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Determination and implementation of environmental water requirements for estuaries

Janine Adams

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Determination and implementation of environmental water requirements for estuaries

Janine Adams

Contents

Foreword

The importance of water management for the wise use of wetlands has been a key theme in the Resolutions and guidance adopted by the Ramsar Convention, as well as being highlighted in the original text of the Convention itself. Following the adoption of Resolution VI.23 (*Ramsar and Water*) in 1996, Ramsar's suite of water-related guidance has been steadily expanded, and it has been brought together in the 4th edition of Ramsar Handbooks 8 (Framework for the Convention's water-related guidance), 9 (River basin management), 10 (Water allocation and management), 11 (Managing groundwater), and 12 (Coastal management).

The present report, which provides a review of methods for determination and implementation of environmental water requirements for estuarine wetland ecosystems, was prepared in response to a request from the Convention's Contracting Parties to the Scientific and Technical Review Panel (STRP) which is reflected in Task 3.3 of the STRP Work Plan for 2003-2005 for the Panel's expert working group on Water Resource Management.

This report complements the adopted guidelines for the allocation and management of water for maintaining the ecological functions of wetlands (Resolution VIII.1, 2002), and focuses on a specific wetland type, namely estuaries. The ecological functioning of estuaries depends on inflows from both the adjacent coastal marine waters as well as freshwater inflows from the river basin upstream. The complex relationship between these two inputs determines, to a large extent, the nature of the estuarine ecosystem and associated services which are provided by that ecosystem. Understanding how the relationship between freshwater inflows and marine inflows can be affected by different drivers, including human activities, is essential to achieving the wise use of estuarine wetland ecosystems.

Dr Heather MacKay, Chair of the Scientific and Technical Review Panel 2009-2012
December 2012

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Morston, the "North Norfolk Coast" Ramsar Site in the UK. ***Photo: Nick Davidson, Ramsar.***

Summary

This report provides a review of available methods for determining the environmental water requirements of estuaries, as well as a discussion of trends in method development and requirements for the successful implementation of environmental water requirements. In most countries the environmental water requirements of estuaries have only recently received attention – in the past these requirements were seldom considered in water resources planning and environmental management, mostly because of the lack of long-term monitoring data on estuarine ecosystems and a limited understanding of the influence of freshwater inflow on the structure and function of estuaries. In some cases it was incorrectly assumed that the environmental water requirements determined for rivers would protect downstream estuarine processes, and in other cases the omission was a result of divided sectoral management of water resources or lack of applicable legislation.

Three countries have made substantial progress in developing methods for assessment of environmental water requirements for estuaries, i.e., Australia, South Africa and the USA, and the main focus of the report is on their experiences. Methods have mostly been developed within practical applications, representing a "learning-by-doing" approach. Recently-used methods take a holistic and adaptive approach and are presented as frameworks that include a number of steps and provide a broad strategy for assessment of environmental water requirements for estuaries. These frameworks also include elements of risk assessment and adaptive management. Most approaches are data-intensive and emphasize long-term monitoring so that the impacts of freshwater inflow alteration can be understood.

Because of limited financial resources, some countries have prioritized specific estuaries for assessment. In other countries, legal battles relating to water use and allocation have resulted in the execution of detailed modeling and monitoring exercises, the development and testing of methods, and the implementation of water allocations to meet environmental water requirements.

This review demonstrates that a range of methods and frameworks is available for determining the environmental water requirements of estuaries. Implementation is currently slow, however, because of costs and lack of expertise as well as inadequate institutional and legal arrangements. Technical expertise is required especially for modeling sediment, hydrodynamic and water quality processes in estuaries and linking these to biotic responses in order to understand the implications for determination of environmental water requirements. Successful implementation of environmental water requirements for estuaries has occurred where there have been strong governance structures, stakeholder participation, monitoring, and feedback in an adaptive management cycle.

1. Introduction

1.1 Ramsar guidance and other materials related to this report

In 2002, Contracting Parties to the Ramsar Convention adopted two Resolutions relating to environmental water allocations:

- Resolution VIII.1 (*Guidelines for the allocation and management of water for maintaining the ecological functions of wetlands*);
- Resolution VIII.2 (*The Report of the World Commission on Dams and its relevance to the Ramsar Convention*).

In addition, the STRP was requested in 2002 at the 8th meeting of the Conference of Contracting Parties (COP8) to review Resolutions VIII.1 and VIII.2 and to prepare further guidance for consideration at COP9.

The STRP's 2003-2005 Work Plan for Working Group 4: Water Resource Management included the preparation of 'Guidance for environmental flow assessment for wetland ecosystems' (Task 3.3) as one of its priorities, with the following objectives:

i) To prepare reviews and associated guidance for Contracting Parties for COP 9 on environmental flow methodologies for rivers and other types of wetland ecosystems and their biophysical components, appropriate for regulated systems - with particular attention given to assistance in the management of dam-related impacts - and unregulated systems;

ii) To prepare guidance, as appropriate, on the processes of determining and implementing environmental flows, building on the existing guidance provided at COP8 (Resolutions VIII.1 and VIII.2, and supporting papers) and a synopsis of material derived from the technical reviews.

This Technical Report has been prepared in response to that request to STRP reflected in Task 3.3(i) in the 2003-2005 Work Plan; it also serves as supplementary material related to the following Ramsar Handbooks (Ramsar Convention, 2011):

- Handbook 8 (*An Integrated Framework for the Convention's water-related guidance*);
- Handbook 9 (*Integrating wetland conservation and wise use into river basin management*);
- Handbook 10 (*Guidelines for the allocation and management of water for maintaining the ecological functions of wetlands*); and
- Handbook 12 (*Wetland issues in Coastal Zone Management*).

1.2 Terminology: "environmental flows" and "environmental water requirements"

At present there is no single, internationally-agreed definition of the term "environmental water requirements", and the terminology continues to evolve over time as the concept becomes more widely accepted and applied. The term "environmental flow (or flows)" has been most commonly adopted to date, irrespective of whether the water in the wetland is flowing or not, and this probably reflects the limited attention currently given to wetland ecosystems other than rivers. In this report the more general term "environmental water requirements" is used in respect of both flowing and non-flowing systems, unless another term is used in a specific source document, example or case study.

"Environmental flows" (or, in this report, "environmental water requirements") refers to the water regime of a river, wetland or coastal zone necessary to maintain the biophysical components, ecological processes, and health of aquatic ecosystems and associated ecological goods and services (Arthington *et al*., 2006). The concept of Environmental Flows is rapidly developing into a suite of frameworks and tools for the protection and restoration of inland and coastal aquatic ecosystems (Naiman *et al*., 2006). Environmental Flows is a sub-discipline of Ecohydrology which encompasses all aspects of research related to flow-ecology relationships (Hannah *et al*., 2004; Naiman *et al*., 2006).

1.3 Scope and purpose of this report

In the Ramsar Classification System for Wetland Types, estuaries fall under Marine and Coastal waters (Category F) where they are defined as including the permanent waters of estuaries and estuarine systems of deltas (Ramsar Convention, 1996). They are distinct and valuable environments in which continual mixing of freshwater and marine water generates a complex array of habitats. Estuaries perform important chemical and physical functions; they trap nutrients, filter toxic pollutants and transform wastes that enter from the watersheds, nearshore ocean, and the atmosphere. Physical functions of estuaries include the amelioration of coastal storm impacts, the attenuation of flooding, and the mitigation of erosion on bordering landmasses (Davidson *et al*., 1991; Kennish, 2000). Commercial activities related to estuaries frequently include shipping, marine transportation, oil and gas recovery, electric power generation, marine biotechnology, aquaculture and mariculture, fisheries production and tourism. Other benefits and services often provided by estuaries include sediment supply, soil formation, genetic resources, raw materials for subsistence and commercial use, aesthetic value, cultural and educational value and water supply. Table 1 gives an overview of the ecosystem services provided by estuaries.

Implementation of environmental water requirement determinations is recognised as being important to support the intrinsic, ecological, social and economic values of estuaries. However, much research in the field of environmental flows has focused on methods for rivers with much less attention given to methods for estuaries. There are a number of well-documented and widely used methods such as In-Stream Incremental Methodology (IFIM), habitat analysis, and Building Block Methodology (BBM) (King and Louw, 1998). Recently, practitioners in the field have adopted a more holistic approach to assess the environmental water requirements not only for the river system but also the associated wetlands, groundwater and estuary systems (Acreman, 2003). In most countries the environmental water requirements of estuaries have only recently received attention. In the past these requirements were ignored, largely because of the lack of long-term monitoring data and an understanding of the structure and function of estuaries. In some cases an incorrect assumption was that the environmental water requirements determined for rivers would protect downstream estuarine processes, while in others the omission was the result of the divided sectoral management of water resources.

Table 1. Ecosystem services of aquatic and water-dependent ecosystems and their importance in estuaries (from Van Niekerk and Turpie, 2012, adapted from Costanza *et al.*, 1997 and Turpie and Clark, 2007)

Ecosystem services		Description	Importance in estuaries
Provisioning services (goods)	Water	Provision of water for subsistence and agricultural use (only applicable in fresher upper reaches)	Low
	Food, medicines	Production of fish and food plants; medicinal plants	High
	Raw materials	Production of craftwork materials, construction materials, fodder and biofuel (especially important in rural and arid areas)	Medium to high
Regulating services	Climate regulation	Carbon sequestration, oxygen and ozone production, urban heat amelioration	High
	Disturbance regulation	Flood control, drought recovery, refuges from pollution events	High
	Water regulation	Provision of dry season flows for agricultural, industrial and household use (only applicable in fresher upper reaches)	Low
	Erosion control and sediment retention	Prevention of soil loss by vegetation cover and capture of soil, e.g., reeds and sedges preventing bank erosion	High
	Ecological regulation	Regulation of diseases and pests such as malaria, bilharzia, liver fluke, black fly, invasive plants due to the effects of salinity.	High
Supporting services	Waste treatment	High retention, therefore effective in breaking down waste and detoxifying pollution. Tidal and fluvial flushing assist with dilution and transport of pollutants	Medium to high
	Refugia/ Nursery areas	Critical habitat for migratory fish and birds, important habitats or nursery areas for species	High
	Export of materials and nutrients	Export of nutrients and sediments to marine ecosystems	High
	Genetic resources	Medicine, products for materials science, genes for resistance to plant pathogens and crop pests, ornamental species	Low
Cultural services (attributes)	Structure and composition of biological communities	The characteristics, including rarity and beauty, that give an area its aesthetic qualities or make it attractive for recreational, religious or cultural activities	High

This review focuses on the methods and frameworks developed for assessment of the environmental water requirements of estuaries. The objectives of this study were to assess the strengths and weaknesses of available methods, to describe recent trends in method development, and to identify requirements for the successful implementation of environmental water requirements for estuaries.

2. The importance of freshwater inflow to estuaries and the changes in estuaries in response to altered freshwater inflow

The importance of freshwater inflow to estuaries and the changes in estuaries in response to altered freshwater inflow are discussed briefly below. Other studies have addressed this topic in greater detail (Browder and Moore, 1981; Drinkwater and Frank, 1994; Whitfield and Wooldridge, 1994; Bate and Adams, 2000; Alber, 2002; Estevez, 2002; Gillsanders and Kingsford, 2002; Fohrer and Chicharo, 2012). This section provides an overview of the topic for the benefit of readers new to the field.

2.1 Estuary types

A classification of estuary types can provide a useful framework for understanding the characteristics of estuaries in general, why they occur where they do, what features they share and, most importantly, how they function (Davidson *et al*. 1991). However, this is a complex and difficult task because of the high variability that exists among estuaries worldwide. Classification has generally been aimed at grouping estuaries based on different characteristics, including such aspects as geological (e.g., substrate type, historical formation and depth), physical (e.g., circulation, currents and mouth states), chemical (e.g., nutrients, pH, turbidity, salinity and dissolved oxygen levels) and biological (e.g., community composition and food web structure) characteristics (Simenstad and Yanagi, 2012).

Whitfield and Elliot (2011) classified estuaries into three primary categories (river mouths; valleys; lakes and lagoons) based on geomorphology (estuary morphometrics and mouth dimensions) and hydrography (river flow and salinity). This is a useful classification for determining sensitivity of an estuary to changes in freshwater inflow (Tables 2 and 3):

River mouths are dominated by riverine influences and can take the form of a single or multiple-mouth estuary. The estuary is usually fresh or oligohaline (salinity < 5 ppt) but conditions can range from riverine to estuarine.

Valleys are located in a drowned river valley and can consist of a single channel or a number of tributaries. A full salinity gradient from fresh to marine conditions is common but the estuary is seldom hypersaline.

Lagoons and lakes are located on a coastal plain where there is a strong supply of marine sediment which results in the development of barrier beaches, dunes or bars. These systems can become closed to the sea, resulting in hypersaline conditions.

Changes in freshwater inflow will influence the mixing between fresh and saltwater, and this mixing determines the physical and chemical properties of the estuary, the length of the estuary, inundation levels, and residence time (Fohrer and Chicharo, 2012). Mixing processes are influenced more by the river inflows in estuaries of the river mouth type. Tides and river inflows are important in valley types, whereas wind can control mixing processes in lagoons and lakes.

2.2 The response of estuaries to changes in freshwater inflow

Any long-term change in the quantity, quality and timing of freshwater inflow will influence the structure and function of an estuary through changes in geomorphology, hydrology, water quality, exchanges with the sea, habitat availability, connectivity and ecological processes. Changes typically include a reduction of freshwater inflow volume, but human interventions can also lead to increases in freshwater inflow through interbasin water transfers, agricultural return flow, and stormwater flows from urban areas. These changes will alter the ability of the estuary to provide the goods and services that

Table 2. Primary estuary types and the relationship to other existing classifications (Whitfield and Elliot, 2012)

Estuary ecosystem type	Alternative terminology used in classifications by others
River mouths	Delta front estuaries and deltaic formations
Valleys	Drowned river valleys, fjords, fjards, firths, rias, estuarine bays, and some tectonic estuaries
Coastal lakes and lagoons	Blind estuaries, bar-built and intermittently open estuaries, coastal plain estuaries, barrier beaches and estuarine embayments

support mankind. Management of estuaries in terms of the environmental water requirements is necessary to balance the use of estuaries with the ability to deliver goods and services. Tables 4 and 5 outline the responses of permanently open and intermittently closed estuaries to a reduction in freshwater inflow which influences the abiotic characteristics, causing changes in the abundance, productivity, distribution, and composition of the biota. The effect of these changes on the provision of ecosystem services is indicated.

To a large extent, the inflow of freshwater controls the hydrodynamics of an estuary and therefore the sediment transport within the system and the nature of the mouth (i.e., whether open or closed). Upstream dams can attenuate smaller river floods that might otherwise help to maintain the physical shape and structure of an estuary. Floods are needed to regularly scour accumulated marine and catchment sediment from the estuary, deepening the mouth and resetting the salinity regime**.** Upstream dams reduce the erosion capacity of river floods with the result that estuary channel dimensions shrink, sediments accumulate in the subtidal zone, and flood tidal deltas are deposited. Reduced freshwater input can thus result in sediment build-up and an increase in the frequency and length of time during which the mouth of an estuary is closed to the sea (see Table 5). This will lead to reduced scouring of the bar at the mouth and marked siltation of the channel (e.g., Tuggerah Lakes in New South Wales, Wilson Inlet in Western Australia; Lukatelich *et al*., 1987). Artificial breaching of the mouth may then become an option. In New South Wales, Australia, artificial breaching is primarily undertaken to prevent flood damage to properties along estuary shorelines (Gillsanders and Kingsford, 2002). The situation is similar in South Africa.

Influence of changes in freshwater inflow on estuary mouth closure

Freshwater input plays an important role in ensuring that the mouths of intermittently open estuaries remain open to allow tidal exchange with nearshore marine water. Tidal exchange is important for the full functioning of all estuarine attributes. For example, any restriction of tidal exchange can lead to the loss of zonation and diversity of salt marsh plants which are at the base of primary productivity. In high rainfall areas, if tidal exchange is restricted because of a closed estuary mouth, the water level in the estuary may rise and sediment salinity may be reduced for long periods. This weakens salt marsh plants and allows encroachment into those areas by brackish reeds or even terrestrial species not resistant to salinity. Closure of the mouth also prevents recruitment of invertebrates and fish to the estuary from the sea. Freshwater inflow thus influences the 'connectivity' of nursery habitats for certain species within estuaries. Species may inhabit a variety of freshwater and estuarine habitats at different stages of their life cycle and the loss of connectivity between these habitats due to reduced freshwater supply can influence the survival of juvenile organisms reliant on those habitats to complete their life cycle.

Influence of changes in freshwater inflow on salinity

Reduction in freshwater inflow can result in saline water extending further upstream and displacing brackish habitats at the expense of saline habitats (Adams *et al*., 1992; Wortmann *et al*., 1998). Freshwater inflow determines the extent of the longitudinal salinity gradient as well as the extent and structure of the vertical salinity stratification in an estuary. Within this gradient, researchers have observed certain areas, i.e., the river estuary interface (REI zone), that appear to be biologically distinct and richer than others (Bate *et al*., 2002). Reductions in freshwater inflow will shrink the most productive part of the estuary; the brackish middle to upper or mesohaline mixing zone of the estuary. Such compressions have caused losses in primary and secondary productivity and fishery resources in certain Black Sea deltas (Rozengurt and Haydock, 1981, cited in Jay and Simenstad, 1994).

Reduced freshwater inflow may result in the estuary becoming hypersaline, particularly when this is coupled with high evaporation rates and low rainfall. Alternatively, the opening of upstream impoundment floodgates can also negatively affect the salinity regime in estuaries as a large release of freshwater can change the salinity in the estuary from full sea water to full freshwater and back again over a short period of time (Irlandi *et al*., 1997). A sudden drop in salinity following a management response to high salinity can result in severe physiological stress for estuarine biota.

Influence of changes in freshwater inflow on water quality

Freshwater inflow has a strong influence on the water quality characteristics of an estuary. The delivery of dissolved and particulate matter and the concentrations thereof is affected by changes in the timing and quantity of freshwater entering an estuary (Alber, 2002). Reduced input of nutrients and organic matter to estuaries has implications for productivity and trophic structure in these systems. Generally there is a positive relationship between phytoplankton biomass and freshwater inflow, particularly as a result of increased nutrient availability with increased inflow (Malone *et al*., 1988; Mallin *et al*., 1993; Snow *et al*., 2000). The same pattern holds for pelagic consumers: both euryhaline copepods and fish attain significantly higher biomass in estuaries having a longitudinal salinity gradient (Schlacher and Wooldridge, 1996). Residence time (the length of time that material remains in an estuary) is also important, however.

Influence of changes in freshwater inflow on fisheries

Reduced fisheries production has been attributed to altered freshwater inflow in many estuaries, particularly in those dominated by rivers (Livingston *et al*., 1997). High spring run-off is a cue in the life histories of many fish and shellfish (Alber, 2002). Whitfield (1994) found that the abundance of newly-recruited marine fishes into Eastern Cape estuaries, South Africa, showed a significant positive correlation with longitudinal salinity gradients within the systems studied. It was suggested that it is the riverine and estuarine olfactory cues associated with the salinity gradients which attract the postflexion larvae and early juveniles into estuaries and not the salinity gradients *per se*. These findings were confirmed by James (2006) in laboratory experiments specifically designed to test those observations.

Sensitivity of different estuary types to changes in freshwater inflows

Bar-built or barrier estuaries are the types most sensitive to change in freshwater inflow because a reduction in freshwater inflow has the effect of increasing the size of the bar at the estuary mouth, thus reducing the influence of the marine water inflows (Table 4). Estuaries that normally only have intermittent connections to the sea are known as TOCEs (temporarily open/closed estuaries) in South Africa and ICOLLs (intermittently open lakes and lagoons) in Australia. These systems also occur on the southeastern coast of New Zealand, the southeastern coasts of Brazil and Uruguay as a well as the southwestern coasts of India and Sri Lanka (Perissinotto *et al*., 2010). Many of these systems have been degraded as a result of reduced freshwater inflow and eutrophication. Freshwater abstraction can increase residence time of a body of water in an estuary, increasing pollutant concentration and eutrophication. The three dominant hydrodynamic states in these estuaries are; open mouth, semi-closed and closed mouth (Snow and Taljaard, 2007). In the semi-closed state, the mouth of an estuary is nearly closed with only a shallow, narrow opening allowing water to "trickle" out to sea, but the mouth is then too perched and shallow for tidal exchange. However seawater may enter the estuary during spring high tides (Van Niekerk *et al*., 2002).

In principle all estuaries are sensitive to reductions and changes in freshwater inflow and studies which determine the freshwater inflow requirements should treat each estuary as a unique complex system. Indicators have been identified that could be used to establish the extent to which estuaries would be sensitive to inflow modification (Taljaard *et al*., 2004; Lamberth *et al*., 2008). The volume of the natural mean annual runoff that an estuary receives is probably the most important parameter to consider when in judging the potential sensitivity to reduced freshwater inflow. In general the larger the natural mean annual runoff into an estuary, the less sensitive it is likely to be to small reductions in river inflow as long as the mouth remains open most of the time. However, the bathymetry of an estuary can cause exceptions. In estuaries that are permanently open to the sea the most important effect of reduced seasonal base flow or extended duration of low flow is an extension in the upstream intrusion of saline marine water. Evaporation can result in hypersaline conditions particularly in arid and semi-arid areas where freshwater inputs are reduced in estuaries that are closed to the sea (Table 3).

The reasons that estuaries are often only intermittently connected to the sea include the size of the estuary, the supply of marine sediment and the degree of wave action in and near the mouth, absence of protection of the mouth by rocks, beach slope, and low mean annual run-off. Larger estuaries are less prone to mouth closure than are smaller estuaries because of greater tidal flow through the mouth – in larger estuaries the tidal flow provides the primary driving force keeping the mouth open. Small estuar-

Table 3. Sensitivity of different estuary types to changes in freshwater inflow

	River mouths	**Valleys**	**Coastal lakes and lagoons**
Mouth closure & loss of marine connectivity	Low	Moderate	High
Eutrophication	Low	Moderate	High
Saline intrusion	High	Moderate	Low
Hypersalinity	Low	Moderate	High

Table 4. Response of an open estuary to a reduction in water quantity (volume of freshwater inflow) and potential human impacts in terms of the provision of ecosystem services

Abiotic driver	Biotic response	Effect on ecosystem services
SEDIMENT		
Increased marine sedimentation	Loss of open water habitat Biota with a preference for sand displace mud species	Activities such as boating & fishing affected
Reduced input of fluvial sediments	Erosion and loss of wetland habitat	Loss of ecotourism as areas with recreational, tourist appeal lost
No sediment input to marine environment	Loss of habitat	Loss of beaches, coastal erosion
RETENTION		
Increase in stratification and hypoxia of bottom waters	Death of sensitive organisms	Bait collection & fisheries affected. Loss of protein rich food source
Increase in retention of pollutants	Accumulation of toxins in fish and shellfish	Not suitable for consumption, reduced food supply
Eutrophication and decrease in water transparency	Toxic algal blooms Decrease in biodiversity Loss of submerged aquatic vegetation	Aesthetic appeal, recreation and tourism lost Increased health risk form toxic algae blooms (ingesting blue green algae, shellfish poisoning)
Reduced flushing of pathogens	Accumulation of toxins in fish and shellfish	Human health issues Aquaculture affected
SALINITY		
Reduced freshwater inflow to marine environment	Loss of spawning and migration cues in the marine environment for invertebrate & fish recruitment	Reduced fisheries Loss of protein food source
Longitudinal salinity gradient lost	Decrease in habitat diversity Reduced productivity in the river estuary interface zone Reduced fish & invertebrate recruitment	Loss of estuary nursery function - fisheries affected – loss of livelihoods for fishing communities
Increase in saltwater intrusion	Intrusion of marine predators, invasive alien species, parasites and diseases. Loss of brackish habitats, species richness and productivity	Reduced fisheries
NUTRIENTS		
Reduced nutrient input	Decrease in primary and secondary productivity	Loss of fisheries

Table 5. Response of an intermittently closed estuary to a reduction in water quantity (volume of freshwater inflow) and an increase in the duration and frequency of closed mouth conditions. Potential human impacts in terms of the provision of ecosystem services are indicated.

Abiotic driver	Biotic response	Effect on ecosystem services
No tidal exchange	Loss of intertidal habitat and wetlands Loss of diversity (e.g., intertidal salt marsh & waders)	Wetland purification capacity, erosion control and flood mitigation lost
Loss of marine connectivity	Loss of invertebrate & fish recruitment, interruption of life cycles Decline in salt tolerant biota	Reduced fisheries
Loss of marine – catchment connectivity	Loss of recruitment of catadromous species that live in freshwater and breed in the sea (e.g., eels & freshwater mullet)	Reduced food security and loss of cultural aspects
Increase in water level	Loss of intertidal habitat e.g., intertidal salt marsh and waders	Loss of tourist appeal, bird watching Surrounding property flooded which results in artificial breaching
Decrease in water level	Die-back of submerged plants Nursery habitats for invertebrates and fish lost Reduced foraging & nesting habitat for waterbirds.	Loss of bait and fisheries resources Reduced ecotourism
Eutrophication and decrease in water transparency	Loss of submerged aquatic vegetation such as seagrass, harmful algal blooms, fish kills.	Loss of assimilative capacity (waste treatment) Loss of fisheries Reduced recreational value Decreased value surrounding real estate
Increase in retention of pollutants	Accumulation of toxins in fish and shellfish	Not suitable for consumption, reduced food supply
Increase in retention of human pathogens		No contact recreational activities, declines in public health
Hypersaline conditions	Die-back of wetlands Change in species composition, reduced abundance and community composition.	Banks destabilized, loss of buffers and flood control

ies have less tidal marine inflow and are very sensitive to reductions in river inflow and thus reduction in the amount of outflow, because this is the main force keeping the mouth open. If outflow decreases below a certain volume the mouth closes and remains closed until such time as river inflow increases sufficiently to cause the water level inside the estuary to rise and the mouth to be breached.

The larger the amount of sediment available in the adjacent marine environment, and the stronger the wave action, the greater the likelihood that the estuary mouth will close. In estuaries where there is not a large amount of sediment available, for example on a rocky coastline or where longshore transport is quite far offshore, an estuary tends to be less likely to experience mouth closure due to river inflow reduction. The mouth is also less prone to closure when it is protected against wave action, for example by a headland (Taljaard *et al.*, 2004).

Summary

In summary, changes in freshwater inflows, particularly those resulting from human activity, alter the dynamic nature of estuaries. This has serious implications because the temporal and spatial heterogeneity to which the biota have adapted is altered, sometimes permanently. Estuaries occur at the lower ends of large river catchments but their complexity and relatively small size makes them susceptible to human impacts upstream. The manner in which estuary characteristics are influenced by freshwater inflow is often not the result of a single flow event, but rather that of characteristic flow patterns occurring over weeks or months. In estuaries there is a much larger buffer or delay effect between river inflow patterns and their effect on abiotic parameters than there is in rivers (Taljaard *et al*., 2004). For these reasons, methods for determining the environmental water requirements of rivers are not easily transferred to estuaries. The strong longitudinal gradients of abiotic characteristics and changes in response to tides and freshwater inflow influence the biotic composition and function. Estuaries are complex systems which therefore require holistic and process-based approaches for determining the freshwater inflow requirements. A sound approach would require that the investigator has an understanding of the natural variability in the quantity and timing of freshwater, including whether or not this has changed over time and how it is likely to change in the future (Olsen *et al*., 2006). Setting up scenarios of future possible changes in inflow is important because they can be effectively communicated to stakeholders as they identify the implications of alternative courses of action in terms of the social, economic and ecological implications.

3. Methods and frameworks used to determine the environmental water requirements of estuaries

The term “Methods” describes the scientific (technical) tools used to investigate the freshwater inflow required to sustain the ecological function of an estuary (Dyson *et al*., 2003). “Approaches” are ways of working to derive the assessments using, for example, expert teams, whereas “frameworks” provide a broad strategy for assessments of environmental water requirements. Frameworks include a set of steps, linked components or tools that cover all aspects of the process of establishing agreed environmental flow allocations to estuaries (Gippel *et al*., 2009a). Understanding the relationships between freshwater inflow, estuary condition, and estuary resources is the basis of estuary environmental water requirement assessments and Alber (2002) classified the approaches into three types:

- Inflow-based methods determine an acceptable level of deviation in freshwater inflows relative to the natural or reference freshwater inflow regime.
- Condition-based methods determine the freshwater inflow required to maintain agreed conditions within the estuary.
- Resource-based methods determine the freshwater inflow required to maintain suitable conditions for particular resources (e.g., certain commercially or culturally important species).

Table A.1 in the annex to this report indicates the countries and estuaries where these methods have been applied.

3.1 Inflow-based methods

Inflow-based methods rely on hydrological analyses and assume that if the inflow is maintained then this will maintain estuary condition and resources as well. The percent-of-flow approach (Flannery *et al*., 2002) is an inflow-based method for unimpounded rivers that was applied to Southwest Florida estuaries. It set limits to freshwater withdrawals as a percentage of stream flow at the time of withdrawal. Other inflow-based methods such as the Indicators of Hydrologic Alteration (IHA) trend analysis method have been applied to Georgia (USA) estuaries (Alber and Flory, 2002).

The advantages of this approach are that it is simple, rapid and cost effective. However, the weaknesses are the lack of supporting ecological information and the assumption that ecosystem change is linear and that only flow influences estuary health. The approach would be less useful in highly-regulated and altered systems.

3.2 Resource-based methods

Resource-based methods focus on organisms and fisheries that are of economic importance. Freshwater inflows are set on the basis of the requirements of the selected biotic or fisheries resources, and the goal is to protect the estuary by focusing on key resources. One of the early studies considered the pink shrimp, *Farfantepenaeus duorarum*, as an indicator of the health and productivity of the Florida Bay ecosystem. The pink shrimp simulation model (Browder *et al*., 1999) was used to show the influence of upstream water management and the response of the shrimps to changes in salinity.

Resource-based methods have also been used in Texas (USA), which has had a long history of environmental water management for estuaries. After a drought in the 1950s which caused low flow, hypersalinity, fish kills, and the loss of blue crabs and white shrimp in the estuaries (Copeland, 1966; Hoese, 1967; Montagna *et al*., 2002), legislation was passed to give consideration to the environmental water requirements of bays, estuaries and arms of the Gulf of Mexico. The Texas Estuarine Mathematical Programming model (TxEMP, Matsumoto *et al*., 1994; Powell and Matsumoto, 1994; Powell *et al*,. 2002) was used to model salinity inflow and fishery harvest relationships. A series of relationships between historic monthly inflow and the catch of various fish, crustaceans and mollusks were used as the basis for the model (Matsumoto *et al*., 1994, cited in Alber, 2002). Other resource-based methods have been used in the South Florida Water Management District and in tropical Australia (Table A.1 in the annex to this report). Halliday *et al*. (2003) and Robins *et al*. (2005) developed a framework for determining environmental flows to sustain estuary-dependent fisheries (Figure 1).

Robins *et al*. (2005) used correlative analyses in the Fitzroy River Estuary to relate catch to flow and rainfall variables. The method used to assess the environmental water requirements of the Suwanee River estuary involved the identification of 'target habitats' to be protected within the estuary (Figure 2). Thereafter, existing and new knowledge was used to recommend the salinities needed to sustain the target habitats (Mattson, 2002). Five target habitats were identified and recommendations made in terms of the freshwater inflow needs to maintain the salinity regime suitable to the particular habitat.

The advantages of these resource-based methods are that they have stakeholder buy-in because of the economic, social and political value of the resource, particularly with regard to recreational and commercial fishing. Therefore it is important that the indicator chosen by the scientists should be linked to the resources valued by society (Alber, 2002). These factors as well as the availability of time series data (from commercial catch or landing records) has resulted in environmental water allocations to sustain fisheries becoming a key feature of many Australian water management plans (Halliday *et al*., 2003).

Lack of data particularly with regard to commercial fisheries would limit the application of this framework to other estuaries, and an obvious disadvan-

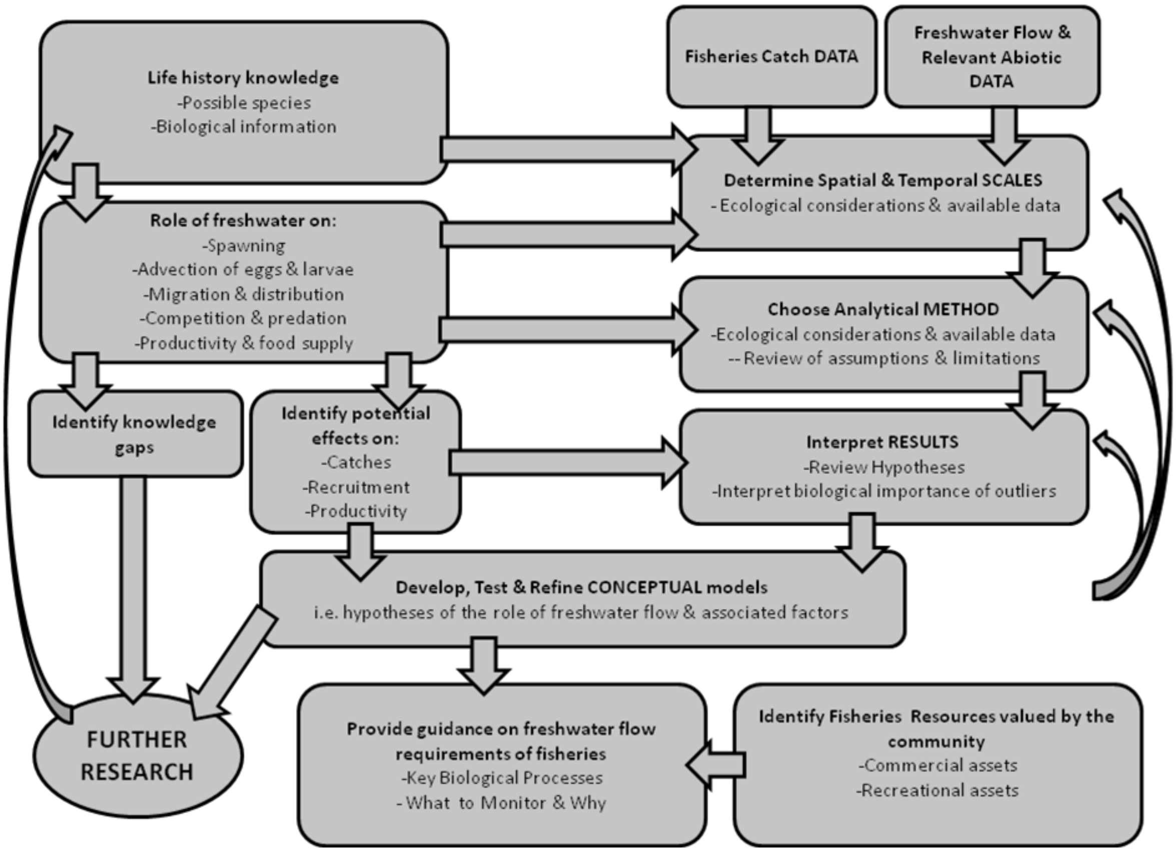

Figure 1. Generalised framework to identifying aspects of the freshwater flow regime that are potentially important to estuarine fisheries production (after Robins et al. 2005).

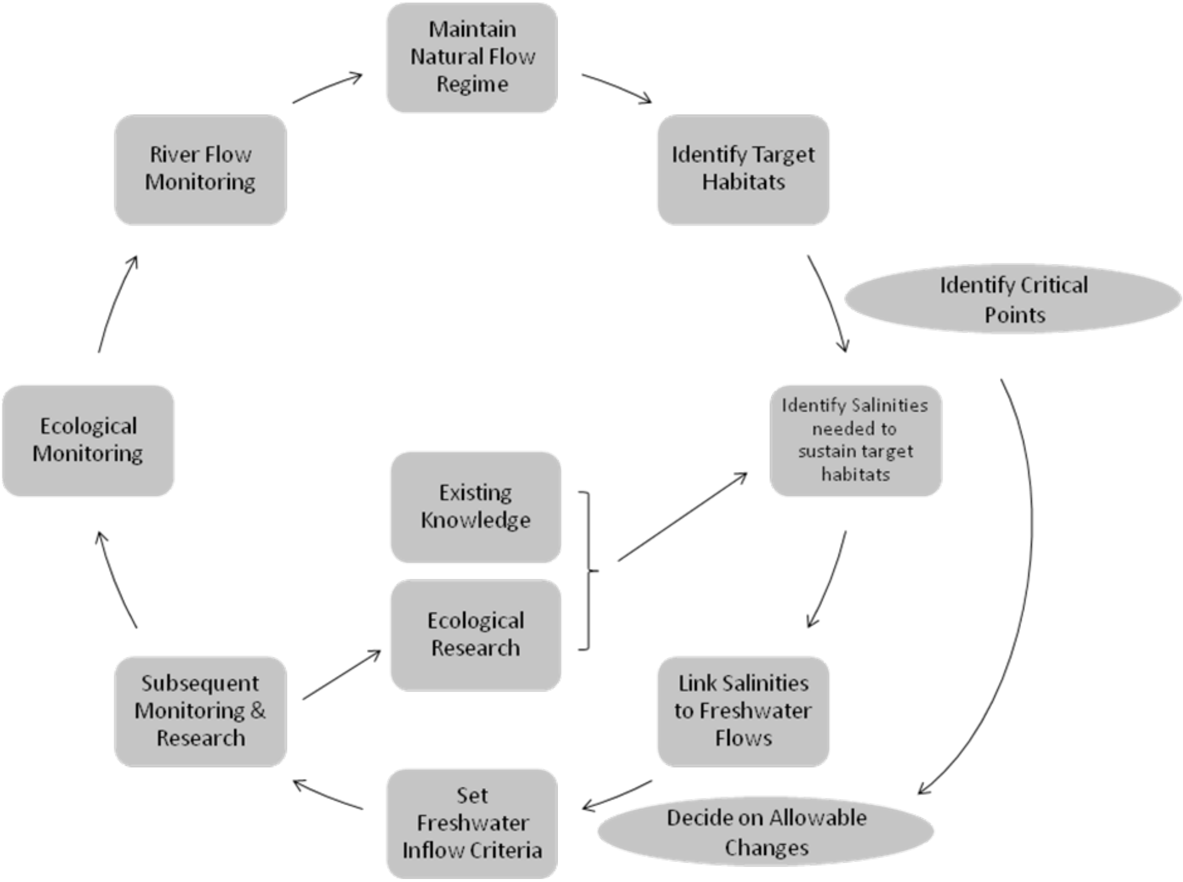

Figure 2. An example of the resource-based approach to assess the environmental water requirements of the Suwannee River Estuary, Florida (after Mattson, 2002).

tage is that these methods are based on a limited number of species and their habitat requirements, which may overlook other important resources with different inflow requirements (Alber, 2002). Another disadvantage is that the models require large data sets even when the number of target species is small.

3.3 Condition-based methods

In this approach, environmental water requirements are set to maintain specific physical and habitat conditions in order to protect the estuarine ecosystem. For example, the X_2 approach sets the freshwater inflow to maintain specific conditions (e.g., salinity) at a given point in an estuary. In the San Francisco Bay Estuary, California, freshwater inflow is managed so that the X_2 (the distance from the Golden Gate Bridge to the 2 ppt isohaline, measured 1 m off the bottom and averaged over more than 1 day) is positioned where it may be beneficial to aquatic life (CALFED, 2002, cited in Alber, 2002). Significant statistical relationships had previously been found between X_2 and the supply of phytoplankton and phytoplankton-derived detritus, the abundance of mysids and shrimp, the survival of salmon smolts and the abundance of planktivorous, piscivorous and bottom-foraging fish (Kimmerer and Schubel, 1994; Jassby *et al.*, 1995). This X_2 location changes in relation to the freshwater inflow into the estuary.

An advantage of this approach is that it has many components of adaptive ecosystem management involving scientists, managers and a consortium of federal and state agencies working in the estuary. The approach also considers all trophic levels (Alber, 2002).

Disadvantages are that the approach excludes alternative models that could be explicitly tested (Kimmerer, 2002) and the method can only be applied in an estuary if empirical relationships between salinity and ecological processes, e.g., phytoplankton production, are understood.

3.4 Holistic Ecosystem Methods and Frameworks

The review of available methods indicates that recent studies have taken a holistic and adaptive approach and are mostly presented as frameworks which provide a broad strategy for the assessments of environmental water requirements for estuaries. Methods used in these frameworks are holistic, in that they consider the entire ecosystem and include multi-disciplinary teams and stakeholders.

Holistic methods have mostly developed from practical applications, a learning-by-doing approach. For example, in Australia Peirson *et al.* (2001) addressed the requirements of the Richmond River estuary which formed the basis of the proposed methods of the National River Health Program (Peirson *et al.*, 2002). In South Africa scientists had been working with the Department of Water Affairs and Forestry on the freshwater requirements of estuaries at least ten years prior to the formalisation of methods in 1999 (Taljaard *et al.*, 2004). Indeed a survey by Moore (2004) and a question on how the concept of environmental flows became established in various countries elicited a majority response from respondents that this was as a result of the introduction of Environmental Flow Assessment (EFA) projects either by government agencies or sources from outside the country.

Ecosystem-based approaches are more holistic, but data requirements are intensive. An ecosystem-based approach generally makes use of experts from a range of disciplines, with knowledge of both living (biotic) and non-living (abiotic) components of the estuarine ecosystem, which implies that consensus among experts may not always be achieved (Dyson *et al.*, 2003). Studies vary in their selection of parameters that are evaluated and the timeline over which the implications of change are assessed. These types of studies are generally replicable and can transfer to other sites or systems (Dyson *et al.*, 2003).

Good physical, chemical, water quality and ecological data are needed to determine appropriate environmental water requirements. For example, fundamental to the FLOWS method used for estuaries in Victoria, Australia, is the development of flow relationships between physical and ecological objectives using conceptual models of key species and processes. Conceptual models are also used in the benchmarking method in Queensland, Australia (Table A.2 in the annex to this report). The confidence in the assessment is dependent on an understanding of the relationship between flows, abiotic and biotic responses. Data are however not always available. This was identified as a major stumbling block by the different Australian states when the applicability of the Peirson *et al.* (2002) environmental water requirement method was investigated (Gippel, 2002). The FLOWS method was also adapted in the environmental water requirement assessment of the Jiaojian Basin, China, where researchers required a method which represented an asset-based, holistic approach (Gippel *et al.*, 2009b).

Benchmarking is a "top down" method that defines environmental water requirements in terms of acceptable levels of change from the natural flow regime (Arthington *et al.*, 1998). The effects of changes are benchmarked by comparison with similar river reaches that have already been modified. The method can be used to evaluate the consequences of many different scenarios of flow regulation and appears to be suitable for poorly studied areas (Schofield *et al.*, 2003). The concept of "benchmarking" has recently been incorporated into an environmental water requirement method called ELOHA (Ecological Limits of Hydrological Alteration). This approach involves quantification of stress/response relationships and environmental water requirement guidelines for different classes of rivers with contrasting flow regime types (Arthington *et al.*, 2006). It is a flexible framework for assessing and managing environmental water requirements across large regions and is being used to integrate environmental water requirements into regional water resource planning and management worldwide (Poff *et al.*, 2010).

Disadvantages of the benchmarking approach are that there are often uncertainties about processes at the benchmark or reference estuary sites, and there are difficulties in separating flow and non-flow related impacts and understanding the lag effects of impacts. The South African method for the determination of the ecological reserve for estuaries (Resource Directed Measures (RDM) method) addresses this by defining a reference state for each studied estuary. An Estuarine Health Index is then used to assess the present state of the estuary and deviation from the reference condition (Figure 3). The health index identifies flow and non-flow related impacts. The ecological importance of an estuary (Turpie *et al.*, 2002) together with the present state assessment is then used to recommend an Ecological Reserve Category which defines the level of protection afforded to an estuary. Resource Quality Objectives are also set to maintain water quantity, quality, habitat and biotic integrity to keep the estuary in the recommended ecological state, and monitoring requirements are identified. The method also evaluates different freshwater inflow scenarios. Hydrological specialists provide monthly runoff datasets for each scenario; these are analysed by the hydrodynamic specialists and then presented to ecological specialists for their assessment. This is an ecosystem approach that requires an understanding of the effect of changes in

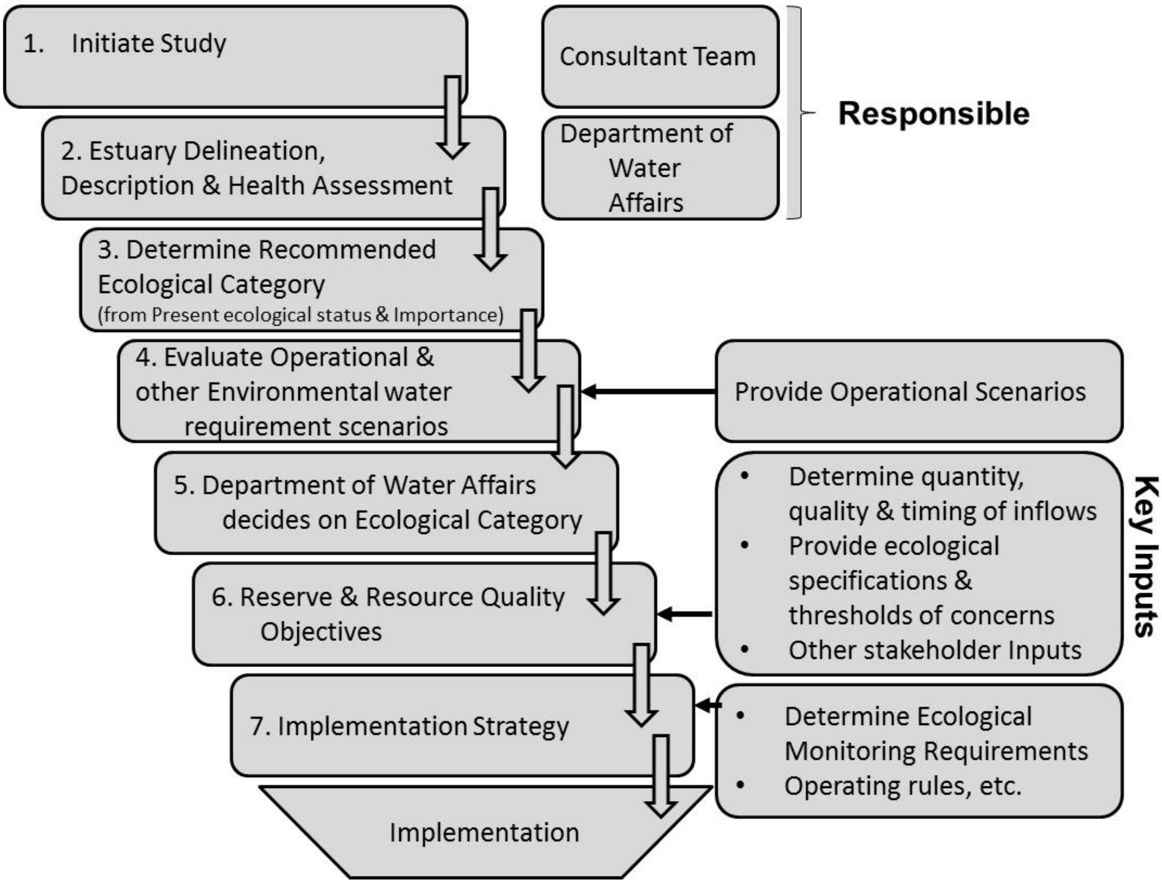

Figure 3. The procedures for the determination of the preliminary ecological water requirements (reserve) for South African estuaries (after DWAF 2004).

river inflow on abiotic components (e.g., hydrodynamics, sediment dynamics, and water quality) and, subsequently, the response of biotic components (e.g., microalgae, macrophytes, invertebrates, fish and birds) (Adams *et al*., 2002; Taljaard *et al*., 2004; DWAF, 2004).

The South African method was developed in response to the National Water Act (No. 36 of 1998), which establishes the Reserve (of water) for basic human needs and ecosystems, wherein a certain amount of water must be set aside for basic human needs and ecosystems before water can be allocated for other uses. Methods for the determination of the environmental water requirements of estuaries were published in 1999, and studies have been completed on a variety of estuary types from different biogeographic zones in South Africa (see Table A.2 in the annex to this report). According to Close (2005), a disadvantage of the approach is that the risk to components influenced by the flow alterations is not considered.

Risk assessment approaches have been used in Australia and the UK (Table A.2 in the annex to this report). The Peirson *et al*. (2002) method was an ecosystem approach that included aspects of risk assessment (Figure 4). In the absence of detailed hydrodynamic data on the Fitzroy River estuary, Australia, Gippel *et al*. (2008) applied a risk assessment approach. Close (2005, 2007) reviewed reviewed available methods for determining environmental water requirements for estuaries and recommended the BAFFLER (Bayesian Adaptive Framework for Flows to Maintain Estuarine Resources) approach to be followed for the Hill and Moore Rivers, Western Australia (Table A.2). This method relies on risk assessment and incorporates levels of uncertainty and prediction of estuarine response to altered freshwater inputs. The approach includes monitoring and adaptive management which allows for updating and re-evaluation of understanding and hypotheses and therefore improves decision making in knowledge-poor environments. A national framework for assessing and implementing environmental water requirements for estuaries in Australia has recently been proposed (Gippel *et al*. 2009b). This is a two-tiered approach, one for assessing simple, data-poor, low-value systems, or for prioritising multiple estuaries, and a detailed approach for complex, data-rich,

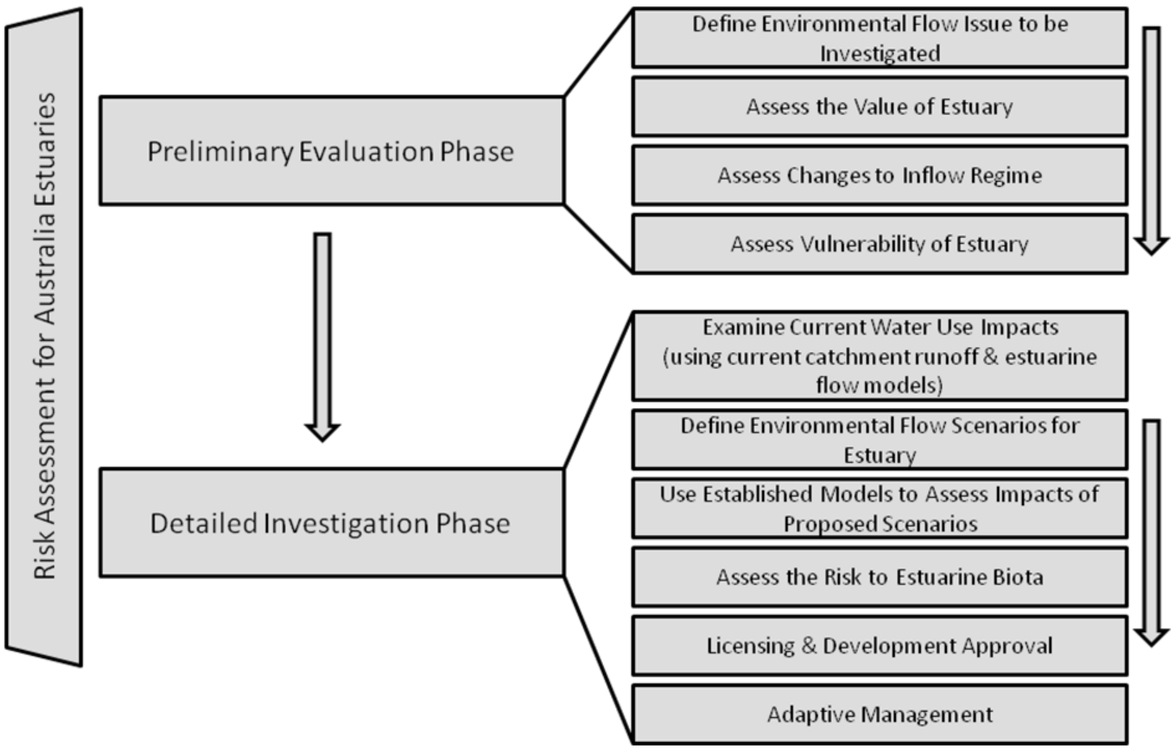

Figure 4. The key steps used in the risk assessment/ecosystems approach used for Australian estuaries (after Peirson et al., 2002).

high-value estuaries. The detailed assessment is a 13-step process termed an Estuary Flows Map. An important aspect of this framework is the flexibility to allow application of a range of scientific assessment methods to each particular estuary.

Most of the recent approaches / frameworks have identified the importance of **adaptive management** and monitoring. Richter *et al*. (2005) proposed the six-step ESWM (ecologically sustainable water management) framework which focuses on determining the flow requirements of rivers prior to the commencement of hydropower projects and includes whole, functioning ecosystems (including estuaries), variable flow regimes, and use of interdisciplinary science teams. The case study was the Apalachicola River and Bay where a flow regime was identified to maintain the biological diversity and productivity of the system (Richter *et al*., 2003). Implementation of the flow recommendations occurs on a trial basis, the system is monitored to test responses and hypotheses, and further research is conducted if needed. This framework was applied to the Savannah River-floodplain-estuarine system and used in the adaptive management of Thurmond Dam (Table A.2).

Olsen *et al*., (2006) described the **Integrated Water Resource Management (IWRM) framework** which was tested in the Laguna de Terminos Estuary, Mexico, and in Samana Bay, Dominican Republic (Table A.2). This is a low-cost approach suitable for use in developing countries that includes socio-economic aspects in the assessment. The framework involves stakeholders and incorporates both scientific and traditional knowledge. The main goal is to create and sustain a governance process that is just, transparent and accountable to those affected by its actions. The interests of the many upstream and downstream stakeholder groups in the watershed and estuary are linked. This process involves the negotiation of plans and policies, subsequent decision making, monitoring, education and enforcement.

3.5 Models as tools in environmental water requirement studies

Confidence in the determination of the environmental water requirements of estuaries requires detailed modeling studies linking hydrology, hydrodynamics, water quality, and biotic responses. Comprehensive environmental water requirement assessments for estuaries will always require some level of modeling, indicating the need for technical expertise in these studies.

Early studies on the environmental water requirements of estuaries were effective at modeling salinity changes and the effect on indicator organisms (e.g., Lambert and Fruh, 1978). Examples where simple models have been used to relate salinity structure to freshwater flow include the investigations by Jassby *et al*. (1995) in California and an investigation for the Swan River, Western Australia, by Kurup *et al*. (1998) (Table A.3 in the annex to this report). In Tasmania, Davies and Kalish (1994) examined effects of upstream storages on the flushing of the Derwent Estuary, and Davies *et al*. (2002) investigated specific flow requirements for the upper Derwent Estuary by modeling relationships between flow and ecosystem functioning. The U.S. Environmental Protection Agency (USEPA) Water Quality Analysis Simulation Program (WASP5), which consists of two stand-alone computer programs, was used to determine the freshwater allocations for the Pascogoula River and estuary (Harza 1995, cited in Peirson *et al*., 2002). Chan *et al*. (2002) investigated the impacts of hydrological changes on the Swan River estuary using a coupled hydrodynamic-ecological numerical model, which was employed to make assessments of pre-modification and post-modification scenarios, with the major focus placed on the likely changes to phytoplankton biomass and species composition.

Models have also attempted to integrate the physical, chemical and biological processes in an estuary. Slinger (2000) identified and linked five models used to assess the environmental water requirements of South African estuaries. These models were used to simulate the response of two estuaries to a range of inflow scenarios. In a study on three estuaries in China, researchers incorporated three types of water requirements into flow requirement calculations: the water cycle, the biological cycle, and the habitat (Yang *et al*., 2005). A bioenergetic model was used by Hae-Cheol and Montagna (2009) to relate macrobenthic biomass and salinity regimes in order to assess the implications of changes in freshwater inflow to benthic ecosystem dynamics. Ecohydrology models have now been applied to a number of estuaries (Wolanski, 2007). Such a model was developed for the low flow condition in the Guadiana Estuary in Spain and Portugal and was used to predict ecosystem health and test the response of the system to different management scenarios (Wolanski *et al*., 2006).

A combination of hydraulic and hydrodynamic modeling and Geographic Information Systems (GIS) tools can be effectively used to communicate about

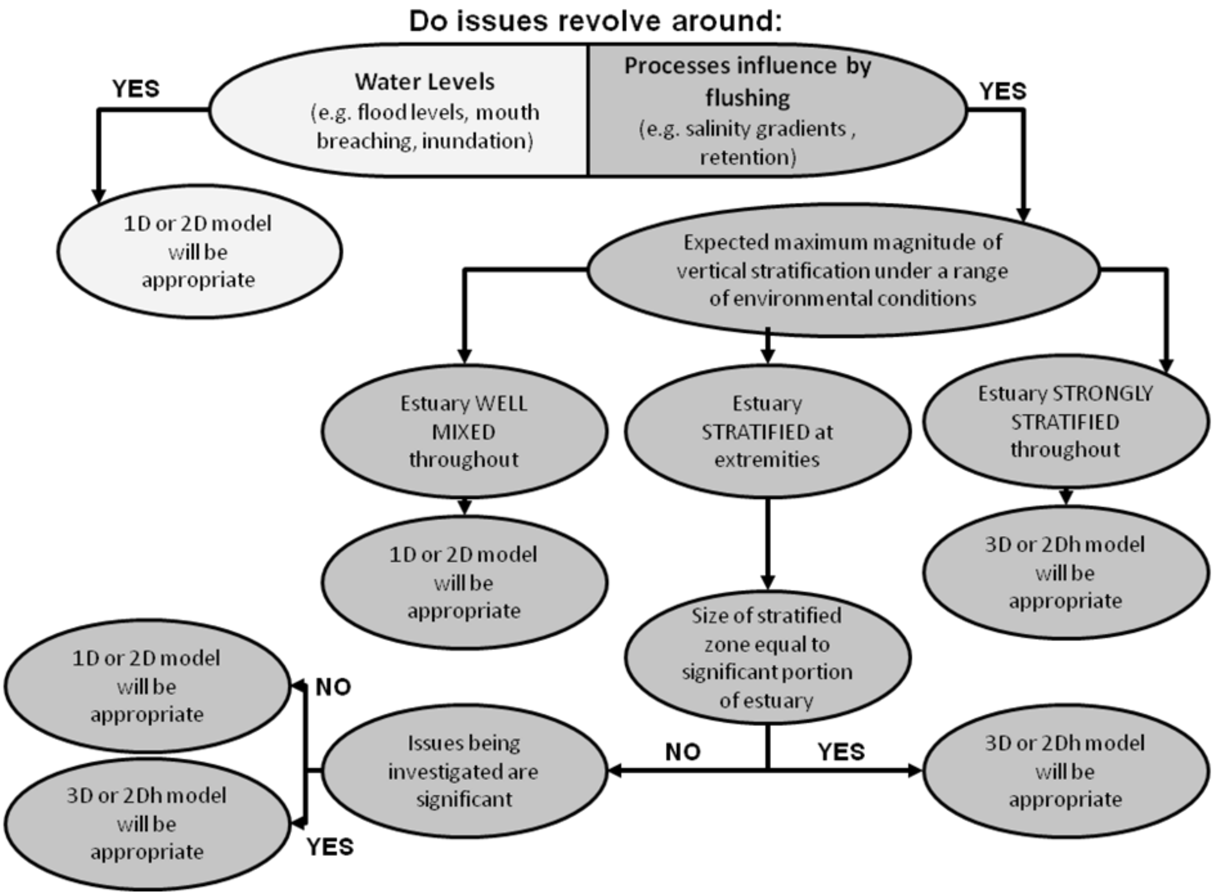

Figure 5. A decision tree used to determine the type of numerical model most suited to estuaries (1D = one dimensional, 2D = two dimensional, 2Dh = two dimensional horizontal, 3D = three dimensional (after Van Ballegooyen et al., 2004).

environmental water requirements, as was done for the delta of the Senegal River (Duvail and Hamerlynk, 2003). The delta was substantially modified by the construction of the Diama dam in 1986, after which no floods reached the floodplain or estuarine areas downstream, which remained dry. In 1994, managed flood releases from the dam were initiated. Hydraulic modeling was developed as a tool to support stakeholder negotiations on the desired characteristics of the managed flood releases. Initially, a water balance model was developed. The data were then integrated into a one-dimensional hydraulic model, MIKE 11 (DHI, 2000). When associated with a Digital Elevation Model and a Geographic Information System (ArcView), the model provided a dynamic description of floods. Flood extent, water depth, and flood duration data were combined with ecological and socio-economic data. The water requirements of the different stakeholders were converted to flood scenarios and the benefits and constraints analysed. A consensus scenario was reached through a participatory process (Duvail and Hamerlynck, 2003).

The purpose of the study, complexity of the estuary, and available expertise will determine the type of model to be used. For example, there are a number of predictive tools that can be used to assess the hydrodynamics (or water circulation patterns) of estuaries. These range from 3D numerical models, 2D numerical models, 1D numerical models, water balance models, and statistical relationships to conceptual models (Van Ballegooyen *et al*., 2004). Figure 5 indicates a decision tree for application of numerical modeling. Numerical modeling can be used to assess the incremental effects of changes in river inflow which are difficult to derive from a number of once-off sampling surveys.

4. Trends in method development and implementation

4.1 Factors influencing method development and implementation

Although there has been an increase in the development and application of environmental water requirement assessment methods for estuaries, this review has found that substantial progress in implementation has primarily taken place in three countries: Australia, South Africa, and the USA. South Africa has assessed the environmental water requirements of approximately 10% of the country’s estuaries using the same method each time, whereas Australia has applied different methods to determining environmental water requirements for approximately 5% of the country’s estuaries.

Other countries where initiatives are underway are China (Sun and Yang, 2004; Sun *et al*., 2008; Sun *et al*., 2009; Zhao *et al*. 2009), Taiwan (Liu *et al*., 2005), the Dominican Republic and Mexico (Olsen *et al*., 2006). Tasmania is in the process of developing and refining an environmental water assessment methodology through the Tasmanian Environmental Flows Project (TEFlows Project) (Gippel *et al*., 2009a).

Different methods are developed and used in response to different social, economic and political pressures. In China the influences of changes in runoff in the Yangtze Estuary were studied before the construction of the Three Gorges Dam (Luo and Shen, 2002; Chen and Chen, 2002, as cited in Sun and Yang, 2004). The USA has the longest history of environmental water assessments for estuaries, which have often been prompted by drought and deterioration in estuarine health. In Europe the focus is more on estuary water quality: management objectives are set for estuaries through the Water Framework Directive to achieve good ecological status in all water bodies (Acreman *et al*., 2010).

Dam construction and the necessary environmental impact assessments have resulted in a number of studies. In Portugal, Morais *et al*. (2009) investigated the changes in the Guadiana Estuary in response to the filling of the Alqueva Dam.

4.2 Freshwater requirements of the marine environment

Estuarine habitats often extend beyond the mouth of an estuary, and offshore habitats in the marine environment are dependent on nutrient and sediment inputs from catchments (Loneragan and Bunn, 1999; Robins *et al*., 2005; Lamberth *et al*., 2009). In any environmental water requirement study this is an important aspect that needs to be identified at the onset. In this context, Tasmania now requires that freshwater allocations be determined for freshwater dependent ecosystems (Pinto, in Gippel, 2002). The omission of methods for determination of environmental water requirements of the marine environment from the current South African methods comes as a result of the divided sectoral management of water resources and marine resources (Taljaard *et al*., 2004). Worldwide there is a need for integrated water resource management and a catchment to coast ecosystem management approach. The term Integrated Coastal and River Basin Management is being used by UNEP (http://www.gpa.unep.org) (Olsen *et al*., 2006), which reflects growing recognition of this need.

4.3 Institutional barriers to implementation

A major stumbling block to the assessment and implementation of environmental water requirements is the lack of legislation and inadequate institutional and governance arrangements. Management of estuaries in most countries is shared among multiple government departments and cooperative governance is poor. For example in New South Wales, Australia, water planning is administered by the Department of Water and Energy, while estuary management is driven by local government committees (Gippel *et al*., 2009a). The Murray-Darling Basin receives water inflows from multiple states, and therefore to ensure integration the Australian Commonwealth Government is responsible for water planning across the whole basin. In Tasmania, estuarine water requirements were ignored because it was assumed that the minimum flows determined for rivers would protect downstream estuarine processes. However, there is now growing recognition that estuaries need separate environmental water requirement assessments (Gippel, 2002).

Moore's (2004) survey on perceptions and interpretations of environmental water requirements indicated that the issue of implementation is a cause for concern. Factors hampering implementation have been related to cost, expertise, adequate institutional and legal arrangements, and effective stakeholder participation. High confidence assessments require detailed studies with high resource requirements and long time frames. Technical expertise is required to model the sediment, hydrodynamic and water quality processes. However, there are many occasions where lack of resources and data result in estuary water requirement assessments based on expert panels and qualitative risk assessments. Gippel *et al*. (2009a) suggested bridging funding from national government to ensure implementation of estuary environmental water requirements until a "user pays" system could be developed.

4.4 Adaptive management of freshwater inflows to estuaries

There are a few successful case studies of adaptive management and monitoring in a number of countries. For nearly 20 years the adaptive management framework has been recognised as the most effective approach to natural resource management (Holling, 1978). This provides for the integration of science as knowledge progresses which would facilitate optimal management and use of environmental flows.

Monitoring has been occurring since 1997 in the lower Hastings River, Australia, to detect impacts caused by increased water extraction at Koree Island (Bishop, 2005). Detailed studies in Australia include those for the Murray River (South Australia, MDBC, 2000; Geddes, 2005; MDBC, 2008), Fitzroy Estuary (Queensland), Derwent Estuary (Tasmania), and the Richmond Estuary (New South Wales).

The USA Texas Parks and Wildlife Department, Coastal Fisheries Division, has an extensive monitoring program for fish in all Texas bays, and the Texas Water Development Board monitors and collates river inflow and bay hydrographic data to estimate flows to the coast (Powell *et al*., 2002). Adaptive management in allocating environmental water requirements to the Nueces Estuary, Texas, has been ongoing since the construction of the Choke Canyon Reservoir in 1982. This has been a stakeholder driven process that has increased estuary health while providing a sustainable water supply to the region (Montagna *et al*., 2009).

In the Great Brak Estuary (South Africa), a mouth management plan involving water releases from the Wolwedans Dam has ensured that the mouth has remained open at important times, i.e., spring / summer to ensure fish recruitment and survival of salt marsh (Adams *et al*.,1999). The construction of the dam 3 kilometers upstream of the head of the tidal influence of the estuary in 1989 reduced freshwater input to the estuary and increased the frequency and duration of mouth closure (Slinger, 2000).

In the Savannah River system, water releases for ecosystem purposes have been conducted from Thurmond Dam annually in spring since 2004 (Wrona *et al*., 2007). As part of an adaptive management plan, scientists have been monitoring the impact of flow restoration on various ecological processes and water quality. The process is iterative, where each controlled flood pulse is viewed as an experiment that is monitored and scientifically refined over time. The resultant learning through testing, evaluation, and modifying management actions results in effective adaptive management (Holling, 1978; Walters, 1986). Central to the practice of adaptive management is sustained and carefully targeted monitoring (Olsen *et al*., 2006).

4.5 Implications of climate change

Future management of environmental water requirements for estuaries will need to consider climate change effects as changes in precipitation and run-off will alter estuary responses. Sea level rise, increased temperatures, and coastal storms will lead to changes in physical processes (e.g., modification in mouth conditions, salinity regimes, nutrient pulses, sediment regimes) and biological responses with an impact ultimately on ecosystem services. For example sea level rise and reduced freshwater inflow will increase salinity and result in longer flooding, leading to loss of salt marsh and mangrove habitat. Banks will become destabilized, resulting in erosion and loss of buffers for flood control. According to global climate change predictions, freshwater runoff to coastal areas will decrease in mid-latitudes and increase around the equator and at higher latitudes (Day *et al*., 2012). The outer tropics and subtemperate zone will be drier, and high latitudes will become wetter. Management should focus on maintaining healthy estuarine ecosystems so that they will be better able to adapt to climate change. This may require ongoing review of and adjustments to the environmental water allocations for estuaries.

5. Conclusions

Strengthening implementation

This review has shown that a range of methods is available for determining the environmental water requirements of estuaries. What is urgently needed is the implementation of recommendations to ensure the protection of estuaries and rehabilitation of stressed or degraded estuarine ecosystems. A method or framework will only be as good as the protection the environmental water requirements have afforded to an estuary. There will be progress if a learning-by-doing approach is initiated and there is implementation, monitoring, and feedback in an adaptive management cycle. On the basis of a number of international reviews, case studies and analysis, Le Quesne *et al*. (2010) proposed a number of guidelines for advancing the implementation of environmental water requirements. These included undertaking a phased approach, limiting allowable water abstraction as soon as possible, and developing clear objectives for environmental water requirement policy based on an inclusive, transparent and well-communicated process. The need for a clear institutional framework, including independent oversight, was also emphasized. Successful local pilot projects were thought to be vital for building technical capacity and political support.

Improving data and knowledge

The implementation of environmental water requirements requires a sound understanding of estuarine processes and the relationship between abiotic drivers and biotic responses. Basic hydrological and biological data are needed to improve confidence in assessments. Quantitative data are required to improve predictions so that there is less reliance on expert opinion. Research should focus on the identification and separation of flow and non-flow related impacts. Information on ecological needs and tolerances of different biota are also important research topics. More demonstration flow restoration projects are needed to validate conceptual models through action research.

Transferability of methods and frameworks

There are many ways in which estuaries have been defined, but this review has identified that the methods used to determine estuarine environmental water requirements have been influenced more by the available knowledge of the system in question and the available budget than by the type of estuary. The same methods and frameworks are being applied across a variety of estuary types in both South Africa and Australia.

Most of the recent methods for determining the environmental water requirements of estuaries fall into the holistic or ecosystem approach. Frameworks have been developed which are not prescriptive about which scientific methods should be used for assessments. These frameworks include elements of risk assessment and adaptive management. Most approaches are data rich and emphasize the need for long term monitoring in estuaries so that the impacts of freshwater inflow alteration and the variable nature of these systems can be understood.

Including social, economic and cultural issues

Because of the demand for freshwater resources and climate change effects on water availability, the necessity of environmental water requirement assessments for estuaries will increase. Future studies should include social, economic and cultural issues in an integrated water resources management framework because of the high levels of competing water uses and the need to link these issues to the process of formulating environmental water requirements. It is the scientist's role to indicate the consequences of different flow scenarios so that trade-offs can be based on sound environmental knowledge. Ecosystem services can be used to communicate results. However, strong governance structures are also needed to ensure implementation and management of environmental flows.

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The Morecambe Bay Ramsar Site in the United Kingdom. ***Photo: Nick Davidson, Ramsar***

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Fawley, the 'Solent and Southampton Water' Ramsar Site in the UK.
Photo: Nick Davidson, Ramsar.

Annex

Table A.1. Examples of inflow, condition and resource based methods used to determine the environmental water requirements of estuaries

Country	Method	Estuary	Reference
Inflow-based methods			
USA	Percent-of-flow	South-Western Florida estuaries	Flannery *et al*., 2002
USA	Water withdrawal regulations	Georgia estuaries: Savannah; Ogechee; Altamaha; Satilla; St Marys	Alber & Flory, 2002
Condition-based methods			
USA	X^2 approach isohaline position	San Francisco Bay estuaries	Jassby *et al*., 1995
Resource-based methods			
USA	Pink shrimp model-indicator species	Florida Bay, Florida, USA	Browder & Moore, 1981, Browder *et al*., 2002
USA	TxEMP	Nueces Estuary, Galveston Bay & Trinity-San Jacinto Estuary	Matsumoto *et al*., 1994 Powell *et al*., 2002
USA	Texas Freshwater Inflow methodology	1. Upper Lavaca Bay 2. Guadalupe & Nueces estuaries 3. Sabine-Neches, Trinity-San Jacinto, Lavaca-Colorado, Guadalupe, Mission-Aransas, Nueces, Laguna Madre 4. San Antonio Bay 5. Nueces Marsh	1. Kalke & Montagna, 1991 2. Montagna & Kalke, 1992 3. Montagna & Kalke, 1995 4. Montagna & Yoon, 1991 5. Alexander & Dunton, 2002, Montagna *et al*., 2009
USA	Valued Ecosystem Component Methods 1.Environmental flows for indicator species. 2.Use of SAV to determine minimum and maximum flows. 3.Environmental flows for target habitats.	1.Loxahatchee River & Estuary. 2.Caloosahatchee Estuary 3.Suwannee River Estuary	Alber, 2002 1.SFWMD, 2001 as cited in Alber 2002 2.Doering *et al*., 2002 3.Mattson, 2002
China	Protection of critical habitat	Yangtze River Estuary	Sun *et al*., 2009 Zhao *et al*., 2009
Australia	Determining flows for fisheries	Gladstone harbour and Cape Capricorn	Halliday & Robins, 2007
Australia	Determining flows for fisheries	Fitzroy, Calliope and Boyne River estuaries	Robins *et al*., 2005, Halliday & Robins, 2007

Table A.2. Examples of holistic ecosystem methods and frameworks used to determine the environmental water requirements of estuaries

Country	Method	Estuary	Reference
UK	Risk Assessment Approach	UK estuaries	Binnie *et al*., 1998
Australia	Risk Assessment Approach	Lake Condah and Darlot Creek the major tributary of the Fitzroy River, Australia	Gippel *et al*., 2008
China	Risk Assessment approach	Jiaojiang and Lingjiang estuaries	Gippel *et al*., 2009b
South Africa	Resource Directed Measures Method / Ecological Reserve Method	Orange, Olifants, Palmiet, Breede, Great Brak, Goukamma, Knysna, Swartvlei, Keurbooms, Matjies, Sout, Tsitsikamma, Kromme, Seekoei, Sundays, East Kleinemonde, Nahoon, Mtata, Mhlanga, Mdloti, Thukela, Siyaya, Mhalthuze, Nhlabane, St Lucia estuaries	Department of Water Affairs and Forestry reports. Adams *et al*., 2002, Taljaard *et al*., 2004
Australia	National River Health Programme approach	1. Richmond River Estuary 2. Emigrant Creek 3. Hawkesbury Nepean River and estuary, 4. Lower Hastings River 5. Shoalhaven	1. Peirson *et al*., 2002. 2. Bishop *et al*., 2001 3. Cox & Peirson 2003 4. Bishop 2005 5. Boyes 2006
Australia	Benchmarking & risk assessment ELOHA Ecological Limits of Hydrological Alteration – Queensland	1. FitzRoy River Estuary 2. Burnett Basin 3. Barron Basin 4. Pioneer Valley 5. Condamine-Balonne Basin 6. Logan Basin, Mary Basin, Burdekin Basin	1. Brizga *et al*., 2002 2. Brizga, 2000; Brizga *et al*., 2000 3. Brizga *et al*., 2001a, 2001b 4. Brizga *et al*., 2001c, 2001d 5. DNR 2000 6. Arthington *et al*. 2006
Australia	FLOWS Victoria	Werribee & Gellibrand estuaries	Sherwood 1983, Sherwood *et al*. 2005, Hardie *et al*. 2006, Lloyd *et al*. 2008
Australia	BAFFLER,	Wilson & Torbay estuaries (Bayesian Adaptive Framework for FLows to maintain Estuarine Resources)	Close 2005, 2007
USA	Ecological Sustainable Water Management, ESWM framework	1. Apalachicola River and Bay, Gulf of Mexico, Florida 2. Savannah River- floodplain-estuarine system and adaptive management of Thurmond dam.	1. Richter *et al*. 2003, 2005 2. Richter *et al*. 2006 Wrona *et al*. 2007

Table A.3. Examples of modelling studies used to determine the environmental water requirements of estuaries

Country	Method	Estuary	Reference
USA	Numerical modeling	Lavaca-Tres Palacios Estuary and the Matagorda Bay system, Texas	Bao & Mays, 1994
USA	Numerical modeling	Pascagoula River & Estuary	Harza, 1995, Riecke, 2002, cited in Peirson *et al*., 2002.
USA	Bioenergetic model	Lavaca-Colorado Estuary	Hae-Cheol & Montagna, 2009
Australia	Numerical modeling	Derwent Estuary, Tasmania	Davies, *et al*., 2002
Australia	Hydrodynamic-ecological numerical model	Swan River, Australia	Chan, *et al*., 2002
Australia	Simple Estuarine Response Model, SERM	Brunswick River estuary- New South Wales, Huon River estuary- Tasmania, Maroochy River estuary- Queensland, Port Phillip Bay- Victoria, Wilson Inlet- Western Australia Gippsland Lakes	Baird, *et al*., 2001
Australia	Simple flow and salt models	Swan River, Western Australia	Kurup, *et al*. 1998
China	Salinity, fresh-water inflow relationships	Haihe, Zhangweixin, Luanhe estuaries	Sun & Yang, 2004
Portugal	Ecohydrology model	Guadiana Estuary, South Portugal	Wolanski *et al*., 2006
France	Hydrographic, biogeochemical and hydrody-namic linked models	Seine River Estuary	Even *et al*. 2007
Senegal	Hydraulic, hydrodynamic modeling, GIS & decision support	Senegal River floodplain and estuarine areas	Duvail & Hamerlynk, 2003
China	Water cycle, bio-logical cycle, and habitat water requirements	Haihe River Basin: Haihe, Luanhe, and Zhangweixin estuaries	Yang *et al*., 2005

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