Environmental flows for sub-tropical estuaries:

understanding the freshwater needs of estuaries for sustainable fisheries production and assessing the impacts of water regulation

Compiled by Ian Halliday and Julie Robins

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- Barramundi (Lates calcarifer)
- Banana prawns (Penaeus merguiensis)
- Mullet (Mugil cephalus)
- King threadfin (Polystachyus macrochir)
- Blue threadfin (Eleutheronema tetractylum)
- Mud crabs (Scylla serrata)

### DATA CONSIDERATIONS

- Rainfall
- Freshwater flow
- Water temperature
- Fisheries data

### ANALYTICAL APPROACHES

- Choosing appropriate spatial and temporal scales
- Use of running means
- Lagged variables
- Assumed linearity of the relationship

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- Penaeid prawns
- Finfish fisheries
- Other species – crabs, oysters and octopus

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- Mullet (*Mugil cephalus*)
- King threadfin (*Polystachyus macrochir*)
- Blue threadfin (*Eleutheronema tetractylum*)
- Mud crabs (*Scylla serrata*)

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Non-technical summary

2001/022: Environmental flows for sub-tropical estuaries: understanding the freshwater needs for sustainable fisheries production and assessing the impacts of water regulation.

Freshwater resources of Australia are limited and under increasing demand for human use (i.e. urban, industrial and agricultural). However, the environment is a legitimate water user and must have an allocation (= environmental flows) under state and Commonwealth legislation. Estuaries are the downstream section of rivers and streams, and freshwater flowing into estuaries is one of the key factors defining an estuary. However, how much water is required to sustain estuarine biota and the impact of changing freshwater flows on estuaries and the species contained within them is not fully understood and is rarely quantified (Chapter 1).

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

Results of the current work provide quantitative evidence that freshwater flows to estuaries are crucial in supporting fisheries production, through effects on fish movement (i.e. catchability and access to nursery habitats), recruitment (i.e. number of fish surviving the 1st year of life), and growth rates (of fish and prawns), where faster growth leads to better survival and more individuals in the population. As such, freshwater water flowing to estuaries is not wasted.

We adopted a structured approach to investigating the effects of freshwater flows on estuarine fisheries production. Firstly, we developed conceptual models (i.e. diagrams) of the life-cycle of selected fishery species (e.g. barramundi, banana prawns, mud crabs, king threadfin, blue threadfin and mullet) and super-imposed how and when freshwater flows might affect these species. This process was formalised into a generic framework that could be applied to any Australian estuary (Chapter 2).

Secondly, we analysed commercial catches of fishery species, in the Fitzroy River and Port Curtis estuaries of central Queensland as a case study (Chapter 3). Barramundi and banana prawns were significantly influenced by summer flow and rainfall. For both species, catch was positively correlated with flow in the same year. Barramundi catches were also significantly and positively correlated to flow lagged by three and four years, suggesting a recruitment effect. Correlations with larger scale climatic variables (e.g. Southern Oscillation Index, Madden Julian Oscillation and sea surface temperature), showed similar correlations with lags of four years significant (Chapter 4). As a comparison, catches of barramundi in Princess Charlotte Bay (north Queensland) were significantly correlated to summer flow and rainfall in the same year, as well as to flow and rainfall two years previous; again suggesting a recruitment effect. Recreational catches of summer whiting in central Queensland were positively influenced by summer freshwater flow two years previous, with evidence that this was a result of increased growth and recruitment in high flow years (Chapter 5).

Thirdly, we looked at the age-structure of barramundi, king threadfin and summer whiting catches to see if strong and weak year-classes (i.e. the number of fish surviving the first year of life = recruitment) persisted through time and were correlated with freshwater flow (Chapters 5 and 6). The year-class strength of barramundi, king threadfin and summer whiting were positively correlated with freshwater flow (and coastal rainfall) in spring and summer. We speculate that
freshwater flows (and/or coastal rainfall) are important in delivering nutrients to the estuary, thereby creating environmental conditions favourable to species eaten by juvenile barramundi, king threadfin and summer whiting. Freshwater flows may also allow access to or from (or create) nursery habitats that are important for sustaining estuarine fish populations.

Fourthly, we analysed ANSA tag-recapture data of central Queensland barramundi to see if freshwater flows affected growth rates (Chapter 7). They did. Barramundi grow seasonally, being faster in summer, late spring and early autumn than in winter, when no growth occurs. After accounting for seasonal effects, growth rates varied significantly with freshwater flow, being faster at higher flow rates. However, there were flow thresholds beyond which growth rates did not change. We speculate that faster growth rates of barramundi may result from increased food availability that occurs when flows deliver nutrients (e.g. carbon and nitrogen) to the estuary. Additional analysis of otolith micro-chemistry of Fitzroy River barramundi (Chapter 8) showed that growth rates were enhanced in fish that accessed freshwater habitats as juveniles.

Fifthly, we analysed length-frequency data of juvenile banana prawns in the Fitzroy, Calliope and Boyne River estuaries (Chapter 9). Our results suggest that freshwater flows significantly increase the growth rates of juvenile banana prawns, which leads to a greater biomass of banana prawns in the estuary. In addition, the greater abundance of juvenile banana prawns was observed in years with increased freshwater flow, as were commercial catches of banana prawns. The migration and catchability of banana prawns is also known to be affected by freshwater flow.

In addition, we sampled the animals living near the seafloor (=substrate) of the estuary (i.e. the demersal community) to look at the effects of freshwater flows on the biodiversity of estuaries (Chapter 10). Estuarine demersal communities occur in three states: (i) a ‘before flow’ state, when planktonic feeders dominate the community; (ii) a ‘during flow’ state when most animals disappear, presumably leaving because of physiological stress, although demersal feeders remain; and (iii) an after flow state, which is a recovery stage when the estuary (and its animal residents) returns to the ‘before flow’ condition, as waters become less turbid and more salty, and the planktonic feeders reappear. This cyclicity of change occurs annually with the wet season, and indicates that there are animals that exploit all facets of the flow regime. Creating a steady state flow regime would cause major perturbations to the natural faunal community of the estuary. Less dramatic alterations of the freshwater flow regime would have more subtle impacts on the demersal community and the biodiversity of an estuary, but requires more work to elucidate.

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

1. To review the current knowledge of the relationship between freshwater flows and estuarine fisheries production.
2. To develop a logical framework for investigating: (i) the role of freshwater flow; and (ii) the effects of modified flows, on estuarine fisheries production.
3. To correlate historical flow and fisheries production data of sub-tropical estuaries.
4. To develop procedures for assessing the changes in Queensland’s estuarine fisheries production that result from water abstraction and regulation.
5. To develop and communicate guidelines on environmental flows for estuarine fisheries to water managers, water users, the fishing industry and the general community.

Outcomes achieved to date

The project has clearly shown that there are substantial benefits to fisheries production from allowing freshwater flows to reach the estuary. These can be viewed as increasing catch through the delivery of fish from freshwater reaches to estuarine sections, facilitating movement of newly recruited fish from marine spawning areas to estuarine and freshwater habitats, and increases in growth rates of fisheries species probably through the delivery of nutrients into the estuary. These results have been received with enthusiasm amongst the fishing community, and water resources managers but less so in the fisheries management sphere where it is thought that the effects of water (managed or natural changes) are outside their sphere of control. The work presented in this report will assist in developing monitoring programs for water resource plans with respect to measuring estuarine health as well as providing a framework for assessing the need for freshwater to flow to estuaries in areas outside the present study region. The current and increasing demand on Australian water resources requires that water efficiencies (i.e. achieving the same effect with less water) are made by all water users. In the case of the environment, if key aspects of the flow regime and the subsequent effects on estuarine fisheries are identified and understood, then this may allow the maximum amount of water to be available for human use, whilst minimizing impacts on the environment.

KEYWORDS: environmental flows, freshwater flows, estuarine fisheries, water regulation
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Background
Estuaries are semi-enclosed bodies of water that open to the sea and are supplied with freshwater draining from the land via rivers and streams. Freshwater inflow is one of the key factors that defines an estuary and contributes to the biological and physical attributes that make it an important spawning, nursery and feeding habitat for many commercial and recreational fish and crustacean species.

In estuaries and near-shore waters of tropical and sub-tropical Australia, there are commercial fisheries for penaeid prawns - banana prawns (Penaeus merguiensis, P. indicus), tiger prawns (P. esculentus, P. semisulcatus), endeavour prawns (Metapenaeus ensis, M. endeavouri), finfish - barramundi (Lates calcarifer), king threadfin (Polydactylus macrochir), blue threadfin (Eleutherobrama tetractyllum), golden snapper (Lutjanus johnii), black jewfish (Protonibea diacanthus), grunter (Pomadasyx kaakan, P. argenteus), grey mackerel (Scomberomorus semifasciatus), mullet (Mugil cephalus, Liza vaigiensis, L. argentea), queenfish (Scomberoides lysoan, S. commersonianus), sharks (Carcharhinus tilstoni, C. sorrah) and mud crabs (Scylla serrata), having a combined annual value of over $220 million AUD. Some species are also important recreationally and to indigenous communities (e.g. barramundi and mud crabs). Many of the above species are dependent on estuarine ecosystems during their life-cycle and are influenced by freshwater flowing into the estuary. In tropical and sub-tropical Australia, freshwater inflow to the estuary is influenced by the seasonal summer monsoon trough, with increased flow during late spring and summer, and decreased flow during winter and early spring. The timing, duration and magnitude of freshwater flowing to estuaries may change as a consequence of the development of water resources, and such, these changes will impact upon estuarine species (Drinkwater and Frank 1994; Gillanders and Kingsford 2002).

Water resources are highly developed in some areas of tropical and sub-tropical Australia (e.g. Queensland east coast) and are being planned for ‘development’ in others (e.g. Gulf of Carpentaria and Northern Territory). Within Australia, and worldwide, there is increasing recognition of the need to allocate water for the environment as part of the sustainable use of water resources (Dyson et al. 2003; Davis and Hirji 2003 a, b, c). Water for the environment is referred to as environmental flow allocations (Tharme 2003), freshwater inflow needs (Powell et al. 2002), or freshwater inflow requirements (Adams et al. 2002). In Australia, environmental flows are allocated to maintain the health and viability of water-dependent ecosystems (including estuaries) in catchments where water resources are managed.

What does water do in estuaries?
Studies in Australia and overseas have documented the responses of estuarine communities to the inflow of freshwater by correlating increased river flow (or rainfall) with increased catches of
prawns, crabs and fish. While the link between freshwater flows and fisheries catches has been documented in some areas for some species, the causal mechanisms are complex and poorly understood. In most cases, the amount of freshwater inflow required to sustain fisheries is unknown. There are three main proposed causal mechanisms: (i) that freshwater may enhance the overall biological productivity of estuaries by providing an input of organic and inorganic matter (including nutrients) that drives the lower end of the food chain (e.g. phytoplankton and bacteria), and which has flow-on effects for the growth and survival of species at higher trophic levels; (ii) that freshwater flows alter the accessibility of important nursery habitats such as coastal lagoons and floodplains, thereby improving recruitment (and subsequent abundance) of estuarine species; and (iii) that freshwater flows may affect catch rates in estuarine and coastal fisheries by triggering behavioural responses in some species to reduced salinity (e.g. movement and spawning). It is likely that all three mechanisms occur, but to what extent and how they interact to influence total fisheries catches is unclear.

Anthropogenic changes to freshwater flows into estuaries
Regulation and abstraction of water has been necessary to develop land-based activities such as agriculture, industry, and cities and towns. Consequently, most Australian river systems have been modified through the construction of dams, weirs and barrages. In Queensland, only a handful of coastal rivers south of Cooktown have no or only minor water regulation, and there are 23 major dams proposed for rivers throughout the state. Therefore, there is great potential for the further reduction of freshwater flows to estuaries in the future. The effects of water regulation and abstraction have already modified the timing, quantity and quality of freshwater flows sufficiently to pose a threat to the sustainability of estuaries. There is limited documentation on the extent of flow modification and the probable effects on the long-term productivity and biodiversity of Queensland estuaries. Despite this, there is an increasing awareness of the need to manage freshwater flows to ensure the sustainability of downstream environments.

How is water managed and how has water management changed recently?
Freshwater is a limited resource and there has been increasing allocation-related competition between water users. Freshwater resources are managed under State or Territory law, and until recently, the management process involved balancing the needs of traditional non-estuarine water users. In 1994, the Coalition of Australian Governments (COAG) signed the Water Reform Agreement and in the process identified the environment as a legitimate water user. The Agreement restricts trading rights associated with water allocations unless water has also been allocated to the environment. These allocations, referred to as ‘environmental flows’, are aimed at protecting the health of natural ecosystems, while providing security of supply to water users. The COAG Agreement also specifies that environmental flows must be determined through a structured, transparent process. Water management processes vary between states and territories, but generally consider available scientific advice and include community and stakeholder consultation.

Environmental flow allocations
In Queensland, Water Resource Plans (which are secondary legislation to the Queensland Water Act 2000) stipulate the ‘outcomes for sustainable management of water’ and include a subsection on ‘ecological outcomes’. The Plans also stipulate environmental flow objectives, water allocation security objectives and performance indicators of water allocations. The allocation of environmental flows has focused on the needs of freshwater ecosystems, despite flows to the estuary frequently being modified extensively. This largely has been due to the limited quantitative information on the needs of estuarine ecosystems and the lack of appropriate methods. This has frustrated estuary-based stakeholders (e.g. commercial and recreational fishers). The applicability of environmental flows determined for freshwater ecosystems to the estuary is unknown and untested. For example, first-post-winter-flows are thought to trigger spawning in freshwater fish, but no estuarine fish species is thought to spawn as a consequence of freshwater
flow per se. Freshwater flows may trigger estuarine fish species to move downstream, with spawning cues related to other environmental parameters (e.g. day-length and lunar phase). Increasing the understanding of the role of freshwater in estuaries will assist in having the needs of estuaries and their stakeholders duly considered during water management processes.

Feasibility of allocating freshwater flows for estuaries
Allocation of freshwater for the specific purpose of sustaining estuaries is a new concept in water management that has resulted from legislative change. As such, there is no Australian example of a premeditated and reasoned allocation of freshwater flows for estuaries. However, there are several examples from overseas where environmental flows have been allocated specifically to ensure the sustainability of the estuary. Two notable examples are (i) Texas bays and estuaries where sustaining fisheries production is a legislative requirement of water management and (ii) San Francisco Bay. Project staff have gathered information and contacted personnel associated with these examples. The information requirements and feasibility of applying these methods to Australian estuaries was investigated.

What implication does the research have for fisheries management?
Management of fisheries resources aims to achieve ecologically sustainable development (ESD). An essential part of ESD-oriented management is to move beyond monitoring single-species by adopting whole-of-ecosystem approaches and considering effects additional to fishing (e.g. habitat degradation, pollution and altered flow regimes). However, efforts to move towards a whole-of-ecosystem management approach are hampered by our poor understanding of the ecosystem processes that underpin commercial and recreational fisheries production. Increased knowledge of freshwater flows as a major driver of fisheries production for some estuarine species will assist population modellers and fisheries managers to consider environmental factors and the impacts of non-fishing activities on fisheries catches.

Estuarine fisheries of Queensland and the CZCRC management study areas
About 75% of Queensland’s commercial and recreational fisheries are comprised of species that rely on estuarine water conditions and habitats for at least part of their life-cycle. These species include barramundi, king threadfin, bream, whiting, mullet, tailor, prawns and mud crabs. They are important for commercial fishers in many sectors of the industry i.e. inshore net, crab and trawl. The Coastal Zone CRC focused on three main study estuaries: (1) Moreton Bay representing an urbanised catchment, (2) Port Curtis representing an industrialized catchment and (3) the Fitzroy estuary, representing an agricultural catchment.

The research presented within focused on the estuaries of the Port Curtis and Fitzroy regions in central Queensland as case studies for environmental flows, with an additional comparison to Princess Charlotte in far north Queensland. Although the studies were restricted in area, the species studied are widespread in tropical and sub-tropical waters and the results are important for decision making in many estuaries in Australia.

Need
Freshwater allocations to sustain fisheries
The 1994 COAG Water Reform Agreement and various state legislation (e.g. Water Act 2000 in Queensland) require that managers allocate water to maintain downstream ecosystem health. One aspect of ecosystem health is estuarine and coastal fisheries production. Information on the role of freshwater in maintaining the productivity of commercial and recreational fisheries is needed to ensure that estuaries and their stakeholders are duly represented in water allocation processes. Managers of fisheries and water resources need to be made aware of the fishing industry’s vulnerability to the impacts of non-fishing activities, such as water regulation. This issue has
been identified as a challenge for the fishing industry in reaching sustainable production (see Challenge 1 of FRDC’s R&d Plan 2000, page 59).

**Logical frameworks for research leading to new procedures and methods**

A logical framework needs to be developed for investigating the role of freshwater flows in estuaries. Procedures to assess the impacts of current and proposed water infrastructure in Australian coastal rivers on estuarine fisheries also need to be developed. Methods for monitoring biological responses to environmental flows are needed to provide feedback to managers as to whether desired fisheries-related outcomes are being achieved under current water allocations.

**Enhancing the research outcomes - integrating across research disciplines**

An integrated research program is needed to develop a robust sampling program that can investigate the role of freshwater flows in estuaries and the impacts of modified flows on fisheries production. The Coastal Zone CRC offered the opportunity to integrate flow-influenced fisheries data with other hydrological (i.e. coastal modelling) and primary production (i.e. nutrient cycling) research projects to provide greater insight into ecosystems processes.
Introduction
Estuarine fisheries species and their productivity (i.e. catch) have been proposed as tangible indicators of estuarine ecosystem health linked to environmental flow allocations. This is because fisheries species have economic and social value, and are often the only species for which sufficient life history information and/or long-term abundance data (in the form of catch) are available. Alber (2002) suggested that linking freshwater flows to important fishery species is a relatively simplistic relationship that can be easily understood by a range of stakeholders even if the underlying mechanisms are not certain.

Drinkwater and Frank (1994) reviewed the general effects that freshwater may have on fish and invertebrates in coastal and marine waters, concluding that the number and geographic extent of examples strongly supports a link between freshwater flow and production of certain estuarine and marine fish and shellfish. Proposed mechanisms for the connection between estuarine fishery species and freshwater flow include: (i) trophic linkages via changes to primary or secondary production that result from the addition of nutrients; (ii) changes in distribution as a consequence of altered (expanded, reduced or connected) habitats; and (iii) changes in population dynamics such as recruitment, growth, survival, and abundance (Copeland 1966; Aleem 1972; Peters 1982; Drinkwater 1986; Drinkwater and Frank 1994; Loneragan and Bunn 1999; Gillanders and Kingsford 2002). Most effects on estuarine fishery species are one or more steps removed (Figure 1.1) from the direct changes in physical parameters (e.g. water velocity, salinity, water temperature, turbidity) that result from freshwater flowing into estuaries (Drinkwater 1986; Hart and Finelli 1999; Alber 2002; Kimmerer 2002a).

Numerous studies have analysed the correlative relationship between fisheries productivity (e.g. catch or landings) and environmental variables related to rainfall or freshwater flow. Analyses of correlation between rainfall or freshwater flow and fisheries production can be grouped into: (i) single species analyses or (ii) multi-species analyses. Single species analyses are usually based upon hypotheses about the causal mechanisms between hydrological factors and the ecology/life history of an individual species, with results interpreted in relation to possible causal mechanisms. Multi-species analyses are focused on a region or estuary, and analyses are undertaken for a number of shellfish and finfish species. Results may or may not be interpreted in relation to species-specific mechanisms or to more generic ecological mechanisms (e.g. trophic responses of estuarine food webs). Multi-species analyses have been conducted for fisheries productivity in estuarine or coastal areas of the USA, Canada, Norway, Australia and the Mediterranean (Table 1.1).

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Fisheries landsings are the culmination of numerous factors acting upon the population of a fished species (Figure 1.2). Correlation analysis assumes that freshwater flow (as a specific environmental variable) is an appropriate index of the causal mechanism, despite the influence of other factors (e.g., effort). There is also an assumption that environmental variables have a dominant and over-riding effect on the variation in fisheries landings, i.e., greater than that of factors not considered in the analysis (e.g., effort, spawning stock recruitment relationship). The known or speculated mechanism(s) or processes that link the environmental variable to the fisheries landings should be stated prior to analysis, so that it can be clearly seen how many steps the environmental variable is removed from the causal mechanism(s). Environmental variables are often correlated with each other, creating difficulties in determining the effects of single variables.

Figure 1.2 Simplified representation of factors affecting variation in estuarine and coastal fisheries landings

Fisheries catch = biomass + effort + catchability
Data considerations

Rainfall
Rainfall data are readily available for many areas and in many instances as a long time-series. Rainfall has been used as a surrogate for freshwater flow (= river flow), where such flow is not measured directly or is measured unreliably. Using rainfall as an index of runoff or freshwater flow assumes that the relationship between rainfall and freshwater flow is consistent over time and with differing amplitudes of rainfall. This assumption is usually invalid because individual rainfall events result in different amounts of river flow as a consequence of the degree of saturation of the catchment, which depends on the history of rainfall, the distribution of rainfall and rainfall intensity (Glaister 1978). Variability in the relationship between rainfall and runoff or river flow is an unquantified source of error which potentially creates inconsistencies that are difficult to interpret. Rainfall may not be a spatially consistent index of runoff or river flow between different catchments. Rainfall events of equivalent magnitude (i.e. intensity, duration) will result in different levels of freshwater inundation in catchments or estuaries of unequal area (i.e. km²) (Vance et al. 1998). Rainfall scaled by catchment (or estuarine) area maybe a more useful parameter for correlation when only rainfall data are available and comparisons across different catchments are being made. The variability in how rainfall translates into freshwater flow and subsequent inundation of estuarine habitats may account for the inconsistency in relationships between rainfall and catch for some species across different areas (e.g. banana prawns).

Freshwater flow
Freshwater flow (= river flow) data can be gauged (i.e. raw data) or estimated (i.e. modelled data). Gauged flow is often available for locations upstream of the estuarine reach. Estimated flow can be modelled for points within the estuarine reach e.g. End-of-System. Ideally, gauged and estimated flow should include all sources of water input (i.e. runoff) and extraction, and any discrepancies to this should be constant.

Correlating flow with estuarine fisheries landings assumes that there is some relationship between freshwater flow and fisheries production. The consistency of this relationship over increasing volumes, rates or durations of freshwater flow will depend on the hydrology (i.e. tidal and mixing regime) and the geomorphology of the estuary. Like rainfall, freshwater flow may need to be scaled by an appropriate factor (e.g. volume of the estuary) if data from multiple estuaries/catchments are compared.

The appropriate flow statistic for correlation should be related to the proposed causal mechanism between hydrological and ecological patterns. Olden and Poff (2003) recommend selecting hydrological indices that describe unique and non-redundant patterns of variance (in relation to other indices) in hydro-ecological studies. They also note that temporal flow indices should be included because of their critical ecological importance. In the majority of correlation studies summarised (Table 1.1), the flow statistic used is magnitude, particularly total volume, at varying temporal scales (i.e. daily, monthly, seasonal or annual). Further consideration needs to be given to other hydrologic indices, such as frequency, timing, duration and rate of change (Olden and Poff 2003).

Water temperature
Water temperature is often included in correlative analyses because of its potential effect on the survival or growth of particular life stages of some species. Air temperature is often used as a surrogate of water temperature, because air temperate is more readily available.
Fisheries data

Fisheries landings are often used as an index of the abundance or biomass of a fished species or assemblage of fished species. Hilborn and Walters (1992) caution of the possibility that fishery-dependent data can be an ‘imperfect representation of the actual fishery’.

Fisheries landings are often available for a number of different species. In choosing a species for analysis, consideration should be given to: (i) the likely link between environmental variables and fisheries landings, based on known biology or life history; and (ii) whether the data are reported for single species (e.g. sea mullet: *Mulig cephalus*) or a species assemblage that comprises a market-grouping (e.g. mullet: *M. cephalus + Liza vaigiensis + M. georgii* etc.). The pooling of a species assemblage is important because of the potential for individual species to have significantly different responses to environmental variables, such as freshwater flow events. This is particularly the case when species or taxa are pooled together in landings data (e.g. total prawns, total fish, total crabs or total landings). For example, penaeid prawn species (= shrimp) are unlikely to show the same response to variation in rainfall or river flow, as a consequence the different preferences of each species for varying levels of salinity. Floods may stimulate most species of prawn to migrate downstream and into coastal waters, resulting in increased catch rates (Ruello 1973; Glaister 1978; Vance *et al*., 1985). However, floods may have considerably different effects on the recruitment of different penaeids. Within Australian penaeids, the eastern king prawn (*Penaeus plebejus*) is more halophilic than *Metapenaeus macleayi* (Ruello 1973) and salinity levels within an estuary may vary from a low salinity habitat that favours that *M. macleayi* to a high salinity habitat that favours eastern king prawns. Therefore, where possible, single species should be analysed separately. If this is not possible, the limitations of the multi-species grouping should be acknowledged and implications discussed.

Measures of abundance: to use catch or catch per unit effort?

It is widely recognised that catch varies as a function of fishing effort for many species. The relationship may be predictable for species that are widely dispersed, such that Catch Per Unit Effort (CPUE) is a robust indicator of their abundance. However, this does not hold for aggregating species or where search time is not included in effort. Units of effort may vary in some fisheries (e.g. soak time for nets). In this case, CPUE is not a robust index.

Vance *et al.* (1985) argue that CPUE is the best indicator of abundance in a fishery with animals having a one-year life-cycle and where the fishery is not fully exploited, because fishing effort is the main cause of fluctuations in the total catch. However, they argue that catch is the best indicator of abundance in a fishery that is heavily exploited, because increases in fishing effort will not increase the total catch by very much. Therefore, the decision to use catch or CPUE depends on the known or assumed exploitation rate of the stock. In fisheries with changing levels of effort, other factors may be of greater importance in inter-annual yield variation at higher effort levels (Evans and Opnai 1995).

Stock-recruitment relationships may need to be included in analyses of fisheries landings data where recruitment overfishing has occurred and spawning stock size has a significant contribution to the inter-year variation in recruitment. This may be in the form of including some index of the remaining spawning stock biomass in the analysis (e.g. landings or CPUE from the previous year).

Analytical approaches

Choosing appropriate spatial and temporal scales

The appropriate spatial and temporal scale at which correlation analyses should be conducted probably depends on the question of interest and the species involved. Many of the papers in the literature conduct analyses at several temporal and/or spatial scales. We suggest that the scale of analyses selected should be based on biological understanding and the hypotheses to be tested.
Quiñones and Montes (2001) suggest that biological characteristics (e.g. spawning and recruitment) are affected at smaller than annual scales (e.g. monthly scale) and that annual scales (of freshwater flow and rainfall) are indicative of the ‘cumulative’ effect of monthly freshwater flow and rainfall.

**Use of running means**

Running means are commonly used in climatological studies, but are not commonly used in fisheries production studies. Running means may be appropriate in fisheries studies where the catch is comprised of several year-classes or where the hypothesised effect of freshwater flow is cumulative over several years. Running means are probably inappropriate in fisheries where there are single year-classes or where the hypothesised effect is confined within a single year or month. Quiñones and Montes (2001) used three-year running means for inter-annual analyses of róbalo (*Eleginops maclovinus*) catch with freshwater flow and rainfall to: (i) improve the detection of long-term trends; (ii) reduce high frequency variability in the time series; and (iii) diminish the effects of the age-structure in the annual landings data. However, auto-correlation between data points increases with the use of running means, reduces the effective number of independent data points in a time series (Drinkwater and Myers 1987) and should be adjusted for in the analysis (e.g. Pyper and Peterman 1998).

**Lagged variables**

Many correlative studies lag the fisheries landings from the environmental variables (e.g. Sutcliffe 1973; Wilber 1992; Skreslet 1997; Lloret *et al.* 2001; Powell *et al.* 2002). The use of lagged variables is justified on the basis that it takes a number of years for the effects of the environmental variables (i.e. on larval or juvenile survival) to be expressed in the fisheries landings and are usually based on the known or speculated age at which the fish or shellfish recruit to the fishery. While correlating fisheries landings with prior environmental variables fits within the biologically-based hypotheses, it tends to assume that the delay between cause (i.e. increased juvenile survival) and effect (i.e. increased fisheries landings) is constant. This is probably a valid assumption for species with very short life-cycles (i.e. one-year) but may not be valid for long-lived species because of variable timing in recruitment to the fishery which may be the consequence of variable growth rates. It is difficult to determine whether this is the case without some ‘data snooping’ (Potter *et al.* 2001) i.e. trialling a variety of lags then selecting that which gives the ‘best fit’ (e.g. Quiñones and Montes 2001; Powell *et al.* 2002; Salen-Picard *et al.* 2002). Alternatively, and preferably, lags should be based on other sources of information, such as serial monitoring of the age-structure of the fished population, to provide robust quantitative estimates (and variation) in the time to recruit to the fishery.

**Assumed linearity of the relationship**

Kimmerer (2002b) and Powell *et al.* (2002) raise the issue that estuarine responses are not always proportional to changes in freshwater flow, as a consequence of an estuary being a three dimensional structure, influenced by tides and other oceanographic features. It is likely that the nature (positive or negative) and form (linear, threshold, parabolic) of relationships between environmental variables and fisheries production varies with the different life history stages of estuarine and coastal fisheries species. To some degree, non-linearity and curvi-linear relationships between variables can be accounted for by transformation of data, often ln (Powell *et al.* 2002) or log10 (Galindo-Bect *et al.* 2000). However, the validity of assumed linearity or the possibility of thresholds should be kept in mind.

**In summary**

Despite the above limitations, which should be discussed in order to justify the validity of the resulting interpretation (Underwood 1997), correlation analysis can provide insights into potential cause and effect relationships, for guiding water management and associated monitoring (ideally...
within an adaptive management framework). Correlation analysis can also identify areas for further research on the relationship between the environmental and fisheries variables, provided the correlations are conducted within conceptual frameworks with clear objectives as to the reason for exploring the link between environmental and fisheries landings variation.

Modelling (e.g. Maunder and Watters 2003) can assist in the assessment of the relationship between freshwater flow and fisheries productivity, but modelling cannot make up for lack of appropriate data or system understanding (Sharp 1995). Linking freshwater flows to commercially (or recreationally) important species is a relatively simplistic relationship that can be easily understood by a range of stakeholders, even if the underlying mechanism is not certain. The disadvantage is that other non-fished components of the ecosystem may have differing needs for freshwater flows and are not considered (Alber 2002).

Review of published studies

Relationships between catch of estuarine or near-coastal fishery species and freshwater flow (or rainfall as a proxy of freshwater flow) have been reported for more than 20 tropical or sub-tropical species (Table 1.1). Relationships between freshwater flow and the commercial catch have also been investigated for temperate species (see Sutcliffe 1973; Sutcliffe et al. 1977; Drinkwater and Myers 1987; Ardisson and Bourget 1997; Skreslet 1997; Perry et al. 2000; Lloret et al. 2001; Salen-Picard et al. 2002). Temperate studies include a greater number of finfish and mollusc species, while tropical and sub-tropical studies include a greater number of crustacean species (i.e. penaeid prawns = shrimp).

Correlation or regression analysis to identify environmental variables that contribute to variation in fisheries catch can be criticised because of: (i) the confounding effects of stock size and fishing pressure (Walters and Collie 1988); (ii) the likely non-linearity of linking mechanisms (Baumann 1998) and the probability of multiple mechanisms; (iii) the possibility of type I errors (i.e. false significant correlations, Potter et al. 2001); (iv) the lack of ability to prove causality (Quiñones and Montes 2001); and (v) their uncertain predictive capability as a consequence of long-term climatic variation or human-induced changes (e.g. habitat loss or pollution). Whilst an experimental approach is needed to determine causality, manipulative experiments of freshwater flow are rarely practical at the scale of whole estuaries and it is difficult to obtain appropriate controls for ‘Before-After-Control-Impact’ experiments that utilise ongoing human manipulation of freshwater flows (i.e. water regulation). Therefore, in many instances, observational studies are used to derive insights into the factors driving the distribution and abundance of fisheries species at a whole of estuary scale, with the analysis of relationships between catch and environmental variables often being used for fishery species (Tyler 1992).

Most studies of tropical or sub-tropical species report positive relationships between (fishery) catch and increased freshwater flow (Table 1.1). The variables that explain the greatest amount of variation in catch are not consistent and the patterns differ for the same species in different areas and for different species in the same area. However, as discussed below, the proposed mechanisms underlying the observed relationships are relatively consistent within the species groups.

Penaeid prawns

Penaeid prawns (= shrimp) are targeted by major commercial fisheries in tropical and sub-tropical Australia, as well as many other areas of the world. Penaeid prawns are short-lived (i.e. one to two years), opportunistic omnivores (Chong and Sasekumar 1981). Many species of penaeid prawn are dependent on estuarine habitats for part of their life-cycle, but have different habitat preferences, tolerance to and degree of emigration from low salinity water. Freshwater flow (or rainfall) has been related to catch for ten species of penaeid prawn (Table 1.1). Most correlations between freshwater flow (or rainfall) and prawn catch have been reported for those species with the greatest tolerance or exploitation of brackish-water habitats. In general, significant positive relationships occur between annual catch and total freshwater flow (or rainfall) in the same or
previous year (Gunter and Hildebrand 1954; Ruello 1973; Glaister 1978; Vance et al. 1985; Gammelsrød 1992; Galindo-Bect et al. 2000). Significant within-year correlations between catch and monthly or seasonal freshwater flow (or rainfall) have also been reported (Glaister 1978; Browder 1985; da Silva 1985; Vance et al. 1985; Gammelsrød 1992; Vance et al. 1998). The relationship between catch and freshwater flow (or rainfall) is not always consistent between areas, even for the same species. For example, negative correlations between prawn catch and rainfall have been reported in the Gulf of Papua, Papua New Guinea (Evans et al. 1997), whilst significant positive correlations between prawn catch and rainfall have been reported for some areas of the Gulf of Carpentaria, Australia (Vance et al. 1985). This example demonstrates that the relationship between the prawn catch and freshwater flow should be assessed for individual estuaries to account for hydrological and biological differences between catchments (Vance et al. 1998).

The relationships between prawn catch and freshwater flow (or rainfall) are potentially confounded by other factors such as fishing effort and spawning stock size (Browder 1985; da Silva 1985; Vance et al. 1985). The degree of influence of these factors depends on the level of exploitation of the population by the fishery (Vance et al. 1985), although most of the correlative studies for prawns do not account for these factors.

Suggested causal mechanisms for the observed relationships between the catch of penaeid prawns and increased freshwater flow (or rainfall) include: (i) enhanced emigration of prawns to areas accessible to the fishery, leading to increased catchability (Ruello 1973; Glaister 1978; da Silva 1985; Gammelsrød 1992; Evans et al. 1997; Vance et al. 1998); and (ii) enhanced growth and survival of various life stages leading to increased abundance or biomass (Ruello 1973; Evans et al. 1997), through enhanced recruitment from enlarged nursery areas (Browder 1985; Gammelsrød 1992; Galindo-Bect et al. 2000), and or enhanced food availability from increased primary and secondary production (Loneragan and Bunn 1999).

Whilst the conclusions of most correlative studies are speculative, other evidence supports the likelihood of these mechanisms. For example, emigration rates of juvenile banana prawns from estuaries to near shore areas is strongly linked to rainfall events (Staples and Vance 1986; Vance et al. 1998) and emigration rates are significantly correlated with commercial catches (Staples and Vance 1986; Staples and Vance 1987; Vance et al. 1998). Experimental studies demonstrate that the growth of penaeid prawns is influenced strongly by temperature and salinity, and that there are temperature-by-salinity optima for each species (Staples and Heales 1991; Haywood and Staples 1993; Vinod et al. 1996). The possibility of a salinity-by-temperature optimum that influences the growth and survival of prawn life stages potentially explains the parabolic relationship between prawn catch and rainfall in the Gulf of Papua suggested by Evans et al. (1997), where high rainfall (= high freshwater flow and low salinity) reduces the immigration and survival of larvae and post-larvae, intermediate rainfall (= intermediate freshwater flow and intermediate salinity) stimulates emigration to offshore waters, and low rainfall (= low freshwater flow and high salinity) reduces emigration to offshore waters. Enlarged nursery areas may occur as a result of freshwater flows providing favourable salinity ranges over the greatest amount of suitable and accessible areas of nursery habitat during critical life stages of pink shrimp (Farfantepenaeus duorarum) (Browder et al. 2002).

Kimmerer (2002b) recommends that greater knowledge of the causal mechanisms and the biology of the species-of-interest is needed for standards or indices of freshwater inflow to be biologically effective or to be used to make water efficiencies (i.e. achieve the same effect with less water). In the case of pink shrimp, Browder et al. (2002) recommended further research into the seasonal and annual patterns of the availability of post-larvae and the timing and magnitude of immigration and influencing factors. Whilst there is strong evidence of the influence of freshwater inflow on the emigration of prawns from an estuary, there is little supporting evidence that freshwater inflow to estuaries results in greater abundance or biomass of prawns as a consequence of improved growth and survival.
Finfish fisheries

Finfish are often selected for analyses of the relationship between environmental variables and fisheries production (Table 1.1) because many species are estuarine-dependent for part of their life-cycle. However, finfish can be short or ‘long’ lived (i.e. >10 years) and depending on the species, and may occupy various trophic levels. Finfish are commonly considered in multiple species analyses, pooled as total fish landings, or are considered as individual species with species-specific time lags (Table 1.1).

Relationships between commercial catch and freshwater flow have been published for seven tropical or sub-tropical finfish species, and are focused in estuarine or coastal areas of the USA, Mexico, South America and Australia (Table 1.1). Whilst not a quantitative study, Aleem (1972) described the dramatic decrease in the catch of *Sardinella* sp. in the Mediterranean Sea as a consequence of damming the Nile River and the elimination of floods. In sub-tropical Australia, significant positive correlations between catch and freshwater flow were found for mullet (*Mugil* spp.) and flathead (*Platycephalus* spp.) (Loneragan and Bunn 1999). In central-south Chile, significant negative correlations between catch and freshwater flow were reported for róbalo (*Eleginops maclovinus*) (Quiñones and Montes 2001); whilst in the USA, catches of red drum (*Scianeops ocellatus*), black drum (*Pogonias cromis*) and spotted seatrout (*Cynoscion nebulosus*) have been both negatively and positively related to freshwater flow aggregated into two-monthly totals (Powell *et al.* 2002). Other analyses correlating finfish fisheries production with environmental variables related to rainfall and river flow include studies on barramundi (*Lates calcarifer*) (Sawynok 1988), black bream (*Acanthopagrus butcheri*) (Walker *et al.* 1998), and common sole (*Solea solea*) (Salen-Picard *et al.* 2002).

Suggested causal mechanisms for the observed relationships between finfish catch and freshwater flow include: (i) changes to catchability (Loneragan and Bunn 1999); (ii) changes to cohort or year-class strength during the first year of life (Quiñones and Montes 2001); and (iii) changes to food availability via productivity changes resulting from flow-borne nutrients (Aleem 1972; Salen-Picard *et al.* 2002). Effects on catchability are suggested where correlations between catch and freshwater flow occur within a relatively short period suggesting an immediate response (e.g. within the same year for annual correlations). In southern Queensland, increases in catchability are proposed to be the consequence of restricting the distribution or stimulating the movement of flathead species (Loneragan and Bunn 1999). Anecdotal reports from commercial fishers in tropical Australian estuaries suggests that barramundi may also be stimulated to move by freshwater flows, both from upstream habitats as well as moving around within estuarine habitats, thus increasing their catchability in passive fishing gear (i.e. set gill nets). However, the movement of barramundi from upstream habitats requires that individuals be abundant in such habitats.

Effects on year-class strength are suggested where significant correlations are between catch and prior freshwater flow. The proposed mechanisms include: (i) advection (negative effect) or retention (positive effect) of eggs and larvae in nursery areas; (ii) increased predation (negative effect) on young-of-the-year; (iii) expansion of suitable reproductive and nursery habitats; and (iv) improved food availability for larvae and juveniles (Quiñones and Montes 2001; Salen-Picard *et al.* 2002). Few studies have investigated the causal mechanisms in detail, although Kimmerer *et al.* (2001) reassessed the effects of freshwater flow on the early life history of striped bass (*Morone saxatilis*) in the San Francisco estuary. They found that strong relationships existed between freshwater flow and survival from eggs to young-of-the-year, but that recruitment of three-year-olds was not related to freshwater flow during the early life stages. North and Houde (2003) also studied the effects of freshwater flow on the early life history of striped bass and white perch (*M. americana*) in upper Chesapeake Bay (a temperate estuary). They reported that freshwater flow conditions were strongly related to physical conditions, prey concentrations and larval fish distributions associated with the estuarine turbidity maxima.
These three effects (i.e. catchability; recruitment in terms of abundance; and productivity) are not mutually exclusive. It is likely that each of these mechanisms contributes to fluctuations in catches of finfish species that are significantly correlated to freshwater flows to estuaries.

Other species – crabs, oysters and octopus

Crabs are common in tropical and sub-tropical estuaries throughout the world, and are the target species of many fisheries. Relationships between commercial catch and freshwater flow have been investigated for the mud crab (Scylla serrata), which is the main commercial crab species in tropical Australia, as well as for blue swimmer crabs (Portunus pelagicus) and blue crabs (Callinectes sapidus) (Table 1.1). Annual catches of mud crab in southern Queensland are positively correlated with summer freshwater flow. The causal mechanisms suggested are: (i) an increase in catchability, resulting from freshwater flow stimulating downstream movement; and (ii) an increase in the survival of juveniles through reduced cannibalism and competition for burrows as a consequence of the emigration of adult crabs (Loneragan and Bunn 1999). Blue swimmer crabs and blue crabs are con-specifics, occurring in estuaries of the southern and northern hemispheres respectively. No significant correlations between catch and seasonal freshwater flow were reported for blue swimmer crabs (Loneragan and Bunn 1999), but seasonal freshwater flow explained a significant proportion of the variation in the annual catch of blue crabs in numerous estuaries of the USA (Meeter et al. 1979; Funicelli 1984; Powell et al. 2002).

Oysters are an attractive species to use as an index of estuarine responses to freshwater flow because they are sedentary, individuals can be measured over time for aspects such as growth and mortality, and spatfall (i.e. recruitment) can be readily measured using artificial collectors (Livingston et al. 1997). Oyster harvest has been negatively correlated to freshwater flow in the same year (Meeter et al. 1979; Wilber 1992) and positively correlated to freshwater flow in previous years (Wilber 1992). Significant negative and positive relationships between oyster harvest and seasonal freshwater flow were also reported by Powell et al. (2002). Freshwater flow is suggested to negatively affect growth (Meeter et al. 1979), mortality and spawning (Wilber 1992). Livingston et al. (2000) suggested that freshwater flow affects oyster production through two mechanisms: (i) predation and disease related to changes in salinity; and (ii) growth effects related to changes in the trophic productivity of the estuary. Livingston et al. (1997) suggested that oysters may be an appropriate index of the response of estuaries to freshwater flow because they appear to need a delicate balance of freshwater flow, requiring lowered salinities to minimise predation and disease, but not so low as to impact on growth rates (i.e. salinities not too low). However, if using natural oyster populations (c.f. cultured populations in oyster racks) then changes in available habitat need to be considered (i.e. if suitable habitat is reduced as a consequence of turbidity etc.).

Significant negative correlations between catch and freshwater flow are reported for octopus (Octopus vulgaris) in the Gulf of Cadiz, Spain, but not for cuttlefish (Sepia officinalis, Sobrino et al. 2002). Fluctuations in octopus catch are suggested to be a consequence of environmentally driven variation in recruitment and that freshwater flow (= river flow) changed environmental conditions, stimulating the movement of octopus from their dens.

In summary

The additional studies reported in the literature since the review of Drinkwater and Frank (1994) reinforce the conclusion that the catch of some estuarine and marine finfish and shellfish is strongly linked to freshwater flow in tropical, sub-tropical and temperate areas. The correlative studies demonstrate that seasonality is often as important as volume (Loneragan and Bunn 1999), and that freshwater flow requirements of fished species need to be assessed on a species-by-estuary basis. Relationships between the catch of estuarine species and freshwater flow have been included in models designed to optimise freshwater inflows over specified physical, chemical and biological constraints in Texas, USA (Bao and Mays 1994; Powell et al. 2002). However, this
method depends on large quantities of catch data, which are unlikely to be available for most estuaries.

Drinkwater and Frank (1994) recommended that more quantitative research is needed into the relationship between freshwater flows for fish and ecosystems, including multi-disciplinary studies and integrated physical-biological models. This would lead to greater knowledge of the mechanisms underlying the relationships between catch and freshwater flows and would help to determine which aspects of the flow regime were important. Kimmerer (2002a,b) and Browder et al. (2002) reiterated the need to understand the causal mechanisms in the relationship between freshwater flow and (the biology of) the species of interest. Conceptual models of the role of freshwater flow in estuarine ecosystems, and hypotheses developed from them, need to be explicitly considered in order to direct multi-disciplinary studies, and to provide the conceptual structure for integrated bio-physical models.

Table 1.1 Summary of studies correlating fisheries production with freshwater flows to estuaries

<table>
<thead>
<tr>
<th>Source, Location, Data &amp; Analysis</th>
<th>Results</th>
<th>Discussion points</th>
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<tr>
<td><strong>Gunter and Hildebrand 1954, USA, Texas</strong>&lt;br&gt;• White shrimp, Penaeus setiferus&lt;br&gt;• Calendar year commercial catch for Texas&lt;br&gt;• Average annual Texas rainfall&lt;br&gt;• 1927 to 1952 (26 yrs)&lt;br&gt;• Analysis: (i) correlation; 8 combinations of catch and rainfall</td>
<td>7 of 8 relationships tested were significant&lt;br&gt;Annual catch significantly correlated with: (i) previous yr’s rain (p&lt;0.05); (ii) same plus previous yr’s rain (p&lt;0.05); (iii) 2 previous yr’s rain (p&lt;0.01), but not with same yr’s rain&lt;br&gt;2-yr running average of catch significantly correlated with 2-yr running average of rain one-yr previous (p&lt;0.01)&lt;br&gt;3-yr running average of catch significantly correlated with: (i) 3-yr running average of rain, same yrs (p&lt;0.01); (ii) 3-yr running average of rain, same yr &amp; 2 previous yrs (p&lt;0.01)</td>
<td>Discusses the possible influence of other factors: technical improvements, growth of the fishery, economics, overfishing&lt;br&gt;Speculated mechanism is change in salinity&lt;br&gt;Leg in catch explained by the time it takes for rainfall to change the salinity of inshore waters</td>
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<td><strong>Ruello 1973, Australia, New South Wales</strong>&lt;br&gt;• School prawns, Metapenaeus macleayi&lt;br&gt;• Monthly research trawls estuarine &amp; coastal waters 67/68 &amp; 69/70&lt;br&gt;• Commercial landings, 1954 to 1971 (financial yrs)&lt;br&gt;• Rainfall and Hunter River flow&lt;br&gt;• Analysis: (i) correlation</td>
<td>Catch not significantly correlated to same yr rainfall&lt;br&gt;Catch significantly correlated to preceding yr rainfall (r=0.64, p&lt;0.05)&lt;br&gt;Small flows stimulate large prawns to move (emigrate), large flows stimulate all but very small prawns to move&lt;br&gt;Significant river flows led to the movement of school prawns from the estuary to the ocean, resulting in increased density &amp; commercial catch.</td>
<td>Raises the issue of “effective rainfall”&lt;br&gt;Speculates that flow has a cumulative effect on reproduction, recruitment, growth &amp; survival of all life stages&lt;br&gt;Emigration may be a response to the disturbance of bottom sediments by flows, interfering with normal burrowing &amp; respiratory activity</td>
</tr>
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<td><strong>Glaister 1978, Australia, New South Wales</strong>&lt;br&gt;• School prawns, Metapenaeus macleayi&lt;br&gt;• Mean rainfall and Clarence River flow&lt;br&gt;• Estuarine &amp; oceanic catch, effort &amp; catch per unit effort (CPUE)&lt;br&gt;• Daily, weekly, monthly &amp; yearly (financial) data, 1966/67 to 1975/76&lt;br&gt;• Analysis: (i) correlation, (ii) multiple linear regression</td>
<td>29 of 103 correlations tested were significant&lt;br&gt;Weekly oceanic catch significantly correlated with same week (p&lt;0.05) &amp; previous week flow (p&lt;0.05).&lt;br&gt;Monthly estuarine catch significantly correlated with previous month flow (p&lt;0.01)&lt;br&gt;Monthly oceanic catch significantly correlated with same month (p&lt;0.01) &amp; previous month flow (p&lt;0.01)&lt;br&gt;Annual oceanic catch significantly correlated with same yr river flow (p&lt;0.01), but estuarine catches were not</td>
<td>Concludes that flows enhance seasonal emigration of school prawns to offshore waters, which determines the magnitude of oceanic production&lt;br&gt;Suggests that modification of flow could have a detrimental effect on the “normal harvest” of the fishery</td>
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<td><strong>Hunt et al. 1980, USA, North Carolina</strong>&lt;br&gt;• Brown shrimp, Penaeus aztecus&lt;br&gt;• Monthly commercial catch Pamlico Sound, 1972-77 (5 yrs)&lt;br&gt;• Wind, Pamlico River flow, salinity, air &amp; water temp., rainfall&lt;br&gt;• Analysis: multivariate regression to develop a predictive harvest model</td>
<td>Juvenile abundance highly correlated with commercial harvest (r=0.94)&lt;br&gt;Harvest correlated with water temperature &amp; salinity&lt;br&gt;River flow was poorly predicted salinity, so used salinity as the predictor of catch</td>
<td>Salinity of 10 &amp; water temp. of 20°C are threshold values acting on post larval settlement &amp; juvenile growth (April &amp; May)&lt;br&gt;These levels determine subsequent production</td>
</tr>
</tbody>
</table>
### Vance et al. 1985. Australia, Gulf of Carpentaria
- **Banana prawns, *Penaeus merguiensis***
- Commercial catch 1970 to 1979
- Research data juveniles for Norman River
- Rainfall, wind and air temp.
- Gauged river flow
- June to May grouping of data
- Seasonal data (used in multiple regression)
- **Analysis**: (i) single variable correlation analysis and (ii) forward-selection multiple regression analysis

### Gammelsrød 1992, (Est. Coast. Shelf Sci), Mozambique
- **Red-leg banana prawns, *Penaeus indicus***
- Commercial catch, effort, size classes, Zambezi River flow, rainfall
- 1974 to 1988
- Used climatic year: Oct to Sept
- **Analysis**: (i) linear regression, (ii) stepwise multiple regression, (iii) predicted catch based on discharge
- see also da Silva 1985

- **Banana prawns, *Penaeus merguiensis***
- Catch and effort data 1974 to 1993
- Rainfall (Oct to Sept)
- Flow for Fly, Kikori, Purari, Vailala & Lakekamu Rivers
- **Analysis**: (i) CLIMPROD, (ii) linear regression

### Table: Environmental Flows for Fisheries in Sub-tropical Estuaries

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<tr>
<td>Commercial prawn catch not significantly correlated to juvenile abundance in Karumba region</td>
<td>Commercial prawn catch increasingly correlated to annual rainfall and regional prawn catch significantly correlated. Regional prawn catch significantly correlated with: (i) Mitchell winter rainfall ($r=0.89$, $p&lt;0.01$); (ii) Karumba spring ($r=0.76$, $p&lt;0.01$), summer ($r=0.80$, $p&lt;0.01$) &amp; annual rainfall ($r=0.86$, $p&lt;0.01$); (iii) Mornington ls. winter ($r=0.78$, $p&lt;0.01$) &amp; annual rainfall ($r=0.74$, $p&lt;0.01$); (iv) Limmen Bight winter ($r=0.82$, $p&lt;0.01$) &amp; annual rainfall ($r=0.77$, $p&lt;0.01$); (v) Groote Eylandt winter ($r=0.75$, $p&lt;0.01$), spring rainfall ($r=0.69$, $p&lt;0.05$);(vi) Weipa spring rainfall ($r=0.67$, $p&lt;0.01$)</td>
<td>Only significant negative Spearman Rank correlation for mean monthly rainfall at one station &amp; banana prawn CPUE in the Gulf of Papua for the calendar year, ($r=0.4434$, $p&lt;0.057$)</td>
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<td>10 of 30 correlations between mean seasonal or total annual rainfall &amp; regional prawn catch significant.</td>
<td>Karumba region catch correlated with summer river flow ($r=0.80$, $p&lt;0.01$) &amp; annual flow ($r=0.82$, $p&lt;0.01$)</td>
<td>Only significant negative Spearman Rank correlation for mean monthly rainfall at one station &amp; banana prawn CPUE in the Gulf of Papua for the calendar year, ($r=0.4434$, $p&lt;0.057$)</td>
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<td>3 of 30 correlations between annual regional prawn catch &amp; mean seasonal or annual temperature significant</td>
<td>3 of 24 correlations between annual regional prawn catch &amp; seasonal wind component significant</td>
<td>Rainfall models explained between 42% &amp; 72% of the variation in regional banana prawn catches</td>
</tr>
<tr>
<td>5 of 24 correlations between annual regional prawn catch &amp; seasonal wind component significant</td>
<td>No significant correlations of catch &amp; rainfall.</td>
<td>Discusses the problem of variables being significant correlated but having no supporting biological mechanism. They did not use these variables in further analyses or predictive models.</td>
</tr>
<tr>
<td>Rainfall models explained between 42% &amp; 72% of the variation in regional banana prawn catches</td>
<td>No significant correlations of catch &amp; rainfall.</td>
<td>The issue of regional variation in environmental factors, possible reflecting the different timing of larval recruitment into GOC estuaries.</td>
</tr>
<tr>
<td><strong>Analysis</strong>: (i) single variable correlation analysis and (ii) forward-selection multiple regression analysis</td>
<td>11 out of 18 correlations significant for flow.</td>
<td>Raises the issue that the size of the spawning stock could be influencing juvenile recruitment and subsequent commercial catches.</td>
</tr>
<tr>
<td>Neurological mode of wet season runoff, dry season runoff, wet season effort.</td>
<td>Points out that the results suggest hypotheses rather than “solid conclusions”.”</td>
<td>No flow recommendations.</td>
</tr>
<tr>
<td>Points out that the results suggest hypotheses rather than “solid conclusions”.”</td>
<td>Postulated mechanisms: (i) lower salinities stimulate the recruitment to the fishery of a greater portion of the population; (ii) larger flows creates a greater amount of “activated” nursery areas for the recruitment process</td>
<td><strong>Analysis</strong>: (i) linear regression, (ii) stepwise multiple regression, (iii) predicted catch based on discharge</td>
</tr>
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<td>Notes that timing of floods appears to be important with late floods resulting in greater production</td>
<td>Timing of flow with spring tides might be important</td>
<td><strong>Analysis</strong>: (i) CLIMPROD, (ii) linear regression</td>
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**Notes:**
- Biological mode of wet season runoff, dry season runoff, wet season effort.
- Points out that the results suggest hypotheses rather than “solid conclusions”.”
- Postulated mechanisms: (i) lower salinities stimulate the recruitment to the fishery of a greater portion of the population; (ii) larger flows creates a greater amount of “activated” nursery areas for the recruitment process
- Timing of flow with spring tides might be important

**Discusses the problem of variables being significant correlated but having no supporting biological mechanism. They did not use these variables in further analyses or predictive models.**

**The issue of regional variation in environmental factors, possible reflecting the different timing of larval recruitment into GOC estuaries.**

**Raises the issue that the size of the spawning stock could be influencing juvenile recruitment and subsequent commercial catches.**

**No flow recommendations.**

**Biological mode of wet season runoff, dry season runoff, wet season effort.**

**Notes that timing of floods appears to be important with late floods resulting in greater production.**

**Timing of flow with spring tides might be important.**
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<tr>
<th>Vance et al. 1998. Australia, north-eastern Gulf of Carpentaria</th>
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<tbody>
<tr>
<td>• Banana prawns, <em>Peneaus merguiensis</em></td>
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<tr>
<td>• Research sampling post larvae &amp; juveniles</td>
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<tr>
<td>• Commercial catch in Albatross Bay</td>
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<td>• Spring 1986 to autumn 1992</td>
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<tr>
<td>• Temp., Embley River salinity, light penetration &amp; rainfall</td>
</tr>
<tr>
<td>• Data groupings: pre-wet (Oct-Dec), wet (Jan-Mar); early dry (Apr-June); dry (July-Sept)</td>
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<tr>
<td><strong>Analysis:</strong> (i) regression, (ii) tested for autocorrelation</td>
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</tbody>
</table>

| Catch significantly correlated with (i) combined pre-wet & wet season emigrating prawn abundance (R²=0.82, p<0.01); (ii) pre-wet & wet season benthic juvenile abundance (R²=0.71, p<0.03); (iii) Catch positively but not significantly correlated with (i) pre-wet & wet season total rainfall (R²=0.25, p=0.31); or (ii) mean river salinity (R²=0.56, p=0.09) |

| Suggests that the size of the river catchment area is likely to be the most important factor determining the strength of the correlation between rainfall & offshore catch, as catchment area will affect the duration & volume of freshwater inundation in the estuary |

<table>
<thead>
<tr>
<th>Galindo-Bect et al. 2000. Mexico, Gulf of California</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Shrimp, <em>Litopenaeus stylirostris</em></td>
</tr>
<tr>
<td>• Annual landings &amp; CPUE (landings/number of trollers)</td>
</tr>
<tr>
<td>• Colorado River flow (log10 transformed) &amp; number of trollers (i.e. effort)</td>
</tr>
<tr>
<td>• 1977 to 1996</td>
</tr>
<tr>
<td><strong>Analysis:</strong> (i) correlation, (ii) multiple regression</td>
</tr>
</tbody>
</table>

| Significant downward trend in landings between 1977 & 1996 |
| 5 of 6 correlations for landings significant |
| None of the 6 correlations for CPUE with flow & effort were significant |
| Landings significantly correlated with same yr river discharge (r=0.54, p<0.05), landings significantly correlated with previous yr river flow (r=0.67, p<0.001) |
| Landings significantly correlated with CPUE (r=0.77, p<0.001) |
| Best model was the product of lagged river discharge (log transformed) & effort (r=0.80, p<0.001); landings = 232 + 1.67*(log_lagged flow*number of trollers) |

| Unknown cause of link between flow & production of the shrimp fishery |
| Possibly through enhanced survival of early life stages in enlarged nursery areas, although *L. stylirostris* is a euryhaline species with post-larvae & juveniles occurring in hypersaline habitats |

<table>
<thead>
<tr>
<th>Browder 1985. USA, Gulf of Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Pink shrimp, <em>Peneaus duorarum</em></td>
</tr>
<tr>
<td>• Landings of Tortugas shrimp grounds</td>
</tr>
<tr>
<td>• Standardised effort (monthly)</td>
</tr>
<tr>
<td>• Quarterly average water level at a station in the Shark River, principal tributary of the Florida Everglades</td>
</tr>
<tr>
<td>• Air temp. &amp; CPUE lagged by 3 months</td>
</tr>
<tr>
<td><strong>Analysis:</strong> multiple regression</td>
</tr>
</tbody>
</table>

| Standardized effort, water level lagged one quarter & CPUE lagged four quarters explained 88% of the variation in the 14 years of combined quarterly data |
| Oct-Dec and July-Sept water levels had the greatest influence on annual landings |

<table>
<thead>
<tr>
<th>da Silva 1985. Mozambique</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Red-leg banana prawns, <em>Peneaus indicus</em></td>
</tr>
<tr>
<td>• Total annual catch, monthly fishing effort</td>
</tr>
<tr>
<td>• Catch data from one company, 1974 to 1983</td>
</tr>
<tr>
<td>• Zambezi River flow</td>
</tr>
<tr>
<td><strong>Analysis:</strong> abundance indices analysed by length groups, &amp; related to river runoff</td>
</tr>
</tbody>
</table>

| Best correlations between total catch rate of *P. indicus* & Zambezi runoff were obtained for the recruitment period with a 1-month lag between runoff & catch rate, & were always better for smaller length groups (13.5 cm) than for the total number or catch weight |
| Average size of individuals has decreased, either due to high fishing pressure or movement of small prawns out of the river triggered by artificial flows |

| Zambezi River runoff is inferred to affect either directly or indirectly, the recruitment strength of *P. indicus* to fishing areas |

<table>
<thead>
<tr>
<th>Staples and Vance 1986. Australia, south-eastern Gulf of Carpentaria</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Banana prawns, <em>Peneaus merguiensis</em></td>
</tr>
<tr>
<td>• Research sampling of emigrating prawns</td>
</tr>
<tr>
<td>• Commercial catch offshore of Karumba</td>
</tr>
<tr>
<td><strong>Analysis:</strong> (i) correlation, (ii) multiple regression</td>
</tr>
</tbody>
</table>

| Strong correlation between rainfall & commercial catch due to increased emigration of juvenile prawns |
| Emigration rates significantly correlated to rainfall, juvenile numbers & tide range, but when pooled into monthly data, emigration rate was highly correlated with rainfall of same month (R²=0.74) |

| Annual juvenile emigration is a function of resident prawn density & rainfall. At low resident densities, emigration is related to juvenile numbers & rainfall. At high densities, rainfall increasingly determines emigration strength & subsequent commercial catch. |

<table>
<thead>
<tr>
<th>Staples and Vance 1987. Australia, Gulf of Carpentaria</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Banana prawns, <em>Peneaus merguiensis</em></td>
</tr>
<tr>
<td>• Fortnightly research sampling post larvae, juveniles, emigrating juveniles &amp; adolescents, Sept. 1978 to March 1979</td>
</tr>
<tr>
<td>• Tide, rainfall, juvenile abundance</td>
</tr>
<tr>
<td><strong>Analysis:</strong> forward step-wise multiple regression</td>
</tr>
</tbody>
</table>

| (Not strictly a commercial catch correlation) |
| Multiple immigration of post-larvae into the estuaries, but was variable between estuaries |
| The number & size of emigrating juvenile & adolescent prawns significantly correlated with (i) juvenile numbers, (ii) tide phase & (iii) rainfall, but differed between estuaries |

| Timing of rainfall compared to prawn development was important in influencing the contribution of an estuary to the offshore fishery |
CZCRC and FRDC Final Report

Environmental Flows for Fisheries in Sub-tropical Estuaries

Wilber 1992. USA, Florida
- **Oysters, Crassostrea virginica**
- Total annual landings, CPUE (per registered oystermen per yr)
- 1960 to 1984 (24 yrs)
- Apalachicola River Flow: (i) mean low & high flow events for the 1, 7, 30 & 60 consecutive days & 90 & 120 consecutive days for low flows; (ii) annual mean monthly-minimum, monthly-mean, & monthly-maximum flow
- Analysis: (i) linear regression of annual CPUE & flow, with 2-year lag; (ii) regression analysis using the number of days where flow was above or below a threshold, (iii) predicted CPUE in 1983 & 1984 based on regression equations
- Significant negative correlation CPUE & same year flow (due to 3 particular yrs)
- Significant positive correlation CPUE & min. flows with: (i) 2-yr lag [1 (r=0.69), 7 (r=0.65), 30 (r=0.64), 60 (r=0.60), 90 (r=0.62) and 120 (r=0.63) day flows]; and (ii) 3-yr lag of min. flows [1 (r=0.42) and 90 (r=0.61) day flows]
- No proof of a cause & effect relationship, but “supports ecological based rationale that freshwater inflow affects oyster production”
- Significant positive correlation between min. flow & oyster productivity lagged by 2 & 3 yrs consistent with growth to marketable size.
- Suggests that flow events influence oyster predation, most of which are excluded from estuaries at salinities of 15
- Concludes an inverse relationship between spat survival & estuarine salinities
- More frequent low flows may be detrimental to oyster production
- Notes that this scenario may be different in different estuaries

Livingston *et al.* 2000. USA, Gulf of Mexico, Apalachicola Bay
- **Oysters Crassostrea virginica**
- Larval density, spatfall, growth rates, biomass in
- Measured water quality parameters
- Modelled water quality parameters
- Analysis: (i) stepwise linear regression
- Larvae significantly correlated with oyster density, secchi readings & mean bottom salinity, & inversely correlated to bottom salinity max., but low r-value
- Oyster density significantly correlated with average surface current velocity & bottom min. salinity, & inversely correlated with bottom temp., surface colour & max. surface temp.
- Average growth of new oysters was significantly correlated with turbidity
- Growth of old oysters was inversely correlated with bottom temp., river flow, oyster density, & surface current velocities, but was positively correlated with surface salinity variation
- "Bar growth" was positively correlated with surface water colour, secchi readings & average bottom salinities
- Overall oyster mortality was positively correlated with max bottom salinity & surface residual current velocity

Sawynok 1998. Australia, central Queensland
- **Barramundi, Lates calcarifer**
- Recaptures of tagged fish 1984-1997
- Fitzroy River flow, & rainfall
- Analysis: (i) plots Oct-Feb flow & rainfall with % of juveniles tagged, (ii) average daily linear growth plotted against monthly flow
- (Not strictly a commercial catch correlation)
- Higher levels of recruitment (i.e. % of juveniles tagged) occurred with high river flows (91-million ML) in October to February, except for 87/88
- Average daily growth was 0.61 mm/day/fish for monthly flow >2.5 million ML, & was 0.90 mm/day/fish for monthly flow >2.5 million ML

Walker *et al.* 1998. Australia, Victoria
- **Black bream, Acanthopagrus butcheri**
- Research sampling Gippsland Lakes District
- Otolith-based year-class strength estimates
- River flow, SOI, rainfall, temperature
- Analysis: (i) dynamic regression analysis, (ii) Durbin-Watson statistic for 1st and 2nd order autocorrelations, (iii) ARIMA
- Recruitment strength predicted by: (i) temperature prior to spawning (Oct.), (ii) temp. during spawning (Feb.), & (iii) rainfall after spawning (May)
- No significant models were found using river flow or SOI
- Strong year-classes corresponded with avg. summer air temperatures >26°C; weak year-classes corresponded with avg. summer air temperatures <24°C
- Recruitment positively correlated with high May rainfall
- Best models accounted for 41% of the variation in the relative year-class strength

**H:** year-class strength related to larval survival, which depends on favourable environmental conditions for optimal food production & larval growth
### Quiliones and Montes 2001. Central-south Chile
- **Róbalo**, *Eleginops maclovinus*
- Annual landings
- Itata & Bio-Bio River flow, monthly & annual
- Cumulative rainfall, monthly & annual
- Landings, flow & rainfall smoothed using 3-yr running means
- **Analysis**: (i) correlation lagged (1-5 yrs), (ii) Pearson correlation coefficients, d.f. adjusted for autocorrelation, (iii) linear regression & (iv) stepwise regression

### Sutcliffe 1973. Canada, Gulf of St Lawrence
- **Lobsters**
- **Halibut**
- St Lawrence River flow
- **Analysis**: (i) correlation, 8- or 9-yr lag

### Salen-Picard et al. 2002. Mediterranean Sea, Gulf of Lions
- **Common sole** *Solea solea*
- Rhine River flow 1920-2000
- Seasonal polychaete sampling 1993-2000
- Seasonal dietary sampling of juvenile sole
- **Analysis**: (i) cumulative mean deviation method, (ii) Spearman rank correlation coefficient, time lags: polychaetes 1 to 48 months, landings 1 to 8 years; d.f. adjusted for serial autocorrelation

### Powell 1977. USA, Texas, San Antonio Bay System
- **Fish harvest** (7 species)
- **Shellfish** harvest (crabs, oysters, brown & white shrimp)
- 1962 to 1976 (15 yrs)
- **Analysis**: (i) correlation, (ii) ranked white shrimp harvest from best to worst & looked for similarities/differences in the seasonal flows

### Meeter et al. 1979. USA, Florida, Apalachicola estuary
- **Commercial landings, 1957-1977**
- **Monthly catch blue crabs & shrimp, 1972-1977**
- Flow (log), rainfall (square-root)
- **Analysis**: (i) spectral & cross-spectral analyses, (ii) correlation

### Analysis
- **Landings correlated with annual Bio-Bio River flow lagged by 4-yr** ($r =-0.80$, $p=0.05$)
- **Landings correlated with annual Itata River flow lagged by 3-yr** ($r = -0.94$, $p=0.01$)
- **Landings not significantly correlated with combined rivers annual flow**
- **Landings correlated with annual rainfall, lagged by 4-yr** ($r =-0.75$, $p=0.05$), but correlated with mean March rainfall, lagged by 4-yr ($r=0.78$, $p=0.05$).
- **Best stepwise linear regression model**: Landings = 177.01 – 0.59*annual mean rainfall – annual mean Itata flow lagged by 3-yr ($r = 0.93$, $p=0.05$)
- **No discussion as to why one river has a 4-yr lagged effect, while the other has a 3-yr lagged effect**

- **Annual commercial landings at two fishing ports positively correlated to mean annual flow** ($r=0.84$, $p=0.01$ Port of Martigues; $r=0.93$, $p=0.001$ Port of Sete) lagged by 5-yr

- **Significant correlations between catch & sea temp for Alewife** ($r =0.850$) 6-yr lag, **Butterfish** ($r =0.739$) 3 to 5-year lag, **Atlantic cod** ($r =-0.661$) 4-yr lag, **Atlantic herring** ($r =0.604$) 2-yr lag, **Atlantic menhaden** ($r =-0.872$) 3-yr lag, **Redfish** ($r =-0.728$) 8-yr lag, **Silver hake** ($r =-0.781$) 5-yr lag, **Striped bass** ($r =-0.631$) 3-yr lag, **Yellowtail flounder** ($r =0.792$) 2-yr lag, **Hard clams** ($r =-0.805$) 10-yr lag, **Soft-shell clams** ($r =-0.798$) 7-yr lag

- **Developed an approx. gauged freshwater inflow regime (monthly % distribution) to meet minimum sustaining fishery requirements**
- **No details are provided as to how the minimum sustaining fishery requirements were arrived at**

### Environment Flows for Fisheries in Sub-tropical Estuaries

<table>
<thead>
<tr>
<th>Species</th>
<th>Catch Correlation</th>
<th>Time Lag</th>
<th>Percentage of Significant Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Róbalo</td>
<td>Positive</td>
<td>4-yr</td>
<td>100%</td>
</tr>
<tr>
<td>Silver hake</td>
<td>Positive</td>
<td>5-yr</td>
<td>75%</td>
</tr>
<tr>
<td>Red drum</td>
<td>Positive</td>
<td>3-yr</td>
<td>50%</td>
</tr>
<tr>
<td>Yellowtail flounder</td>
<td>Positive</td>
<td>2-yr</td>
<td>25%</td>
</tr>
<tr>
<td>Hard clams</td>
<td>Positive</td>
<td>10-yr</td>
<td>10%</td>
</tr>
<tr>
<td>Soft-shell clams</td>
<td>Positive</td>
<td>7-yr</td>
<td>5%</td>
</tr>
</tbody>
</table>

**Proposed that (i) flow influences the survival rates of Róbalo in the first year (negative relationship)** due to (a) washout of eggs & larvae or (b) a trophic effect that increases the predation on 0+ Róbalo year-class, (ii) rainfall in March leads to flow that expands the area of suitable reproductive & nursery habitat
- **No flow recommendations.**

**Speculated a 2-step process: higher survival of larvae & juveniles in the yr of the flood, followed by an increase in the fecundity of the populations for a few years (3-yr to maturity with fecundity increasing with size)**
- **Both are the consequence of a trophic response to flood events, i.e. increases in short & long-lived polychaetes increased the survival & growth of different life history stages of sole.**
<table>
<thead>
<tr>
<th>Study</th>
<th>Analysis</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Funicelli 1984. USA, Texas estuaries</strong>&lt;br&gt;[57x798]&lt;br&gt;• Analysis: (i) stepwise GLM&lt;br&gt;• Analysis yielded 19 statistically significant regression equations relating to eight species groups Shellfish, Penaeid shrimp, White shrimp, Blue crab, Oyster, Finfish, Spotted seatrout, red drum</td>
<td>• Study indicates that reduced flows will directly reduce river borne nutrients &amp; freshwater inundation of deltaic marshes, negatively impacting on habitats &amp; commercial fisheries production</td>
<td></td>
</tr>
<tr>
<td><strong>Drinkwater and Myers 1987. Canada, Quebec</strong>&lt;br&gt;[57x706]&lt;br&gt;• Analysis: (i) linear regression, (ii) regression equations for predicting catches of subsequent years, (iii) predicted catch correlated with observed landings&lt;br&gt;• Ho: Variability of invertebrate &amp; fish abundance due to environmental factors&lt;br&gt;• Correlations of r&gt;0.5 for: Lobster, Soft shell clams, Butter-fish, Redfish and, Flounder&lt;br&gt;• None significant due to high autocorrelation in the data</td>
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<tr>
<td><strong>Kimmerer and Schubel 1994 San Francisco Bay / Sacramento / San Joaquin Delta estuary (Workshop)</strong>&lt;br&gt;[57x610]&lt;br&gt;• Goal: consensus among the scientific community regarding the flow needs of the estuary&lt;br&gt;• Selected the location of a salinity of 2-psu at the bottom as an index on which a standard should be based&lt;br&gt;• Found significant relationships between the historical value of $\chi^2$ &amp; all trophic levels i.e. total input of organic carbon, abundance of mysid Neomysis mercedis, bay shrimp Crangon franciscorum, longfin smelt, starry flounder, survival of striped bass from egg to young-of-the-year, striped bass year-class strength, survival of salmon smolts, &amp; biomass of molluscs&lt;br&gt;• Biological responses to the optimum $\chi^2$ were sigmoidal, with a region of rapid increase in response to decreasing $\chi^2$, followed by a levelling off at high value of $\chi^2$&lt;br&gt;• Most biological responses increased monotonically with decreasing $\chi^2$; none showed a clear maximum at intermediate values of $\chi^2$</td>
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<tr>
<td><strong>Powell and Malstaff 1994. USA, Texas, Guadalupe Estuary</strong>&lt;br&gt;[57x436]&lt;br&gt;• Red drum (Sciaenops ocellatus n=19)&lt;br&gt;• Black drum (Pogonias cromis n=24)&lt;br&gt;• Spotted seatrout (Cynoscion nebulous n=19)&lt;br&gt;• Blue crabs (Callinectes sapidus, 24 years)&lt;br&gt;• Eastern oyster (Crassostrea virginica n=24)&lt;br&gt;• Brown shrimp (F. aztecus, n=27)&lt;br&gt;• White shrimp (L. setiferus, n=27)&lt;br&gt;• Annual landings (+ effort for shrimp)&lt;br&gt;• G(auged) &amp; EOS flow (bimonthly)&lt;br&gt;• Average minimum air temperature&lt;br&gt;• Analysis: (i) all possible subsets regression to select the 10 best predictors (raw &amp; ln transformed), (ii) serial correlation using runs test, autocorrelation using Durbin-Watson test; (iii) observed historic catches plotted against the predicted harvests&lt;br&gt;• Derived harvest-inflow equations for each species-group.&lt;br&gt;• Harvest is linear function of ln transformed combined inflows for 2 month period (lagged to suit species life history). Equations for each species are provided in text.&lt;br&gt;• Red drum ($R^2=0.69$, p=0.0001, Gflow &amp; temp.), ($R^2=0.52$, p=0.0011, EOS flow &amp; temp.)&lt;br&gt;• Black drum ($R^2=0.66$, p=0.0001, Gflow &amp; temp.), ($R^2=0.44$, p=0.0024, EOS flow &amp; temp.)&lt;br&gt;• Blue crabs ($R^2=0.78$, p=0.0001, Gflow &amp; temp.), ($R^2=0.62$, p=0.0001, EOS flow &amp; temp.)&lt;br&gt;• Seatrout ($R^2=0.61$, p=0.0002, Gflow &amp; temp.), ($R^2=0.60$, p=0.0003, EOS flow &amp; temp.)&lt;br&gt;• Oysters ($R^2=0.88$, p=0.0001, Gflow &amp; temp.), ($R^2=0.83$, p=0.0001, EOS flow &amp; temp.)&lt;br&gt;• Brown shrimp ($R^2=0.89$, p=0.0001, Gflow, effort &amp; temp.), ($R^2=0.88$, p=0.0001, EOS flow, effort &amp; temp.)&lt;br&gt;• White shrimp (adj. r² = 0.77, p=0.0001, G flow &amp; temp.), ($R^2 = 0.73$, p=0.0001, EOS flow &amp; temp.)&lt;br&gt;• Analysis of data for the other 4 estuaries gave similar results although the degree of fit varied considerably between estuaries for any one species</td>
<td></td>
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<tr>
<td><strong>Skreslet 1997. Norway</strong>&lt;br&gt;[57x224]&lt;br&gt;• NE artic cod Gadus morhua&lt;br&gt;• Melt water discharge&lt;br&gt;• Year-class strength positively correlated with melt water discharge 1-yr in advance&lt;br&gt;• Commercial landings of juvenile cod positively correlated with melt water discharge 3-yrs in advance</td>
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</tr>
</tbody>
</table>

**Chapter 1. Review of rainfall/river flow and estuarine fisheries landings**

22
<table>
<thead>
<tr>
<th>Country</th>
<th>Authors</th>
<th>Study Area</th>
<th>Methods/Species</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada, Quebec</td>
<td>Ardisson and Bourget 1997.</td>
<td>Gulf of St Lawrence</td>
<td>Maximum abundance, biomass, mean weight of juveniles of 5 epibenthic species: (i) Hydroid Obelia longissima (ii) Bivalves Hiatella arctica, Mytilus edulis (iii) Cirripedes Semibalanus balanoides, Balanus crenatus</td>
<td>Cumulative spring runoff, mean annual runoff 1975 to 1985 (10 years). Analysis: (i) simple linear regression, spearman correlation test; (ii) polynomial regression of 2nd and 3rd orders; (iii) GLM; (iv) GAM; (v) Bonferroni corrections &amp; non-parametric correlations. No analyses adequately modelled the data. No significant relationships observed.</td>
</tr>
<tr>
<td>Australia, southeast Queensland</td>
<td>Loneragan and Bunn 1999.</td>
<td>Calendar year commercial landings</td>
<td>Analysis: (i) correlation: total catch with seasonal flows from preceding September to December; (ii) Pearson correlation coefficients; (iii) regressions equations fitted for significant correlations and used to predict catches as a function of minimum &amp; maximum seasonal flows. Summer flows significantly correlated with catches of mud crabs ($R^2 = 0.80$, $p&lt;0.01$), total crabs ($R^2 = 0.75$, $p&lt;0.01$), total prawn ($R^2 = 0.74$, $p&lt;0.01$), bay prawns ($R^2 = 0.05$), tiger prawns ($R^2 = 0.01$), flathead ($R^2 = 0.69$, $p&lt;0.05$). Total annual flow significantly correlated with catches of school prawns ($R^2 = 0.05$), grease prawns ($R^2 = 0.05$), tiger prawns ($R^2 = 0.05$), mullet ($R^2 = 0.05$), flathead ($R^2 = 0.05$), total fish ($R^2 = 0.05$). Winter flow significantly correlated with mullet ($R^2 = 0.05$), school prawns ($R^2 = 0.05$). Long-term data (flow &amp; total fish catch), after accounting for year, flow explained 25% of the variation in fish catch.</td>
<td></td>
</tr>
<tr>
<td>USA, Texas</td>
<td>Ritter et al. 2000.</td>
<td>White shrimp (P. setiferus, n=35), Brown shrimp (P. aztecus, n=73), Blue crabs (Callinectes sapidus, n=33), Spotted seatrout (Cynoscion nebulosus, n=20), Red drum (Sciaenops ocellatus, n=20), Black drum (Pogonias cromis, n=33)</td>
<td>Effort for brown shrimp Analysis (i) regression analysis, (Based on methods of TxEMP, Powell &amp; Malstaff 1994)</td>
<td>Derived a harvest-inflow equations for each species group i.e., harvest = some linear function of ln transformed combined inflows for a two month period. Equations are provided for each species, containing between 3 and 5 inflow parameters i.e., two months of inflow. Significance levels were white shrimp (adj. $R^2 = 0.50$, $p=0.0001$), brown shrimp (adj. $R^2 = 0.75$, $p=0.0001$), blue crabs (adj. $R^2 = 0.58$, $p=0.0001$), spotted seatrout (adj. $R^2 = 0.63$, $p=0.0001$), red drum (adj. $R^2 = 0.59$, $p=0.0013$), black drum (adj. $R^2 = 0.41$, $p=0.0017$).</td>
</tr>
<tr>
<td>North-west Mediterranean Sea</td>
<td>Lloret et al. 2001.</td>
<td>13 Commercial species that were dominated by fisheries for 1- &amp; 2-yr old individuals. Monthly catch, Rhône &amp; Muga Rivers flow &amp; wind-mixing index.</td>
<td>Analysis: (i) decomposed environmental time series into trend &amp; seasonality, (ii) linear relationships analysed with annual data, (iii) transfer function time series analysis. H$_2$ recruitment is influenced by river discharge &amp; wind condition during the spawning &amp; recruitment season through enhanced fertilisation or larval retention. Catch &amp; CPUE significantly positively correlated (at different time lags) with river flow &amp; wind-mixing-index during the reproductive season. Significant time lags were identified for 2 to 6 months, 6 to 10 months, 16 to 18 months, 18 to 26 months across a number of species &amp; sizes caught.</td>
<td></td>
</tr>
</tbody>
</table>
Powell et al. 2002. USA, Texas, Galveston Bay
- Red drum (Sciaenops ocellatus n=19)
- Black drum (Pogonias cromis n=24)
- Spotted seatrout (Cynoscion nebulosus n=19)
- Blue crabs (Callinectes sapidus, 24 years)
- Eastern oyster (Crassostrea virginica n=24)
- Brown shrimp (F. aztecus, n=27)
- White shrimp (L. setiferus, n=27)
- Flounder (Paralichthys lethostigma)
- Annual landings (effort for shrimp)
- G(auged) & EOS flow (bimonthly)
- Average minimum air temperature
- Analysis: (i) all possible subset regression analysis to select the 10 best predictors (raw & ln transformed); (ii) serial correlation using runs test, autocorrelation using Durbin-Watson test; (iii) observed historic catches plotted against the predicted harvests, (Based on methods of TxEMP).

Sobrino et al. 2002. Spain, Gulf of Cadiz
- Common octopus (Octopus vulgaris, n=18)
- Cuttlefish (Sepia officinalis, n=18)
- Landings (kg by month), effort
- Monthly Sea Surface Temperature; Monthly river flow, mean rainfall rates – aggregated into ‘pluvial year’ = September to June
- Analysis: (i) parametric correlation analysis, with Pearson correlation coefficient; (ii) stepwise multiple regression

- Derived a harvest-inflow equations for each species group i.e., harvest = some linear function of ln transformed combined inflows for a two month period. Equations are provided for each species, containing between 3 and 5 inflow parameters i.e., two months of inflow.
- Significance levels were red drum (adj. R² = 0.59, p=), black drum (adj. R² = 0.41, p=), spotted seatrout (adj. R² = 0.52, p=), blue crabs (adj. R² = 0.76, p), eastern oyster (adj. R² = 0.46, p=), white shrimp (adj. R² = 0.57, p=), brown shrimp (adj. R² = 0.49, p<), flounder (adj. R² = 0.54, p=)
- Removed up to 10% of the outliers in order to maximise the correlation, but number not used is specified for each species.

- Significant negative correlations existed for octopus but not for cuttlefish
- Landings of octopus (which comprise 28% of the cephalopod catch) were significantly correlated with the previous rain season coefficient (Rain \(^{-1}\), r=-0.69, p<0.01, river discharge in January (River\(^1\), r=-0.83, p<0.01), February (River\(^2\), r=-0.67, p<0.01), & December (River\(^{12}\), r=-0.65, p<0.01), & SST coefficients for months February =-0.56, p<0.05, April =-0.60, p<0.05, May =-0.64, p<0.01, June =-0.68, p<0.01.
- Identified that Rain \(^{-1}\) (&River\(^{1}\) River\(^2\)), River\(^{12}\) & SST\(^{5}\) & SST\(^{6}\) should be used as the variables affecting abundance of octopus
- Generated a significant multiple regression with an R\(^2\) of 0.76
- Octopus abundance of depends annual recruitment, probably defined at early planktonic stages
- Rainfall hypothesized to have a negative effect on egg-laying or paralarvae survival
- SST affects abundance through (i) an indirect effect on cephalopod paralarvae via food availability or predation or (ii) as a direct effect on paralarvae mortality
- River flow may change environmental conditions forcing octopus to leave relatively unsheltered dens
- Cuttlefish a euryhaline species able to tolerate fluctuations in salinity