Assessment of Information Needs for Freshwater Flows into Australian Estuaries

Final Report

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Scheltinga, D.M., Fearon, R., Bell, A. and Heydon, L.

Australian Government
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FARI Australia Pty Ltd and the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management.

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1 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 in the past and solving conflicts surrounding allocations for these uses and for ‘environmental flows’ are a key element of national water reform. 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 entered into the agenda of 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 consideration 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). Although the framework referred generally to ‘river systems’, estuaries are not mentioned specifically and the major focus as been on freshwater reaches of Australian rivers (i.e. those of prime interest to the water resources industry).

The water reform agenda continued with some amendments (i.e. 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 key areas 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.

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 7).

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, 1998; 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, 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 action 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 flow influences and ecological roles in many estuaries, all states and territories are faced with a difficult problem in allocating flows that can be solved only through further research and development (R&D).

What this means is that although estuaries are not excluded from the water reform agenda or NWI, they are not included explicitly and thus tend to be less well considered than freshwater areas. This, combined with the large number of knowledge needs around the influence of flows on estuaries, and thus their flow requirements, means that estuaries are difficult to include in water planning arrangements 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 highlighting 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.

2 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 are important ecosystems in their own right and 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. An assessment of the value of Australian estuaries by Blackwell (2005) comprehensively reviewed the EGS estuaries may provide. This review includes an indication of which EGS have been valued in some way and for those that had not an assessment of likely importance (Table 2.1).

Table 2.1. 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' of 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 (see summary in Appendix 2) and the resultant draft values are listed in Table 2.2.

Table 2.2. Suggested draft values for Australian estuaries for the purposes of identifying and prioritising knowledge needs (see Appendix 2). 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.

Reduced flows can modify a number of the 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).

3 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 – see Figure 3.1, relating freshwater inflow to estuarine conditions (abiotic environment) and resources (biotic environment), provides a starting point for development of this framework. This model diagrammatically represents the influences of flows on estuarine abiotic conditions and ultimately estuarine biota (resources).

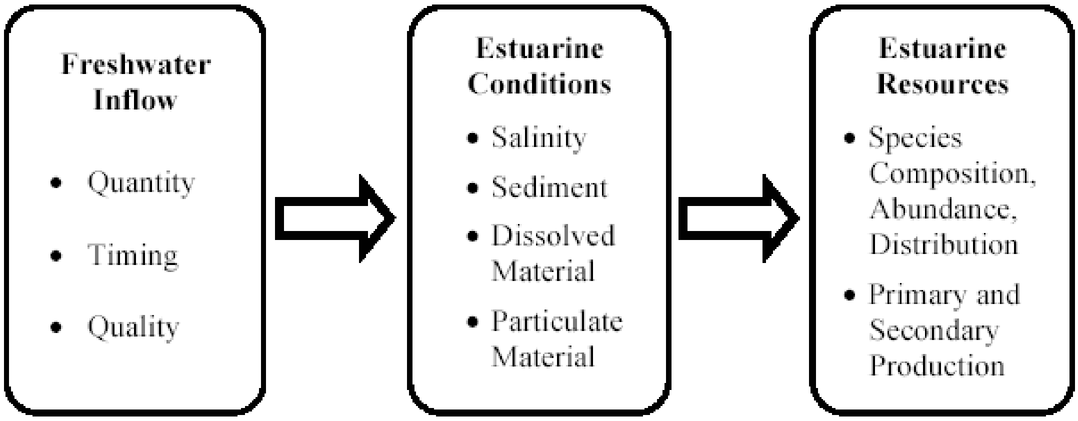

Figure 3.1. Simplified conceptualisation of the effects of freshwater flows on estuarine condition, biodiversity and production (from Alber, 2002).

A limitation of this model is that it does not represent the broad range of recognised ecosystem goods and services provided by estuaries, focusing solely on living resources. Similarly, 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. Further, the terms ‘resource’ and ‘conditions’ are used in different contexts in Australia. Also, this model does not recognise the role of the saltwater/tidal regime.

Another simple model is provided by Taljaard *et al*. (2004 – cited in 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.

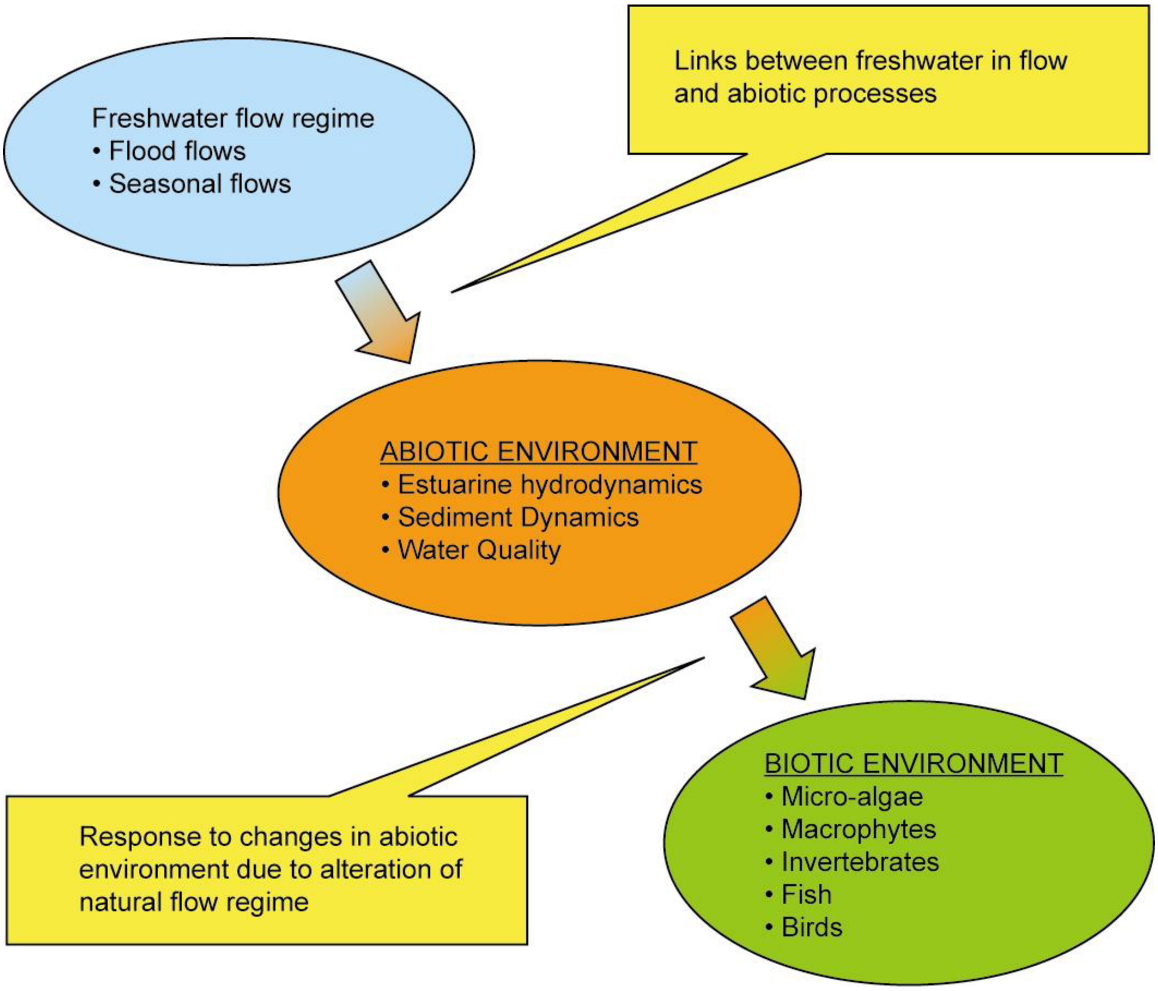

Figure 3.2. Simplified conceptualisation of the effects of freshwater flows on abiotic and biotic components of estuaries (from Taljaard *et al*., 2004 – cited in Close, 2005).

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 (Fig. 3.2). 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 3.1. One potential link not shown in the diagram is that between freshwater inflow and estuarine values, and it might be envisaged that in some areas the presence or absence of freshwater flows may impact amenity and spiritual/cultural values.

Table 3.1. Suggested draft values and their relevance to abiotic and biotic components of estuaries (see item 3 in Figure 3.3).

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).

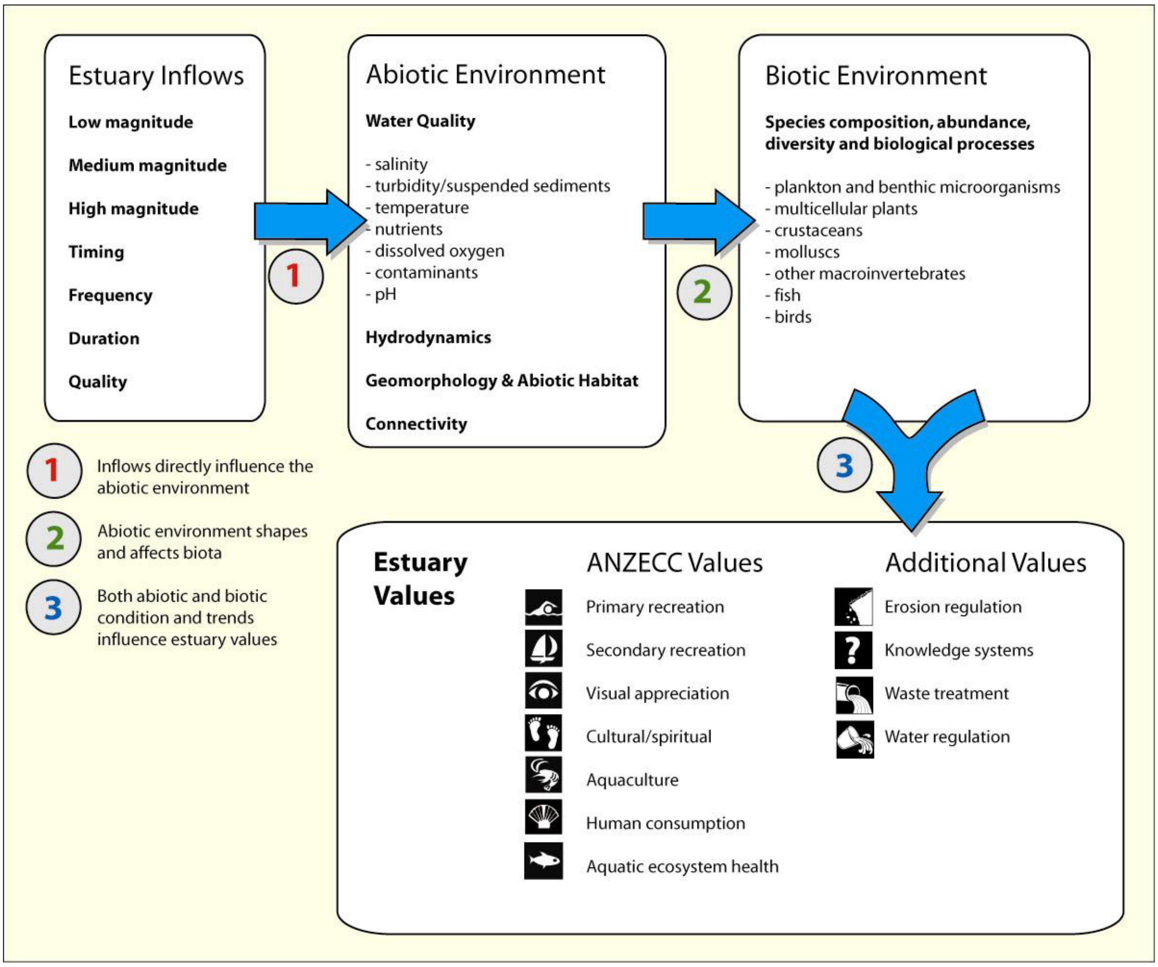

Figure 3.3. Conceptual diagram summarising the influence of flows and the potential impacts of changes to flow regime on estuaries and the concomitant impact on values.

This conceptualisation of potential links between flows and ecological response (Fig. 3.3) provides a starting point for the assessment of current knowledge about each of the links in Australian estuaries, as follows:

- estuary inflows: Section 4,
- estuarine abiotic environment: Section 5, and
- estuarine biota: Section 6.

3.1 Geographical variation

Australia's estuaries have been categorised into classes on the basis of their geomorphological characteristics (Fig. 3.4; see Young, 2001; Heap *et al*., 2001; Harris, 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.

The 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.

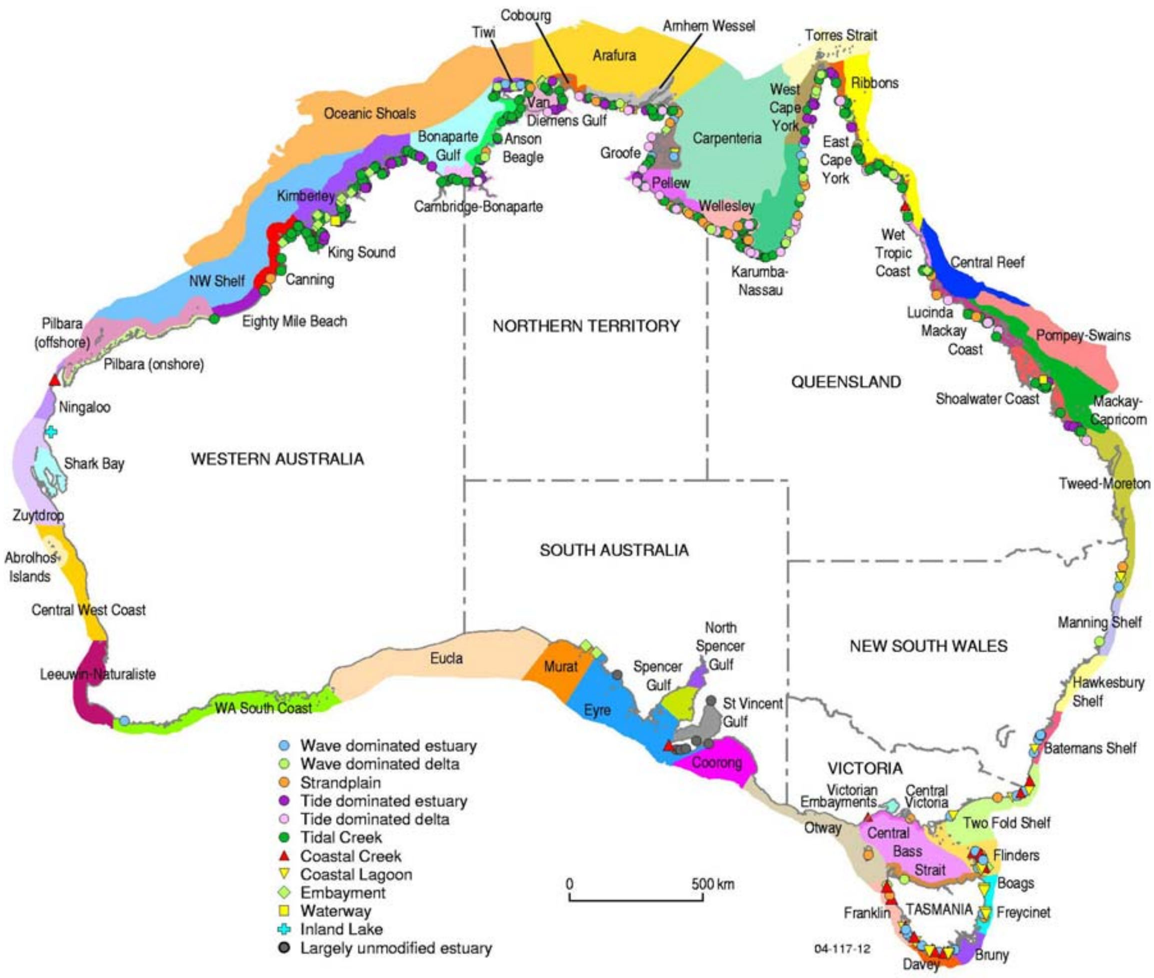

Figure 3.4. Map of Australia showing the distribution of estuaries by class and region (from OzEstuaries, 2006).

The most common types of estuary in Australia are tide-dominated (i.e. tidal creeks/flats, tidal estuaries and tidal deltas – see www.ozestauries.org) meaning that they are well flushed by tides. Consequently, stratification is uncommon and the waters are generally turbid though 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 the most common type of estuary in Australia.

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 discharge and intermittent.

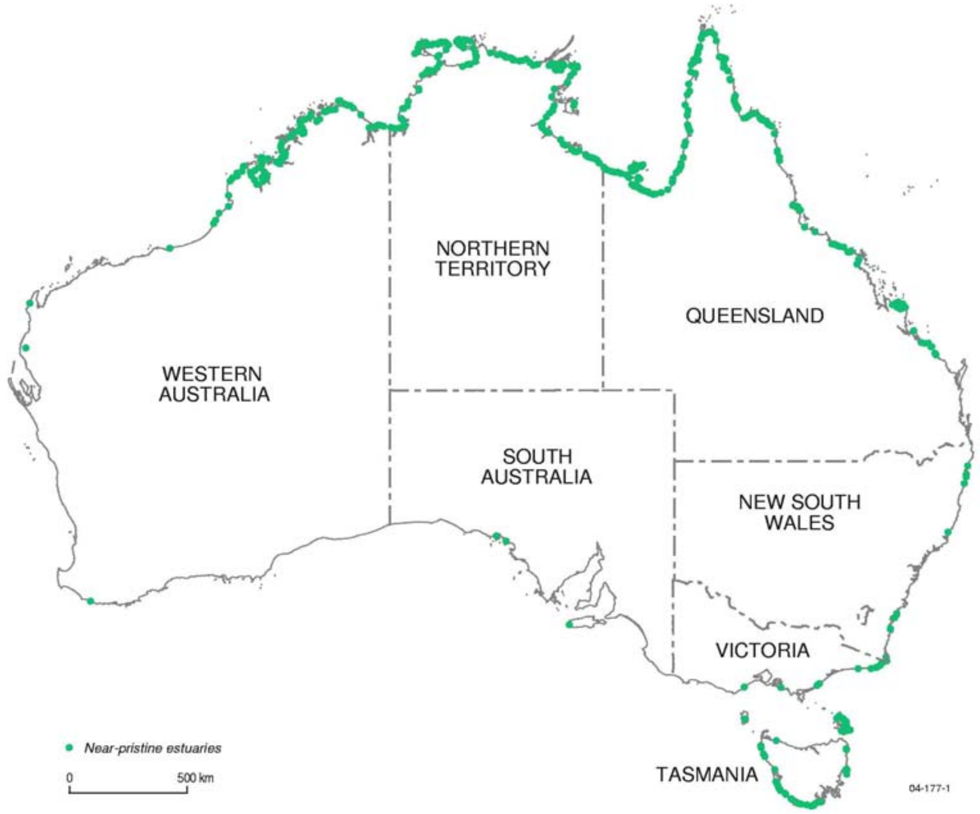

Figure 3.5. Australia’s near pristine estuaries (from OzEstuaries, 2006).

The majority of the estuaries in the north of Australia, many of which are also pristine or largely unmodified (Fig. 3.5), are tide-dominated and consequently well mixed (Table 3.2). In contrast, many estuaries in the south of Australia, are wave dominated (wave-dominated estuaries, lagoons and strandplains) 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 and scouring of the central basin). 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 3.6 shows the distribution of seasonal flow regime types for Australian rivers.

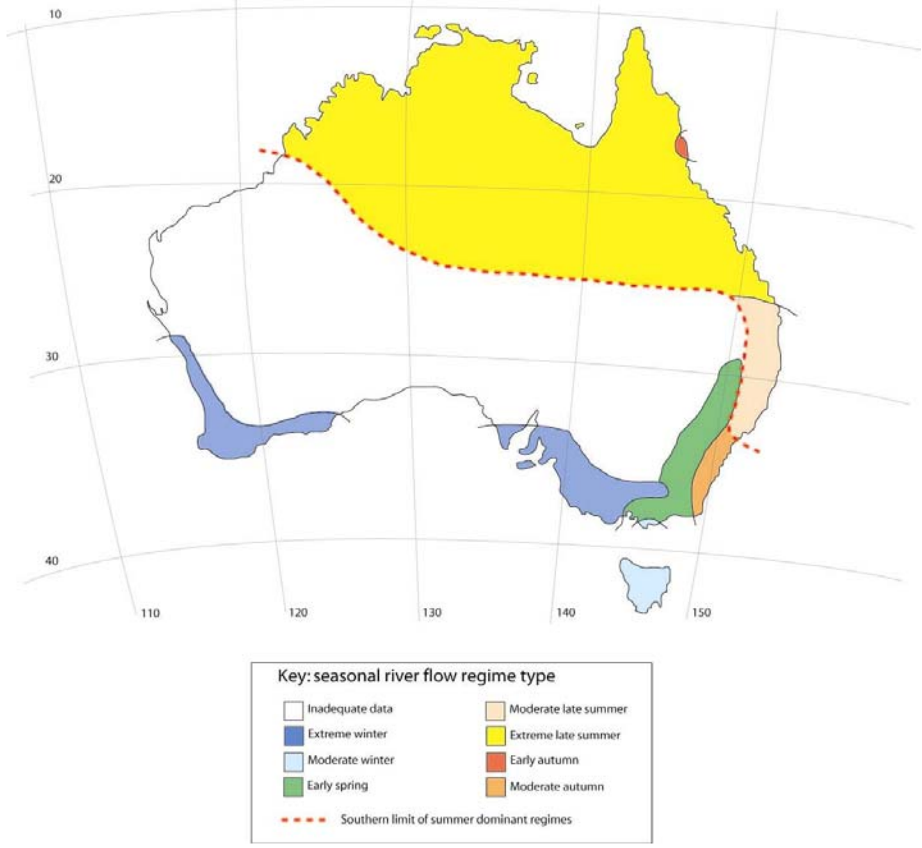

Figure 3.6. Seasonal patterns of river flow regime type (flow zone) (from Gillanders and Kingsford, 2002 (adapted from Finlayson and McMahon, 1988)).

Table 3.2. 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).

3.2 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 group of similar, regulated rivers as each will have its own specific flow regime (Chessman and Jones, 2001). The possibility for replication is often negligible as large, regulated Australian rivers vary widely in all facets of ecological, physical and flow parameters. Even comparing different flow regimes within the one river over time is fraught due to 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 the matter (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. In many situations, estuaries may not yet express the full impacts of changed flow regimes. In addition, 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 a response to a widespread environmental or ecosystem change.

Despite the difficulties highlighted above in performing research on environmental flows much research has been carried out in freshwater systems and is starting to be carried out in estuaries.

The following sections (4, 5 and 6) detail what is currently known about the effect of freshwater inflows on estuarine hydrodynamics, biogeochemistry, health and productivity within Australia.

4 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; see Appendix 3) 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. To do this properly we need to know what the river's flow regime is/was and how it can affects an estuary's abiotic and biotic environment (see Sections 5 and 6, respectively). However, with regard to river flows, only limited information on the three main elements is available for Australian estuaries. In addition, historical information is even more sparse so it is often difficult to determine the baseline flow regime for comparison with existing conditions. However, If you have flow gauges, present hydrology can be modelled and then used to model what the hydrology (flows) were when there was no development in the catchment.

The quantity of each flow is a critical factor. 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 (Jones *et al*., 2002 – cited in 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 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 but that the sediments are not the original source) 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, which equals flow, is very important as an increase in flow followed by a decrease almost always results in a large algal bloom (Thompson, 2001), including the now famous summer bloom of 2000 (Robson and Hamilton, 2003). The flow results in an input of nutrients either directly or by stratifying the estuary, resulting 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 when the valves on dams are opened).

The complexity of these flow characteristics makes them difficult to predict in a mechanistic fashion. Empirical data exists for some rivers but is often limited in estuaries both spatially and in detail across the hydrograph. In the majority of cases the actual volume and timing of flows reaching the estuary is not monitored. However, the above factors can be modelled in a statistical sense (although not deterministically because of climate variability, etc.) in many rivers (e.g. using the Integrated Quality and Quantity Model (IQQM) model). Although for ungauged rivers, where these flow models cannot be calibrated easily, these factors are reliant on rainfall-run-off models as well as river routing models. In these cases the statistical accuracy is lower (but can still be acceptable). Therefore, even though the volume and timing of flows reaching an estuary is 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.

Temporal pattern, quantity and quality of flows are related and connected in complex ways. Another way of expressing the relationship of inflows to ecological response is to consider 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 magnitude of flow may perform a different function in different climatic zones around the country (e.g. the extreme summer flows in the northern tropics versus the winter maximum flows for most of Tasmania's estuaries). For example, the Peirson *et al*. (2002) methodology for determining environmental flow requirements for estuaries uses three flow magnitudes as a basis for characterising inflow (see Appendix 4).

5 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. This list is expanded from 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).

5.1 Water quality

With respect to freshwater inflows to estuaries, the main physico-chemical water quality parameters of interest are nutrients, salinity, turbidity and temperature, though organic matter, dissolved oxygen and pH may also be affected. 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, 2001b, 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 of a water body 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.

5.1.1 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 actual area of an estuary as increased freshwater flow reduces the estuary length and reduced flow allows the tide to push saline waters 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 run-off from the catchment affected by salinity (Malcolm Robb, December 2005, pers. comm.).

The volume of freshwater inflow may cause significant stratification within an estuary with low-salinity freshwater tending to float above the denser, high-salinity seawater (OzEstuaries, 2006). In estuaries where tidal currents are not strong enough to mix the water column then stratification can occur. This may lead to anoxic and hypoxic events because bottom waters are effectively isolated from surface waters which contain higher dissolved oxygen due to gas exchange across the water surface and 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.).

5.1.2 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 (faster currents) 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 solids 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).

5.1.3 Temperature

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

5.1.4 Nutrients

Of all the water quality parameters, nutrient dynamics have received the most attention with respect to flows. 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 flow of the Fitzroy River (Qld) 97% of the dissolved organic carbon (DOC) within flood waters pass straight through the estuary with some being taken up within 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).

Delivery of nutrients to the Fitzroy River estuary during low flow is principally in the form of dissolved inorganic nutrients in contrast to high flow periods when a mixture of both dissolved and particulate nutrients from the upper catchment occurs (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 slightly less, 760 tonnes, exported (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 increase 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 a one-off release. 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, water quality of the Hawkesbury-Nepean River during low flows is likely to be more affected by the additions of wastewater from sewage treatment plants 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).

5.1.5 Dissolved oxygen

In general, dissolved oxygen (DO) concentrations in estuaries more relate to the availability of degradable detritus and stratification than 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, the amount of organic matter present and/or phytoplankton production, which 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).

5.1.6 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.

5.2 Hydrodynamics

The hydrodynamics of estuaries are dominated to varying degrees by tides, waves and freshwater input. The resultant 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.

The issue of freshwater inflow as a flushing mechanism needs to be considered very carefully as the situation in Australia is very different from that in Europe and North America in that Australian river flow is more episodic. Australian systems generally have a relatively higher proportion of land-derived nutrients so that 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 inflows as a flushing mechanism is equivocal in the Australian context. (This paragraph comes from 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 concluded to reflect inadequate tidal water movement to facilitate the transport and dispersion of larvae (Neira and Potter, 1992b – cited in Cappo *et al*., 1998).

A change to the inflow regime of an estuary is a change in hydrology and all observed changes to the abiotic and biotic environment are a result of some aspect of this change in hydrology. Therefore, particular aspects of hydrodynamics and its impact on abiotic and biotic environment are discussed throughout the text of Sections 4, 5 and 6.

5.3 Geomorphology and abiotic habitat

Freshwater inflow regime is an important factor in determining estuarine geomorphology, i.e. its size and shape. 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 document flow as influencing 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 (Sherwood *et al*., 1998 – cited in 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 (Kelly 2000 – cited in 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 (Peirson, 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 (Wooldridge, 1999 – cited in 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; Wooldridge, 1999 – cited in Barton, 2003; de Villiers and Hodgson, 1999 – cited in 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 flow-on effects to the biota present in estuaries (see Peirson *et al*., 2002), but these relationships are complex and not well studied.

5.4 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).

6 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 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 6.1 at the end of this chapter). However, there are a number of potential confounding factors 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; Finlayson *et al*., 1994 – cited in Growns and Growns, 2001). Table 6.1 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 suppressing the establishment of pests by flushing them 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 (Roberts, 2002; McCosker, 1994a both – cited in 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, however he draws this issue out as an important knowledge need for the Murray-Darling basin.

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, a negative relationship can also occur such as production decreasing due to decreased 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 5.

6.1 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-western Western Australia show 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 here in temperate West Australian estuaries (Gaughan and Potter, 1994, 1995). This has been supported with international data (Byun *et al*., 2005). Byun *et al*. (2005) showed through simulation 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 nutrients in the Swan River estuary (Chan and Hamilton, 2001; Robson and Hamilton, 2003) (phytoplankton biomass is related to nutrients in the Swan estuary as occurs 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).

6.2 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 which 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 (Adams *et al*., 1992 – cited in 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 (fresher water) 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 (Koch, 1999 – cited in 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 varies depending on several factors, particularly whether the algae occurs in the intertidal or subtidal zone, and may be direct or indirect (freshwater flow affects animals which feed on algae) (Gillanders and Kingsford, 2002). The affects 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 (Saenger, 1996 – cited in Platten, 1996)

It is thought that Australian saltmarshes are likely to be greatly affected by altered flows (Gillanders and Kingsford, 2002).

6.3 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 (*Penaeus merguiensis*, in tropical North Qld, Central Qld and the Logan River), school (*Metapenaeus macleayi*, in the Hunter River, Logan River and Clarence River), eastern king (*Penaeus plebejus*, Logan River), tiger (*Penaeus esculentus*, Logan River) and greasy (*Metapenaeus bennettae*, Logan River) prawns 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 influences the relationship between catch and flow. Therefore, each estuary will need its own assessment (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 eastern king prawn and moreton bay bugs (*Thenus orientalis*) and increased river outflow. In contrast, analysis of relationships between catch rates of banana prawns and mud crabs (*Scylla serrata*) and river flow in coastal waters adjacent to the Pioneer Valley was examined by Platten (2000) and no direct correlation was observed for the mud crabs, however results strongly suggest a time-lag effect. There was a clear relationship between catch and flow in 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, which are supported by other studies, these are (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). However, stable isotope values of freshwater inflows are distinct and can be traced through the estuarine food web. Stable isotopes may therefore prove to be a useful tool for examining the connection between freshwater inflows and estuarine consumers (Fry, 2002a – cited in Rozas *et al*., 2005).

6.4 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 flow and a positive effect the year following a 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 study 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 catchment.

6.5 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, have been shown to change as a result of increased freshwater flow and lowered salinity (Sakai and Nishihira, 1991 – cited in 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 principal mechanism for the differences in macroinvertebrate fauna at the different flow sites were due to the differing hydrological regime, 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.).

6.6 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 fishers 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 (i.e. years) 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 what little rainfall entered the system was trapped in the series of dams and weirs meaning a total lack of flow. In the wet years the opposite occurred, with water backed up in the impoundments continuing to flow into the estuary long after rainfall had stopped. So these impoundments have the effect of intensifying the effect of both dry and wet periods (Marcus Sheaves, 2006, pers. comm. (Sheaves *et al.*, in prep)).

6.7 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 occurred around flows probably due to the presence of freshwater for drinking close to their feeding grounds, with the size of flow being 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 (Yates *et al*., 1993 – cited in Ravenscroft and Beardall, 2003). As with other fauna, optimal flow regimes to maintain the health of bird populations is likely to be estuary specific (Ravenscroft and Beardall, 2003).

In spring, 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 6.1. 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^{3}s^{-1}) and 2.9 x10^{6} ML (91.9 m^{3}s^{-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 5th to 95th 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

6.8 Geographic considerations

Hamilton and Gehrke (2005) reported that environmental flow research has been concentrated primarily in the temperate freshwater rivers of Australia as that is the region where most rivers suffer flow impacts from regulation. In contrast, most research into the effects of flow on estuarine biota has taken place in tropical and subtropical regions (Fig. 6.1). There is therefore spatial heterogeneity in the amount of knowledge on impacts of flows 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 6.1 shows the locations of studies examining the relationship between freshwater inflows and estuarine biota mapped over the distribution of seasonal patterns of river flow.

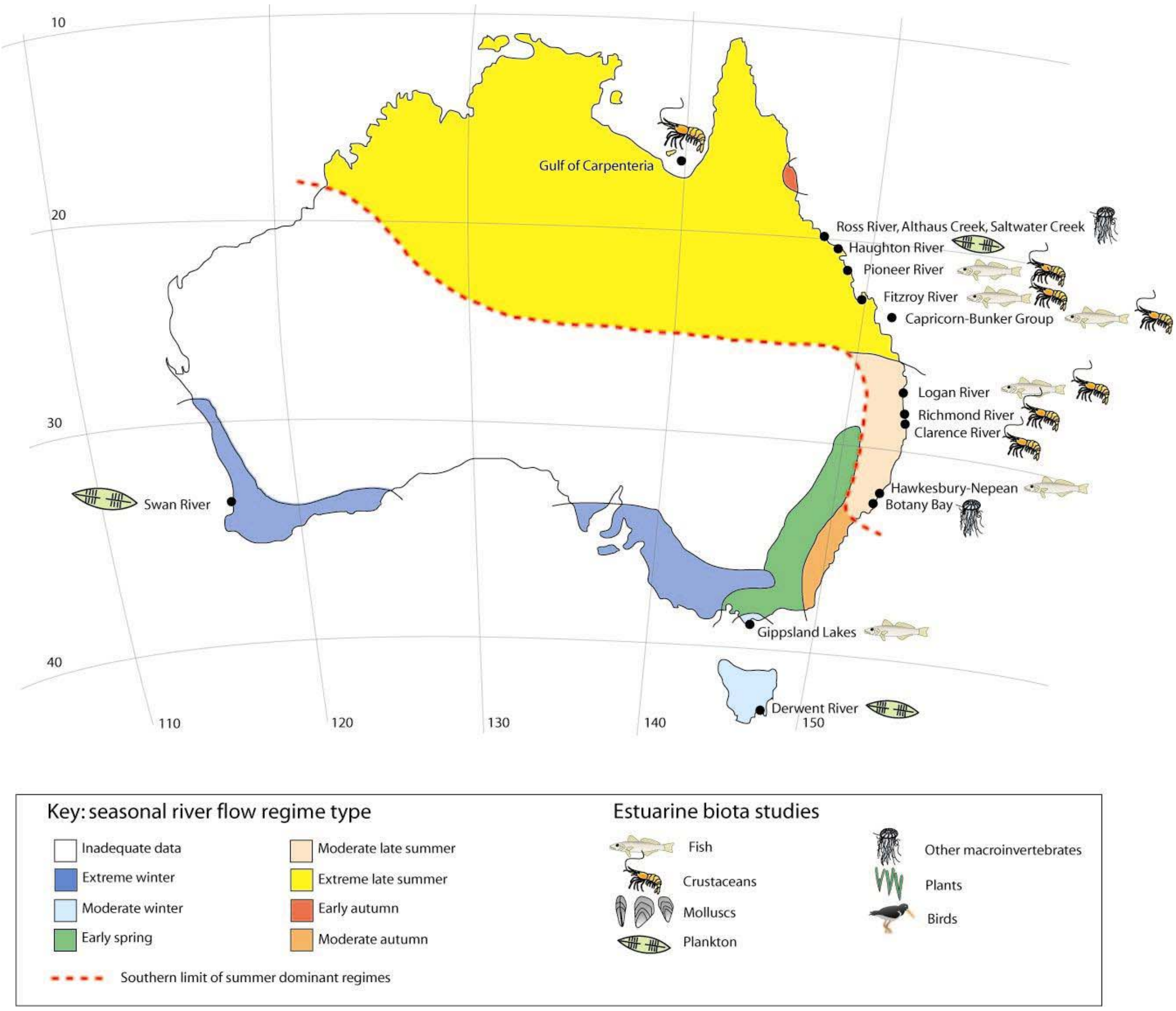

Figure 6.1. The locations of studies examining the relationship between river flows and estuarine biota mapped over the distribution of seasonal patterns of river flow (modified from Gillanders and Kingsford, 2002 (adapted from Finlayson and McMahon, 1988)).

7 Current Methodologies for Determining Freshwater Flows to Estuaries From Around Australia

All states have undertaken activities towards implementing Council of Australian Governments (COAG, 1994) water reforms including development of environmental flow programs and have policy documents relating to determination of flow allocations (see Arthington and Pusey, 2003; Schofield and Burt, 2003). The flow allocation processes prior to the initiation of the National Water Initiative 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. The flow allocation assigned to rivers is influenced by social, economic and environmental factors. Some of the difficulties in setting these allocations are outlined by Allan and Lovett (1997 – cited in 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 often 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 (see Appendix 6 for more information on the principles and policies related to the regulation of freshwater flows in each state). The National Water Initiative seeks to address some of the problems highlighted by these criticisms.

7.1 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, 1998; Arthington *et al*., 1998a,b; Arthington and Zalucki, 1998; 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 freshwater allocation to freshwater ecosystems" (Close, 2005, p. 11) and despite recent attempts to address estuarine 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).

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 approaches 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. However, this said, 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.

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 (see Appendix 6) 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 (see Appendix 6). 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, 2002). 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 were 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 which is a Tasmanian Government initiative that provides a powerful and objective framework to assist conservation and restoration management activities (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.

8 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, in consultation with environmental flows and estuary experts consulted during this project.

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.

8.1 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. A separate process may be required to identify research needs of flow managers comprehensively.

The prioritisation process was conducted during a two-day workshop attended by representatives from state and Commonwealth governments, research institutions and industry representatives. For a full description of the workshop process, objectives and outputs see the 'Workshop Report' (Appendix 7). The process to identify and prioritise knowledge-needs is summarised in Figure 8.1.

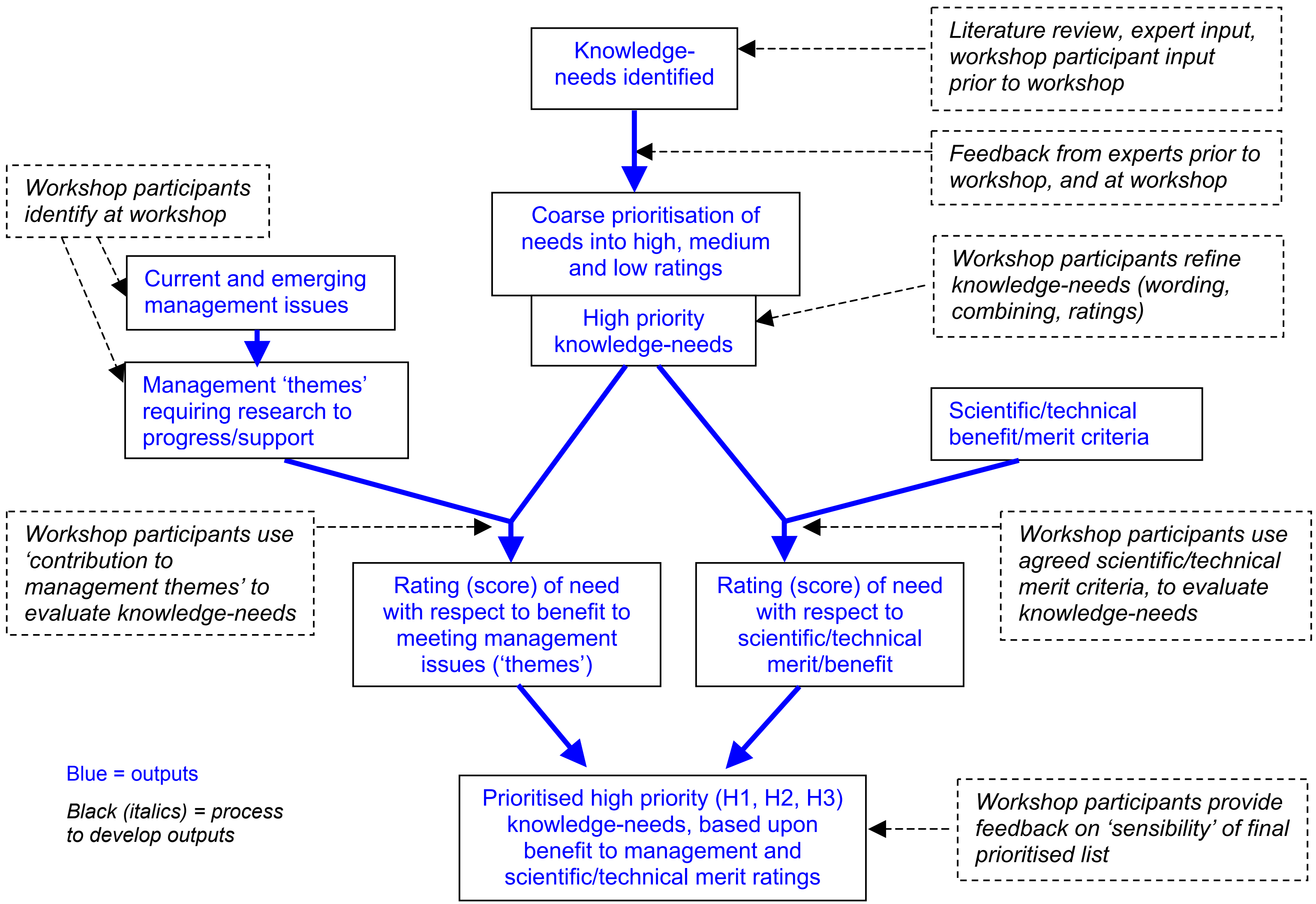

Figure 8.1. Process (included outputs) to prioritise knowledge-needs for freshwater flows to estuaries research.

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 8 for the full initial list of 69 knowledge-needs identified).

Through the workshop process a list of 19 ‘high priority’ knowledge-needs were identified and agreed to by the workshop participants (see Table 8.1).

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.

8.1.1 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?).

Participants then ranked the knowledge-needs according to scientific merit using the discussion as a basis.

8.1.2 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 (see Appendix 9 for further detail of the underlying management issues of each management theme) 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 theme 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 8.1).

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

During the workshop each 'high' priority knowledge-need was further ranked in terms of their scientific merit and benefit to management from highest (H1) to lowest (H3).

Table 8.1 shows the resulting rankings. They are listed in priority order of benefit to management because of the focus on ensuring the research leads to practical outcomes. The rank for scientific merit is also indicated.

Table 8.1. '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**

Code	Knowledge Needs	Benefits to management†	Scientific merit†
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
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

Code	Knowledge Needs	Benefits to management[†]	Scientific merit[†]
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**
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 8.2.

Table 8.2. 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**

Knowledge Needs	Priority
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**
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**

Knowledge Needs	Priority
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
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

8.3 Frameworks for organising knowledge needs

Initially the identified knowledge-needs were grouped, using the framework developed in this report (Section 3, Figure 3.3), under ten themes generally relating to freshwater flows, abiotic environment and biotic environment (Table 8.3; see Appendix 8).

Table 8.3. High priority knowledge-needs identified as contributing to the themes identified within Section 3, Appendix 8, 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 8.1 for knowledge-need wording and code.

Table 8.4 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 following framework does demonstrate the links between the science and management needs.

Table 8.4. 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 8.1 for knowledge-need wording and code.

Finally, a framework based around the Adaptive Management Framework (AMF) was proposed at workshop for organising the research priorities (Figure 8.2).

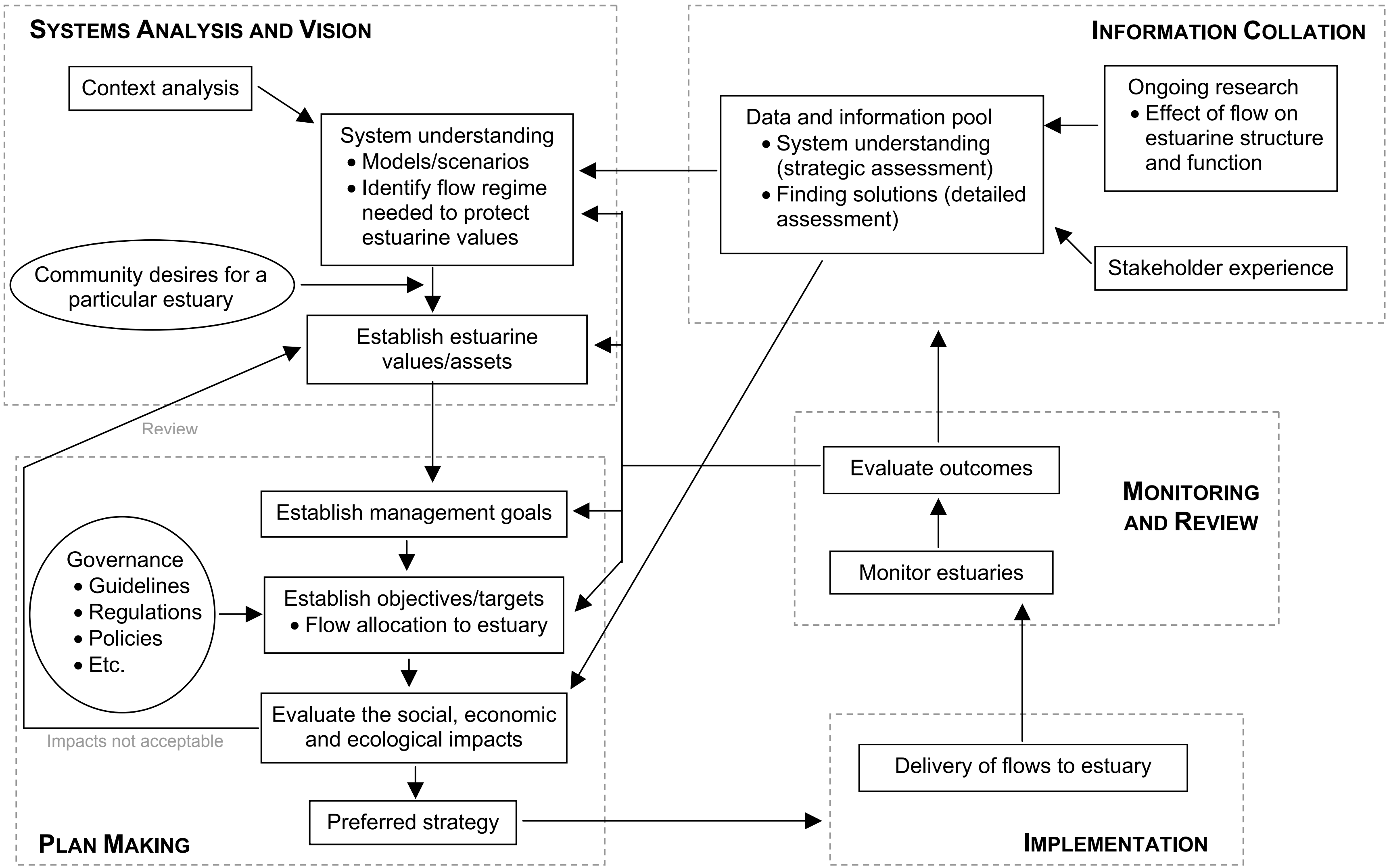

Figure 8.2. Modified Adaptive Management Framework relating to freshwater flows to estuaries (based upon an AMF (Lawrence and Bennett, 2002) with workshop participants and project team modifications specific to estuary flows).

The knowledge-needs have here been aligned to the modified AMF (Table 8.5). There are parts of the framework for which needs have not been specifically identified. For example, social knowledge-needs, as mentioned previously, were not actively investigated and will therefore be underrepresented here.

Table 8.5. 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*

Adaptive Management Framework Theme	Knowledge-need that (when filled) will contribute to theme[†]
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.

8.4 Conclusions

These knowledge-needs, identified and prioritised through a process involving literature reviews and expert (scientific and management) opinion, span a range of topics and spatial and temporal scales. Their value in terms of scientific merit and benefits to managing flows to estuaries were used to prioritise the knowledge needs. The separation of scientific and management values provides the flexibility to weight these two aspects differently so that different organisations or individuals can consider the importance of these aspects to their own purpose and needs.

In terms of comprehensiveness, the 19 high-priority knowledge needs provide a good coverage of the core components of an environmental-based framework, reasonable coverage of the major management themes identified and patchy coverage of a modified adaptive management framework. This lack of comprehensiveness according to some frameworks is a consequence of the process used to identify the knowledge needs, which was biased in favour of biophysical knowledge needs. To overcome this limitation two options are offered:

(i) repeat the identification and prioritisation process with a focus on non-biophysical literature as the basis for identifying the knowledge needs, to complement this more biophysically-focused process; or

(ii) undertake a different identification and prioritisation process that uses a management-based framework in the first instance, to focus investigation of knowledge-needs in key management areas.

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Appendix 2: Determination of draft values which may be present in Australian estuaries.

The environmental values of estuaries as an ecosystem are made up of the ecosystem goods and services provided by the ecosystem through water quality, habitat, flora and fauna, and physical attributes. Determining the environmental values of any particular estuary should be undertaken through a transparent process involving community input and based on local understanding and knowledge of the particular estuary. However, a list of potential values, ‘draft values’ that might be recognised for any particular estuary, is required to underpin a framework for determining knowledge needs and priorities. The process described here groups relevant ecosystem goods and services of estuaries to provide and initial list of draft values.

Table A2.1. List of ecosystem goods and services potentially provided by estuaries and their equivalent categories under other models. Entries in italics are additional to those listed in the Millennium Ecosystem Assessment (2005).

Category	Ecosystem goods and services	ANZECC WQ Values	Notes
Provisioning services	Food (fisheries)	Human consumption	Includes productivity of fisheries species and their food sources. General productivity covered under ecosystem health (though in practice these are indistinguishable)
	Fibre (*including clothing and shelter*)		Not a major value in Australia
	Fuel		Not a major value in Australia
	Genetic resources	Aquatic ecosystem health	Potential future service
	Biochemicals, natural medicines and pharmaceuticals	Aquatic ecosystem health	Potential future service
	Ornamental resources	Aquatic ecosystem health	Potential future service
Regulating services	Air quality regulation		Depends on extent and ecosystem health
	Climate regulation		Depends on extent and ecosystem health
	Water regulation		Flood mitigation, ponded pastures
	Erosion regulation		

Category	Ecosystem goods and services	ANZECC WQ Values	Notes
	Water purification	Aquaculture	Also includes an element of waste treatment
	Waste treatment		
	Disease regulation		Include in waste treatment
	Pest regulation		Some marine pests but not a major value
	Population balance	Aquatic ecosystem health	
	Translocation and dispersion		Usually valued as part of Human consumption or ecosystem health or cultural and spiritual reasons rather than connectivity *per se*
	Natural hazard regulation		Include in erosion regulation (e.g. storms)
Cultural services	Cultural diversity	Cultural and spiritual	
	Spiritual and religious values	Cultural and spiritual	
	Knowledge systems		Science and understanding
	Inspiration	Visual appreciation	
	Aesthetic and *serenity* values	Visual appreciation	
	Social relations	Cultural and spiritual	
	Sense of place	Cultural and spiritual	
	Cultural heritage, historic and artistic values	Cultural and spiritual	
	Recreation and ecotourism	Primary and secondary recreation	
	Non-use value (existence, *bequest)*	Aquatic ecosystem health	Difficult to define – adequately covered under aquatic ecosystem health

Category	Ecosystem goods and services	ANZECC WQ Values	Notes
Supporting services	Soil formation		Minimal
	Photosynthesis		Supports values of provision of food and aquatic ecosystem health
	Primary production		Supports values of provision of food and aquatic ecosystem health
	Nutrient cycling/regulation		Supports water purification
	Water cycling		Supports water purification
	Refugia function		Supports values of provision of food and aquatic ecosystem health
	Nursery function		Supports values of provision of food and aquatic ecosystem health

Water quality values for estuaries can be defined through reference to the National Water Quality Management Strategy, ANZECC guidelines (NWQMS, 2000). The NWQMS water quality values relevant to flow impacts on estuaries are:

- aquatic ecosystems,
- primary industries (aquaculture and human consumption of aquatic foods),
- recreation (including primary and secondary recreation) and aesthetics, and
- cultural and spiritual values.

Combining those values that are relevant to Australia and expanding the accepted water quality values provides a comprehensive draft list of suggested values for estuaries (Table A2.2).

Table A2.2 List of suggested draft values for estuaries derived from a comprehensive list of ecosystem goods and services provided by estuaries. Entries in **bold** are standard ANZECC water quality values.

Suggested Draft Value	Notes
Human Consumption (fisheries)	primary and secondary productivity is a separate though closely related draft value
Aquatic Ecosystem Health	includes broad-scale regulatory services, future uses, biodiversity/population structure and provision of habitat
Water regulation	includes flood mitigation
Erosion regulation	sedimentation, buffering by riparian areas, protection from storm events

Suggested Draft Value	Notes
Aquaculture	includes provision of clean, but not freshwater
Waste treatment	includes water purification and disease regulation from sources such as industry, waste water discharge, aquaculture, agriculture
Cultural and spiritual	includes a range of social, cultural and spiritual services that are highly locality-specific. May include aspects of tourism
Knowledge systems	science and understanding
Visual Appreciation	may include aspects of tourism
Primary Recreation	may include aspects of tourism
Secondary Recreation	may include aspects of tourism

One further value should also be considered namely shelter provided by estuaries for ports, harbours marinas and moorings, whether recreational or commercial. This value will not be overly influenced by flows and is not considered here.

Appendix 3: Components of flow regime.

The following information is taken from Poff *et al*. (1997, pp. 770-771).

"The magnitude of discharge[1] at any given time interval is simply the amount of water moving past a fixed location per unit time. Magnitude can refer either to absolute or to relative discharge (e.g. the amount of water that inundates a floodplain). Maximum and minimum magnitudes of flow vary with climate and watershed size both within and among river systems.

The frequency of occurrence refers to how often a flow above a given magnitude recurs over some specified time interval. Frequency of occurrence is inversely related to flow magnitude. For example, a 100-year flood is equalled or exceeded on average once every 100 years (i.e. a chance of 0.01 of occurring in any given year). The average (median) flow is determined from a data series of discharges defined over a specific time interval, and it has a frequency of occurrence of 0.5 (a 50% probability).

The duration is the period of time associated with a specific flow condition. Duration can be defined relative to a particular flow event (e.g. a floodplain may be inundated for a specific number of days by a ten-year flood), or it can be a defined as a composite expressed over a specified time period (e.g. the number of days in a year when flow exceeds some value).

The timing, or predictability, of flows of defined magnitude refers to the regularity with which they occur. This regularity can be defined formally or informally and with reference to different time scales (Poff, 1996). For example, annual peak flows may occur with low seasonal predictability or with high seasonal predictability.

The rate of change, or flashiness, refers to how quickly flow changes from one magnitude to another. At the extremes, 'flashy' streams have rapid rates of change, whereas 'stable' streams have slow rates of change.

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[1]Discharge (also known as streamflow, flow, or flow rate) is always expressed in dimensions of volume per time. However, a great variety of units are used to describe flow, depending on custom and purpose of characterisation: Flows can be expressed in near-instantaneous terms (e.g. ft^3/s and m^3/s) or over long time intervals (e.g. acre-ft/yr [or ML/yr or GL/yr]).

Appendix 4: List of predicted effects on estuarine processes from alteration of freshwater inflows

Table A4.1. Check list of predicted effects on estuarine processes of alterations to low, middle/high and all freshwater inflows (from Pierson *et al.,* 2002).

Inflow magnitudes	Associated processes potentially impacting on estuarine ecosystem
Low magnitude inflows	
Low – 1	Increased hostile water quality conditions at depth
Low – 2	Extended duration of elevated salinity in upper-middle estuary adversely affecting sensitive fauna
Low – 3	Extended duration of elevated salinity in upper-middle estuary adversely affecting sensitive flora
Low – 4	Extended duration of elevated salinity in lower estuary allowing invasion of marine biota
Low – 5	Extended duration when flow-induced currents cannot suspend eggs or larvae
Low – 6	Extended duration when flow-induced currents cannot transport eggs or larvae
Low – 7	Aggravation of pollution problems
Low – 8	Reduced longitudinal connectivity with upstream river systems
Low – 9†	Increased retention times in estuary reaches
Low – 10†	Nutrient influxes from groundwater as driven by saline water intrusion
Low – 11†	Reduced longitudinal connectivity with the downstream marine environment
Middle/high magnitude inflows	
M/H – 1	Diminished frequency that the estuary bed is flushed of fine sediments and organic material (reduction in physical habitat quality)
M/H – 2	Diminished frequency that deep sections of the estuary are flushed of organic material (reduction in water quality)
M/H – 3	Reduced channel maintenance processes
M/H – 4	Reduced inputs of nutrients
M/H – 5	Reduced lateral connectivity and reduced maintenance of ecological processes in water bodies adjacent to estuary
All magnitude inflows	
All – 1	Altered variability in salinity structure
All – 2	Dissipated salinity/chemical gradients used for animal navigation and transport
All – 3	Decreases in the availability of critical physical habitat features, particularly the component associated with higher water velocities

Table is taken from Close (2005, p. 6). †the checklist of impact processes arising from Peirson *et al.* (2002) is not a static thing. There are now eleven 'Low' impact processes (Keith Bishop, 2006, pers. comm.).

Appendix 5: 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 6: Legislation and policies relevant to the regulation of freshwater flows with possible relevance to estuaries.

Below is a summary of the major governmental legislation and policies with regard to environmental flows and water management, though few specifically address the flow requirements of estuaries.

Australian Government

- **Water Reform Framework**
  The Framework includes provisions for water entitlements and trading, environmental requirements, institutional reform, public consultation and education, water pricing and research. See: http://www.deh.gov.au/water/policy/coag.html
- **National Water Initiative**
  The Intergovernmental Agreement on a National Water Initiative (NWI) renewed commitments of the 1994 Water Reform Framework Agreement and set a new schedule of actions. By June 2005, all states and territories, except for Western Australia, had signed the NWI.
- **Water Policy Agreement**
- **National Water Quality Management Strategy**
- **National Framework for Marine and Freshwater Quality Protection**
- **National Strategy for Ecologically Sustainable Development**
- **National Principles for the provision of Water for Ecosystems**
- **Council of Australian Governments' (COAG) Framework Agreement on Water Resources Policy Reforms**
- **Australian and New Zealand Environment and Conservation Council (ANZECC)**
  Guidelines for Fresh and Marine Water Quality
- **The National Land and Water Resources Audit**
- **Wetlands Policy of the Commonwealth Government of Australia**
  The policy recognises changes to water flow patterns and water quality as a major threat to Australia's Wetlands. See:
  http://www.deh.gov.au/water/wetlands/publications/policy.html

New South Wales

New South Wales has set river flow objectives that include among other things "maintaining or rehabilitating estuarine processes and habitats" (Chessman and Jones, 2001, p. 8).

- **Estuary Management Policy**
- **Estuary Management Program**
  The purpose of this program is the production of estuary management plans which are entirely consistent with the tenets of total catchment management and ecologically sustainable development.
- **The NSW State Rivers and Estuaries Policy**
- **NSW Coastal Policy**
- **Wetlands Management Policy**

This Policy will assist in providing wetlands with water of appropriate volume and quality

- **NSW Weirs Policy**
- **Water Quality Objectives (WQOs) and River Flow Objectives (RFOs)**
(information provided by The Department of Environment and Conservation, NSW – Penny Vella and Peter Scanes).
The NSW Government and community have specified the environmental values and level of protection they are seeking for ambient water quality for surface fresh and estuarine waters in each NSW catchment, through agreed Water Quality Objectives (WQOs) (http://www.epa.nsw.gov.au/ieo) and other related targets such as salinity targets.

  WQOs are the environmental values and human uses that have been identified by the community and NSW Government for a waterway as long-term management goals and the water quality needed to protect them. Where WQOs are being achieved the aim is to protect them. Where WQOs are not being achieved the aim is to achieve them over time, with contributions from all sources of pollution within the catchment. Water quality refers to the physical, chemical and biological attributes of water that affect its ability to support environmental values and human uses.

  The NSW Government has also approved River Flow Objectives (RFOs) across most of the streams in NSW, following extensive community consultation. These can be found at www.environment.nsw.gov.au/ieo. The RFOs are 12 high-level objectives that represent the key features of flow regime that support (or impact on) environmental values, including aquatic ecosystems, wetlands and water quality. The RFOs reflect best practice in the science and management of river flows by taking a holistic approach to managing flows for the needs of the whole aquatic ecosystem, rather than concentrating only on identified known species or sites. All of the RFOs help contribute to key ecological flow needs in estuaries, but RFO 12 (“Maintain or rehabilitate estuarine processes and habitats”) specifically recognises the importance of estuaries.

  Applying these objectives, NSW is implementing the National Water Quality Management Strategy and Australian Water Quality Guidelines, as agreed to by all the jurisdictions.

  In addition, as part of the same framework, marine WQOs are shortly to be released.

- ***Water Management Act 2000***
The *Water Management Act 2000* states Parliament’s intention that, within one year of the new Act coming into operation, certain ‘special’ water resources must be identified and management plans containing Environmental Water Allocations (EWAs) made in respect of them. In respect of water resources generally, EWAs should be established for all state water sources as soon as practicable.
- **The NSW Water Reforms**

__Northern Territory__

- ***The Northern Territory Water Act (1992)***
The Act covers the investigation, use, control, protection, management and administration of water resources within the Northern Territory.

Queensland

- **State Coastal Management Plan**
  The State Coastal Management Plan describes how the coastal zone is to be managed as required by the *Coastal Protection and Management Act 1995*. The state coastal plan provides coastal management policy direction and defines how these directions should be implemented by government, industry and the community. Environmental flows to estuarine systems are considered. See: http://www.epa.qld.gov.au/environmental_management/coast_and_oceans/coastal_management/state_coastal_management_plan/

- ***Queensland's Water Act 2000***
  Water allocation is dealt with principally under the *Water Act 2000.* Under the Act, a Water Resource Plan (WRP) can be created as subordinate legislation to provide a framework for allocating and managing surface and groundwater in an ecologically sustainable manner and stays in effect for ten years. The definition of a waterway or 'watercourse' under the Act explicitly excludes estuaries unless they are specifically included in regulations.

  1. Watercourse means a river, creek or stream in which water flows permanently or intermittently –
     (a) in a natural channel, whether artificially improved or not; or
     (b) in an artificial channel that has changed the course of the watercourse;

     but, in any case, only –

     (c) unless a regulation under paragraph (d), (e) or (f) declares otherwise: at every place upstream of the point (*point A*) to which the high spring tide ordinarily flows and reflows, whether due to a natural cause or to an artificial barrier; or
     (d) if a regulation has declared an upstream limit for the watercourse: the part of the river, creek or stream between the upstream limit and point A; or
     (e) if a regulation has declared a downstream limit for the watercourse: the part of the river, creek or stream upstream of the limit; or
     (f) if a regulation has declared an upstream and a downstream limit for the watercourse: the part of the river, creek or stream between the upstream and the downstream limits.

  2. Watercourse includes the bed and banks and any other element of a river, creek or stream confining or containing water.

- **State Interest Planning Policy for Queensland Waters**
  The Environmental Protection Agency state interest in Queensland waters incorporates water quality (including ecosystem health), water quantity or environmental flows, and water use, for streams, wetlands, and groundwater systems. See: http://www.epa.qld.gov.au/publications?id=377

- **Environmental Protection (Water) Policy**
  The Environmental Protection (Water) Policy 1997 (EPP Water) helps protect Queensland's waterways, now and in the future. The EPP Water identifies five environmental values to be protected:
  - biological integrity (maintaining the water quality so the plants and animals living in the waterway can survive)
  - suitability for recreational use
  - suitability for drinking after minimal treatment
  - suitability for agricultural use
  - suitability for industrial use

  http://www.epa.qld.gov.au/environmental_management/planning_and_guidelines/policies_and_strategies/protection_policies/#gen12

- **Waterway barriers**
  The construction or raising of a waterway barrier requires a development approval under the *Integrated Planning Act 1997*. Waterway barriers are structures such as dams and weirs across a waterway that stop, or form a significant barrier to the flow of water and to fish movement. Waterways include rivers, creeks, streams, watercourses or inlets of the sea, in fresh, brackish and salt waters (i.e. including estuarine areas). Included in the development approval is an assessment under the *Fisheries Act 1994*, administered by the Department of Primary Industries and Fisheries (DPI&F). An exemption may be given under the *Fisheries Act 1994* for the need to provide fish passage at the waterway barrier works provided DPI&F is satisfied that passage is not necessary or desirable for the best management, use, development or protection of fisheries resources or fish habitat. Certain minor waterway barrier works are self-assessable and do not require an approval provided they meet the criteria set out in relevant self-assessable codes.

- ***Wild Rivers Act 2005***
  The intention of the *Wild Rivers Act 2005* is to protect the natural values of declared 'wild' rivers by regulating future development activities within the river and its catchment area.

South Australia (information from Liz Barnett (and colleagues), 2006, pers. comm.).

- ***Natural Resources Management Act 2004***
  The *Natural Resources Management (NRM) Act 2004* repeals the *Animal and Plant Control Act 1986*, the *Soil Conservation and Land Care Act 1989*, and the *Water Resources Act 1997*. The Act promotes sustainable and integrated management of and provides protection for the state's natural resources, and establishes a state-wide peak body, the Natural Resources Management Council, which is responsible for developing the state NRM plan.

- **State NRM Plan 2006**
  The State NRM Plan 2006 is a requirement of the *NRM Act 2004* and contains strategic policy at a state level for managing South Australia's natural resources. It is based on a set of guiding principles that aim to clarify the thinking and intent behind successful and sustainable natural resources management. The two themes prominent in the NRM Plan are: 1) landscape scale, or whole-of-ecosystem, approaches; and 2) genuine community engagement.

- **Regional NRM Plans**
  Under the *NRM Act 2004*, Regional NRM Boards must prepare and maintain a regional NRM Plan for each NRM region across South Australia. These must contain water allocation plans for prescribed water resources within each of the regions.

- ***Environment Protection Act 1993***
  The *Environment Protection Act 1993* establishes the Environment Protection Authority, and provides for the protection of the environment; EPA Strategic Plan 2004-2007; Environment Protection (Water Quality) Policy 2003 (also Waste, Air and Noise policies); Codes of Practice or Guidelines.

- **The Environment Protection (Water Quality) Policy 2003**
  The Environment Protection (Water Quality) Policy 2003 provides a state-wide approach to the protection of water quality from point and diffuse pollution sources across all South Australian water bodies (the *NRM Act 2004* focuses more on water management, water quantity and biodiversity conservation than on environmental protection). The Water Quality Policy is expected to provide improvements in the environmental quality of aquatic ecosystems and benefit the community and industry

as a result of improved recreational, tourism, aquacultural, agricultural and industrial opportunities.

- ***Coast Protection Act 1972***
  The *Coast Protection Act 1972* provides for the conservation and protection of the beaches and coast of the state, and other purposes, and establishes the Coast Protection Board. The Act is currently undergoing amendment to the *South Australian Coast Act 1972*, in which the objects are: a) to promote the principles of ecologically sustainable development in relation to the use and management of the coast and coastal environment of the state; and b) to provide for the implementation and coordination of measures to protect the coast and coastal environment of the state.
- ***Dolphin Sanctuary Act 2005***
  The *Dolphin Sanctuary Act 2005* establishes a sanctuary to protect the dolphin population of the Port Adelaide River estuary and Barker Inlet and its natural habitat, and to provide for the protection and enhancement of the Port Adelaide River estuary and Barker Inlet. Included in the objects is that water quality within the Port Adelaide River estuary and Barker Inlet should be improved to a level that sustains the ecological processes, environmental values and productive capacity of the Port Adelaide River estuary and Barker Inlet.
- **South Australia’s Strategic Plan 2004**
  There are six interrelated objectives in the Strategic Plan – Growing Prosperity, Improving Wellbeing, Attaining Sustainability, Fostering Creativity, Building Communities and Expanding opportunity. In Objective 3, Attaining Sustainability, Target 3.1 is to increase environmental flows by 500 GL in the Murray-Darling and major tributaries by 2008 as a first step towards improving sustainability in the Murray-Darling Basin, with a longer-term target to reach 1500 GL by 2018.
- **Environmental Flows for the River Murray 2005**
  ‘Environmental Flows for the River Murray: South Australia’s framework for collective action to restore river health 2005 – 2010’ 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. The strategy builds on existing River Murray plans and management activities and provides strategic direction to the management of environmental flows in the River Murray in South Australia.
- **River Murray Environmental Flows Program**
  The Program provides policy advice to government on environmental flows issues, in conjunction with on-ground delivery of water resources services in the Murray-lands region.
- **Murray-Darling Basin Commission Integrated Catchment Management Policy**
- **Living Coast Strategy 2004**
  Sets out environmental policy directions for sustainable management of South Australia’s coastal, estuarine and marine environments.
- **Marine Planning Framework for South Australia 2006**
  Provides for the development of six marine plans covering state waters in South Australia’s eight marine bioregions based on the principles of ecologically sustainable development, ecosystem-based management and adaptive management. The marine plans establish an overarching strategic planning framework to guide state and local government planners and natural resources managers in the development and use of the marine environment.

- **Blueprint for the South Australian Representative System of Marine Protected Areas 2004**
  A commitment to conserve and protect areas of high conservation value, species that are rare, threatened or have special needs, and a framework for the integrated management of a range of human activities whilst achieving the conservation objectives of Marine Protected Areas.
- **Draft Estuaries Policy and Action Plan 2005**
  Coordinates management, planning, conservation, research and monitoring, and community involvement in estuaries (aligns with the State Natural Resources Management Plan and State Planning Strategy).
- **Wetlands Strategy for South Australia 2003**
  Wetland conservation, management and protection (aligns with State Natural Resources Management Plan).
- **Water Proofing Adelaide 2004**
  A strategy for effective, affordable, socially and environmentally acceptable management of Adelaide's water use and water systems.
- **Management Plan for the South Australian Lakes and Coorong Fishery 2005**
  Provides a five-year framework to address key challenges facing the future management of the Lakes and Coorong fishery and sets out a formal ecologically sustainable development based harvest strategy for the fishery. The management plan includes an outline of the current best knowledge regarding the requirements of native fish and provides direction for the management of environmental flows.

Tasmania

- ***Tasmanian Water Management Act 1999***
  The Act recognises the 'environment' as a legitimate user of water. Encompassed within the Act is the provision for issuing of licenses for: water allocations, water diversions, approval for dam building (both on- and off-stream). The Act also provides for management of the state's groundwater resources.
- **The Tasmanian Water for Ecosystems Policy**
  Provides guidelines on determining environmental flow requirements:
  http://www.dpiwe.tas.gov.au/inter.nsf/WebPages/JMUY-55A8CZ?open
- **State Policy on Water Quality Management**
  http://www.dpiwe.tas.gov.au/inter.nsf/WebPages/CDAT-53LVTP?open
- **Water Development Plan**
  The Water Development Plan has as one of its goals the determination of environmental flow requirements for Tasmania's catchments. Environmental flow requirements have been determined for a number of the catchments in the north-east and central-north regions of Tasmania (Tasmanian Department of Primary Industries, Water and Environment, 2001).
  http://www.dpiwe.tas.gov.au/inter.nsf/ThemeNodes/LBUN-4Y53BQ?open

Victoria

- **State Environmental Protection Policy (Waters of Victoria)**
  Is the principal policy for protecting the beneficial uses of Victoria's water environments. It provides a legal framework for government agencies, businesses and other members of Victoria's communities to work together to protect and rehabilitate Victoria's surface water environments.
- ***Water Act 1989***

- **Victorian Coastal Strategy**
  This Strategy brings together the many stakeholders and agencies with responsibility for managing different parts of the coast, its catchments, waterways and the nearshore marine environment to facilitate coordination and ensure an integrated approach is taken in the management of Victoria's coast.
- **Our Water Our Future Action Plan**
  The plan has set out a range of reforms to improve the way in which Victoria's water is shared.

Western Australia

- **Draft Environmental Water Provisions Policy for Western Australia**
  The policy has been formulated using the 'National Principles for the Provision of Water for Ecosystems' as a basis. Water use must be sustainable (there must be inter-generational equity and it must not be environmentally damaging). Also, when water is diverted from the environment its use must be productive.
- **State Policy for Management of Waterways in Western Australia**
- **State Water Quality Management Strategy**

The Rights in Water and Irrigation Act 1914 (amended 2000)

Appendix 7: Knowledge-needs for freshwater flows to estuaries – Workshop report.

Overview of the processes of the workshop

The workshop process was developed by the Coastal CRC in consultation with Land and Water Australia (LWA) and the Fisheries Research and Development Corporation (FRDC). The workshop formed part of a broader project commissioned by LWA and FRDC to identify the knowledge-needs relating to freshwater flow for estuaries.

To develop an effective workshop plan (see workshop process chart below), the overall workshop scope, objectives and desired outputs had to be clearly defined. These are outlined below.

Scope of the workshop

To refine, agree on, and prioritise high-level knowledge-needs pertaining to the management of freshwater flows to estuaries.

Key objectives of the workshop

1. to identify and agree on the major management themes and knowledge-needs
2. prioritise the knowledge-needs

Key outputs:

1. a list of major management themes linked with associated knowledge-needs
2. a prioritised (agreed) list of knowledge-needs
3. input to the 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

Workshop activities were designed (refer to process chart) to ensure these objective were met and the outputs produced. Prior to the workshop, approximately 100 experts were asked to indicate their top twenty knowledge-needs from the list identified in the report. The list of 69 knowledge-needs were then coarsely ranked into high, medium and low priority. This list was used as the basis for the workshop discussions.

An overview of the workshop process is set out below (Figure A7.1). The process chart (see Tables A7.3 and A7.4) sets out the specific activities.

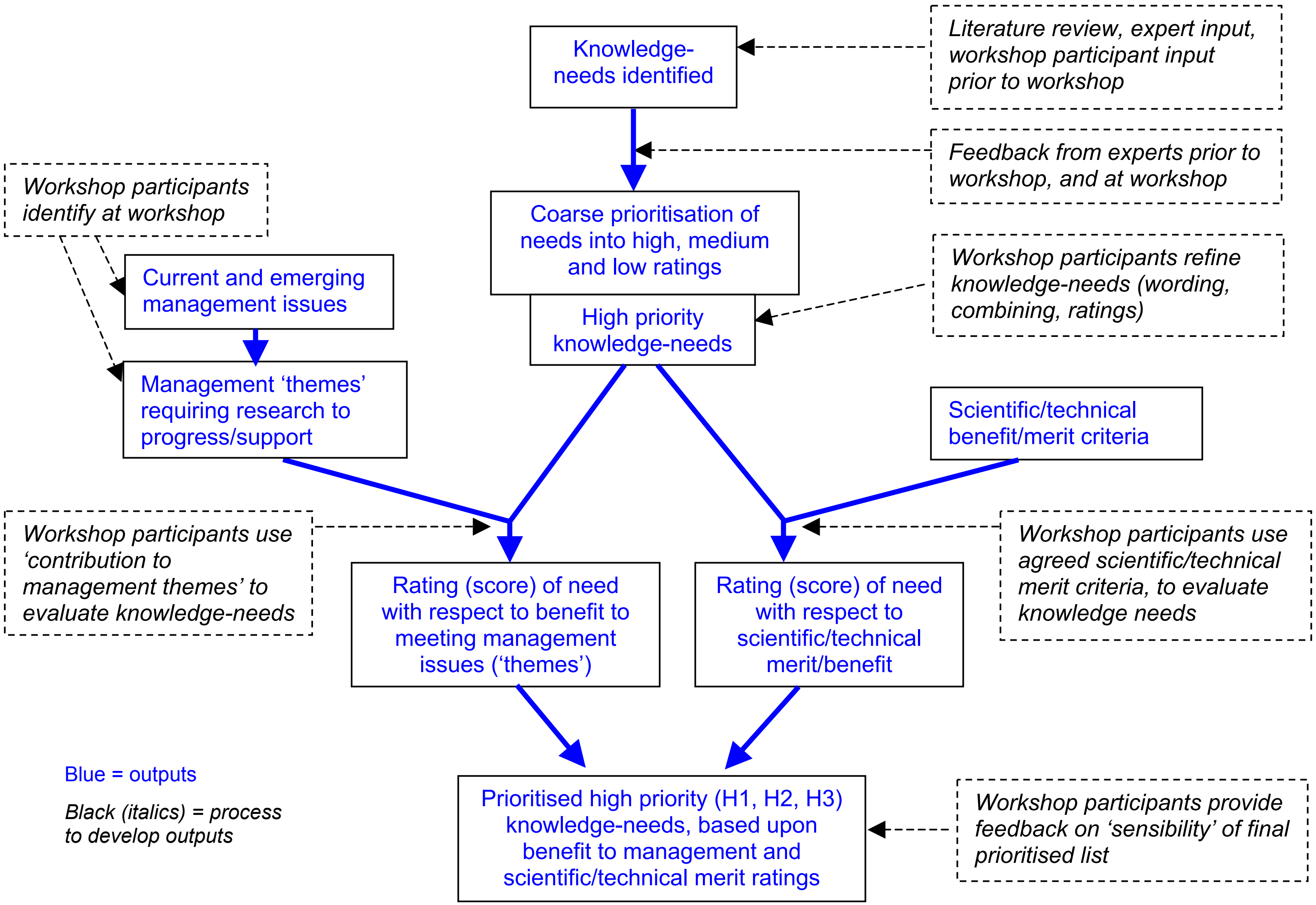

Figure A7.1. Process (included outputs) to prioritise knowledge-needs for freshwater flows to estuaries research.

Workshop proceedings

The following provides a description of the purpose, processes, outputs and outcomes from each of the major sessions of the workshop. A more detailed process chart (Tables A7.3 and A7.4) follows these descriptions. The major and synthesised outputs of the sessions are reported here and in Section 8 of this report.

A wide range of estuarine, flows and management experts attended the two-day workshop. A list of the participants is included in Table A7.1.

Table A7.1. Workshop attendees.

Name	Organisation
Amanda Gordon	National Water Commission – ACT
Angela Arthington	Griffith University – Qld
Anissa Lawrence	Oceanwatch – NSW
Bill Peirson	Water Research Lab, Uni NSW – NSW
Brendan Edgar	Land and Water Australia – ACT
Brian Bycroft	Dept Natural Resources, Mines and Water – Qld
Bruce Coates	Dept Natural Resources – NSW
Bruce Pease	Dept of Primary Industries – NSW
Christine Crawford	University of Tasmania – Tas
Crispian Ashby	Fisheries Research and Development Corporation – ACT
Danielle Warfe	Dept Primary Industries, Water and Environment – Tas
David Osborn	Dept Environment and Heritage – ACT
David Scheltinga	Coastal CRC/FARI Australia Pty Ltd – Qld
Ian Halliday	Dept of Primary Industries and Fisheries – Qld
Ian Webster	CSIRO – ACT
Jeff Ross	University of Tasmania – Tas
Jeremy Hindell	Dept of Primary Industries – Vic
Jim Donaldson	Land and Water Australia – ACT
Justin Brookes	University of South Australia – SA
Kurt Derbyshire	Dept of Primary Industries and Fisheries – Qld
Louise Rose	Dept Environment and Heritage – ACT
Marcus Sheaves	James Cook University – Qld
Matt Barwick	Fisheries Research and Development Corporation – ACT
Michael Martin	Dept Agriculture, Forestry and Fisheries – ACT
Patrick Hone	Fisheries Research and Development Corporation – ACT

Penny Vella	Dept Environment and Conservation – NSW
Peter Scanes	Dept Environment and Conservation – NSW
Peter Thompson	CSIRO – Tas
Qifeng Ye	South Australian Research and Development Institute – SA
Rachel Mackenzie	Coastal CRC – Qld
Regina Souter	Coastal CRC/FARI Australia Pty Ltd – Qld
Richard Davis	Land and Water Australia – ACT
Rob Tucker	Intergovernmental Coastal Advisory Group – SA
Tor Hundloe	University of Queensland – Qld

Context for workshop participants (Day 1, Sessions 1-5)

Purpose and process

As the workshop was not the starting point for the process of identifying priority knowledge-needs relating to freshwater flow for estuaries, it was important to ensure all participants understood the background to the workshop and how the workshop fitted with the project as a whole. It was also important that participants had a clear understanding of the scope and purpose of the workshop. This was achieved through a series of presentations with Patrick Hone from FRDC providing the broader context for the whole project, Richard Davis from LWA presenting on the purpose and scope of the workshop itself and what the client agencies wanted to get out of it and David Scheltinga (Coastal CRC/FARI Australia Pty Ltd) presenting more detailed information on the project outputs to date and how the workshop would link with them. The workshop process flow chart (Figure A7.1) was also presented to provide participants with clarity about how the individual activities linked together.

Outputs and outcomes

As this session was primarily contextual, there were limited outputs and outcomes. However, the list of participants' expectations (Table A7.2) aligned well with the objectives of the workshop. The most common expectations related to providing input to the prioritisation process and obtaining information on what those priorities actually were and therefore how best to spend research funds.

Table A7.2. Expectations of workshop participants for the workshop.

Workshop participant's expectations
• main issues related to freshwater flows to estuaries (knowledge of what is happening)
• current state of knowledge
o technical
• methods to determine flows
• what do estuaries need
o flow allocation
o for fisheries
• what are the issues
o geographic variation

• what are the priorities
• what else is happening around Australia
o in relation to flows
o in relation to estuaries
• get more money for research
• how do we prioritise research
• links with other programs
o catchment to sea
o priorities
• where do we spend our research money
• update knowledge
• meet/talk to other estuarine researchers
• contribute to workshop
• take back information
• make sure note that working with a continuum
• how this process relates to other programme goals
• outcomes to enhance other decision

Identification of the management issues (Day 1, Session 6)

Purpose and process

The purpose of this session was to capture as many management issues/needs relating to freshwater flow needs of estuaries as possible and then roughly group them. To ensure a diversity of issues were raised, each participant was asked to write their key management issues on sticky notes (one issue per sticky note). The facilitator then asked each participant to read out a management issue that they had identified to the whole group and the relevant sticky note was collected and placed on butchers paper hanging on the wall. As more issues were raised they were roughly grouped by members of the project team. This process was continued until no more management issues were identified.

Outputs and outcomes

Participants identified over 100 management issues (see Appendix 9) of varying scales relating to flow needs of estuaries. These were roughly grouped into nine categories, however, they were not worked up into management themes at this stage.

Description/addition/refinement of knowledge-needs (Day 1, Session 7)

Purpose and process

The purpose of this session was to present the participants with the collated results of the out-of-session coarse prioritisation process (see Section 8, Tables 8.1 and 8.2 for the finalised list on high, medium and low priority knowledge-needs). Each participants was provided with the list of the knowledge-needs ranked high, medium and low. In light of the fact that the rest of the prioritisation process would only focus on those knowledge-needs identified as 'high' (the top 23) on this list it was important that no major knowledge-needs were overlooked. The participants were asked to assess the knowledge-needs as to whether all those identified as 'high' really were important and if any identified as 'medium' or 'low' were really high. Additionally they were also asked to assess some other newly identified knowledge-needs sent in during the out-of-session prioritisation and suggest any knowledge-needs that had not been identified.

Outputs and outcomes

The activity started with assessing the five 'new' knowledge-needs identified by individuals out-of-session. These were reworded slightly and voted on by the group (more than 30% of the group had to vote for their inclusion on the high priority list)[2]. Of these new knowledge-needs, two were voted as high priority and three were considered to be captured in knowledge-needs already identified as high priority. The two new high priority knowledge-needs were as follows:

- What are the most appropriate tools for testing different flow scenarios (predicting)?
- What are the relationships between estuarine and nearshore coastal ecological processes and what is the influence of freshwater flow either directly or indirectly?

There was some general discussion about the robustness of the list of high priority knowledge-needs. The two main areas of concern were that some important knowledge-needs were not represented and that there was a great deal of overlap between many of the knowledge-needs from throughout the entire list (high, medium and low). It became evident that the activity could only proceed effectively after the overlapping knowledge-needs were combined and any missing knowledge-needs identified. This was done as a group discussion with the project team grouping the 'to be combined' knowledge-needs as indicated by participants.

Refining and evaluating the high scored knowledge-needs (Day 1, Session 8)

Purpose and process

The purpose of this activity was for small groups to clarify and refine the descriptions of the high priority knowledge needs identified in the previous activity and provide preliminary recommendations to the whole group as to their scientific significance. This would then form the basis of individual assessment of the scientific merit/benefit of each knowledge-need. To ensure the expertise of the participants was effectively utilised and to save time, small groups worked on a sub-set of the 'needs' with individuals self selecting which group they joined according to the knowledge-needs relevant to them. Each group was asked to provide a qualitative assessment of the needs according to the pre-determined criteria, which would also form the basis of the individual assessments planned for the next activity. The groups were also given scope to provide comment on the criteria themselves.

Outputs and outcomes

This process successfully fulfilled its main objectives of refining and clarifying the descriptions of the 'high' priority knowledge-needs (see Section 8, Table 8.1) and providing preliminary recommendations back to the group as to their significance. However, the group activity also identified that many of the 'needs' could not be satisfactorily assessed against the criteria. After the reporting back, there was much discussion of the criteria and alternative criteria were suggested. The group consensus was that in the time available, appropriate criteria could not be agreed upon and that individuals had sufficient scientific expertise to be able to assess the scientific importance of each knowledge-need without formal criteria but with consideration of all the criteria discussion that had taken place during the session.

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[2]This 30% rule reflects the fact that the pre-workshop list of high priorities represented those gaps identified as being in the top-20 by 28% or more of respondents.

Individual scoring of knowledge-needs (Day 1, Session 9)

Purpose and process

The purpose of this activity was to obtain individual input from all participants about the scientific merit/benefit of each knowledge-need to further prioritise them. The original plan was for each participant to score each 'need' against the criteria. However, as discussed above, the criteria were not considered appropriate and the group agreed to individually rank (1 being high) the high priority knowledge-needs according to their scientific merit/benefit. At this stage, they were not required to consider them in the context of management needs. The individual rankings were provided to the project team on the morning of the second day.

Outputs and outcomes

Participants provided these rankings to the project team. These were then collated to provide an overall ranking. The prioritised list of knowledge-needs based on scientific merit/benefit is provided in Section 8, Table 8.1.

Refinement of management themes (Day 2, Session 2)

Purpose and process

This activity was designed to develop management themes based on the management issues identified during Day 1, Session 6. The management issues were already roughly organised and small groups worked on each aggregation of issues and worked them into a management theme. The groups then reported back to the wider group.

Outputs and outcomes

Nine management themes were identified, although some of these were considered to have two phases.

The management themes identified were as follows:

1. Political/Policy
    a. Development of decision-support processes and systems
    b. Development of implementation tools
2. Suitably sensitive models to integrate knowledge of flow regime and effects on ecological and other values that will allow testing of flow scenarios
3. Access to and application of knowledge and research outcomes to extension and capacity building for managers, government, industry and the community
4. Determination and assessment of flow delivery to achieve desired management outcomes
5. How to manage environmental flow allocations in the context of other interventions (e.g. entrance management, dredging, global warming, water quality degradation)
6. 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
7. Effect of flow regime (timing, magnitude, frequency, quality, duration) on the structure and function of estuarine ecosystems and other associated values
8. What institutional coordination, regulatory and governance arrangements are required and at what scale(s)
9. 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

Match knowledge-needs against management themes (Day 2, Session 3)

Purpose and process

The objective of this session was to integrate the scientific and management components of the process to ensure that the 'needs' identified as highest priority reflected both these imperatives. Each small groups was asked to address one management theme and score the contribution of each 'high' scored knowledge-need to that management theme.

Outputs and outcomes

While ostensibly this activity met its objectives and the list of needs was further prioritised according to both scientific and management needs (see Section 8, Table 8.1), this activity also raised significant issues with respect to the appropriateness of linking the knowledge needs as they had been articulated with the identified management themes. The usefulness of the list was limited by: (i) the knowledge-needs did not represent a comprehensive account of what is needed to satisfy a management theme; (ii) the management themes were typically very high-level (coarse) whereas the knowledge-needs were less so; and (iii) the knowledge-needs focused on biophysical knowledge-needs whereas the management themes were not limited to any discipline.

The prioritised list generated by this activity was designed to be combined with the scientific merit/benefit score obtained to become the final output of the workshop. However, because of the issues outlined above, the participants did not believe it adequately represented their priorities and was not an appropriate deliverable for the client. This meant that the next session was modified to deal with this situation.

Facilitated discussion on developing a useful mechanism for capturing the workshop outputs

Purpose and process

There were no formal objectives for this session developed prior to the workshop. This session focused on collaboratively drawing together the outputs from the rest of the workshop to ensure that a list of priority knowledge-needs could be generated for use in developing a research program. The attendees participated in a facilitated group discussion to develop an agreed approach to meeting this need with input from the clients about the practicality of any of the suggested approaches.

Output and outcomes

A number of different approaches were discussed and it was agreed that a framework of some sort would be useful. One of the participants suggested a framework loosely based on the adaptive management framework which was generally accepted by the group as a good starting point for discussion. The management themes were then mapped to this framework and due to time constraints the project team was given the task of further developing this framework and mapping the workshop outputs to the framework.

Section 8 of this report contains the finalised 'prioritised' list of knowledge-needs and discussion on the possible frameworks that could be used to organise them.

Table A7.3. DAY 1 (Thursday 9 March) – workshop process chart

Session	Start time	Workshop task/session	Activities	Objective	Materials required	Who to present/run session
	9.30	*Morning tea on arrival*				
1	10:00	**Welcome**	Patrick Hone to present			Patrick Hone, Executive Director, FRDC
2	10:10	**Facilitator's Introduction**	Rachel and David to introduce themselves and explain their roles. Rachel to explain the process for the day and set some ground-rules	All participants have a clear understanding of Rachel and David's roles, the process for the day and know the basic ground-rules	issues' box Butchers paper	Rachel
3	10:20	**Workshop background**	Richard to provide a outline of the overall purpose of the workshop and what FRDC and LWA would like to achieve by the end of it – the **WHY** Opportunity for questions of clarification from participants	Provide a clear outline of the purpose of the workshop for participants	Laptop Lightpro	Richard Davis
4	10:40	**Introductions and expectations**	**Key Question** *Introduce yourself and your organisation and tell us what you hope to get out of the workshop?*	Who's here and what for (what they want to get out of the workshop)	whiteboard (electric if possible) whiteboard markers	Rachel
5	11:00	**Report overview (20 min)**	Outline project plan (report) and process – the **HOW** Questions of clarification.	Provide a clear outline of the process to prepare the report and the information in it (and the limitations)	Laptop Lightpro	Dave

Session	Start time	Workshop task/session	Activities	Objective	Materials required	Who to present/run session
6	11:20	**Identification of the management issues**	Dave to introduce overarching conceptual framework and then the task itself and broad process (including splitting the task over 2 days) (5 mins) Concept mapping Each participant to spend 5 minutes writing their top management issues on sticky notes. Go around room and each person to read out their 'top issue'. Collect and stick on to butchers paper in evolving groups. Continue until all issues have been identified and roughly grouped.	Identification of management issues (i.e. the major management needs of flows information) Q) What are the key/critical needs for management?	Butchers paper Large sticky notes Chunky markers	Rachel to run session Dave and Reg to collect sticky notes and stick on butchers paper
	12:30	*Lunch*	Hand out list of knowledge-needs			
7	13:15	**Description/addition/refinement of knowledge-needs**	Dave to present collated results of the ranking of the knowledge-needs. New knowledge-needs should be kept separate. Participants then vote on 'new knowledge-needs' (>30% people agree) Show final list and check that there are no huge anomalies.	Group consensus agreement of knowledge-needs identified Q) Do we need to modify the wording/content? Add? Delete? Add (agree) new knowledge-needs identified by people before the workshop Agree on high score (check on medium – should they be high?) We have an agreed list of high, medium and low knowledge-needs	Lightpro laptop	Rachel and Dave

Session	Start time	Workshop task/session	Activities	Objective	Materials required	Who to present/run session
8	14:00	**Refining and evaluating the high scored knowledge-needs**	Dave to present prioritisation criteria Break into between 5 and 7 small groups depending on the number of highs and the number of participants. Each group to spend 20 minutes on each knowledge-need to provide a quick and dirty assessment of: (1) Clarify/refine the knowledge-need (2) Significance/importance of this knowledge-need (3) qualitative assessment against criteria Reporting back – to provide some information about the knowledge-need to all participants, for their consideration when prioritising these knowledge-needs	Provide a clear outline of the criteria to use Q) What is the significance /importance of the knowledge-need (this session is to focus on the scientific/technical aspects of the knowledge-need) Inform broader group – 'group' all use criteria in the same way – common use Facilitate discussion about knowledge-needs and criteria Tease out knowledge-needs (refine) Tease out criteria (refine)	Proforma Pens	Rachel, Dave and Reg to roam
	15:30	*Afternoon tea*				
8 cont.	15:50	**Report back**	Each group to spend 3 minutes per knowledge-need and reporting back on the 3 points above and comment on the suitability of the evaluation criteria. Agree on any changes to criteria	Facilitate discussion about knowledge-needs and criteria Tease out knowledge-needs (refine) Tease out criteria (refine)	Lightpro laptop	Rachel Dave to scribe

Session	Start time	Workshop task/session	Activities	Objective	Materials required	Who to present/run session
9	16:30	**Individual scoring of knowledge-needs**	Individually – quantitative score	Individual scores for each criteria for each 'high' knowledge-need (what is the scale?)	Scoring sheets	Dave to be available to answer questions
	By 18:00	**Completed scores provided to facilitators for interpretation**				Rachel and Reg to input data as it becomes available

Table A7.4. DAY 2 (Friday 10 March) – workshop process chart

Session	Start time	Workshop task/session	Activities	Objective	Materials required	Who to present/run session
1	9:00	**Review of Day 1**	Update on progress achieved on day 1 – including results of the scoring of knowledge-needs (scientific/technical aspects) Agenda and process for day 2	Ensure participants are okay with process	Outputs from day 1	Rachel
2	9:25	**Refinement of management themes**	Reiterate intended use of the management themes. Break into small groups. Review grouped 'management themes'. Discuss for 15 minutes to come up with a brief sentence that captures that 'theme'. Report back	Turn the 'key/critical needs for management' lists into themes List of management themes to be used to further evaluate, and prioritise the knowledge-needs	Sheets from day 1 with stickies	Rachel – others to roam
	10:15	*Morning tea*				

Session	Start time	Workshop task/session	Activities	Objective	Materials required	Who to present/run session
3	10:35	**Match knowledge-needs against management themes**	Small group sessions – each group to address 1 management theme (group same as that that 'named' the management theme in the about session) and score the contribution of each high scored knowledge-need to that management theme. Reporting back – of scores and 1-2 brief comments to explain.	Complete matrix of knowledge-needs vs. management themes Which knowledge-needs fit into the most themes	Matrix	Rachel. Dave to scribe. Reg to assist
	13:00	*Lunch*		Facilitators to process final score to identify highest priority knowledge-needs.		
5	14:00	**Outputs**	Present outcomes, i.e. Prioritised list of knowledge-needs – based on evaluation with respect to scientific/technical aspects and management needs List of key research themes and which knowledge-needs fit within them. Discussion from participants	Give participants an overall picture of 'where we are at' Validity of process – did it make sense?	Filled in matrix	Dave
6	15:35	**Wrap-up**				Crispian and Richard
7	15:50	**Farewell and appreciation**				Andrew Campbell, Chief Executive, Land and Water Australia
	16:00	**Finish**	Afternoon tea			

Appendix 8: 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.

Appendix 9: Management themes identified during the workshop with their underlying management issues.

Management Theme 1. **Political/Policy**

a. Development of decision-support processes and systems
b. Development of implementation tools

- decision-support tools link catchments → estuaries
- are existing models good enough to make informed decision making re: environmental flows?
    - if not, what needs to be improved
- to clarify if there is the need for new knowledge/info to expand and inform the development of new water quality/flow guidelines
- capacity of hydrodynamic models
- practical tools for environmental water managers
- development of decision-support processes and systems to allow consideration of potential competing values

Management Theme 2. **Suitably sensitive models to integrate knowledge of flow regime and effects on ecological and other values that will allow testing of flow scenarios**

- decision-support tools link catchments → estuaries
- are existing models good enough to make informed decision making re: environmental flows?
    - if not, what needs to be improved
- to clarify if there is the need for new knowledge/info to expand and inform the development of new water quality/flow guidelines
- capacity of hydrodynamic models
- practical tools for environmental water managers
- suitable sensitive models to integrate knowledge of flow and effect of ecological and other values to allow testing of flow scenarios

Management Theme 3. **Access to and application of knowledge and research outcomes to extension and capacity building for managers, government, industry and the community**

- efficient medium for getting hold of best existing information on estuaries in a form that is management friendly to make decisions
- how do we educate the community about estuary processes e.g. ICOLLS close naturally and not always good to force open
- how do we ensure research undertaken relating to estuaries is translated into management actions for regional NRM groups/catchment management authorities → information/communication flows

Management Theme 4. **Determination and assessment of flow delivery to achieve desired management outcomes**

- management issues
    - E-flows are only part of the answer
        - need to consider upstream processes
        - restoration instream and on land
- management

    - Total catchment management of water allocations. i.e. extraction ?? has implications for estuary
- set flow rules as part of water sharing plans
- flow rules for Regulated vs. Unregulated
- can environmental flow 'principles' and quantitative 'rules' be developed for each different type of estuary?
- how do you ensure water is delivered to where you want it
- how do we balance estuary needs against other water uses/demands
    - prioritising
    - demonstrating benefit
- how do we make allocations decision in the absence of knowledge
- how much water allocation can occur before estuarine structure and function is altered
- 'flow rules' for tidal pool extraction
- what components of the freshwater flow regime can be compromised (or when)?
- monitoring and evaluation of environmental flow outcomes
- defining of flows
- natural flows
- environment flows
- use of highly treated water sources for flow replacement (i.e. consequences of absence of 'natural' water characteristics
- is developing of a portable approach system for determining environmental flow really realistic or practical

Management Theme 5. **How to manage environmental flow allocations in the context of other interventions (e.g. entrance management, dredging, global warming, water quality degradation)**

- how to manage changes to structure and function
- holistic movement of estuaries
- entrances have effects - manipulate
- dredging
- global warming
- water quality degradations
- interaction of environmental flow allocation with other human interventions
- how to manage environmental flow allocations in the context of other human interventions for example
- dealing with modified estuary
- management of fresh water flow to modified estuaries and their catchments (confounding factors)
- entrance management of coastal processes (i.e. sand movement/littoral drift) to maintain estuarine health, mitigate flowing to development and maintain navigation requirements

Management Theme 6. **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

- identify estuary values - assets .. where; .. spatial
- can we assign biodiversity values (priorities) to estuaries

- what is the point of a management framework when we don't know what role flows play in estuaries
- management - governments responsible for triple bottom line: to economic health links; to environmental health links; to happy people (in the constituency)
- at present the manner flow allocations are made is NOT transparent, is NOT based on sound science, is NOT based on real world economics
- Management
    - o biodiversity values
    - o economic values
- as these will determine the magnitude, etc of environmental flows
- economically valuing estuaries in particular ecosystems services to ensure the true environmental costs are considered in development decision, e.g. marine based biodiversity banking
- Govt needs to be aware and have a scientific basis on the benefits of environmental flows to justify expenditure and gather community support
- which estuaries are under (potential) threat from land and water use change
- identify where trade-off pressures are greatest (or potentially greatest)
- provide water for Aboriginal cultural needs
- valuing ecosystem services
- which estuaries are most important for primary production? – quantify
- management for what? value
- identification of HCV environmental assets that is defendable
- specific attributes of ecosystem values
- what is it (in ecological terms) that flows need to be managed for – in an 'Australia-wide' sense
- establishing the values people hold for estuary use in different parts of Australia
- who cares? how does this influence the process
- how do we set environmental flow objectives with competing estuarine values and outcomes
- how does what community and management see as the issues mesh with what needs to be research to achieve the knowledge

Management Theme 7. **Effect of flow regime (timing, magnitude, frequency, quality, duration) on the structure and function of estuarine ecosystems and other associated values**

- estuarine healthy = ?
- quantity of freshwater water required to maintain estuarine health
- what is the effect of flow, including seasonal/event variations, on estuarine water quality and receiving water quality
- water quality
    - o eutrophication
    - o human health
    - o contaminants
- spatial/temporal scale
- river-estuary-sea
- short/long-term
- drought vs. flood
- what is estuarine health and how does this relate (interact with) fishery health
- how do freshwater flows drive estuarine function? and structure? how important are they and where and when they're important
- e-flows strategy for estuaries
- knowledge needs: flow requirements for estuarine processes and key biota

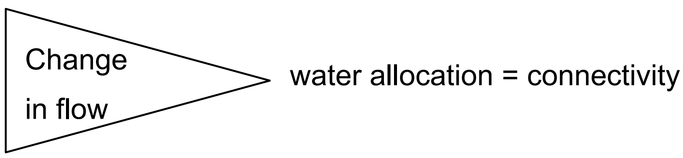
- better quantification impact on non-consumptive use
- Fish
    - flows
    - recruitment
    - nurseries
    - harvesting/resource allocation
- measurement of flow to estuaries at estuary/freshwater interface
- how does water allocation alter estuarine function and structure
- flow regime → hydrodynamics → biogeochemistry → habitat → biodiversity, recruitment, productivity → resilience to climate drought and other pressures → flow regulation
- what flows are required to sustain estuarine habitats
- Sensitivity of estuary to freshwater inflows → what part of flow regime
- critical flow-related needs of specific attributes
- capability to estimate/measure ecological impacts and ‘small’ reductions in flow and cumulative effects
- geomorphological issue ; sedimentation ; navigation ; fishing holes ; estuary closure
- recognition importance of flow for physical shape of estuaries
- what are the water quality requirements of environmental flows, e.g. nutrient loads, heavy metals, thermal pollution

Management Theme 8. **What institutional coordination, regulatory and governance arrangements are required and at what scale(s)**

- Institutional
    - co-ordinated management
    - roles and responsibilities
- Management
    - a national approach (agreements)
    - a mechanism to allocate flows (water)
- who owns water? where in the hydrological cycle does someone get to ‘own’ water
- time pressure for quick decisions
- how well are different types of estuaries protected by conservation/legislation/statutes
- coordination across multiple agencies for estuarine management
- jointly deciding on catchment management and estuarine management issues across diverse interest groups and agencies
- Infrastructure: need to develop and operate infrastructure so that flows can be input to estuaries.
- coastal developments → including population → how to ensure developments can be constructed not to impact on flows or quality → need to complimentary
- where does what needs to be done fail to be achievable in light of what can be done?

Management Theme 9. **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**

- what changes?
- rainfall
    - timing (storm events)
    - amount



- sea-level rise requires more water = status quo
- water temperature

- risk assessment for all estuaries; rank estuaries
- human responses
- interaction of climate change with flow regimes and Water Quality, and ecological consequences and human responses to climate change