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Assessment of Information Needs for Freshwater Flows into Australian Estuaries

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Assessment of Information Needs for Freshwater Flows into Australian Estuaries

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Back cover image: Mouth of the Burdekin River, in Queensland's dry tropics, Queensland Environmental Protection Agency.

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1 Executive Summary

OBJECTIVES

This report was jointly commissioned by the Fisheries Research and Development Corporation and Land & Water Australia to assess the information needs for freshwater flows into estuaries. This report is based on the results of a desk study together with the outputs from an expert workshop. It has the following objectives:

1. create a logical framework showing the potential links between freshwater inflows and ecological responses;
2. assess current knowledge about each of these links in Australian estuaries;
3. identify the critical links where further research and development (R&D) would provide maximum benefit; and
4. collate available information on current decision-making processes/frameworks for environmental flow management.

NON-TECHNICAL SUMMARY

There is a large body of national and international research on the effects of flows on freshwater ecosystems and to a lesser extent on the functioning and health of estuaries. However, while many studies discuss the links between water quality and production within estuaries, few have discussed the links between freshwater flows and estuarine production. This is particularly true in Australian systems. Understanding these links is of growing importance given the current effort to determine allocations of freshwater for environmental flows throughout many Australian rivers. Without this understanding, the environmental allocations of freshwater to estuaries may not be adequate for maintaining estuarine functions on which depend a range of ecosystem services.

Recognising the importance of this topic, the Fisheries Research and Development Corporation (FRDC) and Land and Water Australia (LWA) requested an assessment of the priority research topics on the effects of freshwater flows into Australian estuaries. To do this a three step approach was developed, including: (1) a rapid review of the literature and limited interviews; (2) a workshop; and (3) a final report containing prioritised research topics based on the above inputs that was reviewed by experts from around Australia. The report focussed on biophysical R&D needs; knowledge-needs relating to social and economic factors were included when they were identified during the course of the project.

The review proposed a conceptual framework comprising the sequential effects of freshwater inflows on the estuarine abiotic environment, the biotic environment and estuarine environmental values.

There is clear evidence from around the world that alterations to freshwater flow regime affect estuarine abiotic conditions such as salinity, sediment/turbidity, water temperature, nutrients and organic matter, dissolved

oxygen, pH, hydrodynamics, geomorphology. There is also evidence of effects on abiotic habitat and ecosystem connectivity.

The evidence is less clear on links between freshwater flows and the estuarine biotic environment. Although it has been suggested that estuarine assemblages will be affected by freshwater flow, there are few studies showing what these effects are. Generally, there is a positive relationship between freshwater flows and primary production of an estuary due to the increased nutrients coming into the system, though there are also instances of negative relationships. The exact mechanisms that underlie these relationships are not well understood but, in general, increased inflows result in changes to recruitment, survival, growth and/or dispersal of biota. A summary of the influence of flows on estuarine productivity suggests there are three main mechanisms: (1) through trophic pathways, (2) through distribution, and (3) through population dynamics.

A diverse range of knowledge needs was identified through discussions and reviews prior to the expert workshop. These were reduced to a total of 52 knowledge-needs (19 'high priority', 14 'medium priority' and 19 'low priority') at the workshop. The 'high priority' knowledge-needs were then further prioritised by examining: a) their benefit to the needs of managers, and b) their scientific or technical merit and benefit. They are shown in the table below in priority order of benefit to management because of the focus on ensuring the research leads to practical outcomes.

Code	Knowledge Needs	Benefits to management†	Scientific merit†
A	How do different freshwater flow regimes influence habitat-biota relationships (e.g. woody debris, macrophyte beds, soft bottoms, sand bars, rocky outcrops, saltmarshes and saltflats, mangroves, extent and dynamics of the salt wedge, spatial and temporal variability of freshwater-saltwater habitat availability)?	H1	H1
B	What are the essential flow regime conditions needed to maintain estuarine health?	H1	H2
C	To develop a conceptual understanding of the major ecological processes and linkages in rivers and their estuaries.	H1	H2
D	How do different types of human impacts (dams, entrance management, agricultural, aquaculture, transport, urban, etc.) interact with altered freshwater flows to affect estuarine functioning?	H1	H2
E	What should we be routinely monitoring (biota, water quality, geomorphology, etc.) in an estuary that has environmental flows to make sure that we are meeting the flow objectives and outcomes?	H1	H2

Code	Knowledge Needs	Benefits to management†	Scientific merit†
F	What values do communities place on estuaries?	H1	H3
G	What are the most appropriate tools for testing different flow scenarios (predicting)?	H1	H3
H	How is estuarine productivity changed by freshwater flows and does changed primary productivity translate to changed secondary productivity?	H2	H1
I	What are the flow and water quality requirements of species (flora and fauna) recognised as ecological assets, (e.g. requirements for reproduction, recruitment, dispersal, distribution and abundance, persistence)?	H2	H1
J	What is the role of flows on commercial and recreational fisheries species and their supporting ecosystems (e.g. spawning success, migration and distribution, predation rates, trophic pathways)?	H2	H2
K	What is the relative significance of sources and sinks of water under different flow scenarios to estuaries, in particular what is the role of groundwater flows on estuaries particularly during low-flow periods?	H2	H2
L	What is the relationship of the full range of flows to estuarine morphology and geomorphological processes?	H2	H2
M	What is the relationship between freshwater inflow, water quality and the biogeochemistry of estuaries?	H2	H2
N	What are the relationships between estuarine and nearshore coastal ecological processes and what is the influence of freshwater flow either directly or indirectly?	H2	H2
O	What is the spatial zone of influence of natural and altered sequences of flow events, including quantity, quality and timing of flows?	H2	H3
P	What are: • the indicator species that indicate the level of health, or degradation, of an estuaries, and • the flow regime requirements and tolerances of these indicator species? How should we measure estuarine ecosystem health? What existing methods have already proven viable and what are the key aspects of health needing new/better metrics and measurement techniques?	H3	H3
Q	What will be the effects of climate change or variability on environmental flow needs to estuaries?	H3	H3

Code	Knowledge Needs	Benefits to management†	Scientific merit†
R	Is it possible to develop a common nation-wide assessment approach and if so what are the essential data requirements for estuarine systems to determine and assess outcomes for appropriate environmental flows?	**H3**	**H3**
S	What are the effects on an estuary of implementing environmental flows, particularly estuaries that have been 'starved' of flows for a relatively long time?	**H3**	**H3**

†Rankings: H1 (High priority 1) is the highest priority knowledge-need down to H3 (High priority 3) which is the lowest priority of the 'highs'.

The knowledge-needs identified in this report will almost certainly need to be addressed via a range of different research projects with consideration for integrated physical-biological models, multidisciplinary studies and quantitative research. In general there is a need to increase knowledge of the relationships between freshwater flows and estuarine health and productivity. The significance and scale of the knowledge-needs may vary considerably from one geographic location and estuary type to another. They will also vary in relation to the environmental, economic and social values of each estuary. The spatial variation in the R&D priorities was not determined in this review.

Several frameworks for grouping the knowledge-needs were discussed during the workshop and are included in this report. The table below shows the high priority R&D when they are grouped under the requirements for managing estuaries.

Management Theme	**Knowledge-need contributing to the theme†**
Political/Policy a. Development of decision-support processes and systems b. Development of implementation tools	G, F, R
Suitably sensitive models to integrate knowledge of flow regime and effects on ecological and other values that will allow testing of flow scenarios	G, C, E, K,
Access to and application of knowledge and research outcomes to extension and capacity building for managers, government, industry and the community	F, D, G, C, E,
Determination and assessment of flow delivery to achieve desired management outcomes	D, E, A, B, J, H, K, I, L, O, M, N, G, P, S
How to manage environmental flow allocations in the context of other interventions (e.g. entrance management, dredging, global warming, water quality degradation)	D, Q

Values a. What are the valued attributes (including biological, cultural, commercial, recreational, intrinsic) which require protection and are critically dependant on flow b. Decision-makers tool: framework which equitably considers impacts on all values	F, P,
Effect of flow regime (timing, magnitude, frequency, quality, duration) on the structure and function of estuarine ecosystems and other associated values	D, C, A, B, J, H, K, I, L, O, M, N, Q
What institutional coordination, regulatory and governance arrangements are required and at what scale(s)	R, F, C
Understanding the ecosystem and water quality consequences of the interaction of climate change with flow regimes and human responses to climate change under various scenarios	A, B, Q, D, G, J, H, K, I, L, O, M, N

†See knowledge-needs table above for wording and code.

The high priority R&D would contribute strongly to the determination of flows to achieve defined management outcomes as well as providing a better understanding of the structure and functioning of estuarine ecosystems. They make only minor contributions to social and institutional management issues such as identification of social values and institutional coordination, regulation and governance. This is in accordance with the focus of the consultancy.

These priorities for biophysical research were endorsed by a wide diversity of researchers, managers and policy analysts at the workshop. While they provide guidance for investments that will support better water allocation decisions, the challenge now will be to find the resources to undertake the research that will elucidate the links between freshwater flows and estuarine functioning and transmit this knowledge into action.

Conclusion

In terms of comprehensiveness, the 19 high-priority knowledge needs provide a good coverage of the core components of a research framework into freshwater flows into estuaries. These needs give a reasonable coverage of the major management themes and a good coverage of the major biophysical components of the modified AMF. However, socio-economic and institutional needs were not assessed (apart from those that arose opportunistically) during this study and the full range of research needs for freshwater flows into estuaries should include these additional issues in order to continue to refine the framework for targeting research investment to meet priority policy and management knowledge needs.

The outputs and the likely outcomes from this project are:

OUTPUTS

1. synthesis of major management themes linked with associated knowledge-needs;
2. analysis of gaps and knowledge needs;
3. prioritised and nationally agreed (amongst key research and management stakeholders) compilation of knowledge-needs;
4. a report outlining general issues surrounding flows and estuaries, including prioritised knowledge-needs, which provides information to assist FRDC and LWA to determine funding priority (and acquire money for funding priority) research needs for environmental flows for estuaries.

LIKELY OUTCOMES

1. initial agreement among key stakeholders in the research community on research priorities relevant to e-flows and estuaries;
2. improved coordination of research agendas of relevant bodies and research groups from each state and territory;
3. enhanced informal networks both within the research and management communities dealing with estuarine flows and also across these two groups;
4. an improved strategic position for Australian research into estuarine flows resulting in greater likelihood that future research will benefit both the fishing industry and Australian community through the essential ecosystem services provided by Australia's most valuable ecosystem.

KEYWORDS: environmental flow, estuary, knowledge gaps, research, ecosystems, flow regime, management.

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2 Introduction

Water is a critical resource management issue in Australia and is recognised as being "part of Australia's natural capital, serving a number of important productive, environmental and social objectives" (IGA-NWI, 2004, p. 1). The demand for water for residential supplies, agriculture, industry, and other human needs has increased with population growth. Solving conflicts over water allocations for these uses while retaining sufficient water for 'environmental flows' is a key element of Australia's national water reforms. One of the many competing 'uses' for freshwater flows are environmental flows into estuaries, the highly valuable receiving-waters of all seaward draining waterways.

The need for reform of water resource policy has long been recognised and formally recognized by the Council of Australian Governments (COAG) in June 1993. The result was a report commissioned from a 'Working Group on Water Resource Policy' ultimately leading to the Council endorsing in February 1994 a framework for the reform of the Australian water industry. A key component of the framework was the provision of allocations for the environment and in particular that "environmental requirements, wherever possible, will be determined on the best scientific information available and have regard to the inter-temporal and inter-spatial water needs required to maintain the health and viability of river systems and ground water basins" (COAG Communiqué, 1994, section 4d). The framework referred generally to 'river systems'; estuaries were not mentioned specifically. The major focus was on freshwater reaches of Australian rivers (i.e. those of prime interest to the water resources industry).

The water reform agenda was modified and extended in subsequent years with the inclusion of ground water and stormwater management in 1996 and the Tripartite agreement in 1999. ARMCANZ and ANZECC formed the *National Principles for the Provision of Water Ecosystems* which states that "the goal for providing water for the environment is to sustain and where necessary restore ecological processes and biodiversity of water dependent ecosystems" (ARMCANZ, 1996, p. iii). The framework includes the principles that:

- all water uses should be managed in a manner which recognises ecological values,
- further allocation of water for any use should only be on the basis that natural ecological processes and biodiversity are sustained, and
- provision of water for ecosystems should be made using the best scientific information.

The emphasis on reform was stepped up in June 2004 with the COAG agreement on a National Water Initiative (NWI) and the establishment of the National Water Commission (NWC). The NWI specifies several areas that critical for water reform, with the following key elements (IGA-NWI, 2004, p. 4):

- water access entitlements and planning framework,
- water markets and trading,
- best practice water pricing,

- integrated management of water for environmental and other public benefit outcomes,
- water resource accounting,
- urban water reform,
- knowledge and capacity building, and
- community partnerships and adjustment.

The NWI has been signed by all states and mainland territories except Western Australia, although Western Australia has recently indicated its intention to join the NWI.

The NWI agreement (IGA-NWI, 2004) recognises the need to “ensure the health of river and groundwater systems by establishing clear pathways to return all systems to environmentally sustainable levels of extraction” (p. 1). The agreement, thus, ostensibly includes the environmental flow needs of estuaries which may also be relevant under provisions dealing with “environmental externalities” (p. 15), “environmental and other public benefit outcomes” (p. 16), and in the “assessment of the socio-economic costs and benefits of the most prospective options, including on downstream users, and the implications for wider natural resource management outcomes” (p. 17).

The NWI includes a provision that the states and territories party to the agreement will “modify their existing legislation and administrative regimes where necessary” (IGA-NWI, 2004, p. 5) in order to achieve the outcomes of the agreement including meeting environmental and other public benefit outcomes. Moreover, integrated management of environmental water is to be achieved by “identifying the desired environmental and other public benefit outcomes with as much specificity as possible” (IGA-NWI, 2004, p. 16). Many of these activities within each state were well underway under the existing water reform framework and are being continued, including the assessment of flows for estuaries (see Section 8).

The importance of flows to the estuarine reaches of riverine systems has become increasingly recognised in Australia over the past decade (Drinkwater and Frank, 1994; Arthington and Zalucki, 1998a; Loneragan and Bunn, 1999; Alber and Florey 2002; Gillanders and Kingsford 2002; Peirson *et al*., 2002; Robins *et al*., 2005; Close, 2005). A significant issue identified in all previous studies is the number of deficiencies in our understanding of the influence of flows on estuarine ecosystems, and the “knowledge gaps on estuarine function and particularly ecological processes, making it difficult to set flow objectives and assess different flow scenarios” (Close, 2005, p. 2). Moreover, each estuary has unique characteristics and the geographic spread and climatic variability around the Australia continent makes generalisations difficult.

The NWI also requires water planning initiatives to recognise that “settling the trade-offs between competing outcomes for water systems will involve judgements informed by best available science, socio-economic analysis and community input” (IGA-NWI, 2004, p. 7). A fundamental principle for determining Environmental Water Allocations is that allocations should be determined using the best scientific information available for the water regimes necessary to sustain the ecological values of water dependent ecosystems, along with socio-economic analysis and community input (Gardner, 2005).

Under the NWI, states and territories are responsible for providing accurate and timely information on a range of water issues “including the science underpinning the identification and implementation of environmental and other public benefit outcomes” (IGA-NWI, 2004, p. 21). A key driver of environmental flows to estuaries under NWI is the requirement to protect, acknowledge, sustain and enhance high conservation value rivers, wetlands and groundwater systems (IGA-NWI, 2004). There is an agreement for all parties to “identify the key knowledge and capacity building priorities needed to support ongoing implementation” of the agreement on an ongoing basis (IGA-NWI, 2004, p. 21). Because of the preliminary nature of scientific information on the influences of flow on the ecological functioning of estuaries, all states and territories are faced with a difficult problem in allocating flows base don present knowledge. This can be solved only through further research and development (R&D). In the meantime, estuaries are difficult to include in water planning arrangements on an equal footing with freshwater systems, and may simply end up with ‘what is left over’ after other entitlements and allocations have been determined.

This ‘high-level’ review of information needs for managing freshwater flows to estuaries was undertaken with the purpose of assessing current knowledge strengths and gaps so that future R&D can be prioritised. The assessment was based on a rapid review of literature and semi-structured interviews with experts from around Australia (see list in Appendix 1). To complement this process a workshop was held in March 2006 to bring together experts on environmental flows and estuarine science to help refine the information provided here and prioritise research needs.

The objectives of the project were to:

- create a logical framework showing the potential links between freshwater inflows and ecological responses in a range of climatic and geomorphological zones around Australia,
- assess current knowledge about each of these links in Australian estuaries,
- identify the critical links where further R&D would provide maximum benefit, and
- collate available information on current decision-making processes/frameworks for environmental flow management and identify aspects for incorporating flow-requirements into estuaries.

3 The Value of Australia's Estuaries

Estuaries are a highly valued ecosystem worldwide (e.g. Costanza *et al.*, 1997) though their value is often unrecognised (Blackwell, 2005). Estuaries form the habitat for many species during some part of their life cycle, thus contributing to aquatic biodiversity. The full range of ecosystem goods and services (EGS) provided by estuaries is likely to be broad but is poorly understood. A comprehensive assessment of the value of Australian estuaries by Blackwell (2005) includes an indication of which EGS have been valued in some way (Table 3.1).

Table 3.1. List of ecosystem goods and services potentially provided by estuaries and an indication of whether their value has been estimated (modified from Blackwell, 2005).

Category	Ecosystem goods and services	Literature[1]
Provisioning services	Food (fisheries)	▲ ● ■
	Fibre (*including clothing and shelter*)	▲ ● ■
	Fuel	■
	Genetic resources	
	Biochemicals, natural medicines and pharmaceuticals	
	Ornamental resources	□
Regulating services	Air quality regulation	
	Climate regulation	
	Water regulation	■
	Erosion regulation	□
	Water purification	□
	Waste treatment	■
	Disease regulation	
	Pest regulation	□
	Population balance	▲
	Translocation and dispersion	
	Natural hazard regulation	▲ ● ■

Category	Ecosystem goods and services	Literature[1]
Cultural services	Cultural diversity	
	Spiritual and religious values	□
	Knowledge systems	▲
	Inspiration	
	Aesthetic and *serenity* values	■
	Social relations	
	Sense of place	
	Cultural heritage, historic and artistic values	▲
	Recreation and ecotourism	▲ ● ■
	Non-use value (existence, bequest)	●
Supporting services	Soil formation	
	Photosynthesis	
	Primary production	
	Nutrient cycling/regulation	▲
	Water cycling	
	Refugia function	▲
	Nursery function	▲ ■

Categorisation and types of EGS come from modification of Millennium Assessment (2005) and synthesis with information from Robinson and Clouston (n.d.); Curtis (2004); Wilson *et al*. (2002) and de Groot *et al*. (2002). Italics represent categories added to the Millennium Assessment.

[1] ▲ Costanza *et al*. (1997) estimate. ■ International peer reviewed literature estimate. ● Domestic peer reviewed literature estimate. □ No economic values in peer reviewed literature but expected to be substantial.

An assessment of the financial value of EGS also provides an indication of which aspects of an ecosystem may form an 'environmental value' for the community. Environmental values are defined in the ANZECC water quality guidelines as: "particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and which require protection from the effects of pollution, waste discharges and deposits" (ANZECC, 2000, pp. 2-6). Although such values differ from estuary to estuary depending on the unique properties of each catchment, river and coastal zone, and the values of the local community, broad 'default' values can be generated (e.g. the ANZECC water quality values). Suggested draft values for estuaries were developed for the purposes of this review by assessing the available ecosystem goods and services against the literature and expert opinion. The resultant draft values are listed in Table 3.2.

Table 3.2. Suggested draft values for Australian estuaries for the purposes of identifying and prioritising knowledge needs. Italicised values are those that are additional to ANZECC water quality values.

Suggested Draft Value	Description and Examples
Aquatic ecosystem health	Ecosystem integrity for broad-scale regulatory services, biodiversity for potential future uses (e.g. bioprospecting) and provision of habitat for all organisms.
Aquaculture	Provision of 'clean' water for estuarine aquaculture and possibly seed stock. Waste disposal is covered below.
Cultural and spiritual	Includes a range of social, cultural and spiritual services that are highly locality-specific. May include aspects of tourism.
Erosion regulation	Sedimentation and settlement of particulates and, buffering (e.g. by riparian areas) as well as protection from natural hazards such as storm events and surges.
Human consumption	Fisheries productivity. Primary and secondary productivity of non-fisheries organisms is included under aquatic ecosystem health.
Knowledge systems	Increasing science and understanding.
Recreation (primary contact)	Swimming and any activity that allows for prolonged and intimate exposure to the water (e.g. water skiing). May include aspects of tourism.
Recreation (secondary contact)	Recreational activities in which direct exposure to water is rare or unlikely (e.g. boating and fishing). May include aspects of tourism.
Visual appreciation	Aesthetic values for viewing estuarine systems. May include aspects of tourism.
Waste treatment	Water purification and disease regulation through biological and geochemical processes (from all sources, i.e. industry, waste water discharge, aquaculture, agriculture).
Water regulation	Flood mitigation, drainage and interaction with ponded pastures on estuarine flood planes.

Changes in flows can modify a number of the ecosystem values recognised for estuaries. The value that has received the most attention with respect to environmental flows is the production of fish, shellfish and crustaceans for human consumption. However, some studies have recognised threats that can impact values more broadly. For example, for the Murray River, Lamontagne *et al*. (2004) listed the risks from reduced flows as including:

- a decline in the catch rates of commercial/recreational fisheries,
- a decline in the diversity of plants,
- degradation of important habitat for native fish and waterbirds,
- impacts to the local fishing, tourism and recreation industry,

- towns and agricultural land adjoining the Lower Lakes becoming inundated by rising water as a result of complete closure of the Murray Mouth,
- water in the Coorong becoming more saline with less freshwater inflow, and
- excessive nutrients and blooms of toxic blue-green algae.

These threats have the potential to impact values related to human consumption, but also recreation, visual appreciation, waste treatment and water regulation. Another example is a new study by the University of Tasmania studying the effects of flows on aquaculture of oysters, the first of its kind worldwide (Christine Crawford, December 2005, pers. comm.). The broader recognition of the values of Australia's estuaries is important not only in justifying further investment in R&D for their management but as an important consideration in many (but not all) comprehensive frameworks for planning flow allocations (see Arthington *et al*., 2004*;* Peirson *et al*., 2002; Close, 2005).

4 Framework for Assessment of Information Needs for Freshwater Flows into Australian Estuaries

Given the broad and complex requirements for understanding the roles of natural flow and the impacts of altered flows in estuaries, this review proposes a framework that describes the generic links between flow and the status of an estuary. The simple scientific model of Alber (2002) (Figure 4.1), relating freshwater inflow to estuarine conditions (abiotic environment) and resources (biotic environment), provides a starting point for development of this framework.

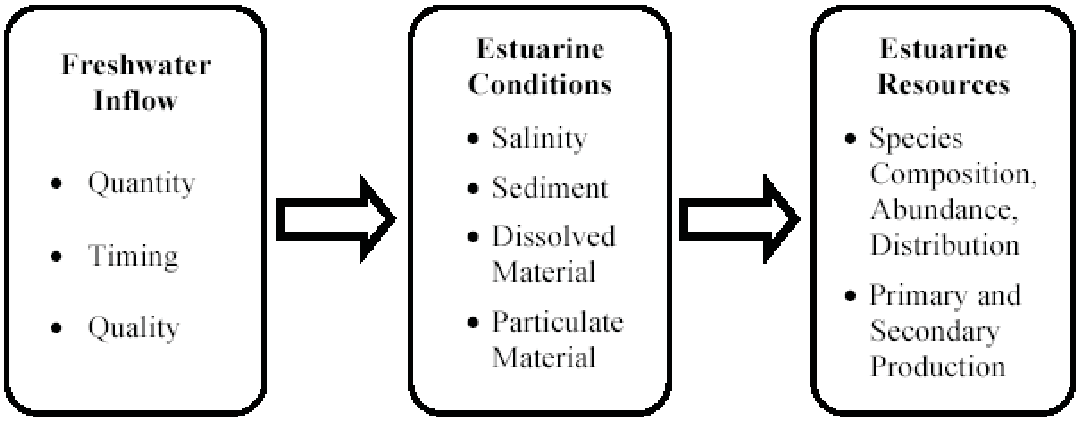

Figure 4.1. Simplified conceptualisation of the effects of freshwater flows on estuarine condition, biodiversity and production (from Alber, 2002).

There are a number of limitations of this model:

- it does not represent the broad range of recognised ecosystem goods and services provided by estuaries, focusing solely on living resources,
- the estuarine abiotic ‘conditions’ listed are limited to basic water quality parameters and do not cover the broader range of condition or ‘state’ indicators that can be influenced by natural and altered flows,
- the terms ‘resource’ and ‘conditions’ are used in different contexts in Australia, and
- this model does not recognise the role of the saltwater/tidal regime.

Another simple model (Figure 4.2) is described by Close, 2005 and is used in the South African ‘reserves’ method for determining flows to estuaries (Adams *et al*., 2002). This model is similar to that of Alber (2002) but uses more relevant headings and has an expanded list of parameters.

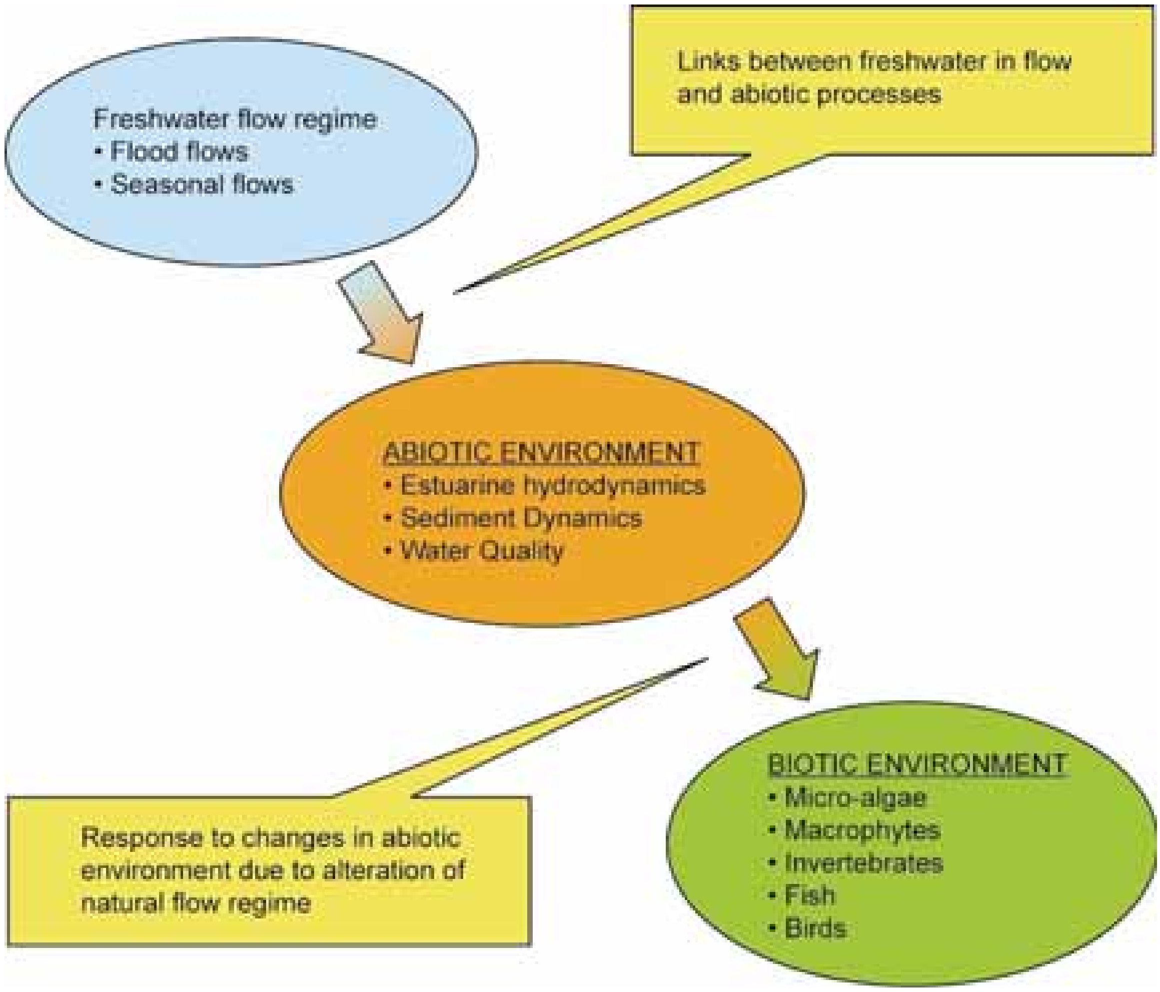

Figure 4.2. Simplified conceptualisation of the effects of freshwater flows on abiotic and biotic components of estuaries (from Taljaard *et al*., 2004 – cited in Close, 2005).

A simple conceptual diagram that borrows elements from each of these models and incorporates the ‘draft environmental values’ was developed as an initial framework for discussing and communicating potential R&D needs (Figure 4.3). The arrows in the diagram represent the ‘potential links’ between freshwater inflows and ecological responses. The primary influence of flows is on the abiotic condition of the estuary waters and sediments and these effects in-turn affect the biotic components of the ecosystem. An important direct effect of flow on biota is the longitudinal connectivity it provides between the estuarine and freshwater reaches of a river system or the ocean (e.g. Intermittently Closed and Open Lakes and Lagoons (ICOLLs)) and the lateral connectivity between the estuary and floodplain lagoons. Other physical impacts of flows on organisms are mediated through effects on hydrology and hydrodynamics of the estuary (e.g. sheer, suspension, directional cues). The diagram recognises that a number of elements are required to accommodate the draft environmental values summarised in Table 4.1. One potential link not shown in the diagram is that between freshwater inflow and estuarine amenity and spiritual/cultural values.

Table 4.1. Suggested draft values and their relevance to abiotic and biotic components of estuaries (see item 3 in Figure 4.3).

Suggested Draft Value[1]	Abiotic Components				Biotic Component
	Water Quality	Hydrodynamics	Geomorphology and abiotic habitat (including geochemical processes)	Connectivity	Species composition, abundance, diversity and biological processes (e.g. primary and secondary productivity)
Aquatic ecosystem health	✓	✓	✓	✓	✓
Aquaculture	✓	✓			
Cultural and spiritual	✓	✓	✓	✓	✓
Erosion regulation		✓	✓		✓
Human consumption	✓		✓	✓	✓
Knowledge systems	✓	✓	✓	✓	✓
Recreation (primary contact)	✓				
Recreation (secondary contact)	✓			✓	✓
Visual appreciation	✓		✓	✓	✓
Waste treatment		✓	✓		✓
Water regulation		✓			✓

[1]values in italics are those additional to ANZECC water quality values.

Understanding these interactions is the primary need for future R&D to better manage freshwater flows to estuaries. Even if researchers can identify environmental flow change as a cause of specific conditions in an estuary, the pathways that link stream flow to ecological response are numerous and complex (Hart and Finelli, 1999; Bunn and Arthington, 2002). This makes it difficult to determine exactly how any particular change in flow initiates the observed biological response, and therefore difficult to model or predict future ecological outcomes. Moreover, most of the research to date focuses on a single factor with few multifactorial experiments being carried out (Gillanders and Kingsford, 2002).

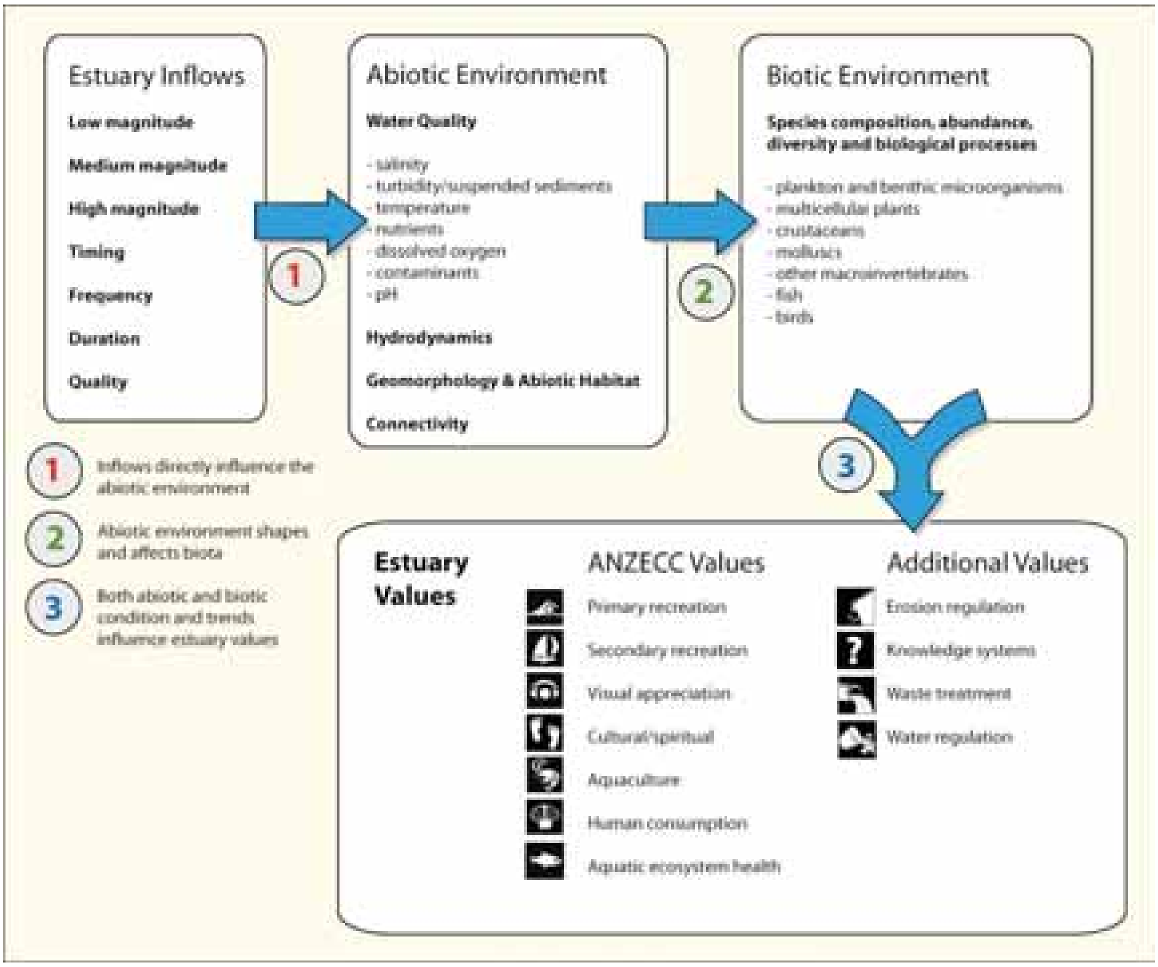

Figure 4.3. Conceptual diagram summarising the influence of flows and the potential impacts of changes to flow regime on estuaries and the concomitant impact on values.

This conceptualisation of potential links between flows and ecological response (Figure 4.3) is used to structure the remainder of this report:

- estuary inflows: Section 5,
- estuarine abiotic environment: Section 6, and
- estuarine biota: Section 7.

4.1 Geographical variation

Australia's estuaries have been categorised on the basis of their geomorphological characteristics (Young, 2001; Heap *et al*., 2001; Harris *et al*., 2002; Ryan *et al*., 2003; and www.ozestauries.org). These characteristics are likely to modify the influence of freshwater flows on the estuarine ecosystem, though as noted by Peirson *et al*. (2002) there is little empirical evidence to support such generalisations.

Under these classifications (Figure 4.4), coastal waterway classes comprise:

- embayments and drowned river valleys,
- wave-dominated estuaries,
- wave-dominated deltas,

- coastal lagoons and strandplain-associated creeks,
- tide-dominated estuaries,
- tide-dominated deltas, and
- tidal creeks/flats.

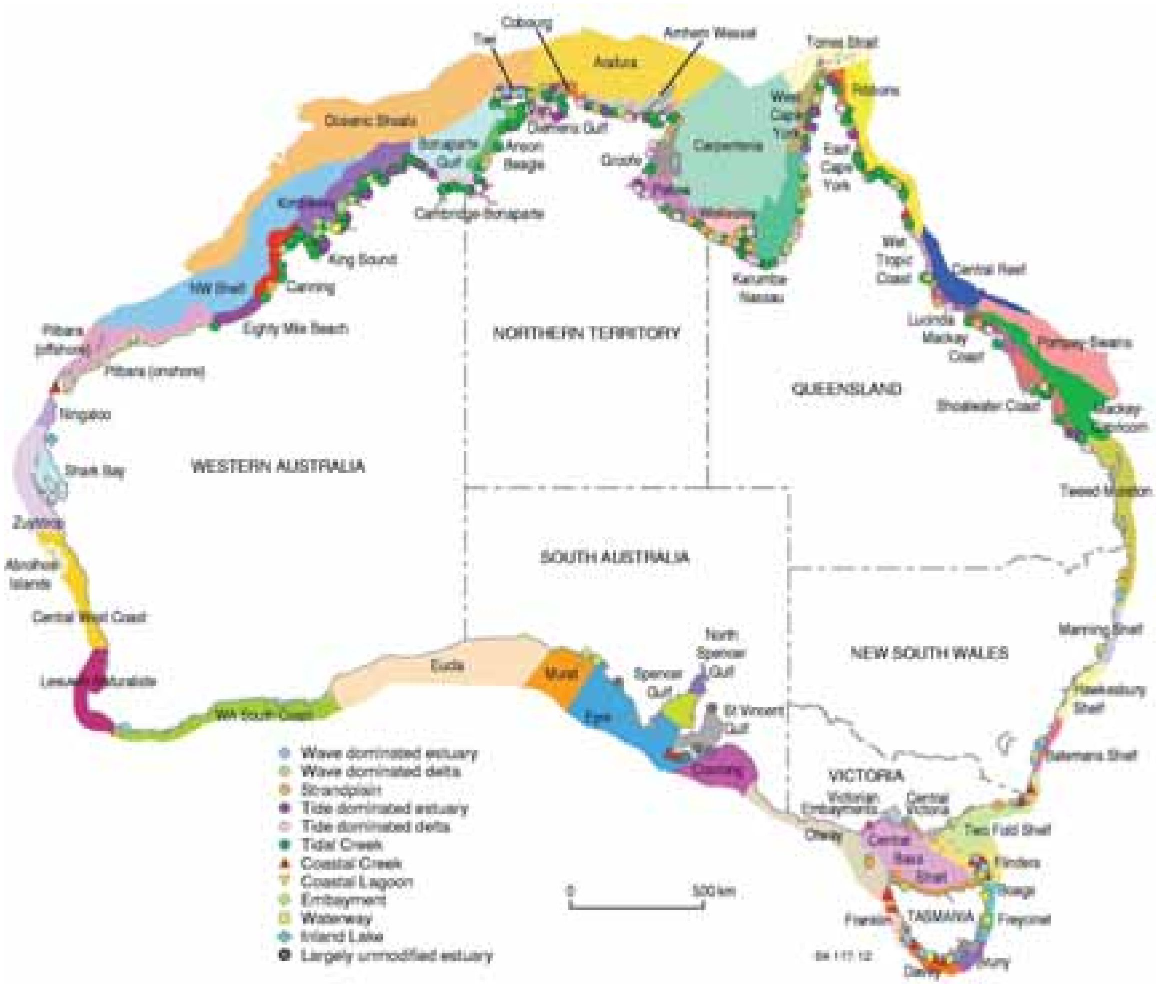

Figure 4.4. Map of Australia showing the distribution of estuaries by class and region (from OzEstuaries, 2006).

Tide-dominated estuaries (i.e. tidal creeks/flats, tidal estuaries and tidal deltas – see www.ozestauries.org) are the most common type in Australia. The majority of the estuaries in the north of Australia, many of which are also pristine or largely unmodified (Figure 4.5), are tide-dominated and consequently are well mixed (Table 4.2). In tide-dominated estuaries estuaries, stratification is uncommon and the waters are generally turbid although marine flushing results in some export of material to the ocean. A diverse range of both marine and brackish estuarine habitats are supported and intertidal flats, mangroves, saltmarshes and saltflats tend to trap and allow for processing (e.g. denitrification) of sediment and pollutants. In some tide-dominated deltas, river flow is sufficient to wash material out to sea, but ‘tidal creeks’ in which river flow is intermittent to non-existent are more common.

The influence of freshwater flows on tide-dominated estuaries will be modified by the energy of tidal flushing. In some estuaries modifications such as channel straightening (e.g. Queensland’s Fitzroy River), or removal of barriers at the mouth of the river (e.g. Queensland’s Brisbane River bar cutting) have increased the effects of tidal currents. Although the influence of flows on water quality will be diffused and diluted through tidal exchange, other elements, such as spawning cues and occasional flood flows that connect floodplain pools and provide terrigenous run-off will be critical to the normal functioning of the estuary. The management of environmental flows will be particularly important in tidal creeks where freshwater inflows are usually of low volume and intermittent.

Figure 4.5. Australia’s near pristine estuaries (from OzEstuaries, 2006).

Many estuaries in the south of Australia, are wave dominated and experience little tidal flushing and may be intermittently closed to the sea. Many are highly modified, being subject to both urban and rural pressures. When river flow is high or when barriers are breached flooding may flush material to the sea. The habitats of such waterways are diverse but can be constrained by chemical conditions such as highly variable salinity induced by poor exchange with the marine environment. Flooding is uncommon but can result in large impacts (e.g. entrance breaching). Turbidity is usually low except where resuspension by wind occurs or during large run-off events. A central basin may be present and acts as a 'trap' for terrigenous sediment and pollutants assisted by the long residence time of water and allowing for processing (e.g.

denitrification) of nutrients. Even when these types of estuaries receive only small, intermittent freshwater flows, they have the potential to be a major driving force as they may be the major or sole source of freshwater and other materials to the ecosystem.

Finally, wave-dominated deltas are also commonly present in the south and share many features with the other wave-dominated waterways. Key differences are that river discharge is typically high, and commonly flushes marine water, sediment and associated contaminants to the sea. The consequent short residence time means that little trapping or *in situ* processing occurs in the estuary. Flows are key driving forces for the structure and condition of these types of estuaries.

The types of estuaries distributed around Australia are determined partly by local rainfall and climatic conditions but are also influenced by wave energy and tidal range. Consequently estuaries of different types exist within each climatic zone and will respond differently to freshwater flow regimes and inflows characteristic of the region. Figure 4.6 shows the distribution of seasonal flow regime types for Australian rivers.

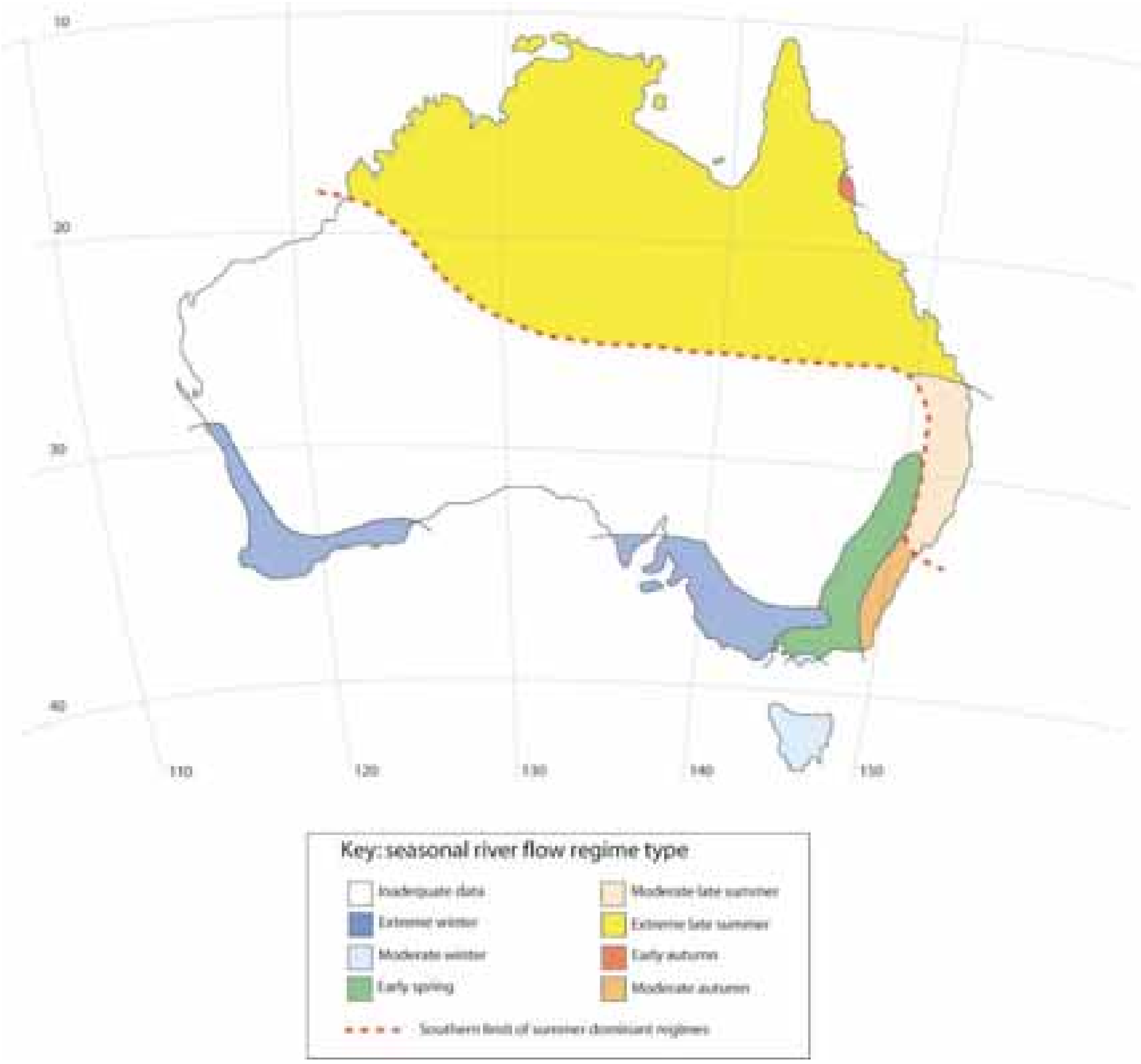

Figure 4.6. Seasonal patterns of river flow regime type (flow zone) (from Gillanders and Kingsford, 2002)

Table 4.2. Characteristics relevant to flow determinations and dominance in seven Australian regions of four grouped geomorphological categories of estuaries.

Relevance to Flows	Type of Estuary			
	Tidal creeks	**Tidal estuaries and Tidal deltas**	**Wave-dominated estuaries and Lagoons/strandplain creeks**	**Wave-dominated deltas**
Characteristics				
river inflows	Low discharge	moderate to high discharge	low-moderate discharge	moderate to high discharge
low flows	few low flows	mitigated to some extent by tidal flushing	likely to be important drivers of estuarine condition when present	mitigated to some extent by size of estuary
moderate flows	small and mitigated to some extent by tidal flushing	mitigated to some extent by tidal flushing and size of waterways	likely to be important drivers of estuarine condition	likely to be important drivers of estuarine condition
high flows	may be dramatic particularly as creeks with extreme summer rainfall are common in Northern Australia	may be dramatic particularly where there is extreme rainfall concentrated over short periods.	significant effects. May open temporarily closed estuary mouths	tend to completely flush the estuary
mixing/flushing	high from tidal action and during rare extreme flows	high from tidal action	Low-none	high
instream and intertidal processing	high (capture in vegetation)	high (capture in vegetation)	high (long residence time – but may become overloaded)	low
flow impacts	rare and mitigated to some extent by tidal flushing	mitigated by tidal flushing and size of waterway	key drivers of estuarine condition, particularly in closed estuaries	flow rate determines the structure and condition of the estuary

Relevance to Flows	Type of Estuary			
	Tidal creeks	**Tidal estuaries and Tidal deltas**	**Wave-dominated estuaries and Lagoons/strandplain creeks**	**Wave-dominated deltas**
Dominant types in each Coastal Region (from OzEstuaries, 2006)				
North West Coast	50%	27%		
Gulf of Carpentaria	48%	17%	14%	
North East Coast	41%	16%		17%
South East Coast			77%	10%
Great Australian Bight	31%		53%	
South West Coast			83%	11%

Sources include: www.ozestuaries.org; Young (2001); Harris *et al*. (2002); Ryan *et al*. (2003).

4.2 Complexity of estuarine research

Our current understanding of the influence of flows on estuaries is confounded by a number of factors arising from the complexity of the processes influencing these systems. Some of the major issues identified during the review of literature and interviews are listed below.

By its nature environmental flow research is hindered by the inability to compare a regulated river, which has a specific environmental flow regime, with a control because similar regulated rivers each have different flow regimes (Chessman and Jones, 2001). Even comparing different flow regimes within the one river over time is difficult because of large fluctuations in rainfall, temperature and other variables. Lag time will also confound these studies and make it difficult to clarify the beneficial or other outcomes of environmental flow regimes (Chessman and Jones, 2001). The impact of particular flow changes may take years or decades to manifest and many other factors will likely change in this time period, further complicating interpretation (Chessman and Jones, 2001). Other changes to estuaries and their catchments (e.g. riparian removal) will also have lagged effects which continue to impact estuarine ecosystems and processes. The duration of the time lags probably differs for different changes to estuaries and their catchments, making it extremely difficult to identify which changes cause which impacts.

Another constraint for research is that the amount of water allocated for environmental flows is typically low (<10%) compared to total water use and often low compared to natural climatic and seasonal fluctuations (long-term and short-term). Chessman and Jones (2001) note that this makes the effects of environmental flows subtle and difficult to distinguish from the natural influence of aspects of the total flow regime. In a related issue, it is difficult to apply understanding of the effects of major flooding and drying events (though they often are better studied and understood, see Arthington *et al*., 2005) to the more subtle changes resulting from environmental flows (Chessman and Jones, 2001).

Other factors that affect estuarine ecosystems such as land use, riparian conditions and waste water discharge can be altered by changes in flow regime and the allocation of environmental flows and are therefore confounding factors, making it difficult to determine the changes resulting from flow and those resulting from other factors (Chessman and Jones, 2001).

Widespread, whole-of-ecosystem events can also impact individual estuaries and their fisheries in complex ways. For example, the relationship discovered by W.H. Sutcliffe, between Quebec lobster landings and the lagged discharge from the St. Lawrence River system successfully predicted lobster catches from the early 1970s to the mid-1980s. The discharge-related estimates failed, however, to forecast the steady increase in lobster landings since 1984. Changes in the geographical distribution of the reported landings and fishing effort, the age at recruitment, and the possibility that lobster landings are regulated more by storm incidence than run-off were examined but none of these parameters explained recent deviations between predicted and observed landings. The expansion of lobster populations at the same time elsewhere in eastern North America suggests that it was a response to a widespread environmental or ecosystem change.

Despite these difficulties much valuable research on the impacts of changes in flow on downstream ecosystems has been carried out in Australian freshwater systems and is starting to be carried out in estuaries. The following sections (5, 6 and 7) detail what is currently known about the effect of freshwater inflows on estuarine hydrodynamics, biogeochemistry, health and productivity within Australia.

5 Freshwater Inflow

“Alteration to natural flow regimes represents an important disturbance influencing the health and sustainability of flow dependant ecosystems. Although freshwater inflow is recognised as an integral process influencing estuarine form and function, until recently there has been little consideration of the freshwater requirements of estuarine ecosystems. With increasing understanding of estuarine processes, important links between estuaries and their catchments have become recognised. It is now agreed that effective management of freshwater resources must consider the potential impacts of flow alteration on estuarine environments” (Close, 2005, p. iii).

The main elements of a flow regime are quantity (magnitude), temporal pattern (frequency, duration, timing and rate of change) (Poff *et al*., 1997) and quality. It is essential that any determination of environmental flows for estuaries considers all these aspects of a natural or altered flow regime and not just total annual flows, minimum flows or other partial measures. This requires knowledge of the river’s historical and current flow regime and how it can affect an estuary’s abiotic and biotic environment (see Sections 5 and 6, respectively). However, only limited current information on the three main flow regime elements - quantity, timing and quality - is available for Australian estuaries. Historical information is even more sparse, so it is often difficult to determine the baseline flow regime for comparison with existing conditions. Sometimes, the current and historical flow regimes can be obtained from hydrological models.

The quantity of flow provides a crude measure of deviation from traditional flows. For example, the Murray-Darling Basin Commission has concluded that the river system requires at least two thirds of its natural flow (in average volumetric flow and in flow variability) to create a “high likelihood of returning or maintaining it as a ‘healthy, working river’” (Goss, 2003, p. 620). One half of a river’s natural flow is expected to create a “moderate likelihood” of achieving the above result (Goss, 2003, p. 620). However, arguments against the use of this two-thirds rule have been put forward by Arthington and Pusey (2003, p. 390) who point out that riverine ecosystems respond to different elements of the flow regime and recommend “that river-specific benchmark models be developed throughout Australia using well-established quantitative field techniques for the assessment of river condition”.

In ecosystems where riverine inputs are the main source of nutrients to estuaries (e.g. Swan River and Wilson Inlet in WA – noting that the recycling of these nutrients and subsequent release from sediments can be important) then the timing of flows can be a particularly important part of the flow regime (Peter Thompson, 2006, pers. comm.). For phytoplankton in the Swan River timing of rainfall is very important as an increase in flow followed by a decrease almost always results in a large algal bloom (Thompson, 2001), including the well-studied summer bloom of 2000 (Robson and Hamilton, 2003). The high flow results in an input of nutrients and estuarine stratification results in anoxia and sediment nutrient release. Either will result in a bloom if the subsequent flow is reduced such that the residence time is long enough for the cells to proliferate (Peter Thompson, 2006, pers. comm.).

Timing, including frequency of flows, is driven by climatic and hydrological processes and involves a number of characteristics including:

- pattern of seasonal flows,

- timing of extreme flow,
- frequency of extreme flow,
- predictability of flow,
- duration of flood flow, low/intermittent flow and no-flow events, and
- daily, monthly, seasonal, annual and inter-annual flow variation.

(It should be noted that for regulated rivers, timing of flows can also be determined by irrigation needs and releases from dams).

The complexity of these flow characteristics makes them difficult to predict in a mechanistic fashion. Empirical data exists for some rivers but there is more limited data available for estuaries both spatially and in detail across the hydrograph. In the majority of cases flows reaching the estuary are not monitored. However, flows can be modelled statistically (although not deterministically because of climate variability, etc.) in many rivers (e.g. using the Integrated Quality and Quantity Model (IQQM) model). Therefore, even though the volume and timing of flows reaching an estuary are usually not monitored, they can be predicted statistically using models with good accuracy (well gauged rivers) or moderate accuracy (poorly gauged and ungauged rivers).

Although the size of the total flow is an important factor, research has shown that “maintenance of critical facets of the natural flow regime can be more important than total flow (Poff *et al*., 1997)” (Hamilton and Gehrke, 2005. p. 246) for maintaining ecosystem health and production. For example, Loneragan and Bunn (1999) suggested that seasonality of flows is often as important as the volume of a flow to the health of estuarine biota. Bunn and Arthington (2002, pp. 493-500) developed four principles that explain the roles of natural flows and the effects of altered flow regimes on aquatic biodiversity. These principles are that:

1. “Flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition”,
2. “Aquatic species have evolved life history strategies primarily in direct response to their natural flow regimes”,
3. “Maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species”, and
4. “The invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regime”.

Quality of the flow is also a crucial issue. If the water quality of environmental flows differs significantly from that expected under natural conditions, the receiving waters of an estuary and consequently the habitat and biota may be impacted positively or negatively. The impact of inflow water quality of estuaries will be determined by the size, tidal exchange rate and water quality of the estuary itself. There is only scattered information on the quality of flows reaching most Australian estuaries.

The quantity of flows can be simplified as the low, moderate and high magnitude flows entering an estuary. Low magnitude flows are generally background flows that reach an estuary from run-off from the catchment throughout the year and help maintain salinity, water currents and longitudinal connectivity with upstream areas (Peirson *et al*., 2002). Due to the aridity of much of the continent many estuaries have extremely small or non-existent flows for much of the year (see OzEstuaries, 2006). High magnitude flows maintain physical habitat by flushing sediments and maintaining channels, delivering nutrients and organic matter, and allow lateral connectivity (see Peirson *et al*., 2002). Each of the three magnitudes of flow may perform a different function in different climatic zones (e.g. the extreme summer flows in the northern tropics may perform quite different functions to the winter maximum flows in Tasmanian estuaries). The Peirson *et al*. (2002) methodology for determining environmental flow requirements for estuaries uses these three flow magnitudes as a basis for characterising inflow.

6 Abiotic Environment

There is clear evidence from around the world that alterations to freshwater flow regime affect the geochemical processes, water quality and abiotic habitats of estuaries (Rozas *et al*., 2005; Gillanders and Kingsford, 2002; Scharler and Baird, 2000; Peirson *et al*., 2002). The simple conceptualisation of Alber and Florey (2002) lists salinity, sediment, dissolved material and particulate material as the key estuarine abiotic conditions that might be affected by altered flow regimes. Their list is expanded from the Australian and international literature to include:

- salinity,
- sediment/turbidity,
- water temperature,
- nutrients and organic matter,
- dissolved oxygen,
- pH,
- hydrodynamics – including water velocity, shear stress, mixing and circulation patterns,
- geomorphology and abiotic habitat, and
- connectivity.

(e.g. Aleem, 1972; Jordan *et al*., 1991; Mallin *et al*., 1993; Boesch *et al*., 1994; Jassby *et al*., 1995; Boynton *et al*., 1995; Davies and Kalish, 1994; Vörösmarty and Sahagian, 2000; Webster *et al*., 2001, 2003; Alber and Flory, 2002; Gillanders and Kingsford, 2002; Peirson *et al*., 2002; Lamontagne *et al*., 2004; Rozas *et al*., 2005; Douglas *et al*., 2005; Ford *et al*., 2005).

6.1 Water quality

The main physico-chemical water quality parameters of interest for freshwater inflows to estuaries are nutrients, salinity, turbidity and temperature, though organic matter, dissolved oxygen and pH may also be important. However, "the main cause of poor water quality in regulated rivers is not necessarily the flow regulation itself, although this can exacerbate the problem. Poor water quality usually results from inappropriate catchment and channel management, so it could be argued that manipulation of flows (under the guise of 'environmental flows') to ameliorate this problem, by flushing or diluting contaminants for example, addresses the symptom and not the cause of the problem" (Gippel, 2001, p. 82).

Reduction of freshwater flow can lead to decreased flushing and increased stratification of a water body. Stratification of estuaries is caused by differences in density between fresh and saline waters. Stratification can lead to anoxic conditions and poor water quality and result in decreased fish, shellfish and crustacean abundance, and contamination of tissues; nutrients may also be released from sediments causing algal blooms (Peirson *et al*., 2002). Deeper estuaries (typically, drowned river valleys) are more susceptible to stratification as a result of reduction in freshwater flow.

6.1.1 Salinity

Flows have a major impact on the salinity of an estuary, which in turn impacts the species living there, particularly the invertebrates and plants (see Drinkwater and Frank, 1994). Altered flows can result in changes to the area of an estuary as increased freshwater flow reduces the estuary length and reduced flows allow saline waters to penetrate further inland (see Gillanders and Kingsford, 2002).

In some cases reduced flows may result in the estuary and nearshore waters becoming hypersaline. An extreme example occurs in some estuaries in Western Australia which are threatened by hypersaline conditions arising from sea water intrusion and evaporation as well as saline run-off from the catchment salinity (Malcolm Robb, December 2005, pers. comm.).

In estuaries where tidal currents are not strong enough to mix the water column then stratification can occur with low-salinity freshwater floating above the denser, high-salinity seawater (OzEstuaries, 2006). This may lead to anoxic and hypoxic events because bottom waters are effectively isolated from the gas exchange across the water surface and from photosynthesis by plants (OzEstuaries, 2006).

A study by Davies and Kalish (1994) on the Derwent River, Tasmania, showed a clear relationship between river flow and the location of a salt wedge in the estuary. Flows of 75 m^3/s were needed to displace the salt wedge from its reference position. They also found a negative relationship between salinity and dissolved oxygen (DO), high salinity resulted in low DO, thus periodic high flows were needed to maintain adequate DO levels.

Maintenance of a salinity gradient can be of importance for juvenile fish which often have a wider salinity tolerance than the adults (Liz Barnett, 2006, pers. comm.).

6.1.2 Turbidity/sediments

Low flows can result in reduced turbidity as slower currents allow suspended sediments to settle out of the water column. Barriers such as dams and weirs also help this process and act as a physical barrier to sediment movement downstream. When high flows occur, turbidity can increase as rainfall and run-off carry terrestrial sediments into rivers and estuaries. In addition, higher water velocities help resuspend bottom sediments or increase bank erosion. However, in tide-dominated estuaries, tidal forces can be the critical element influencing turbidity in an estuary.

In the Fitzroy River estuary Ford *et al*. (2005) reported that, during low flows, concentrations of suspended sediments were approximately 20 mg/l compared to more than 1,000 mg/l at maximum high flow discharge. Due to the slow settling rates of the very fine particles delivered by the flood waters it may take some months for the suspended sediment concentrations to return to pre-flood levels (Ford *et al*., 2005).

“During flow events of sufficiently elevated discharge, salt water may be completely flushed out of the estuary rendering the estuary fresh along its full length. In this case, sediment flocculation and settling within the estuary would be minimal and one might expect the estuary to be a relatively efficient transmitter of fine sediments” to nearshore systems (Webster *et al*., 2003, p. 17).

6.1.3 Temperature

Water temperature is mainly determined by climatic conditions and not by the temperature of inflows in Australia’s relatively shallow estuarine systems (Ian Webster, 2006, pers. comm.). However, there are few studies on the effects of altered flow on estuarine water temperature. Shallower estuarine waters can be warmed during summer (Gillanders and Kingsford, 2002) and dam releases contain cooler waters, which eventually reach the estuary.

6.1.4 Nutrients

Of all the water quality parameters, nutrient dynamics have received the most attention with respect to flows into estuaries. Research from the Richmond River estuary in NSW identifies nutrient retention as a key element in estuarine nutrient cycling as water flow flushes estuaries, reducing nutrient retention and assimilation and therefore reducing the likelihood of eutrophication (Eyre, 1997). Many unregulated tropical and sub-tropical estuaries naturally have low nutrient retention due to high flushing (Eyre, 1997). It is therefore likely that the nutrient retention of regulated rivers, experiencing lower and less intense flows will increase, altering the nutrient environment and possibly leading to algal blooms.

Ford *et al*. (2005) have shown that during high flows in the Fitzroy River (Qld) 97% of the dissolved organic carbon (DOC) within flood waters pass straight through the estuary. During low flow conditions the estuary itself is a net source of DOC (Ford *et al*., 2005). In contrast, under both low and high flow conditions the Fitzroy estuary is a source of particulate organic carbon (POC) to coastal seas (though POC export is much higher during high flows due to the added POC contained in incoming flood waters) (Ford *et al*., 2005).

Nutrients delivered to the Fitzroy River estuary during low flow are principally in the form of dissolved inorganic nutrients, in contrast to high flow periods when there is a mixture of both dissolved and particulate nutrients from the upper catchment (Douglas *et al*., 2005). During low flows, the estuary acts as a nutrient sink, i.e. it uses up almost all particulate nutrients entering the system. In contrast, during high flows total nitrogen (TN) inputs (2,420 tonnes) equalled the amount of TN exported to Keppel Bay (Douglas *et al*., 2005). During the same high flow period 980 tonnes of total phosphorous (TP) was imported into the estuary with 760 tonnes of it being exported into the ocean (Douglas *et al*., 2005).

“Under high flow conditions the delivery and export of dissolved silica (DSi) [to/from the Fitzroy River estuary] were in balance. Under low flow conditions the internal estuarine sources/sinks were too small to be detected suggesting that DSi produced by diagenesis in the sediments was taken up by mpb [microphytobenthos] before it could enter the water column.” (Douglas *et al*., 2005, p. 8).

A study into the effects of a single freshwater release into the Kromme estuary (South Africa) by Scharler and Baird (2000) found that increases in dissolved nutrient concentrations were short-lived (less than 7 days) with no long-lasting effects occurring. Clearly this result would vary from estuary to estuary. However, the authors concluded that in order to enhance the nutrient status of the ‘freshwater starved’ estuary a continuous release strategy needs to be implemented rather than one-off releases. It is unsure how this conclusion applies to Australian estuaries as generally most do not naturally receive continuous inflows.

Reduced flow may increase problems associated with pollutants as there is less water available for dilution (Gillanders and Kingsford, 2002). For example, the water quality of the Hawkesbury-Nepean River is likely to be more affected by the additions of wastewater from sewage treatment plants during low flows than during high flows because of the dilution ratio (SCA, 2000). However, increased flow may also increase nutrient levels as the increased current results in the resuspension of nutrient-bearing sediments (SCA, 2000).

6.1.5 Dissolved oxygen

In general, dissolved oxygen (DO) concentrations in estuaries are influenced more by the availability of degradable detritus and stratification than by the levels of DO in freshwater inflows (Ian Webster, 2006, pers. comm.). However, several rivers in the Burdekin region (Qld) now have constant flow year round which has resulted in large freshwater reaches becoming clogged with pest plants. This results in anoxic waters which then get washed into the estuary causing animal kills (Scheltinga and Heydon, 2005).

Low dissolved oxygen is usually not a problem in well-mixed estuaries. However, altered flows may change mixing patterns, salinity, temperature, nutrient levels, and the amount of organic matter present and/or phytoplankton production; this can result in hypoxic conditions (Gillanders and Kingsford, 2002). Hypoxic conditions occur in some Australian estuaries as a result of localised algal blooms, but these generally result from high inputs of nutrients from sources other than freshwater flows (Fearon, 2006).

6.1.6 pH

When seawater (approximately pH 8.2) mixes with river water (typically pH 7-7.5), pH tends to decrease. Chemical modelling shows that altered freshwater flows have the potential to change natural pH ranges and gradients in estuaries because river water has a much higher pH than seawater if it evaporates to the same salinity (Radke, 2002).

Changed pH can result in animal kills and disease outbreaks, poor water quality, release of metals and other toxicants, and loss or disturbance of habitat.

6.2 Hydrodynamics

The hydrodynamics of estuaries are dominated to varying degrees by tides, waves and freshwater input. The resulting water movement is important for maintaining the health of an estuary. It facilitates the movement of biota, maintains geomorphology and affects water quality. Reduced freshwater inflows can result in decreased flushing and vertical mixing of a water body resulting in poor water quality.

Freshwater inflows may not be useful as a flushing mechanism in Australia. Australian river flow is more episodic than it is in Europe and North America, and Australian systems generally have a relatively higher proportion of land-derived nutrients. Thus inflows actually represent the source of the ‘contamination’ rather than a mechanism for dissipating it. In the Gippsland Lakes, the ‘best’ estuarine condition occurred during dry years when inflows were relatively small. However, it should also be noted that estuarine systems rely on nutrient inputs from rivers to maintain their production. Therefore, the potential role of flows as a flushing mechanism is unclear in the Australian context (Ian Webster, 2006, pers. comm.).

Reduced water velocities can alter important physical habitats by allowing more fine sediments to settle out of the water column. Low velocities may also impact on eggs and larvae by reducing the time they remain suspended in the water column and affecting their transport to or from the estuary.

The flushing characteristics of an estuary are also influenced by the type of estuary and by river discharge. Flushing regimes and intermittent closure of estuary mouths can greatly affect larval transport. The low reported occurrence of marine-spawned larvae in Wilson Inlet was believed to reflect inadequate tidal water movement to facilitate the transport and dispersion of larvae (Cappo *et al*., 1998).

6.3 Geomorphology and abiotic habitat

Freshwater inflow regime is an important factor in determining estuarine geomorphology. Changes to water regimes can have significant impacts on a channel's geomorphology primarily through altering sediment transport and water velocity (Young, 2001). International and Australian literature state that flow affects features such as channel depth, deltas, sand banks, mouth opening/closing regime and habitat for benthic and intertidal communities through the movement of water and sediments into, and out of, estuaries (Aleem, 1972; Boesch *et al*., 1994; Wortmann *et al*., 1998; Alber and Flory, 2002; Cluett and Radford, 2003; Choi *et al*., 2005; see Gillanders and Kingsford, 2002).

An important geomorphological aspect for many of the estuaries along the coastline of temperate Australia, particularly coastal lagoons, is the opening and closing of estuary mouths. Estuary mouths naturally close at times of small freshwater input when sandbars form across the mouth. River flow therefore plays a major part in maintaining entrance openings in lagoonal type systems and is probably important in virtually all Intermittently Closed and Open Lakes and Lagoon (ICOLL) systems (Ian Webster, 2006, pers. comm.).

On the south-east coast of Australia, a number of estuaries function predominantly as coastal lakes intermittently separated from the ocean. On the south-west coast, temporary closure of estuary mouths is also a common feature. The Murray River is an iconic Australian river which has had its flows reduced to on average only 27% of the natural median annual flow. This has resulted in the complete closure of the mouth occurring for the first time in 1981, and again in 2003 (Lamontagne *et al*., 2004) – with continual dredging of the mouth occurring at present. In the Glenelg River estuary where the estuary mouth is narrow and restrictive, tides may be delayed up to 4 hours compared to oceanic tides as the estuary slowly fills up or empties (Barton and Sherwood, 2004). A consequence of this effect is that the tidal range in the estuary may be reduced relative to that of the ocean (Barton and Sherwood, 2004).

Mouth closure and sediment build-up affect tidal exchange and subsequently impact water quality. The tidal prism of an estuary is the volume of water exchanged in a tidal cycle. It can give an indication of the ability of an estuary to reduce pollution impacts by moving pollutants into the ocean. The residence time of pollutants may be much longer than predicted on the basis of a simple tidal prism model. Fish kills have been observed to accompany mouth openings, for example, large numbers of spawning common galaxias, adult smelt and gudgeon were killed in the Gellibrand River estuary in April 2000, when deoxygenated waters filled the main channel from fringing wetlands (Barton and Sherwood, 2004).

Sediment transport is a natural occurrence within Australian river systems. Consequences of restricting the natural sediment load (as a result of sediment build-up behind dams and weirs) include channel scouring and reduced bed slope (Pearson, 1994). However, the downstream reduction in sediment transport caused by regulated flows may be balanced by other inputs resulting from changed land uses (SCA, 2000). Alternatively, decreases in freshwater flow through water extraction or diversion can decrease the effective scour of channels during floods (Barton, 2003). In this case, the frequency of river flooding decreases, and shoaling within the channel occurs over a longer period, requiring a flood of greater erosive capacity to remove the built-up volume of sediment (Peirson *et al*., 2002; Barton, 2003).

Changes to the geomorphology of an estuary and also changes to depth during large flows alter the extent of the estuary and thus the available types, areas and spatial/temporal distribution of habitats. Restriction of sediment loads can result in changes to habitat with a scarcity of soft substrate benthos due to an absence of sediments. Changes to habitat have direct effects on the biota present in estuaries (see Peirson *et al*., 2002), but the relationships are complex and not well studied.

6.4 Connectivity

Flows influence both the longitudinal and lateral connectivity of an estuarine system, with low inflows maintaining longitudinal connectivity and high flows allowing lateral connectivity (i.e. with floodplain lagoons, etc.). The habitable area available (e.g. for feeding or nursery grounds) is thus influenced by the flow regime.

A loss of longitudinal connectivity between the estuary and upstream river systems can have severe impacts on fauna which migrate during their lifecycle between fresh and salt waters (e.g. eels, barramundi). A loss of lateral connectivity between the estuary and adjacent waterbodies can have severe impacts on fauna that use these water bodies as nursery grounds. Recent research on floodplain wetlands associated with the Fitzroy River (Qld) has shown that relatively small-scale local flooding can be sufficient to maintain water levels in estuarine littoral pools and produce biologically useful connectivity (Coastal CRC AW (Fitzroy Wetlands Connectivity) project draft report – Marcus Sheaves, 2006)).

"The loss of [lateral] connecting flow is also likely to result in ecological processes in the adjacent waterbodies not being activated or maintained. Note that connectivity loss, particularly marine-estuary connectivity as resulting from estuary-mouth closure, may also result from the processes concerning reductions in flushing and channel-maintenance flows" (Peirson *et al*., 2002, p. 15).

7 Biotic Environment

Drinkwater and Frank (1994) reviewed the literature relating to the effects of river regulation and diversion on marine fish and invertebrates and reported that the distribution, abundance and health of fish and invertebrates changed when freshwater flows were altered. They also found that species composition changed with altered river flow. Changes in migration patterns, spawning habitat and recruitment were thought to be the main mechanisms causing these changes.

Although it has been suggested that estuarine assemblages will be affected by freshwater flow there are few studies showing what the effects on assemblages are.

For the lower Murray River, which has had its flows reduced to on average only 27% of the natural median annual flow, Lamontagne *et al*. (2004) listed the risks from the reduced flows as including:

- loss of spawning cues for some native fish,
- restriction of fish migration,
- excessive sediment and nutrients entering the Lower Lakes,
- degradation of habitat for migratory birds, and
- change to habitat.

The authors found that reduced flows resulted in, among other things:

- a decline in the catch rates of commercial/recreational fisheries,
- a decline in the diversity of plants, and
- degradation of important habitat for native fish and waterbirds.

In contrast, other studies from Australia, and internationally, have shown that for some species there is no significant relationship between the measured aspect of freshwater inflows and abundance or biomass of estuarine biota (Ardisson and Bougert, 1997; Loneragan and Bunn, 1999 Chan and Hamilton, 2001; see Table 7.1 at the end of this chapter). However, there are a number of effects potentially confounding these interpretations. For example, the structural features affecting river flow, such as weirs or dams, the purpose of the impoundment and how it is operated have been shown to have differing effects on river biota (Armitage, 1984;Growns and Growns, 2001). Table 7.1 summarises research on the relationship of abundance/biomass and fishery catches of estuarine biota to river flows.

Faunal distributions within estuaries are affected by freshwater flows (Rozas *et al*., 2005; Gillanders and Kingsford, 2002; Scharler and Baird, 2000; Peirson *et al*., 2002). However, there is little specific knowledge on the processes or effects of particular flow quantities and seasonal patterns.

A specific example concerns the distribution of pest species. Cappo *et al*. (1998) noted that seasonal floods may help to maintain estuarine health by flushing pests out, overcoming their weak osmoregulation or limiting light under turbid conditions. Normal environmental flow regimes can help to control pest plants as reported in the Gingham Watercourse, Australia (Mawhinney, 2003) while altered flows (increased or decreased) may help pest plants survive, grow or spread (SCA, 2000; Bunn and Arthington, 2002).

It is likely that altered flow regimes also impact the health of estuarine biota (Drinkwater and Frank, 1994). Many of these impacts may be sub-lethal and difficult to measure and there have been no reported studies on this area of environmental flows in estuaries. For example Goss (2003) acknowledges that there is some evidence for lower than normal thresholds of river salt concentrations having sub-lethal effects on species and ecosystems over long time periods.

Generally, there is a positive relationship between freshwater flows and primary production of an estuary due to the increased nutrients coming into the system (Flint *et al*., 1986; Nixon 1992; Mallin *et al*., 1993; Boynton *et al*., 1995). However, production can also decrease due to reduced light penetration as a result of increased turbidity, as has occurred in Georgia, USA (Drinkwater and Frank 1994; Alber and Flory, 2002). The exact mechanisms that underlie these relationships are not always well understood but in general, increased inflows result in either positive or negative changes to:

- recruitment,
- survival,
- growth, and
- dispersal.

(Gammelsrød, 1992; Sutcliffe *et al*., 1983; Beamish *et al*., 1994; Turner, 1992; Ardisson and Bourget, 1997; Alber and Flory, 2002; Robins *et al*., 2005; Gillanders and Kingsford, 2002). However, current knowledge does not allow us to link descriptions of flow unambiguously to the dynamics of estuaries and estuarine species.

Another summary of the influence of flows on estuarine productivity suggested there are three main mechanisms (see review by Robins *et al*., 2005), namely:

1. through trophic pathways – flows transport nutrients which influence primary production (with flow-on affects in food webs),
2. through distribution – flows may reduce or increase the habitable area available (including connectivity effects), and
3. through population dynamics – flows may affect recruitment, spawning cues, survival or growth rates, and patterns of movement.

Some of the better-known links between the abiotic environment of an estuary on biota driven by increased and decreased flows are given in Appendix 2.

7.1 Plankton and benthic microorganisms

“Many studies have found a positive correlation between phytoplankton biomass and the magnitude of freshwater inflow (Malone *et al*., 1988; Mallin *et al*., 1993; Harding, 1994; Gillanders and Kingsford, 2002, p. 270; Grange *et al*., 2000). This is thought to be due to hydrodynamic conditions keeping plankton within the estuary and increased nutrient availability increasing primary production (Gillanders and Kingsford, 2002).

Grange *et al*. (2000) compared the chlorophyll *a*, zooplankton and ichthyonekton concentration of a freshwater deprived estuary (Kariega) and a freshwater enriched estuary (Great Fish) in South Africa. They found significantly higher concentrations of all three groups in the freshwater enriched estuary and related this back to increased nutrients, food and olfactory cues for larval migration due to elevated river discharge.

Studies in the Swan River estuary in south-west Western Australia show that the size and duration of flows may be key determinants of spawning success, migration and recruitment of estuarine plankton (Cappo *et al*., 1998; Chan and Hamilton, 2001). In tropical estuaries of Queensland, McKinnon and Klumpp (1998) suggest that the distribution of zooplankton communities within an estuary responds to freshwater input, which appears to drive both the quantity and quality of particulate material available to higher consumers.

The mixing zone of saltwater and freshwater has been shown to be important for plankton with the abundance of zooplankton and larval fish increasing in this zone in temperate West Australian estuaries (Gaughan and Potter, 1994, 1995). This has been supported by international data (Byun *et al*., 2005). Byun *et al*. (2005) showed that a reduction in the vertical mixing of a tide-dominated, turbid, estuarine embayment in Korea, due to episodic inputs of freshwater inflows from a reservoir during the period of neap tides, was the main physical controlling process on the occurrence of spring algal blooms.

Freshwater flows and salinity appear to be more important in regulating the succession of phytoplankton than does nutrients in the Swan River estuary (Chan and Hamilton, 2001; Robson and Hamilton, 2003). Phytoplankton biomass is related to nutrients in the Swan estuary – this is also true in other estuaries across Australia (Peter Thompson, 2006, pers. comm.). “Freshwater flow affects the residence time available for different phytoplankton taxa to grow. It also influences succession between marine, estuarine and freshwater phytoplankton taxa according to the extent that it hinders intrusion of marine water into the estuary” (Chan and Hamilton, 2001, p. 869).

In the relatively deep Derwent and Huon estuaries in Tasmania where oceanic inputs of nitrogen are the dominant source of nutrients, blooms of the toxic dinoflagellate *Gymnodinium catenatum* are related to the timing of freshwater flows (Hallegraeff *et al*., 1995). However, the mechanism is more complex than that occurring in other Australian estuaries as the river is not the main source of nutrients. For a bloom to occur the following conditions need to be met: water temperature >14°C at the time of bloom initiation, a flow of 100,000 megalitres over a three-week period from the Huon River and calm waters (windspeed <5 m/s for 5 days or more) (Hallegraeff *et al*., 1995). Research suggests oceanic nitrate supports the blooms with the major river influence being on hydrodynamics (stratification and entrainment) not nutrient supply (Peter Thompson, 2006, pers. comm.).

Altering the freshwater flow regime therefore has the potential to significantly affect planktonic species assemblages and abundance with a flow-on effect up trophic levels. Also, biological processes performed by benthic microorganisms may be affected but currently there are no studies on this.

“Biogeochemistry is the science of how nutrients are transformed and transported within an aquatic system. Nutrients are essential for primary production (plant and phytoplankton growth) which ultimately represents the foundation for the estuarine ecosystem including higher organisms such as fish, crustaceans, marine mammals and birds.” (Webster *et al*., 2003, p. iv).

During periods of low flow of the Fitzroy River (Qld) most nutrients delivered to the estuary come from industrial discharges (sewage treatment plants and meatworks) (Webster *et al*., 2003). “These nutrients sustain the phytoplankton growth in the water column in the upper half of the estuary where the water is relatively clear. It would appear that the consumption of phytoplankton by mussels and other grazers allows for elevated fish and crab catches in this part of the estuary.” (Webster *et al*., 2003, p. iv). “In the lower half of the estuary, the tidal currents are stronger and suspended sediment concentrations are relatively high. Penetration of light into the water column is much reduced, causing phytoplankton growth to be severely inhibited.” (Webster *et al*., 2003, p. iv).

During high flows in the Fitzroy estuary “primary production in the water column is likely to be negligible” due to “highly turbid conditions and phytoplankton being swept down estuary and out through the mouth” (Webster *et al*., 2003, p. 40). However, “primary production by the microphytobenthos may occur on the intertidal areas along the sides of the estuary channel” (Webster *et al*., 2003, p. 40).

7.2 Multicellular plants

Little is currently known about the relationship between freshwater flows and the aquatic or riparian vegetation of estuaries. It is thought, from studies in the Oven River, that for freshwater systems at least, there may be an impact on species composition, particularly affecting river bank herbs and wetland vegetation, though the effects are likely to be subtle (Cottingham *et al*., 2001).

Studies from a range of estuaries, including Sydney Harbour, found many factors including drainage, exposure, salinity tolerance, nutrient levels, depth of water, fruiting season, colonising ability and capability for local vegetative spread will determine which species are most likely to survive and benefit from an environmental flow (SCA, 2000; Gillanders and Kingsford, 2002). An environmental flow during the fruiting season may help in the dispersal and germination of species, as demonstrated in the Hawkesbury-Nepean River (SCA, 2000).

Numerous water quality parameters, such as turbidity (light availability), temperature, salinity, toxicants (herbicides) and nutrients have been shown to affect seagrass and thus any change to freshwater flow which results in a change to water quality is likely to result in a change to the seagrass community structure. Irlandi *et al*. (2001) examined how seagrass (*Thalassia testudinum*) responded to the restoration of more natural freshwater flows in South Florida. Their data suggests that the seagrass would only be affected when high amounts of freshwater entered Biscayne Bay resulting in prolonged exposure to low salinity. Therefore, reduced freshwater inflow should have a positive effect on seagrass biomass provided the low flow did not result in hypersaline conditions.

Wortmann *et al*. (1998) developed a mathematical model to analyse the role of freshwater inflow on spatial patterns and biomass of estuarine macrophytes in South Africa. They found that low flows resulted in the mouth of the estuary closing and therefore stopping the normal tidal variation. This threatened the survival of normally submerged macrophytes as the water levels dropped.

Mouth closure may also result in increased water levels, which would affect the survival of normally terrestrial plants.

Estuaries with regular freshwater input have been shown to have different plant communities distributed from the mouth to the head of the estuary, while rivers with little or no freshwater inflow had low plant diversity (Wortmann *et al*., 1998). This study also showed that low flows to South African estuaries resulted in seagrass moving into the upper reaches and displacing brackish and freshwater plants. While increased seagrass area did have benefits, there was an overall loss of diversity in the system.

A study on the seagrass *Zostera capricorni* in Moreton Bay (Qld) found salinity levels affected germination success and rate under aerobic conditions, with seeds exposed to lower salinities germinating faster and more successfully. Water temperature and oxygen content also influenced germination (Brenchley and Probert, 1998).

Experimental laboratory studies of the effects of water motion on the seagrass *Thalassia testudinum* showed that intermediate flow rates yielded the highest biomass and largest blade area (Gillanders and Kingsford, 2002).

Changes to macrophyte distribution have occurred within the Hawkesbury-Nepean system from changes to channel morphology (SCA, 2000). As a result of altered flow regime, sediment starvation and sand extraction, the amount of available habitat for macrophyte beds has been reduced (SCA, 2000). Salinity levels may become more stable when flows are reduced and result in seagrass colonising the upper estuarine areas, as has been demonstrated by a model of South African estuaries (Gillanders and Kingsford, 2002).

The effects of altered freshwater flow on algae depends on several factors, particularly whether the algae occurs in the intertidal or subtidal zone. These effects may be direct or indirect (e.g. freshwater flow affects animals which feed on algae) (Gillanders and Kingsford, 2002). The effects of altered freshwater flow on algae are likely to be similar to those on seagrass with different species being affected by different factors and in different ways (Gillanders and Kingsford, 2002).

Mangrove habitat has been lost from the Clarence River due to reduced tidal penetration (Pollard and Hannan, 1994), while increased inundation has been shown to be detrimental to *Avicennia* mangroves in the Brunei-Muara District (Choy and Booth, 1994). Reduction of freshwater flows to mangroves is likely to reduce the supply of nutrients, which would alter the growth and salt-regulating mechanisms of the plants (Platten, 1996). It is thought that Australian saltmarshes are likely to be greatly affected by altered flows (Gillanders and Kingsford, 2002).

7.3 Crustaceans

A relationship between estuarine (or near-coastal) fisheries catch and freshwater flow has been reported for 22 tropical (or subtropical) fisheries (Robins *et al*., 2005). Of the few Australian crustacean fisheries examined, banana prawns (*Penaeus merguiensis*, in tropical North Qld, Central Qld and the Logan River), school prawns (*Metapenaeus macleayi*, in the Hunter River, Logan River and Clarence River), eastern king prawns (*Penaeus plebejus*, Logan River), tiger prawns (*Penaeus esculentus*, Logan River) and greasy prawns (*Metapenaeus bennettae*, Logan River) as well as mud crabs (*Scylla serrata*, Logan River) showed a positive relationship between catch and increased freshwater flow in the same or previous year, while the blue swimmer crab (*Portunus pelagicus*, Logan River) showed no significant correlation (Vance *et al*., 1985, 1998; Staples and Vance, 1986; Ruello, 1973; Glaister, 1978; Loneragan and Bunn, 1999; Cappo *et al*., 1998; Robins *et al*., 2005). However, “the relationship between catch and freshwater flow (or rainfall) is not always consistent between areas, even for the same species” (Robins *et al*., 2005, p. 345). From data for prawns at least, it is suggested that hydrological and biological differences between catchments influence the relationship between catch and flow. Therefore, each estuary needs to be assessed separately (Robins *et al*., 2005).

In the Fitzroy River estuary, Calliope River estuary and the Boyne River estuary (Central Qld) banana prawn growth has been shown to be influenced positively by freshwater flows and negatively by increasing temperature (Ian Halliday, 2006, pers. comm., Coastal CRC/FRDC project).

Analysis of commercial fishing data collected from the Capricorn Bunker group (Platten, 1996) suggests an apparent link between catch rates of both eastern king prawn and moreton bay bugs (*Thenus orientalis*), and increased river outflow. The relationships between catch rates of banana prawns and mud crabs (*Scylla serrata*) and river flow in coastal waters adjacent to the Pioneer Valley were examined by Platten (2000). No direct correlation was observed for the mud crabs, although the results strongly suggest a time-lag effect. However, there was a clear relationship between flow and the catch of banana prawns, as well as an obvious time-lag effect.

"Most correlations between freshwater flow (or rainfall) and prawn catch have been reported for estuarine-dependent species or those with a greater tolerance or exploitation of brackish-water habitats" (Halliday *et al*., 2005, p. 11). These species have all been from tropical or sub-tropical waters. The relationship between temperate crustacean species and flows has been examined in several species in the northern hemisphere but not in Australia" (see Robins *et al*., 2005, p. 344 for references).

There are three suggested reasons for the reported correlation between flow and catch of penaeid prawns (Robins *et al*., 2005):

- enhanced emigration and the resulting increase in catchability,
- enhanced growth and survival, and
- enhanced recruitment.

Increased catchability and survival of juveniles are suggested reasons for the reported correlation between flow and catch of mud crabs (Robins *et al*., 2005).

It is often hard to determine what effects flows have on crustacean recruitment and survival as there are many other variables that can influence crustaceans and may confound the results of most field studies (Rozas *et al*., 2005). Stable isotopes may prove to be a useful tool for examining the connection between freshwater inflows and estuarine consumers (Rozas *et al*., 2005).

7.4 Molluscs

Both negative and positive relationships between oyster (*Crassostrea virginica*) harvest and flows have been reported in the United States, with some showing a negative effect in the year of a large flow and a positive effect the year following a large flow (Robins *et al*., 2005).

In Spain, studies have reported a negative relationship between flow and catch of the common octopus (*Octopus vulgaris*) but no correlation was found for the cuttlefish (*Sepia officinalis*) (Robins *et al*., 2005).

A new study being undertaken by the University of Tasmania will clarify the impact of flows on oyster aquaculture in estuaries (Christine Crawford, December 2005, pers. comm.). The project is the first of its kind in the world and is also novel in that it incorporates socio-economic analysis of water use across the estuary's catchment.

7.5 Other macroinvertebrates

Recruitment, growth, movement, survival and reproduction of invertebrates are influenced by freshwater run-off and its related changes to salinity, temperature and sediment loads (Gillanders and Kingsford, 2002). Similarly, Montagna and Kalke (1992) reported that estuaries in Texas with more freshwater flow support greater invertebrate density and biomass. While several studies have examined the effect of flows on freshwater invertebrates, most have studied crustaceans.

Reported effects of increased water motion on estuarine biota can vary, with laboratory studies showing both negative and nil effects on the growth rates of some invertebrates (Eckman and Duggins, 1993).

The structure of coral communities in Okinawa, Japan, has been shown to change as a result of increased freshwater flow and lowered salinity (Gillanders and Kingsford, 2002) or increased turbidity/sedimentation. Reduced freshwater flows resulting in hypersaline waters could also adversely impact corals (Gillanders and Kingsford, 2002).

Growns and Growns (2001) examined the effects of flow regulation on macroinvertebrates and periphytic diatoms in the freshwater section of the Hawkesbury-Nepean River and found several differences between regulated sites below impoundments or weirs and non-regulated sites or sites located above weirs/impoundments. Some groups responded well to flow regulations (e.g. amphipods) while others were severely impacted (e.g. plectopterans). It seems likely that there would be a similar range of effects on estuarine invertebrates.

Growns and Growns (2001) reported that the differing hydrological regimes were the principal mechanism for the differences in macroinvertebrate fauna rather than water quality effects.

Research examining invertebrates of estuaries around Townsville (Qld) has shown that significant freshwater flows cause a decrease in salinity resulting in the removal of nereid and lumbrinerid polychaetes from the system. They return when salinities return to normal (Janine Sheaves, 2005, pers. comm.).

7.6 Fish

A negative or positive relationship between estuarine (or near-coastal) fisheries catch and freshwater flow has been reported for 22 tropical (or subtropical) fisheries from around the world (Loneragan and Bunn, 1999; Robins *et al*., 2005). Of the few Australian finfish fisheries examined, mullet (*Mugil* sp., Logan River), barramundi (*Lates calcarifer*, tropical Australian estuaries) and flathead (*Platycephalus* sp., Logan River) showed a positive relationship between catch and increased freshwater flow, while whiting (*Sillago* sp., Logan River) showed no significant correlation (Loneragan and Bunn, 1999; Robins *et al*., 2005).

Preliminary analysis of the relationship between the catch rates of recreational and commercial fish and river discharge from the Burdekin and Fitzroy rivers (in Central Qld) suggest a significant link (Platten, 1996). Commercial fishing data collected from the Capricorn Bunker group (in Central Qld) suggest an apparent link between catch rates and increased river outflow for the following species: coral trout (*Plectropomus* spp), cod (Serranidae – *Epinephelus* spp predominately), pearl perch (*Glaucosoma scapulare*), hussar (*Lutjanus adetii*) and snapper (*Chrysophrys auratus)*. At offshore reefs near the Burdekin River, a relationship may exist with red throat emperor (*Lethrinus* spp) and coral trout *(Plectropomus* spp) and river discharge (Platten, 1996).

In the Fitzroy River estuary, king threadfin (*Polydactylus macrochir*) show the same results (positive correlation) as barramundi for year class strength, even though they have a very different life history using estuaries as juveniles and then moving into the marine environment as adults (Ian Halliday, 2006, pers. comm., Coastal CRC/FRDC project).

Analysis of relationships between catch rates and river flow in coastal waters adjacent to the Pioneer Valley was examined by Platten (2000). A negative correlation was observed for flow and catch rates with barramundi (*Lates calcarifer*), however time lag effects were probable. A clear relationship was found for mullet (primarily *Mugil cephalus*) and blue salmon (*Eleutheronema tetradactylum*) but no obvious lag effects for either species. There was some evidence for correlation between catch of king salmon (*Polydactylus sheridani*) and freshwater flow, as well as a probable lag effect of 2-3 years.

The relationship between temperate fish species and flows has been examined in several species in the northern hemisphere but not in Australia (see Robins *et al*., 2005, p. 344 for references).

Loneragan and Bunn (1999) and Robins *et al*. (2005) reported that there are three possible reasons for the correlation between freshwater inflow and finfish catch. These are:

- changes in catchability,
- changes to cohort or year-class survival, and
- changes to food availability.

Changes to catchability may result from increased fish movement or decreased range and are suggested when there is a short delay between flows and catch. A lag period between flow and catch suggests there has been a change to cohort or year-class survival. There are several mechanisms driving this phenomenon including; survival of eggs and larvae, predation rates, nursery/habitat area availability, growth rate to catchable size and food availability. However, few studies have examined these mechanisms and it is likely that all may contribute to the relationships observed (Robins *et al*., 2005).

Strong correlations between rainfall and recruitment have been reported for Northern Territory and Queensland barramundi, black bream in the Gippsland Lakes, and black bream and mulloway at the River Murray mouth though the mechanisms behind this relationship remain unknown (Cappo *et al*., 1998). However, low salinities are favourable for the survival of barramundi, bass and black bream larvae (Battaglene and Talbot, 1993; Cappo *et al*., 1998).

Hoedt and Dimmlich (1995) reported links between anchovy spawning, zooplankton productivity and freshwater flows into nearshore and shelf habitats near Phillip Island, Victoria, showing that the effects of freshwater flows extend beyond the estuary. Cottingham *et al*. (2001) and Bunn and Arthington (2002) reported that modification of freshwater flow regime and the associated infrastructure may impact fish in several ways, including:

- barriers to movement, loss of longitudinal and lateral connectivity,
- release of water with altered properties such as cold water or low dissolved oxygen,
- changes in habitat availability and heterogeneity – rapid changes to water levels increase the risk of stranding and reduced low flows decrease habitat availability, and
- changed flow stimuli such as seasonal flow inversions or unseasonable flow pulses.

A study of the fish fauna of the Ross River estuary (Townsville) during extended dry periods compared to wet periods shows a switch from a marine fauna throughout the estuary during dry periods to a marine-fresh faunal gradient during wet periods. The important point is that in dry periods, the rainfall entering the system was trapped in the series of dams and weirs. In the wet years water collected in the impoundments continued to flow into the estuary long after rainfall had stopped. So the impoundments had the effect of intensifying the effect of both dry and wet periods (Marcus Sheaves, 2006, pers. comm. (Sheaves *et al.*, in prep)).

7.7 Birds

“Environmental flows can play a crucial role in the maintenance of the integrity of wetlands and their related bird populations” (SCA, 2000, p. 26). Studies from the United Kingdom have shown that waterbird numbers and densities were consistently greater in corridors associated with freshwater flows compared to those on mudflats at all estuaries examined (Ravenscroft and Beardall, 2003). However, estuarine populations of several species occasionally grew around flows probably due to the presence of freshwater for drinking close to their feeding grounds. The size of flow was an important factor (Ravenscroft and Beardall, 2003).

Freshwater flows may also influence the availability of food for waterbirds. Studies from the UK suggest freshwater inflows decrease salinity and maintain the activity of invertebrates, resulting in increased numbers of euryhaline invertebrates, the prey items of waders (Ravenscroft and Beardall, 2003). As with other fauna, optimal flow regimes to maintain the health of bird populations are likely to be estuary specific (Ravenscroft and Beardall, 2003).

In Australia, migratory birds visit the marshes and mudflats associated with the Hawkesbury-Nepean River to feed. It has been proposed that summer environmental flows would benefit these populations as it would increase the available area of marsh and mudflat for feeding (SCA, 2000). Flows would also benefit the resident bird populations by stimulating plant growth and increasing the area of nesting habitat available (SCA, 2000). “Given the right season and water depth, birds will breed in response to an environmental flow, however the specific requirements (season and depth) vary between species” (SCA, 2000, p. 26).

A confounding factor in examining the links between flows and bird populations is that birds are extremely mobile and are able to use resources over a large area. Therefore, any relationship between flow and bird numbers can be extremely hard to determine as bird presence or absence may be the result of environmental conditions hundreds of kilometres away and not related to what is happening locally (Reid and Brooks, 2000).

“Moreover, birds possess a high degree of behavioural complexity, which may further confound responses to changing hydrological conditions. For example, there is concern among managers that successive breeding failures within a wetland, as a result of shortened flood duration, may cause birds to shun that wetland during subsequent floods, even if hydrological management has since ensured that inundation occurs for a period sufficient for successful breeding” (Reid and Brooks, 2000, p. 489).

Table 7.1. Summary of relationship between abundance of Australian estuarine biota and river flows.

Estuary/Location	Species	Correlation to Flow	Flow Amount	Flow Timing	Explanation for Correlation	Reference
PLANKTON						
Swan River SW WA	Phytoplankton	No correlation (total cell densities)	Range	Rainfall is highly seasonal, with >90% occurring between April and October. Flow is similarly skewed, and lags rainfall by about one month	NA	Chan and Hamilton, 2001
Swan River SW WA	Chlorophyte	Negative	Chlorophyte blooms are restricted to a flow range from 40 ML day^{-1} to 1,000 ML day^{-1}	As above	Cells are flushed from the estuary and changes in recirculation, turbulence, stratification, water clarity, salinity and nutrient availability have significant effects on phytoplankton communities	Chan and Hamilton, 2001
Haughton River Central Qld	Chlorophyll	Positive	High river flow	Summer	The degree of mixing, determined by tidal state and freshwater input driving both the quantity and quality of particulate material available for consumption	McKinnon and Klump, 1998
Swan River SW WA	Dinophyte	Negative	Blooms to flows of <15 ML day^{-1}	Rainfall is highly seasonal, with >90% occurring between April and October. Flow is similarly skewed, and lags rainfall by about one month	Cells are flushed from the estuary and changes in recirculation, turbulence, stratification, water clarity, salinity and nutrient availability have significant effects on phytoplankton communities	Chan and Hamilton, 2001

Estuary/Location	Species	Correlation to Flow	Flow Amount	Flow Timing	Explanation for Correlation	Reference
Derwent River, Huon River SE Tas	*Gymnodinium catenatum* (dinoflagellate)	Positive	100,000 ML over a three-week period (from the Huon River)	Combined with water temperatures >14°C and calm waters (windspeed <5 m/s for five days or more)	Not discussed	Hallegraeff *et al.*, 1995
Swan River SW WA	Bacillariophyta	Negative (but moderate densities continue to occur at flow rates up to 10,000 ML day^{-1})	Range	Rainfall is highly seasonal, with >90% occurring between April and October. Flow is similarly skewed, and lags rainfall by about one month	Cells are flushed from the estuary and changes in recirculation, turbulence, stratification, water clarity, salinity and nutrient availability have significant effects on phytoplankton communities	Chan and Hamilton, 2001
Haughton River Central Qld	Zooplankton	Positive	Increased river flow	Summer	The degree of mixing, determined by tidal state and freshwater input driving both the quantity and quality of particulate material available for consumption	McKinnon and Klump, 1998
Derwent River SE Tas	*Gladioferens spinosus* (zooplankton)	Positive	Unknown	High flows in October, low flows in April	Not discussed	Taw and Ritz, 1978
Derwent River SE Tas	*Gladioferens pectinatus* (zooplankton)	Negative	Unknown	As above	Not discussed	Taw and Ritz, 1978
Derwent River SE Tas	*Sulcanus conflictus* (zooplankton)	Negative	Unknown	As above	Not discussed	Taw and Ritz, 1978

Estuary/Location	Species	Correlation to Flow	Flow Amount	Flow Timing	Explanation for Correlation	Reference
CRUSTACEANS						
South-East Gulf of Carpentaria	*Penaeus merguiensis* (banana prawn)	Positive	-	-		Vance *et al*., 1985, 1998; Staples and Vance, 1986
Northern Gulf of Carpentaria	*Penaeus merguiensis* (banana prawn)	No correlation	-	-	NA	Cappo *et al*., 1998
Fitzroy River Central Qld	*Penaeus merguiensis* (banana prawn)	Positive	-	Summer flow	Increases in catchability and recruitment	Robins *et al*., 2005
Fitzroy River, Calliope River and Boyne River Central Qld	*Penaeus merguiensis* (banana prawn)	Positive	-	Summer flow	Increased growth rates during periods of flow	Halliday, 2006, pers. comm. (CRC/FRDC project)
Logan River SE Qld	*Penaeus plebejus* (eastern king prawn)	Positive	The total annual flow (January to December) for the period when catch records are available (1988-1995) ranged from 39,526 ML in 1993 to 818,179 ML in 1988, which includes some of the lowest and highest flows on record	The mean flows in summer and autumn were much higher than those for winter and spring for both the historical and recent flow data	Increased nutrients resulting in increased primary productivity. Or the stimulation of the emigration of juveniles into the lower estuary as a result of increased run-off in summer	Loneragan and Bunn, 1999
Logan River SE Qld	*Penaeus esculentus* (tiger prawn)	Positive	As above	As above	As above	Loneragan and Bunn, 1999

Estuary/Location	Species	Correlation to Flow	Flow Amount	Flow Timing	Explanation for Correlation	Reference
Logan River SE Qld	*Metapenaeus bennettae* (greasy prawn)	Positive	As above	As above	As above	Loneragan and Bunn, 1999
Fitzroy River Central Qld	*Penaeus plebejus* (eastern king prawn)	Positive	-	-	Increased catchability due to translocation of prawns offshore	Platten, 1996
Capricorn-Bunker Group Central Qld	*Penaeus plebejus* (eastern king prawn)	Positive	-	-	Increased catchability due to translocation of prawns offshore	Platten, 1996
Pioneer River Central Qld	*Penaeus merguiensis* (banana prawn)	Positive Lag: clear relationship – lag from 1-3 yrs	-	High summer rainfall	Increased estuarine productivity	Platten, 2000
Richmond and Clarence rivers Far North NSW	*Metapenaeus macleayi* (school prawn)	Positive	-	-		Ruello, 1973; Glaister, 1978
Logan River SE Qld	*Portunus pelagicus* (blue swimmer crab)	No correlation	The total annual flow (January to December) for the period when catch records are available (1988-1995) ranged from 39,526 ML in 1993 to 818,179 ML in 1988, which includes some of the lowest and highest flows on record	The mean flows in summer and autumn were much higher than those for winter and spring for both the historical and recent flow data	NA	Loneragan and Bunn, 1999

Estuary/Location	Species	Correlation to Flow	Flow Amount	Flow Timing	Explanation for Correlation	Reference
Logan River SE Qld	*Scylla serrata* (mud crab)	Positive	As above	As above	Increased catchability as higher rainfall and hence river flow stimulates the downstream movement of mud crabs. This mechanism may also result in increased survival of juveniles due to a decrease in cannibalism by adults	Loneragan and Bunn, 1999
Capricorn-Bunker Group Central Qld	*Thenus orientalis* (moreton bay bugs)	Positive	-	-	Increased catchability due to translocation	Platten, 1996
Pioneer River Central Qld	*Scylla serrata* (mud crab)	No correlation Lag: clear relationship – lag from 1-3 yrs	-	-	NA	Platten, 2000
OTHER MACROINVERTEBRATES						
Ross River, Althaus Creek and Saltwater Creek Central Qld	Nereids and lumbrinerids (polychaetes)	Negative	-	-	Reduced salinity results in polychaete removal from the system. Polychaetes return when salinity returns to 'normal'	Janine Sheaves, 2005, pers. comm.
Botany Bay Central NSW	*Catostylus mosaicus* (jellyfish)	No relationship between rainfall and timing of recruitment	-	-	NA	Pitt and Kingsford, 2003

Estuary/Location	Species	Correlation to Flow	Flow Amount	Flow Timing	Explanation for Correlation	Reference
FISH						
Logan River SE Qld	*Mugil* sp. (mullet)	Slight positive	The total annual flow (January to December) for the period when catch records are available (1988-1995) ranged from 39,526 ML in 1993 to 818,179 ML in 1988, which includes some of the lowest and highest flows on record	The mean flows in summer and autumn were much higher than those for winter and spring for both the historical and recent flow data	Not discussed	Loneragan and Bunn, 1999
Logan River SE Qld	*Sillago* sp. (whiting)	No correlation	As above	As above	NA	Loneragan and Bunn, 1999
Logan River SE Qld	*Platycephalus* sp. (flathead)	Positive	As above	As above	Increased catchability	Loneragan and Bunn, 1999
Fitzroy River Central Qld	*Lethrinus* spp (red throat emperor)	Positive	-	-	Increased catchability	Platten, 1996
Fitzroy River Central Qld	*Lates calcarifer* (barramundi)	Positive	Mean and median annual discharge of ~5.2x10^6 ML (164.8 m^3s^{-1}) and 2.9 x10^6 ML (91.9 m^3s^{-1}), respectively	High summer flows, low or zero winter flows	Enhanced juvenile survival due to altered accessibility, productivity and/or carrying capacity of nursery habitats	Staunton-Smith *et al.*, 2004
Fitzroy River Central Qld	*Lates calcarifer* (barramundi)	Positive	From 5^{th} to 95^{th} percentile of flow experienced over study	Summer flow	Growth influenced by increasing flow	Robins *et al.*, 2006 – cited by Halliday, 2006, pers. comm.

Estuary/Location	Species	Correlation to Flow	Flow Amount	Flow Timing	Explanation for Correlation	Reference
Fitzroy River Central Qld	*Lates calcarifer* (barramundi)	Positive	-	Summer flow	Immediate increase in catch through connectivity and lagged response (3-4 years) in catch due to strong year class strength	Robins *et al.*, 2005
Fitzroy River Central Qld	*Polydactylus macrochir* (king threadfin)	Positive	unknown	Summer flow	Strong year class strength, indicating high survival of young of the year	Halliday, 2006, pers. comm. (CRC/FRDC project)
Capricorn-Bunker Group Central Qld	*Plectropomus* spp (coral trout)	Positive	-	-	Increased catchability and possibly increased feeding intensity	Platten, 1996
Capricorn-Bunker Group Central Qld	Serranidae – *Epinephelus* spp predominately (cod)	Positive	-	-	As above	Platten, 1996
Capricorn-Bunker Group Central Qld	*Glaucosoma scapulare* (pearl perch)	Positive	-	-	As above	Platten, 1996
Capricorn-Bunker Group Central Qld	*Lutjanus adetii* (hussar)	Positive	-	-	As above	Platten, 1996
Capricorn-Bunker Group Central Qld	*Chrysophrys auratus* (snapper)	Positive	-	-	As above	Platten, 1996
Pioneer River Central Qld	*Lates calcarifer* (barramundi)	Not clear Lag: probable lag 3-4 years	-	-	NA	Platten, 2000

Estuary/Location	Species	Correlation to Flow	Flow Amount	Flow Timing	Explanation for Correlation	Reference
Pioneer River Central Qld	*Mugil cephalus* (mullet)	Positive Lag: not obvious	-	Catch correlated with large summer flows (1991). Above average winter flows may also have some influence	Increased estuarine productivity	Platten, 2000
Pioneer River Central Qld	*Polydactylus sheridani* (king salmon)	Some evidence Lag: probable lag 2-3 years	-	-	As above	Platten, 2000
Pioneer River Central Qld	*Eleutheronema tetradactylum* (blue salmon)	Positive Lag: not obvious	-	Catch correlated with larger summer and total wet season flows	As above	Platten, 2000
Gippsland Lakes E Vic	*Acanthopagrus butcheri* (black bream)	Positive	-	High flows in May	Increased recruitment due to increased nutrients→primary production→food supply for juvenile fish	Walker *et al*., 1998
Hawkesbury-Nepean Central NSW	*Macquaria novemaculeata* (Australian bass)	Positive	Study measured flows ≤1,000 ML day^{-1}	Flows throughout the entire year are important	Increased recruitment	Growns and James, 2005

7.8 Geographic considerations

Hamilton and Gehrke (2005) reported that environmental flow research has been concentrated primarily in the temperate freshwater rivers of Australia, primarily because that is the region where there is the greatest impact from river regulation. In contrast, most research into the effects of flow on estuarine biota has taken place in tropical and subtropical regions (Figure. 7.1). There is therefore spatial mismatch in the basic knowledge on the impacts of flows on estuaries around Australia.

Most historical flow work has been undertaken with an interest on commercial fisheries species. This means that a lot is known about impacts on a few iconic species (e.g. barramundi) but little work has been undertaken on the broader implications of altered flow regimes.

Figure 7.1 shows the locations of studies examining the relationship between freshwater inflows and estuarine biota mapped over the distribution of seasonal patterns of river flow.

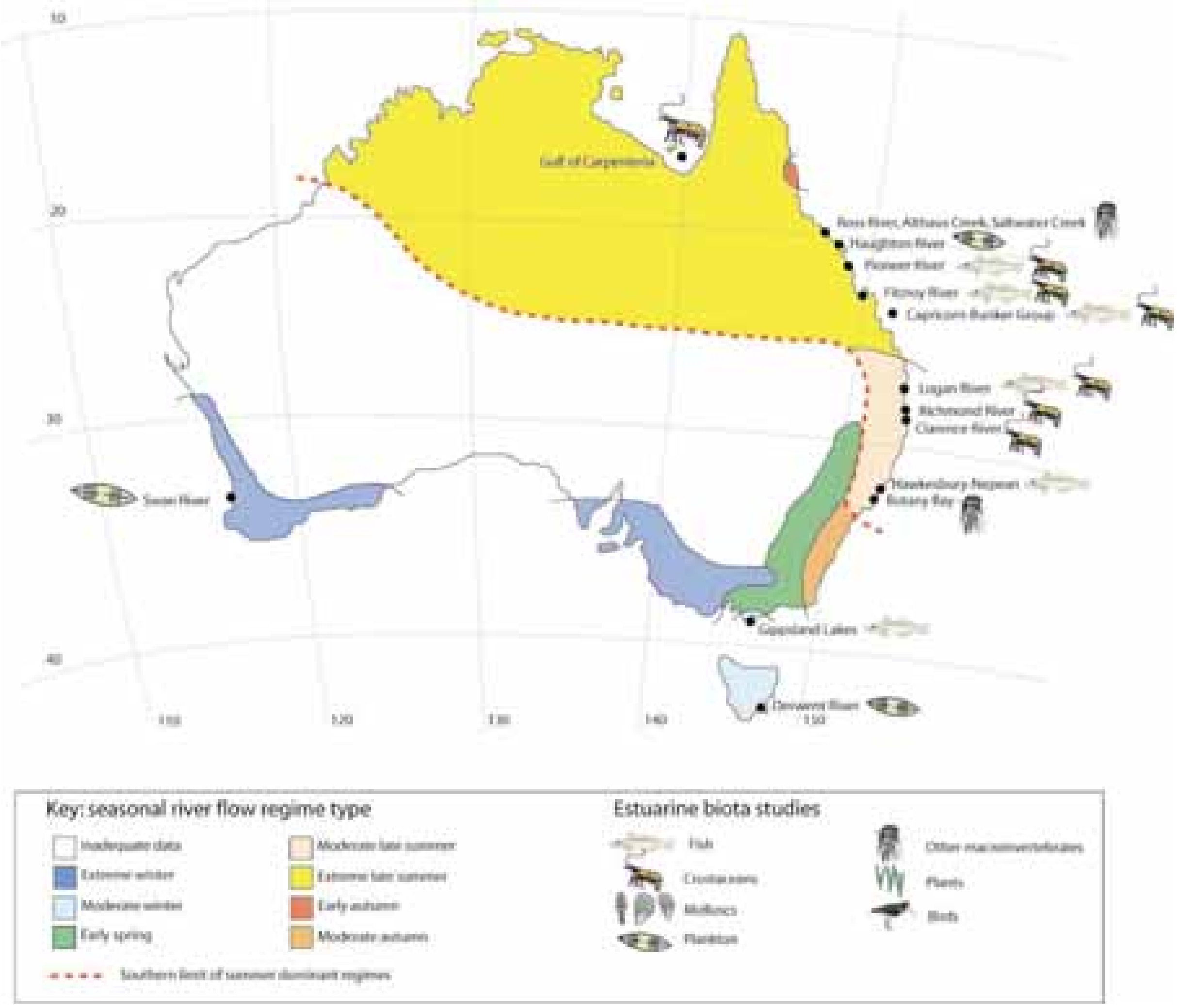

Figure 7.1. The locations of studies examining the relationship between river flows and estuarine biota mapped over the distribution of seasonal patterns of river flow (modified from Gillanders and Kingsford, 2002).

8 Current Methodologies for Determining Freshwater Flows to Estuaries in Australia

All states have developed environmental flow programs and have issued policy documents relating to the determination of flow allocations (see Arthington and Pusey, 2003; Schofield and Burt, 2003). However, these flow allocation processes have been criticised.

For example, the focus on environmental flow allocations is traditionally based on resource use and Schofield *et al*. (2003) noted that policies seldom identify outcomes for ecological protection and river health. Some of the difficulties in setting these allocations are outlined by Schofield *et al*., 2003:

- "most flows were what was feasible given existing allocations and infrastructure, and are a compromise between optimal and socially acceptable
- the scientific basis for decisions was often uncertain, given lack of data and little monitoring to build upon the poor information base
- the approach was often species-specific, with full integration of ecosystems difficult to achieve
- species with economic/recreational use received disproportionate attention when flow requirements were assessed
- some environmental allocations were undertaken in part to achieve economic and other benefits
- the process is complex, requiring detailed scientific information and cooperation between a number of agencies and community and environmental interests that have often had a long history of competitive relationships.

Although that description is a few years old it is probable that it is still fairly accurate" (Schofield *et al*., 2003, p. 23).

Another criticism is that due to tight timeframes, the determination of environmental flow allocations in some states occurs with little river-specific research being carried out and decisions rely heavily on expert advice and opinion (Schofield *et al*., 2003; Arthington *et al*., 2004). Moreover, control of flows is undertaken under a range of heads-of-power and a raft of legislative instruments. The National Water Initiative seeks to address some of these problems.

8.1 Examples of estuarine flow management by the states and territories

A further criticism that is not explicitly addressed by the NWI is that estuarine flow needs are seldom considered in water planning arrangements (e.g. Zann, 1996; Gardner, 2005). There has been a growing recognition of the need to extend flow determination methodologies to estuaries and there have been several excellent reviews of methods for determining environmental flows (e.g. see Arthington *et al*., 1998a,b; Arthington and Zalucki, 1998a; Peirson *et al*., 2002; Tharme, 2003; Arthington *et al*., 2004; Close, 2005). All reviews highlight the recent emergence of this field, and the consequent difficulties arising from lack of appropriate information and need for further R&D to support effective decision-making about flow allocations for estuaries. “Until recently, most environmental flow investigations in Australia addressed allocation to freshwater ecosystems” (Close, 2005, p. 11). Despite recent attempts to address estuarine flow needs there currently is no single standardised method for estimating environmental flow needs for estuaries in Australia, or internationally. This is due to the lack of “information on the freshwater requirements of estuaries to permit standard environmental flow methods to be applied” (Halliday *et al*., 2005, p. 4).

Estuarine flow needs have been included in most coastal river water allocation plans, but the knowledge on which these needs is based and the methodology used is usually rather limited. In a review of ecological water requirements for the Hill and Moore River estuaries in Western Australia, Close (2005) reviewed, and provided examples of four categories of approach used to determine flow requirements. The four approaches are specifically designed to address different flow related issues, and are: holistic ecosystem approaches; inflow based approaches; resource-based approaches; and condition-based approaches (Close, 2005). The author also assessed the suitability of specific methodologies being used in Australia, South Africa and America for application to Australian estuaries. The review highlighted several disadvantages of existing approaches and suggested a hybrid technique that addressed some of these deficiencies and combined the strengths of many of the existing systems. Despite the development of this range of methods, efforts to determine appropriate flows for estuaries are rare in Australia.

Examples of where estuarine flow requirements have been explicitly included in planning arrangements include most Queensland Water Resource Plans (such as the Logan, Burnett, Mary, Pioneer, Fitzroy, Barron rivers and the Moreton Region). In Queensland a raft of legislation is relevant to water quality and quantity in estuaries but the principal legislation for managing flow allocations is the *Water Act 2000* (Qld). Under the Act regulations can be created to create water resource plans which detail the objectives for flow requirements, allocations and monitoring to “advance the sustainable management of water” (section 38). Several plans have been enacted as subordinate legislation under the Act, namely:

- Water Resource (Barron) Plan 2002
- Water Resource (Border Rivers) Plan 2003
- Water Resource (Boyne River Basin) Plan 2000
- Water Resource (Burnett Basin) Plan 2000
- Water Resource (Condamine and Balonne) Plan 2004
- Water Resource (Fitzroy Basin) Plan 1999
- Water Resource (Georgina and Diamantina) Plan 2004
- Water Resource (Moonie) Plan 2003
- Water Resource (Pioneer Valley) Plan 2002
- Water Resource (Warrego, Paroo, Bulloo and Nebine) Plan 2003

The *Water Act* itself defines ‘watercourses’ to exclude estuarine reaches of rivers, unless these areas are specifically included within the Plans. The plans for the Barron, Boyne, Burnett and Pioneer rivers contain provisions for managing flows for estuaries. Peirson *et al*. (2002, p. 51) note that the “Queensland Government has specified that environmental flow requirements of estuaries be assessed and with regard to the following factors: water quality and quantity; natural flow regimes (frequency and timing); impacts on estuarine productivity; impacts on mangrove distribution and species composition; nutrient and sediment supply; salinity; fresh water, estuarine and inshore habitats; the function of the river in providing a corridor for wildlife to move between habitats including fresh water and marine habitats); species diversity; and species population dynamics”.

For example, the plan for the Barron River (Water Resources (Barron) Plan 2002 (Qld)) provides that water is to be allocated and managed *inter alia* “to:

- provide wet season flow to benefit native plants and animals in estuaries; and
- maintain long term water quality suitable for riverine and estuarine and monitoring the condition of estuarine” (section 12).

Specific provisions require that the flow regime maintain the abiotic elements of the estuary (section 14) and estuarine habitats be included in monitoring programs (section 58). Most importantly, the estuary is included as a ‘node’ for which specific flow objectives are defined (Schedule 5). The plan was developed through extensive community consultation and recognises the value placed on the estuary of the river and its links to the waters of the Great Barrier Reef. The general process for flow allocations to estuaries has been criticised for being overly qualitative and using little data (Gippel, 2001). However, a much wider range of estuarine issues have been considered in later Water Resource Plans.

Much attention has been directed to determining appropriate flow allocations in Victoria (see SKM, 2002) but little attention has been given to the flow requirements of estuaries. At the time of writing the Victorian State Government was awaiting a report on the modification of e-flow techniques developed for Victorian rivers for estuarine use (Michaela Dommisse, January 2006, pers. comm.) and a project to develop a generic methodology based on the “FLOWS” method has commenced.

New South Wales is currently preparing water sharing plans for most of the unregulated rivers in the state (called the 'Macro Water Sharing Planning Process'). These plans will set rules that share water between users and the environment. The plans will be developed for most of the state's estuaries. (Penny Vella and Peter Scanes, 2006, pers. comm.).

In Tasmania flows are managed under the *Water Management Act 1999* (Tas.) and administered through the Department of Primary Industries, Water and Environment. The Water Assessment and Planning Branch is currently developing a holistic environmental flows methodology framework for Tasmania that will include coverage of the requirements of estuaries. This framework relies on interrogating the Conservation of Freshwater Ecosystem Values (CFEV) database (Danielle Warfe, 2006, pers. comm.). The CFEV database identifies significant ecosystem values within a catchment, including estuaries and saltmarshes subject to freshwater flows, which can then be used to develop the goals of environmental flows recommendations (Danielle Warfe, 2006, pers. comm.). Also relevant is the Tasmanian Water for Ecosystems Policy which provides guidelines on determining environmental flow requirements.

In South Australia the Department for Environment and Heritage (DEH) is leading the development of an Estuaries Policy and Action Plan. Outcome 1 of the policy – Better management of estuaries for environmental, social and economic sustainability – includes a task in Action 1.1.3 to identify environmental flow needs for priority estuaries and to ensure they are provided using a whole-of-catchment approach. The coordinating role is allocated to Regional Natural Resources Management (NRM) Boards, with DEH, Department of Water, Land and Biodiversity Conservation (DWLBC), the EPA, Local Government and Primary Industries and Resources South Australia (PIRSA) providing support roles.

Under South Australia's *Natural Resources Management Act 2004*, regional NRM Boards must prepare a water allocation plan for the prescribed water resources in each region, which will be taken to form part of the board's regional NRM plan. Water allocation plans provide for the sustainable use of water resources, including the allocation of water for the environment.

The 'Wetlands Strategy for South Australia 2003', including estuaries within marine/coastal wetlands, contains an action under its Objective 1 – To manage wetlands as integrated parts of NRM at local, regional, national and international scales. Action 1.3 (where the continuing 'health' of wetlands found in South Australia is reliant on the quantity and quality of water supplies coming from other states or territories) continues to pursue appropriate water sharing and cooperative management arrangements through existing or future formal agreements.

The Department of Water, Land and Biodiversity Conservation has developed a strategy, 'Environmental Flows for the River Murray: South Australia's framework for collective action to restore river health 2005-2010'. The strategy is principally concerned with the delivery and management of flows to priority ecological assets in South Australia (inclusive of the Murray mouth, Coorong and lower lakes), as one critical input to the overall management of river health. There is also a specific Asset Environmental Management Plan for the Lower Lakes, Coorong and Murray Mouth. This area is recognised nationally in terms of flow needs under the 'Intergovernmental Agreement on Addressing Water Overallocation and Achieving Environmental Objectives in the Murray-Darling Basin', which was agreed by COAG at the same time as the National Water Initiative (NWI).

Another agreed action of the NWI was to establish a National Water Commission (NWC) (IGA-NWI, 2004). The NWC is an independent statutory body in the Prime Minister's portfolio established under the *National Water Commission Act 2004* with the role of driving the national water reform agenda. The Commission provides advice to COAG and oversees two of the three elements of the $2 billion Australian Government Water Fund (namely Raising National Water Standards and Water Smart Australia Program).

One role of the Commission is to review the activities, policies and plans of the states and territories to report on progress of water reform. At the time of writing the Commission had gathered only preliminary information on the current activities of each jurisdiction which included no relevant updates on planning for estuaries (Harry Abrahams, 2005, pers. comm.). However, a number of current projects are reviewing progress and a more comprehensive review of activities nationally will be available in June 2006.

9 Knowledge-needs and their Prioritisation

This section provides information on the knowledge-needs relating to freshwater flows and estuaries that have been identified directly from the literature, and in consultation with environmental flows and estuary experts.

This report has a biophysical focus and as such knowledge-needs relating to social and economic factors were not actively pursued. However, they were included when identified during the course of the project. A separate consultancy would be needed to adequately determine social and economic knowledge-needs.

The significance and scale of the knowledge-needs identified here may vary considerably from one geographic location and estuary type to another. They will also vary in relation to the environmental, economic and social values of each estuary. The spatial variation in the R&D priorities was not determined in this consultancy.

The knowledge-needs identified here will almost certainly need to be addressed via a range of different research projects with consideration for integrated physical-biological models, multidisciplinary studies and quantitative research. In general there is a need to increase knowledge of the relationships between freshwater flows and estuarine health and productivity.

9.1 Knowledge-need prioritisation

The purpose of this project was to identify and then prioritise scientific knowledge-needs relating to freshwater flows into estuaries. Although these knowledge-needs were aligned to management-needs, the project was not designed to identify every knowledge gap within a particular management issue or theme. This means that the knowledge-needs identified in this report are the best scientific assessment of research required to understand estuarine flows but may not include all research requested by flow managers.

The prioritisation process was conducted during a two-day workshop attended by representatives from state and Commonwealth governments, research institutions and industry representatives. The process to identify and prioritise knowledge-needs is summarised in Figure 9.1.

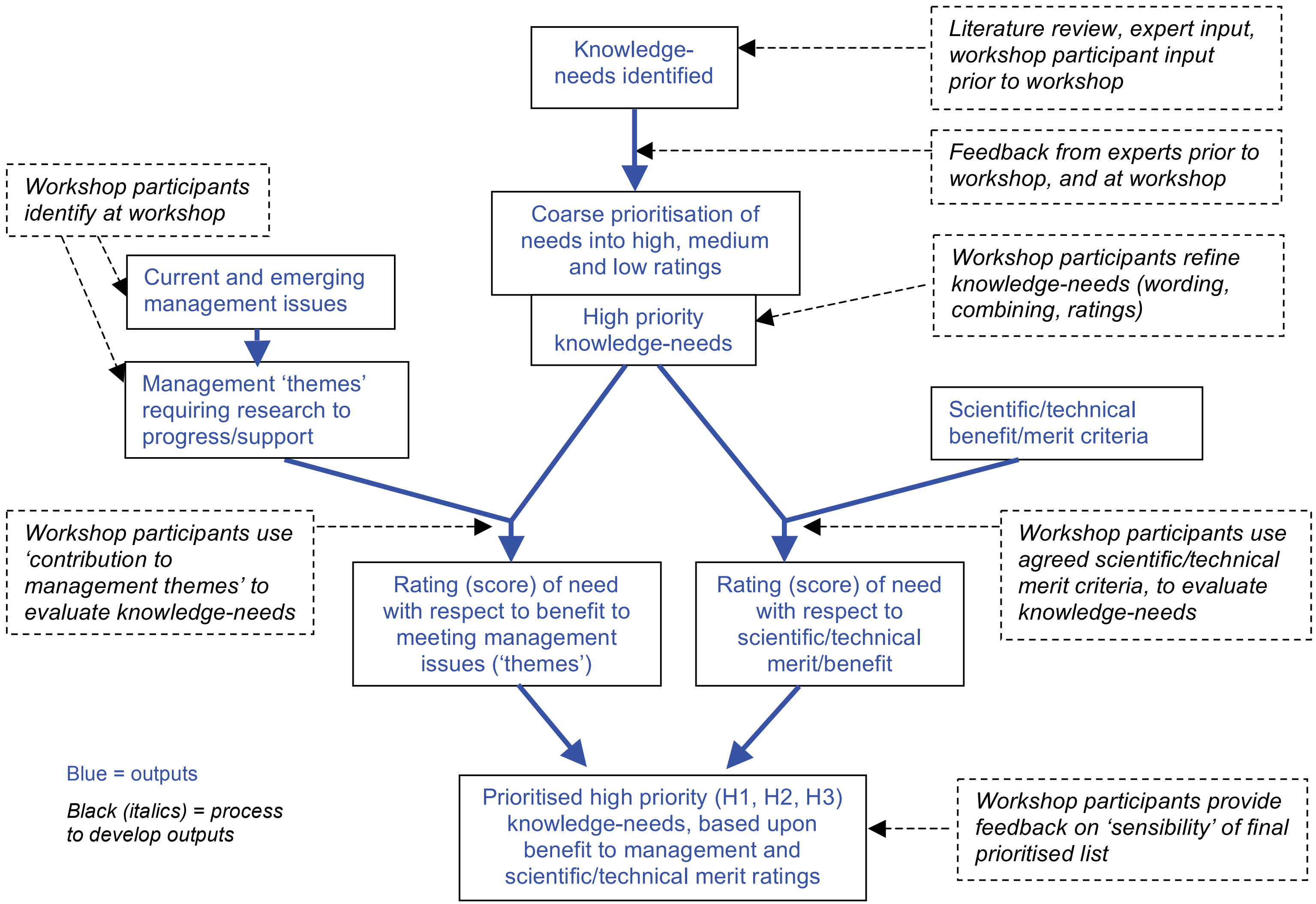

Figure 9.1. Process (included outputs) to prioritise knowledge-needs for freshwater flows to estuaries research.

Prior to the workshop, over 100 experts from Australia were asked to indicate their top 20 knowledge-needs from the list compiled from a review of the literature and discussions with experts. The experts were also asked to identify any knowledge-needs not already identified in the list. Thirty-two responses were received. The knowledge-needs were then coarsely ranked into high, medium and low priority on the basis of the commonly identified priorities. This ranked list of 69 knowledge-needs (plus an additional five unranked knowledge-needs newly identified in the expert responses) was then used as the basis for the workshop discussions (see Appendix 3 for the full initial list of 69 knowledge-needs identified).

A list of 19 'high priority' knowledge-needs were identified and agreed to by the workshop participants (see Table 9.1). The 'high priority' knowledge-needs were then prioritised by examining: a) their scientific or technical merit and benefit, and b) their benefit to the needs of managers.

9.1.1 Scientific merit criteria

The criteria used as a basis for group discussion about the scientific merit and benefits to arise from filling each knowledge-need were as follows:

- transferability (i.e. can acquired knowledge be transferred nationally, to other estuaries of the same estuary type, with the same seasonal flow patterns or in the same climatic zone, or is it estuary specific information?),
- value to progressing other knowledge-needs (i.e. does this knowledge gap need to be filled before other needs can be addressed, at the same time as other needs, or is other information needed before this knowledge-need can be researched?),
- value added to existing research (i.e. by doing research to fill this need does the information obtained add to other existing research, or research programs, resulting in an increased benefit?), and
- innovative (i.e. is the research required to fill this need innovative and/or applied research?).

Workshop participants ranked the knowledge-needs according to scientific merit using the above criteria as a basis.

9.1.2 Benefits to management

Critical management issues were identified by workshop participants and grouped into management themes of related issues. The management themes identified during the workshop were as follows:

A. Political/Policy
    a. Development of decision-support processes and systems
    b. Development of implementation tools
B. Suitably sensitive models to integrate knowledge of flow regime and effects on ecological and other values that will allow testing of flow scenarios
C. Access to and application of knowledge and research outcomes to extension and capacity building for managers, government, industry and the community
D. Determination and assessment of flow delivery to achieve desired management outcomes

E. How to manage environmental flow allocations in the context of other interventions (e.g. entrance management, dredging, global warming, water quality degradation)
F. Values
    a. What are the valued attributes (including biological, cultural, commercial, recreational, intrinsic) which require protection and are critically dependant on flow
    b. Decision-makers tool: framework which equitably considers impacts on all values
G. Effect of flow regime (timing, magnitude, frequency, quality, duration) on the structure and function of estuarine ecosystems and other associated values
H. What institutional coordination, regulatory and governance arrangements are required and at what scale(s)
I. Understanding the ecosystem and water quality consequences of the interaction of climate change with flow regimes and human responses to climate change under various scenarios

During the workshop each knowledge-need was scored against each of the identified management themes in terms of 'will knowledge acquired by addressing that knowledge-need contribute to that management theme?' This information was then used to rank the knowledge-needs in terms of their benefits to management (see Table 9.1).

9.2 Results of the prioritisation of 'high' priority knowledge needs

Table 9.1 shows the resulting rankings against scientific merit and benefit to management from highest (H1) to lowest (H3). They are listed in priority order of benefit to management because of the focus on ensuring the research leads to practical outcomes.

Table 9.1. 'Scientific merit' and 'benefit to management' ranking of the identified 'high priority' knowledge needs.

Code	Knowledge Needs	Benefits to management†	Scientific merit†
A	How do different freshwater flow regimes influence habitat-biota relationships (e.g. woody debris, macrophyte beds, soft bottoms, sand bars, rocky outcrops, saltmarshes and saltflats, mangroves, extent and dynamics of the salt wedge, spatial and temporal variability of freshwater-saltwater habitat availability)?	**H1**	**H1**
B	What are the essential flow regime conditions needed to maintain estuarine health?	**H1**	**H2**
C	To develop a conceptual understanding of the major ecological processes and linkages in rivers and their estuaries.	**H1**	**H2**

Code	Knowledge Needs	Benefits to management†	Scientific merit†
D	How do different types of human impacts (dams, entrance management, agricultural, aquaculture, transport, urban, etc.) interact with altered freshwater flows to affect estuarine functioning?	H1	H2
E	What should we be routinely monitoring (biota, water quality, geomorphology, etc.) in an estuary that has environmental flows to make sure that we are meeting the flow objectives and outcomes?	H1	H2
F	What values do communities place on estuaries?	H1	H3
G	What are the most appropriate tools for testing different flow scenarios (predicting)?	H1	H3
H	How is estuarine productivity changed by freshwater flows and does changed primary productivity translate to changed secondary productivity?	H2	H1
I	What are the flow and water quality requirements of species (flora and fauna) recognised as ecological assets, (e.g. requirements for reproduction, recruitment, dispersal, distribution and abundance, persistence)?	H2	H1
J	What is the role of flows on commercial and recreational fisheries species and their supporting ecosystems (e.g. spawning success, migration and distribution, predation rates, trophic pathways)?	H2	H2
K	What is the relative significance of sources and sinks of water under different flow scenarios to estuaries, in particular what is the role of groundwater flows on estuaries particularly during low-flow periods?	H2	H2
L	What is the relationship of the full range of flows to estuarine morphology and geomorphological processes?	H2	H2
M	What is the relationship between freshwater inflow, water quality and the biogeochemistry of estuaries?	H2	H2
N	What are the relationships between estuarine and nearshore coastal ecological processes and what is the influence of freshwater flow either directly or indirectly?	H2	H2
O	What is the spatial zone of influence of natural and altered sequences of flow events, including quantity, quality and timing of flows?	H2	H3

Code	Knowledge Needs	Benefits to management†	Scientific merit†
P	What are: • the indicator species that indicate the level of health, or degradation, of an estuaries, and • the flow regime requirements and tolerances of these indicator species? How should we measure estuarine ecosystem health? What existing methods have already proven viable and what are the key aspects of health needing new/better metrics and measurement techniques?	**H3**	**H3**
Q	What will be the effects of climate change or variability on environmental flow needs to estuaries?	**H3**	**H3**
R	Is it possible to develop a common nation-wide assessment approach and if so what are the essential data requirements for estuarine systems to determine and assess outcomes for appropriate environmental flows?	**H3**	**H3**
S	What are the effects on an estuary of implementing environmental flows, particularly estuaries that have been 'starved' of flows for a relatively long time?	**H3**	**H3**

†Rankings: H1 (High priority 1) is the highest priority knowledge-need down to H3 (High priority 3) which is the lowest priority of the 'highs'.

The remaining knowledge-needs, ranked as 'medium' or 'low' priority in the initial screening, are shown in Table 9.2. These were not ranked against scientific merit or management needs.

Table 9.2. Identified medium and low priority knowledge needs.

Knowledge Needs	Priority
Is fisheries catch data accurate enough to use when trying to determine a change in fisheries production due to flows: • what are the implications/effects of fisheries management (e.g. restrictions, changes in methods over time, etc.) on using fisheries catch data? • is fisheries data flawed as it is usually not validated, and • what are the implications/effects of using low resolution fisheries data that is difficult to specifically link to a particular river/estuary?	**Medium**
What methods can be used to measure important water levels (e.g. satellite imagery of fluctuations in water level, distribution of wetted habitat areas, degree of connectivity)?	**Medium**
Can existing estuarine flow models be adapted for use in other estuaries?	**Medium**
What are the movement and migration requirements of key species occurring in estuaries with different types of flow regime in different parts of Australia?	**Medium**
What are the 'key' species of an estuary and can we develop recruitment models for them that can be applied to different estuaries with different flow regimes?	**Medium**

Knowledge Needs	Priority
What are the habitat requirements of estuarine biota?	**Medium**
What are the spawning cues and nursery habitat requirements of estuarine biota?	**Medium**
What are the factors driving recruitment patterns of estuarine biota?	**Medium**
Need knowledge of the basic biology, life cycle and ecology of a species to determine what mechanism is responsible for an observed change in numbers in relation altered flow.	**Medium**
Are relationships reported between catch and freshwater flows confounded by: • fishing effort/pressure, • spawning stock size, • non-linear links/multiple links, • type I errors, • lack of the ability to prove causality, and • uncertainty of predictive capabilities due to climate change and human pressures.	**Medium**
Research needed into time-lagged effects, which may better indicate 'real' changes resulting from flows?	**Medium**
Need a model that accurately and reliably predicts the relationship between flow variability and habitat.	**Medium**
Can the study of representative species from an estuary provide a template for managing environmental flows for other estuaries of the same estuary type nationally/regionally, within the same seasonal river flow regime zone?	**Medium**
What are the water quality tolerances (e.g. turbidity, nutrients, salinity, pH, temperature) of estuarine biota?	**Medium**
Are existing hydrodynamic models sensitive enough to be able to model the implications of change in flow regime in terms of important estuarine features (e.g. fluctuations in water level, distribution of wetted habitat areas, degree of connectivity among habitat patches, etc).	**Low**
What are the impacts of toxicants on invertebrates and other biota during low flow periods when the dilution factor is reduced?	**Low**
Can estuaries be classified according to their biotic similarities?	**Low**
What is the species composition, diversity and community structure of estuarine flora and fauna, including waterbirds?	**Low**
What are the basic life histories of estuarine biota likely to be impacted by altered freshwater inflows?	**Low**
What are the natural and altered estuarine inflows and hydrodynamics, as revealed by historical and current gauging station data?	**Low**
What flow factors affect waterbirds and what are the impacts of altering flows on waterbirds?	**Low**
How do flows impact on food availability for waders?	**Low**
What are the impacts of cold water releases from impoundments on estuaries?	**Low**

Knowledge Needs	Priority
How do saltmarshes respond to the physical variables that change as a result of altered flows and what are the flow-on effects on other species associated with saltmarshes if there was a change to inundation or saltmarsh habitat?	Low
Need a model of estuarine hydrodynamics, freshwater and tidal currents and pattern, and sediment movement that accurately and reliably predict the possibility of river mouth opening/closure.	Low
Where, or in what type of estuaries, can generalisations be made regarding their functioning?	Low
What are the movement patterns and migration requirements of estuarine biota?	Low
What are the impacts on mangroves of changes to nutrients and dissolved oxygen as a result of altered flow?	Low
What are the impacts of flow on marine farming activities?	Low
How does birdlife use the estuary habitat, both temporal and spatial variability?	Low
Develop a protocol for assessing fish passage requirements as part of environmental flow studies.	Low
What is the response of mudflat benthos to freshwater?	Low
Develop an appropriate (standardised) technique for ageing tropical estuarine fish.	Low

9.3 Frameworks for organising knowledge needs

Three alternatives were developed during the workshop for grouping the high priority knowledge needs.

The first was based on the conceptual framework developed in this report (Section 4, Figure 4.3) and lists the knowledge needs under the ten themes relating to freshwater flows, abiotic environment and biotic environment (Table 9.3; see Appendix 3).

Table 9.3. High priority knowledge-needs identified as contributing to the themes identified within Section 3, Appendix 3, of this report.

Themes	Associated knowledge-need[†]
Flow needs assessment and evaluation	B, P, E, Q, R, S
Characteristics of freshwater flow regime (inflows) to estuaries	O, K
Influence of freshwater flows on estuarine biota at the community level	A, H, N
Influence of freshwater flows on estuarine biota at the species level	J, I

Influence of freshwater flows on estuarine hydrodynamics and geomorphology	L
Influence of freshwater flows on estuarine water quality and biogeochemistry	M
Transferability of knowledge to other estuaries	C
Influence of freshwater flows on estuarine values	D, F
Basic information of estuarine biota	*No high priority knowledge-needs identified*
Methods for examining flow effects	G

†See Table 9.1 for knowledge-need wording and code.

The second grouping (Table 9.4) shows the alignment of the 'high priority' knowledge-needs with the management themes identified during the workshop. The usefulness of this categorisation is limited by: (i) the absence of a comprehensive list of R&D needs within each management theme; (ii) the coarseness of the management themes; and (iii) the focus on biophysical knowledge-needs. Despite these limitations, the framework does demonstrate the links between the science and management needs.

Table 9.4. High priority knowledge-needs identified as making a major contribution or being essential for each management theme.

Management Theme	**Knowledge-need that (when filled) will contribute to theme†**
Political/Policy a. Development of decision-support processes and systems b. Development of implementation tools	G, F, R
Suitably sensitive models to integrate knowledge of flow regime and effects on ecological and other values that will allow testing of flow scenarios	G, C, E, K,
Access to and application of knowledge and research outcomes to extension and capacity building for managers, government, industry and the community	F, D, G, C, E,
Determination and assessment of flow delivery to achieve desired management outcomes	D, E, A, B, J, H, K, I, L, O, M, N, G, P, S
How to manage environmental flow allocations in the context of other interventions (e.g. entrance management, dredging, global warming, water quality degradation)	D, Q

Values a. What are the valued attributes (including biological, cultural, commercial, recreational, intrinsic) which require protection and are critically dependant on flow b. Decision-makers tool: framework which equitably considers impacts on all values	F, P,
Effect of flow regime (timing, magnitude, frequency, quality, duration) on the structure and function of estuarine ecosystems and other associated values	D, C, A, B, J, H, K, I, L, O, M, N, Q
What institutional coordination, regulatory and governance arrangements are required and at what scale(s)	R, F, C
Understanding the ecosystem and water quality consequences of the interaction of climate change with flow regimes and human responses to climate change under various scenarios	A, B, Q, D, G, J, H, K, I, L, O, M, N

†See Table 9.1 for knowledge-need wording and code.

The third grouping was based around the Adaptive Management Framework of Lawrence and Bennett (2002) which was proposed during the workshop and here modified to be specific to estuary flows (Figure 9.2). There are parts of the framework for which needs have not been specifically identified (Table 9.5). For example, social knowledge-needs were not actively investigated during the consultancy and are underrepresented in this framework.

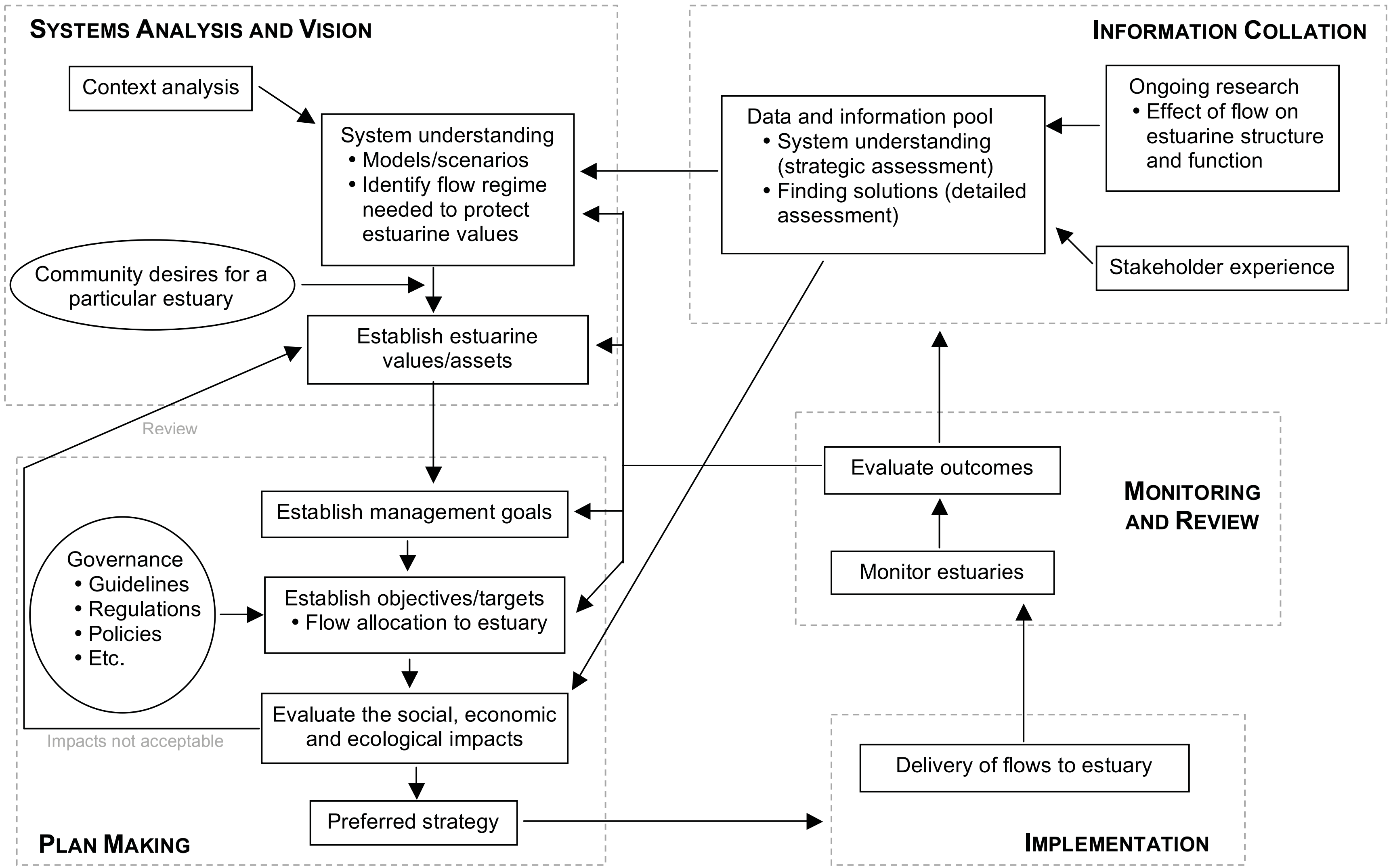

Figure 9.2. Modified Adaptive Management Framework relating to freshwater flows to estuaries (based upon an AMF (Lawrence and Bennett, 2002) with workshop participants and project team modifications specific to estuary flows).

Table 9.5. High priority knowledge-needs identified as making a major contribution to the AMF theme it is listed against.

Adaptive Management Framework Theme	**Knowledge-need that (when filled) will contribute to theme**†
INFORMATION COLLATION	
Data and information pool • System understanding (strategic assessment)	L, M, A, H, N, O, K
Data and information pool • Finding solutions (detailed assessment)	B, P, E, Q, R, S
Ongoing research • Effect of flow on estuarine structure and function	A, H, N, J, I, L, M
Stakeholder experience	*No high priority knowledge-needs identified*
SYSTEMS ANALYSIS AND VISION	
Context analysis	*No high priority knowledge-needs identified*
System understanding • Models/scenarios	G, C, E, K
System understanding • Identify flow regime needed to protect estuarine values	D, E, A, B, J, H, K, I, L, O, M, N, G, P, S
Establish estuarine values/assets	F, P
Community desires for a particular estuary	*No high priority knowledge-needs identified*
PLAN MAKING	
Establish management goals	*No high priority knowledge-needs identified*
Establish objectives/targets • Flow allocation to estuary	G, B, P, E, Q, R, S, D
Evaluate the social, economic and ecological impacts	F
Preferred strategy	*No high priority knowledge-needs identified*
Governance • Guidelines • Regulations • Policies • Etc.	G, F, R

IMPLEMENTATION	
Delivery of flows to estuary	*No high priority knowledge-needs identified*
MONITORING AND REVIEW	
Evaluate outcomes	D, A, B, J, H, K, I, L, O, M, N, G, S
Monitor estuaries	E, P

†See Table 8.1 for knowledge-need wording and code.

9.4 Conclusions

In terms of comprehensiveness, the 19 high-priority knowledge needs provide a good coverage of the core components of a research framework into freshwater flows into estuaries. These needs give a reasonable coverage of the major management themes and a good coverage of the major biophysical components of the modified AMF. However, socio-economic and institutional needs were not assessed (apart from those that arose opportunistically) during this study and the full range of research needs for freshwater flows into estuaries should include these additional issues in order to continue to refine the framework for targeting research investment to meet priority policy and management knowledge needs.

10 References

Adams, J.B., Bate, G.C., Harrison, T.D., Huzinga, P., Taljaard, S., van Niekerk, L., Plumstead, E.E., Whitfield, A.K. and Wolldridge, T.H. 2002. A method to assess the freshwater inflow requirements of estuaries and application to the Mtata Estuary, South Africa. *Estuaries* **25:** 1382-1293.

Alber, M. 2002. A conceptual model of estuarine freshwater inflow management. *Estuaries* **25**:1246-1261.

Alber, M. and Flory, J. 2002. *The Effect of Changing Freshwater Flows to Estuaries: A Georgia Perspective*. Georgia Coastal Research Council; USA.

Aleem, A.A. 1972. Effect of river outflow management on marine life. *Marine Biology* **15**: 200-208.

ANZECC. 2000. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. *Volume 1*, *The Guidelines (Chapters 1-7)*. Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ). Paper Number 4. Department of the Environment and Heritage; Canberra.

Ardisson P.L. and Bougert, E. 1997. A study of the relationship between freshwater runoff and benthos abundance: a scale-oriented approach. *Estuarine*, *Coastal and Shelf Science* **45**: 435-454.

ARMCANZ. 1996. *National Principles for the Provision of Water for Ecosystems*. Sustainable Land and Water Resources Management Committee. Subcommittee on Water Resources. 14 p. Occasional Paper SWR Number 3, July. Agriculture and Resource Management Council of Australia and New Zealand and Australian and New Zealand Environment and Conservation Council.

Armitage, P.D. 1984. Environmental changes induced by stream regulation and their effect on lotic macroinvertebrate communities. In: A. Lillehammer and S.J. Salveit (eds), *Regulated Rivers*. pp. 139-166. Oslo University Press; Olso.

Arthington, A.H. 1998. *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Holistic Methodologies*. LWRRDC Occasional Paper 26/98. Land and Water Resources Research and Development Corporation (LWRRDC); Canberra.

Arthington, A.H. and Pusey, B.J. 2003. Flow restoration and protection in Australian rivers. *River Research and Applications* **19**: 377-395.

Arthington, A.H. and Zalucki, J.M. (eds). 1998a. *Water for the Environment: Recent Approaches to Assessing and Providing Environmental Flows*. 144 p. Proceedings of the Australian Water and Wastewater Association (AWWA) Forum. AWWA; Brisbane.

Arthington, A.H. and Zalucki, J.M. (eds). 1998b. *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods*. (Authors – Arthington, A.H. Brizga, S.O., Pusey, B.J., McCosker, R.O., Bunn, S.E., Loneragan, N., Gowns, I.O. and Yeates, M.) LWRRDC Occasional Paper 27/98.

Arthington, A.H., Balcombe, S.R., Wilson, G.A., Thoms, M.C. and Marshall, J. 2005. Spatial and temporal variation in fish assemblage structure in isolated waterholes during the 2001 dry season of an arid-zone river, Cooper Creek, Australia. *Marine and Freshwater Research* **56**: 25-35.

Arthington, A.H., Brizga, S.O. and Kennard, M.J. 1998a. *Comparative Evaluation of Environmental Flow Assessment Techniques: Best Practice Framework*. 26 p. LWRRDC Occasional Paper 25/98.

Arthington, A.H., Pusey, B.J., Brizga, S.O., McCosker, R.O., Bunn, S.E. and Growns, I.O. 1998b. *Comparative Evaluation of Environmental Flow Assessment Techniques: R&D Requirements*. LWRRDC Occasional Paper 24/98. Land and Water Resources Research and Development Corporation (LWRRDC); Canberra.

Arthington, A.H., Tharme, R.E., Brizga, S.O., Pusey, B.J. and Kennard, M.J. 2004. Environmental flow assessment with emphasis on holistic methodologies. In: R. Welcomme and T. Petr (eds), *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries*. Volume II. Pp. 37-65. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2004/17.

Barton, J. 2003. *Estuarine Health Monitoring and Assessment Review*. State Water Quality Monitoring and Assessment Committee. 92 pp.

Barton, J. and Sherwood, J. 2004. *Estuary Opening Management in Western Victoria: An information analysis*. Parks Victoria Technical Series, Number 15. Parks Victoria; Melbourne.

Battaglene, S.C. and Talbot, R.B. 1993. Effects of salinity and aeration on survival of and initial swim bladder inflation in larval Australian bass. *The Progressive Fish-culturist* **55**: 35-39.

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

Blackwell, B.D. 2005. *The Economic Value of Some of Australia's Natural Coastal Assets: The Value of Their Ecosystem Goods and Services*. Draft Final Report to Coastal CRC. Coastal CRC; Indooroopilly.

Boesch, D.F., Josselyn, M.N., Mehta, A.J., Morris, J.T., Nuttle, W.K., Simenstad, C.A. and Swift, D.J.P. 1994. Scientific Assessment of Coastal Wetland Loss, Restoration and Management in Louisiana. *Journal of Coastal Research: An International Forum for the Littoral Sciences*. Special Issue Number 20. 103 p. Fort Lauderdale; Florida.

Boynton, W.R., Garber, J.H., Summers, R. and Kemp, W.M. 1995. Input, transformations and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. *Estuaries* **18**: 285-314.

Brenchley, J.L. and Probert, R.J. 1998. Seed germination responses to some environmental factors in the seagrass *Zostera capricorni* from eastern Australia. *Aquatic Botany* **62**: 177-188.

Bunn, S.E. and Arthington, A.H. 2002. Basic principles and consequences of altered hydrological regimes for aquatic biodiversity. *Environmental Management* **30**: 492-507.

Byun, D., Wang, X., Hart, D. and Cho, Y. 2005. Modeling the effect of freshwater inflows on the development of spring blooms in an estuarine embayment. *Estuarine*, *Coastal and Shelf Science* **65**: 351-360.

Cappo, M., Alongi, D.M., Williams, D.M. and Duke, N. 1998. A review and synthesis of Australian fisheries habitat research: major threats, issues and gaps in knowledge of coastal and marine fisheries habitats – a prospectus of opportunities for the FRDC. *Ecosystem Protection Program*, *Volume 2: Scoping Review*. Prepared by AIMS for FRDC.

Chan, T.U. and Hamilton, C.P. 2001. Effect of freshwater flow on the succession and biomass of phytoplankton in a seasonal estuary. *Marine Freshwater Research* **52**: 869-884.

Chessman, B. and Jones, H. 2001. *Integrated Monitoring of Environmental Flows: Design Report*. Department of Land and Water Conservation; NSW.

Choi, S., Yoon, B. and Woo, H. 2005. Effects of dam-induced flow regime change on downstream river morphology and vegetation cover in the Hwang River, Korea. *River Research and Applications* **21**: 315-325.

Choy, S.C. and Booth, W.E. 1994. Prolonged inundation and ecological changes in an Avicennia mangrove: implementations for conservation and management. *Hydrobiologia* **285**: 237-247.

Close, P.G. 2005. *Information Requirements and a Recommended Procedure for the Determination of Ecological Water Requirements for the Hill and Moore River Estuaries*. Report CENRM 01/05. 84 pp. Centre of Excellence in Natural Resource Management; University of Western Australia.

Cluett, L.J and Radford, B.T.M. 20035. Downstream morphological change in response to dam construction: a GIS based approach for the Lower Ord River, Western Australia. *Water Science and Technology* **48**: 1-8.

COAG Communiqué. 25 February 1994. Attachment A. http://www.coag.gov.au/meetings/250294/attachment_a.htm

Costanza, R., D'arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R., Sutton, P. and van den Belt, M. 1997. The value of the world's ecosystem services and natural capital. *Nature* May, **387**: 253-260.

Cottingham, P., Hannan, G., Hillman, T., Koehn, J., Metzeling, L., Roberts, J. and Rutherfurd, I. 2001. *Report of the Ovens Scientific Panel on the Environmental Condition and Flows of the Ovens River*. 90 p. Cooperative Research Centre for Freshwater Ecology; Canberra.

Curtis, I. 2004. Valuing ecosystem goods and services; A new approach using surrogate market and the combination of multiple criteria analysis and a Delphi panel to assign weights to the attributes. *Ecological Economics* **50**: 163-194.

Davies, P.E. and Kalish, S.R. 1994. Influence of river hydrology on the dynamics and water quality of the upper Derwent Estuary, Tasmania. *Australian Journal of Marine and Freshwater Research* **45**: 109-30.

de Groot, R., Wilson, M. and Boumans, M. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics* **41**: 393-408.

Douglas, G., Ford, P., Moss, A., Noble, B., Packett, B., Palmer, M., Revill, A., Robson, B., Tillman, P. and Webster, I. 2005. *Carbon and Nutrient Cycling in a Subtropical Estuary (the Fitzroy), Central Queensland.* Technical Report No. 14. 72 pp. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management; Indooroopilly.

Drinkwater, K.F. and Frank, K.T. 1994. Effects of river regulation and diversion on marine fish and invertebrates. *Aquatic Conservation Freshwater and Marine Ecosystems* **4**: 135-151.

Eckman, J.E. and Duggins, D.E. 1993. Effects of flow speed on growth of benthic suspension feeders. *Biological Bulletin* **185**: 28-41.

Estevez, E.D. 2002. Review and assessment of biotic variables and analytical methods used in estuarine inflow studies. *Estuaries* **25**: 1291-1303.

Eyre, B. 1997. Water quality changes in an episodically flushed sub-tropical Australian estuary: a 50 year perspective. *Marine Chemistry* **59**: 177-187.

Fearon, R. 2006. Dead Zones and Australia's Pollution Halo. Article for 2006 State of the Environment Report. In review.

Flint, R.W., Powell, G.L. and Kalke, R.D. 1986. Ecological effects from the balance between new and recycled nitrogen in Texas coastal waters. *Estuaries* **9**: 284-294.

Ford, P.W., Tillman, P., Robson, B. and Webster, I.T. 2005. Organic carbon deliveries and their flow related dynamics in the Fitzroy estuary. *Marine Pollution Bulletin* **51**: 119-127.

Gammelsrød, T. 1992. Variation in shrimp abundance on the Sofala Bank, Mozambique and its relation to the Zambezi River runoff. *Estuarine*, *Coastal and Shelf Science* **35**: 91-103.

Gardner, A. 2005. *Environmental water allocations in Australia*. Paper presented at the Sustainable Water Management International Symposium. 15-16 September 2005.

Gaughan, D.J. and Potter, I.C. 1994. Relative abundance and seasonal changes in the macrozooplankton of the lower Swan Estuary in south-western Australia. *Records of the Western Australian Museum* **16**: 461-474.

Gaughan, D.J. and Potter, I.C. 1995. Composition, distribution and seasonal abundance of zooplankton in a shallow, seasonally closed estuary in temperate Australia. *Estuarine and Coastal Shelf Science* **41**: 117-135.

Gillanders, B.M. and Kingsford, M.J. 2002. Impacts of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanography and Marine Biology: an Annual Review* **40**: 233-309.

Gippel, C.J. 2001. Australia's environmental flow Initiative: filling some knowledge gaps and exposing others. *Water Science and Technology* **43**: 73-88.

Glaister, J.P. 1978. The impact of river discharge on distribution and production of the school prawn *Metapenaeus macleayi* (Haswell) (Crustacea: Penaeidae) in the Clarence River region, northern New South Wales. *Australian Journal of Marine and Freshwater Research* **29**: 311-323.

Goss, K.F. 2003. Environmental flows, river salinity and biodiversity conservation: managing trade off in the Murray-Darling Basin. *Australian Journal of Botany* **51**: 619-625.

Grange, N., Whitfield, A.K., De Villiers, C.J. and Allanson, B.R. 2000. The response of two South African east coast estuaries to altered river flow regimes. *Aquatic Conservation: Marine and Freshwater Ecosystems* **10**: 155-177.

Growns, I.O. and Growns, J.E. 2001. Ecological effects of flow regulation on macroinvertebrate and periphytic diatom assemblages in the Hawkesbury-Nepean River, Australia. *Regulated Rivers: Research and Management* **17**: 275-293.

Growns, I. and James, M. 2005. Relationships between river flows and recreational catches of Australian bass. *Journal of Fish Biology* **66**: 404-416.

Hallegraeff, G.M., McCausland, M.A. and Brown, R.K. 1995. Early warning of toic dinoflagellate blooms of *Gymnodinium catenatum* in southern Tasmanian waters. *Journal of Plankton Research* **17**: 1163-1176.

Halliday, I.A., Robins, J.B., Sale, B. and Marsh, R.W. 2005. *Freshwater Flow Requirements of Estuarine Fisheries: Data Review and Research Needs*. 41 p. LWA Tropical Rivers Program. QI05099 Project Report Series. Queensland Department of Primary Industries and Fisheries, and Land and Water Australia; Australia.

Hamilton, S.K. and Gehrke, P.C. 2005. Australia's tropical river systems; current understanding and critical knowledge gaps for sustainable management. *Marine and Freshwater Research* **56**: 243-252.

Harding, L.W. 1994. Long-term trends in the distribution of phytoplankton in Chesapeake Bay roles of light, nutrients and streamflow. *Marine Ecology Progress Series* **104**: 267-291.

Harris, P.T., Heap, A.D., Bryce, S.M. Porter-Smith, R., Ryan, D.A. and Heggie, D.T. 2002. Classification of Australian Coastal depositional environments based upon a quantitative analysis of wave, tidal and fluvial power. *Journal of Sedimentary Research* **72 (6),** 858-870.

Hart, D.D. and Finelli, C.M. 1999. Physical-biological coupling in streams: the pervasive effects of flow on benthic organisms. *Annual Review of Ecology and Systematics* **30**: 363-395.

Heap, A., Bryce, S., Ryan, D., Radke, L., Harris, P. and Heggie, D. 2001. An inventory of ecological habitats in Australia's estuaries and coastal waterways: a geoscience perspective. In: A. Calladine and M. Waycott (ed.), *Australian Marine Sciences Association and the New Zealand Marine Sciences Society Journal*, 3-6 July, p. 131. James Cook University; Townsville, Qld.

Hoedt, F.E. and Dimmlich, W.F. 1995. Egg and larval abundance and spawning localities of the anchovy (*Engraulis australis*) and pilchard (*Sardinops neopilchardus*) near Phillip Island, Victoria. *Australian Journal of Marine and Freshwater Research* **46**: 735-743.

IGA-NWI. 2004. Intergovernmental Agreement on a National Water Initiative Commonwealth of Australia and the Governments of New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory.

Irlandi, E., Orlando, B., Maciá, S., Biber, P., Jones, T., Kaufman, L., Lirman, D. and Patterson, E.T. 2001. The influence of freshwater runoff on biomass, morphometrics, and production of Thalassia testudinum. *Aquatic Botany* **72**: 67-68.

Jordan, T.E., Correll, D.L., Miklas, J. and Weller, D.E. 1991. Long-term trends in estuarine nutrients and chlorophyll, and short-term effects of variation in watershed discharge. *Marine Ecology Progress Series* **75**:121-132.

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

Lamontagne, S., McEwan, K., Webster, I., Ford, P., Leaney, F. and Walker, G. 2004. *Coorong*, *Lower Lakes and Murray Mouth*. *Knowledge Gaps and Knowledge Needs for Delivering Better Ecological Outcomes*. Water for a Healthy Country National Research Flagship CSIRO; Canberra.

Lawrence, P. and Bennett, J. 2002. The adaptive management framework for coastal environments. *Water* **29**: 19-22.

Loneragan, N.R. and Bunn, S.E. 1999. River flows and estuarine ecosystems: implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. *Australian Journal of Ecology* **24**: 431-440.

Mallin, M.A., Paerl, H.W., Rudek, J. and Bates, P.W. 1993. Regulation of estuarine primary production by watershed rainfall and river flow. *Marine Ecology Progress Series* **93**: 199-203.

Malone, T.C., Crocker, L.H., Pike, S.E. and Wendler, B.W. 1988. Influences of river flow on the dynamics of phytoplankton production in a partially stratified estuary. *Marine Ecology Progress Series* **48**: 235-249.

Mawhinney, M.A. 2003. Restoring biodiversity in the Gwydir Wetlands through environmental flows. *Water Science and Technology* **48**: 73-81.

McKinnon, A.D. and Klumpp, D.W. 1998. Mangrove zooplankton of North Queensland, Australia. I. Plankton community structure and environment. *Hydrobiologia* **362**: 127-143.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being; Synthesis*. Island Press; Washington D.C. (World Resources Institute). Also available as at 16/8/05 from: http://www.millenniumassessment.org/en/products.asp

Montagna, P.A. and Kalke, R.D. 1992. The effect of freshwater inflow on meiofaunal and macrofaunal populations in the Guadalupe and Nueces estuaries, Texas. *Estuaries* **15**: 307-326.

NWQMS. 2000. *National Water Quality Management Strategy; Number 4: Australian and New Zealand Guidelines for fresh and marine water quality*. *Volume 1*, *The guidelines*. Australian and New Zealand Environment and Conservation Council, Agricultural and Resource Management Council of Australian and New Zealand.

Nixon, S.W. 1992. Quantifying the relationship between nitrogen input and the productivity of marine ecosystems. *Proceedings Advances in Marine Technology Conference* **5**:57-83.

OzEstuaries. 2006. www.ozestuaries.org

Pearson, B. 1994. Rivers - Ecological Implication of Water Board Activities. Nature Conservation Council of NSW: Sydney, NSW.

Peirson, W.L., Bishop, K., Van Senden, D., Horton, P.R. and Adamantidis, C.A. 2002. *Environmental Water Requirements to Maintain Estuarine Processes*. 147 p. Environmental Flows Initiative Technical Report Number 3. Commonwealth of Australia; Canberra.

Pitt, K.A. and Kingsford, M.J. 2003. Temporal and spatial variation in recruitment and growth of medusae of the jellyfish *Catostylus mosaicus* (Schyphozoa: Rhizostomae). *Marine and Freshwater Research* **54**: 117-125.

Platten, J.R. 1996. *The Influence of River Freshwater Discharge on Fishery Catch Rates in Queensland Waters*. EPA; Queensland.

Platten, J.R. 2000. *The Relationship Between Fishery Catch Rates and River Flow – Pioneer Valley*. EPA; Queensland.

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

Pollard, D.A. and Hannan, J.C. 1994. The ecological effects of structural flood mitigation works on fish habitats and fish communities in the lower Clarence River system of southeastern Australia. *Estuaries* **17**: 427-461.

Radke, L.C. 2002. *Water allocation and critical flows: potential ionic impacts on estuarine organisms*. Proceedings of Coast to Coast 2002 – 'Source to Sea', Tweed Heads. pp. 367-370.

Ravenscroft, N.O.M. and Beardall, C.H. 2003. The importance of freshwater flows over estuarine mudflats for wintering waders and wildfowl. *Biological Conservation* **113**: 89-97.

Reid, M.A. and Brooks, J.J. 2000. Detecting effects of environmental water allocations in wetlands of the Murray-Darling Basin, Australia. *Regulated Rivers: Research and* Management **16**: 479-496.

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

Robins, J., Mayer, D., Staunton-Smith, J., Halliday, I., Sawynok, B. and Sellin, M. 2006. Variable growth rates of a tropical estuarine fish species (barramundi, *Lates calcarifer* Bloch) under different freshwater flow conditions. *Journal of Fish Biology* (in press).

Robinson, J. and Clouston, B. n.d. *The Ecosystem Goods and Services Provided by Wetland Areas and Approaches to Modelling*, *Evaluation and Estimating Their Value*. Draft unpublished paper prepared for the Coastal CRC, Indooroopilly.

Robson, B.J. and Hamilton, D.P. 2003. Summer flow event induces a cyanobacterial bloom in a seasonal Western Australian estuary. *Marine and Freshwater Research* **54**: 139-151.

Rozas, L.P., Minello, T.J., Munuera-Fernandez, I., Fry, B. and Wissel, B. 2005. Macrofaunal distributions and habitat change following winter-spring releases of freshwater into the Breton Sound estuary, Louisiana (USA). *Estuarine*, *Coastal and Shelf Science* **65**: 319-336.

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

Ryan, D.A., Heap, A.D., Radke, L. and Heggie, D.T. 2003. *Conceptual Models of Australia's Estuaries and Coastal Waterways: Applications for Coastal Resource Management.* Geoscience Australia. Record 2003/09. 136 pp. Canberra, Australia.

SCA. 2000. *Final Report - Experimental Environmental Flow Strategy*. Sydney Catchment Authority Contract 14849. Australian Museum Business Services. 304 p.

Scharler, U.M. and Baird, D. 2000. The effects of a single freshwater release into the Kromme Estuary. 1: general description of the study area and physico-chemical responses. *Water SA* **26**: 291-300.

Scheltinga, D.M. and Heydon, L. 2005. *Report on the Condition of Estuarine*, *Coastal and Marine Resources of the Burdekin Dry Tropics Region*. 230 p. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management; Indooroopilly.

Schofield, N. and Burt, A. 2003. Issues in environmental water allocation – an Australian perspective. *Water Science and Technology* **48**: 83-88.

Schofield, N., Burt, A. and Connell, D. 2003. *Environmental water allocation: principles*, *policies and practices*. Product Number PR030541. Land and Water Australia; Canberra.

SKM. 2002. *The Flows Method*. *A method for determining environmental water requirements in Victoria*. The State of Victoria, Department of Natural Resources and Environment, February 2002.

Staples, D.J. and Vance, D.J. 1986. Emigration of juvenile banana prawns *Penaeus merguiensis* from a mangrove estuary and recruitment to offshore areas in the wet-dry tropics of the Gulf of Carpentaria, Australia. *Marine Ecology Progress Series* **27**: 239-252.

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

Sutcliffe, W.H., Loucks, R.H., Drinkwater, R.H. and Coote, A.R. 1983. Nutrient flux and its biological consequences. *Canadian Journal of Fisheries and Aquatic Sciences* **40**: 1692-1701.

Taw, N. and Ritz, D.A. 1978. Zooplankton distribution in relation to the hydrology of the Derwent River estuary. *Australian Journal of Marine and Freshwater Research* **29**: 763-775.

Tharme, R.E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19**: 397-441.

Thompson, P.A. 2001. Temporal variability of phytoplankton in a salt wedge estuary, the Swan River, Western Australia. *Hydrological Processes* **15**: 2617-2630.

Turner, R.E. 1992. Coastal wetlands and penaeid shrimp habitat. In: R.H. Stroud (ed.), *Marine Recreational Fisheries* 14. pp. 97-104. National Coalition for Marine Conservation; Savannah.

Vance, D.J., Haywood, M.D.E., Heales, D.S., Kenyon, R.A. and Loneragan, N.R. 1998. Seasonal and annual variation in abundance of postlarval and juvenile banana prawns *Penaeus merguiensis* and environmental variation in two estuaries in tropical northeastern Australia: a six year study. *Marine Ecology Progress Series* **163**: 21-36.

Vance, D.J., Staples, D.J. and Kerr, J.D. 1985. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguiensis*) in the Gulf of Carpentaria, Australia. *Journal du Conseil International pour l'Exploration de la Mer* **42**: 83-97.

Vörösmarty, C.J. and Sahagian, D. 2000. Anthropogenic disturbance of the terrestrial water cycle. *BioScience* **50**: 753-765.

Walker, S., Sporic, M. and Coutin, P. 1998. *Development of an Environment-Recruitment Model for Black Bream: a Case Study for Estuarine Fisheries Management*. 74 p. Project 96/102. Marine and Freshwater Resources Institute; Victoria.

Webster, I.T., Parslow, J.S., Grayson, R.B., Molloy, R.P., Andrewartha, J., Sakov, P., Seong Tan, K., Walker S.J. and Wallace, B.B. 2001. *Gippsland Lakes Environmental Study Assessing Options for Improving Water Quality and Ecological Function*. 83 p. CSIRO; Glen Osmond.

Webster, I.T, Ford, P.W., Robson, B., Margvelashvili, N. and Parslow, J. 2003. *Conceptual Models of the Hydrodynamics, Fine Sediment Dynamics, Biogeochemistry and Primary Production in the Fitzroy Estuary*. Technical Report No. 8. 43 pp. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management; Indooroopilly.

Wilson, M.A., Costanza, R., Boumans, R. and Liu, S. 2002. Integrated assessment and valuation of ecosystem goods and services provided by coastal systems. Draft under review in Proceedings of the Royal Irish Academy, Dublin. http://www.pugetsound.org/pdf/tourism/2002_coastal_services.pdf

Wortmann, J., Hearne, J.W. and Adams, J.B. 1998. Evaluating the effects of freshwater inflow on the distribution of estuarine macrophytes. *Ecological Modelling* **106**: 213-232.

Young W.J. (ed.) 2001. *Rivers as Ecological Systems: The Murray Darling Basin*. Murray Darling Basin Commission, Canberra.

Zann, L. 1996. The coastal zone: an introduction. In: *State of the Marine Environment Report for Australia*. pp. 2-8. Department of the Environment, Sport and Territories; Canberra.

11 Further Reading

Adams, J.B. and Talbot, M.M.B. 1992. The influence of river impoundment on the estuarine seagrass *Zostera capensis* Setchell. *Botanica Marina* **35**: 69-75.

Adams, J.B., Knoop, W.T. and Bate, G.C. 1992. The distribution of estuarine macrophytes in relation to freshwater. *Botanica Marina* **35**: 215-226.

Alongi, D.M. 1990. Ecology of tropical soft - bottom benthic ecosystems. *Oceanography and Marine Biology: an Annual Review* **28**: 381-496.

Anonymous. 2005. *Draft Environmental Flow Guidelines*. Australian Capital Territory, Canberra

Anonymous. 2002. *Integrated Monitoring of Environmental Flows*. *An Overview*. Department of Land and Water Conservation; NSW.

Anonymous. 2002. No 10. Freshwater flows to estuaries and coastal waters. In: *Advice to Water Management Committees*. 5 p. Department of Land and Water Conservation; NSW.

Arthington, A.H., Rall, J.L., Kennard, M.J., Pusey, B.J. 2003. Environmental flow requirements of fish in Lesotho Rivers using the drift methodology. *River Research and Applications* **19**: 641-666.

Arthington, A.H. and Long, G.C. 1996. *Trial of the South African Building Block Methodology for Defining the Instream Flow Requirements (IFR) of the Logan River System, Southeastern Queensland, Australia*. Centre for Catchment and In-stream Research; Griffith University, Brisbane, and Department Natural Resources; Brisbane.

Arthington, A.H., Brizga, S.O., Choy, S.C., Kennard, M.J., Mackay, S.J., McCosker, R.O., Ruffini, J.L. and Zalucki, J.M. 2000. *Environmental Flow Requirements of the Brisbane River Downsteam from Wivenhoe Dam*. 539 pp. South East Queensland Water Corporation Ltd and Centre for Catchment and In-Stream Research, Griffith University, Brisbane.

Arthington, A.H., Brizga, S.O., Choy, S.C., Mackay, S.J., Pusey, B.J. and Werren, G.L. 2001. *Current Environmental Conditions and Impacts of Existing Water Resource Development. Estuarine and Marine Ecosystems*. Pioneer Valley Water Resource Plan, Appendix J. 50 pp. Queensland Government (Department Natural Resources and Mines).

Arthington, A.H. and Lloyd, R. (eds) 1998. *Logan River Trial of the Building Block Methodology for Assessing Environmental Flow Requirements: Workshop Report*. Centre for Catchment and In-Stream Research and Department Natural Resources; Brisbane.

Arthington A.H., Lorenzen K., Pusey B.J., Abell R., Halls, A., Winemiller K.O., Arrington D.A. and Baran, E. 2004. River fisheries: ecological basis for management and conservation. In: R. Welcomme and T. Petr (eds), *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries Volume I*. pp. 21-60. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2004/16.

Arthington, A.H. and Pusey, B.J. 1993. In-stream flow management in Australia: methods, deficiencies and future directions. *Australian Biologist* **6**: 52-60.

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

Bao, Y. and Mays, L.W. 1994. New methodology for optimization of freshwater inflows to estuaries. *Journal of Water Resources Planning and Management* **120**: 199-217.

Bao, Y. and Mays, L.W. 1994. Optimization of freshwater inflows to Lavaca-Tres Palacios, Texas, estuary. *Journal of Water Resources Planning and Management* **120**: 218-236.

Beckmann, M.C., Scholl, F. and Mattaei, C.D. 2005. Effects of increased flow in the main stem of the River Rhine on the invertebrate community of its tributaries. *Freshwater Biology* **50**: 10-24.

Beneti, A.D., Lanna, A.E. and Cobalchini, M.S. 2004. Current practices for establishing environmental flows in Brazil. *River Research and Applications* **20**: 427-444.

Benke, A.C., Chaubey, I., Ward, G.M. and Dunn, E.L. 2000. Flood pulse dynamics of an unregulated river floodplain in the southeastern U.S. coastal plain. *Ecology* **81**: 2730-2741.

Benson, N.G. 1981. The freshwater-inflow-to-estuaries issue. *Fisheries* **6**: 8-10.

Bernacsek, G. 2000. *Capacity and Information Base Requirements for Effective Management and Sustainable Development of Fish Biodiversity*, *Fish Stocks and Fisheries Threatened or Affected by Dams During the Project Cycle*. Word Commission on Dams Secretariat; South Africa.

Bishop, K.A. and Bell, J.D. 1978. Observations on the fish fauna below Tallowa dam (Shoalhaven River, New South Wales) during river flow stoppages. *Australian Journal of Marine and Freshwater Research* **29**: 543-549.

Bishop, K.A. and Peirson, W.L. 2005. A national approach for assessing the ecological implications of changing freshwater inflows to Australian estuaries: a process based on processes. In: *Proceedings of the National Symposium on Ecosystem Research and Management of Fisheries*. Symposium held in Adelaide, September 2004. Joint publication by ASFB and SARDI Aquatic Research.

Blaber, S.J.M, Brewer, D.T. and Salini, J.P. 1995. Fish Communities and the Nursery Role of the Shallow Inshore Waters of a Tropical Bay in the Gulf of Carpentaria, Australia. *Estuarine*, *Coastal and Shelf Science* **40**: 177-193.

Blaber, S.J.M. and Blaber, T.G. 1980. Factors affecting the distribution of juvenile estuarine and inshore fish. *Journal of Fish Biology* **17**: 143-162.

Board, G.A.W. 1996. *Environmental Flow Requirements Boyne River Downstream of Awoonga Dam*. Department of Natural Resources; Queensland.

Bourman, R.P. and Barnett, E.J. 1995. Impacts of river regulation on the terminal lakes and mouth of the River Murray, South Australia. *Australian Geographical Studies* **33**: 101-115

Brizga, S.O. 1998. Methods addressing flow requirements for geomorphological purposes. In: A.H. Arthington and J.M. Zalucki (eds), *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods*. pp. 8-46. Land and Water Resources Research and Development Corporation; Canberra.

Brock, M.A., Smith, R.G.B. and Jarman, P.J. 1999. Drain it, dam it: alteration of water regime in shallow wetlands on the New England tableland of New South Wales Australia. *Wetlands Ecology and Management* **7**: 37-46.

Brook, I.M. 1982. The effect of freshwater canal discharge on the stability of two seagrass benthic communities in Biscayne National Park, Florida. *Oceanologica Acta* **4**: 63-72.

Browder, J.A. 1985. Relationship between pink shrimp production on the Tortugas grounds and water flow patterns in the Florida everglades. *Bulletin of Marine Science* **37**: 839-856.

Bunn, S.E., Loneragan, N.R. and Yeates, M. 1998. The influence of river flows on coastal fisheries. In: A.H. Arthington and J.M. Zalucki (eds), *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods*. pp. 106-114. Land and Water Resources Research and Development Corporation; Canberra.

Cain, G.A. 1979. *Tidal and Freshwater Influx Investigations and Simulations in the Brisbane Estuary*. Central Queensland University; Queensland.

Campbell, I.C. (ed.). 1986. *Stream Protection The Management of Rivers for Instream Uses*. 249 p. Water Studies Centre; East Caulfield, Australia.

Carriquiry, J.D. and Sanchez, A. 1999. Sedimentation in the Colorado River delta and upper Gulf of California after nearly a century of discharge loss. *Marine Geology* **158**: 125-145.

Collings, G.J. and Cheshire, A.C. 1998. Composition of subtidal macroalgal communities of the lower Gulf waters of South Australia, with reference to water movement and geographical separation. *Australian Journal of Botany* **46**: 657-669.

Copeland, B.J. 1966. Effects of decreased river flow on estuarine ecology. *Journal of Water Pollution Control Federation* **38**: 1831-1839.

Curtin, T.B. 1986a. Physical observations in the plume region of the Amazon River during peak. II. Water masses. *Continental Shelf Research* **6**: 53-71.

Curtin, T.B. 1986b. Physical observations in the plume region of the Amazon River during peak. III. Currents. *Continental Shelf Research* **6**: 73-86.

Cyrus, D.P. 1988. Episodic events and estuaries: effects of cyclonic flushing on benthic fauna and diet of *Solea bleekeri* (Teleostei) in Lake St Lucia on the south-eastern coast of Africa. *Journal of Fish Biology* **33**: 1-7.

Dauvin, J.-C., Thiebaut, E. and Wang, Z .1998. Short-term changes in the mesozooplanktonic community in the Seine ROFI (Region of Freshwater Influence) (eastern English Channel). *Journal of Plankton Research* **20**: 1145-1167.

Davies, P.E., Warfe, D., Parslow, J. and Telfer, D. 2002. *Environmental Flows for the Lower Derwent River*. 75 pp. Final Report to the DPIWE.

Davis, J.A., Froend, R.H., Hamilton, D.P., Horwitz, P., McComb, A.J., Oldham, C.E. and Thomas, D. 2001. Environmental Water Requirements to Maintain Wetlands of National and International Importance. Environmental Flows Initiative Technical Report Number 1, Commonwealth of Australia, Canberra.

Davis, R. and Hirji, R. 2003a. Environmental flows: concepts and methods. *Water Resources and Environmental Technical Note C1*. The World Bank; Washington DC.

Davis, R. and Hirji, R. 2003b. Environmental flows: case studies. *Water Resources and Environmental Technical Note C2*. The World Bank; Washington DC.

Davis, R. and Hirji, R. 2003c. Environmental flows: flood flows. *Water Resources and Environmental Technical Note C3*. The World Bank; Washington DC.

Day, J.W., Madden, C.J., Twilley, R.R., Shaw, R.F., McKee, B.A., Dagg, M.J., Childers, D.L., Raynie, R.C. and Rouse, L.J. 1994. The influence of Atchafalaya River discharge on Fourleague Bay, Louisiana (USA). In: K.R. Dyer and R.J. Orth (eds), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Proceedings of ECSA22/ERF Symposium. Institute of Marine Studies, University of Plymouth. pp. 151-160. Olsen & Olsen; Fredensborg.

Deeley, D.M. and Paling, E.I. 1999. *Assessing the Ecological Health of Estuaries in Australia*. Land and Water Resources Research and Development Corporation; Canberra.

Deen, A. and Ragavan, R. 2002. Environmental flow investigations of the Hawkesbury-Nepean Rivers, NSW, Australia. In: *Environmental Flows 2002*. 4th Ecohydraulics Conference, South Africa. pp. 50. March 2002.

de Groot, R. 1992. Functions of Nature: Evaluation of Nature in Environmental Planning, Management and Decision Making. Wolters-Noordhoff; Netherlands.

Drinkwater, K.F. 1986. On the role of freshwater outflow on coastal marine ecosystems - a workshop summary. In: S. Skreslet (ed.), *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. pp. 429-438. Proceedings of the NATO Advanced Research Workshop, 21-25 May 1985, Boho, Norway. Springer-Verlag, and NATO Scientific Affairs Division; Berlin.

Drinkwater, K.F. and Myers, R.A. 1987. Testing predictions of marine fish and shellfish landings from environmental variables. *Canadian Journal of Fisheries and Aquatic Science* **44**: 1568-1573.

Drinkwater, K.F., Harding, G.C., Vass, W.P. and Gauther, D. 1991. The relationship of Quebec lobster landings to freshwater runoff and wind storms. In: J.-C. Therriault (ed.). *The Gulf of St. Lawrence: small ocean or big estuary?* pp. 179-187. Department of Fisheries and Oceans (Canadian Special Publications of Fisheries and Aquatic Sciences **113**).

Driver, P.D., Harris, J.H., Closs, G.P. and Koen, T.B. 2005. Effects of flow regulation on carp (*Cyprinos carpio* L.) recruitment in the Murray-Darling Basin, Australia. *River Research and Applications* **21**: 327-335.

DPIWE. 2002. *The Tasmanian Natural Resources Framework*. 35 p. The Department of Primary Industries, Water and Environment; Tasmania.

Dyer, K.R. and Orth, R.J. (eds). 1994. *Changes in Fluxes in Estuaries: Implications from Science to Management*. Proceedings of ECSA22/ERF Symposium. 484 p. Institute of Marine Studies, University of Plymouth. Olsen & Olsen; Fredensborg.

Dyson, M., Bergkamp, G. and Scanlon, J. (eds). *Flow: The Essentials of Environmental Flows.* pp. 11-28. IUCN (The World Conservation Union); Switzerland & U.K. 118 pp.

Eckman, J.E. and Duggins, D.O. 1993. Effects of flow speed on growth of benthic suspension feeders. *Biological Bulletin* **185**: 28-41.

Flannery, M.S., Peebles, E.B. and Montgomery, R.T. 2002. A percent-of-flow approach for managing reductions of freshwater inflows from unimpounded rivers to Southwest Florida Estuaries. *Estuaries* **25**: 1318-1332.

Funicelli, N.A. 1984. Assessing and managing effects of reduced freshwater inflow to two Texas estuaries. In: V.S. Kennedy (ed.), *The Estuary as a Filter*. pp. 435-446. Academic Press; Orlando.

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

Gammelsrød, T. 1996. Effect of Zambezi River management on the prawn fishery of the Sofala Bank. In: M.C. Acreman and G.E. Hollis (eds), *Water Management and Wetlands in Sub-Saharan Africa*. pp. 119-123. IUCN; Switzerland.

Gandolfi, C., Guariso, G. and Togni, D. 1997. Optimal flow allocation in the Zambezi River system. *Water Resources Management* **11**: 377-393.

Garvine, R.W. 1986. The role of blackish plumes in open shelf waters. In: S. Skreslet (ed.), *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. pp. 47-66. Proceedings of the NATO Advanced Research Workshop, 21-25 May 1985, Boho, Norway. Springer-Verlag, and NATO Scientific Affairs Division; Berlin.

Geddes, M.C. 2005. *Ecological outcomes for the Murray Mouth and Coorong from the managed barrage release of September-October 2003*. Report prepared for the Department of Water, Land and Biodiversity Conservation. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Aquatic Sciences Publication Number RD03/0199-2.

Gehrke, P.C. and Harris, J.H. 2001. Regional-Scale Effects of Flow Regulation on Lowland Riverine Fish Communities in New South Wales, Australia. *Regulated Rivers: Research and Management* **17**: 369-391.

Gehrke, P.C., Astles, K.L. and Harris, J.H. 1999. Within-catchment effects of flow alteration on fish assemblages in the Hawkesbury-Nepean River system, Australia. *Regulated Rivers: Research and Management* **15**: 181-198.

Gehrke, P.C., Brown, P., Schiller, C.B., Moffat, D.B. and Bruce, A.M. 1995. River regulation and fish communities in the Murray-Darling River system, Australia. *Regulated Rivers: Research and Management* **11**: 363-375.

Gippel, C. 2001. Hydrological analyses for environmental flow assessment. In: *Proceedings of MODSIM 2001*. pp. 873-880.

Gobler, C.J., Cullison, L.A., Koch, F., Harder, T.M. and Krause, J.W. 2005. Influence of freshwater flow, ocean exchange, and seasonal cycles on phytoplankton – nutrient dynamics in a temporarily open estuary. *Estuarine*, *Coastal and Shelf Science* **65**: 275-288.

Goodbody, I. 1961. Mass mortality of a marine fauna following tropical rains. *Ecology* **42**: 150-155.

Gosper, D.G., Briggs, S.V. and Carpenter, S.M. 1983. Waterbird dynamics in the Richmond valley, New South Wales, 1974-77. *Australian Wildlife Research* **10**: 319-327.

Govoni, J.J. 1997. The association of the population recruitment of gulf menhaden, *Brevoortia patronus*, with Mississippi River discharge. *Journal of Marine Systems* **12**: 101-108.

Govoni, J.J. and Grimes, C.B. 1992. Surface accumulation of larval fishes by hydrodynamic convergence within the Mississippi River plume front. *Continental Shelf Research* **12**: 1265-1276.

Govoni, J.J., Hoss, D.E. and Colby, D.R. 1989. The spatial distribution of larval fishes about the Mississippi River plume. *Limnology and Oceanography* **34**: 178-187.

Grange, N. and Allanson, B.R. 1995. The influence of freshwater inflow on the nature, amount and distribution of seston in estuaries of the Eastern Cape, South Africa. *Estuarine*, *Coastal and Shelf Science* **40**: 403-420.

Grimes, C.B. and Kingsford, M.J. 1996. How do riverine plumes of different sizes influence fish larvae: do they enhance recruitment? *Marine and Freshwater Research* **47**: 191-208.

Grimes, C.B. and Finucane, J.H. 1991. Spatial distribution and abundance of larval and juvenile fish, chlorophyll and macrozooplankton around the Mississippi River discharge plume, and the role of the plume in fish recruitment. *Marine Ecology Progress Series* **75**: 109-119.

Gunter, G. 1961. Some relations of estuarine organisms to salinity. *Limnology and Oceanography* **6**: 182-190.

Gunter, G. and Hildebrand, H.H. 1954. The relation of total rainfall of the state and catch of the marine shrimp (*Penaeus setiferus*) in Texas waters. *Bulletin of Marine Science of the Gulf and Caribbean* **4**: 95-103.

Hannan, J.C. and Wlliams, R.J, 1998. Recruitment of juvenile marine fishes to seagrass habitat in a temperate Australian estuary. *Estuaries* **21**: 29-51.

Harman, C. and Stewardson, M. 2005. Optimizing dam release rules to meet environmental flow targets. *River Research and Applications* **21**: 113-129.

Harpman, D.A., Sparling, E.W. and Waddle, T.J. 1993. A methodology for quantifying and valuing the impacts of flow changes on a fishery. *Water Resources Research* **29**: 575-582.

Harris, J.H. 1984. Impoundment of coastal drainages of south-eastern Australia, and a review of its relevance to fish migrations. *Australian Zoologist* **21**: 235-250.

Harris, J.H. and Gehrke, P.C. 1994. Modelling the relationship between streamflow and population recruitment to manage freshwater fisheries. *Australian Fisheries* **6**: 28-30.

Hayball, N. unknown. Ensuring environmental flows for wetlands through Wetland Water Licences. Department of Water, Land and Biodiversity Conservation SA

Hedpeth, J.W. and Rozengurt, M.A. 1985. Diversion and estuaries. *Estuaries* **8**: 31A.

Hill, J.E. and Cichra, C.E. 2002. Minimum flows and levels criteria development: Evaluation of the importance of water depth and frequency of water levels/flows on fish population dynamics: Literature review and summary. 64 pp. Special Publication SJ2002-SP2.

Hirji, R. and Panella, T. 2003. Evolving policy reforms and experiences for addressing downstream impacts in World Bank water resources projects. *River Research and Applications* **19**: 667-681.

Hopkinson, C.S. and Vallino, J.J. 1995. The relationship among mans activities in watersheds and estuaries: a model of runoff effects on patterns of estuarine community metabolism. *Estuaries* **18**: 598-621.

Howell, J. and Benson, D. 2000. Predicting potential impacts of environmental flows on weedy riparian vegetation of the Hawkesbury-Nepean River, south-eastern Australia. *Austral Ecology* **25**: 463-475.

Hughes, D.A. and Hannart, P. 2003. A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology* **270**: 167-181.

Huizinga, P. and Van Nierkerk, L. 2002. The role of river flow in maintaining physical processes in South Africa’s estuaries. In: *Environmental Flows 2002*. 4th Ecohydraulics Conference, South Africa. pp. 29. March 2002.

Hunt, J.H., Carroll, R.J., Chinchilli, V. and Frankenberg, D. 1980. Relationship between environmental factors and brown shrimp production in Pamlico Sound, North Carolina. North Carolina Department of Natural Resources, Special Scientific Report Number 33. 29 p.

International Water Management Institute. 2005. *Environmental Flow Methodologies. List of References.* http://www.lk.iwmi.org/ehdb/EFM/Visitors/ViewAllReference.asp

Irlandi, E., Macia, S. and Serafy, J. 1997. Salinity reduction from freshwater canal discharge: effects on mortality and feeding of an urchin (*Lytechinus variegates*) and a gastropod (*Lithopoma tectum*). *Bulletin of Marine Science* **61**: 869-879.

Jackson, G. and Jones, G.K. 1999. Spatial and temporal variation in nearshore fish and macro invertebrate assemblages from a temperate Australian estuary over a decade. *Marine Ecology Progress Series* **182**: 253-268.

Jansson, A., Folke, C., Rockstrom, J. and Gordon, L. 1999. Linking freshwater flows and ecosystem services appropriated by people: the case of the Baltic Sea drainage basin. *Ecosystems* **2**: 351-366.

Jansson, R., Nilsson, C., Dynesius, M. and Andersson, E. 2000. Effects of river regulation on river-margin vegetation: a comparison of eight boreal rivers. *Ecological Applications* **10**: 203-224.

Jassby, A.D. and Powell, T.M. 1990. Detecting changes in ecological time series. *Ecology* **71**: 2044-2052.

Jayasuriya, R.T. 2003. Modelling the economic impact of environmental flows for regulated rivers in New South Wales, Australia. *Water Science and Technology* **48(7)**: 157-164.

Jerling, H.L. and Wooldridge, T.H. 1994. The mesozooplankton of a freshwater starved estuary. In: K.R. Dyer and R.J. Orth (eds), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Proceedings of ECSA22/ERF Symposium. Institute of Marine Studies, University of Plymouth. pp. 301-307. Olsen & Olsen; Fredensborg.

Jones, B.G., Martin, G.R. and Senapati, N. 1993. Riverine-tidal interactions in the monsoonal Gilbert River fan delta, northern Australia. *Sedimentary Geology* **83**: 319-337.

Jorge da Silva, A. 1986. River runoff and shrimp abundance in a tropical coastal ecosystem - the example of the Sofala bank (central Mozambique). In: S. Skreslet (ed.), *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. pp. 330-344. Proceedings of the NATO Advanced Research Workshop, 21-25 May 1985, Boho, Norway. Springer-Verlag, and NATO Scientific Affairs Division; Berlin.

Judge, M.L. and Craig, S.F. 1997. Positive flow dependence in the initial colonization of a fouling community: results from *in situ* water current manipulations. *Journal of Experimental Marine Biology and Ecology* **210**: 209-222.

Kaartvedt, S. and Nordby, E. 1992. Impact of a controlled freshwater discharge on zooplankton distribution in a Norwegian fjord. *Journal of Experimental Marine Biology and Ecology* **162**: 279-293.

Karim, K., Gubbels, M.E. and Goulter, I.C. 1995. Review of determination of instream flow requirements with special application to Australia. *Water Resources Bulletin* **31**: 1063-1077.

Kidd, R. and Sander, F. 1979. Influence of Amazon River discharge on the marine production system off Barbados, West Indies. *Journal of Marine Research* **37**: 669-681.

Kimmerer, W.J. 2002. Physical, Biological, and Management Responses to Variable Freshwater Flow into the San Francisco Estuary. *Estuaries* **25**: 1275-1290.

Kimmer, W.J. 2002. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages? *Marine Ecology Progress Series* **243**: 39-55.

Kimmer, W.J. and Schubel, J.R. 1994. Managing freshwater flows into San Francisco Bay using a salinity standard: results of a workshop. In: K.R. Dyer and R.J. Orth (eds), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Proceedings of ECSA22/ERF Symposium. Institute of Marine Studies, University of Plymouth. pp. 411-416. Olsen & Olsen; Fredensborg.

King, A., Mahoney, J. and Tonkin, Z. 2004. *Assessing the Effectiveness of Environmental Flows on Fish Recruitment in Barmah-Millewa*. 2003/2004 Annual Progress Report (BMF 2004.09)

Kingsford, M.J. and Suthers, I.M. 1994. Dynamic estuarine plumes and fronts: importance to small fish and plankton in coastal waters of NSW, Australia. *Continental Shelf Research* **14**: 655-672.

Kingsford, R.T. 1999. Managing the water of the Border Rivers in Australia: irrigation, Government and the wetland environment. *Wetlands Ecology and Management* **7**: 25-35.

Kingsford, R.T. 2000. Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**: 109-127.

Lercari, D. and Defeo, O. 1999. Effects of freshwater discharge in sandy beach populations: the mole crab *Emerita brasiliensis* in Uruguay. *Estuarine*, *Coastal and Shelf Science* **49**: 457-468.

Leveau, M., Lochet, F., Goutx, M. and Blanc, F. 1990. Effects of a plume on the distribution of inorganic and organic matter off the Rhone River. *Hydrobiologia* **207**: 87-93.

Livingston, R.J. 1997. Trophic response of estuarine fishes to long-term changes of river runoff. *Bulletin of Marine Science of the Gulf and Caribbean* **60**: 984-1004.

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

Livingston, R.J., Niu, X.-F., Lewis, F.G. and Woodsum, G.C. 1997. Freshwater input to a gulf estuary: long-term control of trophic organisation. *Ecological Applications* **7**: 277-299.

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

Loneragan, N.E. and Bunn, S.E. 1996. River flows and estuarine ecosystems: implications for coastal fisheries. In: A.H. Arthington and G.C. Long (eds), *Rapid Procedure for Practical In-stream Flow Assessments*. *Logan River Trial of the Building Block Methodology for Assessing Environmental Flow Requirements: Background Papers*. pp. 315-328. Land and Water Resources Research and Development Corporation; Canberra.

Loneragan, N.E. and Bunn, S.E. 1999 River flows and estuarine ecosystems: implications for coastal fisheries from a review and a case study of the Logan River, Southeast Queensland. *Australian Journal of Ecology*, 24:431-440.

Loneragan, N.R. and Potter, I.C. 1990. Factors influencing community structure and distribution of different life-cycle categories of fishes in shallow waters of a large Australian estuary. *Marine Biology* **106**: 25-37.

Longley, W.L. 1994. *Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs.* Texas Water Development Board and Texas Parks and Wildlife Department; Austin, Texas.

Lukatelich, R.J., Schofield, N.J. and McComb, A.J. 1987. Nutrient loading and macrophyte growth in Wilson Inlet, a bar-built southwestern Australian estuary. *Estuarine, Coastal and Shelf Science* **24**: 141-165.

Mallin, M.A., Paerl, H.W., Rudek, J. and Bates, P.W. 1993. Regulation of estuarine primary productivity by watershed rainfall and river flow. *Marine Ecology Progress Series* **93**: 199-203.

Malone, T.C., Crocker, L.H., Pike, S.E. and Wendler, B.W. 1988. Influences of river flow on the dynamics of phytoplankton productivity in a partially stratified estuary. *Marine Ecology Progress Series* **48**: 235-249.

Mackas, D.L. and Louttit, G.C. 1988. Aggregation of the copepod *Neocalanus plumchrus* at the margin of the Fraser River plume in the Strait of Georgia. *Bulletin of Marine Science* **43**: 810-824.

Mackay, S.J., Arthington, A.H., Kennard, M.J. and Pusey, B.J. 2003. Spatial variation in the distribution and abundance of submersed aquatic macrophytes in an Australian subtropical river. *Aquatic Botany* **77**: 169-186.

Maes, J., Van Damme, S., Meire, P. and Ollevier, F. 2004. Statistical modeling of seasonal and environmental influences on the population dynamics of an estuarine fish community. *Marine Biology* **145**: 1033-1042.

Maher, M., Cooper, S. and Nichols, P. 1999. *Australian river restoration and management criteria for the legislative framework for the twenty-first century*, *based on an analysis of Australia and international experience*. Report to LWRRDC: Brisbane. LWRRDC Occasional Paper Number 02/00.

Maheshwari, B.L., Walker, K.F. and McMahon, T.A. 1995. Effects of regulation on the flow regime of the River Murray, Australia. *Regulated Rivers: Research and Management* **10**: 15-38.

Mann, K.H. and Lazier, J.R.N. 1991. Vertical structure in coastal waters: freshwater run-off and tidal mixing. In: K.H. Mann and J.R.W. Lazier (eds), *Dynamics of Marine Ecosystems: Biological-physical Interactions in the Oceans*. pp. 111-158. Blackwell Scientific; Boston.

Marchland, M. 2002. Environmental flows from river basins into the coastal domain: a loss for society. In: *Environmental Flows 2002*. 4th Ecohydraulics Conference, South Africa. pp. 3. March 2002.

Marsh, N., Kennard, M., Stewardson, M. and Arthington, A. 2005. Using the River Analysis Package to quantify the effect of flow change on in-stream habitat availability. Engineers Australia. *29th Hydrology and Water Resources Symposium*. 21–23 February 2005, Canberra.

Martin, T.J., Cyrus, D.P. and Forbes, A.T. 1992. Episodic events: the effects of cyclonic flushing on the ichthyoplankton of St Lucia estuary on the southeast coast of Africa. *Netherlands Journal of Sea Research* **30**: 273-278.

Matsumoto, J., Powell, G. and Brock, D. 1994. Freshwater inflow needs of estuary computed by Texas estuarine MP model. *Journal of Water Resources Planning and Management* **120**: 693-714.

Matthews, J.B. 1986. A framework for discussion of marine zooplankton production in relation to freshwater runoff. In: S. Skreslet (ed.), *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. pp. 107-115. Proceedings of the NATO Advanced Research Workshop, 21-25 May 1985, Boho, Norway. Springer-Verlag, and NATO Scientific Affairs Division; Berlin.

Mattson, R.A. 2002. A resource-based framework for establishing freshwater inflow requirements for the Suwannee River Estuary. *Estuaries* **25**: 1333-1342.

McCosker, R.O. 1998. Methods addressing the flow requirements of wetland, riparian and floodplain vegetation. In: A.H. Arthington and J.M. Zalucki (eds), *Comparative evaluation of environmental flow assessment techniques: review of methods.* pp 47-65. Land and Water Resources Research and Development Corporation Occasional Paper No. 27/98; Canberra. 141 pp.

McIvor, C.C., Ley, J.A. and Bjork, R.D. 1994. Changes in freshwater inflow from the Everglades to Florida Bay including effects on biota and biotic processes: a review. In: S.M. Dalis and J.C. Ogden (eds), *Everglades. The Ecosystem and its Restoration*. pp. 117-146. St Lucia Press; Boca Raton, Florida.

McKinnon, S.G., Lupton, C.J. and Long, P.E. 1995. *A Fisheries Resource Assessment of the Calliope River System in Central Queensland*. Department of Primary Industries; Queensland.

Miller, M.C. 1983. *The Effect of a Tidal Barrage on Estuarine Water Quality*. Water Quality Council of Queensland; Brisbane.

Mitchell, R. 1976. A possible relationship between rate of river flow and recruitment in an estuarine bivalve population. In: S. Skreslet, R. Leinebø, J.B.L. Mattews and E. Sakshaug (eds), *Freshwater on the Sea*. pp. 203-209. Proceedings from a symposium on the influence of fresh-water outflow on biological processes in fjords and coastal waters, 22-25 April 1974, Geilo, Norway. The Association of Norwegian Oceanographers; Oslo.

Montagna, P.A., Alber, M., Doering, P. and Connor, M.S. 2002. Freshwater inflow: science, policy and management. *Estuaries* **25**: 1243-1245.

Montagna, P.A., Kalke, R.D. and Ritter, C. 2002. Effect of restored freshwater inflow on macrofauna and meiofauna in Upper Rincon Bayou, USA. *Estuaries* **25**: 1436-1447.

Montague, C.L. and Ley, J.A. 1993. A possible effect of salinity fluctuation on abundance of benthic vegetation and associated fauna in Northeastern Florida Bay. *Estuaries* **16**: 703-717.

Monteiro, P. and Matthews, S. 2003. Catchment2Coast: making the link between coastal resource variability and river inputs. *South African Journal of Science* **99**: 1-3.

Moore, M. 2004. *Perceptions and Interpretations of Environmental Flows and implications for future water resource management – a Survey Study*. 72 pp. Masters Thesis. Department of Water and Environmental Studies, Linköping University, Sweden.

Morant, P. and Quinn, N. 1999. Influence of man and management of South African estuaries. In: B.R. Allanson and D. Baird (eds), *Estuaries of South Africa*. pp 289-320. Cambridge University Press; Cambridge.

Myers, R.A. 1998. When do environment-recruitment correlations work? *Reviews in Fish Biology and Fisheries* **8**: 285-305.

Nichols, M.M. 1977. Response and recovery of an estuary following a river flood. *Journal of Sedimentary Petrology* **47**: 1171-1186.

Onuf, C.P. and Quammen, M.L. 1983. Fishes in a California coastal lagoon: effects of major storms on distribution and abundance. *Marine Ecology Progress Series* **12**: 1-14.

Papworth, M.P. and Lewis, B. 2003. The development of an historical baseline of water balance and environmental flows. *Water Science and Technology* **48**: 139-147.

Parslow, J., Margvelashvili, N., Palmer, D., Revill, A. Robson, B., Sakov, P., Volkman, J., Watson, R. and Webster, I. 2003. The Response of the Lower Ord River and Estuary to Management of Catchment Flows and Sediment and Nutrient Loads. Final Science Report. OBP Project 3.4/4.1/4.2.

Peirson, W.L., Nittim, R., Chadwick, M.J. and Bishop, K.A. 2001. Impact of flow reduction on Australian estuarine habitats. In: *Proceedings of MODSIM 2001*. pp. 893-898.

Peirson, W.L., Nittim, R., Chadwick, M.J., Bishop, K.A. and Horton, P.R. 2001. Assessment of changes to saltwater/freshwater habitat from reductions in flow to the Richmond River estuary, Australia. *Water Science and Technology* **43**: 89-97.

Phillips, J. and Lavery, P. 1997. Waychinicup Estuary, Western Australia: the influence of freshwater inputs on the benthic flora and fauna. *Journal of the Royal Society of Western Australia* **80**: 63-72.

Plumstead, E.E. 1990. Changes in icthyofaunal diversity and abundance within the Mbashe estuary, Transkei, following construction of a river barrage. *South African Journal of Marine Science* **9**: 399-407.

Poff, N.L., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B.D., Arthington, A.H., Meyer, J.L., Stanford, J.A. and Rogers, K.H. 2003. River flows and water wars: emerging science for environmental decision-making. *Frontiers in Ecology and the Environment* **1**: 298-306.

Pollard, D.A. 1994. A comparison of fish assemblages and fisheries in intermittently open and permanently open coastal lagoons on the south coast of New South Wales, southeastern Australia. *Estuaries* **17**: 631-646.

Pollard, O.A. and Hannan, J.C. 1994. The ecological effects of structural flood mitigation works on fish habitats and fish communities in the lower Clarence river system of Southeastern Australia. *Estuaries* **17**: 427-461.

Pontee, N.I., Whitehead, P.A. and Hayes, C.M. 2004. The effect of freshwater flow on saltation in the Humber Estuary, north east UK. *Estuarine*, *Coastal and Shelf Science* **60**: 241-249.

Powell, G.L. 1981. Estuarine comparisons: the seasonal effects of freshwater inflows on Texas estuaries and their fisheries. *Estuaries* **4**: 264.

Powell, G.L. and Matsumoto, J. 1994. Texas estuarine mathematical programming model: a tool for freshwater inflow management. In: K.R. Dyer and R.J. Orth (eds), *Changes in Fluxes in Estuaries: Implications from Science to Management*. pp. 401-406. Olsen and Olsen; Fredensborg.

Powell, G.L., Matsumoto, J. and Brock, D.A. 2002. Methods for determining minimum freshwater inflow needs of Texas Bays and Estuaries. *Estuaries* **25**: 1262-1274.

Powell, G.V.N., Kenworthy, W.J. and Fourqurean, J.W. 1989. Experimental evidence for nutrient limitation of seagrass growth in a tropical estuary with restricted circulation. *Bulletin of Marine Science* **44**: 324-340.

Puckridge, J.T., Sheldon, F., Walker, K.F. and Boulton, A.J. 1998. Flow variability and the ecology of large rivers. *Marine and Freshwater Research* **49**: 55-72.

Pusey, B.J., Arthington, A.H. and Kennard, M.J. 2004. Hydrologic regime and its influence on broad-scale patterns of fish biodiversity in north-eastern Australian rivers. *Proceedings of the Fifth International Symposium on Ecohydraulics. Aquatic Habitats, Analysis and Restoration*. pp. 75-81. Madrid, Spain.

Quiñones, R.A. and Montes, R.M. 2001. Relationship between freshwater input to the coastal zone and the historical landing of the benthic/demersal fish *Eleginops maclovinus* in central-south Chile. *Fisheries Oceanography* **10**: 311-328.

Quinn, N.W., Breen, C.M., Whitfield, A.K. and Hearne, J.W. 1999. An index for the management of South African estuaries for juvenile fish recruitment from the marine environment. *Fisheries Management and Ecology* **6**: 421-436.

Preen, A.R., Lee Long, W.J. and Coles, R.G. 1995. Flood and cyclone related loss, and partial recovery, of more than 1,000 km^2 of seagrass in Hervey Bay, Queensland, Australia. *Aquatic Botany* **52**: 3-17.

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* **10**:1163–1174.

Ritter, C., Brock, D., Wentzel, M., Austin, B., Matsumoto, J., Malstaff, G., Solis, R., Jia, Z. and Powell, G. 2000. *Values and Constraints for the TxEMP Model Used in the Freshwater Inflow Analysis of the Mission-Aransas Estuary*. Texas Water Development Board; Austin, Texas.

Ritter, C., Montagna, P.A. and Applebaum, S. 2005. Short-term succession dynamics of macrobenthos in a salinity-stressed estuary. *Journal of Experimental Marine Biology and Ecology* **323**: 57-69.

Robson, B.J. and Matthews, T.G. 2004. Drought refuges affect recolonization in intermittent streams. *River Research and Applications*. **20**: 753-763.

Rodriguez, C.A., Flessa, K.W. and Dettman, D.L. 2001. Effects of upstream diversion of Colorado River water on the estuarine bivalve mollusc *Mulinia coloradoensis*. *Conservation Biology* **15**: 249-258.

Rogers, S.G., Target, T.E. and Van Sant, S.B. 1984. Fish-nursery use in Georgia salt-marsh estuaries: the influence of springtime freshwater conditions. *Transactions of the American Fisheries Society* **113**: 595-606.

Rozengurt, M.A. and Herz, M. 1985. Relationships between freshwater inflow and commercial/recreational fish catches in San Francisco Bay. *Estuaries* **8**: 29A.

Saldanha, C.M. and Achuthankutty, C.T. 2000. Growth of hatchery raised banana shrimp *Penaeus merguiensis* (de Man) (Crustacea: Decapoda) juveniles under different salinity. *Indian Journal of Marine Sciences* **29**: 179-180.

Salen-Picard, C., Darnaude, A.M., Arlhac, A.M. and Harmelin-Viven, M.L. 2002. Fluctuations of macrobenthic populations: a link between climate-driven river run-off and sole fishery yields in the Gulf of Lions. *Oceanologica* **133**: 380-388.

Sammut, J., White, I. and Melville, M.D. 1996. Acidification of an estuarine tributary in eastern Australia due to drainage of acid sulphate soils. *Marine and Freshwater Research* **47**: 669-684.

Sawynok, B. 1998. *Fitzroy River Effects of Freshwater Flows on Fish: Impact on Barramundi Recruitment*, *Movement and Growth*. Infofish Services; Rockhampton, Queensland.

Schiedeck, D. and Schöttler, U. 1991. The influence of freshwater runoff on the population density of juvenile Arenicola marina L. (Polychaeta). In: M. Elliott and J.-P. Ducroty (eds), *Estuaries and Coasts: Special and Temporal Comparisons*. Olsen and Olsen; Denmark.

Schlacher, T.A. and Wooldridge, T.H. 1996. Ecological responses to reductions in freshwater supply and quality in South Africa's estuaries: lessons for management and conservation. *Journal of Coastal Conservation* **2**: 115-130.

Schroeder, W.W. 1978. Riverine influence on estuaries: a case study. In: M.L. Wiley (ed.), *Estuarine Interactions*. *Proceedings of the 4th Biannual International Estuarine Research Conference*. pp. 347-364. October 2-5, 1977. Mt Pocono, Pennsylvania. Academic Press.

Schumann, E.H. and Pearce, M.W. 1997. Freshwater inflow and estuarine variability in the Gamtoos Estuary, South Africa. *Estuaries* **20**: 124-133.

Serafy, J.E., Lindeman, K.C., Hopkins, T.E. and Ault, J.S. 1997. Effects of freshwater canal discharge on fish assemblages in a subtropical bay field and laboratory observations. *Marine Ecology Progress Series* **160**: 161-172.

Sheaves, M. 1998. Spatial patterns in estuarine fish faunas in tropical Queensland: a reflection of interaction between long-term physical and biological processes? *Marine and Freshwater Research* **49**: 31-40.

Siebentritt, M.A., Ganf, G.G. and Walker, K.F. 2004. Effects of an enhanced flood on riparian plants of the River Murray, South Australia. *River Research and Applications*. **20**: 765- 774.

Simon, T.P. 2000. The use of biological criteria as a tool for water resource management. *Environmental Science and Policy* **3**: 43-49.

Sinclair, M., Budgen, G.L., Tang, C.L., Therriault, J.C. and Yeats, P.A. 1986. Assessment of effects of freshwater runoff variability on fisheries production in coastal waters. In: S. Skreslet (ed.), *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. pp. 139-160. Proceedings of the NATO Advanced Research Workshop, 21-25 May 1985, Boho, Norway. Springer-Verlag, and NATO Scientific Affairs Division; Berlin.

Sklar, F.H. and Browder, J.A. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. *Environmental Management* **22**: 547-562.

Skreslet, S. 1997. A conceptual model of the trophodynamical response to river discharge in a large marine ecosystem. *Journal of Marine Systems* **12**: 187-198.

Skreslet, S. (ed.). I986. *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. Proceedings of the NATO Advanced Research Workshop, 21-25 May 1985, Boho, Norway. Springer-Verlag, and NATO Scientific Affairs Division; Berlin.

Skreslet, S. 1986. Freshwater outflow in relation to space and time dimensions of complex ecological interactions in coastal waters. In: S. Skreslet (ed.), *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. pp. 3-12. Proceedings of the NATO Advanced Research Workshop, 21-25 May 1985, Boho, Norway. Springer-Verlag, and NATO Scientific Affairs Division; Berlin.

Skreslet, S. 1981. Information and opinions on how freshwater outflow to the Norwegian coastal current influences biological production and recruitment to fish stocks in adjacent seas. *The Norwegian Coastal Current* **2**: 712-748.

Skreslet, S. 1976. Influence of freshwater outflow from Norway on recruitment to the stock of Arcto-Norwegian cod (*Gadus morhua*). In: S. Skreslet, R. Leinebø, J.B.L. Mattews and E. Sakshaug (eds), *Freshwater on the Sea*. pp. 233-237. Proceedings from a symposium on the influence of fresh-water outflow on biological processes in fjords and coastal waters, 22-25 April 1974, Geilo, Norway. The Association of Norwegian Oceanographers; Oslo.

Slinger, J.H., Taljaard, S. and Largier, J.L. 1994. Changes in estuarine water quality in response to a freshwater flow event. In: K.R. Dyer and R.J. Orth (eds), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Proceedings of ECSA22/ERF Symposium. Institute of Marine Studies, University of Plymouth. pp. 51-56. Olsen & Olsen; Fredensborg.

Smetacek, V.S. 1986. Impact of freshwater discharge on production and transfer of materials in the marine environment. In: S. Skreslet (ed.), *The Role of Freshwater Outflow in Coastal Marine Ecosystems*. pp. 85-106. Proceedings of the NATO Advanced Research Workshop, 21-25 May 1985, Boho, Norway. Springer-Verlag, and NATO Scientific Affairs Division; Berlin.

Snow, G.C., Adams, J.B. and Bate, G.C. 2000. Effect of river flow on estuarine microalgal biomass and distribution. *Estuarine*, *Coastal and Shelf Science* **51**: 255-266.

Sparks, R.E. and Spink, A. 1998. Disturbance, succession and ecosystem processes in rivers and estuaries: effects of extreme hydrologic events. *Regulated Rivers: Research and Management* **14**: 155-159.

Stenseth, N.C., Mysterud, A., Ottersen, G., Hurrell, J.W., Chan, K.S. and Lima, M. 2002. Ecological effects of climate fluctuations. *Science* **297**: 1292-1296.

Stevens, D.E. and Miller, L.W. 1983. Effects of river flow on abundance of young chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento-San Joaquin River system. *North American Journal of Fisheries Management* **3**: 425-437.

Stewardson, M.J. 2002. Incorporating flow variability into environmental flow regimes using the flow events method. In: *Environmental Flows 2002*. 4th Ecohydraulics Conference, South Africa. pp. 58. March 2002.

Stewardson, M.J., Fenton, J.D. and Cottingham, P. 2001. Applying the flow events method in an environmental flow study of the Broken River. In: *Proceedings of MODSIM 2001*. pp. 881-886.

Stora, G., Arnoux, A. and Galas, M. 1995. Time and spatial dynamics of Mediterranean lagoon macrobenthos during an exceptionally prolonged interruption of freshwater inputs. In: G. Balvay (ed.), *Space Partition within Aquatic Ecosystems*. pp. 123-132.

Sumpton, W. and Greenwood, J. 1990. Pre- and post-flood feeding ecology of four species of juvenile fish from the Logan-Albert estuarine system, Moreton Bay, Queensland. *Australian Journal of Marine and Freshwater Research* **41**: 795-806.

Sutcliffe, W.H. 1972. Some relations of land drainage, nutrients, particulate material and fish catch in two eastern Canadian bays. *Journal of the Fisheries Research Board of Canada* **29**: 357-362.

Sutcliffe, W.H. 1973. Correlations between seasonal river discharge and local landings of American lobster (*Homarus americanus*) and Atlantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St Lawrence. *Journal of the Fisheries Research Board of Canada* **30**: 856-859.

Sutcliffe, W.H., Drinkwater, K. and Muir, B.S. 1977. Correlations of fish catch and environmental factors in the Gulf of Maine. *Journal of the Fisheries Research Board of Canada* **34**: 19-30.

Talbot, M.M.B., Knoop, W.T. and Bate, G.C. 1990. The dynamics of estuarine macrophytes in relation to flood/siltation cycles. *Botanica Marina* **33**: 159-164.

Tennet, D.L. 1976. Instream flow regimes for fish, wildlife, recreation and related environmental resources. *Fisheries* **1**: 6-10.

Ter Morshuizen, L.D., Whitfield, A.K. and Paterson, A.W. 1996. Influence of freshwater flow regime on fish assemblages in the Great Fish River and estuary. *South African Journal of Aquatic Sciences* **22**: 52-61.

Tharme, R.E. 2002. Emerging global trends in environmental flow assessment. In: *Environmental Flows 2002*. 4th Ecohydraulics Conference, South Africa. March 2002. pp. 60.

Thiel, R., Sepulveda, A., Kafemann, R. and Nellen, W. 1995. Environmental factors as forces structuring the fish community of the Elbe Estuary. *Journal of Fish Biology* **46**: 47-69.

Thompson, P.A., Adeney, J. and Gerritse, R. 1997. Phytoplankton in the Swan River: Research results 1993-1996 and management implications. In R.A. Davis (ed.), *Managing Algal Blooms*. pp. 1-14. CSIRO Land and Water; Canberra.

Thompson P.A. 1998. Spatial and temporal patterns of factors limiting phytoplankton in a salt wedge estuary, the Swan River, Western Australia. *Estuaries* **21**: 801-817.

Thompson, P.A. and Hosja, W. 1996. Temporal dynamics of nutrient limitation of phytoplankton from the Swan River estuary, Western Australia. *Australian Journal of Marine and Freshwater Research* **47**: 659-667.

Thompson, P.A., Waite, A. and McMahon, K. 2003. The dynamics of a cyanobacterial bloom in a hypereutrophic, stratified, weir pool. *Marine and Freshwater Research* **54**: 27-37.

Thoms, M.C. and Sheldon, F. 2002. An ecosystem approach for determining environmental water allocations in Australian dryland river systems: the role of geomorphology. *Geomorphology* **47**: 153-168.

Tunbridge, B.R. and Glenane, T.J. 1988. *A Study of Environmental Flows Necessary to Maintain Fish Populations in the Gellirand River and Estuary*. Arthur Rylah Institute for Environmental Research; Melbourne.

Turek, J.G., Goodger, T.E., Bigford, T.E. and Nichols, J.S. 1987. *Influence of Freshwater Inflows on Estuarine Productivity*. NOAA; Woods Hole, Massachusetts.

Turner, R.E. and Rabalais, N.C. 1994. Changes in the Mississippi River nutrient supply and offshore silicate-based phytoplankton community responses. In: K.R. Dyer and R.J. Orth (eds), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Proceedings of ECSA22/ERF Symposium. Institute of Marine Studies, University of Plymouth. pp. 147-150. Olsen & Olsen; Fredensborg.

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

Walker, K.F. and Thoms, M.C. 1993. Environmental effects of flow regulation on the lower River Murray, Australia. *Regulated Rivers: Research and Management* **8**: 103-119.

Ward, J.V. and Stanford, J.A. (eds). 1979. The ecology of regulated streams. 398 p. Plenum Press; New York.

Werren, G. and Arthington, A.H. 2002. The assessment of riparian vegetation as an indicator of stream condition, with particular emphasis on the rapid assessment of flow-related impacts. In: J. Playford, A. Shapcott and A. Franks (eds), *Landscape Health of Queensland*. pp. 194-222. Royal Society of Queensland, Brisbane.

Whitfield, A.K. and Elliott, M. 2002. Fishes as indicators of environmental and ecological changes within estuaries: a review of progress and some suggestions for the future. *Journal of Fish Biology* **60**: 1-22.

Whitfield, A.K. 1997. A review of factors influencing fish utilization of South African estuaries. *Transactions of the Royal Society of South Africa* **51**: 115-137.

Whitfield, A.K. 1994. Abundance of larval and 0+ juvenile marine fishes in the lower reaches of three southern African estuaries with differing freshwater inputs. *Marine Ecology Progress Series* **105**: 257-267.

Whitfield, A.K. and Wooldridge, T.H. 1994. Changes in freshwater supplies to southern African estuaries: some theoretical and practical considerations. In: K.R. Dyer and R.J. Orth (eds), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Proceedings of ECSA22/ERF Symposium. Institute of Marine Studies, University of Plymouth. pp. 41-50. Olsen & Olsen; Fredensborg.

Whitfield, A.K. and Bruton, M.N. 1989. Some biological implications of reduced freshwater inflow into eastern Cape estuaries: a preliminary assessment. *South African Journal of Science* **85**: 691-694.

Whittington, J. 2000. *Development of Relationships Between Flow Regime and River Health*. Outcomes of a Joint CRC FE and QDNR workshop. CRC for Freshwater Ecology, Canberra.

Wilber, D.H. and Bass, R. 1998. Effect of the Colorado River diversion on Matagorda Bay epifauna. *Estuarine*, *Coastal and Shelf Science* **47**: 309-318.

Wilber, D.H. 1992. Associations between freshwater inflows and oyster productivity in Apalachicola Bay, Florida. *Estuarine*, *Coastal and Shelf Science* **35**: 179-190.

Wilson, G.C. 2002. Fish otolith microstructure as a tool for defining environmental flow requirements in freshwater ecosystems. In: *Environmental Flows 2002*. 4th Ecohydraulics Conference, South Africa. pp. 64. March 2002.

Witman, J.D. and Grange, K.R. 1998. Links between rain, salinity, and predation in a rocky subtidal community. *Ecology* **79**: 2429-2447.

Woodall, P.F. 1985. Waterbird populations in the Brisbane region, 1972-83, and correlates with rainfall and water heights. *Australian Wildlife Research* **12**: 495-506.

Wright, L.D. and Coleman, J.M. 1973. Variations in morphology of major river deltas as functions of ocean wave and river discharge regimes. *The American Association of Petroleum Geologists* **57**: 370-398.

Young, W.J., Lam, D.C.L., Ressel, V. and Wong, I.W. 2000. Development of an environmental flows decision support system. *Environmental Modelling and Software* **15**: 257-265.

Zedler, J.B. and Onuf, C.P. 1984. Biological and physical filtering in arid-region estuaries: seasonality, extreme events and effects of watershed modification In: V.S. Kennedy (ed.), *The Estuary as a Filter*. pp. 415-432. Academic Press; Orlando.

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Appendix 2: Impact of abiotic change on biota.

Table A5.1 summarises some of the better-known links between the abiotic environment of an estuary on biota driven by increased and decreased flows. However, presently “little is known about the importance of freshwater in the ecology of the intertidal zone or about the impact on wildlife from its reduction or removal” (Ravenscroft and Beardall, 2003, p. 89).

This summary is modified from that provided by Gillanders and Kingsford (2002, table 8) incorporating additional information from this review.

Table A5.1. Known relationships between the abiotic environment and estuarine biota under conditions of decreased and increased flows.

Estuarine Abiotic Environment Parameter	**Effect on Biota**
Salinity	
increased	• marine species out-compete brackish water species • increased survival of coral • increased mortality of oysters due to disease • marine fish in estuary • increased biomass of marine fish • increase in survival of some seagrasses, decline in others • seagrass colonise upper estuary • reduced seagrass germination • decreased coral growth rates • die-back of some mangroves • decreased algal growth
decreased	• increased mortality of crabs near freshwater input, mortality of mud crab eggs and larvae • death of corals • low salinities unsuitable for newly settled post-larvae of prawns • mortality of some juvenile fish • adult mud crabs move to areas with higher salinities • stimulates migration • decreased recruitment of crabs near freshwater input • alters spawning cues • decrease in abundance/biomass of meiofauna • reduced growth rates of invertebrate larvae • mortality of shallow water macroalgae • one possible reason for negative correlation of phytoplankton with flow in Swan River estuary (WA) (Chan and Hamilton, 2001)

Estuarine Abiotic Environment Parameter	Effect on Biota
Turbidity	
increased	• increased mortality of benthic organisms, particularly sessile ones, due to smothering or interference with feeding (sediment deposition) • decreased seagrass species richness • decline in ability of predators to catch prey • decreased seagrass growth rates • loss of seagrass and phytoplankton • decreased seagrass biomass • increased ephytic loads • one possible reason for negative correlation of flow with phytoplankton in Swan River estuary (Chan and Hamilton, 2001) • Increased catchability as higher rainfall and hence river flow stimulates the downstream movement of mud crabs. This mechanism may also result in increased survival of juveniles due to a decrease in cannibalism by adults (Loneragan and Bunn, 1999)
decreased (improved light penetration)	• increase in ability of predators to catch prey • increased seagrass biomass
Temperature	
increased	• possible coral bleaching with increased temperature • distribution
decreased	• distribution
Nutrients	
decreased (nutrient deficiencies)	• decrease in prawn and fish biomass • reduced primary production and its flow-on effect on growth rates, abundance/biomass, consumer (fisheries) production • one possible reason for negative correlation of flow with phytoplankton in Swan estuary (WA) (Chan and Hamilton, 2001)
increased	• increase in prawn and fish biomass • increased mortality due to hypoxia/anoxia caused by breakdown of organic matter • increased primary production and its flow-on effects (e.g. for prawns in the Logan River (Qld) (Loneragan and Bunn, 1999)) • increased growth rate due to increased food availability • decrease or increase in seagrass survival • increase in macroalgae • increase in phytoplankton, including possible blooms (e.g. in Haughton River (Qld) additional nutrients stirred up by flows (McKinnon and Klump, 1998)) • increase in zooplankton in Haughton River (Qld) because mixing by flows and currents alters both the quantity and quality of particulate material available for consumption (McKinnon and Klump, 1998) • stratification of the water column, flushing (e.g. Bacillariophyta in Swan River (WA) have negative correlation with seasonal flows (Chan and Hamilton, 2001))

Estuarine Abiotic Environment Parameter	Effect on Biota
pH	
altered flows	• change natural pH ranges and gradients in estuaries because river water has a much higher pH than seawater if it evaporates to the same salinity • changed pH can result in animal kills and disease, poor water quality, release of metals and other toxicants and loss or disturbance of habitat
Dissolved oxygen	
altered flows	• may change mixing patterns, salinity, temperature, nutrient levels, the amount of organic matter present and/or phytoplankton production which can result in hypoxic conditions
Contaminants	
increased (reduced dilution or increased input)	• reduced larval survival • reduces benthic infauna
Hydrology	
increased water velocity	• organisms (including their gametes and larvae) get flushed out of the system • increased migration due to mouth opening • changed spawning and migration cues (e.g. stimulation of the emigration of juvenile prawns in the lower Logan River (Qld) as a result of increased run-off (Loneragan and Bunn, 1999)) • stratification of the water column, flushing and turbulence (e.g. Bacillariophyta (phytoplankton) in the Swan River (WA) have a negative correlation with seasonal flows (Chan and Hamilton, 2001))
decreased water velocity	• loss of spawning and migration cues • barriers to migration – estuary mouth closure
altered circulation patterns	• distribution • transport of larvae through currents
reduced water height	• migration of fish prevented by barriers and lost connectivity • reduced recruitment from loss of connectivity • exposure of normally submerged vegetation results in death • drainage of saltmarshes, mangroves and other riparian areas • loss of connectivity with floodplain pools and other systems • reduced foraging and nesting habitat for waterbirds
increased water height	• increased habitat availability • increased connectivity with floodplain pools and other systems
Habitat quality	
increased flows	• enhanced juvenile barramundi survival due to altered accessibility, productivity and/or carrying capacity of nursery habitats in Fitzroy River (Qld) (Staunton-Smith *et al.*, 2004)

Estuarine Abiotic Environment Parameter	**Effect on Biota**
General	
	• positive correlation of abundance with flow for some species (flathead, mud crabs) but only slight or no correlation with others (mullet, whiting, swimmer crabs) in Logan River (Qld) (Loneragan and Bunn, 1999) • increased catchability of crabs and flathead in Logan River estuary (Loneragan and Bunn, 1999) • positive correlation of catch of prawns and bugs with flow in Fitzroy River (Qld) because of increased catchability when prawns are moved offshore (Platten, 1996) • positive correlation of catch of red throat emperor, coral trout, coral cod perch, hussar, snapper in Fitzroy River (Qld) because of increased catchability possibly because of increased feeding intensity (Platten, 1996) • negative correlation of populations of some zooplankton with high summer flows in the Derwent (Tas) but no explanation offered (Taw and Ritz, 1978) • increased recruitment of Australian bass in Hawkesbury-Nepean (NSW) gives positive correlation with flow (Growns and James, 2005) • high summer flows increase catch of prawns, salmon and mullet in Pioneer River (Qld) because of increased estuarine productivity (Platten, 2000) • no correlation of populations of some phytoplankton with rainfall in the Swan River (WA) but no explanation offered (Chan and Hamilton, 2001)

Appendix 3: Starting (pre-workshop) list of knowledge-needs and report themes.

THEME	Knowledge-need
1	**FLOW NEEDS ASSESSMENT AND EVALUATION**
1a	Can a fully holistic approach to determining environmental flow regime needs of an estuary (that includes understanding how flow effects hydrology, geomorphology, biogeochemistry, biotic components, ecosystem processes) be developed that is practical and functional?
1b	What are the essential data (i.e. hydrodynamic, geomorphic, water quality, ecological) for estuarine systems needed to determine appropriate environmental flows?
1c	What are the essential flow regime conditions needed to maintain estuarine health and productivity?
1d	How should we measure estuarine ecosystem health? What existing methods have already proven viable and what are the key aspects of health needing new/better metrics and measurement techniques?
1e	Develop a protocol for assessing fish passage requirements as part of environmental flow studies.
1f	Develop an agreed protocol for the assessment of beneficial outcomes from environmental flow to estuaries.
1g	What should we be routinely monitoring (biota, water quality, geomorphology, etc.) in an estuary that has environmental flows to make sure that we are meeting the flow objectives/flows are adequate to maintain estuarine health and production?
1h	What are the effects on an estuary of implementing environmental flows, particularly estuaries that have been ‘starved’ of flows for a relatively long time?
1i	What will be the effects of climate change or variability on environmental water allocations to estuaries if worst-case scenarios of decreased run-off in parts of the Australia do occur?
1j	What are: • the ‘key’ (indicator) species that indicate the level of health, or degradation, of an estuaries, and • the flow regime requirements and tolerances of these ‘key’ species?
1k	What are the indicator species of healthy and degraded rivers for different climatic zones, estuary types and seasonal flow regime zones, in Australia? What are the flow regime tolerances of these species?
1l	Is it possible to develop a common nation-wide assessment approach?
2	**CHARACTERISTICS OF FRESHWATER FLOW REGIME (INFLOWS) TO ESTUARIES**
2a	How do estuaries respond to natural and altered sequences of flow events, including quantity, quality and timing of flows?
2b	What are the natural and altered estuarine inflows and hydrodynamics, as revealed by historical and current gauging station data?
2c	What methods can be used to measure important water levels (e.g. satellite imagery of fluctuations in water level, distribution of wetted habitat areas, degree of connectivity)?
2d	What is the role of groundwater flows on estuaries particularly during low flow periods?
2e	Are existing hydrodynamic models sensitive enough to be able to model the implications of change in flow regime in terms of important estuarine features (e.g. fluctuations in water level, distribution of wetted habitat areas, degree of connectivity among habitat patches, etc).

3	**INFLUENCE OF FRESHWATER FLOWS ON ESTUARINE BIOTA AT THE COMMUNITY LEVEL**
3a	What are the habitat-biota relationships and how do they vary in space and time with different freshwater inflow regimes?
3b	What critical habitat elements (such as woody debris, macrophyte beds, soft bottoms, sand bars, rocky outcrops, saltmarshes and saltflats, mangroves) are needed to sustain estuarine flora and fauna?
3c	What is the relationship between flow variability and habitat (e.g. changes to habitat availability with change in flow)?
3d	What changes in habitat use occur under different flow regimes?
3e	How do saltmarshes respond to the physical variables that change as a result of altered flows and what are the flow-on effects on other species associated with saltmarshes if there was a change to inundation or saltmarsh habitat?
3f	How is estuarine productivity enhanced by freshwater flows, and does enhanced primary productivity translate to increased secondary productivity?
3g	What is the response of mudflat benthos to freshwater?
3h	In estuaries or embayments with multiple river inputs what are the effects of altering the flow of one river but not all? Can the effects of flow regulation in one river be offset by maintaining natural flow in another?
3i	What are the processes (actual energy flow process) by which freshwater flows increase production in an estuary?
4	**INFLUENCE OF FRESHWATER FLOWS ON ESTUARINE BIOTA AT THE SPECIES LEVEL**
4a	What are the movement and migration requirements of key species occurring in estuaries with different types of flow regime in different parts of Australia?
4b	What are the flow requirements of ‘key’ species for: • connectivity and access to habitat, • cues for larvae movement, • migration cues, and • enhanced biological production?
4c	What is the role of flows on fisheries species in terms of: • spawning success (including egg and larval survival) – issues include; timing of spawning with flows, trigger for spawning and the effect of flows on the quality of spawning habitat, • migration and distribution – issues include; effects of flow on different life stages, effects on nursery areas, habitat access, food availability, water quality parameters (e.g. salinity and turbidity), triggers for migration (spawning or juvenile), • predation rates – issues include; turbidity or changed distribution of predators, and • trophic pathways – issues include; changes to primary production and growth rates?
4d	What are the impacts on mangroves of changes to nutrients and dissolved oxygen as a result of altered flow?
4e	What are the impacts of toxicants on invertebrates and other biota during low flow periods when the dilution factor is reduced?
4f	What flow factors affect waterbirds and what are the impacts of altering flows on waterbirds?
4g	How do flows impact on food availability for waders?
4h	What are the flow regime requirements and tolerances of plants?
4i	What are the freshwater inflow requirements of estuarine fish species?
4j	What are the links between flows (volume, timing, etc.) and recruitment in species such as mulloway, black bream, yellow-eye mullet, galaxids, lampreys, eels, congollis, etc.?
4k	What are the impacts of flow on non-commercial estuarine fish species?

5	**INFLUENCE OF FRESHWATER FLOWS ON ESTUARINE HYDRODYNAMICS AND GEOMORPHOLOGY**
5a	How does freshwater inflow effect hydrodynamics of estuaries in terms of the zone of impact (i.e. extent and dynamics of the salt wedge, spatial and temporal variability of freshwater-saltwater habitat availability)?
5b	What is the relationship of the full range of flows to estuarine morphology and geomorphologic processes?
5c	What are the long-term effects of altered flow on sediment input/output, and therefore on changing channel structures and habitat types?
5d	Need a model that accurately and reliably predicts the relationship between flow variability and habitat.
5e	Need a model of estuarine hydrodynamics, freshwater and tidal currents and pattern, and sediment movement that accurately and reliably predict the possibility of river mouth opening/closure.
5f	Need a protocol for the design of appropriate estuarine opening regimes for estuaries where artificial opening occurs.
6	**INFLUENCE OF FRESHWATER FLOWS ON ESTUARINE WATER QUALITY AND BIOGEOCHEMISTRY**
6a	What is the relationship between freshwater inflow and the biogeochemistry of estuaries?
6b	What are the impacts of cold water releases from impoundments on estuaries?
7	**TRANSFERABILITY OF KNOWLEDGE TO OTHER ESTUARIES**
7a	Can existing estuarine flow models be adapted for use in other estuaries?
7b	Can estuaries be classified according to their biotic similarities?
7c	Can the study of representative species from an estuary provide a template for managing environmental flows for other estuaries of the same estuary type nationally/regionally, within the same seasonal river flow regime zone?
7d	What are the 'key' species of an estuary and can we develop recruitment models for them that can be applied to different estuaries with different flow regimes?
7e	Can we use finding of the links between freshwater flows and fisheries productivity for tropical Australia to extrapolate to temperate rivers, or between estuaries of the same type, with the same region, within the same seasonal flow regime type?
7f	Can we develop a common conceptual understanding of the major ecological processes and linkages in rivers and their estuaries?
7g	Where, or in what type of estuaries, can generalisations be made regarding their functioning?
8	**INFLUENCE OF FRESHWATER FLOWS ON ESTUARINE VALUES**
8a	What values do communities place on estuaries?
8b	What are the impacts of flow on marine farming activities?
8c	What is the role of flow in delivering nutrients etc. to our estuaries where aquaculture occurs and how does flow influence the life history of some of our commercial and recreational fish (or if it does in fact)?
8d	Do different types of human impacts (agricultural, aquaculture, transport, urban, etc.) interact with altered freshwater flows to affect estuarine functioning?
9	**BASIC INFORMATION OF ESTUARINE BIOTA**
9a	What is the species composition, diversity and community structure of estuarine flora and fauna, including waterbirds?
9b	What are the basic life histories of estuarine biota?

9c	What are the water quality tolerances (e.g. turbidity, nutrients, salinity, pH, temperature) of estuarine biota?
9d	What are the habitat requirements of estuarine biota?
9e	What are the movement patterns and migration requirements of estuarine biota?
9f	What are the spawning cues and nursery habitat requirements of estuarine biota?
9g	What are the factors driving recruitment patterns of estuarine biota?
9h	Develop an appropriate (standardised) technique for ageing tropical estuarine fish.
9i	How does birdlife use the estuary habitat, both temporal and spatial variability?
9j	What is the distribution, flow requirements and ecology needs of in-channel macrophytes and riparian vegetation?
9k	Need knowledge of the basic biology, life cycle and ecology of a species to determine what mechanism is responsible for an observed change in numbers in relation altered flow.
10	**METHODS FOR EXAMINING FLOW EFFECTS**
10a	Is fisheries catch data accurate enough to use when trying to determine a change in fisheries production due to flows: • what are the implications/effects of fisheries management (e.g. restrictions, changes in methods over time, etc.) on using fisheries catch data? • is fisheries data flawed as it is usually not validated, and • what are the implications/effects of using low resolution fisheries data that is difficult to specifically link to a particular river/estuary?
10b	Are relationships reported between catch and freshwater flows confounded by: • fishing effort/pressure, • spawning stock size, • non-linear links/multiple links, • type I errors, • lack of the ability to prove causality, and • uncertainty of predictive capabilities due to climate change and human pressures.
10c	Research needed into time-lagged effects, which may better indicate ‘real’ changes resulting from flows?
10d	Integrated physical-biological models, multidisciplinary studies and quantitative research are needed to increase our knowledge of the relationships between freshwater flows and estuarine health and productivity.

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