, A. K. Abundance of larval and 0+ juvenile marine fishes in the lower reaches of three southern African estuaries with differing freshwater inputs. *Mar. Ecol. Prog. Ser.*, **105:** 227–267 (1994).

Whitfield, A. K., and A. W. Paterson. Flood-associated mass mortality of fishes in the Sundays estuary. *Water SA*, **21:** 385–389 (1995).

Whitfield, A. K., and H. M. Kok. Recruitment of juvenile marine fishes into permanently open and seasonally open estuarine systems on the southern coast of South Africa. *Ichthyolog. Bull.*, **57:** 1–39 (1992).

Whitfield, A. K., and M. N. Bruton. Some biological implications of reduced fresh water inflow into Eastern Cape Estuaries: A preliminary assessment. *S. Afr. J. Sci.*, **85:** 691–695 (1989).

Whitfield, A. K., and T. D. Harrison. River flow and fish abundance in a South African estuary. *J. Fish Biol.*, **62:** 1467–1472 (2003).

Whitfield, A. K., and T. H. Wooldridge. Changes in freshwater supplies to southern African estuaries: Some theoretical and practical considerations. **In:** *Changes in Fluxes in Estuaries: Implications from Science to Management* (K. R. Dyer, and R. J. Orth, Eds.). Fredensborg, Denmark: Olsen & Olsen (1994).

Whitfield, A. K., and R. H. Taylor. A review of the importance of freshwater inflow to the future conservation of Lake St Lucia. *Aquat. Conserv.*, **19:** 838–848 (2009).

Wilber, D. H. Associations between freshwater inflows and oyster productivity in Apalachicola Bay, Florida. *Estuar. Coast. Shelf Sci.*, **35:** 179–190 (1992).

Wilber, D. H. The influence of Apalachicola River flows on blue crab, *Callinectes sapidus*, in north Florida. *Fish Bull.*, **92:** 180–188 (1994).

Wissel, B., and B. Fry. Tracing Mississippi River influences in estuarine food webs of coastal Louisiana. *Oecologia* **144:** 659–672 (2005).

Wingate, R. L., and D. H. Secor. Effects of winter temperature and flow on a summer–fall nursery fish assemblage in the Chesapeake Bay, Maryland. *Trans. Am. Fish Soc.*, **137:** 1147–1156 (2008).

Wooldridge, T. H. Exchange of two species of decapod larvae across an estuarine mouth inlet and implications of anthropogenic changes in the frequency and duration of mouth closure. *S. Afr. J. Sci.,* **87:** 519–525 (1991).

Young, G. C., and I. C. Potter. Influence of exceptionally high salinities, marked variations in freshwater discharge and opening of estuary mouth on the characteristics of the ichthyofauna of a normally-closed estuary. *Estuar. Coast. Shelf Sci.,* **55:** 223–246 (2002).

Zale, A. V., and T. G. Adornato. Comparative influences of abiotic variables on seasonal abundances of hybrid striped bass and white bass in the Grand Lake tailwater, Oklahoma. *J. Freshw. Ecol.*, **11:** 257–269. (1996).

Zestser, I. S., and H. A. Loaiciga. Groundwater fluxes in the global hydrological cycle: Past, present and future. *J. Hydrol.*, **144:** 405–427 (1993).