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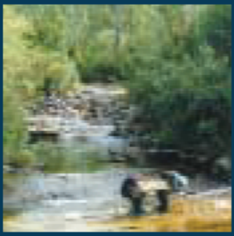
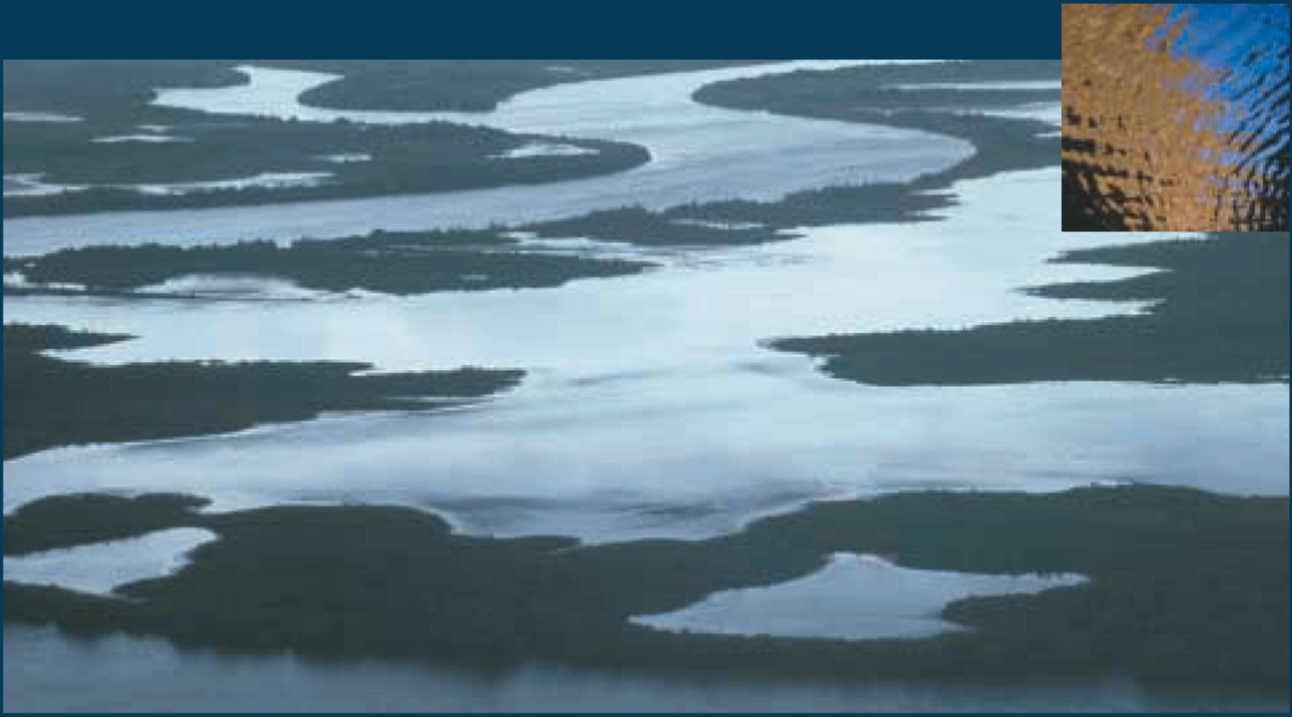
ENVIRONMENTAL FLOWS INITIATIVE TECHNICAL REPORT

REPORT NUMBER 3

Environmental Water Requirements to Maintain Estuarine Processes





Natural Heritage Trust
Helping Communities Helping Australia
A Commonwealth Government Initiative

Environment Australia
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EXECUTIVE SUMMARY

The purpose of this report is to present and explain a method of determining appropriate levels of environmental flows to Australian estuaries.

Environmental flows are water flows maintained solely for environmental reasons, to maintain the health and biodiversity of a particular waterbody.

Estuaries are the downstream reaches of rivers where they enter the coastal ocean and a influenced by tidal motions. The upstream catchment supplies an estuary with fresh water which mixes with salt water entering from the sea. The physical, chemical, sediment, water quality and ecological processes within estuaries are exceedingly complex primarily due to their dynamic nature, complex mixing processes, stochastic influences, strong antecedent effects and the vast number of complex ecological linkages.

The objectives of this report are to:

(a) Provide a methodology to identify those estuaries in Australia that are threatened by current or future changes to the fresh water flow regime;
(b) Develop a method for determining appropriate environmental flows that will protect these estuaries against decline in their ecological character;
(c) Identify information gaps in determining environmental flow requirements of estuaries;
(d) Identify the requirements for measuring the effectiveness of environmental flow allocations to estuaries; and,
(e) Identify the practical limitations and opportunities available for implementation of environmental flows to these systems.

Objectives (a) and (b) have been achieved by:

1. developing a checklist of major ecological processes by which changes to estuary fresh water inflows may cause impacts on estuarine ecosystems and the adjacent marine environment; and,
2. providing a systematic, multidisciplinary adaptive management methodology that uses the checklist to ensure to assess the risk to the estuarine ecosystems associated with reduced fresh flows to estuaries.

The checklist is adapted and expanded from Bishop (1999) who developed a checklist based on a literature review (which strongly relied on the review of Drinkwater and Frank, 1994) and is presented in terms of three ranges of estuarine fresh water inflow:

Low magnitude inflows (Low-):

Low-1: *increased hostile water-quality conditions at depth*

Low-2: *extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive fauna*

Low-3: *extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive flora*

Low-4: *extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota*

Low-5: *extended durations when flow-induced currents cannot suspend eggs or larvae*

Low-6: *extended durations when flow-induced currents cannot transport eggs or larvae*

Low-7: *aggravation of pollution problems*

Low-8: *reduced longitudinal connectivity with upstream river systems*

Middle and high magnitude inflows (M/H-):

M/H-1: *diminished frequency that the estuary bed is flushed fine sediments and organic material (physical-habitat quality reduction)*

M/H-2: *diminished frequency that deep sections of the estuary are flushed of organic material (subsequent water quality reduction)*

M/H-3: *reduced channel-maintenance processes*

M/H-4: *reduced inputs of nutrients and organic material*

M/H-5: *reduced lateral connectivity and reduced maintenance of ecological processes in waterbodies adjacent to the estuary*

Across all inflow magnitudes (All-):

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*

The methodology was developed from literature review of the (limited) studies undertaken overseas as well as experience with investigations on the Richmond River, New South Wales (Peirson *et al.*, 1999). Two phases of investigation are proposed: preliminary evaluation and detailed investigation.

Once the preliminary evaluation of different estuaries has been completed, the estuaries should be able to be categorised according to risk from reduced fresh water inflows.

The methodology has been presented as a single pass process. However, because relevant information is often limited, it may be necessary to repeat steps of the methodology when better information becomes available.

The structure of the methodology is:

Preliminary Evaluation Phase

PEP Step 1: Define the environmental flow issue to be investigated.
PEP Step 2: Assess the value of the estuary
PEP Step 3: Assess changes to inflow
PEP Step 4: Assess the vulnerability of the estuary.

Detailed Investigative Phase

DIP Step 1: Examine the likely impact of current water use on transport, mixing, water quality and geomorphology using catchment runoff and estuarine flow models
DIP Step 2: Define environmental flow scenarios for the estuary
DIP Step 3: Use the established models to assess the impact of proposed scenarios.
DIP Step 4: Assess the risk to estuarine biota
DIP Step 5: Licensing and development approval
DIP Step 6: Adaptive Management

Once an assessment has been completed for a given estuary, the impacts of changed development scenarios can be assessed by repeating DIP Steps 2 to 6.

The information and measurements required to set flow requirements are documented in this report. If undertaken in an appropriate way, this data will also allow the effectiveness of environmental flow allocations to estuaries to be assessed.

Good physical, chemical, water quality and ecological data for estuarine systems is absolutely foundational to robust predictions of appropriate environmental flows and review of implemented fresh water flow regimes.

The collection and facilities of the Water Reference Library were invaluable to this investigation. It is important that all documents, data and models relevant to individual Australian estuaries be assembled within reliable archives and maintained.

The practical limitations and opportunities available for implementation of environmental flows to estuarine systems are discussed within this report.

At present, there appears to be limited communication between estuary managers at Australian State and Federal level. It is recommended that an appropriate forum be developed to improve communication between these agencies.

The best test of the adequacy and robustness of the checklist and methodology developed within this project would be a trial determination of appropriate environmental flows for an Australian estuary. We recommend that this be commenced as soon as possible.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

The purpose of this report is to present and explain a method of determining appropriate levels of environmental flows to Australian estuaries. Although the geographic extent of an estuary within a catchment or river basin may be very limited:

- estuaries are primary catchment drainage sites to the coastal ocean; and,
- the physical, chemical, sediment, water quality and ecological processes within estuaries are exceedingly complex primarily due to their dynamic nature, complex mixing processes, stochastic influences, strong antecedent effects and the vast number of complex ecological linkages.

This report is structured as follows:

- We begin in Chapter 2 with the investigative background of this project within Environment Australia's ecological programs associated with rivers and a clear statement of the specific objectives of this investigation.
- In Chapter 3, we review the concept of environmental flows and the key features of estuarine systems. The key differences between estuarine and fluvial systems are highlighted.
- Broad overviews of the relevant ecological, physical and water quality processes in Australian estuaries are presented in Chapters 4, 5 and 6.
- Chapter 7 is a brief summary of Appendix 6 which assembles the key relevant water policy initiatives of Australian government authorities and briefly describes some of the major estuarine investigations undertaken within Australia.
- Chapter 8 is a brief summary of Appendix 7 which is a review of Australian and international estuarine environmental flows studies.
- Based on this material, a methodology to determine appropriate environmental flows to estuaries to maintain their key processes and ecology is described in Chapter 9.
- Chapter 10 lists the information required to support such a methodology and ensure that robust conclusions can be reached by the investigative process.
- Chapter 11 briefly describes some of the practical limitations and opportunities afforded by the assessment of environmental flows to estuaries.
- Chapter 12 concludes this investigation with recommendations for future action.

2. BACKGROUND

2.1 Commissioning

In 1999, Environment Australia (EA), http://www.ea.gov.au/, the federal government (Commonwealth) Department of the Environment and Heritage, invited proposals (Tender No. 54/99) from suitably qualified organisations to investigate the environmental water required to maintain estuarine processes. The Water Research Laboratory, University of New South Wales (WRL) was chosen to undertake this work.

The objectives of this project are to:

- Provide a methodology to identify those estuaries in Australia that are threatened by current or future changes to the fresh water flow regime;
- Develop a method for determining appropriate environmental flows that will protect these estuaries against decline in their ecological character;
- Identify information gaps in determining environmental flow requirements of estuaries;
- Identify the requirements for measuring the effectiveness of environmental flow allocations to estuaries; and,
- Identify the practical limitations and opportunities available for implementation of environmental flows to these systems.

This investigation was commissioned by EA because:

- Divisions of administrative responsibility often result in the management of estuaries being separated from that of their upstream catchments. Thus, catchment management authorities have traditionally had little responsibility for, or expertise in, estuarine management.
- Modification of river flows by various forms of regulation or abstraction alters the flux of water through estuaries. Ecological processes impacted by fresh water flow modification include, for example, nutrient dynamics, algal blooms, fish breeding and migration, and blocking of estuarine mouths. Other processes such as vegetation distributions, and consequently bank stability, may be affected by changes in the dynamics of salt water intrusion.

The project was commissioned by EA as a component of much wider activities within the National River Health Program.

2.2 The National River Health Program (NRHP)

The aims of the NRHP are primarily to deliver a new, standardised methodology for the assessment of river health, and to develop effective approaches to the allocation of environmental flows for Australia’s waterways. The specific objectives of the NRHP are to:

- provide a sound information base on which to establish environmental flows;
- undertake a comprehensive assessment of the health of inland waters, identify key areas for the maintenance of aquatic and riparian health and biodiversity and identify stressed inland waters;
- consolidate and apply techniques for improving the health of inland waters, particularly those identified as stressed; and
- develop community, industry and management expertise in sustainable water resources management and raise awareness of environmental health issues and needs of our rivers.

The NRHP consists of two main components, namely the Australia–wide Assessment of River Health and the Environmental Flows Initiative (EFI). The Australia–wide Assessment of River Health is a 3 year program (1998–2001) providing an assessment of the condition of over 6000 river sites across Australia. It involves the collection of macroinvertebrate samples and associated physical habitat information and subsequent analysis of data derived from these samples by a statistical prediction and classification scheme known as AusRivAS, the Australian River Assessment Scheme.

The EFI component of the NRHP is intended, for a particular system, to:

- identify the environmental values of the system;
- undertake targeted research to identify environmental risks to the system and flow requirements to sustain environmental values;
- identify and trial preferred management options for reducing environmental risks and establishing environmental flow requirements; and
- evaluate trials and adjust management regimes.

Three targeted environmental flows projects include this project, which focuses on the environmental water requirements of estuaries. Two other targeted projects, investigating the environmental water requirements of groundwater dependent systems (EA Tender 55/99) and the environmental water requirements to maintain wetlands of national and international importance (Tender 53/99), were also undertaken by other organisations.

3. ESTUARIES, THEIR ECOSYSTEMS AND ENVIRONMENTAL FLOWS

3.1 Environmental Flows

"Environmental flows", or "environmental water", describes fresh water flow (typically instream flow) that is maintained (or not allowed to be used for other, typically anthropogenic, purposes) solely for environmental reasons, to maintain the health and biodiversity of a particular water–related entity, such as a river, wetland, groundwater system or estuary. For example, water may be extracted from a particular river for a particular industry. However, an environmental flow may be maintained down the river, not diverted to this industry, to maintain downstream river and/or estuarine ecosystems by allowing natural flows to progress through the system.

Any flow storage or diversion structure that alters the flow regime of a surface or groundwater system can influence the health of downstream aquatic ecosystems. Examples of anthropogenic influences on flow regime include:

- dams, weirs and tidal barrages (for purposes including water supply, flood control and hydro–electricity)
- domestic water supply and water treatment works
- industry water supply
- irrigation water supply
- sewage treatment works (including possible effluent re–use)
- catchment modifications (anything that alters the rainfall–runoff process; for example, clearing vegetation and introducing impervious catchment surfaces (roofs, roads and paving) will increase the quantity of surface runoff and reduce base flows)
- channel modifications such as dredging, realignment and lining
- construction of instream obstructions and the creation of obstructions through sedimentation and debris buildup (which may include large woody debris, litter and other sources)
- withdrawals from groundwater systems.

The flows diverted by these works may or may not be able to be controlled and/or measured. For example, the quantity of water a particular irrigator may extract out of a river may be unregulated.

Environmental flows are essential to the minimisation of negative influences on the health of aquatic ecosystems resulting from alterations to flow regime.

3.2 Estuaries

There are many different definitions of estuaries, often depending on the legislative context under which the definition is made (see Appendix 4).

Cameron and Pritchard (1963) define an estuary as “a semi-enclosed body of water which has a free connection with the open sea water which is measurably diluted with fresh water derived from land drainage”.

Fairbridge (1980) defines an estuary as “an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, usually being divisible into three sectors: (a) a marine or lower estuary, in free connection with the open ocean; (b) a middle estuary, subject to strong salt and fresh water mixing; and (c) an upper or fluvial estuary, characterised by fresh water but subject to daily tidal action.”

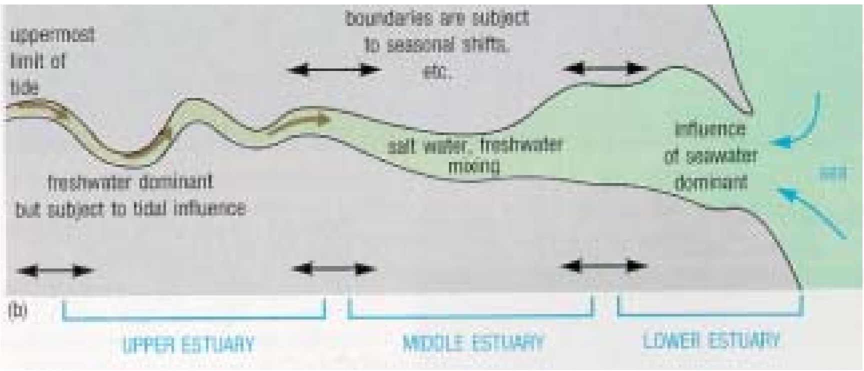

Figure 1. A schematic of an estuary showing division into different regions - after Fig. 6.4 (b) of Waves, Tides and Shallow-Water Processes (1989)

From a continental point-of-view, estuaries are the recipients of almost all of the runoff and groundwater flow yielded by a catchment. Very little surface or groundwater flow enters the coastal ocean directly via the coast. It is the rivers that act as the primary drainage system of a catchment, and, as the rivers enter the coastal zone, they become estuaries. During periods of high rainfall, groundwater systems are recharged from the rivers or by surface percolation and, during periods of low river flow, the same groundwater systems discharge to the river. Water that is not returned to the atmosphere by evaporation or evapo-transpiration by plants flows downstream to the estuary.

Consequently, estuarine systems are exceedingly vulnerable to catchment pollution. Conservative contaminants released within a catchment will eventually make their way downstream and contaminate the estuary. These include industrial contaminants, pesticides from agricultural activity and polluted runoff from urban drainage systems.

Correspondingly, water flow through and across catchment soils entrains dissolved and suspended nutrients that are transported to the estuary downstream. Within estuaries in a pristine state, nutrient-rich fresh waters from the catchment mix with highly oxygenated waters from the ocean, making them the most biologically productive regions of the marine environment. Many forms of marine life spawn in estuaries and many species of water birds are dependent on estuaries for breeding and feeding.

With over 80% of Australia's population residing in coastal regions, the ecological impact of urban development on Australian estuaries is correspondingly significant.

3.3 The Distinctive Nature of Estuarine Ecosystems

The significance of environmental flows on ecosystems has been the subject of intense investigation for approximately 20 years (see Arthington, 2000 for a recent review). As a consequence, the literature addressing environmental flows in rivers is large. Nevertheless, the understanding of flow-related processes in rivers and streams is very limited.

In spite of the significance of estuaries within catchment systems, studies of environmental flows to estuaries are relatively scarce. Significant reported investigations are described in Appendix 7 with a concise summary in Chapter 8.

It is important to highlight the fundamental differences between fluvial and estuarine flow systems particularly with regard to the Australian climates (see Section 5.3.1 for more details).

Much of the environmental flow literature for rivers is focussed on very low flow conditions. If river beds completely dry out during periods of intense drought, this can have a catastrophic impact on the in-stream ecology. Therefore, a major concern has been to maintain at least small flows in rivers to protect the bed from drying out. In fluvial systems, flow only occurs in a downstream direction and there are direct relationships between depth and flow.

In contrast, in estuaries there is no direct relationship between depth and fresh water flow except under very high flow conditions. Flow depth is controlled primarily by ocean water levels and tides. Under moderate to low fresh water inflows within estuaries, alternating upstream and downstream flow (flood and ebb tides) are generated in response to tidal fluctuations in water level at the mouth.

In rivers, only one water mass type is under investigation and, whilst water quality issues are complex due to the intricate interactions of nutrients with in-stream biota, the scope of water quality investigations are generally focussed on the location and intensity of nutrient or pollutant sources and their impact downstream.

Within estuaries, water quality issues are far more complex than in river systems due to their internal mixing of fresh and saline waters. Estuarine biota have differing tolerances to and dependencies on fresh and saline waters. Therefore, estuaries are inhabited by much more diverse biota than rivers with diversity supplemented by fluxes of taxa from both fluvial and marine origin. This biodiversity within estuarine systems makes ecological response to water quality impacts more difficult to predict. Nutrients and pollutants are dispersed by both tidal and fresh water inflows and relative importance of these dispersion processes will change in relation to the level of fresh water flow.

Like rivers, many estuaries feature weir structures (or tidal barrages) that impound fresh water during dry periods. Such structures will reduce the size of an estuary, its associated habitats, reduce the amount of estuarine tidal flushing and create barriers to the upstream movement of biota (especially fish). In contrast with rivers, fresh water flow has an important impact on estuary mouth morphology at the ocean. Littoral drift along the coast due to wave action acts to close tidal entrances. Consequently, reduced fresh water flow can result in complete or partial closure of estuary entrances. This can, in turn:

- obstruct diadromous fish and crustacean migration;
- alter estuarine flushing and water quality; and,
- alter the estuarine salinity gradient.

As a consequence, it is not a simple issue to establish an appropriate amount of fresh water flow for an estuary, both technically (due to the many complex physical, chemical and biological processes in estuaries) and socio–economically (due to the many competing uses for water within and between estuarine water users and those that may exist upstream).

The purpose of this report is to develop and present a risk-assessment methodology capable of determining appropriate levels of fresh water flow to estuarine systems either to avoid damage or to maintain or rehabilitate the instream ecology (including biodiversity).

To highlight the key differences between fluvial and estuarine systems, a summary is presented in Table 1 below.

Table 1 – Key Relevant Differences Between Fluvial And Estuarine Systems.

Characteristic	*Rivers*	*Estuaries*
1. *Flow direction*	Uni-directional	Reversing
2. *Depth determined by*	Flow	Primarily tides
3. *Flow cross section determined by*	Sedimentary regime	Sedimentary regime, flocculation, littoral drift
4. *Water masses*	Fresh only	Fresh and salt
5. *Pollutant flushing by*	Rainfall runoff	Rainfall runoff and Tidal flows
6. *Water Quality changes*	Downstream of source	Both upstream and downstream of source
7. *Antecedent effects in relation to physical and chemical character*	Moderate	Potentially very important
8. *Biota*	Limited diversity	More diverse
9. *Ecological interactions*	Less complicated	Much more complicated
10. *Size of literature pertinent to environmental flows*	Large	Small
11. *Understanding of environmental flow effects*	Limited	Very limited

These key characteristics listed in Table 1 are examined in more in Chapters 4, 5 and 6 which examine important ecological, physical and water quality processes in detail.

4. RELEVANT ESTUARINE ECOLOGICAL PROCESSES

In a review of literature concerning fresh water flow management in riverine estuaries, Estevez (2000) concluded:

“Fresh water is an integral part of the definition of an estuary and so deserves primacy in all aspects of estuarine ecology, as a matter of first principles. Changes to inflows have harmed many estuaries in the world, and have the potential to harm more.”

The basis of this conclusion is illustrated within this chapter initially by providing a glimpse of the evidence of impacts on estuarine ecosystems as caused by changes to the fresh water inflow regime. The potential major impacting processes involving changes to fresh water inflows are then listed and briefly expanded upon. The point is then made that estuarine ecosystems are complex, highly valued and linked to other ecosystems. Based on this understanding it is argued that there is a strong imperative to protect and maintain estuarine ecosystems. It is also argued that protecting estuaries from inflow-reduction impacts is by no means a straightforward task, particularly given their complexity, and the very limited knowledge of their ecological functioning. A general approach to a protection process, operating in a knowledge-poor environment, is then expanded upon. It is suggested that adaptive management approaches appear most appropriate. Other issues touched on in this context include important features of necessary investigations and means of narrowing-down such investigations in order to obtain cost-effective results.

4.1 Evidence of impacts on estuarine ecosystems caused by changes to the inflow regime

Drinkwater and Frank (1994) presented a comprehensive review of the effects of fresh water regulation and diversion on the adult and larval stages of fish and invertebrates in coastal and marine waters including estuaries. The authors described declines in coastal fisheries noting their general association with reductions in fresh water inflow. These were described in relation to effects on migration, spawning success, advection of eggs and larvae, species competition and distribution, general productivity, food supply, and water quality. It was emphasised that extensive ecological considerations are required during the planning stage of fresh water-modification projects to minimise potential impacts in estuaries.

The above view was supported strongly by the findings of an extensive study (Jassby *et al.* 1995) in the San Francisco Bay-delta, in the United States. Importantly, fresh water inflows there were significantly and positively correlated with nine ecosystem attributes: organic carbon, phytoplankton supply, abundance of one invertebrate taxon, biomass of benthic macroinvertebrates and the survival/abundance of five fish taxa. Similar results, involving nutrients, phytoplankton, zooplankton, ichthyoplankton and ichthyonekton, have been found in a number of South African estuaries (Grange *et al.*, 2000).

Reinforcing these findings, Powell and Matsumoto (1994) quoted a considerable range of studies which have showed that fresh water inflow is an essential factor influencing biological productivity of estuarine areas as diverse as the Black Sea, the Caspian Sea, the Nile Delta, the Gulf of St. Lawrence, Chesapeake Bay, and the bays and estuaries of the Gulf of Mexico (particularly those within the U.S. states of Texas and Florida).

Within Australia, Glaister (1978) and Ruello (1973) described reductions in commercial crustacean catches in NSW estuaries in relation to natural decreases in fresh water inflows. Bunn *et al.* (1998), and Loneragan and Bunn (1999), summarised a range of similar incidences in Queensland which speculated that river regulation is likely to have substantial effect on the production of coastal fisheries. This has been long recognised by commercial fishermen (McLeod, 2001).

4.2 Major ecological processes involving changes in fresh water inflows

In an examination of ecological studies focusing on the effects of fresh water inflows to Texas bays and estuaries, Longley (1994) identified thirteen different functions of fresh water inflows. Longley also examined the wider scientific literature and developed a list of fifteen impacts attributable to reduced fresh water inflows. The most significant impacts identified were:

- increased salinities and vertical stratification of the water column,
- penetration of the salt-wedge farther upstream allowing intrusion of predators and parasites of estuarine species, and increased intrusion into groundwater and surface water resources
- increased frequency of benthic anaerobic conditions and decreased inputs of nutrient and organic matter used by estuarine species,
- loss of characteristic species and economically important seafood harvests, and
- increases in erosion of delta areas resulting from the reduction of sediment flux.

Bishop (1999) assessed the potential impacts of large-scale water diversions on the fisheries of the Clarence River estuary, N.S.W., and the adjacent marine environment. An initial stage of this work involved the development of a checklist of major ecological mechanisms (processes) by which fresh water inflow reductions may impact the estuary. The checklist was based on a literature review which strongly relied on the review of Drinkwater and Frank (1994). Most of the impacts identified by Longley (1994) were subsumed into the list.

An adapted and expanded version of Bishop's (1999) checklist is presented here and can be found in Table 2 below. Sixteen major processes are identified and they are grouped in relation to the fresh water inflow magnitudes where they are likely to have most relevance: eight in respect to low fresh water inflows, five in respect to moderate-and-high fresh water inflows, and three in respect to all inflow magnitudes. Details of the processes are given within within the table.

Table 2 - Checklist of major ecological processes by which reduced estuary inflows may cause impacts on estuarine ecosystems and the adjacent marine environment[1].

Low-magnitude inflows (Low-):

Low-1: increased hostile water-quality conditions at depth

- reduced inflows, and concomitant reduced vertical mixing (turbulence), resulting in hostile water-quality conditions (e.g. low DO at depth) in deep sections within the upper-middle estuary where water retention times are protracted; higher salinity at depth would aggravate problems with DO; demersal eggs and large-size taxa are at most risk because they are found in deeper sections where water quality is likely to be most hostile

Low-2: extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive fauna

- reduced inflows resulting in extended durations of elevated salinity in the upper-middle estuary; fauna with low salinity tolerance (eggs, larvae, juveniles or adults) could be adversely affected through physiological stress and/or by competition and predation from colonising large fauna normally found in the lower estuary; increased parasitism may also be involved; avoidance response to salinity may cause occupation of suboptimal habitat and/or overcrowding; Odum (1970) indicated that the low-salinity region of an estuary acts as an important nursery ground for juvenile fish and invertebrates

Low-3: extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive flora

- reduced inflows resulting in extended durations of elevated salinity in the upper-middle estuary; instream and/or riparian plants with low salinity tolerance will be adversely affected through physiological stress; a considerable range of subsequent impacts could result: loss of shelter and foraging areas (riparian & instream plants) for fauna, reduced water quality as plants have diminished capacity to trap nutrients and sediments (riparian & instream), reduced bank stability if riparian plants die and subsequent water-quality deterioration if collapsed bank materials release nutrients to the water

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[1] This checklist is adapted and expanded from Bishop (1999) who developed a checklist based on a literature review which strongly relied on the work of Drinkwater and Frank (1994). All processes could lead to reductions in survival and growth rates, abundance, biomass & diversity of the biota. The processes are grouped in relation to the fresh water inflow magnitudes where they are likely to have the greatest relevance. DO = dissolved oxygen.

Low-4: extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota

- reduced inflows resulting in extended durations of elevated salinity in the lower estuary; marine biota thus able to colonise the lower portion of the estuary; sensitive biota either displaced through competition or predated upon, and may be additionally disadvantaged by high-salinity induced physiological stress

Low-5: extended durations when flow-induced currents cannot suspend eggs or larvae

- reduced inflows resulting in extended durations when flow-induced currents cannot suspend eggs or larvae in the upper-middle estuary; eggs or larvae settle to the bottom and mortality results

Low-6: extended durations when flow-induced currents cannot transport eggs or larvae

- reduced inflows resulting in extended durations when flow-induced currents cannot transport eggs or larvae in the upper-middle estuary to favourable habitats for later life-history stages (inhibition of advection); growth/recruitment opportunities are lost

Low-7: aggravation of pollution problems

- reduced inflows aggravating pollution problems in the upper-middle estuary originating from either agricultural, industrial or urban pollution sources; may include consequent biological ‘pollution’ (e.g. algal blooms, etc); lowered dilution of pollutants and/or stratification-induced deoxygenation causing the releases of toxicants from estuary-bed sediments; higher salinity at depth would aggravate problems with DO; consequent lowered abundance of fish, shellfish and crustacea, and contamination of tissues; nutrients may also be released from sediments causing algal problems for example.

Low-8: reduced longitudinal connectivity with upstream river systems

- decreased inflows can sever, or halt the establishment of, connectivity between the estuary and upstream river systems; this can have severe impacts on fauna with diadromous lifecycles (e.g. mobile fauna such as fish and crustaceans)

Middle- and high-magnitude inflows (M/H-):

M/H-1: diminished frequency that the estuary bed is flushed fine sediments and organic material (physical-habitat quality reduction)

- reduced inflows greatly altering the frequency that the bed of the upper-middle estuary is flushed of fine sediments and organic material (i.e. high flows causing substrate turnover); this is significant as many fauna lay their eggs on or within hard substrates - the presence of sediment/organic matter will result in lowered reproductive success as suitable egg deposition/attachment sites will become limited

M/H-2: diminished frequency that deep sections of the estuary are flushed of organic material (subsequent water quality reduction)

- reduced fresh water inflows greatly altering the frequency that organic material deposited on the bed of deep sections in the upper-middle estuary is flushed out; this is significant as a high organic load can result in hostile water-quality conditions (for example, low DO); again demersal eggs and poorly mobile taxa are at most risk

M/H-3: reduced channel-maintenance processes

- reduced inflows greatly reducing channel-maintenance processes (mediated by flushing flows) in the upper-middle estuary with a result that major habitat contraction occurs in the longterm; deep sections of the estuary are most vulnerable as very large flows are required to remove infilling material; again demersal eggs and large-sized taxa are at most risk; could be relevant to the lower estuary in respect to the closing of the estuary mouth through the deposition of transported marine sands; a range of impacts on migrating fauna may result from the reduced estuary-marine connectivity; water quality impacts could occur if tidal exchange flushing is substantially reduced

M/H-4: reduced inputs of nutrients and organic material

- decreased inflows subsequently reducing the input of natural river-borne nutrients and organic material; reduced primary production followed by reduced zooplankton abundance along the length of the estuary and into adjacent coastal areas; fish and crustacean abundance diminishes in response to decreased food supply and sheltering areas (instream plants)

M/H-5: reduced lateral connectivity and reduced maintenance of ecological processes in waterbodies adjacent to the estuary

- decreased inflows can sever, or halt the establishment of, connectivity between the estuary and adjacent waterbodies (floodplain billabongs, wetlands, etc) for mobile fauna; the loss of connecting flows may also result in ecological processes in the waterbodies not being activated or maintained

Across all inflow magnitudes (All-):

All-1: altered variability in salinity structure

- altered variability of inflows to the estuary, and the consequent change in patterns of variation in the salinity structure of the estuary, is likely to disrupt life cycles as suitably-timed breeding and/or migration cues for fish and crustaceans are masked; can also have relevance to plants; growth/recruitment opportunities are lost because of a lack of synchronization with the temperature regime.

All-2: dissipated salinity/chemical gradients used for animal navigation and transport

- reduced inflows which subsequently dissipate salinity & other chemical gradients out from the mouth of the estuary, and/or along the estuary; this is significant as there is evidence (Odum 1970; Grange et al. 2000) that some juvenile estuarine fish & invertebrates species use such gradients to navigate there way into and along estuaries. Salinity-gradient upstream transport mechanisms could also be inhibited.

All-3: decreases in the availability of critical physical-habitat features, particularly the component associated with higher water-velocities

- reduced inflows lower water velocities thereby altering an important physical habitat component, particularly in the upper estuary where tide-induced water currents are less prevalent. Biota favouring higher velocity areas are disadvantaged; generally native biota are disadvantaged more than alien biota.

4.2.1 Salinity-mediated processes.

Processes directly involving changes to the salinity structure of an estuary are most common. Three such processes are within the low-inflows group (processes Low-2,3,4), and two are in the all-inflow-magnitudes group (All-1,2). Salinity is indirectly relevant to a further two processes (Low-1,7) as rises in salinity are associated with reductions in dissolved oxygen (Bayly and Williams, 1976, Deeling and Paling, 1999, Davies and Kalish, 1994). This link would aggravate the issues of hostile water quality at depth (Low-1) and the anoxia-driven release of pollutants from estuary-bed sediments (Low-7).

Many complex follow-on impacts may occur as a result of these processes. The most notable concerns salinity impacts on the instream and riparian flora (Low-3): loss of shelter and foraging areas for fauna, bank instability and multi-linked water quality reduction (Table 2).

The prominence of salinity changes in the processes is not surprising given that complex patterns of salinity in estuaries are considered to have a profound influence on the distribution of estuarine organisms (Deeling and Paling, 1999). Warwick and Williams (1984; in Binnie, Black and Veatch, 1998) considered salinity to be the 'master factor' governing estuarine biota distributions, conditional on water quality conditions remain favourable. Similarly, TEL Pty. Ltd. (1996) stated that the salinity regime of an estuary is a fundamental determinant of the distribution of much its flora and fauna. However, when assessing the role of salinity, it is clearly important to recognise the complexities introduced by confounding environmental variables such as temperature. A large array of complex observations are required to isolate out the influence of salinity.

4.2.2 Reductions in inflow-induced currents and vertical mixing.

Processes involving changes in inflow-induced currents and vertical mixing are the next-most common. Four processes involve these changes, and as would be expected, all but one (All-3) are within the low-inflows group. Two of the processes (Low-1,7) concern water quality changes induced by diminished vertical mixing (i.e. reduced water turbulence). Two further processes concern direct physical impacts on eggs and larvae, specifically, reductions in their suspension in the water column (Low-5) and their transport along the estuary (Low-6: advection). The remaining process (All-3) concerns the loss of the physical habitat component associated with higher water velocities induced by fresh water inflows.

These processes would be most relevant to areas where tide-induced currents are least prevalent, i.e. in the upper reaches of estuaries and/or in estuaries which have mouths that significantly restrict tidal exchange.

4.2.3 Reductions in connectivity associated with the loss of water depth.

Two processes (Low-8 & M/H-5) concern the loss of connectivity, an issue of particular relevance to migrating fauna such as fish and crustaceans. Process Low-8 concerns the longitudinal connectivity between the estuary and the upstream river system. It is placed within the low-magnitude inflow group of processes as water depths, sufficient to allow the movement of fauna across tidal-barrier riffles, usually become available within the low-inflow range. Process M/H-5 concerns the lateral connectivity between the estuary and waterbodies adjacent to the estuary (i.e. floodplain billabongs, wetlands, etc). It is placed within the moderate-and-high magnitude inflow group of processes as water depths, sufficient to allow the lateral movement of fauna between waterbodies, usually become available within the moderate-to-high inflow range. Only water diversion schemes with large transfer and/or storage capacities would be capable of impacting such inflows. The loss of 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.

4.2.4 Reductions in flushing and channel-maintenance flows.

Three processes (M/H-1,2,3) involve reductions in flushing or channel-maintenance inflows. Each of these processes are within the moderate-to-high inflow group. This grouping is consistent with the understanding that episodes of high bed shear stress are required to flush or maintain estuary channels.

Two processes involve the reduction of habitat quality by the reduced frequency of flushing inflows. These are probably most relevant to moderate-magnitude inflows. They specifically concern reduced physical-habitat quality where hard substrates are coated by sediments or organic material for prolonged periods (M/H-1), and water-quality deterioration due to the accumulation of organic material and subsequent high biochemical oxygen demand (M/H-2).

The other process specifically involves the reduced frequency of channel-maintenance fresh water inflows resulting in habitat contraction (M/H-3). This would be most relevant to high-magnitude inflows. Clearly, only water diversion schemes with large storage capacities would be capable of impacting such inflows. Pertinent also is the nature and amount of bed material being carried along the estuary. Estuaries with large volumes of such materials, which would reflect catchment geology and integrity, and/or estuary-bank stability, would be most prone to impacts arising from this process. Estuaries that have mouths which are prone to closure as a result of the deposition of transported marine sands, would also be vulnerable to this process. Mouth closure (that is, severed marine-estuary connectivity) has many ramifications for the numerous fauna that migrate between the estuary and the ocean. Poor water quality may also result from reductions in tidal flushing.

4.2.5 Reduced input of river-borne nutrients and organic material.

One process (M/H-4) concerns reductions in the input of river borne nutrients and organic material. This is an important process as the input of this material “drives” estuarine foodwebs and is responsible for the high productivity of estuaries (Grange *et al.*, 2000, Loneragan and Bunn, 1999; Binnie, Black and Veatch, 1998). The materials stimulate phytoplankton and benthic production, which are thought to be important primary sources in coastal foodwebs (Loneragan and Bunn 1999).

This process is within the moderate-and-high inflow group. This is consistent with the understanding that organic matter and nutrients (bound to sediments) primarily enter rivers from their catchments during major rainfall events, events which generate moderate-to-high inflows. In general, only water diversion schemes with relatively large transfer and/or storage capacities compared with catchment yield would be capable of impacting such inflows.

4.2.6 Reduced dilution of pollutants.

One process, aggravation of pollution problems (Low-7), partially concerns the reduced dilution of pollutants arising from agricultural, industrial or urban sources. Reductions in inflow-induced currents and vertical mixing are also relevant to this process.

The process is grouped in the low-inflow group because this is the condition when dilution is pertinent. Clearly, this process is only relevant to polluted estuaries. It would be particularly relevant to estuaries or estuary areas where tide-induced currents are least prevalent (that is, in estuaries which have mouths that significantly restrict tidal exchange, and/or in the upper reaches of estuaries).

4.3 Estuarine systems are complex, highly valued and linked

In the process of investigating the potential ecological impacts of fresh water extraction from the Richmond River estuary, north-eastern NSW, Peirson *et al.* (1999) recognised the complexity of estuarine ecosystems and stated that they have a vast number of biotic (living) and abiotic (non-living) components and linkages.

This complexity can be readily appreciated by considering the number of major inflow-related processes outlined above in Table 2. Further appreciation arises when interactions between the processes are considered. Other complications arise from the possibility of subsequent cascading effects arising from apparently unrelated processes. Antecedent conditions may have a profound influence on the nature of estuarine communities and their response to impactors (Rainer, 1981).

Compounding the above complexity, Australian estuaries incorporate a wide diversity of habitats for plants and animals. Many estuarine organisms use multiple habitats during their lifecycle. At least eleven broad estuarine habitat categories have been identified (NSW Government 1992) and these are described in Appendix 5. In NSW, estuaries have been classified as 'Estuarine Wetlands', a subset of 'Coastal wetlands' (Pressey and Harris, 1988).

Estuarine habitats are highly valued by some sectors of society for their scenic qualities and their high productivity, and the dependent commercial and recreational fisheries. They also can have high conservation value if they provide viable habitat for threatened or endangered flora and fauna.

Their importance extends beyond their physically-defined boundaries given near-shore marine production is commonly dependent on outputs from estuaries (Drinkwater and Frank, 1994; Loneragan and Bunn, 1999). There are also substantial other links with the marine environment given the large flux of fish and invertebrates which move through the estuarine-marine interface, an activity which is critical for the completion of their lifecycles (for example, diadromous and catadromous fish – barramundi, mullet and eels)

Strong links also exist inland up into rivers with respect to diadromous migrations of fauna (movements between the sea/estuary and rivers/streams). Harris (1984) indicated that in south-eastern Australia there are twenty-three species of diadromous fish, eleven of which are amphidromous (migrations not for breeding, e.g. sea mullet), eight catadromous (migrates to the sea/estuary for breeding, e.g. Australian bass and barramundi, eels), and four anadromous (migrates to fresh waters to breed, e.g. lampreys). Links also exist nationally and internationally in respect to the migration of waterbirds. Birds migrate from continent to continent and many migratory waders come to Australia during the non-breeding season to replenish their fat reserves.

Accordingly, the value, and the significance of efforts to protect and maintain estuaries, should not be considered simply in isolation. Clearly, a regional, national and even an international perspective is needed.

4.4 The imperative to protect and maintain estuarine ecosystems

There is clearly an imperative to protect and maintain estuaries given the combination of their high value and the vulnerability to the essential estuarine processes to reductions in fresh water inflows. It is recognised that fresh water inflows fluctuate naturally and therefore the diverse processes would naturally stress estuaries. However, the key questions are:

- how far can the natural stressors be extended?
- are there thresholds beyond which inflow-reduction impacts cause a noticeable escalation of biological risks?

In managing the environmental impact of water extraction it is of course vitally important to have some understanding of the way in which biological risks change in relation to, i.e. are linked with, the changing impacts arising from water extraction. Currently there is negligible information on these biological-risk *versus* water-extraction relationships for estuaries around Australia. Exceptions are the studies of Peirson *et al.* (1999) and Bishop *et al.* (2001) within the Richmond River estuary NSW, and Bishop (1995) within the Hastings River estuary, also in north-eastern NSW.

4.5 An approach in a knowledge-poor environment?

Binnie, Black and Veatch (1998) stated that relationships and interactions between the biota and fresh water inflows in United Kingdom estuaries are at present poorly understood. This situation clearly arises because of the complexity of the inflow-reduction processes as well as the dearth of investigations which have been undertaken on the issue. These authors further stated that estuary managers and nature-conservation groups alike, should accept that precise quantitative answers cannot be provided regarding the impact of inflow reductions on the ecology of estuaries.

The knowledge is also quite poor in relation to sub-processes within the major processes. An example of this is the estuarine biotas' response (tolerance) to changes in salinity, an important water-quality variable directly involved in five major inflow-reduction processes. There have been advances in knowledge relevant to this sub-process in the fresh water-upper-end of estuaries. This has arisen from the consolidation of information on the impacts of dryland salinity on Australian fresh water ecosystems (for example, Hart *et al.*, 1991; Nielsen and Hillman, 2000), and from investigations into aquatic plants within South African estuaries (Adams and Bate 1994). However, while salinity thresholds have been identified for a range of biota, they rarely include the consideration of medium to long-term chronic effects, or specifications for the time of exposure. With most toxicants, the effect on plants and animals is dependent on both concentration and time of exposure (Hellawell 1986). The Bishop *et al.* (2001) modelled salinity-versus-exposure 'signature' (Figure 2) for the area of major biological change along the Emigrant Creek estuary in north-eastern NSW illustrates this. It is difficult to know whether the biological change was caused by a low concentration for an extended time period (e.g. 0.5 ppt salinity for > 30% of the time, i.e. 'press' disturbances), or a high concentration for a short period (e.g. 5 ppt for ~5% of the time, that is, 'pulse' disturbances).

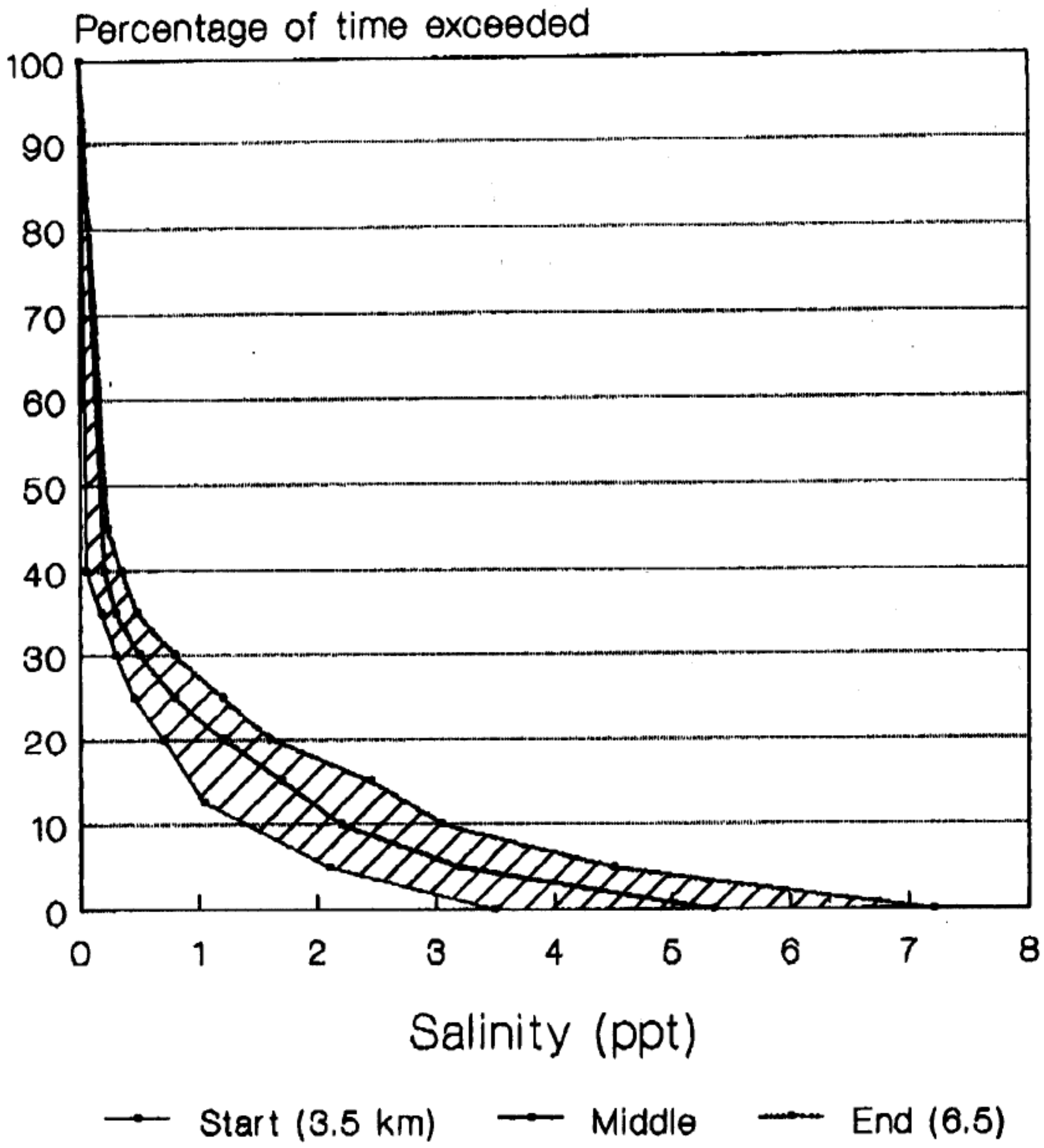

Figure 2. Salinity-versus-exposure 'signature' through the section of major biological change along the Emigrant Creek estuary. Based on changes in aquatic and riparian vegetation starting at 3.5km, middle at 5km and ending 6.5km downstream of the tidal limit.

Peirson *et al.* (1999) undertook a risk assessment of fresh water reductions in an estuary focusing on salinity-mediated changes. These authors described the complexities involved in understanding the way in which salinity influences biotic communities. In the process of modelling habitat availability in the estuary they utilised salinity thresholds derived from the literature which were relevant to various groups of biota. The potential weaknesses of the thresholds (limits) were recognised and therefore they were referred to as 'indicative' or 'working' thresholds, based on best-available information. The modelling depicted links between the level of fresh water extraction and the extent of habitat contraction and this was the basis of the risk assessment. The authors qualified their work as follows:

> *"Given the complexities of estuarine ecosystems and inaccuracies which may occur in the methodologies, particularly in relation to the range of working thresholds utilised, it is imperative that any implemented extraction regime be viewed as an interim condition, to be revised once substantial knowledge is gained through ensuing scientific research and monitoring. This is a fundamentally important feature of any adaptive management system."*

4.5.1 Adaptive management approaches

Reinforcing the appropriateness of the above risk analysis, Jones (2001) recently argued that risk-based assessments of salinity impacts are ideally suited to an **adaptive management approach** (*sensu* Walters, 1986; Knights and Fitzgerald, 1994). Although not explicitly stated, an adaptive management approach is recommended by Arthington *et al.* (1998) as an important part of a Best Practice Framework for devising environmental flows in rivers and streams.

The adaptive management approach is clearly not ideal given the initial uncertainty and the subsequent potential for later change in water-extraction controls. However, it is all that is possible given the paucity of relevant knowledge. There needs to be some attempt to predict risks on the basis of currently-available knowledge, given the imperative to protect and maintain estuaries in the face of strong and increasing pressures to extract fresh water. Grant and Bishop (1998) used the terrestrial-ecosystem analogy '*the bulldozers are already moving*' to illustrate the grave situation in fresh water systems regarding water-extraction pressures. They further stated that:

> *"... it is very important that an applicable method is utilised even though it is probable that initial estimates may yield under- or overestimates. The error is not a major concern if an adaptive management system is in place - i.e. allowing estimated flow requirements to be revised once knowledge is gained through monitoring of the interim-set flows. In most situations it would be beneficial to minimise the initial error by choosing the most applicable assessment method(s)."*

Conceptually, risk assessment is the initial **predictive component** of an environmental flows investigation, and monitoring is the **detection component** which loops back into the prediction process. If the predictive component is based on sound knowledge then high-quality predictions will result, and accordingly, the importance of the detection component will be reduced. However, given the state of knowledge on inflow-reduction processes, the quality of the detection component will be an important issue for a long way into the future. Deeling and Paling (1999), and Fairweather (1999), both indicated that much developmental work, particularly the ongoing selection, evaluation and refinement of environmental indicators, is required before the ecological health of Australian estuaries can be accurately and cost-effectively assessed.

4.5.2 An important feature of the predictive and detection components

The detection component focuses on the assessment of ecological 'health', Fairweather (1999) recognised that multiple variables are required to represent the multiple facets of ecosystem health. Similarly, Deeling and Paling (1999) indicated a hierarchy of environmental indicators is required for assessing the health of Australian estuaries.

The use of multiple variables is also relevant to the predictive component of investigations. Peirson *et al.* (1999) used such an approach in their predictive risk assessment and stated:

> *"Estuarine ecosystems have a vast number of biotic (living) and abiotic (non-living) components and linkages. It is therefore never possible to make meaningful predictions concerning ecosystem health by considering just one component of the ecosystem. For this reason a range of ecosystem components were targeted. That is, the investigation took a multifaceted approach which attempts to account for the potentially high level of ecosystem complexity."*

Bishop *et al.* (2001) also used a multifaceted approach in the Emigrant Creek estuary. South African investigations into environmental-flows for estuaries are generally multidisciplinary and usually involve specialists in hydrology, hydrodynamics, water quality, botany, benthic invertebrates, fish and birds (Adams pers. comm. 2000; e.g. Scharler *et al.*, 1998). Similarly, in the United Kingdom, Binnie, Black and Veatch, 1998) argued for a holistic approach to estuary management where risk assessment involves the consideration of water quality, plant communities, invertebrate communities, fish communities and specifical recreational and commercial fisheries and fish migrations.

There are clearly parallels with recommended approaches for environmental-flows investigations in fresh waters. For example, in Australia, Arthington *et al.* (1998) recommends that a multidisciplinary approach is a key feature of a Best Practice Framework in such investigations.

4.6 Narrowing down investigations to obtain cost-effective results

Given the paucity of information on inflow-reduction processes, any environmental-flows investigation could be projected endlessly. However, investigation funds are always limited and so there is a need to set priorities in order to obtain cost-effective findings.

4.6.1 Overall scale of an investigation.

Initially, the overall scale or the importance of the investigation should be determined by considering, in combination, the following questions:

1. What is the maximum proportion of fresh water inflows (or the tidal pool) which are intended to be extracted? Are moderate-to-high magnitude inflows significantly impacted, or is it only the low-magnitude inflows?
2. What is the value of the estuary from a conservation (e.g. pristine versus degraded, the presence of threatened or endangered species or communities, listed wetlands, rare habitats, etc., possible guidelines for assessing the conservation significance of estuaries are given by Edgar *et al.*, 1999), commercial fisheries, recreational fisheries and scenic/tourism perspectives (regional, national and international links also require consideration)?

If the proportion of fresh waters to be extracted is quite small, and the estuary's value is found to be quite low, then a low-scale investigation is appropriate. Obviously the opposite applies if the value is high and the extraction proportion is large. Between these two limits, the scale of investigations must be determined as part of the methodology described in Chapter 9.

4.6.2 A process focus.

If only low-magnitude inflows are impacted then the five major processes concerning moderate-to-high inflows (i.e. processes M/H-1,2,3,4,5; Table 2 on page 8) can be given lower priority. Some of these processes may be eliminated because the estuary in question does not normally carry large volumes of mobile bed material, or is not prone to mouth closure resulting from the deposition of transported marine sands.

Other characteristics of an estuary may also make investigation of certain major processes a lower priority. For example, Process Low-7 may not required detailed investigation if the estuary does not have any significant pollutions (either caused by negligible pollution sources or a high level of tidal flushing). Similarly, Process Low-1 could be given a low priority if the estuary is predominately shallow, and Process Low-3 could be ignored if highly turbid waters meant that plants were virtually absent from the estuary (particularly the case if riparian plants were also rare).

4.6.3 Focus within an estuary.

Generally, it is expected that processes involving changes to the salinity structure of an estuary (i.e. five processes concerning direct impacts and two processes concerning indirect impacts) will have to be examined. As the intensity and nature of salinity changes will vary along the length of the estuary, it will be important to determine the estuarine-long distribution of valuable and vulnerable components (e.g. threatened or endangered species with low salinity tolerances, or beds of submersed salt-sensitive plants used as important sheltering and feeding areas).

It is also expected that there would generally be a focus on the upper arms of an estuary as the biota there are likely to be most vulnerable to a number of inflow-reduction processes. This is because:

- Salinity is lowest and least variable in the upper estuary, and accordingly, the biota in these areas are least likely to tolerate increases in salinity (Peirson *et al.*, 1999 assumed this to be the case in the Richmond River estuary in north-eastern NSW)
- The suitable-salinity-habitat zone in the upper estuary may be 'squeezed' (i.e. contracted) rather than displaced up the estuary as it is the case for the middle- and lower-estuary zones. If tidal-barrier riffles are present, under habitat-squeeze events fauna in the upper estuary have no where else to go as, under low inflow conditions, it is unlikely that they could move upstream. Increased competition, predation and reductions in food supply can result.
- The low-salinity region of an estuary acts as an important and relatively safe nursery ground for juvenile fish and invertebrates (Odum, 1971). Aquatic plant beds in these regions are also likely to be important staging areas for fauna making migrations up into fresh waters (e.g. Harris, 1986 indicated this was the case for larval and juvenile Australian bass in south-eastern Australia)
- Less tidal flushing occurs in the upper reaches of an estuary, a result of the reduction in tidal prism with increasing distance from the sea (see Section 5.2.5 below). Accordingly, in the upper estuary, currents and the vertical mixing of waters are most dependent on estuary fresh water inflows. The implication of this is that the impacts of four major inflow-reduction processes are likely to be most intense in the upper reaches of an estuary: deterioration of water quality at depth (Process Low-1), egg and larval suspension (Low-5), egg and larval transport (advection; Low-6), and the loss of physical habitat associated with higher water velocities (All-3).

- Longitudinal connectivity to the upstream river system has greatest relevance to the upper estuary.
- It is important to note that this suggestion of a general upper-estuary emphasis is mainly a result of the likelihood that a range of major impacting processes are likely to be most focussed (i.e. most intense) on the upper estuary. The suggestion does not arise because it is likely that there is greater biological activity in the upper estuary – this may or may not be the case and will depend very much on the character of the estuary.

5. RELEVANT ESTUARINE PHYSICAL PROCESSES

In this chapter, we summarise those physical estuarine processes that determine transport and mixing processes within estuaries. This is to provide a physical context for the ecological process checklist contained in Table 2 on page 8. Excellent published summaries with a broader view of estuarine processes include books by Dyer (1973), Ippen (1966) and Fischer *et al.* (1979).

As noted in the Chapter 3, mixing and interaction of fresh and saline waters occurs within estuaries. The density of fresh and saline waters is different and estuaries tend to stratify with the fresh water flowing over and above saline water intruding from the open ocean. However, turbulent mixing is induced by the tidal flow adjacent to the bed and banks of the estuary and this tends to destroy any stratification. The salinity structure of an estuary is determined by the relative strengths of the stratification and mixing processes which, in turn, dominate transport and dispersion within estuaries.

Note that stratification can also be induced by sediment entrainment or thermal heating of estuarine waters and mixing can also be induced by wind. However, the stratification and mixing induced by these processes tends to be weaker than that caused by salinity and tidal flow.

The transport and mixing processes within an estuary are determined by:

- physical form;
- stratification and tidal mixing; and,
- fresh water inflow.

Discussion of each of these is contained in this chapter followed by a description of the numerical tools available to estimate transport and dispersion in estuaries.

5.1 Physical Form

5.1.1 Classification

In a similar manner to geographical/geomorphological descriptions of estuaries internationally, Australian estuaries have recently been classified by Digby et al (1999). This document which provides other useful background information for this investigation.

The classification scheme proposed is based on easily-quantifiable, biologically-important physical characteristics. Statistical analysis was carried out on an Australian Estuarine Database of 780 estuaries which incorporated spatial, geographic, morphologic and climatic data. Biological parameters used in the estuary classification included the proportion of mangrove and saltmarsh habitat. Criteria used to classify the estuaries included:

- geomorphology
- evolutionary stage
- hydrological processes
- climate
- water quality
- habitat
- land use
- aesthetic values.

Digby et al (1999) defined four morphological estuary types in Australia:

- drowned river valley systems

  This is an estuary resulting from the rapid rise in sea level which occurred during the Flandrian transgression, between 18000 and 5000 years ago. Sea levels were approximately 100 m below the present level, due to water being held in the massive ice sheets which covered large portions of the earth's surface. The sea level steadily rose to its present level between 18000 and 5000 years ago, due to the melting of the ice sheets. Drowned river valleys formed throughout the world in areas where sedimentation was unable to keep pace with the steady rise in sea level. Another characteristic of these estuaries is that river inflow is low compared to the tidal flow of the estuary (Luketina, 1998). Examples include San Francisco Bay, Sydney Harbour, Broken Bay and Georges River.
- barrier estuaries

  This is a drowned river valley in which sedimentation has kept pace with the rise in sea level. In these estuaries, the ratio of river flow to tidal flow is quite high and a river delta usually forms. Sediment load carried by these rivers is also quite high. These estuaries are relatively common in tropical regions throughout the world (examples include the Ganges, Nile, Mekong and Mississippi rivers). Australian examples can be found in northern Queensland.
- open ocean embayments, and
- saline coastal lakes.

(Internationally, fjords are an important estuarine category. These are the result of glacial erosion of old river valleys, for example, Milford Sound. There are no fjords in Australia.)

These estuaries have a variety of morphological evolution characteristics, entrance conditions, tidal behaviour and depositional environments.

A classification scheme for all Australian estuaries was assembled, based on the presence of a single or multiple mouth, constricted or unconstricted mouth, branched or unbranched main drainage lines, and whether the main drainage line was a channel or bay. An estuary may exhibit any combination of the above physical characteristics, giving 32 possible physical types of estuaries.

5.1.2 Estuary Mouths

The classification system proposed by Digby et al (1999) is useful in assessing the general nature of estuarine systems around Australia. However, it is important to note that:

- The form of the mouth of an estuary can be transformed dramatically in response to antecedent fresh water inflows and littoral drift.

  A consequence of flow variability for estuaries whose entrance is exposed to high littoral drift is that nearshore sand movements and reduced river flow can allow the sand bars to form in the mouth of the estuary and exchange of the estuarine water with the sea can be significantly reduced. Under these circumstances:
  - tidal flushing of the estuary is dramatically reduced; and,
  - tidal mixing of the estuary is reduced making stratified conditions more likely.

  All of these factors can have significant implications for water quality and the ecology.

- Anthropogenic structures have had a profound impacts on many of the major estuarine systems around Australia. These fall into two categories:
  - *Tidal barrages* that prevent the ingress of salt water upstream within an estuary.

    There are both natural and man-made barriers to salt water intrusion and the length of the estuarine component of a river can be very short. The most dramatic man-made example is the weir at the mouth of the Murray/Darling system. Tidal barrages on the Fitzroy and Burdekin Rivers in Queensland have reduced the tidal area of their estuaries by as much as 40%. Naturally formed gravel bars on the Bellinger prevent intrusion of saltwater. In such systems, a large portion of an estuary that would exist in the absence of the barrier is transformed into a fluvial environment. However, the implications for the estuary downstream of the barrier are substantially reduced tidal flushing due to the reduced tidal prism as well as reduced estuarine habitats.

Upstream of tidal barrages, the water levels are held artificially high. This will result in decreased flow-induced currents and flooding of habitats previously subject to occasional inundation.

- *Training walls* that maintain navigable depths within the entrance but make the entrance more hydraulically efficient.
  It is to be noted that following European settlement, significant changes have been made to some estuary entrances that include dredging and the construction of training walls (Coltheart, 1998). This can make the entrances more hydraulically efficient and prevent entrances in regions of high littoral drift from closing during periods of low fresh water flow. Under such circumstances (for example, Wallis Lake, NSW, Nielsen, 1992 and the Mary River, NT, Wylie and Roizenblit, 1994 and Wylie *et al.*, 1997), estuaries can move into an unstable mode in which channel scouring persists in concert with an increasing tidal range in the estuary. Greater intrusion of salt water to the estuary will occur.

5.1.3 Ecological Implications

Deeper estuaries (typically, drowned river valleys) are more susceptible to stratification (Section 5.2). Stratification is conducive to anoxia and poor water quality and therefore such estuaries will be more susceptible to reductions in fresh water inflow (Relevant ecological processes, Table 2 on page 8, Low-1 to Low-7 and M/H-1 to M/H-4).

Estuaries with mouths that tend to close during periods of low fresh water flow, will tend to close more easily if fresh water inflows are reduced (M/H-3). This will lead to decreased tidal flushing and increased stratification. This may allow saline water to intrude upstream along the bed and allow bottom water to stagnate. Such estuaries would be susceptible to all of the low flow ecological processes (Low-1 to Low-7).

Where tidal barrages have been placed in estuaries, tidal flushing and estuarine habitats will be reduced with consequent ecological implications downstream but consideration of these is outside the scope of this report. Upstream of the barrage, risk of ingress of salt water is eliminated (All-1) but flow-induced velocities are reduced with associated submergence of habitats previously only subject to occasional inundation (Low-5, Low-6, M/H-1 to 3).

Construction of hydraulically-efficient entrances (using training walls or dredging, for example) will result in increased flushing and intrusion into the estuary by ocean water (Low-2 to Low-4 and All-1, All-2).

5.2 Tidal Mixing and Saline Stratification

Estuaries can be described in terms of their salinity structure. The salinity structure of the estuary is determined by its geometry as well as prevailing and antecedent climatic conditions which include:

- Fresh water inflow;
- Tides, and
- Wind.

Stratification arises because of the differences in density between the fresh and saline waters that interact within estuaries.

Neglecting fjords, four primary classifications of estuarine saline structure have been identified:

1. Highly stratified;
2. Partially stratified;
3. Well-mixed; and,
4. Inverse estuaries.

These are described in turn.

5.2.1 Highly stratified (or salt wedge) estuary

Fresh river flow is buoyant compared to sea water. When the fresh water inflow is high and the estuary relatively deep, the river flow tends to move over the top of saline waters intruding from the sea, creating a so-called “salt wedge” (see Figure 3). Measured salinity profiles in such system show abrupt increases in salinity with depth.

Entrainment occurs across the fresh-saline interface that resists the intrusion by the saline waters at the bed and creates a net circulation of salt water as shown in Figure 3. Entrainment of salt water across the interface results in an increase in the surface salinity towards the mouth of the estuary.

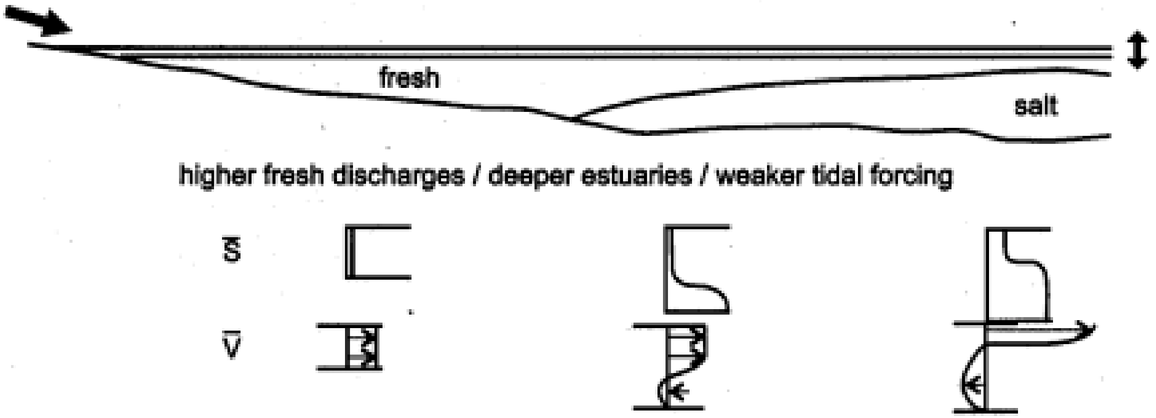

Figure 3 – Schematic vertical section of a salt-wedge estuary. Estuary mouth is at the right. $\overline{S}$ and $\overline{V}$ are the tidally-averaged salinity and velocity profiles at the positions shown along the estuary.

Flushing of the estuary is dominated by the fresh water flow and flow-induced circulations. The relatively strong fresh water inflows associated with salt-wedge estuaries results in strong flushing of the surface waters. However, the poor exchange between the surface and the bed in the stratified region of such estuaries which can result in long resident times for the bottom water leading to dissolved oxygen depletion and anoxia.

5.2.2 Partially-Mixed Estuary

In estuaries where tidal flows are significant, the tidal motion of water in an estuary will generate turbulence on the bed and banks of the estuary. The turbulence acts to mix the fresh and saline waters and reduce saline stratification.

A partially mixed estuary has a saline structure as shown schematically in Figure 4. Salinity can be observed to increase with depth but without the abrupt changes observed in highly stratified systems.

It is to be noted that whilst some stratification remains, the inflow of salt water is favoured on the flood tide and outflow of fresh water on the ebb tide. This can greatly enhance the flushing of such systems beyond that produced by fresh water flow alone.

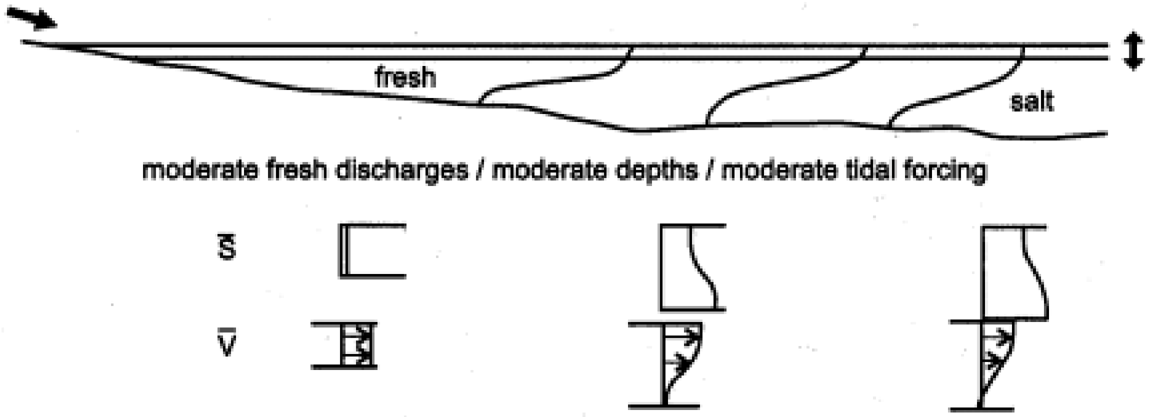

Figure 4 – Schematic vertical section of a partially-mixed estuary. Estuary mouth is at the right. $\overline{S}$ and $\overline{V}$ are the tidally-averaged salinity and velocity profiles at the positions shown along the estuary.

5.2.3 Vertically Well-Mixed Estuary

In estuaries which are relatively shallow with low fresh water inflow and large tidal currents, flow-induced turbulence can be sufficient to destroy all vertical stratification and make the estuary vertically homogeneous. Such estuaries are termed vertically well-mixed. The saline structure of such estuaries is illustrated in Figure 5.

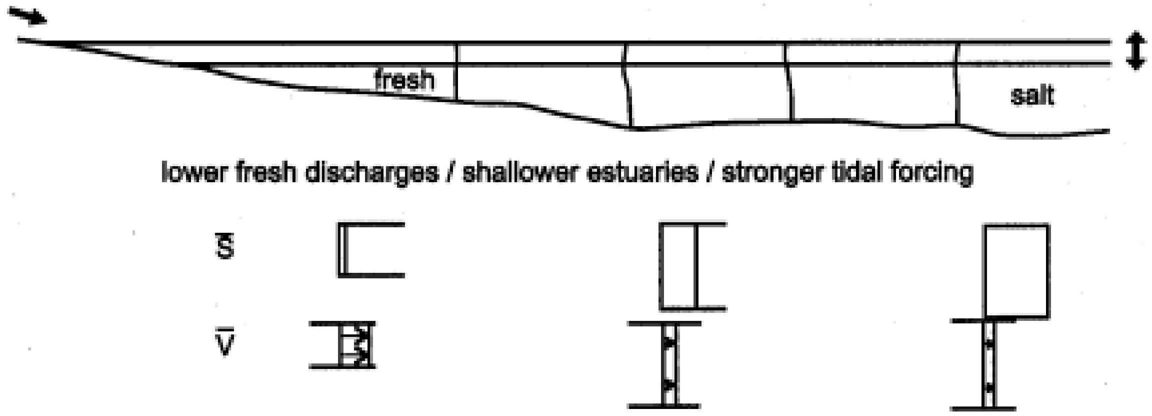

Figure 5 – Schematic vertical section of a vertically well-mixed estuary. Estuary mouth is at the right. $\overline{S}$ and $\overline{V}$ are the tidally-averaged salinity and velocity profiles at the positions shown along the estuary.

5.2.4 Inverse Estuaries

In wide shallow estuaries and tidal embayments, high evaporation rates in the presence of very low fresh water inflow can result in hypersalinity. Under such conditions, the estuarine waters become more dense than the ocean waters. This induces a net circulation in which the dense hypersaline water sinks to the bed of the estuary and flows towards the ocean and is replaced by inflowing seawater at the surface of the estuary. The saline structure and net circulation are as shown in Figure 6.

This circulation pattern is in the opposite direction to the normal estuarine behaviour and is called negative circulation and the estuary is termed inverse.

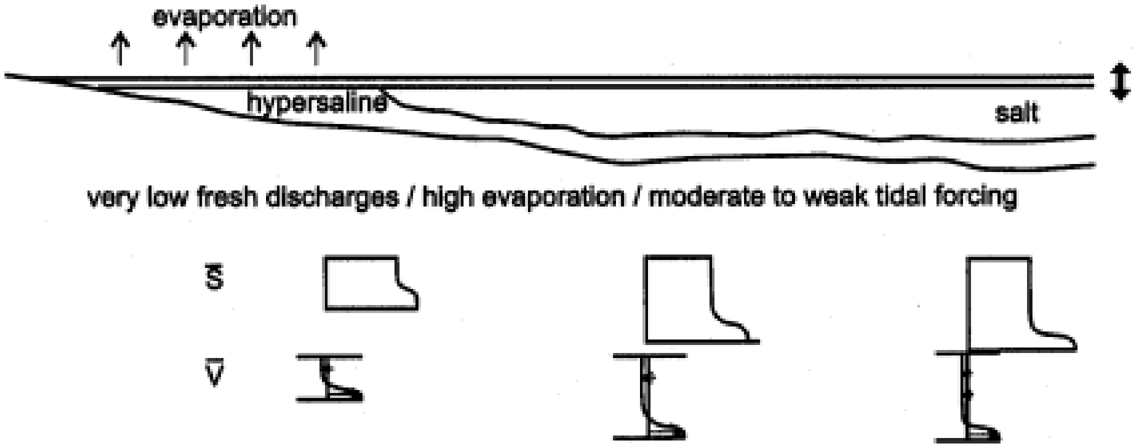

Figure 6 – Schematic vertical section of an inverse estuary. Estuary mouth is at the right. $\overline{S}$ and $\overline{V}$ are the tidally-averaged salinity and velocity profiles at the positions shown along the estuary.

5.2.5 Simple methods for predicting estuarine stratification

As shown in the preceding section, there is an intimate relationship between flow behaviour, saline structure and dominant flushing processes in an estuary. Investigators have sought classification systems that will allow estuaries to be categorised and their saline structure predicted.

Vertical stratification is important in determining estuarine water quality which has a number of ecological implications as discussed in Section 5.2.7. This section presents available simple methods for predicting estuarine saline structure.

Simmons (1955)

The simplest classification is based on determining the quantity of fresh water flowing into an estuary over a tidal cycle in relation to the tidal prism (Simmons, 1955 cited in Dyer, 1979). The balance between estuarine mixing and flushing by the tides and fresh water inflows from rivers is a strong determining factor in the saline structure of estuaries.

The tidal flow is expressed simply as V_T, or the volume of water contained in the estuary between high and low tides:

$$V_T = H\overline{A}$$

where H is the tidal range and $\overline{A}$ is the mean water surface area of the estuary. The relative effect of the river inflow to the tidal flow is expressed in terms of a coefficient *R* which is given by:

$$R = \frac{V_R}{V_T}$$

where $V_R = Q_R T$, Q_R is the river flowrate and T is the tidal period.

Table 3 outlines the different classification based on the value of *R*.

Table 3 – Estuary classification as a ratio of river inflow and tidal flow over a tidal cycle, Simmons (1955)

R	Classification
$1 \leq R$	highly stratified or salt wedge
$R \approx 0.25$	partially mixed
$R \leq 0.1$	well mixed

Hansen and Rattray (1966)

Hansen and Rattray (1966) devised a stratification circulation diagram based on two dimensionless parameters:

$$Stratification\ Parameter = \frac{\delta S}{\overline{S}} = \frac{surface\ to\ bottom\ salinity}{mean\ cross - sectional\ salinity}$$

$$Circulation\ Parameter = \frac{u_s}{u_f} = \frac{net\ surface\ current}{mean\ cross - sectional\ velocity\ (river\ \ flow)}$$

For a two-dimensional estuary:

$$u_s = \frac{1}{h}\int_0^h u dz$$

$$u_f = \frac{1}{d}\int_0^d u dz$$

These quantities are defined graphically in Figure 7. Similar estuaries tend to plot as lines on the stratification-circulation diagrams as shown and described in Figure 8 and Table 4.

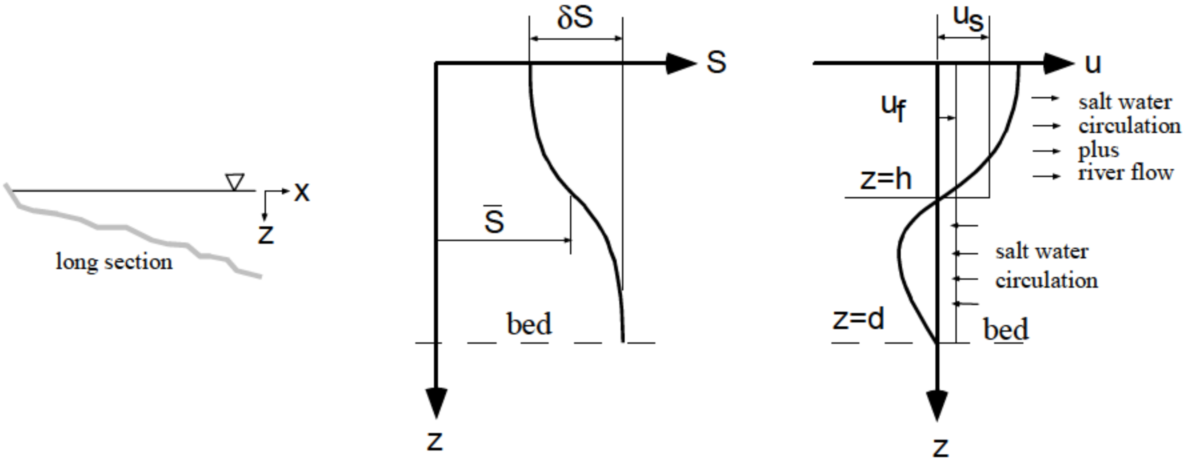

Figure 7. Salinity and velocity profiles in an estuary with definition of the quantities required for Hansen-Rattray estuarine classification.

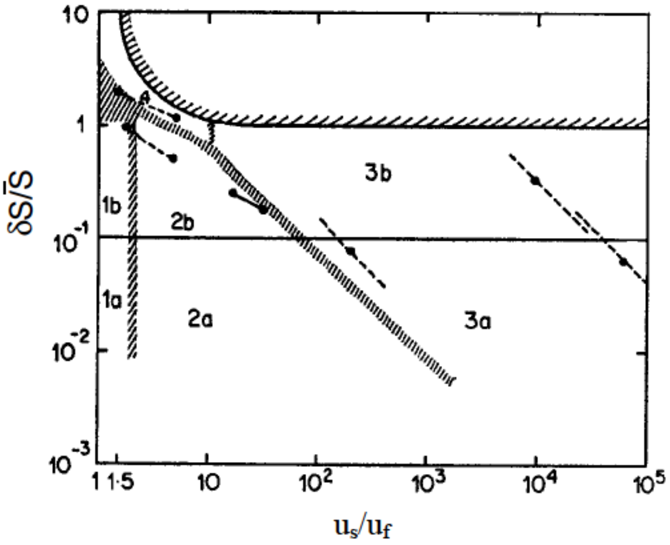

Figure 8. Hansen-Rattray estuarine classification diagram. The major classifications are listed in Table 4. The dashed lines are data from various estuaries. The head of the estuary is at the upper left end of the dashed lines and the mouth at the lower right hand ends.

Table 4 – Estuary classification based on the system of Hansen and Rattray (1966)

Estuary type	Characteristics
1	well mixed estuaries
2	partially mixed estuary
3	deep estuary (partially mixed to well stratified *ie* fjords)
4	salt wedge

Fischer (1976)

The Hansen-Rattray circulation parameters can be calculated from a single survey taken over a couple of tidal cycles and does not require knowledge of the river inflow or the tidal prism. Fischer (1976) showed that the Hansen-Rattray parameters can be related to more fundamental parameters in the form of an estuarine Richardson number Ri_E and a densimetric Froude number Fr:

$$Ri_E = \frac{g' Q_R}{bU^3}$$

$$Fr = \frac{Q_R}{bd\sqrt{g'd}}$$

where b is the breadth or width of the estuary, d is the depth of the estuary, U is the root mean square tidal velocity and g' is the effective acceleration due to gravity:

$$g' = \frac{\rho_s - \rho_R}{\rho_s} g$$

Fischer showed that the stratification was primarily dependent on Ri_E while the circulation was mainly dependent upon Fr.

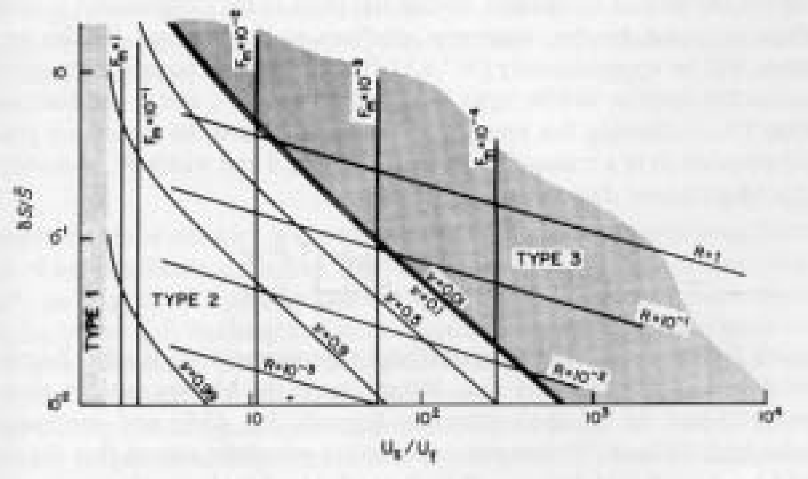

Figure 9. Hansen-Rattray estuarine classification diagram with contours of Richardson number and densimetric Froude number as determined by Fisher (1972).

5.2.6 Some comments on simple predictive methods

The inability of these simple predictive methods to capture any unsteadiness in the inflow is discussed in Section 5.3.2. The Fisher (1972) approach is the most useful as it is the most accurate method of estimating estuary stratification if only flow, bathymetric and tidal data are available. Estuary depth is a critical parameter in determining the saline structure of an estuary as deep estuaries are more likely to stratify. Although use of the Simmons (1955) method is widespread, it makes no acknowledgement of the role of estuary depth in its saline structure. The Hansen and Rattray (1966) approach requires detailed tidal gaugings.

5.2.7 Ecological Implications

Where saline water and sediment–laden river water meet and mix, the increasing salinity may cause sediments in the fresh water to flocculate, resulting in a estuarine turbidity maximum (ETM) and a zone of accelerated particle settling. These regions are also known as estuarine entrapment zones or null zones.

Physically, the ETM occurs at the boundary between a saline downstream reach and an fresh upstream reach.

The ETM may be a region of elevated biological activity as revealed by the detailed investigations in San Francisco Bay (Jassby et al, 1995, see page 129).

General trends in estuarine stratification can be developed from this physical understanding which indicate the environmental susceptibilities of a given estuary:

- A reduction in fresh water inflow will result in saline intrusion further into an estuary regardless of its dominant stratified state (Table 2 on page 8, Low-2 to Low-4 and All-1, All-2).
- A reduction in tidal forcing due to closure or restriction of an entrance will make an estuary more stratified. Water adjacent to the bed in more stratified regions has long residence times and poorer water quality (Low-1 to Low-7 and M/H-1 to M/H-4).
- An increase in tidal forcing by making its entrance or channel more hydraulically efficient will lead to higher mixing and saline intrusion (Low-2 to Low-4 and All-1, All-2).

5.3 Fresh water Inflow

5.3.1 Climatic Classification

Digby *et al.* (1999) describes an Australian estuary classification regime based on climate and hydrology; these are:

- Mediterranean – those dominated by winter floods and summer drought. These estuaries are found mainly in the south-west of Western Australia and are characterised by episodic fresh water supply in winter, possible hypersalinity in summer and restricted exchange with the ocean.
- Temperate – these estuaries are found in Tasmania, Victoria, South Australia and southern New South Wales. There is little seasonality in their fresh water input but flows may increase during late winter and early spring due to snowmelt. These estuaries

are typically stratified for most of the year due to a reasonably constant fresh water input and during flood conditions, the depth of the halocline increases.

- Transitional – these estuaries are dominated by winter storms and are usually well mixed. They may become stratified immediately following a storm event.
- Arid tropical/subtropical – these are found in areas with low annual rainfall and low catchment runoff. The rivers flow only during and immediately after major storms or cyclones and these estuaries have very high evaporation rates. Permanent inverse estuaries with higher salinity than the adjacent seawater can occur – examples include Shark Bay in Western Australia.
- Wet and dry tropical/subtropical – most Australian estuaries (68%) fall in this category. These systems are dominated by episodic short-lived large fresh water inputs during summer and very little or no flow during winter. Under high flows, salt water may be flushed out of these estuaries completely. Many of these estuaries have a high tidal range, so following a flushing event, a salt-wedge intrudes along the estuary bottom and the estuary progresses from a highly stratified salt-wedge estuary to a partially mixed estuary, to a vertically homogeneous estuary. An example of this type of estuary is Coral Creek, Dickson Inlet in Northern Australia (Digby et al, 1999).

5.3.2 Flow Variability

Thus far we have assumed that fresh water flow to an estuary is steady. However, the estuarine water balance is dominated by fresh water inputs from stormwater runoff, groundwater, direct rainfall onto the estuary surface, evaporation and marine exchange (Deeley and Paling, 1999). These fluxes undergo considerable temporal variability under Australian conditions.

River flows are the main source of fresh water, sediment, nutrients and silica for estuaries. Estuaries on the northern and eastern coast of Australia can undergo distinct phases of salinity, with a fresh phase following a flood flow which can expel all salt water from the estuary. Flushing times in the estuary may be reduced to the order of days under the influence of high river flows. After the passing of the fresh event, ocean waters are able to intrude into the estuary, and stratified conditions may develop. As the river inflow returns to normal, horizontal salinity gradients develop. Simulations on a 50 year time-scale undertaken by Peirson *et al.* (1999) (see page 141), showed that in the Richmond River estuary, saline intrusion fluctuated from the mouth to an upstream distance of approximately 80km within a total estuary length of 100km (see Figure 26 on page 145). These intrusions were in response to periods of extended drought.

5.3.3 Dams

Water storages on fresh water tributaries to estuaries can have significant impacts on fresh water inflows and sediment transport to estuaries.

There is some strong Australian evidence that dams have little impact on floods with an average recurrence interval greater than about 1-2 years. A detailed investigation by Riley (1981) examined the approximately 100 year record of floods at Windsor, NSW and showed that climate is the dominant factor in flood occurrence – no impact of the major storages constructed on the Nepean River system could be observed on floods. The Nepean is one of Australia's most regulated rivers.

In contrast, Davies and Kalish (1994) suggested that there was a significant decrease in flood frequencies at discharges greater than 200 m^3/s and consequently the incidence of flushing flows required for the Derwent River estuary due to upstream dam storage. However, Davies and Kalish (1994) did not examine the effect of dam construction on the flood record of the Derwent in detail.

Hydrologists have well-developed techniques for determining the average recurrence interval of floods. Within any given environmental flow assessment of an estuary, it will be important to quantify what are (ecologically) termed "low", "medium" and "high" magnitude inflows in this report.

The level of river inflow determines the sediment load which is delivered to the estuary. Floods deliver proportionately greater sediment loads than ordinary river flow. It was estimated that more than 100,000 tonnes of sediment was delivered to the Beaufort estuary in Western Australia during a single flood event (Deeley and Paling, 1999). As such, the hydrologic regime of rivers plays an important part in shaping the estuary morphology.

Land use in the catchment has a profound effect on sediment delivery to estuaries following clearing for agriculture and urban development. This leads to increased suspended sediment concentrations in the estuaries, which can impact on biota by causing physical smothering of organisms, increased light attenuation and changes to dissolved oxygen concentrations in the estuary (Deeley and Paling, 1999). Catchment clearance and flow regulation alter flow duration, amplitude and pulse shape (Puckridge *et al*., 1998).

5.3.4 Estuary-Groundwater Interactions

Base flow quantities are critical to environmental flow issues. In general, base flows are sustained by groundwater discharges from underground storages that were previously recharged during periods of rainfall.

Quantifying groundwater storage and discharge is a difficult issue due to the uncertainties and difficulties in observing underground systems.

Estuarine systems are located in the coastal zone for which the soils types are often sandy and porous. The interaction of estuaries and groundwater systems is currently poorly characterised and an area of active research. Many Australian coastal communities rely on aquifers adjacent to estuarine systems for water supply.

A recent review of interaction between estuaries and adjacent coastal groundwater systems is available in Miller and Dorairaj (2000).

5.3.5 Ecological Implications

Part of our knowledge-poor environment (page 18) is a lack of knowledge of the time-dependence of many estuarine processes. Much of the physical investigations to date have focussed solely on steady flows but recent investigations have begun to represent flow variability.

The work by Digby et al (1999) has highlighted the variability in the Australian climate and the work by Peirson et al (1999) have shown that this variability in rainfall results in a strong dependence of saline structure on antecedent rainfall over time scales of months to years. In particular, the effects of drought intensity can how be physically incorporated but more coincident observations of the effect on the water quality and ecology are essential to develop better techniques.

Estuaries downstream of dams or large diversion works may be susceptible to influences on middle to high magnitude inflows and processes (Table 2 on page 8, M/H-1 to M/H-4) will need to be considered.

If pump extraction is the only method of extracting fresh water from the tributaries of an estuary, the volumes will be very small compared to the catchment runoff flows during fresh events. In such cases, the effects on middle to high magnitude flows can usually be ignored.

5.4 Estuarine Flow and Salt Models

In the developed methodology presented in Chapter 9, prediction of estuarine salinity structure is essential. In this section, modelling techniques commonly used to quantify saline structure are described.

5.4.1 Simple flow and salt models

With sufficient data and consistent estuarine structure, simple models that relate salinity structure to fresh water flow can be developed. Examples of these include the investigations by Jassby *et al.*, 1995 (described in Section 7.2.5) in California and an investigation for the Swan River, Western Australia by Kurup et al (1998).

Such model seems to be best suited to strongly stratified systems and require very large data sets to ensure that a full range of flow conditions is represented. They have no predictive capability except for minor changes in flow and must be specifically configured to recognise the influence of antecedent conditions.

5.4.2 Box Models

Box models use equations describing conservation of mass coupled with information about transport within an estuary to partition the waterbody into a series of compartments. Various assumptions must be made regarding mixing and the exchange of water between adjacent boxes.

Box models can be developed for both well-mixed and highly stratified estuaries.

The estuary is divided into a series of segments whose lengths are determined by the extent of the tidal excursion (that is, the distance a water parcel travels between high and low tide). Water within a segment is assumed to be fully mixed at all times. There are several errors in Ketchum’s (1951) approach which have been corrected by Wood (1979).

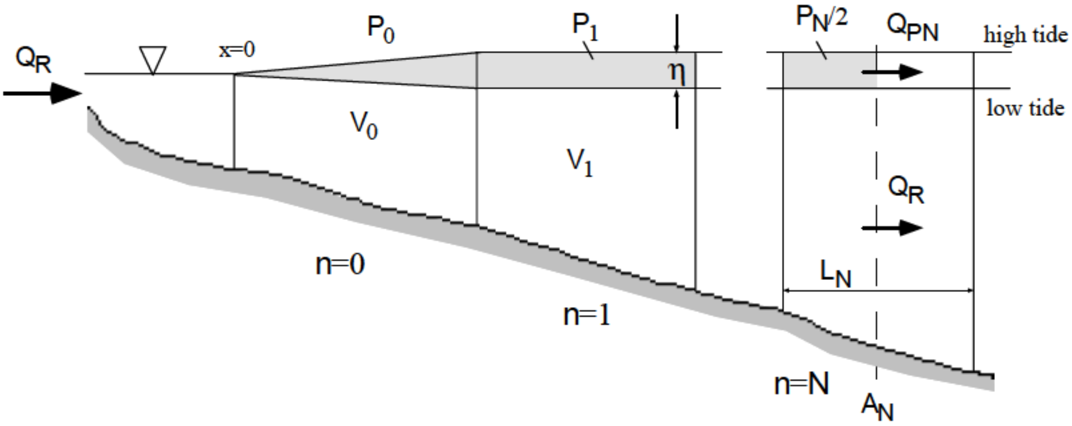

Figure 10 –Schematic of an estuarine box model for a well-mixed estuary. Boxes are numbered from the upstream end, low tide volumes are indicated by the symbol V, and tidal prisms are indicated by the symbol P.

Box models for unstratified systems are constructed as shown in Figure 10. Based on estuary geometry, a series of compartments are defined based on volumes at high and low tide. Salt balance equations to be constructed for each compartment and subject to fresh water inflow at the head of the estuary and an infinite ocean at the downstream boundary. Salinity distributions can be derived based on defined mixing rates within the estuary.

For stratified estuaries, layers of compartments are defined based on observed stratification as shown in Figure 11 below.

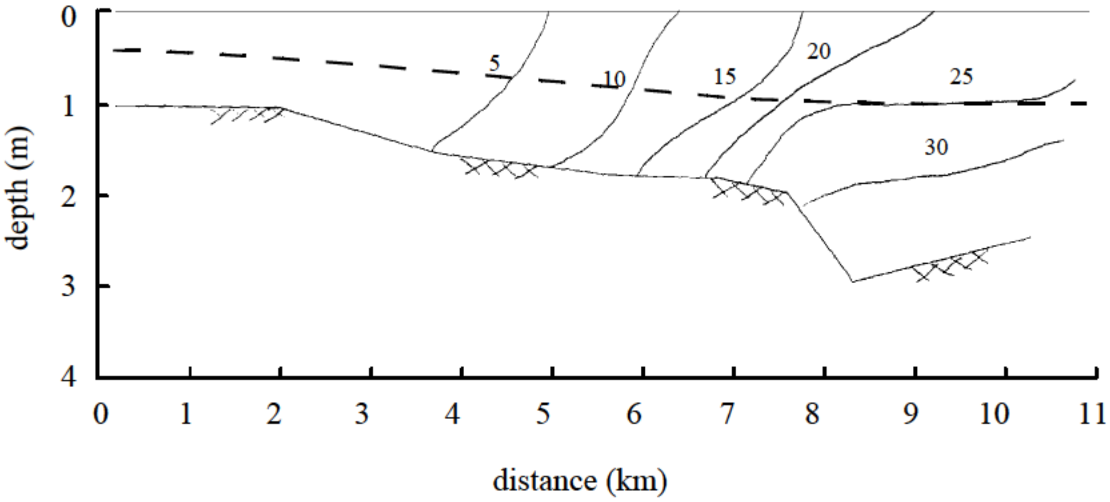

Figure 11 –Isohalines in a stratified estuary. The dashed line shows the approximate vertical position used to delineate between upper and lower layers.

For each set of compartments, salt balance equations can be developed that enable exchange and mixing rates between adjacent compartments to be defined as shown in the schematic Figure 12.

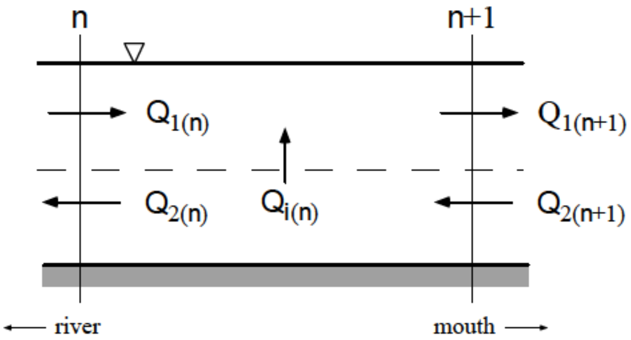

Figure 12 – Schematic of an element of estuarine box model for a stratified estuary. The fluxes of water and salt in such a system are generally in the directions shown.

The primary advantage of such models is their simplicity. Their primary disadvantage is that it is very difficult to get such models to simulate time varying flows. Recorded field data is absolutely foundational to their preparation and operation.

5.4.3 Advection-Diffusion Models

In advection-diffusion models, the estuarine waterbody is represented as a continuum with quantities such as water level, velocity and salinity being computed at a sequence of nodal points.

The computational flow modules are built on equations to represent conservation of mass (the continuity equation) and the balance between fluid motion, pressure gradients, bed drag and turbulent drag (the Reynolds equations). Computational modules for salt use equations to represent conservation of mass as well as transport and turbulent mixing. The equations are solved using discretisation methodologies that include finite difference, finite element and finite volume techniques.

Salinity changes the density of water and therefore also changes both the pressure gradients and turbulent drag. Consequently, for stratified estuaries, the flow and salt modules must be coupled during computation. Equations of state must be used to relate salinity to density (contributions from temperature and sediment can also be included) and the effects of stratification on turbulent drag must also be included.

These models come in hierarchy of representations:

- One dimensional models are used for well-mixed systems in regular channels.
- Depth-averaged, two dimensional models are used for well-mixed systems in irregular channels.

- Laterally-averaged, two dimensional models are used for stratified flow in regular channel systems.
- Three-dimensional models are used when channels are irregular and the flow is stratified.

Appropriate boundary conditions need to be specified that are usually levels at a tidal boundary and the quantity and characteristics (salinity, temperature, sediment) of inflows to the model domain.

The disadvantage of such models is that they are more computationally intensive than box models. However, modern computing techniques make long-term, three-dimensional simulations of estuarine behaviour a practical option for detailed investigations (Tate *et al.,* 2000).

The primary advantages of advection-diffusion type models is their flexibility and general ability to solve fundamental physical descriptions of estuarine behaviour and provide high-resolution results for unsteady conditions (page 141).

6. RELEVANT ESTUARINE WATER QUALITY PROCESSES

Water quality is a loose term that generally relates to the concentrations of a broad range of substances within the water. The term ‘water quality’ is used generally as a measure of the suitability of water for its uses, for example drinking water must satisfy more stringent water quality criteria than waters required for maintaining estuarine ecosystems. It is difficult to draw causal links between the inflow volumes, their characteristics and the resultant estuarine water quality. The aim here is to provide a generalised approach that attempts to identify the most likely issues of importance for an environmental flow assessment.

Within Australasia, the ANZECC water quality guidelines provide specific advice on the requisite characteristics of discharges to estuaries and the likely anthropogenic influences that may alter these characteristics. These specifications include recommended levels for:

- sediment and particulates including inorganic and organic material (these influence turbidity and smothering of benthic communities as well as the transport of pollutants and nutrients)
- nutrients (specified as total phosphorus, filterable reactive phosphorus, oxidised nitrogen, NO_x, total nitrogen) High nutrient levels can lead to increased primary production, shifts in biotic community structure and algal blooms
- bacteria and viruses, such as faecal coliforms
- toxins (including heavy metals, pesticides and synthetic compounds).
- pH, Electrical Conductivity, temperature

These variables have been discussed in detail in the ANZECC water quality guideline documents (ANZECC, 1992, 1998, 2001) and the aim here is to focus on the likely effects of reduced fresh water inflows.

The concentrations of the range of water quality variables within the inflow waters depends largely on the catchment characteristics (e.g. urban versus rural and forested areas, location of point sources such as wastewater treatment plants and intensive agriculture) and the magnitude of the inflow (e.g. high flows carry greater nutrient loads but low flows may be important for leaching chemicals, such as organics and acidic compounds, from the ground). The distribution of inflow locations along the estuary is also an important factor in determining the estuarine concentration gradients. Fresh water inflows occur through both surface water runoff and groundwater inflows. Alteration of the inflow volumes and timing may have consequences for the estuarine water quality as it may:

- alter the regime of loadings of nutrients and organic material to the estuary;

- influence the residence time which has implications for the settling, nutrient uptake and organic decay of planktonic organisms and detrital particles;
- alter the salinity gradient in the estuary; and, therefore
- alter the position of the estuarine turbidity maxima (which in turn influences particle settling).

A number of process-oriented multidisciplinary studies aimed at developing an understanding of the interactions between the key processes that determine ecosystem structure and function have been carried out in Australian estuaries over the past decade. Within these studies, water quality has featured as a key component. The impetus of these studies has been largely based on assessing the pathways and impacts of anthropogenic influences on the environment and hence the focus for the studies has primarily been eutrophication concerns. Most of these studies have been commissioned as one-off type projects and hence have been able to identify short term effects while the more subtle impacts of longer term changes (both natural and anthropogenic) are not well understood. The knowledge base generally relies on interpretation of short term and disparate data sets of varying quality and hence the understanding of the complex processes and their interactions that result in the measured phenomena remains fairly crude.

Eutrophication

Eutrophication is defined as the process whereby human activities within the catchment (for example, clearing, fertiliser addition, sewage treatment and discharge, housing and road development, etc.) have altered the hydrology and load characteristics (nutrients, inorganic sediment, organic material, toxic substances etc.) of the fresh water inflows leading to increased primary production in the estuary . This process can be manifested in a number of ways involving different pathways and water quality processes.

The fate of the inflow substances within an estuary depends on a number of factors including dispersion into the estuarine water, biological uptake, chemical transformations, and settling characteristics. Estuarine water quality affects the ecosystem biota, particularly the primary producers and in turn the higher trophic levels.

Dispersion of inputs

The water circulation and mixing characteristics play an important role determining the water quality. It is important to assess the horizontal and vertical mixing characteristics throughout the estuary as it is these characteristics that determine local flushing rates and residence times. As the higher concentration inflows enter an estuary they are first carried by the ambient currents and mixed with the generally lower concentration ambient waters. Areas with longer residence times (less mixing) are susceptible to longer exposure of higher concentration inputs and processes such as sedimentation, uptake by primary producers (for example, phytoplankton, cynobacteria and macroalga) may occur. The characteristics of downstream oceanic waters and the fresh water inputs, as well as sediment recycling processes must be considered when assessing the likely concentration impacts.

Within the estuary the mixing characteristics influence the flushing or exchange of waters between the ocean and estuary. In the lower reaches of estuaries, the rapid flushing and high levels of turbulence and mixing are the dominant factor controlling the concentrations of the water borne constituents. The time scale for these processes is generally shorter than the biological response time scales and hence the lower estuarine reaches attain more marine character.

In the deeper areas, the decay of organic matter at the sediment surface through microbial decomposition leads to consumption of dissolved oxygen from the water. The dissolved oxygen may be replenished by two mechanisms - vertical mixing between the oxygen-rich surface waters and oxygen-depleted deeper waters, and advection of high oxygen concentration waters into the area. The rate of consumption of DO by microbes may be mediated by the available organic matter. Organic matter is generally only slightly negatively buoyant and hence is susceptible to resuspension. In deeper areas of low tidal range systems, fresh water inflow events may be important for flushing accumulated organic material and low DO waters from the deeper areas. This process has important implications for benthic egg and larval survival.

Nutrients; Biological Uptake and Sediment Recycling

Nutrients are essential ingredients to the growth of primary producers – plants and microfauna. In estuaries a range of plant groups may be stimulated by the addition of nutrients. In the extremities and low lying floodplain/estuary interaction zones the riparian vegetation, mangroves, wetland and saltmarsh areas may influence the nutrient regime. In tidal flats and deeper waters competition for water borne nutrients between epiphytic alga, microflora (for example, phytoplankton and cyanobacteria) and the benthic groups (or microphytobenthos) leads to dominance of different groups in different systems.

The water-borne nutrient conditions in these situations are generally the result of complex biogeochemical transformations that involve inputs from the inflows as a primary source at times of fresh events. During low flow periods, the internal cycling between sediment, water, biota and sediment (again) may control the water-borne concentration. These processes can operate at very short time scales (hours) and have impacts over long periods. Hence it is difficult to gain a good indicator of biota condition through the use of water borne concentration measurements although these measurements due provide some guidance as discussed in the ANZECC water quality guidelines.

The likely major processes affected by alterations to the estuarine fresh water inflows described in Table 2 on page 8 ascribe water quality issues to the *Low-1*, *Low-7, M/H-2*, *M/H-4* and *All-2* flow categories. These are elaborated on below.

Low – 1 increased hostile water-quality conditions at depth

Reduction of the low fresh water inflows often leads to reduced turbulence, reduced vertical mixing and ultimately persistence of stratification (both saline and thermal). This, in turn, results in longer residence times of the deeper waters below the pycnocline. The increased residence time of the deeper waters may deteriorate the water quality through microbial consumption of the DO and flow-on chemical reactions at the sediment surface that release nutrients. Reduced flows also lead to more deposition in the upper reaches that may affect the nutrient recycling between the sediment and water. The layer of fine organic material may cause the development of anoxia micro-layers with thickness of the order of fish egg diameter leading to high mortality of the early stages of fish development for those with benthic eggs.

Low-7: aggravation of pollution problems

This process is relevant in estuaries where specific pollution sources occur (for example, waste water treatment plant discharges, or industrial discharges or leachates from old dump sites). These pollutants may lead to deterioration of water quality that in turn may affect the primary producers and higher trophic levels. For example, point source effluent discharges have been shown to cause increased primary production phytoplankton (for example, Brunswick River Estuary, Hawkesbury River, Moreton Bay) and cyanobacteria. Similarly the bacterial inputs may affect oysters (for example, Wallis Lake) and other fauna. Inputs of toxic chemicals can lead to a variety of effects on biota including mutation and reproduction issues. Similarly the acid runoff due to changes in land use has a implications for the water quality and communities. Acid runoff can cause ulcers or red-spot disease in fish.

M/H-2: diminished frequency that deep sections of the estuary are flushed of organic material (subsequent water quality reduction)

This process is relevant in estuaries where deeper areas occur in the upper and middle reaches and low tidal range systems where stratification leads to long residence times of deeper waters. Reduced fresh water flows results in the concomitant reduction in the dissolved oxygen and enhanced sediment nutrient recycling. The flushing of these deeper areas is affected by the fresh water inflow events that are important for removing the accumulated organic material and replenishing the dissolved oxygen concentrations.

M/H-4: reduced inputs of nutrients and organic material
Reducing the fresh water inflows from natural streams and rivers may lead to reduction in the nutrient loads, organic material and sediment. This could lead to reduced primary production and shifts in ecosystem structure. While this may be viewed as improving water quality the flow on effects to higher trophic levels are inconsistent with preserving the environmental status quo. This particular process demonstrates the careful consideration required when assessing the desired values of the system.

All-2: dissipated salinity/chemical gradients used for animal navigation and transport
As discussed in Section 4.2.1 (Table 2 on page 8, All-2) the change in salinity gradients due to reduced fresh water inflows may affect animal navigation within the system and recruitment from the ocean. The significant water quality impact is related to salinity but the environmental significance relates to the ecology of fauna within the system.

6.1 Estuarine Water Quality Models

6.1.1 Box Models

Box models for water quality and ecological response use the transport and dispersion parameters provided by the flow and salt models described in section 1.6.1. It is models of this type that were investigated by Parslow *et al.* (1999) and have been applied in studies of Port Phillip Bay and more recently in the Derwent Estuary.

Box models provide a simple computational framework in which the complex ecological interactions can be incorporated and investigated. These include components to simulate dissolved oxygen, phosphorous, nitrogen, toxins and the response alga and other life forms to their concentrations in the water column.

Such models must be carefully verified against substantial field data sets to be useful. Although, there are many reported studies of ecological response to nutrient loads, determination of universal values for particular biota remains a challenging task that is hampered by measurement accuracy and limited model input data.

A primary limitation of box models is the difficulty with incorporating unsteady flow behaviour –nutrient input to estuaries usually occurs during fresh events and under such conditions, salinity structure, mixing and nutrient load are all changing at the same time.

6.1.2 Advection-Diffusion Models

Similar to water quality box models, advection-diffusion water quality models use the transport and diffusion parameters supplied by a corresponding flow model.

Advection-diffusion models are used to assess changes in water quality and ecology in estuarine and coastal waters over substantial spatial and temporal scales (for example, Wang *et al.*, 1997). Simulations over relatively short (~1 month) temporal scales are now showing good skill in reproducing chlorophyll-a concentrations in estuarine systems (Yamane *et al.*, 1997).

7. RELEVANT AUSTRALIAN GOVERNMENT POLICIES

Appendix 6 contains a summary of current Australian Government flow policies and initiatives.

Whilst no methodology has yet been proposed by either a state or federal government agency to determine appropriate fresh water inflows to estuaries, there are a number of key policy approaches that are relevant to this investigation. These are:

1. The Council of Australian Governments has determined that water will be allocated to the environment to enhance or restore the health of river systems and that this will be undertaken using an integrated catchment management approach.
2. The ANZECC water quality guidelines recognise the use of risk-based hierarchical decision frameworks and distinguishes between high conservation value ecosystems and disturbed systems.
3. In accordance with the COAG agreements, all state agencies now recognise the importance of protecting and rehabilitating estuarine ecosystems.

Appendix 6 contains a summary of the current Australian state government policies with regard to environmental flows and water management. Although some of these policies have been developed in response to the COAG agreements, there appears to be little consistency between the individual State policies. Very little of the developed policy addresses the specific environmental flow requirements of estuaries. There are three notable exceptions to this:

1. The New South Wales government has been pursuing estuary management consistent with total catchment management and ecologically sustainable development since 1992 through its *Estuary Management Manual* (New South Wales Government, 1992).
2. The South Australian government has enacted specific objectives in relation to variations in salinity in estuaries. The basis of the values selected for these objectives is unknown.
3. 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.

Estuarine ecosystems are complex and the costs associated with undertaking detailed studies of threatened and endangered estuarine species and ecosystems are substantial. It would be of great benefit to each State community if a consistent, nation-wide assessment approach can be developed that will allow State government authorities to benefit from studies undertaken elsewhere within Australia. Hopefully, this document will help to achieve this.

8. ESTUARINE ENVIRONMENTAL FLOW STUDIES – REVIEW SUMMARY

A large amount of literature has developed in relation to environmental flows in aquatic systems - most of this in relation to rivers and streams. Both the facilities of the Water Reference Library as well as direct contact with overseas agencies were used to access relevant material in relation to environmental flows to estuaries.

It appears that only the United Kingdom has endeavoured to address environmental flows to estuaries in a national, systematic fashion. Substantial investigations have been undertaken in South Africa and the United States. A more detailed summary of the relevant material is presented in Chapter 8.

Key findings from this review are presented in this chapter.

South African government agencies have undertaken substantial and detailed investigations of environmental flows to estuaries. Whilst the South African government policy guidelines are well defined, a detailed methodology for the assessment of environmental flows to estuaries does not appear to have been developed. The studies are multidisciplinary and usually involve a team of hydrologists, geomorphologists and ecologists. For the large, permanently open estuaries, the focus is on flow reduction and how this has altered the salinity gradient and biotic response. For the temporarily closed estuaries, the focus is on the relationship between flow and mouth condition.

Concerns about fresh water inflows to estuaries have been expressed in the USA for over twenty years. A National Estuary Program has been underway in the US since 1987 but communications from administrators of the program in Florida seem unaware of any systematic methodology for determining the fresh water flow requirements for US estuaries.

Around the USA, a number of local authorities have responsibility for large and longstanding estuary investigations. Of specific interest is a substantial investigation of links between fresh water inflow to and the ecology in San Francisco Bay. A summary of the findings of this multi-disciplinary group are reported in Jassby *et al.* (1995). Strong correlations were found between fresh water inflow into the Bay-delta and the position of salinity gradients within the Bay-delta. In turn, correlations were also found between salinity and a wide variety of biological productivity, including species numbers. The analysis did not incorporate water use within the estuary itself, although this had been observed to have a direct effect on population abundance independently from the position of salinity gradients in the Bay-delta. The study made a number of recommendations of which the most significant was that assessment should be made of temporal fluctuations in salinity levels.

Strong relationships between fresh water inflow and fish harvest have been observed in Texas estuaries. Based on detailed ecological investigations, sophisticated numerical models have been developed to optimise fish harvest in terms of inflowing fresh water from a number of tributraries (Bao and Mays, 1994a and 1994b).

An investigation was commissioned by the Water Research Centre (Binnie Black and Veatch, 1998a). The United Kingdom seems to be the only attempt internationally to develop a national, systematic approach to determining fresh water inflows to estuaries. The specific objective was to determine the flow at which licensed abstraction ceases.

The methodology is multi-disciplinary and founded on ecological risk assessment and estuarine flow modelling. This investigation notes:

- The assessment of environmental flows is more complex than for fluvial systems and that approaches for dealing with environmental flows for rivers cannot deal with this complexity.
- A risk assessment approach is recommended which should guide the estuary manager towards the required complexity of analysis method.
- Evidence gathered by consulting stakeholders suggests that mean residual flows cannot be reliably set on the basis of estuary type and known issues alone. Each United Kingdom estuary is unique, and results from one location cannot be transposed to another with any confidence.
- Use of computation models is essential to analyse the complex pressures on estuaries today.

Our review revealed only a few substantial Australian investigations to determine appropriate environmental flows to estuaries. These were undertaken for the Derwent River, Tasmania (Davies and Kalish, 1994) and the Richmond River, New South Wales (Peirson *et al.*, 1999). The Derwent study examined the effect of upstream storages on the flushing of the estuary. We believe that the Richmond River study is the first in Australia to link catchment hydrology with an estuarine salt model to an ecological risk analysis.

9. RECOMMENDED METHOD FOR AUSTRALIAN ESTUARIES

9.1 Synthesis

A key objective of this investigation is to develop a method to:

- enable identification of those estuaries in Australia that are threatened or endangered by current or future changes to flow regime; and,
- determine appropriate environmental flows that will protect Australian estuaries against decline in their ecological character.

Limited investigations have been undertaken overseas to examine the flow requirements for estuaries. In this section, we summarise these to develop a methodology that is suited to estuaries within Australian. To provide context for the developed estuarine environmental flows methodology, we present a series of assertions that are supported by the material in earlier chapters of this report.

Environmental flows for estuaries should be determined on a different basis from fluvial systems.
The physical behaviour of rivers and estuaries are fundamentally different which, in turn, provides a different environment for the biota and ecological systems that exist within them.

Ten key differences were summarised in Table 1 on page 8 that relate to the physical, water quality and ecological differences between these environments.

The discipline of estuarine environmental flow assessment is knowledge-poor.
This was discussed in Section 4.5 on page 18. As a result an adaptive management approach is essential to the management of these problems, that is, initial predictions of ecological effects will contain a degree of uncertainty that will only be resolved during a subsequent monitoring phase. The quality of the predictions will always depend on the soundness of the knowledge on which they are based.

Problems associated with major engineering construction
In this context, environmental flows are assumed to refer specifically to fresh water inflows to an estuary from its catchment. The salinity structure, physical structure and ecology will also change as a consequence of changing exchange of water between an estuary and the ocean due to human intervention.

Dramatic changes have occurred to the salinity structure and geomorphology in the vicinity of the mouth of the Murray as a result of the tidal barrages. Similar changes are taking place on the Mary River (N.T.) due to dredging of the entrance. Major changes have been made to the flushing of the Wallis Lakes (N.S.W.) system due to changes to the entrance associated with development. These are all changes that have little to do with modification to environmental flows but have induced dramatic changes to saline intrusion, geomorphology and the ecology. (Section 5.1.2)

It is inappropriate to attempt to remedy such changes to an estuarine environment by modifications to fresh water inflows as these do not address the fundamental causes of change in the estuarine environment.

It is evident that major engineering modifications to an estuarine system will have implications for its ecological value. If there has been significant ecological impact due to engineering construction, substantial remedial construction or rehabilitation may be required.

Assessment of environmental flows to estuaries must recognise the contribution of fresh water and nutrient inflows of the entire upstream catchment
With the exception of the arid regions of inland Australia, estuaries are the primary catchment drainage points. (Section 3.2)

Consequently, reductions in flow from rivers, extractions from groundwater systems as well as fresh water extraction from estuaries themselves will all have an impact on the amount of fresh water flowing to an estuary. The Richmond River study was commissioned to directly examine the impacts of fresh water extraction below the tidal limit but irrigators below the tidal limit and those above both reduce the net fresh water flow to an estuary.

Issues associated with the impact of nutrient inflows on water quality should be approached using appropriate water quality guidelines.
As noted earlier, estuaries can be biologically productive and complex environments. Much of this complexity is due to the mixing of different water masses (fresh inflows and oceanic waters) that occurs in estuaries.

Estuaries also have nutrient and contaminant sources. Therefore, estuarine water quality is dependent on fresh water inflows. High nutrient concentrations can induce eutrophication (accentuated levels of algal growth) with corresponding ecological impact. Biological response to nutrients is complex and in systems where particular biota exhibit a strong response to elevated nutrient levels (algae, for example), reductions in dissolved oxygen or other key chemical species concentrations in the water column can occur with catastrophic effects on the ecology.

In addition, development within the catchment of an estuary generally will entail changes to the fresh water inflows as well as changes to nutrient inflows, pollutant inflows and the physical structure of the estuary. Each change will provoke an ecological response and isolating the significance of changes to fresh water inflow will require careful investigation.

The stated purpose of this report is to address the specific relationship between fresh water flow and ecological response in an estuary. Guidance on the assessment of the impact of other factors must be sought from other state and federal planning instruments.

The ANZECC Water Quality Guidelines recommend appropriate levels for nutrient and contaminant discharges to estuaries as well as methods to assess their significance. In NSW, the *Estuary Management Manual* published by the Department of Land and Water Conservation and guidelines for environmental impact assessment published by the Department of Urban Affairs and Planning are specific planning instruments designed for the assessment of ecological impact of anthropogenic activities on estuarine ecology.

To attempt to alleviate ecological problems created by pollutant inflows by increasing fresh water inflows to estuaries would be misdirected and would only serve to confuse issues that have significant degrees of complexity in their own right.

It must be acknowledged that it is difficult to distinguish between primary causes for these difficult issues. Reductions in fresh water inflows will exacerbate poor water quality within estuarine systems.

Estuaries with perennial poor water quality arising from anthropogenic effects will have lower ecological value.

Assessment of environmental flows to estuaries must recognise the primary features of Australian climates.

Australia is the world’s driest habitable continent. Its climate ranges from temperate to tropical and is located between latitudes that lie within the zone of subsiding air in the southern hemispheric atmospheric circulation resulting in relatively low precipitation in a hemispheric context. In addition, its largest mountain ranges are located along the eastern and south-western coasts which tend to capture moisture carried by the prevailing winds from the surrounding oceans.

A climatic classification of Australian estuaries was reviewed in Section 5.3.1 on page 37.

As a consequence, the climate of the entire Australian continent oscillates between drought and flood. This characteristic leads to extremes in river flow and the salinity structure of many Australian estuaries is highly variable.

This is strong contrast with North America, Europe and much of Asia in which river flow is very strongly influenced by snowmelt in the spring. With reference to the Köppen's classification system (in for example, Ahrens, 1994, p513ff), the distribution of Australian climates has most in common with regions within South Africa.

The Richmond River investigation highlighted the strong temporal variability of fresh water inflows to some Australian estuaries. Simulations of fresh water flow to the estuary over a 50 year period are summarised in Figure 25 (page 143) and shows the characteristic streamflow recession that occurs during drought period – flows vary over nearly 5 orders of magnitude over a two year period. In the Australian context, storms have durations between a few minutes to a few days but droughts may last for years. The lowest streamflows occur during droughts and these are the time when human demand for water will be highest.

The nature of estuarine mixing processes implies that we are dealing with what could be viewed as a storage of fresh water below the tidal limit. The hydrological assessment of such storages should be undertaken with the same hydrological principles that are applied to constructed storages on rivers. Dam planning recognises the cycle of flood and drought within the Australian climate and the storages are designed accordingly. A similar hydrological approach should be taken to fresh water reserves in estuaries.

Rainfall and temperature records are probably the most widely available data sets gathered on the behaviour of climate since European settlement. As shown during the Richmond River investigation, these can be effectively used to examine estuarine inflow behaviour of periods of over 50 years (Figure 26, page 145).

The existence of strong variation in fresh water flow to estuaries has four important implications:

1. Assessment of environmental flows must allow for such behaviour.
2. Proposed flow regimes must mimic natural flows.

3. Investigative tools must be able to incorporate this important feature.
4. Agricultural, industrial, social and political focus will generally be on the very low streamflows during periods of extended drought.

9.2 Recommended Methodology

On the basis of the reviewed material and the synthesis presented above, the following methodology is recommended.

This methodology is composed of two phases: preliminary evaluation and detailed investigation.

The preliminary evaluation should be able to be completed at modest cost provided that appropriate estuarine management data is being gathered by the appropriate responsible government authority. The preliminary evaluation should yield a classification of estuaries by significance and risk as well as the scope of detailed (and more costly) investigative programs.

The purpose of the detailed investigation is to determine an appropriate level of environmental fresh water flow for any given estuary.

Preliminary Evaluation Phase

PEP Step 1: Define the environmental flow issue to be investigated.

There are at least two ways that environmental flows questions can be posed:

1. What are the implications of proposed reduced flows on the environment? (A question concerning proposed *future development* or *assessment of scenarios*)
2. What is the required effective environmental flow regime that is required in this estuary? (A question concerning *estuary rehabilitation or protection* or *determination of critical thresholds*)

Answers to these questions determine the emphasis and scope of the entire investigation.

When proposed future developments are in question, investigators can design a far more focussed study by identifying the likely impacts of the development on the ecosystem and determine those facets most susceptible to the impacts.

Questions regarding estuary rehabilitation, protection or critical salinity thresholds are far more wide ranging and, as a consequence, will need much more detailed investigation.

PEP Step 2: Assess the value of the estuary

High-value estuaries, as opposed to low-value estuaries, warrant more protection from inflow-reduction processes. The value of the estuary should be considered from the following perspectives:

- conservation:
    - high, if pristine, low if degraded
    - high, if threatened or endangered species or communities occur
    - high, if listed wetlands occur
    - high, if rare habitats occur
    - high, if a diverse range of habitats occur
- commercial:
    - high, if productive commercial fisheries occur
    - high, if scenic features attract tourists
- recreational:
    - high, if productive and popular recreational fisheries occur
- scenic:
    - high, if scenic values are high and publicly appreciated
- links:
    - high, if associated with regional, national or international ecological links, treaties or agreements regarding fauna.

This value assessment should be facilitated through a review of the literature, contact with relevant Government Departments, and contact with regionally-pertinent specialists in estuarine ecology.

PEP Step 3: Assess changes to inflow

There are four sources of inflow to an estuary and these and any changes to their magnitude due to human activity will need to be quantified.

A. Fresh water extractions from the estuary or interceptions from its tributaries.
   Changes to the quantity of fresh water inflow will occur due to major dam storages or significant levels of extraction for town water supply, irrigation or other purposes.

B. Salt water exchange at the estuary entrance.
   Many estuaries in Australia have had tidal weirs and major training and dredging works constructed in their downstream reaches. If this is the case, these structures will cause marked adjustments to the ecology of the estuary. Significant anthropogenic changes to the estuary and their impact must be identified. However, it is unlikely that

environmental flows will be able to rectify changes to habitats arising from construction within the estuary.

C. Anthropogenic discharges to an estuary or its tributaries.
Discharges to an estuary or its tributaries must be carefully catalogued. Potentially, these may alleviate the potential need for limits to fresh water extraction in other parts of the system.

Equally, the quality of such discharges may have a significant impact on the estuary and at some stage, it may be necessary to identify potential causes of poor water quality.

D. Groundwater flowing to an estuary.
Fresh water extractions from aquifers linked to an estuary will have the same effect on net fresh water flow as direct extractions. These will need to be carefully identified and catalogued.

It is acknowledged that the tidal behaviour of estuaries has meant their interactions with adjacent aquifers is poorly understood. However, it is crucial that all important potential withdrawals of fresh water are identified.

The assembly of information during this step is a substantial task. However, Australian government authorities are responsible for the overall management of water resources for which the information above is essential. We understand that as a result of COAG agreements, all state governments are in the process of licensing both fresh water extractions and discharges. It is noted that much of this information is already being assembled and presented as part of the national audit.

On the basis of the information assembled during this step, estuarine catchments can be classified according to their level of fresh water usage. The table below suggests recommended values for this classification:

Table 5 – Initial classification of fresh water usage.

Fresh water Usage	Catchment area flowing to storage or major diversion (%)	Water usage as a proportion of stressed river flow[2] (%)
Very high	>10	>85
High	2-10	65-85
Moderate	0.4-2	35-65
Low	<0.4	0-35

It is the view of the authors of this report that a simpler definition of stressed river flow should be sought that has Australian-wide applicability.

The thresholds for the proportion of catchment area flowing to storage or diversion were obtained by reviewing selected Australian estuaries that are reputed to have problems associated with environmental flows.

If there are no significant impoundments or diversions of the main rivers flowing to an estuary, it is likely that only low-magnitude inflows will be affected. In the presence of major engineering structures, both moderate-to-high and low-magnitude inflows will be potentially impacted and will need to be investigated.

PEP Step 4: Assess the vulnerability of the estuary.

An important adjunctive component of this initial step in the investigation is the assessment of the vulnerability of the valued components to the range of potential inflow-reduction processes.

As part of this component, an *interaction matrix* should be prepared. This will highlight the specific vulnerabilities of a given estuary and enable different estuaries to be compared and prioritised for more detailed investigation.

Such a matrix would have the components (for example, fish, riparian vegetation) on the row axis and their vulnerability to different processes listed in the columns as specified in Table 2 on page 8.

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[2] The "stressed river flow" is the mean daily flow exceeded for 80% of days in the month of maximum water usage. If the river ceases to flow for more than 20% of the days in the month of maximum water usage, the mean daily flow exceeded for more than 50% of days is used (DLWC, 1998).

If a specific component is designated as being of high value, and it is vulnerable to a flow-reduction process, then the component in conjunction with the specific process warrants particular consideration.

In practice, the vulnerability of an estuary to a range of processes could be assessed by considering whether (for example only):

- large volumes of mobile bed material are normally carried by the estuary
- the mouth of the estuary is prone to closure resulting from the deposition of transported marine sands
- significant pollution problems exist
- if the estuary is predominately shallow
- if highly turbid waters meant that plants were virtually absent from the estuary (particularly the case if riparian plants were also rare).

In practice, there may be significant gaps in the available information about some estuaries. If this is the case, these gaps will be revealed during this phase of the investigations and the potential values and vulnerability of these estuaries can be noted as requiring appropriate levels of investigation.

Detailed Investigative Phase

DIP Step 1: Examine the likely impact of current water use on transport, mixing, water quality and geomorphology using catchment runoff and estuarine flow models

Studies must be undertaken to understand present estuarine physical, chemical, water quality and sediment transport/geomorphological behaviour. If there is moderate to very high fresh water usage within the catchment of an estuary, the historical behaviour will also need to be investigated as well.

It would be preferable to avoid specialist water quality and geomorphology models as these are difficult to configure and verify. Initially, two compatible numerical models will need to be prepared for the estuarine system:

i. A model of catchment runoff to the estuary including water extraction
ii. A model of flow and salinity within the estuary

Each of these models will need to be carefully configured, calibrated and verified to demonstrate that they are an accurate representation of system behaviour.

In general, the flow-salinity models used will be relatively simple. Of crucial interest to investigations of environmental flows to estuaries will be primarily conditions of low inflow and in such states, estuaries tend to be vertically homogeneous. However, for some estuaries, (particularly those that are deeper or have very weak tidal forcing) the use of more complicated stratified models may be necessary.

It is important that such models be used to predict salinity structure of long periods (>20 years) so that impact of significant droughts can be represented in the assessment.

For many estuaries, once these models are available, desktop calculations can be used to assess water quality and sediment transport behaviour. However, another compatible model must also be available to simulate water quality and sediment transport behaviour, if necessary.

If there are significant implications for estuarine water quality if fresh water inflows are reduced, more sophisticated water quality models will need to be configured. Their transport and dispersion characteristics will be derived from the salinity model.

For assessment of geomorphological change (which might have specific relevance, for example, Table 2 on page 8, M/H-4), appropriate models may need to be invoked. This seems unlikely in view of current evidence that dams do not affect the frequency of floods with a recurrence interval greater than about 1-2 years as presented in Section 5.3.3 on page 39. However, the catchment runoff model will be able to identify whether those events primarily responsible for geomorphological change will have substantially altered due to construction of major storages.

DIP Step 2: Define environmental flow scenarios for the estuary

If it was determined at PEP Step 1, that issues of catchment or estuarine development are to be addressed, environmental impact procedures are well established for the assessment of proposed developments. This stage would merely extend the planning processes undertaken by government authorities to include consideration of the potential impacts on estuaries due to extraction of fresh water and discharges from proposed developments. In particular, it requires that water usage of developments and changes in quantity and quality from new developments be estimated.

Alternatively, if the question concerns estuarine rehabilitation, DIP steps 3 and 4 will have to be undertaken iteratively until the risk assessment has shown that the likely ecological impact on any given component has been reduced to an acceptable level.

DIP Step 3: Use the established models to assess the impact of proposed scenarios.
This is a reasonably simple process if the models have been properly established at step 2 and have been carefully stored for future use.

DIP Step 4: Assess the risk to estuarine biota
For each estuary, two types of living organisms will be particularly important:

i. Endangered/threatened species and/or communities; and,
ii. A range of indicator species or communities (sometimes referred to as biotic condition indicators, page 126).

Records of threatened or endangered species or communities within estuaries should be maintained because these are crucial to any endeavour to maintain biodiversity. In addition, records should also be maintained regarding their known tolerance to changes in salinity.

The biotic condition indicators are crucial in terms of final quantification of changes in aquatic habitat. In general, aquatic vegetation will be one of the dominant biotic condition indicators because of its susceptibility to shifts in salinity and its importance in terms of providing nursery areas for fish and crustaceans. Longley (1994) identified a range of biological indicators worthy of study in this context – phytoplankton, seagrasses, marsh plants, zooplankton, benthic organisms, larval and adult fish, and shellfish. He emphasised that the maintenance of productivity should be focused on, but there should also be specific consideration of the effects of salinity, nutrient and sediment loading.

At this point, it is crucial that all component-process combinations be assessed and key information relevant to processes and/or subprocesses be extracted. For example, are beds of submersed plants present in the upper estuary and what would be the most appropriate 'working' salinity thresholds to represent their salinity tolerance? Generally, it is expected that processes involving changes to the salinity structure of an estuary will have to be examined. As the intensity and nature of salinity changes will vary along the length of the estuary, it will be important to determine the estuarine-long distribution of valuable and vulnerable components. If key information is not available from the desktop or contact work, then field studies would be required. It is also expected that there would generally be a focus on the upper arms of an estuary as the biota there are likely to be most vulnerable to a range of inflow-reduction processes.

Once the species or communities at risk have been identified, a risk analysis must be undertaken using the results provided by the flow-salinity model to assess current as opposed to historical flow conditions and the expected impact of proposed developments within the catchment. It is essential that such a risk analysis be multi-faceted to ensure that all critical aspects of estuarine ecology are represented. Two possible approaches to risk assessment have been described in this report: the model recommended by Binnie, Black and Veatch (1998) for the United Kingdom; and, that used for assessment on the Richmond River, Peirson *et al.* (1998). (See Appendix 7).

It is possible that an assessment will have to be completed prior to reliable information on certain key facets being available. In such cases, the results will have to be treated with caution. It may be possible to account for uncertainty in the risk assessment by applying weightings to those areas where key information is unavailable.

DIP Step 5: Licensing and approval of the acceptability of development scenarios or environmental flow regimes

Once the ecological risk analysis is complete, specification of appropriate environmental flows, as well as licence management and future development approval processes can commence.

Future proponents and new licencees should be required demonstrate that water storage, water use or development does not pose a significant risk to estuarine ecology. Significant risk can be quantified by DIP steps 2 to 4 described above.

For estuarine protection and rehabilitation, the British concept of a minimum residual flow (MRF, page 135) would appear to be an attractive way of dictating when licensed abstractions should cease. The hydrological model in combination with the flow-salinity model will be able to quantify the effects differing levels of MRF on ecological risk to an estuarine system.

With appropriate stream flow measurement equipment, stream conditions relative to a specified MRF would simple to implement, communicate and audit.

DIP Step 6: Adaptive Management

It is evident that this is not a single pass methodology. The foundation of this approach is good information regarding estuary behaviour and ecological characteristics. Good quality salinity and ecological data is expensive to collect and it may be necessary to revisit some steps as better data becomes available through subsequent monitoring and pertinent research (Section 4.5.1). Equally, different development scenarios will be formulated and it will be necessary to judge each development or proposal on its merits.

As also noted in Section 4.5.1, more developmental work, particularly regarding the ongoing selection, evaluation and refinement of environmental indicators, is required before the ecological health of Australian estuaries can be accurately and cost-effectively assessed. Adaptive management must incorporate both prediction and detection investigations. Appropriate multifaceted monitoring data will be essential for the detection investigation. The minimum focus should be the maintenance, or recovery, of productivity and biodiversity. Specific targets will need to be set in order to determine the success or failure of delivered environmental flows.

With time, new development scenarios for catchments will arise. Once the process has been completed on an initial study, new development scenarios can be assessed by repeating DIP steps 2 to 6. It is crucial that all literature, data and computer models be stored in a secure form for future assessments.

9.3 Justification

The recommended methodology is well-suited to the needs of the Australian environment for the following reasons:

1. It recognises the time-dependent nature of salinity structure in Australian estuaries.
   The Australian climate is highly variable and the developed methodology directly incorporates accurate representation of climatic variability.

   We have rejected methods that are founded on concepts of representative flows or fixed reserves because these fail to recognise the time-dependent nature of Australian estuarine systems.
   The methodology automatically incorporates concepts that consider both the long- and short-term variability in fresh water flow.

2. The methodology recognises the dominant role of salinity in estuarine ecology
   Detailed investigations of fresh water impacts on estuarine ecology are expensive to conduct and detailed assessments are rare. The most significant work seems to have been undertaken in San Francisco Bay and many diverse aspects of the estuarine ecology have been linked to the significant salinity points in the estuary.

   It is important that issues of poor water quality induced by pollutive discharges are not confused with the determination of environmental flows. This methodology carefully distinguishes between these whilst acknowledging their inter-relationship.

3. The methodology incorporates a scheme for the rapid assessment of likelihood of the importance of environmental flows to a given Australian estuary.
   Once the *Preliminary Evaluation Phase* of the methodology is complete, regulatory authorities will be in a good position to assess which estuaries should receive priority for assessment of environmental flow requirements.

4. The methodology recognises important multidisciplinary aspects and dependencies.
   In accord with the adaptive management practices, this methodology recognises the key disciplines of hydrology, estuarine hydraulics, geomorphology, ecology and urban and regional planning in reaching an adequate understanding of the environmental flows required by an estuarine system.

5. The methodology recognises that our current understanding is very crude and adaptive management practice is essential.
   Data is continually being gathered by a number of groups with interests in the estuarine ecology and the environment. Good data will contribute to a better understanding of each estuary and it is essential that procedures are put in place for the systematic incorporation of new information.

The proposed methodology recommended by Binnie, Black and Veatch (1998a, summary in Appendix 7) is a well-constructed rival approach. However, we believe that greater interaction between the assessment of fresh water flow and salinity structure and the detailed risk assessment is required.

10. INFORMATION AND MEASUREMENTS REQUIRED TO SET FLOW REQUIREMENTS

The information required to determine environmental flow requirements for estuaries are specified by the recommended methodology.

The information required falls into three main categories:

A. *Water sources and use within the catchment*. These are essential to quantify the natural runoff from a catchment and any reductions from water storage and use. In general, such data will fall into five sub-categories:
   i. *Rainfall data* – Long-term records of rainfall data are maintained by most remote communities and are required by models of catchment behaviour.
   ii. *Constructed storages* – Information about major storages is widely disseminated and should be relatively easy to assemble. In areas of intense agricultural activity, there can be large numbers of small farm dams and precise numbers and their characteristics could be exceedingly difficult to quantify.
   iii. *Fresh water extractions* – all fresh water extractions within a catchment including those located within the estuary itself and aquifer systems should be identified and characterised in terms of extraction flow rate.
   iv. *Discharges* – all discharges to the estuary, its tributaries or groundwater systems should be identified and characterised in terms of discharge rate and biological and chemical characteristics.
   v. *Measurements of streamflow* – these are required for the calibration and verification of models of catchment behaviour.

B. *Estuarine flow, salinity structure and water quality*. To prepare good models of estuarine flow and salinity structure, suitable configuration, calibration and verification data must be available. Calibration data is used to set appropriate values for model parameters and verification data is used to independently check that the selected values are appropriate. The data required for flow and salinity models is as follows:
   i. *Estuary bathymetry* – The bed sets physical limits to an estuary and the bed configuration may develop with time. Surveys of estuary bathymetry should be commissioned by appropriate responsible authorities repeated at appropriate intervals to monitor bed changes.
   ii. *Measurements of tidal behaviour* – A properly-configured estuary flow model should be able to replicate tide levels, tidal lags and tidal discharges throughout

the system. Such data can be acquired by tidal gaugings that measure these parameters over a tidal cycle.

- iii. *Measurements of salinity structure* – For a satisfactory salinity model to be developed, it will be essential that salinity surveys be undertaken. Measurements of saline structure for a range of inflow conditions are required. It is during dry periods that the greatest saline intrusions will occur and data collection programs should be careful to plan for surveys to be undertaken during very dry periods. Surveys should also be taken at low and high tide.
- iv. *Water Quality Surveys* – If water quality is a major concern, field measurements will be essential to assess any predictive tools that might be used. However, collection of water quality data is complicated and careful planning of such exercises by trained specialists is required.

C. *Important estuarine biota* – Information about two key types of estuarine biota need to be assembled.

  - i. *Threatened or endangered species or communities* – A register of recorded sightings and locations of habitat associated with threatened or endangered species or communities should be maintained.
  - ii. *A range of indicator organisms (Biotic condition indicators or BCIs)* (page 126) – Information regarding the salinity tolerance of appropriate indicator organisms must be maintained to allow predictions of ecological response to be checked.

Many state government authorities have already been systematically assembling the required data sets described above. However, there is a need for this information to be systematically assembled for each estuary. If the information is gathered as described in this section, the environmental flow requirements of an estuary will be able to be determined.

It is often difficult to find a systematic assembly of past investigations for a particular estuary. It is recommended that libraries of all relevant material should be maintained. The Water Reference Library provided a primary reference point for this investigation.

The effectiveness of environmental flow allocations to estuaries will also be able to be measured if information is assembled in this way.

11. LIMITATIONS AND OPPORTUNITIES

There are a number of practical limitations and opportunities available for implementation of environmental flows to estuaries.

It is a common statement from estuary managers and scientists throughout the world that even if an appropriate fresh water flow regime is technically established for an estuary, the implementation of the strategy is often thwarted politically, due to the demands of the competing users of the water. Also, in the case of decisions having economic consequences, the resource needs of estuaries may take a lower priority than economic needs.

Such sentiments have been expressed by:

- Brown (2000) relating to San Francisco Bay. He also commented that stakeholders have their own ideas of equity regarding water allocation.
- Kimmerer and Schubel (1994) relating to San Francisco Bay. They also expressed frustration at the “counterproductive practice of using scientists as advocates in adversarial proceedings to allocate resources among competing uses”.

Arguments about the economic value of water often focus on its value to agricultural, municipal and industrial users, neglecting the environment. Even if the environment is considered, it is difficult to assign an economic value to the water flow diverted or maintained to an ecosystem. To do such an analysis, it is necessary to not only define the economic value of the ecosystem (which may be complex), but also determine the relationship between flow and ecosystem response, and this has only been attempted for relatively few species or communities. Economic data may only be available for commercially or recreationally important species, perhaps biasing economic analyses against other resources (or the ecosystem as a whole), and ignoring aesthetic values (Kimmerer and Schubel, 1994).

The problem of understanding an estuary’s economic value may be compounded by the lack of a clear statement of the characteristics that society would consider desirable in the estuary. For example, value–loaded terms to describe desirable estuary management outcomes, such as “productivity”, may indeed be harmful outcomes (Kimmerer and Schubel, 1994). An estuary’s “needs” thus depend on what people want the estuary to do. According to Kimmerer (2000), no matter how much flow is altered, there will be a functioning ecosystem in the estuary, so a decision has to be made on where in the continuum of “estuary–ness” people want it to be. Also, our limited ability to control flow has to be recognised.

In an attempt to overcome political limitations, Kimmerer and Schubel (1994) have described an approach of consensus among the scientific community regarding the flow needs of the San Francisco estuary, achieved through a series of workshops. This approach, it was believed, would provide substantial force behind flow recommendations (rather than the seemingly fractured and conflicting views of individuals and groups with vested interests) and more likely lead to action on the part of regulatory agencies.

At the Third International River Management Symposium in Brisbane, 2000, the Symposium Advisory Committee presented a Vision for Rivers. In this, it was stated that:

> *"We want to be able to swim in clean, fresh river water, drink river water, fish in rivers….We know that it is difficult, if not impossible, to return rivers to pristine condition, even when we know what the conditions were prior to hundreds of years of human impact. What we strive to achieve is a new regime: clean healthy river systems for maintenance of natural environments and biodiversity, provision of safe water supplies for human use and sustainable native fish stocks".*

Much of this vision could be applied to estuaries.

The vision reveals both the limitations and opportunities available for implementation of environmental flows to estuaries. For example, it reveals that we generally cannot return rivers and estuaries to pristine condition, as hundreds of years of anthropogenic influences cannot be reversed. However, it does set the goal of maintaining healthy ecosystems in conjunction with human use of water as a prospect for the present and the future.

In this report, we have developed a methodology that effectively uses the information that should be assembled by estuary managers to determine a measurement of risk to estuarine ecology due to changing fresh water inflows. Such investigations are designed to form a firm foundation for constructive discussions regarding the use of water in our estuarine catchments.

12. CONCLUSIONS AND RECOMMENDATIONS

Australian estuaries are highly complex systems with great differences in climate, geomorphological form, flow, salinity structure and ecological communities. A simple arithmetic approach (for example, flow-duration based analyses) cannot be applied to determine environmental flows for all Australian estuaries.

This report has provided a systematic methodology for assessing the risk to the estuarine ecosystems associated with reduced fresh water inflows to estuaries. This has been prepared with reference to a checklist of major ecological processes (Table 2 on page 8) by which reduced estuary fresh water inflows may cause impacts on estuarine ecosystems and the adjacent marine environment.

CHECKLIST

Low magnitude inflows (Low-):

Low-1: increased hostile water-quality conditions at depth

Low-2: extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive fauna

Low-3: extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive flora

Low-4: extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota

Low-5: extended durations when flow-induced currents cannot suspend eggs or larvae

Low-6: extended durations when flow-induced currents cannot transport eggs or larvae

Low-7: aggravation of pollution problems

Middle and high magnitude inflows (M/H-):

M/H-1: diminished frequency that the estuary bed is flushed of fine sediments and organic material (physical-habitat quality reduction)

M/H-2: diminished frequency that deep sections of the estuary are flushed of organic material (subsequent water quality reduction)

M/H-3: reduced channel-maintenance processes

M/H-4: reduced inputs of nutrients and organic material

Across all inflow magnitudes (All-):

All-1: altered variability in salinity structure

All-2: dissipated salinity/chemical gradients used for animal navigation and transport

This checklist forms the reference point for a two phase program to undertake the ecological, hydrological, water quality and geomorphological studies that need to be completed.

METHODOLOGY

Preliminary Evaluation Phase

PEP Step 1: Define the environmental flow issue to be investigated.
PEP Step 2: Assess the value of the estuary
PEP Step 3: Assess changes to inflow
PEP Step 4: Assess the vulnerability of the estuary.

Detailed Investigative Phase

DIP Step 1: Examine the likely impact of current water use on transport, mixing, water quality and geomorphology using catchment runoff and estuarine flow models
DIP Step 2: Define environmental flow scenarios for the estuary
DIP Step 3: Use the established models to assess the impact of proposed scenarios.
DIP Step 4: Assess the risk to estuarine biota
DIP Step 5: Licensing and development approval
DIP Step 6: Adaptive Management

At the conclusion of the preliminary evaluation phase, different estuaries should be able to be categorised according to risk from reduced fresh water inflows.

Good physical, chemical, water quality and ecological data for estuarine systems is absolutely foundational to robust predictions of appropriate environmental flows.

The collection and facilities of the Water Reference Library were invaluable to this investigation. It is important that all documents, data and models relevant to individual Australian estuaries be assembled within reliable archives and maintained.

At present, there appears to be limited communication between estuary managers at Australian State and Federal level. It is recommended that an appropriate forum be developed to improve communication between these agencies.

The best test of the adequacy and robustness of the checklist and methodology developed within this project would be a trial determination of appropriate environmental flows for an Australian estuary. We recommend that this be commissioned as soon as possible.

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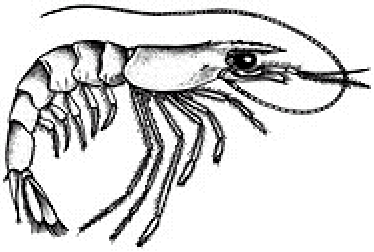
APPENDIX 2. GLOSSARY

Sources included Chow et al (1988), Dictionary of Science and Technology (1992), EPA (2000), Fisher et al (1979), Merriam–Webster's Collegiate Dictionary (2000), Oxford English Dictionary (2000).

abiotic	nonliving characteristic of the environment; the physical and chemical components that relate to the state of ecological resources
abstraction	1. withdrawal of water for anthropogenic purposes, usually by means of pumping (and often regulated), from surface water sources such as rivers and streams, and groundwater sources such as aquifers (via boreholes and wells). 2. the portion of precipitation that does not become direct runoff (primarily water absorbed by infiltration with some allowance for interception and surface storage). 3. the process of merging one or more streams into another stream having greater erosional activity
Alluvial	relating to or consisting of any material that has been carried or deposited by running water
Amphidromous	diadromous migrations not for breeding
Anadromous	referring to fish, such as salmon, that live most of their lives in the ocean but migrate up into fresh water streams and rivers to spawn (produce eggs)
Anthropogenic	of, relating to, or resulting from the influence of human beings on nature
arthropod	any of a phylum (Arthropoda) of invertebrate animals (as insects, arachnids, and crustaceans) that have a segmented body and jointed appendages, a usually chitinous exoskeleton molted at intervals, and a dorsal anterior brain connected to a ventral chain of ganglia
Baroclinic	having the property of baroclinity, a state of fluid stratification in which isobaric (constant pressure) surfaces and isosteric (constant density or constant specific volume) surfaces are not parallel, but intersect
baroclinic circulation	flow driven by density variations
Biotic	of or pertaining to living organisms
Catadromous	diadromous migrations to the sea/estuary for breeding

chitinous	a horny polysaccharide that forms part of the hard outer integument especially of insects, arachnids, and crustaceans
crustacean	any of a large class (Crustacea) of mostly aquatic mandibulate arthropods that have a chitinous or calcareous and chitinous exoskeleton, a pair of often much modified appendages on each segment, and two pairs of antennae and that include the lobsters, shrimps (as shown below, sourced from the Dictionary of Science and Technology, 1992), crabs, wood lice, water fleas, and barnacles 
Delta	a nearly level, often triangular alluvial plain occurring between diverging branches of the mouth of a river
Detritus	loose material (as rock fragments or organic particles) that results directly from disintegration or decay
estuarine turbidity maximum	a zone of accelerated particle settling (also known as estuarine entrapment zones or null zones) at the boundary between a saline downstream reach and an fresh upstream reach.
Diadromous	moving between the sea/estuary and rivers/streams
Eutrophication	a process that increases the amount of nutrients, especially nitrogen and phosphorus, in a marine or aquatic ecosystem, leading to an increase in algae and a decrease in diversity (stimulating the growth of aquatic plant life, usually resulting in the depletion of dissolved oxygen); it occurs naturally over geological time but may be accelerated by human activities, such as waste disposal or land drainage
geomorphology	the study of the surface configuration of the earth, especially the nature and evolution of present landforms, their relationships to underlying structures, and the history of geologic activity as represented by such surface features
isohaline	a line or surface of constant salinity
lentic	of, relating to, or living in still waters (as lakes, ponds, or swamps)
lotic	of, relating to, or living in actively moving water

mysid	the opossum shrimp, a small shrimp–like crustacean of the family Mysidae or the suborder Mysidacea, having biramous thoracic appendages
piscivorous	fish-eating; subsisting on fish; ichthyophagous
plankton	a collective term for the wide variety of plant and animal organisms, often microscopic in size, that float or drift freely in water because they have little or no ability to determine their own movement; found worldwide in both aquatic and marine environments and representing the basic level of many feeding relationships
pycnocline	region of vertical salinity gradient
riparian	relating to or living or located on the bank of a natural watercourse, such as a river or stream
specific volume	the volume per unit mass; the reciprocal of density
stratification	a density gradient in a water column caused by temperature and salinity variations
trophic level	one of the hierarchical strata of a food web characterised by organisms which are the same number of steps removed from the primary producers

APPENDIX 3. ABBREVIATIONS

AFFA	Agriculture, Fisheries and Forestry Australia
All-	Across all inflow magnitudes
ANZECC	Australian and New Zealand Environment and Conservation Council
BDAC	Biodiversity Advisory Council
BCIs	Biotic condition indicators
COAG	Council of Australian Governments
DIP	Detailed Investigative Phase
DO	dissolved oxygen
EA	Environment Australia
EFI	Environmental Flows Initiative
EPA	Environmental Protection Agency
ETM	estuarine turbidity maximum
Low-	Low magnitude inflows
LWRRDC	Land and Water Resources Research and Development Corporation
MRF	minimum residual flow
M/H-	Middle and high magnitude inflows
NEP	National Estuary Program
NHT	Natural Heritage Trust
NSW	New South Wales
NRHP	National River Health Program
PEP	Preliminary Evaluation Phase
ppt	parts per thousand, equal to g/kg, symbolised by ‰; in the measurement of salinity, ppt is equivalent (or very close, see Dauphinee, 1980; Lewis and Perkin, 1981) to practical salinity units (psu)
US	United States
USA	United States of America
WRL	Water Research Laboratory

APPENDIX 4. ESTUARY DEFINITIONS

The noun estuary is derived from an adaptation of the Latin *aestuarium*, properly adjectival meaning ‘tidal’, hence a tidal marsh or opening. The Latin *aestuarium* itself is formed on *aestus*, meaning ‘heat, boiling, bubbling, tide’, akin to *aestas*, meaning ‘summer’. Its etymology dates from 1538 (Oxford English Dictionary, 2000; Merriam–Webster's Collegiate Dictionary, 2000).

The Oxford English Dictionary (2000) defines ‘estuary’ as:

1. (generally). A tidal opening, an inlet or creek through which the tide enters; an arm of the sea indenting the land (rare in modern use)
2. (specifically). The tidal mouth of a great river, where the tide meets the current of fresh water
3. (obsolete). A place where liquid boils up
4. (obsolete). A vapour–bath
5. (attributively, sometimes quasi–adjectively). Estuarine

The Coastal Engineering Research Center (1984) defines an estuary as:

1. that part of a river that is affected by tides;
2. the region near a river mouth in which the fresh water of the river mixes with the salt water of the sea

APPENDIX 5. BROAD CATEGORIES OF ESTUARINE HABITATS IDENTIFIED BY THE NSW GOVERNMENT (1992).

- Open waters;

  Estuarine open waters usually are marine in their characteristics and serve as sheltered waters for marine animals and birds.

- Reefs and rocky shores;

  Reefs and rocky shores are also usually marine in the characteristics and support a diverse ranges of flora and fauna.

- Unvegetated bed sediments;

  The greatest proportion of the submerged areas of estuaries are usually unvegetated. Such beds can differ in the type of sediment tending to be muddy towards the head of the estuary changing to sandy near the mouth of the estuary. In spite of the absence of marine plants, studies have shown substantial populations of fish with prawns being the numerically dominant organisms in some areas.

- Seagrass beds;

  All seagrass are marine angiosperms and have the ability to spread by rhizome activity as well as pollination and seed dispersion. Ruppia are not seagrasses but are a similar group of plants that are found in more brackish waters and are often pollinated above the surface. Seagrass beds serve a number of important ecological roles: as sources of detrital material; in estuarine nutrient cycling; substrate stabilisation; animal habitat; and as a substrate for epibiota (small plants and animals living on the stems). Loss of seagrass beds can have marked ecological consequences for estuarine systems.

- Inter-tidal sand and mudflats;

  Inter-tidal flats are primarily habitats for molluscs, worms, crabs and shrimps. As a consequence, they are attractive feeding areas for birds, particularly wading birds.

- Beaches, dunes and sand-spits;

  These do not form part of the inundated estuarine area but can be important roosting and nesting areas for shorebirds.

- Mangrove forests;

  Mangroves are robust trees that occupy intertidal shallows and are able to withstand inundation with waters with a wide range in salinity. They usually occupy sediments of *rich mud that are often high in nutrients but can be anaerobic. They play an important role in estuarine ecology in nutrient cycling, as habitat for fish, birds, mammals, molluscs and other animals.*

- Saltmarshes;
  Saltmarshes generally occur on the landward side of mangroves where tidal inundation is less frequent. Saltmarshes help maintain estuarine water quality by filtering sediment from land-based runoff and are important habitats for insects and birds.

- Swamp forests;
  Swamp forest occur adjacent to wetland areas and are the most inland habitats directly connected to estuaries. They support many terrestial species of wildlife including mammals and reptiles as well as aquatic organisms. Their waters are typically more brackish in characteristic and their vegetation is tolerant to inundation and mild salinity levels.

- Ephermeral floodplain wetlands and dune lakes;
  These are temporary water bodies that are inundated by rainfall, floods or extreme tides. In general, they experience extreme physical and chemical variations but are not devoid of fauna.

- Fresh water aquatic vegetation.
  The upper reaches of estuaries are often characterised by aquatic plants with some salt tolerance. These include reeds that serve as important habitats for some juvenile fresh water fish.

APPENDIX 6. A SUMMARY OF AUSTRALIAN GOVERNMENT FLOW POLICIES AND INITIATIVES.

Major Estuary Studies

For at least forty years, the degradation of estuaries adjacent to Australia's major population centres has been a cause for significant concern to the community. Investigations have been ongoing for the major capital cities with several major initiatives in recent years. These include:

- The Clean Waterways Program undertaken by Sydney Water (Sydney Water, 1994)
- The Port Phillip Bay Study (CSIRO, 1996)
- The Morton Bay Study (Dennison and Ebal, 1999)
- The Derwent Estuary Program (Davies and Kalish, 1994)

However, the primary focus of these investigations has been the impact of increased pollution on the water quality and ecology of these estuarine systems. To our knowledge, apart from the Derwent Estuary Program (in which the heavy regulation of upstream water storages was considered), these major studies have not recommended appropriate environmental flows for these systems.

National Water Policies

The Council of Australian Governments (COAG) produced a Water Policy Agreement providing for:

- the allocation of water to the environment in order to enhance/restore the health of river systems
- an integrated catchment management approach for water resources
- the establishment of water markets that would allow water entitlements, held by individuals and authorities, to be traded to higher value uses at other locations
- pricing reform to allow progressive movement to full cost recovery.

For the allocation of water to the environment, COAG agreed that there would be regard given to the National Principles for the Provision of Water for Ecosystems and the National Water Quality Management Strategy.

Australian and New Zealand Environment and Conservation Council (ANZECC) Draft Guidelines for Fresh and Marine Water Quality

The Australian and New Zealand Environment and Conservation Council (ANZECC) (1999) has released Draft Guidelines for Fresh and Marine Water Quality. The objective of these guidelines is:

"To maintain and enhance the 'ecological integrity' of fresh water and marine ecosystems, including biological diversity, relative abundance and ecological processes".

The draft ANZECC guidelines (1999) classify ecosystems in three broad categories:

1. High conservation value ecosystems – these are ecosystems which are pristine and often occur in national parks, conservation reserves or remote locations.
2. Slightly to moderately disturbed systems – ecosystems which have been affected to a small but measurable degree by human activity. The biological communities are largely intact and in a generally healthy condition.
3. Highly disturbed systems – these are systems which have been measurably degraded and are of lower ecological value.

The key regional stakeholders are responsible for deciding on an appropriate level of protection based on the community's long term desires for the ecosystem. The philosophy behind this approach is to either maintain the current ecosystem condition or enhance a modified ecosystem by targeting the most appropriate condition level.

The draft ANZECC guidelines propose a framework for levels of protection to be applied to ecosystems fitting the three classifications above. This framework specifies guidelines for biological indicators, physical and chemical stresses, toxicants and sediments.

High Conservation Value Ecosystems
For the high conservation value ecosystems, the guidelines specify no detectable change in biodiversity, physical and chemical indicators or background toxicant levels or sediment loading beyond natural variability. This implies that for these systems, the flow regime must also remain intact.

The guidelines advocate collection of data to establish baseline levels for biological assessment, and biological effects of toxicants and sediments.

Slightly to Moderately Disturbed Ecosystems
For the slightly or moderately disturbed systems, the guidelines recommend determining a reference condition, and collection of data and statistical techniques to assess the departure from this reference condition.

A reference site is a site usually selected in similar, but unimpacted or little changed, ecosystems in the vicinity of the test ecosystem. The main advantages in using reference sites to establish targets are: that the target is reasonably clear (i.e. the reference systems can actually be visited for further clarification); by comparing with another natural system some account can be taken of natural variability and complexity; this procedure is being used nationwide (within Australia) for biological assessment and some of the required physico-chemical data are already being collected. The target is to assess the departure of the studied ecosystem from the condition of the reference ecosystem, and to try to achieve the same condition as the reference (undisturbed) ecosystem.

The problem with this approach is that it may be difficult to find an undisturbed reference site with similar ecological characteristics to the site being studied – in these cases, an ecosystem which may not be pristine but is least disturbed, the existing ecosystem, or a similar nearby ecosystem may be used as a reference ecosystem.

A particular problem with the application of this approach to estuaries is that structure and characteristics change along the estuary and extrapolation from one point to another must recognise this.

Highly Disturbed Ecosystems

The general aim for the highly disturbed ecosystems is to at least maintain the current ecosystem condition, but leaning toward higher water quality in the longer term. The local community (through Catchment Management Committees, etc.) decides which of the three reference conditions are appropriate for their estuary, and aim to restore this condition.

Discussion

The variability and complexity of aquatic ecosystems such as estuaries make them difficult to manage. The ANZECC guidelines introduce the concept of using risk-based hierarchical decision frameworks to assist managers to tailor guidelines according to regional, local or site-specific conditions.

The ANZECC guidelines recommend studying ecosystems in a site-specific fashion and determining whether a certain stressor (in this case, altered fresh water inflow regime) constitutes a low, possible or high risk to the ecosystem.

The National Land and Water Resources Audit

The National Land and Water Resources Audit (Creighton, 2000) is a partnership involving the following stakeholders:

- CRC Coastal Zone, Estuary and Waterway Management
- CSIRO
- Australian Geological Survey Organisation
- University of Queensland
- Fisheries Research and Development Corporation
- Environment Australia
- State And Territory Agencies
- Industry and Community Groups

The goals of the Audit were to:

- develop a process-based understanding of estuaries and their diversity across Australia
- recognise estuary and linked catchment management needs and priorities
- contribute an information base to improve estuary management

The Audit is not yet complete, however, it has identified that 50% of Australia’s estuaries are near pristine and little information exists about them. They are important biodiversity references and benchmarks on which to base management.

Figure 13 below (Creighton, 2000), identifies from the Audit which estuaries in Australia are pristine, largely unmodified, modified or severely modified.

Most of the degraded estuaries lie near major population centres or in areas where there are major industries, agricultural activities or vegetation clearing.

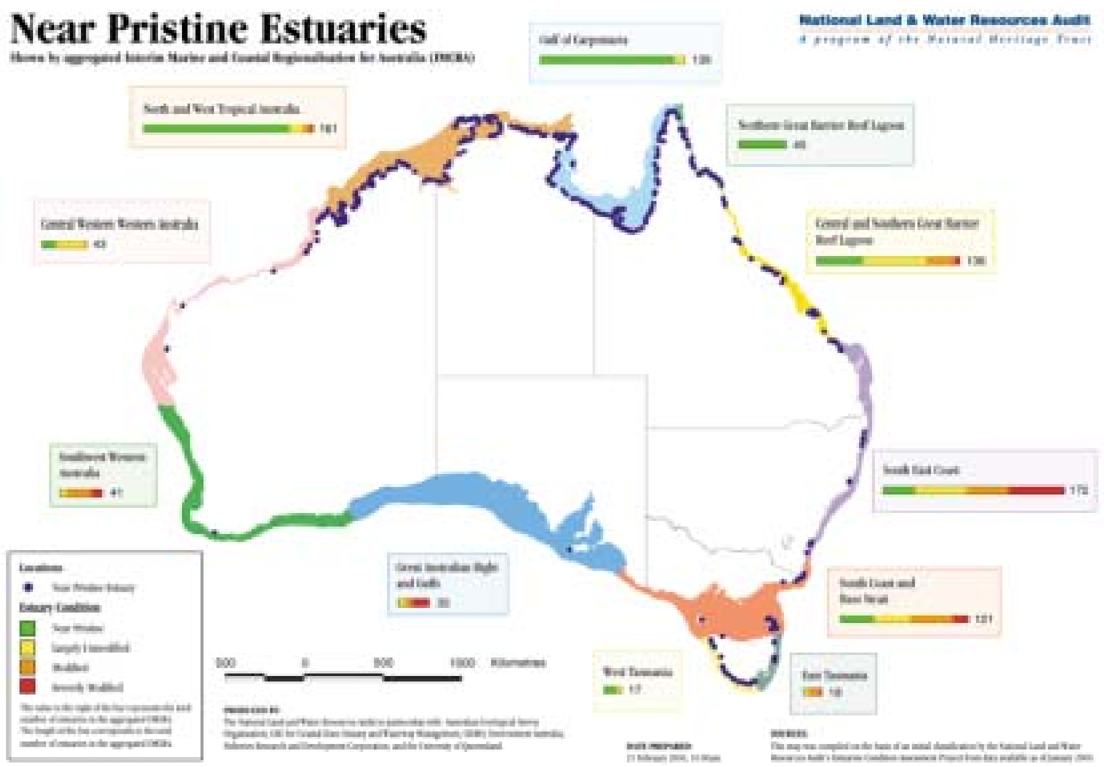


Figure 13 – State of Estuaries in Australia (Creighton 2000)

There is an Australian Estuaries database run by the Australian Geological Survey Organisation (AGSO) which is available on the world wide web on http://www.agso.gov.au/ozestuaries/, and is part of the National Land and Water Resources Audit. This database gives information on all the estuaries in Australia and classifies them as nearly pristine, largely unmodified, modified or severely modified.

New South Wales

Since 1992, the New South Wales government has been operating its 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 Department of Land and Water Conservation (1999) has released a white paper for public comment, outlining the legislation they have developed to replace the *Water Act 1912* and its many amendments. A priority focus in the document is water use efficiency and regulating allocation to maintain sufficient water flow for the environment (Vinall, 2000).

New South Wales has interim water quality objectives (WQOs) and river flow objectives (RFOs) for 31 catchments. The objectives have been released as guidelines to river, water and groundwater management committees preparing river, water and groundwater management plans.

Figure 14 is a map of New South Wales showing all the catchment areas in the State (NSW EPA, 2000). The catchments coloured in pink are those which have environmental objectives set whereas the ones in green are not set due to their being the subject of a Healthy Rivers Commission inquiry, or because environmental objectives are being determined by interstate processes.

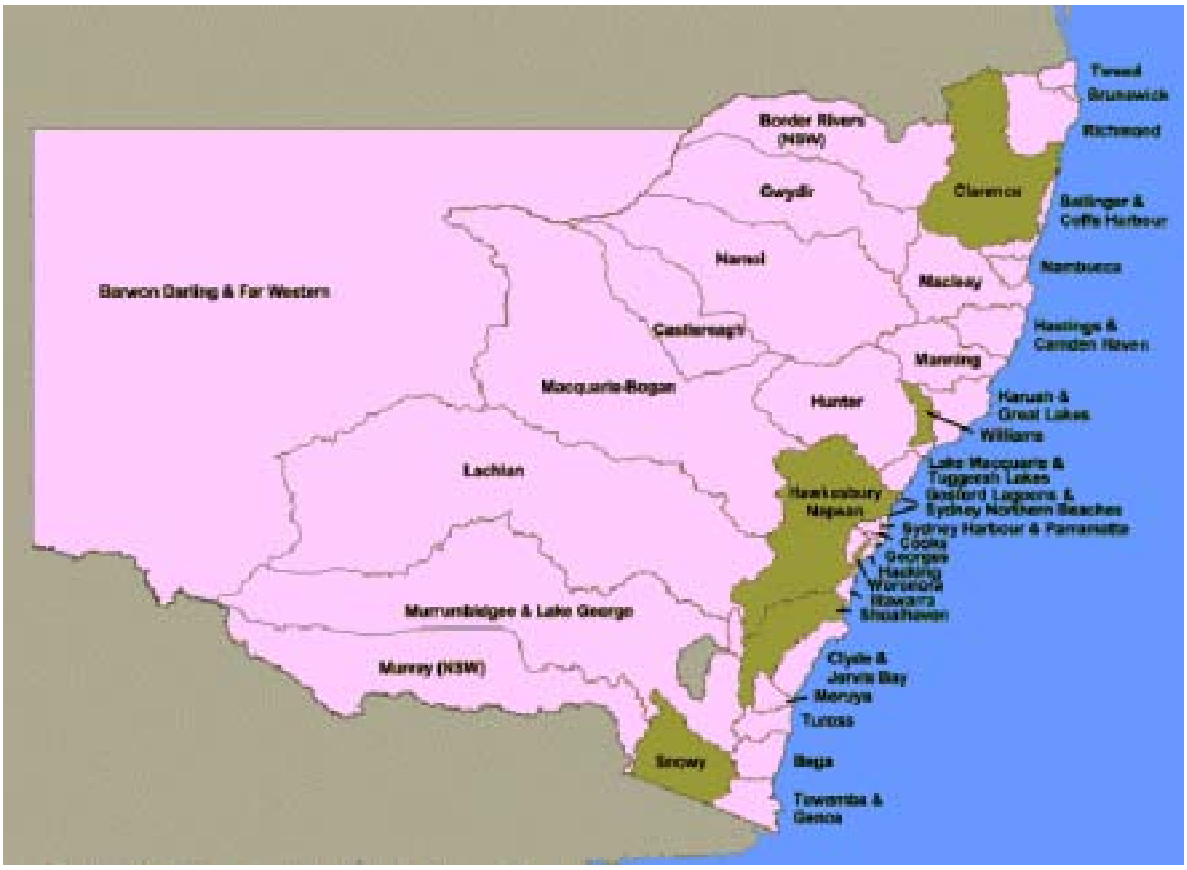


Figure 14 – New South Wales catchments with set environmental objectives (NSW EPA, 2000)

In total, there are twelve coastal river flow objectives, each dealing with a critical element of natural flows in rivers and estuarine processes. These are listed below (NSW EPA, 2000):

- Protect pools in dry times – protect natural water levels in pools of creeks, rivers and wetlands during periods of no flow i.e. no water extractions from streams or wetlands during periods of no flow
- Protect natural low flows – share low flows between the environment and water users and fully protect all *very low flows* (exceeded on 95% of days with flow). The environment should be allocated 50 – 70% of the flow in times of *low flow* (i.e. when

the flow is exceeded on 80% of the days with flow). In high conservation value streams there should be no increase in extraction of low flows.

- Protect important rises in water levels – protect or restore a proportion of high and moderate flows which are important triggering migration and reproduction of plants and animals, providing over-bank flows to wetlands and floodplains, shaping the river channel and controlling water quality and nutrients.
- Maintain wetland and floodplain inundation – maintain or restore the natural inundation patterns and distribution of floodwaters supporting natural wetlands and floodplain ecosystems.
- Mimic natural drying in temporary waterways – mimic the natural frequency, duration and seasonal nature of drying periods in naturally temporary waterways.
- Maintain natural flow variability
- Maintain natural rates of change in water levels – prevent sudden increases or decreases in water levels caused by releases from dams, etc. which could lead to stream collapse or bank erosion.
- Manage groundwater for ecosystems – manage groundwater within natural levels and variability, critical to surface flows and ecosystems.
- Minimise effects of weirs and other structures
- Minimise effects of dams on water quality
- Make water available for unforeseen events – ensure river flow management provides for contingencies
- Maintain or rehabilitate estuarine processes and habitats – i.e. not changing the tidal flow characteristics, salinity conditions or water levels. Upstream river processes are also important e.g. scouring as a result of flooding leading to the opening or closing of river mouths, and reduced occurrences of fresh events leading to severely depleted food sources for estuarine plant and animal species or communities. Draining of acid sulfate soils is also covered by this river flow objective.

These guidelines were developed following an extensive community consultation process involving river and catchment management committees, etc. A separate community consultation process was implemented in each of the 31 catchments and priorities on the specific objectives listed above have been decided.

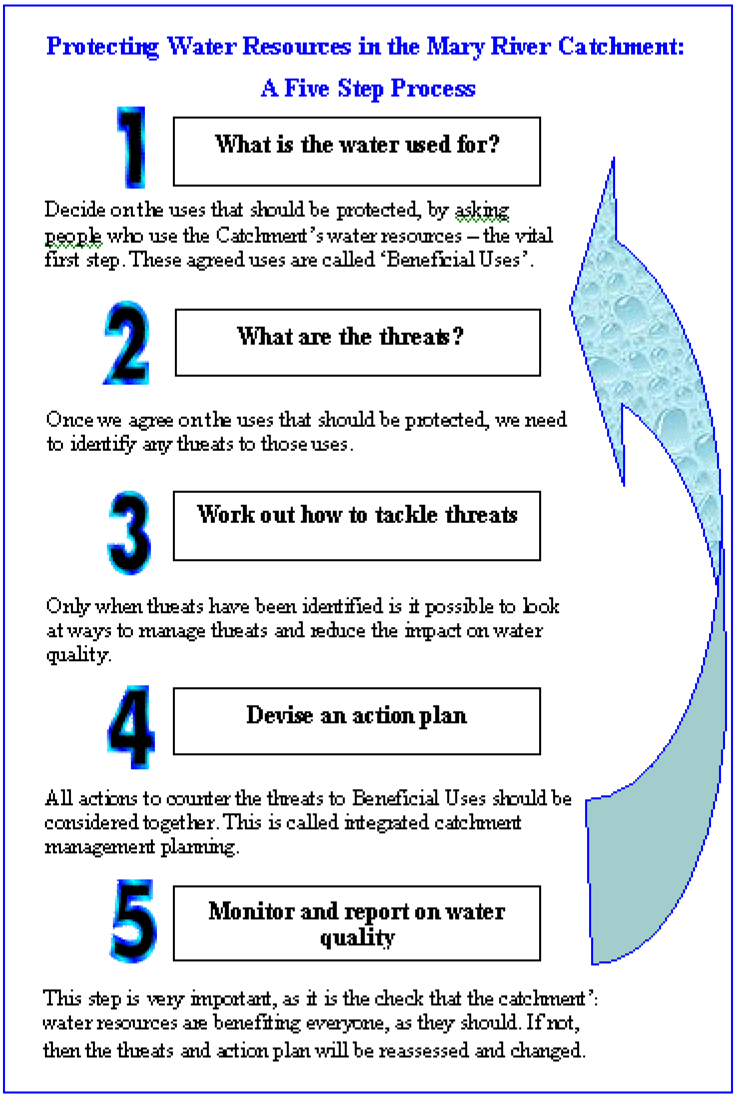
Northern Territory

The Northern Territory Water Act (1992) covers the investigation, use, control, protection, management and administration of water resources within the Northern Territory. Each landholder in the Territory has the right to use a water source (surface or groundwater) situated on their land, for stock and domestic purposes. For uses other than stock and domestic, licences can be granted. Any interference with a waterway or obstruction of flow requires a permit. This includes damming of creeks, pumping from springs, creeks and rivers. Permits and licences are controlled under the Northern Territory Water Regulations, administered by the Department of Lands Planning and Environment.

The Northern Territory Water Act (1992) identifies seven beneficial uses of water:

(a) agriculture - to provide irrigation water for primary production including related research;
(b) aquaculture - to provide water for commercial production of aquatic animals including related research;
(c) public water supply - to provide source water for drinking purposes delivered through community water supply systems;
(d) environment - to provide water to maintain the health of aquatic ecosystems;
(e) cultural - to provide water to meet aesthetic, recreational and cultural needs;
(f) manufacturing industry - to provide water for secondary industry including related research;
(g) riparian - to provide water directly from riparian sources for domestic use, stock, gardens etc.

An example of how the Northern Territory Water Act is applied to the Mary River Catchment is shown in Figure 15 below.



Protecting Water Resources in the Mary River Catchment:
A Five Step Process

1 **What is the water used for?**

Decide on the uses that should be protected, by asking people who use the Catchment's water resources – the vital first step. These agreed uses are called 'Beneficial Uses'.

2 **What are the threats?**

Once we agree on the uses that should be protected, we need to identify any threats to those uses.

3 **Work out how to tackle threats**

Only when threats have been identified is it possible to look at ways to manage threats and reduce the impact on water quality.

4 **Devise an action plan**

All actions to counter the threats to Beneficial Uses should be considered together. This is called integrated catchment management planning.

5 **Monitor and report on water quality**

This step is very important, as it is the check that the catchment's water resources are benefiting everyone, as they should. If not, then the threats and action plan will be reassessed and changed.

Figure 15 – NT Water Act – Application to Mary River Catchment (Lands, Planning and Environment, 2001)

Queensland

The Queensland Environmental Protection Agency (2000a) has released a position paper on coastal management in Queensland. Environmental flows to estuarine systems are considered in this position paper, and where water diversion and impoundments exist, the position paper recommends assessing estuarine environmental flow requirements by considering the following factors (Queensland Environmental Protection Agency, 2000a):

(a) water quality and quantity;
(b) natural flow regimes (frequency and timing);
(c) impacts on estuarine productivity;
(d) impacts on mangrove distribution and species composition;
(e) nutrient and sediment supply;
(f) salinity;

(g) fresh water, estuarine and inshore habitats;
(h) the function of the river in providing a corridor for wildlife to move between habitats including fresh water and marine habitats);
(i) species diversity; and
(j) species population dynamics.

The position paper also states that water use and infrastructure development should ensure the provision of environmental flows that take into account the downstream requirements of the coast, and permit connectivity between the fresh water sections of waterways and the coastal zone.

Queensland's Water Act 2000 provides the basis for water allocation and management planning including the provision of environmental flows (Queensland EPA, 2000b). The development of Water Allocation and Management Plans (WAMPs) involves a thorough assessment of water resources on a catchment or basin basis. A WAMP is designed to provide the framework for clearly establishing environmental flows, water allocations, and the resource management conditions under which trading of water allocations can occur (High Level Steering Group on Water, 1999).

Queensland has a State Interest Planning Policy for Queensland Waters (Queensland Environmental Protection Agency, 2000b). The Environmental Protection Agency State interest in Queensland incorporates water quality, water quantity (environmental flows), and water use, for streams, wetlands and groundwater systems.

The aim of the policy is “To protect or enhance environmental values and valuable features of Queensland's waters to ensure the ecological sustainability of waters in the local government area within a catchment context.” The policy objectives are to “identify in planning schemes the environmental values and valuable features of Queensland's waters within a catchment context in and adjacent to the local government area”, and “to protect the environmental values of Queensland's waters through setting of agreed objectives and assessment provisions in planning schemes”. The Policy is guided by several national strategies and Intergovernmental Agreements, namely

- National Strategy for Ecologically Sustainable Development;
- Intergovernmental Agreement on the Environment;
- National Principles for the Provision of Water for Ecosystems;
- National Water Quality Management Strategy;
- National Strategy for the Conservation of Australia's Biological Diversity; and
- Convention on Wetlands of International Importance (Ramsar Convention).

Queensland also has an Environmental Protection (Water) Policy (1997), which covers:

- 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; and
- suitability for industrial use.

South Australia

In South Australia the Water Resources Act 1997 makes provision for transferable water property rights (High Level Steering Group on Water, 1999). Granting, review and transfer of water licences, including water allocations, is provided by the relevant water allocation plan, which must be developed through an extensive community consultation process. The water allocation plan also formally recognises and protects environmental water provisions. Water allocation plans must be consistent with both the state-wide policy directions contained in the State Water Plan and the relevant catchment water management plan, if the water resource is located within a catchment water management board's area (High Level Steering Group on Water, 1999).

South Australia has an Environment Protection (Marine) Policy (1994). This policy has ten schedules relating to water quality criteria for estuarine and marine waters for various uses (pristine, recreational use, passive recreation, maintenance of water-associated wildlife and marine aquatic ecosystems), as well as water quality criteria for shellfish culture and fish farming).

For the various uses outlined in the policy, there are water hydrography criteria for estuaries which outline a maximum allowed variation of the isohaline over the natural variation, as well as permitted weekly average values of salinity. These are outlined in Table 6 below.

Table 6 – South Australian Environment Protection (Marine) Policy, 1999

Schedule – Environment Protection (Marine) Policy 1994	Criteria
Schedule 5 – Water Quality Criteria for the maintenance of water-associated wildlife	The weekly average salinity should not exceed background variation by more than the values shown: ***Background Permitted Variation*** 0-3.5 ‰ – 1.0 ‰ permitted variation

	3.5-13.5 ‰ – 2.0 ‰ permitted variation > 13.5 ‰ – 4.0 ‰ permitted variation
Schedule 6 – Water quality criteria for the maintenance of marine aquatic ecosystems – Level I protection	No change in the hydrography of flow should be allowed which causes permanent change in isohaline patterns by more than 2% of the natural background variation.
Schedule 7 – Water quality criteria for the maintenance of marine aquatic ecosystems – Level II protection	No change in the hydrography of flow should be allowed which causes permanent change in isohaline patterns by more than 10% of the natural background variation.

Tasmania

Tasmania is currently developing a Water Development Plan, whose working objective is "To provide a strategic context for sustainable water use and development in Tasmania by analysing strategic issues, highlighting strategic choices and provideing a framework for Government and community action" (Tasmanian Department of Primary Industries, Water and Environment, 2001). The project attempts to successfully manage Tasmania's water needs for domestic, agricultural, environmental, recreational and industrial uses.

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). The methodology used in Tasmania to determine environmental flow requirements is the Instream Flow Incremental Methodology (IFIM). This methodology identifies aquatic species and habitats that respond to variations in river flow and provides a direct linkage to hydrological studies and risk assessment (Tasmanian Department of Primary Industries, Water and Environment, 2001).

Victoria

Victoria has a State Environmental Protection Policy (Water). This and other State Environmental Protection Policies (SEPPs) are made under the Environment Protection Act 1970. A SEPP identifies the area to which the policy applies, the beneficial uses of the waters in the catchment or sea (i.e. those valued by the community which require protection), the segments or areas of common use, and environmental quality objectives (water quality objectives set at a level to ensure the protection of the beneficial uses).

The existing water policy framework for Victoria comprises the SEPP (Waters of Victoria), which applies to all surface waters in the State, as well as seven schedules to SEPP for specific catchments in the State and seven stand-alone SEPPs which apply to specific water bodies in Victoria (Victoria Environment Protection Authority, 1999). In Victoria the Water Act 1989 provides the legislative basis for a property rights system of water entitlements and trade. Flow sharing arrangements at approximately 70% of the diversion sites across the State have been negotiated and agreed with stakeholders. The bulk entitlements program enables the provision of water for the environment and a range of negotiations has achieved some improvements to environmental flow regimes (High Level Steering Group on Water, 1999).

The SEPP (Waters of Victoria) was declared in 1988, and reviewed in 1990, and again in 1999. New institutional arrangements were made for coastal and catchment management, and this has led, for example, to the development of the Victorian Coastal Strategy and 10 Regional Catchment Strategies together with associated action plans. The 1999 review also recognised that environmental management is shifting to the use of locally or regionally-specific risk assessment tools. There was recognition of the need for a Statewide statutory policy setting environmental quality objectives and directions. The policy is currently under review to integrate all the stand alone water policies under the one SEPP (Waters of Victoria) umbrella, as well as to incorporate an ecologically-based classification scheme for Victorian waters and reflect advances in monitoring tools.

Western Australia

The Water and Rivers Commission Policy and Planning Division (1999) released a Draft Environmental Water Provisions Policy for Western Australia. The Water and Rivers Commission has responsibility, on behalf of the community, to equitably share water resources between the needs of the environment, social needs and demands to consume water for economic benefit. Broadly, 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.

The Western Australian approach to ensuring that provision is made for the environment in water allocation decision-making uses the concepts of Ecological Water Requirements (EWR’s) and Environmental Water Provisions (EWP’s). Ecological Water Requirements are the water regimes needed to sustain key ecological values of water-dependent ecosystems at a low level of risk, and are determined using the best available scientific information. Environmental Water Provisions are the water regimes that are to be maintained. They are set by water allocation decisions that may involve some compromise between ecological, social and economic goals.

Eighteen guiding principles are detailed in the policy statement and these provide guidance for the generic determination of EWP’s. The first guiding principle is that water allocation decisions are primarily based on ensuring that essential natural ecological processes and the bio-diversity of water-dependent ecosystems are maintained.

The approach to identifying important components of surface water ecosystems for protection is based on the ‘holistic approach’ as described in Arthington et al (1998a). This approach assumes that the natural flow regime maintains, in a dynamic manner, the shape of river channels, the in-stream biota, riparian vegetation, flood-plain and wetland systems, and any estuarine and off-shore systems affected by streamflows.

The framework for the Western Australian Environmental Flows Policy is shown in Figure 16 below.

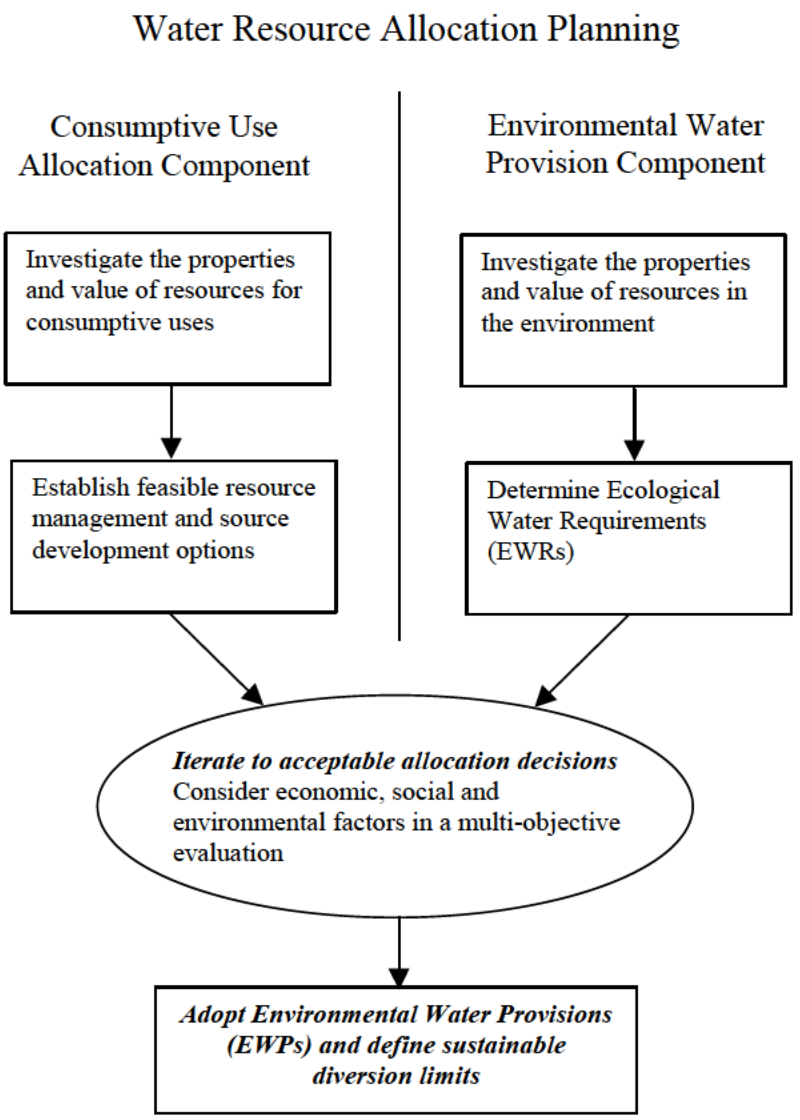


Figure 16 – Western Australian Environmental water provision planning (Water and Rivers Commission, 1999)

APPENDIX 7. REVIEW OF ESTUARINE ENVIRONMENTAL FLOW STUDIES

South Africa

South African environmental flow studies are relatively advanced, including the investigation of estuarine requirements. Unless otherwise stated, much of the information in this Section was provided by Adams (2000).

The estuarine community in South Africa has been involved with a number of contract studies with the Department of Water Affairs (DWAF) to determine the fresh water requirements of specific estuaries.

As a result of this DWAF work many groups in South Africa have focused research on the fresh water requirements of estuaries. Some of these projects have been funded by the Water Research Commission.

South Africa has a variety of different types of estuaries and past fresh water requirement studies have covered a large range of systems, such as the Olifants River on the west coast which has strong seasonal flows (high flow in winter), the Palmiet and Great Brak; and, temporarily closed systems on the south coast and on the east coast on the Tugela (high summer flow), Mkomazi, Mhlathuze (estuarine bay) and Nhlabane (estuarine lake) systems.

The South African approach to defining environmental water requirements of estuaries is to understand the present structure and function of the estuary, gauge to what extent it has changed from natural and predict how it might change in the future if there is further alterations to fresh water input. Studies are multidisciplinary and usually involve a hydrologist, hydrodynamic specialist, water quality specialist, botanist (microalgae and macrophytes), benthic invertebrate specialist, fish specialist and bird specialist.

For the large, permanently open estuaries the focus is on flow reduction and how this has altered the salinity gradient and biotic response. Reduction in the effect of floods and changes in sediment dynamics is also considered to be important as well as whether flow reduction would have an effect on mouth dynamics. For the temporarily closed estuaries the focus is on the relationship between flow and mouth condition, with identification of when the mouth should be open based on fish and invertebrate recruitment. Water level fluctuations in terms of vegetation response is also investigated.

The most definitive document describing the environmental flow requirements for South African estuaries published to date is Department of Water Affairs and Forestry (1999).

Understanding South Africa’s water policy involves familiarity with a considerable amount of jargon. The summary below was obtained from the South African Wetlands Conservation Program (1999):

“*The National Water Policy of 1997 outlines a broad water resource protection approach that integrates a number of key features in a structured decision-making framework:*

- ***Resource-directed measures*** *which focus on the water resource as an ecosystem and set clear objectives for the desired level of protection of that resource (eg. Classification of resources, determination of the reserve, setting of resource quality objectives, etc);*
- ***Source-directed measures*** *that include a wide range of regulatory measures that are intended to control the sources of impacts on water resources such that the objectives for resource protection are achieved (eg. Waste standards, water use licensing, etc);*
- ***Demand Management*** *to keep utilisation within the limits required for protection; and*
- ***Monitoring*** *of the status of the country's water resources to ensure that the Resource Quality Objectives are being met.*

According to the National Water Act (No. 36 of 1998), a water resource is treated as an ecosystem, that includes the physical or structural aquatic habitats, the water, the aquatic biota, and the physical, chemical and ecological processes that link water, habitats and biota. In terms of the Act, Resource Quality Objectives (RQO's), set in terms of a national classification system, will be used to define the desired protection status of water resources in South Africa. Resource quality is defined in the Act as:

- *The quantity, pattern, timing, water level and assurance of instream flow;*
- *The water quality, including the physical, chemical and biological characteristics of the water;*
- *The characteristics and condition of the instream and riparian habitat; and*
- *The character, condition and distribution of the aquatic biota.*
- *The present and historical condition of a water resource, its sensitivity and importance and its potential for restoration are all factors that need to be taken into account in deriving the future management class and related Resource Quality Objectives.*

The Act also makes provision for a "Reserve": a particular water quality and quantity to be set aside to protect the ecological functioning of aquatic ecosystems before water uses such as industry or agriculture can be authorised (Figure 1).”

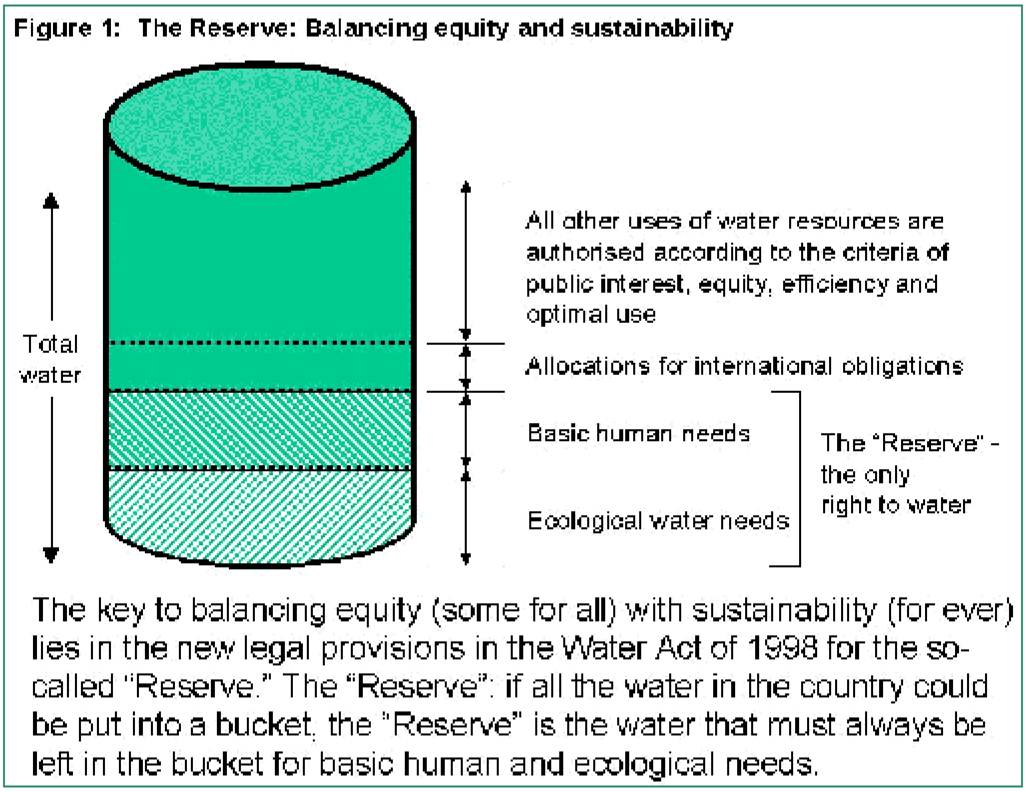


Figure 1: The Reserve: Balancing equity and sustainability

The key to balancing equity (some for all) with sustainability (for ever) lies in the new legal provisions in the Water Act of 1998 for the so-called "Reserve." The "Reserve": if all the water in the country could be put into a bucket, the "Reserve" is the water that must always be left in the bucket for basic human and ecological needs.

Figure 17 – Schematic representation of the South African concept of a "reserve" (Figure 1 in South African Wetlands Conservation Program, 1999)

A schematic of the methodology (as applied to estuaries) is provided in Figure 18 below. Within in the documents reviewed, acronyms are abundant. BHN refers to basic human needs and RQOs are resource quality objectives - specific objectives for the entire ecosystem including fresh water, water quality, vegetation, fish and other biota. RQOs encompass both quantity and quality aspects of any ecosystem component.

Accompanying annotation informs the reader that step 2b is only applicable to rivers and not to estuaries.

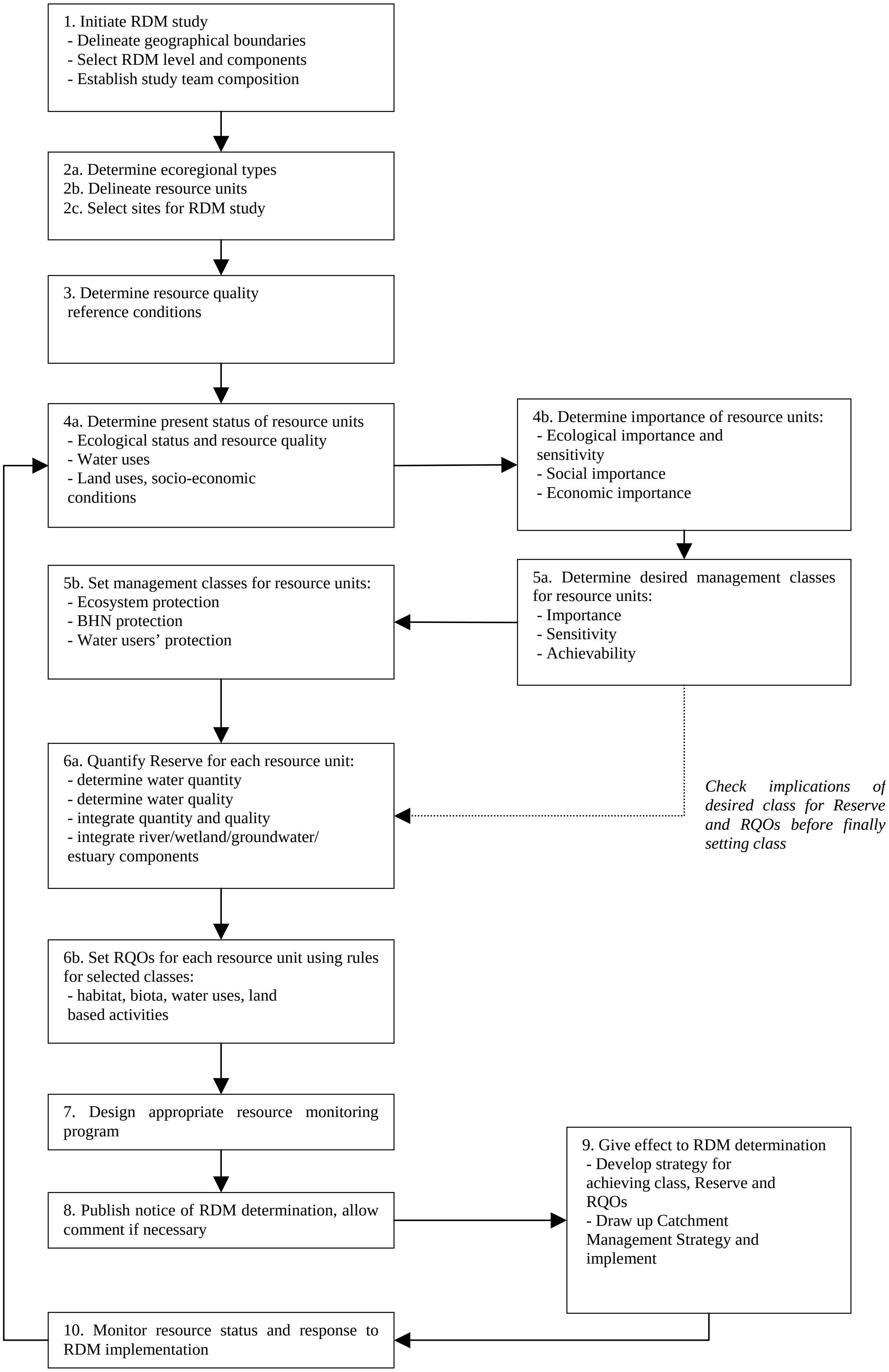


Figure 18: Generic procedure for determination of Resource Directed Measures for aquatic ecosystems

A particular contribution that these detailed South African studies have made is the careful assembly and examination of published information regarding the salinity tolerance of certain types of aquatic vegetation. These investigations incorporate both laboratory experiments and field assessments of vegetation response including some species prevalent in Australia. The most important contributions are contained in Adams and Bate (undated) volumes 1 and 2.

United States of America

US History

The allocation and distribution of fresh water flow is a major environmental and economic issue in the United States that spans at least 23 years. It is impossible in the course of a project of this nature to provide a complete summary of all environmental flow investigations in the United States. Here, we provide an overview of activity in the USA with a focus on specific relevant studies.

In the United States, it has long been identified that estuaries should be recognised in water policy decisions as high value resources for food production, recreation, aesthetics, and urban and industrial development.

The earliest reference that we could find was a document by Lambert and Fruh (1978) in which they investigated the fresh water inflow requirements for Corpus Christi Bay, Texas. Their methodology is summarised in Figure 19 below.

In September 1980, a National Symposium on Fresh water Inflow to Estuaries (Cross and Williams, 1981) was held in San Antonio, Texas (sponsored by the National Coastal Ecosystems Team, US Fish and Wildlife Service, Department of the Interior), during which 76 scientific and management papers were presented. The papers dealt with the institutional and management problems of providing fresh water inflow to estuaries, documented the ecological effects in estuaries of modifying fresh water inflow, and suggested measures to bring fresh water inflow into water planning.

Since that time, several detailed ecological studies focusing on the effects of freshwater inflows to Texas bays and estuaries have been undertaken. From these, Longley (1994) identified thirteen different functions of freshwater inflows. Longley also examined the wider scientific literature and developed a list of fifteen impacts attributable to reduced inflows. The most significant impacts identified were:

- increased salinities and vertical stratification of the water column,

- penetration of the salt-wedge farther upstream allowing intrusion of predators and parasites of estuarine species, and increased intrusion into groundwater and surface water resources
- increased frequency of benthic anaerobic conditions and decreased inputs of nutrient and organic matter used by estuarine species,
- loss of characteristic species and economically important seafood harvests, and
- increases in erosion of delta areas resulting from the reduction of sediment flux.

Particularly within the U.S. states of Texas and Florida, freshwater inflow is an essential factor influencing biological productivity of estuarine areas. Powell and Matsumoto (1994) quoted a considerable range of studies which have showed that freshwater inflow is an essential factor influencing biological productivity of estuarine areas as diverse as the Black Sea, the Caspian Sea, the Nile Delta, the Gulf of St. Lawrence, Chesapeake Bay, and the bays and estuaries of the Gulf of Mexico.

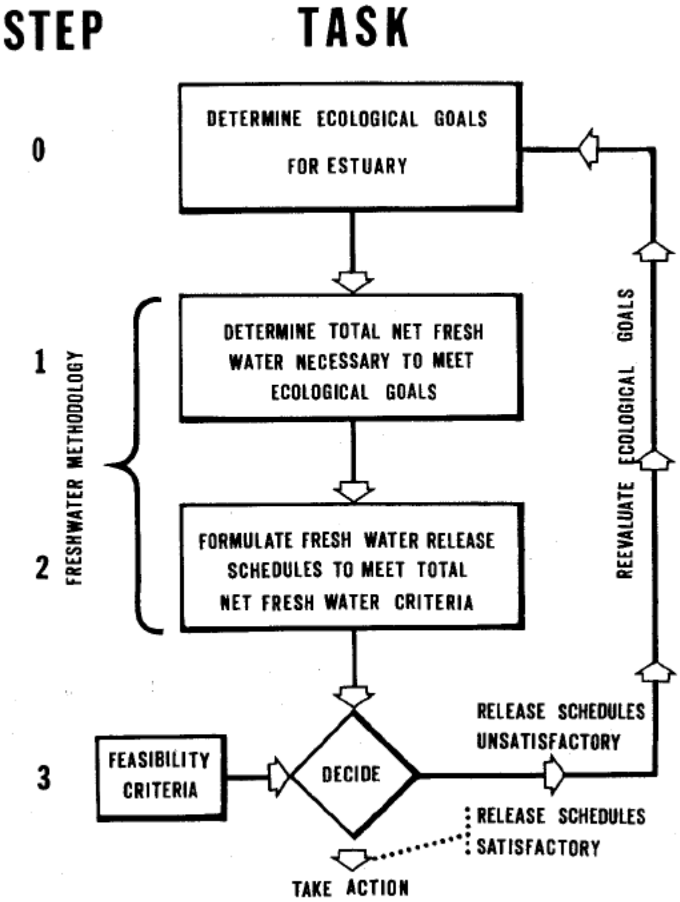


Figure 19: Procedure for determination of fresh water requirements of estuaries by Lambert and Fruh (1978)

The significance of fresh water flows to the fisheries of Texas estuaries has resulted in detailed studies of the relationship between fresh water flow and biological productivity.

Using the results of these studies, sophisticated numerical tools to optimise fish harvest in terms of fresh water supply from a number of tributaries of the estuary (Bao and Mays, 1994a and 1994b).

US National Estuary Program

The National Estuary Program or NEP (http://www.epa.gov/owow/estuaries/nep.htm) was established in 1987 by amendments to the Clean Water Act to identify, restore, and protect nationally significant estuaries of the United States. Unlike traditional regulatory approaches to environmental protection, the NEP targets a broad range of issues and engages local communities in the process. The program focuses not just on improving water quality in an estuary, but on maintaining the integrity of the whole system – its chemical, physical, and biological properties, as well as its economic, recreational, and aesthetic values (EPA Office of Water, 2000a).

The Environmental Protection Agency (EPA) administers the NEP. Each NEP is made up of representatives from federal, state and local government agencies responsible for managing the estuary's resources, as well as members of the community. These stakeholders work together to identify problems in the estuary, develop specific actions to address those problems, and create and implement a formal management plan to restore and protect the estuary.

Most individual estuary NEP's choose a management framework that includes a Management Committee to oversee routine operation of the program; a Policy Committee made up of high–level representatives from federal, state, and local government agencies; a Technical Advisory Committee to guide technical decisions; and a Citizens Advisory Committee to represent the interests of estuary user–groups and the public. Together, the committees develop a Comprehensive Conservation and Management Plan (CCMP) for protecting the estuary and its resources. The objective of each NEP is to create and implement a CCMP that addresses the whole range of environmental problems facing the estuary, as well as the economic and social values of the estuary (EPA Office of Water, 2000a).

Please note that many of the largest estuaries in the USA have not been included within this program. (Where possible, brief descriptions of their programs are provided in sections below.) Twenty–eight estuary programs have been established so far (EPA Office of Water, 2000b):

- Albemarle–Pamlico Sounds, North Carolina (http://h2o.enr.state.nc.us/nep/default.htm)

- Barataria–Terrebonne Estuarine Complex, Louisiana (http://www.btnep.org/)
- Barnegat Bay, New Jersey (http://www.bbep.org/)
- Buzzards Bay, Massachusetts (http://www.buzzardsbay.org/)
- Casco Bay, Maine (http://www.cascobay.usm.maine.edu/)
- Charlotte Harbor, Florida (http://www.charlotteharbornep.com/)
- (Lower) Columbia River Estuary, Oregon and Washington
- Corpus Christi Bay, Texas
- Delaware Estuary, Delaware, New Jersey, and Pennsylvania
- Delaware Inland Bays, Delaware
- Galveston Bay, Texas
- Indian River Lagoon, Florida
- Long Island Sound, New York and Connecticut (http://www.epa.gov/region01/eco/lis/)
- Maryland Coastal Bays, Maryland
- Massachusetts Bays, Massachusetts
- Mobile Bay, Alabama
- Morro Bay, California
- Narragansett Bay, Rhode Island
- New Hampshire Estuaries, New Hampshire
- New York–New Jersey Harbor (Harbor Estuary Program),New York and New Jersey
- Peconic Bay, New York
- Puget Sound, Washington
- San Francisco Estuary, California
- San Juan Bay, Puerto Rico
- Santa Monica Bay, California
- Sarasota Bay, Florida
- Tampa Bay, Florida
- Tillamook Bay, Oregon

The watershed (catchment) areas draining to each estuary shown in Figure 20:

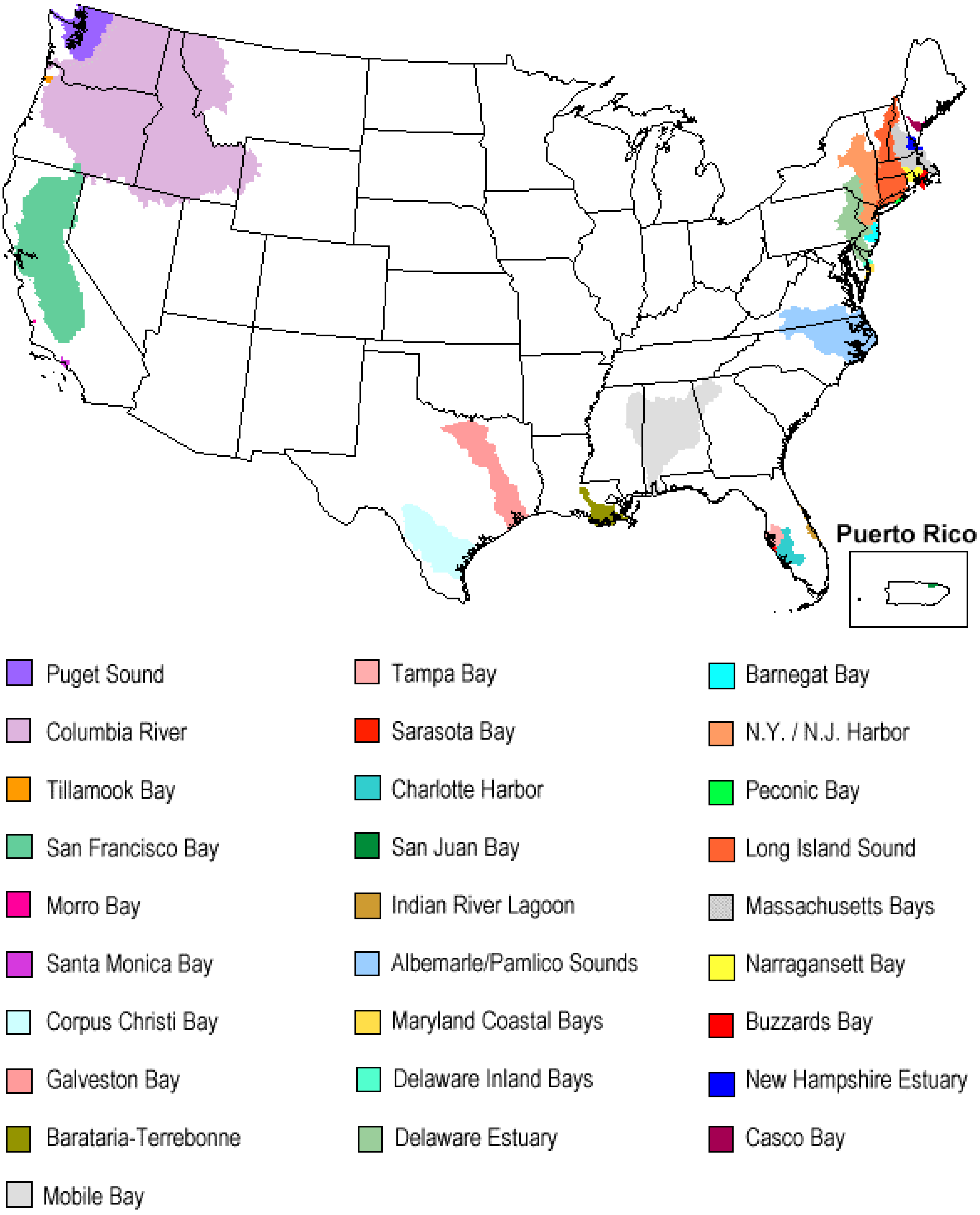


Figure 20: Catchment areas draining to estuaries in the US National Estuary Program (from EPA Office of Water, 2000d)

Based on brief discussions with US bodies, environmental flows are a major issue in all but a few of these estuaries. Of the 28 estuaries in the NEP, environmental flows are not a significant issue or have not been studied in Buzzards Bay (Costa, 2000), Casco Bay (Bayley–Smith, 2000), Long Island Sound (Tedesco, 2000). However, concerns were raised with dams or other obstructions restricting access for anadromous fish by Costa (2000) and

Tedesco (2000) in their particular estuaries. Costa (2000) also identified streamflow isues in relation to inputs of pesticides or nutrients causing environmental degradation, and in well withdrawals for agriculture causing streamflow reductions. (Stefanski, 2000) attributed fisheries decline in Albemarle–Pamlico Sounds, North Carolina to a variety of factors including habitat loss, physical damage, natural events and cycles, excessive harvest pressure, changes in stream flows, and water quality degradation. However, overfishing is believed to be a major cause of declines in catch.

Water flow alterations are a key management issue in Charlotte Harbor, with one of the three Priority Problems in the National Estuary Program identified as “hydrologic alterations – adverse changes to amounts, locations, and timing of fresh water flows, the hydrologic function of floodplain systems, and natural river flows”, and a goal of the NEP being to “provide the proper fresh water inflow to the estuary to ensure a balanced and productive ecosystem” (United States Environmental Protection Agency, 1999).

With reference to Charlotte Harbour, Florida, Corbett (2000) stated “*From what I've seen, there are no set methods of determining the minimum flows needed to an estuary.*” Corbett also noted the use of an indicator species (Vallisneria americana) to determine the overall health of the Caloosahatchee River estuary. This species is especially sensitive to salinity and its growth steadily declines with increasing salinity until approximately 8-9ppt. It will survive in waters with 11-13 ppt, but its density declines when salinity is over 10ppt. It was determined that fresh water flows between 400-600 cubic feet per second from upstream keep the salinity near healthy levels for this species of seagrass at a designated point.

The Environmental Monitoring and Assessment Program of the US EPA no longer uses the term “habitat indicator”, preferring “abiotic condition indicator” and defining a “condition indicator” (itself a replacement for the term “environmental indicator”) as: “a characteristic of the environment that provides quantitative estimates of the state of ecological resources and is conceptually tied to a value” (EPA, 2000). A condition indicator can be abiotic or biotic. Biotic condition indicators were formerly known as response indicators. An “indicator” itself was defined as “in biology, an organism, species, or community whose characteristics show the presence of specific environmental conditions, good or bad”.

However, the US EPA recognises that a common habitat indicator (abiotic condition indicator) for use in estuaries is salinity. Salinity is well–defined, measurable, has ecological significance, and encompasses a number of estuarine properties and processes (Jassby et al, 1995). The data collection and analysis undertaken by Jassby *et al.* (1995) is so large that it is discussed in some detail below. It is demonstrated that temporal variations in fresh water inflow can thus lead to temporal variations in the salinity field and hence changing habitat conditions (Jassby et al, 1995). An estuary’s physical response to fluctuations in fresh water input can be related to some ‘habitat indicator” (Jassby et al, 1995). A habitat indicator is a “physical attribute measured to characterise conditions as necessary to support an organism, population, or community in the absence of pollutants” (Messer, 1990).

Chesapeake Bay

Chesapeake Bay, the largest estuary in the United States, is not in the NEP as it is protected under its own federally mandated program, separate but related to the NEP. In fact, the approach and methods of the NEP developed from the foundation laid by earlier efforts to protect Chesapeake Bay (EPA Office of Water, 2000a).

Chesapeake Bay was the first estuary in the United States to be targeted for restoration and protection. In 1983 the Governors of Maryland, Virginia and Pennsylvania, the Mayor of the District of Columbia, and the EPA Administrator signed the Chesapeake Bay Agreement committing their states and the District of Columbia to prepare plans for protecting and improving water quality and living resources in the Chesapeake Bay. The Chesapeake Bay Program evolved as the institutional mechanism to restore the Bay and meet the goals of the Chesapeake Bay Agreements. The Program guides and coordinates multi–state and multi–agency activities.

Mississippi

The Mississippi Department of Environmental Quality contracted Harza (1995) to determine the instream flow needs of the Pascagoula River, including the estuarine region. On this river, water is extracted by Chevron to refine crude oil into gasoline.

Numerical modelling was undertaken using the US Environmental Protection Agency (USEPA) Water Quality Analysis Simulation Program (WASP5) which consists of two stand–alone computer programs. Hydrodynamic modelling was undertaken using the Dynamic Estuary Model Hydrodynamics Program (DYNHYD5) to simulate flows and heads in the study area and to generate output files describing these condition at specific times and locations. Harza (1995) then used the DYNHYD5 output files as input to the water quality model TOX15 to simulate parameters such as salinities, dissolved oxygen and toxins. The instream flow need was determined on the basis of upstream salt water migration under a variety of flow and tidal conditions (Riecke, 2000).

The models were applied to simulate conditions under two extreme conditions (that would most likely lead to upstream salt migration):

1. the established minimum flow, $7dayQ_{10}$[3], coinciding with high tides
2. the lowest recorded flow (which occurred in 1963) coinciding with high tides

The conclusion of the study was that under both of these conditions, Chevron could withdraw 25 million gallons/day (the current actual withdrawal rate, equal to 1.10 m^3/s) or 100 million gallons/day (the current permitted withdrawal rate, equal to 4.38 m^3/s) without affecting the upstream migration of the salt water wedge. Physically, this occurs because at the withdrawal point the migration of saltwater is primarily controlled by the tides in the Gulf of Mexico due to the lack of slope or gradient in the river (Riecke, 2000).

The Mississippi Department of Wildlife, Fisheries and Parks then focussed on some biological assessments, to determine the ecosystem response to changing flows. To biologically detect changes in salinity amounts and positions it was decided to sample barnacles and other benthic invertebrates using artificial substrate assemblies. The endangered turtle would merely move in response to flows, and sampling of marsh vegetation was also considered (Riecke, 2000).

The Gulf Coast Research Laboratory (GCRL) are currently completing more detailed biological evaluations.

California

California has a particularly complex legal and regulatory framework for water allocation. The State Water Resources Control Board administers California's water rights system, a mix of riparian, appropriative and public trust doctrines (Kimmerer and Schubel, 1994).

Water allocation studies and debates have been going on for decades, yet it is still difficult in California to make equitable allocations of scarce water supplies to farms, cities and the environment. To assist, in 1995 the state and federal governments joined to form the CALFED Bay/Delta Program to develop the basis for water allocation, restore the environment, increase flood protection and improve water quality. Most studies are still mostly in the planning mode, although several tens of millions of dollars have been spent on restoration projects, research and monitoring and planning (Brown, 2000).

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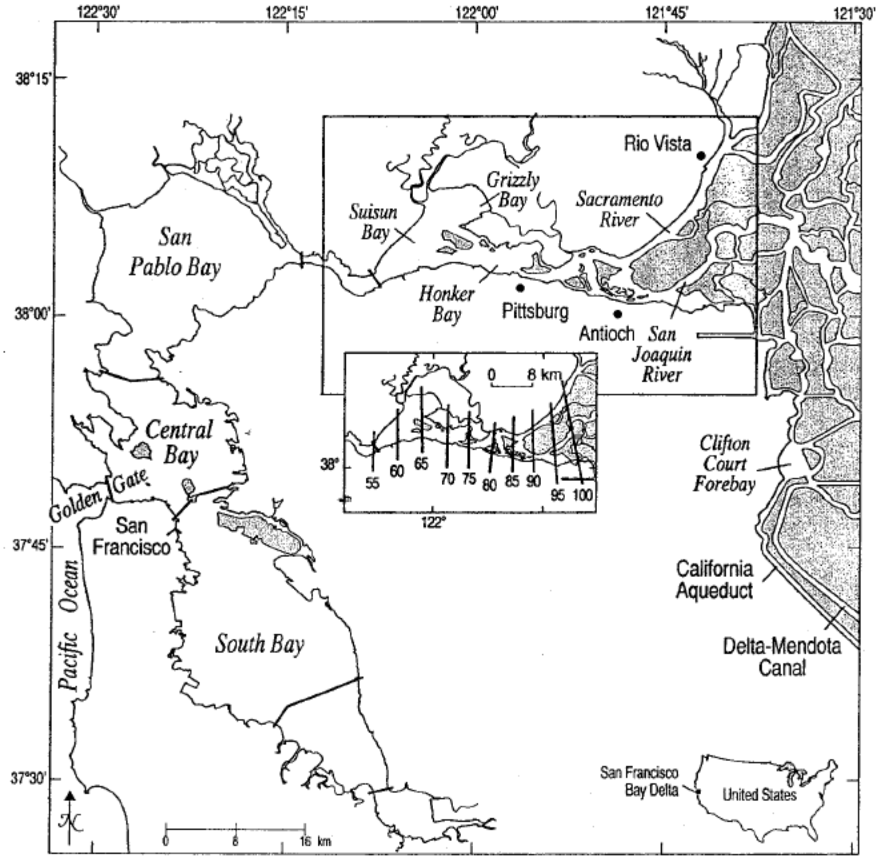
[3] $7dayQ_{10}$ is the average streamflow over 7 consecutive days that may be expected to be reached as an annual minimum no more frequently than once every ten years.

Much of the focus of investigations has been the San Francisco Bay and Sacramento–San Joaquin Delta estuary (known as the Bay–Delta). Kimmerer and Schubel (1994) and Jassby et al (1995) have described the management of fresh water flows into the Bay Delta. Most of the flow into the estuary arrives via the Sacramento and San Joaquin Rivers through an extensive delta system (Figure 21). The region upstream of the confluence of these rivers is known as the "delta", the portion downstream known as San Francisco Bay. The distance from the confluence of the Sacramento and San Joaquin Rivers to the Golden Gate Bridge is approximately 80 km as shown by the inset in Figure 21.



Map of San Francisco Bay/Sacramento-San Joaquin Delta Estuary. The portion of the estuary upstream of the confluence of the Sacramento and San Joaquin rivers is known as the "Delta"; the portion downstream of the confluence, called "San Francisco Bay", is composed of four main subembayments: Suisun, San Pablo, Central, and South bays. Grizzly and Honker bays, in turn, are subembayments of Suisun Bay. *Inset*, Suisun Bay and the western portion of the Delta, with lines positioned at nominal distances (in kilometres) from the Golden Gate along the axis of the estuary.

Figure 21: San Francisco Bay and Sacramento–San Joaquin Delta estuary (from Jassby et al, 1995)

Since 1977, about half of the total possible flow into the estuary has been diverted, about 80% of this for irrigation of agricultural crops, and the rest mainly for municipal and industrial use.

Effective management of the estuary's biological resources required a sensitive indicator of their response to fresh water inflow. As a result of workshops held as a component of the San Francisco Estuary Project, a cross section of the scientific community working on the Bay–delta chose a variable, correlated with fresh water flow, to set required flow standards (as an index of estuarine conditions). The findings are reported in Jassby *et al.* (1995).

It must be noted that large data collection programs have been completed within this estuarine system over the period 1968 to 1991. This allowed importance correlations between fresh water inflow and various biological resources to be made.

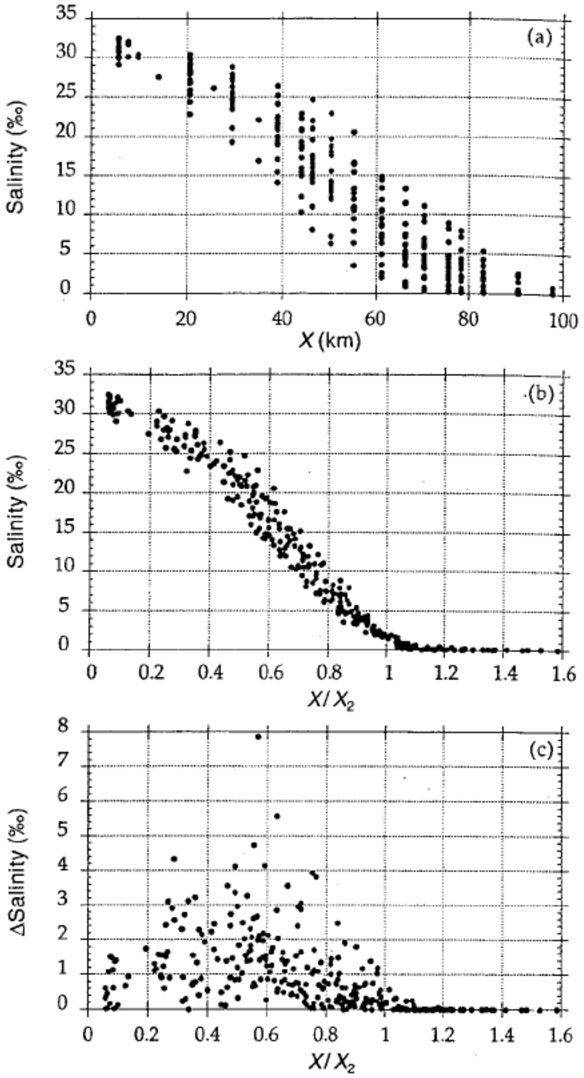
Correlation of salinity with fresh water inflow.

The variable chosen was the longitudinal position in the estuary of a salinity of 2 ppt measured 1 m from the bottom of the water column, averaged over a suitable time period longer than a day, and denoted as X_2. The X_2 location moves primarily in response to flow (secondarily depending on tidal level).

The X_2 index was chosen because:

- it was easy and accurate to measure (much easier and more accurate than measuring the fresh water outflow from the delta, with its tidal influences, many tributaries and extractive water use);
- it was easy to understand
- it was manageable, depending primarily on fresh water flow;
- it was correlated with habitat conditions in the estuary;
- a useable historical database was produced;
- it was correlated with ecosystem responses; and
- it could be used as a policy variable to set standards for managing fresh water flow.

The first observation was that X_2 was a useful length scale for parameterising the spatial structure of the salt field, as shown by a series of vertical salinity profiles collected in the Bay–delta from 1990–1992 (Figure 22).



(a) Vertically averaged salinity vs. distance from the Golden Gate (*X*) along the axis of the estuary, based on salinity profiles collected from January 1990 through February 1992; (b) the same data as in (a), but distances from the Golden Gate are scaled by X_2; (c) bottom minus top salinity values for each vertical profile vs. distance from the Golden Gate, again scaled by X_2.

Figure 22: Depth–averaged salinity in the Bay–delta versus (a) distance from the Golden Gate Bridge, *X* and (b) X/X_2; in (c), bottom minus top salinity for each vertical profile is plotted against X/X_2 (from Jassby et al, 1995).

Figure 22b indicates how the salinity profile data in Figure 22a “collapses” (with only small scatter, probably due to tidal variation) about an equilibrium mean salinity distribution when plotted against the non–dimensional X/X_2. Thus, if X_2 is known, the depth–averaged salinity field can be derived at any longitudinal position in the estuary.

This observation was valid for all salinities less than 4 ppt, so an “X_1” or “X_3” would have been equally applicable. However, it was observed that X_2 marked the location of an estuarine turbidity maximum (see Section 5.2.7 on page 37). This is illustrated in Figure

22c, with strong stratification evident downstream of X_2 (that is, $X/X_2<1$), with little stratification upstream.

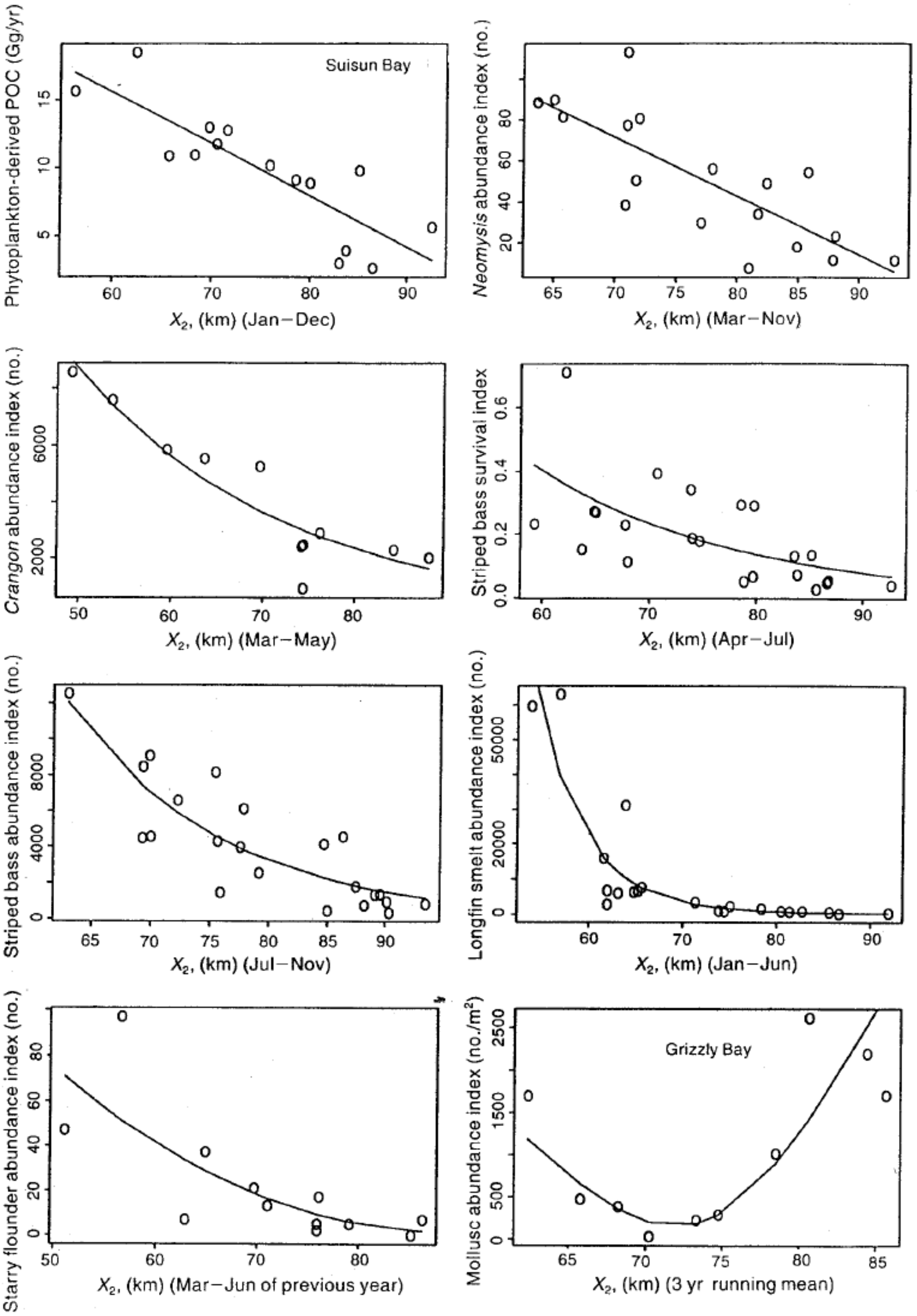
Correlation of salinity with biological variables.

The collapse of this data enabled the investigators to relate X_2 to time and the logarithm of fresh water inflow and thereby construct a linear model. This was compared with measurements and remarkably good correlations were obtained.

Some of the significant statistical relationships between the historical value of X_2 and common estuarine components (ecosystem variables), that were found at all trophic levels, included the following (over annual time scales):

- total input of organic carbon including in situ production
- supply of phytoplankton and phytoplankton–derived detritus from local production and river loading
- abundance of the mysid *Neomysis mercedis*
- abundance of the bay shrimp *Crangon franciscorum*
- abundance of longfin smelt
- abundance of starry flounder
- survival of striped bass from egg to young–of–the–year
- striped bass year class strength
- survival of salmon smolts on passage through the delta
- biomass of benthic macroinvertebrates (molluscs) in Suisun Bay

Note that the fish listed above include planktivorous, piscivorous and bottom–foraging fish. With the exception of mollusc biomass, all of the responses listed above were monotonic, with an increase in abundance, biomass or survival with decreasing X_2 (increasing flow), as shown in Figure 23. Note that mollusc response is a composite of fresh water species (that respond positively to increasing flow) and marine species (that respond negatively). However, it was argued that given the probable role of molluscs and other filter feeders in controlling or suppressing plankton, a reduced mollusc biomass may actually be desirable.



Relationships between various biological variables and X_2, the position of the 2‰ isohaline. ———; fitted values using the generalized linear models summarized in Table 2 (POC: particulate organic carbon). Months refer to averaging intervals.

Figure 23: Ecosystem response to changes in X_2 and flow

Note that the actual mechanisms by which various ecosystem components respond to flow are understood for only a few species. The monotonic increasing biological response (increasing population or survival rates) with increasing flow surprised a number of workshop participants, who expected response to level off at high flows. This belief arose from the expectation that the highest phytoplankton biomass in the upper estuary would occur at intermediate flows, maximising production at other trophic levels.

The monotonic increasing biological response with increasing flow also made setting standards for the estuary based on X_2 somewhat difficult, as there was no upper limit to the amount of flow that would benefit the estuary (thus it was not possible to say that a flow of N should be maintained for example). Standards therefore had to be set in the context of cost–benefit analyses, based on a valuation of the estuary.

However, the workshop consensus was that standards should be based on salinity as the most appropriate index of estuarine conditions, with a recommendation that an upstream limit on the X_2 index be used (the downstream limit unconstrained). Other recommendations included that:

- the development of salinity standards consider the potential importance of the amount and time scale of variability;
- the salinity distribution be continuously monitored (at least 6 stations at a 5 km spacing);
- seasonal salinity standards should be related to the existing water diversion and distribution system; and
- for each season, a matrix should be developed defining the relationship between estuarine organisms, communities, properties and processes; X_2; and fresh water inflow to the estuary.

A limitation of using X_2 as an index of the estuarine community’s response to net fresh water inflow in the Bay–delta was that it did not take account of the extractions or diversions of water within the estuary itself. These water exports were found to have a direct effect on population abundance independent of X_2.

This X_2 value may not have special ecological significance for other estuaries. However, it was believed that the concept of using a near–bottom isohaline position as a habitat indicator and for management purposes should be widely applicable.

Canada

The primary response to our enquiries with Canadian authorities came from Hydro-Québec. They have no requirements to maintain instream flow to estuaries but they did offer a method of comparing estuaries (described in Savard, 1997 and 1999). This appears to be a development of the method of Simmons (1955) with some simple box modelling.

United Kingdom

A significant document has been prepared in the United Kingdom by Binnie Black and Veatch, 1998 for WRc. Its objective is to provide a methodology whereby the minimum residual flow (MRF) to an estuary can be defined. The MRF is defined as the river flow at which licenced abstraction ceases.

Apart from the methodology (which is summarised below), this report makes the following key points:

- The assessment of environmental flows is more complex than for fluvial systems and that approaches for dealing with environmental flows for rivers cannot deal with this complexity.
- A risk assessment approach is recommended which should guide the estuary manager towards the required complexity of analysis method.
- Evidence gathered by consulting stakeholders suggests that mean residual flows cannot be reliably set on the basis of estuary type and known issues alone. Each United Kingdom estuary is unique, and results from one location cannot be transposed to another with any confidence.
- Use of computation models is essential to analyse the complex pressures on estuaries today.

Central to the approach is the use of decision matrices together with elements of risk assessment methodology. In this risk assessment terminology:

- a *hazard* is a situation with the potential to cause harm.
- a *risk* is an expression of the potential of a hazard to cause harm.

Risk can be expressed mathematically as:

$risk = likelihood \times impact$

where:

likelihood is the probability of the estuarine design standards being derogated, assessed by considering the estuary processes and uses and how close they are to the relevant standard; and, *impact* is the consequence of a hazard occurring.

Fresh water abstractions and their associated conditions can then be identified as a *hazard* to the estuarine processes and uses. These techniques can equally be applied to other hazards such as river quality or effluent load.

The report presents a ten stage process for assessing the fresh water needs of estuaries, these are as follows:

1. Review existing reports and check data availability

2. Classify estuary type and select estuary reaches

   The aim is to gain an initial understanding of the estuary dynamics. Four types of classification may be considered:
   - *Scale (size and importance);*
   - *Shape (geomorphology);*
   - *Stratification (using Simmons, 1955) ; and*
   - *Human intervention.*

   The estuary should be divided roughly into the main salinity zones: fresh water, brackish or saltwater. This can be achieved on the basis of salinity measurements, channel geomorphology or changes in ecology. Each zone should then be subdivided into reaches on the basis of major physical features, major changes in use, areas of nature conservation, and, areas of particular interest.

3. Determine external review, complete data and impact matrices.

   Form a check matrix of potential impacts. Determine how to involve external review bodies, such as an Estuary Management Group, in the matrix process. Every effort should be made to consult external bodies at an early stage.

   A data matrix can be used to record the existing types and availability of data and computational models.

   The impact matrix is to quantify the severity of risk from low estuarine fresh water flows on a scale from negligible (Score of 1) to Catastrophic (5).

4. For low impact uses and processes, use simple analysis methods.

   If there is low impact throughout the study area, the use of simple models or statistical techniques to determine the fresh water needs of the estuary should be considered. The study process may then move directly to the analysis stage.

5. Carry out preliminary analysis (OPTIONAL STAGE).

Preliminary analysis should be considered for major studies, where the cost of the preliminary model may not be significant; and where existing models may be quickly used to carry out preliminary analysis.

6. Review design standards and set out study standards.

   Design standards for the study should be determined for each critical use or process which may include: a water quality standard; minimum flows for fisheries; minimum levels for navigation; flows to avoid morphological instability; or, a "no impact" requirement for conservation purposes.

7. Complete risk matrix, seasonal variations and risk assessment.

   A likelihood matrix should be formed classifying likelihood from improbable (score of 1) to frequent (5). The risk matrix is formed by multiplying likelihood and impact.

   Seasonal variations may be incorporated at this stage.

8. For each use and reach, select appropriate analysis method.

   Select computational models of appropriate types and complexity. These should include: hydrodynamic (flow and level); quality (including salinity); morphological (including short term sediment movement); or ecological. Model complexity is selected on the basis of risk.

9. Rationalise and optimise model design.

   Model investigations for an estuary should be undertaken to minimise the duplication of model studies. Models which are able to address flow, quality, sediment and ecological issues should be preferred. Short-term expediency will probably end up costing more for the public in the end.

10. Cost modelling studies.

    The proposed analysis and computational modelling should then be costed. The model costing should include:

    - *realistic modelling costs;*
    - *adequate costs to cover essential data collection for calibration and verification;*
    - *adequate costs for project management; and,*
    - *an appropriate contingency.*

11. Consider joint funding of modelling, or simpler models.

    If the study costs are above the project budget, the following options should be considered:

- *Increasing the budget;*
- *Consideration of joint funding of the models by other organisations; or*
- *Model simplification.*

Note that cost-saving measures such as joint funding or simplication may well cost more due to additional project management expenses or lack of confidence in the results.

12. Set up modelling contracts.
    A detailed project definition and model specification should be drawn up, including:
    - *the scope of work;*
    - *background to the project;*
    - *model types to be used and the extent of modelling;*
    - *a detailed technical specification;*
    - *data collection needs; and*
    - *reporting requirements and deliverables.*

    The specification will need to be written to achieve definition of minimum fresh water flow needs for the estuary as well as assessment of likely hazards.

13. Carry out or manage modelling studies.

14. Analyse model results and set MRF.
    Setting the MRF may be an iterative process that needs to consider a range of stakeholders.

15. Post-project appraisal.
    On completion of the project, a post project appraisal should be carried out and include archiving of all field data and model results for future investigations.

Australia

Arthington Studies

Reports by Arthington (1998), Arthington and Zalucki (1998a) and Arthington et al (1998a,b) were produced as part of a LWRRDC sponsored research project entitled “Comparative Evaluation of Environmental Flow Assessment Techniques”. This project (GRU22) was undertaken between December 1996 and May 1998.

In Arthington and Zalucki (1998a), a review of environmental flow assessment techniques was given. The focus of this review was not just on in–stream fresh water requirements, but also the flow requirements of:

- the riparian zone
- floodplain wetlands
- estuaries and coasts

In the review, the assessment methods were grouped into sections, namely methods addressing flow requirements for:

- geomorphological purposes (Chapter 2);
- wetland, riparian and floodplain vegetation (Chapter 3);
- fresh water fish (Chapter 4);
- estuarine fish (Chapter 5); and
- aquatic invertebrates (Chapter 6)

A total of 38 Australian environmental flow studies were examined as part of the review, which covered approximately 31 rivers or catchments. Of the studies, the majority were in New South Wales, Queensland and Victoria (12 investigations in each State), with a single study in Victoria and a single study in Western Australia.

Arthington and Zalucki (1998b) have compiled papers and reviews presented at a one–day Forum investigating approaches to assessing and providing environmental flows.

Arthington and Lloyd (1998) have trialed the Building Block Methodology (obtained from South Africa) for assessing environmental flow requirements on the Logan River, Queensland. In a similar fashion to Jassby *et al.* (1995), Loneragan and Bunn (1999) have shown increasing prawn and fish catches in the Logan River with increasing fresh water inflow.

Hydro-Electric Corporation Studies

The Hydro–Electric Corporation in Tasmania has recently funded two studies into the environmental impacts downstream of hydro–electric power stations (Hydro–Electric Corporation, 2000).

In the first study, the effects of different flows (no release, steady flows and marked fluctuations in flow) on the hydrology, water chemistry and plant and animal life in streams below hydro–electric power stations were investigated. These parameters in rivers regulated by hydro–electric schemes were compared with the same parameters in reaches of unregulated streams of similar size. The objective of the project was to develop guidelines on the management of hydro–electric stations to help mitigate downstream environmental effects. Both Tasmanian and Mainland Australian hydro–electric schemes were investigated. This study was also funded by the LWRRDC (project HEC1, “Impact of Critical Flow Events on Biota in Regulated Streams”).

The second study was similar, but concerned the effect of extreme events, such as major releases over spillways, on the river biology and environment downstream. The aim of this study was to quantify the variation in habitat area of various fish and invertebrates with water flow at a number of sensitive locations.

According to Bluhdorn (2000), the combined results of these two studies were reported in Davies et al (1999); the report did not consider any estuaries, and, to date, the Hydro–Electric Corporation has not carried out any studies of estuarine processes with reference to environmental flows. However, flows are maintained in the Derwent system to ensure that the estuarine salt–wedge remains downstream of Hobart's water supply intake.

Davies and Kalish (1994) undertook a study pertaining specifically to environmental flows in the Upper Derwent Estuary. Water quality parameters and current velocities were measured in depth profiles at a series of sampling stations throughout the upper estuary of the Derwent River in Tasmania. A two-layer one-dimensional box model was set up to examine the relationships between water quality, estuarine mixing and river flows.

Snapshot surveys were carried out every five to six weeks, with each survey consisting of measurement of salinity, temperature and dissolved oxygen, at up to 12 stations along the estuary. The position of the upper limit (toe) of the salt wedge along the estuary was measured relative to a reference location. Tidal surveys were also performed, and mean daily flow and discharge data were obtained from the Tasmanian Hydro Electric Commission and the Tasmanian Rivers and Water Supply Commission for the periods 1946-55, and 1979-89.

The study found that there was a negative relationship between salinity and oxygen concentration (high salinity meant low oxygen concentration). High oxygen conditions were temporarily restored in the estuary following a major flood that occurred in 1988, but a few months later, the oxygen levels had decreased again. This showed that the flushing effect of the high-volume flood was responsible for removing the oxygen debt from the estuary. The study also determined a relationship between river discharge and the location of the salt wedge in the estuary. It found that there was a critical discharge required to displace the salt wedge from its reference location (75 m^3/s), and when the discharge reaches 150 m^3/s, the salt wedge is displaced by 18 km. Another finding was that a flood of 200-300 m^3/s was required for five days to improve the water quality in the upper estuary (i.e. restore high oxygen levels) for 30 days.

Flow exceedance curves were produced using the flow and discharge data and it was found that an overall decrease of 70% in higher discharge frequencies due to the regulatory effects is apparent, especially for the flood events between 200 and 500 m^3/s. This means that the frequency of flows sufficient to flush the estuary has decreased. The study suggests that estuarine water quality could be improved by means of flushing flows which aim to emulate the mean flood frequencies that occurred prior to the river regulation.

Richmond River, New South Wales

As part of a program to review water licences in the catchment of the Richmond River by the Department of Land and Water Conservation, New South Wales, the use of fresh water by farmers adjacent to the Richmond River estuary was examined.

Peirson et al (1999) carried out a detailed assessment of the impacts of extracting fresh water from below the tidal limit on the ecology of the Richmond River estuary (Figure 24). The catchment consists of three major river arms – the Richmond River, the Wilsons River and Bungawalbin Creek.

Three key dependencies were recognised:

1. Estuarine ecology on the saline structure;
2. Estuarine saline structure on antecendent fresh water inflows; and,
3. Fresh water inflow on the climatic cycles.

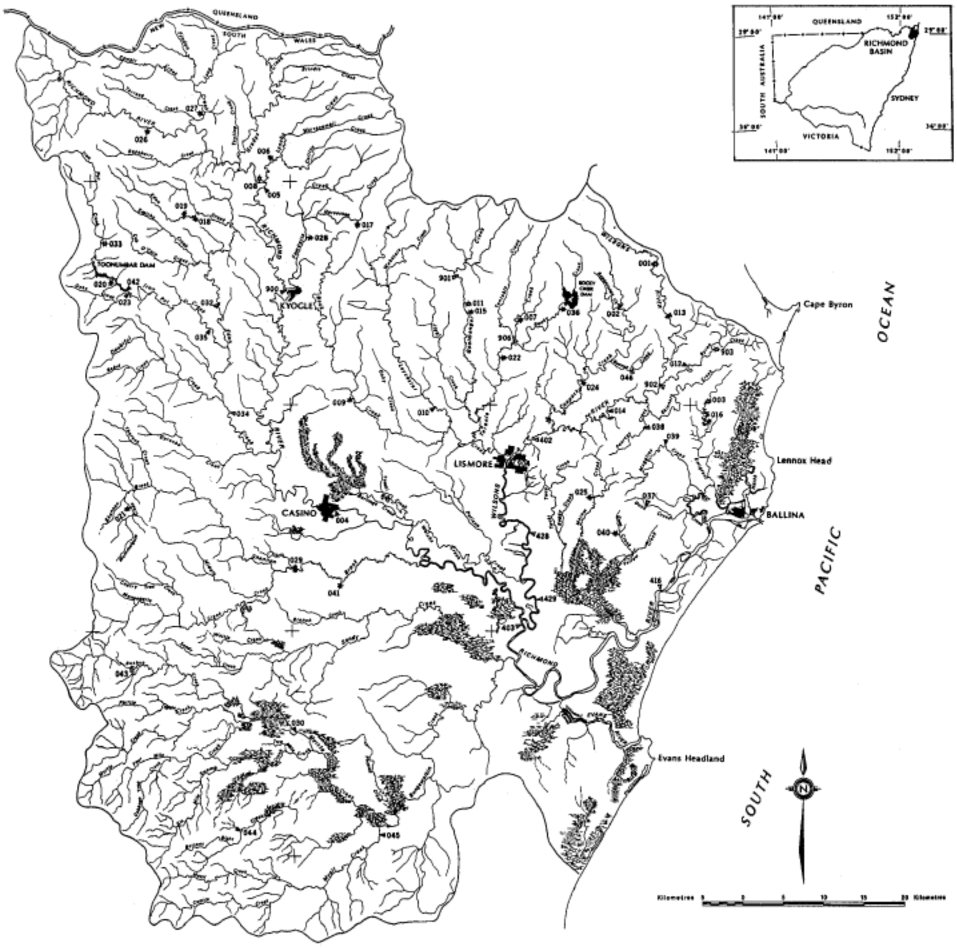


Figure 24 – Richmond River Catchment, New South Wales (Peirson et al 1999)

These three dependencies formed the framework for the investigation which involved:

1. Development of a rainfall/runoff model for the upstream catchments.

   A hydrological model was developed using daily streamflow records extending back to the 1940s as well as daily rainfall records extending back to 1800s. A saturated overland flow model (AWBM, Boughton 1993, Boughton and Carrol 1993) was used to generate the daily streamflow at the tidal limits of the estuary and this provided a good reproduction for periods of low fresh water inflow. An example of the calculated river flow in response to rainfall is shown in Figure 25 below.

   By selecting the driest period on record for special investigation, the hydrological model was used to investigate the impact of drought over a 100 year period.

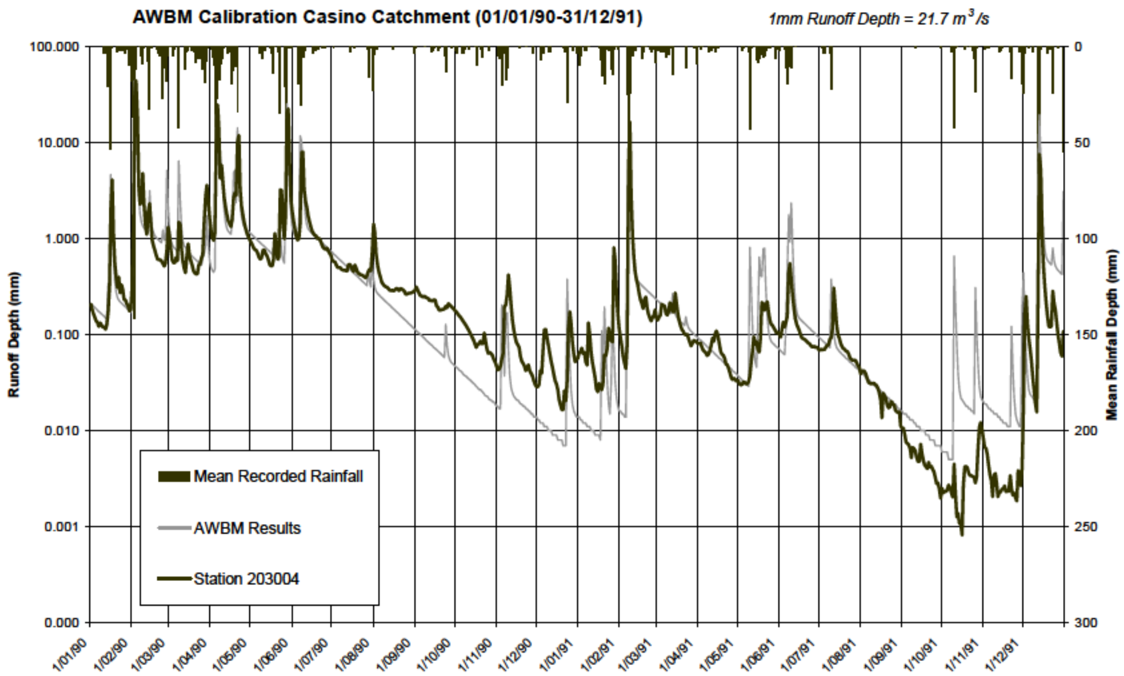


Figure 25 – Casino catchment rainfall and fresh water inflow to the Richmond River estuary during 1990-1991. Note that flow changes over 5 decades during just a two year period.

2. Development of a numerical model of the estuary capable of reproducing short and long-term changes in the longitudinal distribution of salinity.
   A hydrodynamic model (RMA-2, King, 1996) was established, calibrated and verified to replicate recorded tide levels, discharges and lags through the Richmond River estuary.

   A water quality model (RMA-11, King, 1996) was established, calibrated and verified to model the movement of salt within the estuary in response to fresh water flushing and tidal mixing for a period of over 50 years. Sample results are shown in Figure 26 below.

   The driest period on record occurred in the early 1900s on this catchment. Available rainfall data was used to examine saline structure during this very dry period. Salinity intrusion was similar to that experienced during the 1940s and therefore the behaviour observed over a 50 year period could be expected to represent behaviour over a period approaching 150 years.

   For comparison, salt concentrations through the entire estuary were estimated using the model system for the same 50 year period with appropriate modifications to the fresh water inflows, fresh water extractions from the estuary and changes to sea level.

It is important to note that it is long periods of sustained low fresh water inflow that determine the inland excursion of saline waters. During periods of low fresh water inflow, salinity diffuses landward towards the tidal limit gradually reducing the volume of fresh water immediately below the head of the estuary.

Field measurements had shown that during dry periods, the Richmond River estuary (total length 100km from mouth to tidal limit) was vertically homogenous and that tidal excursions were approximately 5km. The vertical homogenity and simple channel structure permitted the use of a one-dimensional numerical model which was carefully calibrated and verified prior to application. For existing conditions, it was shown that the 0.2ppt isohaline fluctuates from between 0 and 70km from the mouth with intrusions greater than 60km occuring once or twice per decade. Figure 15.4 shows the simulated behaviour or the period 1940 to 1997. The behaviour is highly unsteady.

3. Ecological risk analysis

This component was developed from earlier work by Bishop (1995) within the Hastings River estuary. Biota inhabit estuarine environments with varying degrees of tolerance to fresh and saline waters. During the Richmond River investigation (Peirson et al., 1999), considerable effort was made to establish likely threshold salinity impacts for representative fresh water biota. Susceptability was envisaged due to three major mechanisms:

- *Direct physiological stress;*
- *Competition with more salt-tolerant flora or fauna; and,*
- *Behavioural (avoidance of waters with high salinity).*

Estuarine ecosystems have a vast number of biotic (living) and abiotic (non-living) components and linkages. It is, therefore, never possible to make meaningful predictions concerning ecosystem health by considering just one facet of the ecosystem. Assessment must attempt to account for the potentially high level of ecosystem complexity. Issues to be considered must include at least:

- *The relative conservation values of different regions within an estuary;*
- *The vunerability of different species to changes in salinity; and,*
- *The changes in available habitat of given species in response to increased saltwater intrusion.*

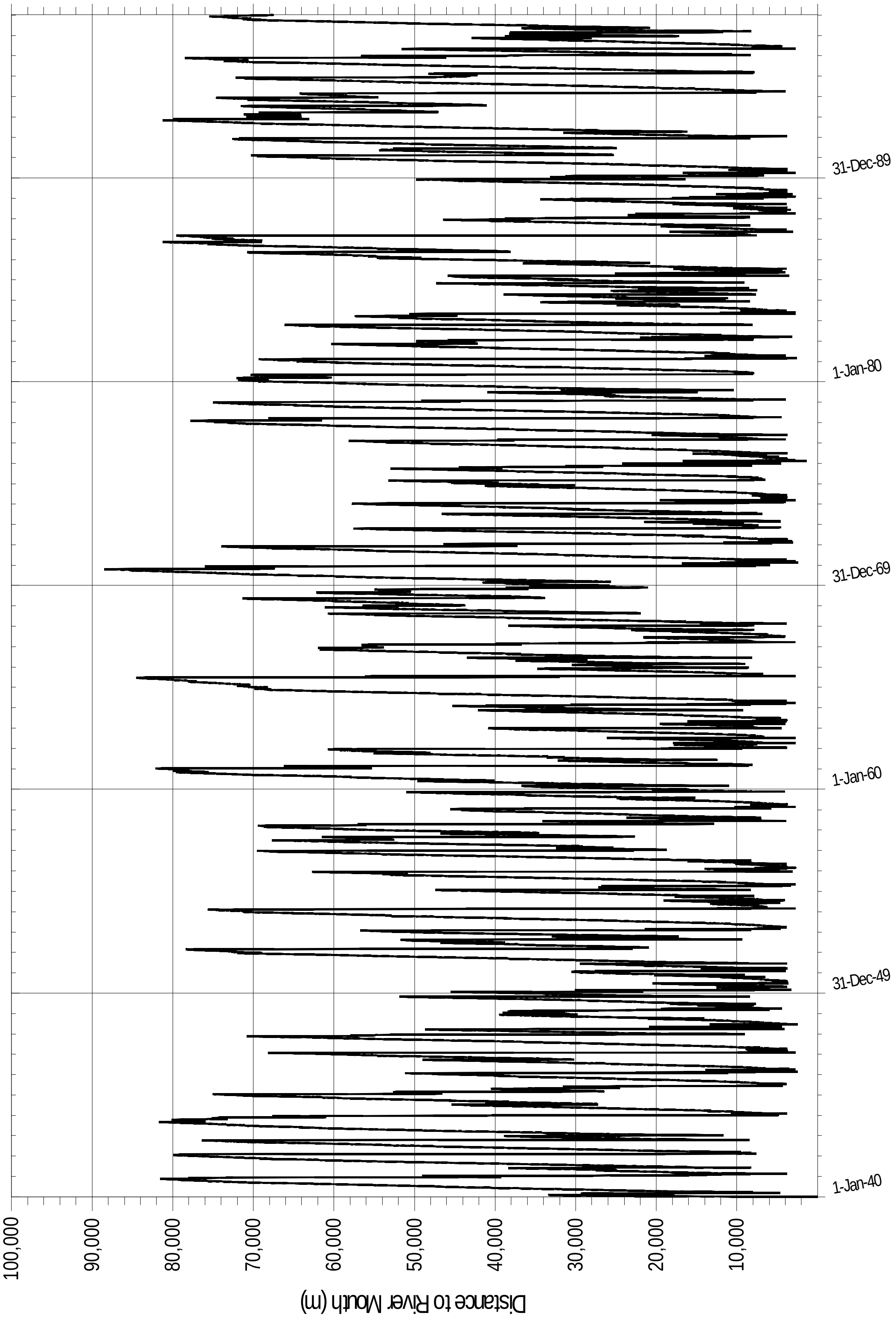


Figure 26 – Model predicted 0.2psu isohaline movement within the Richmond River, 1940 to 1997. Note the excursions of saline water of over 80km during this period.

During the Richmond River investigation, a number of species with similar salinity response characteristics were grouped together and weightings were applied to each group according to the range of species represented and their conservation value.

A major difficulty in habitat analysis is assigning relative values to different components of such complex systems. The methodology used during the Richmond River investigation was able to identify those areas at greatest risk from increased water extraction and to quantify thresholds of significant increase in risk with increasing water extraction.

Risk was quantified by a risk index which was the sum of weighted scores across all ecosystem facets.

Given the complexity of such analysis, other approaches may be possible but this approach is relatively simple and proved effective during the Richmond River investigation.

A desktop identification of the salinity-exposure characteristics (salinity concentration and duration) which best typify transition conditions where fresh water biota would be replaced by more salt-tolerant species was undertaken.

For comparison of fresh water extraction levels, a risk index was composed of a weighted score which was composed as follows:

- *The ecology was assumed to be multifaceted and the primary influence on each facet was changes in salinity.*
- *A facet was related to an important threshold in salinity.*
- *Key plants, fish and animals were selected as representative ecological components within the estuary and their tolerance levels to salinity were related to a specified facet.*
- *Each facet was weighted according to the number of components related to it and then multiplied by a risk weighting according to the level of perceived risk.*
- *The weighted facet scores were summed to obtain the overall risk index.*

The system was effective in distinguishing those arms of the estuary at greatest risk from increased fresh water extraction (Bungawalbin Creek) and other arms that exhibited acceptable levels of risk at current levels.

More recently, Bishop *et al.* (2001) have extended this work to the consideration of environmental flows from a major dam storage a short distance upstream of the Emigrant Creek estuary in north-eastern NSW.