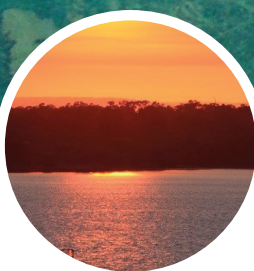




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Research and information priorities for estuary management in southwest Western Australia

2017 Report



An independent report by the Western Australian Marine Science Institution funded and supported by the Department of Parks and Wildlife (former Swan River Trust) and the Western Australian Department of Water.

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Main Cover Photo: The Dawesville Cut, Peel-Harvey Estuary by Felicity Bunny

Back Cover Photo: Dolphin in Leschenault Estuary by Ash Ramsay.

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Executive summary

This report presents a prioritisation of the science and monitoring needs for southwest Western Australia (WA) estuary management as determined through consultation with estuary managers and researchers.

The purpose is to assist researchers to focus on high impact studies, and to help plan a more strategic and collaborative approach to developing information for future management through independent peer reviewed science. The priorities should also help guide the science activities that will be required to support effective policy initiatives such as the Regional Estuaries Initiative, Green Growth Plan for Perth-Peel and the Swan-Canning River Protection Strategy.

Estuaries are a vital part of our landscape both socially and economically. As a community, we receive a wide range of benefits from estuaries – liveability of cities and towns, recreational opportunities, sacred sites, ports and harbours, bird sanctuaries, food resources, flood mitigation, and nutrient assimilation to name some. However, numerous pressures, associated primarily with catchment development and exacerbated by climate change, have resulted in impaired ecosystem health in several popular estuary systems.

These pressures are expected to intensify in the future. If not halted, tipping points may be reached where the environment can no longer absorb additional pressures and the values held by communities may be lost. Such was the case for the Peel-Harvey due to frequent noxious algal blooms in the 1960s. This situation was alleviated, though not fully resolved by a costly engineering solution, the Dawesville Cut. It is unlikely that such interventions are feasible logistically and/or financially in our other at-risk estuaries. Estuarine ecosystems can take a minimum of 15-25 years and extraordinary investment to recover, and complete functioning may take another 25 years or never be restored (Borja et al., 2010).

The challenge facing managers and scientists is to enable further population growth and associated economic activity in these popular areas of the State while maintaining, and in some cases revitalising, healthy estuaries as expected by communities.

Managing the balance at the margins of sustainability means that policy makers and managers need evidence to ensure their decisions are cost-effective and will deliver the desired outcomes. The alternative is uninformed decision-making and policy that is likely to result in substantial investment of public funds, or precautionary regulation of development, without achieving healthy estuaries.

The identification of knowledge gaps for estuary management was established through consultation with estuary managers and researchers. An initial survey identified eleven key themes and associated knowledge gaps across the biophysical and socio-economic spectrum.

A subsequent prioritisation process applied by the Working Group has identified a number of knowledge needs detailed as research priorities and enabling priorities.

This process has shown that some managers and researchers believe that sufficient evidence is not currently available, and is not being developed at the rate required for the imminent management decisions. In some cases, best available information is being used for decision-making, but this information does not provide the certainty of outcome required in all cases.

The key **enabling priorities** that will support both managers and researchers, include the following:

E1. Monitoring and modelling – a stable and enduring platform

A commitment to ongoing baseline monitoring programs that are driven by the needs and questions being asked by manager is a fundamental requirement. Long-term baseline data supports both the determination of current state and model development and validation. A framework with agreed protocols would allow efficient and effective modular model development. Research on other critical knowledge gaps should be undertaken in a way that facilitates inclusion in future models.

E2. Effective, frequent assessment – report on condition/trend

A Report Card Framework is an essential element of an effective science-based estuary management program. This provides all stakeholders with a mechanism to understand the current status and trends in estuary health. In addition, Report Cards enable a broader assessment and communication on the socio-economic elements relevant to estuary management.

E3. Ability to inform catchment management – assess and forecast effectiveness and intervention scenarios

Through integrated system modelling, a predictive capacity to test scenarios of land use change and interventions is a necessity, as well as ensuring the performance of interventions are monitored, assessed and communicated.

E4. Effective Communication

A planned and coordinated communication framework which facilitates evidence-based decision-making rather than opinion.

The key **research priorities** identified, necessary for estuary management are:

R1. *Estuary metabolism and nutrient cycling (Theme: Water Quality)*

The transport, cycling and fate of nutrients and organic matter (including microbial pathways) is a major constraint for understanding water quality and biotic response – and indeed modelling these aspects of estuarine function.

R2. *Ecosystem function and food web dynamics (Themes: Key Habitats and Biota)*

Ecological connectivity, the role of different habitats (e.g. as fish nursery grounds), trophic interdependence and the ecological role of aquatic and fringing plants to mediate eutrophication. Increased understanding of physiological tolerances of key species is also important. Quantitative understanding food webs and their linkages to catchment and estuarine drivers, is further required for ecological modelling.

R3. *Innovation in managing nutrient pollution (Theme: Land use)*

Identifying innovative ways of managing nutrient pollution in urban and rural areas, as well as assessing the performance of Best Management Practices (BMPs) are required to address the problem of diffuse nutrient pollution.

R4. *Climate change impacts (Themes: Coastal Engineering, Habitats, Biota and Human Health)*

Research on coastal inundation patterns related to climate change will allow informed decision-making with respect to infrastructure and coastal community development. Predictive capacity in this research area has a direct ability to reduce the risks and costs associated with poor planning decisions around our estuaries. Similarly, this research could assist with assessment of future human health risk areas, e.g. vectors of mosquito-borne viruses associated with inundation and harmful algal bloom response to climate change.

R5. *Socio-economic assessment and Indigenous knowledge (Theme: Socio-economic aspects)*

Establishing agreed methodologies to assess socio-economic benefits, in a quantitative and spatially explicit way, and one that can be used to assess costs and benefits of future scenarios and planning decisions, is also critical for effective management of our South West estuaries. How to better integrate Indigenous knowledge into management is also required.

R6. *Integrated systems modelling (Themes: all)*

Continued investment in integrated system modelling was seen as important across all themes. This will enable the synthesis of bio-physical data, process understanding and predictive tools to directly support decision-making. Research is needed to link land-use change with estuarine response in a predictive manner.

Finally, we stress the importance of collaboration in bridging the interface between management and research. Robust, ongoing partnerships must be supported and sustained. Given the multi-disciplinary nature of estuary science and the complex social context, true collaborative partnerships are a crucial element in the delivery of an effective science-based framework for estuary management.

1 Introduction

1.1 Background

The *2011 State of the Australian Environment* reported that Australia's southern estuaries are heavily degraded and not improving, and that the rivers that flow into these estuaries are in very poor condition and still degrading (DSEWPaC, 2011).

Most South West estuaries are modified in terms of their hydrological connectivity to both the floodplain and ocean; their catchments have been extensively cleared and used for agriculture, urban and industry developments; and extensive application of water soluble fertilisers has resulted in nutrient loads well in excess of the assimilative capacity of the receiving waters. All of these drivers constitute pressures on estuarine ecosystems. Dramatic reductions in stream flows in the last 10 to 20 years are exacerbating these pressures.

In parallel, community expectations of estuaries are high. Most of the Western Australian population live around estuaries; they are important economically, aesthetically, recreationally and culturally, and therefore the socio-economic context is complex.

Following a number of dolphin deaths in the Swan-Canning and Leschenault Estuaries in 2009, a Dolphin and Estuary Health working group was established to investigate the state of dolphin and estuary health in Western Australia. One of the key recommendations from the final report was to develop a collaborative estuary science structure with broad representation from government, research, industry and community sectors.

In 2012, a forum of 150 delegates gathered to develop a shared vision for the estuaries of southwest Western Australia (Healthy Estuaries 2111 Forum, 2012). Here again, part of the vision was to develop a 'clear understanding of estuary health through an accessible scientific knowledge base and increased technology.'

These findings and approaches are not unique to our region. A key element identified for successful estuary management programs from other parts of the world include a coordinated and strategic science-based understanding of the estuary condition and threats.

In response to these events and recommendations, the Western Australian Marine Science Institution (WAMSI) formed a project to bring together researchers, managers, interested parties and others to build a common agreement on what the knowledge priorities for estuary management are, and enhance the collaborative approach to delivering them. The vision and key elements of what this consultative process is ultimately trying to achieve are summarised in Figure 1.

The focus of the current document is purely on the actual knowledge needs to better support the management of southwestern estuaries, irrespective of the governance structure and the delivery mechanism. A governance and funding model to deliver an aligned research agenda will be addressed in the future.

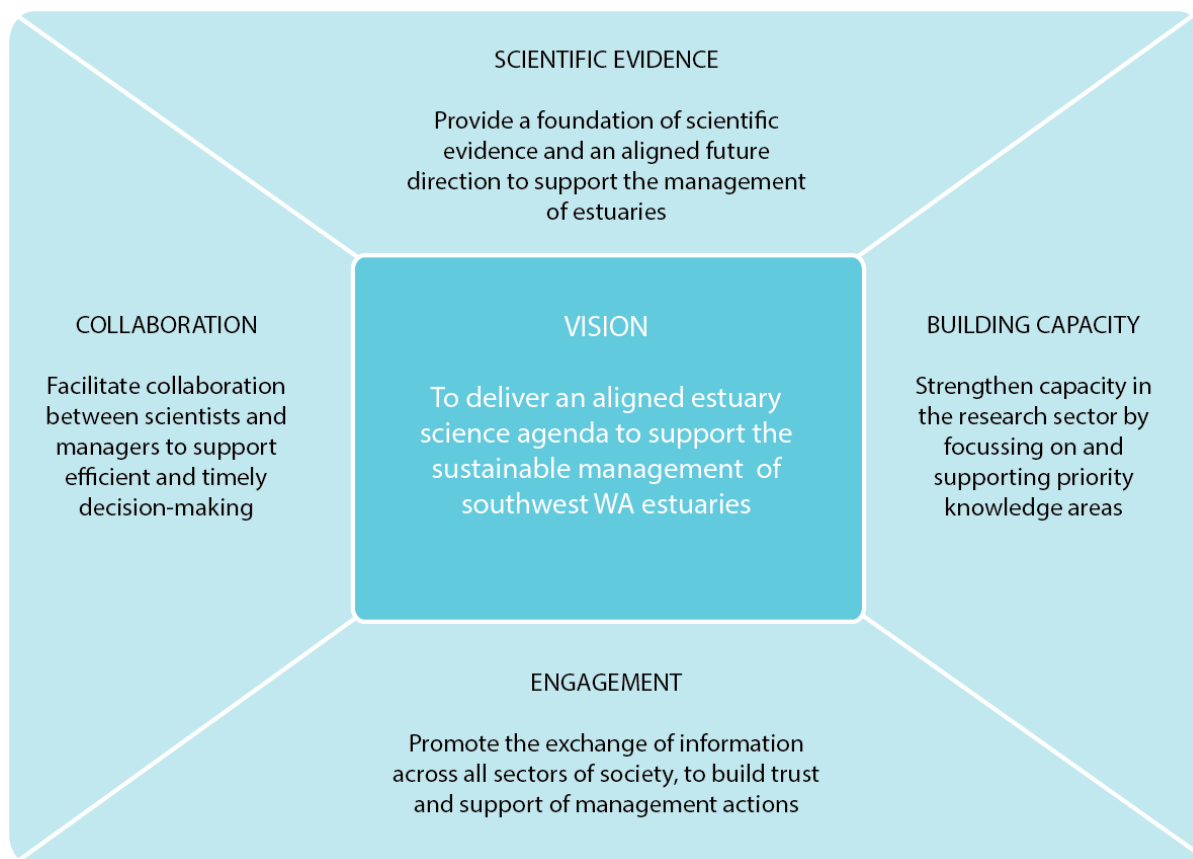


Figure 1 Vision and key elements for this consultative process.

1.2 Estuary Values

Estuaries hold significant social, economic and environmental values. All of the major urban centres of the South West are situated around estuaries, which provide aesthetic values, recreational opportunities, ports for trade, health and well-being benefits for both Indigenous and non-Indigenous communities and tourism opportunities. Environmentally, they are highly productive, diverse ecosystems providing a wealth of ecosystem services such as:

- nutrient assimilation
- carbon dioxide sinks (fringing habitats, seagrass beds and phytoplankton)
- flood mitigation
- storm surge protection
- biodiversity
- nursery habitats for estuarine and marine recreational and commercial seafood species.

In recent years there has been research into the monetary value of estuaries. For example, the seven South West estuaries considered in this report have been estimated to contribute \$805 million USD per annum in services to the Western Australian community and economy (2011 dollar value - Costanza et al. (2014)). However, as identified through this process, the

lack of a consistent model for socio-economic analysis means there is no standard approach or set of figures that can be applied.

That being said, millions of Western Australians do or will live near estuaries as Perth and the South West populations increase. It can be assumed that they will value clean healthy estuaries highly, and expect Government to avoid the collapse of these systems (Metcalf et al., 2014).

1.3 Pressures on Estuaries

Historic and future urban, agriculture and industrial development around estuarine systems has already resulted in impaired condition, and future development (urban, agriculture or industrial) has the potential to cause estuary condition to decline dramatically if not managed sustainably. There are 40 estuaries in the South West region and 166 estuaries in total in Western Australia (NLWRA, 2002). In the latter audit, only one estuary in the southern half of WA was considered near-pristine (Broke Inlet).

The most immediate and direct threat from development pressure is eutrophication, that is, excessive nutrient enrichment expressed as algal blooms, fish kills and anoxic bottom waters. Many South West estuaries are impacted to some extent by eutrophication, with a number of areas showing signs of severe eutrophication; for example the Swan Estuary was noted as one of the most hypereutrophic in a global review of 131 estuarine-coastal ecosystems (Cloern et al., 2013). Reduced rainfall linked to a broader, longer-term climate change in the South West has resulted in a dramatic decline in stream flows in the last 10 to 20 years. This decline in flows combined with increasing trends in water temperatures have exacerbated existing eutrophic symptoms in the brackish water zones of many South West estuaries. Furthermore, urban development in the vicinity of eutrophic waterways may present an increased risk from mosquito-borne viruses such as Ross River Virus.

The major pressures affecting estuaries are a combination of human impacts, climate change and extreme events (Table 1) (Jennerjahn and Mitchell, 2013). Many of these pressures are expected to increase in the future, such as population and agricultural growth, climate change impacts and the frequency of extreme events.

While these pressures can be explained separately, they act together in combinations termed multiple-pressures and their combined impact is often greater than the sum of their parts. Ecological cascades can result where changes in one aspect have significant flow-on effects to other seemingly non-related attributes of the ecosystem.

Consultation suggests that in most South West estuaries we have reasonable a understanding of the level and source of key pressures, however, there is less certainty regarding the potential impact when these multiple pressures act in synergy and as baselines shift due to climate change (Duarte et al, 2009). Yet, decision-makers require estimates of both of these elements for management.

Table 1 Major pressures affecting estuaries (from Jennerjahn and Mitchell, 2013).

Human impacts

Agriculture, urban and industrial activity	Nutrients and other contaminants transported into the estuary
Dredging	Direct impact on the seafloor, turbidity, contaminant release and spoil ground effects
Foreshore infrastructure	Direct clearing of habitat for foreshore
Fishing	Removing species that make up part of the ecosystem
Legacy impacts	Nutrients and toxicity entering the system now due to pollution decades ago (e.g. through groundwater or benthic sediments)

Climate change

Less inflow from rivers	Less freshwater entering estuaries
	Less flushing of nutrients and other contaminants
Higher sea level	Pressure on freshwater species and fringing habitats
Higher temperatures	Estuary water (shallow bodies) heats up to less hospitable levels and/or impacts key biological activities such as spawning

Extreme events

Heatwaves	Serious heating
Major rainfall	Washes large slugs of pollutants into an estuary

There is a strong relationship between catchment clearing and poor water quality (Figure 2). This is due to high sediment and nutrient loading, both of which promote algal blooms, anoxia and fish kills.

The condition of the seven socio-economically important estuaries discussed can be described in general terms as poor or deteriorating. There has already been substantial loss in economic value of our estuaries since their peak of productivity, particularly in terms of commercial fisheries (Fletcher and Santoro and, 2010). Fish kills and algal blooms are a problem in these estuaries so that in some cases artificial oxygenation has been installed – for example, in the Swan and Canning rivers and the Vasse-Wonnerup Estuary.

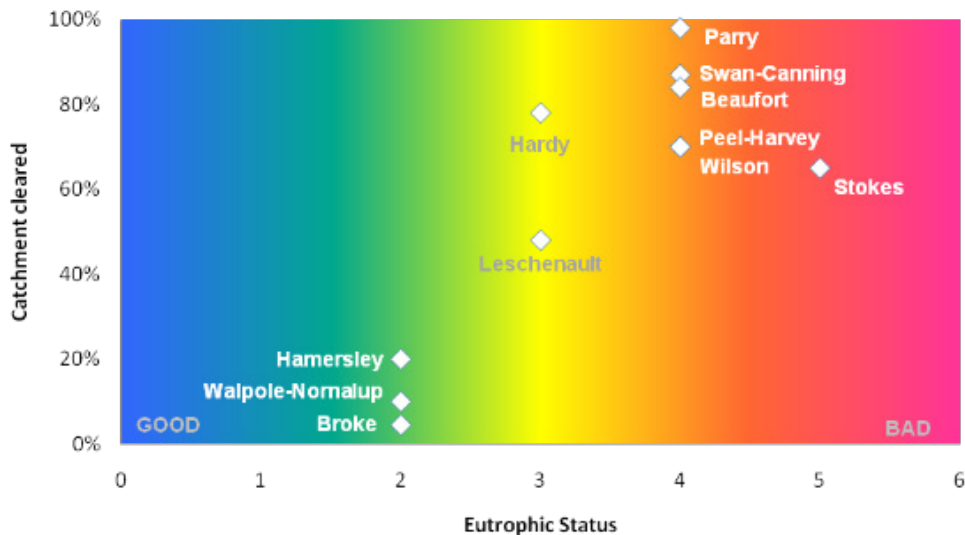


Figure 2 Relationship between catchment clearing and eutrophic status*

*Eutrophic status is based on 5 water quality indicators – chlorophyll a, dissolved oxygen, seagrass loss, macrophyte blooms and harmful algal blooms, following the ASSESSMENT of ESTUARY TROPHIC STATUS (ASSETS) model (Bricker et al., 2003) (DOW, unpublished).

1.4 How pressures can compromise values

Estuaries can withstand, tolerate or adapt to a certain amount of pressure, a state called homeostasis (Elliott & Quintino 2007), and are also resilient to some further change by absorbing disturbance and reorganising while undergoing change and maintaining function (Walker et al., 2004). Estuaries are thought to respond non-linearly to gradual changes in environmental conditions, with sudden and major changes occurring when change can no longer be dealt with by the system (Scheffer et al., 2001).

Eutrophication is a pervasive example of how pressures on the estuary can manifest as altered ecological function with reduced societal benefits. Inputs of nitrogen and phosphorus from the catchments can stimulate plant growth, leading to overgrowth of macrophytes, macroalgae and/or microalgae within the estuary. Overgrowth of macrophytes may have relatively minimal effects on ecosystem function but reduce visual amenity and navigability within the estuary. Overgrowth of macroalgae or microalgae may cause more significant shifts in condition due to dramatic drops in dissolved oxygen when the blooms collapse – potentially causing pervasive whole-of-ecosystem kills in the affected areas, often manifesting to the broader public as “fish kills”. Another more unfavourable outcome is that of harmful algal blooms, which can have human health impacts either from direct contact with the microalgae or by consumption of shellfish, poisoned from the bioaccumulation of algal toxins.

Estuarine ecosystems can take a *minimum* of 15-25 years to recover from severe degradation, and complete functioning may take another 25 years (Borja et al., 2010). It should also be

noted that once a pressure has been reduced, the recovery trajectories in aquatic ecosystems vary, so understanding these pathways is critical to establishing meaningful targets (Duarte, 2009).

1.5 Estuary Management in Western Australia

Estuaries are multiple-use, have multiple jurisdictions and consist of complex land-bound water bodies whose condition is inextricably linked to land activities. As such, there are a great number of agencies and groups with both an interest and an ability to influence estuary health.

The Planning and Development Act administered by the Western Australian Planning Commission (WAPC) and Local Governments provides the initial decision as to what activities can occur on a given parcel of land. This decision is a rather blunt instrument by which to manage pressures on estuaries. However, careful placement of activities and adoption of 'best-practice' in development can dramatically reduce the impact of a given activity on the estuary.

Other smaller levers for Government include the Department of Environmental Regulation's regulation of certain activities and Department of Water's regulation of the use of water.

The Department of Water (DoW) is also the lead agency for providing the technical advice to all other agencies responsible for estuary management in Western Australia (for areas outside of the Swan-Canning, where the Department of Parks and Wildlife has the lead¹). The DoW (and its predecessors the Water and Rivers Commission and the Waterways Commission) has had a history of integrating science studies to meet water quality management and policy needs. DoW's key role has been focused on achieving water quality improvements and preventing further water quality decline through the development of non-statutory Water Quality Improvement Plans (WQIPs), which set out priorities for the range of other agencies and other organisations to undertake.

There has been active management of the State's most at-risk estuaries over the last 20 years (see Appendix E). Water quality improvement plans have been developed for six South West sub-catchments (Figure 3) (DOW, 2010a; DOW, 2012; Hugues-dit-Ciles, et al., 2012; EPA, 2008; SRT, 2009 & WRC, 2003). These detail the catchment nutrient loads, required reduction targets and potential management actions to achieve targets. Where nutrient sources are diffuse, as is the case for most South West estuaries, nutrient reduction requires a range of actions which are not readily implemented and tend to take many years to see improvements. Engineering solutions to improve water quality have been developed for some of the most impacted estuaries, such as artificial oxygenation plants used in the Swan and Canning Rivers

¹ Note the recent amendments to the Swan and Canning Rivers Management Act (2006), previously administered by the Swan River Trust

and the Vasse-Wonnerup Estuary. These address the worst symptoms but have not addressed the underlying problem of catchment-derived nutrient enrichment.

Catchment management groups have also been active in South West estuaries through the preparation of Estuary Management Plans, working in partnership with government and communities delivering on-ground works such as stream and foreshore restoration. Specifically, the regional NRM organisations active in estuary/catchment management are the Peel-Harvey Catchment Council, Perth NRM, South West Catchments Council and South Coast NRM. Links to these groups and their activities can be found via www.nrmwa.org.au.

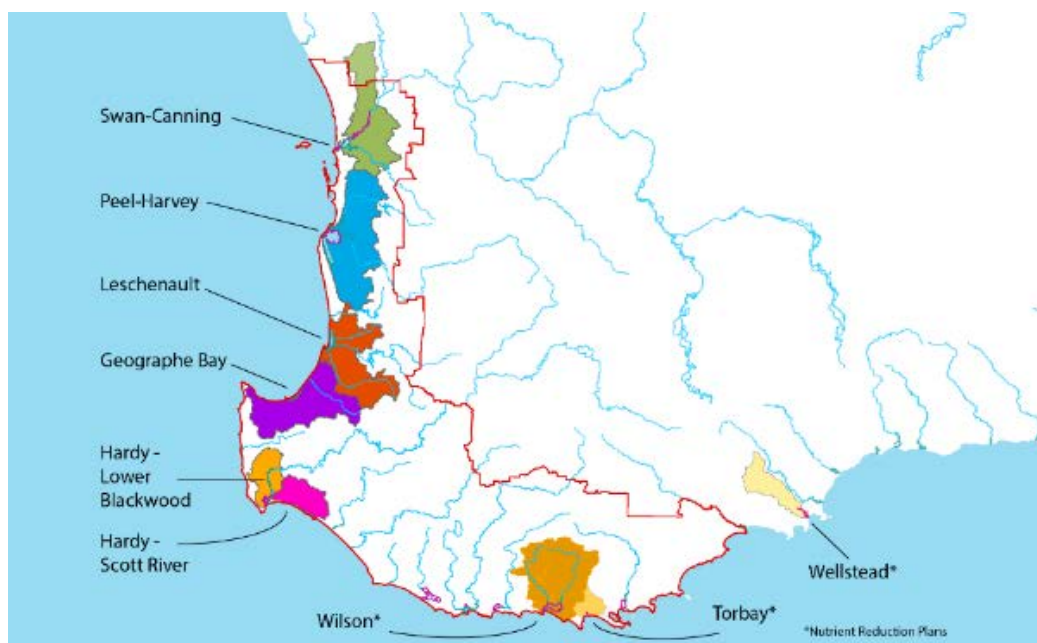


Figure 3 Estuary-catchment water quality improvement plans in the South West region (NB. Wilson, Torbay and Wellstead have nutrient reduction plans, the Greater Avon catchment is excluded).

Estuaries and their catchments are also indirectly influenced through the day-to-day activities of many other agencies. The effect of these activities on estuary condition is rarely explicitly considered.

Conservation of estuarine fauna and flora is the responsibility of the Department of Parks and Wildlife (DPaW) where the estuarine environment is vested in the Conservation Estate. For South West estuaries these areas are limited to sections of the lower Swan and the Walpole-Nornalup Marine Park. The Department of Fisheries (DoF) is responsible for management of exploited fish and invertebrate resources but also assesses risk levels for all aquatic habitats including estuaries.

The *Perth and Peel Green Growth Plan for 3.4 million* (Green Growth Plan) contains a number of measures to cut nutrient run-off into the Swan-Canning and Peel-Harvey estuaries and

ensure the health of these systems over the long term. The implementation of these measures will provide significant improvement in these estuaries.

The South West Native Title Settlement agreement (2015) will have key implications for joint management of conservation and land estates. The Settlement is a landmark native title agreement for the State of Western Australia and is the most wide-ranging native title settlement in Australia to date. It is anticipated that the Settlement will provide for the establishment of joint management arrangements across the South West and will facilitate relationships between the Department of Parks and Wildlife and Noongar people.

Whilst the governance structure is recognised as a critical element in effective estuary management, it is not our intention in this process to propose what the governance model should be, particularly given the complex social context within which estuaries are situated. Rather, it is to establish what the knowledge gaps are for estuary management irrespective of the governance structure. For reference, the current governing agency responsibilities are summarised in Appendix D.

1.6 The role of science in estuary management

Science provides a key input to the evidence base to guide investment priorities for management, to measure and communicate ecosystem condition and trends and to assess the efficacy of intervention technologies. As clearly demonstrated in effective and efficient estuary management programs in other jurisdictions, such as the South East Queensland Healthy Waterways Program and the Derwent Estuary Program, the defining elements include:

- A stable and enduring, science-based monitoring, modelling and reporting platform
- A modelling platform that can provide robust, auditable results including forecasts and scenarios of potential management options
- Consistent, effective and timely reporting to all stakeholders
- Strong collaborative partnerships between government (State and local), research providers and NGOs working towards an aligned strategy.

The risks of not having a strong evidence base for management are high. Statutory land planning places limitations on land use activities to proactively secure a public benefit, or manage public risk. However, without the right information, judgement rather than evidence provides the best available information for planners.

This can lead to development being promoted in areas where this activity will lead to substantial pressures, or the prevention of development in otherwise sustainable areas through precautionary decision-making.

Infrastructure projects can be sited in the wrong place. For example, port and marina developments are generally expanded adjacent to existing infrastructure to concentrate disturbance. However, another area of the foreshore could actually be a better place to develop for transport outcomes for example, resulting in less dredging and causing less environmental impact.

And finally, poor information may lead to higher costs, or the incorrect scale of mitigation efforts being applied to resolve a problem. These may include activities such as drainage management, bar openings, oxygenation, riparian vegetation rehabilitation, regulation or major infrastructure solutions such as the Dawesville Channel. Rural drainage management is one of the major actions that can be taken to improve water quality in estuaries and is currently the major focus of the Regional Estuaries Initiative in the Peel region. However, in an environment of constrained public funding, it is essential that such expenditure is efficient and effective.

A lack of evidence may also result in decisions being made too late to address a particular issue. At some point, inaction due to these delays may result in more complicated issues impacting on an estuary, which can no longer be resolved by a cheap option and instead must be tackled by larger, more expensive or contentious options.

For example, the delay in implementing catchment management activities for the Peel-Harvey resulted in the \$70 million Dawesville Channel construction. This major investment made immediate, temporary improvements to the system but the underlying issues were not resolved and the catchment management options must now still be funded as the health status of the Peel-Harvey Estuary has again declined.

This lag between expert advice, evidence and then reactive decisions made too late, has been seen in numerous systems including the water allocations of the Murray-Darling Basin and the clearing and subsequent salinisation of Western Australia's wheatbelt.

In summary, the costs of poorly informed decisions can be dramatic both in terms of money, unnecessary regulation, environmental and socio-economic harm.

2 Developing science priorities for management

In 2014, the consultation process to determine science needs for estuary management was initiated by WAMSI through a working group of the key agencies responsible for estuary management and university representatives active in estuary research. In the preliminary stages, the Working Group members agreed on six South West estuaries as case studies for this process. They were selected on the basis that they are either socio-economically important, have a reasonable knowledge base or represent the range of issues observed in the South West region. It should be noted that the Vasse-Wonnerup was added to the list after the workshop due to the Vasse Strategy work that commenced in late 2014. The knowledge gaps related to this system were derived from the Vasse Working Group and the research priorities documented by the South West Catchments Council (Hugues dit Ciles, 2014). The seven estuaries identified as case studies for this process are (Figure 4):

- Swan-Canning – iconic waterway of Perth city with significant catchment agriculture and urban land development
- Peel-Harvey, Leschenault and Vasse-Wonnerup - heavily modified urban and rural mixed catchments
- Hardy and Wilson – moderately modified, generally rural catchments, Hardy with open bar, Wilson seasonally open
- Wellstead – a remote, occasionally open estuary near Bremer Bay, also with an extensively cleared, agricultural catchment.

Key socio-economic and environmental statistics for comparison of these seven estuaries are shown in Appendix B.

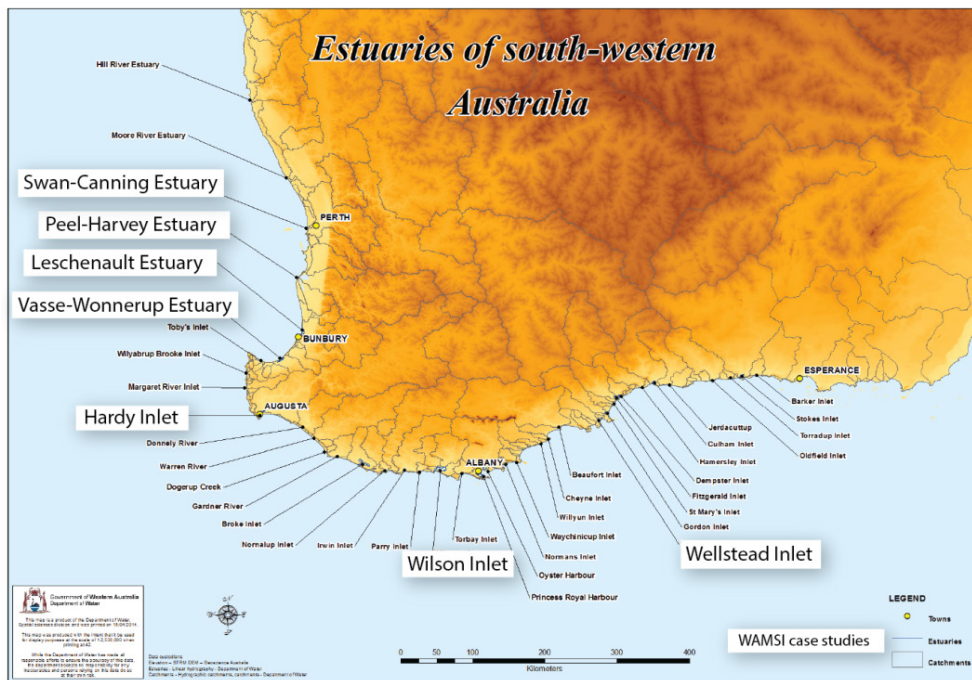


Figure 4 South West estuaries - WAMS case study estuaries highlighted.

A consultative process (Figure 5) has been undertaken to develop a cohesive set of priorities for future research and investment and to improve collaboration in this area. Appendix A acknowledges the participants in this process.

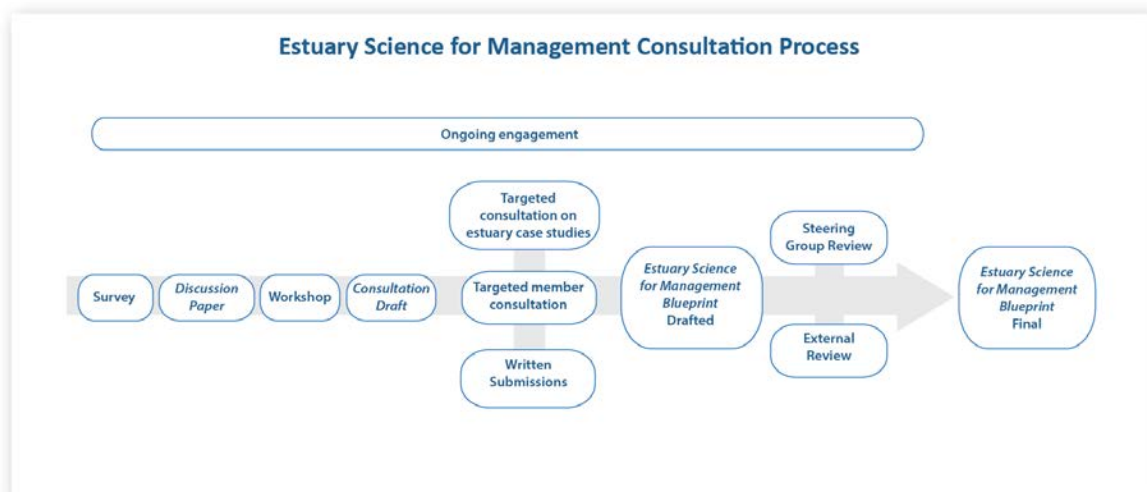


Figure 5 Stages of the consultation process.

The steps that were undertaken include:

- **Initial Survey** - 25 responses to a survey on priorities and capability were received from 19 organisations and 65 individuals. Knowledge gaps were grouped into 11 management themes
- **Workshop** - 56 people from the research and government sectors attended a workshop to clarify priorities for individual estuaries. This workshop was informed by a **Discussion Paper**.
- **Prioritisation** - The working group consolidated the output from the workshop and prioritised knowledge gaps and research priorities based on a framework adapted from David Pannell (Panell, et al., 2013 and 2014) (see Appendix C). The knowledge gaps are broadly grouped under the 11 themes identified in the initial research and management agency survey, and divided into Enabling Priorities and Research Priorities. The Enabling Priorities relate to essential baseline information or decision tools that are essential for management and, in many cases, research investigations as well.

In parallel to the current consultative process, the identification of knowledge gaps has been influenced by the requirements of the Regional Estuaries Initiative (REI) – a four year program to improve the health of six at-risk South West estuaries; the Perth and Peel Green Growth Plan for 3.5 million; the Vasse Strategy and the Swan-Canning River Protection Strategy.

- **Consultation** – The Consultation Draft was released for consultation for one month in July - August 2016.
- **Final report and expert review** - The final report has been reviewed by:
 - Dr Tom Hatton (Independent),
 - Steve Fisher (PHCC)
 - Jan Star (PHCC),
 - John Ruprecht (DAFWA),
 - Greg Claydon (DoW)

The results of the survey, workshop, prioritisation, and consultation inputs are presented in the following sections (3 and 4).

3 Priority knowledge needs for South West estuaries

3.1 Summary of consultation outputs

A varied and extensive range of priorities were agreed by estuary managers and researchers through the consultation process.

Uniformly, there was agreement that:

- Some decisions are already being made without commensurate, defensible evidence and are therefore based only on subjective judgement
- The level of monitoring and reporting must be improved to support efficient and effective management and research
- Prioritisation is necessary as there is limited funding and capability
- A collaborative approach to planning and delivering the level of knowledge required will result in better value for money for the investment of public funds.

The key themes relating to the knowledge gaps that were identified from the initial survey results are:

1. Water quality
2. Key habitats
3. Biodiversity management
4. The effects of catchment land use
5. Coastal engineering and port development
6. Sediment quality
7. Human health
8. Freshwater and hydrology
9. Sustaining resources
10. Socio-economic aspects
11. Integrated system modelling

It is important to recognise the inter-related nature of these themes, each of which essentially concerns the effects of human and natural pressures on the ecological condition ('health') of our estuarine ecosystems and the human populations they support. For each of these themes, specific knowledge gaps have been established, broadly divided into enabling priorities and research priorities. Enabling priorities in this context are described as the science or knowledge that would not be deemed new academic research, and primarily include baseline monitoring, synthesis of current knowledge and development and updating of operational numerical models. These enabling priorities are critical to underpin both management and cutting-edge academic research. Thus, many of the knowledge gaps detailed in the following sections relate to better monitoring, understanding and modelling of estuarine responses to pressures. All listed knowledge gaps are recognised as important, but their relative priority

has been established through the consultation process and by applying the prioritisation methodology detailed in Appendix C.

Formal submissions on the Consultation Draft were submitted by DPaW, DoF, DoP, NRM WA and DoW South coast office. In general terms these comments were positive and some minor revisions to the text were made.

3.2 Water Quality

Importance

Estuaries are situated at the interface between terrestrial, riverine and marine environments and are focal points for major population centres. Estuarine ecosystems are therefore extremely vulnerable to anthropogenic pressures (Kennish, 2002; Lotze et al., 2006), the effects of which are often manifested in declining water quality and cultural eutrophication (Howarth et al., 2011; Statham, 2012). Globally, the most pervading issues include an increasing prevalence of hypoxia and anoxia (Rabalais et al., 2010; Eldridge and Roelke, 2011), algal blooms and fish kills (Anderson et al., 2002; Paerl et al., 2006), and salinisation. Many of these problems are evident in southwestern Australian estuaries. For example, Cloern et al. (2013) showed the Swan Estuary to be one of the most hypereutrophic of the 131 estuarine-coastal ecosystems that were considered in their global review. Maintaining good water quality is important not only for maintaining broader estuarine ecosystem health, but also for supporting human amenity and health.

Primary issues

Declining water quality was identified as the key issue for estuary management by the research and management agencies surveyed. The symptoms and effects of poor water quality, many of which are caused or exacerbated by eutrophication, are evident in many of our systems. Hypoxic conditions periodically impact our estuaries (Hipsey et al., 2014; Tweedley et al., 2015), leading in turn to production of ammonium and hydrogen sulphide and release of sediment-bound nutrients (Middleburg and Levin, 2009; Howarth et al., 2011). Algal blooms, and particularly those of potentially ichthyotoxic dinoflagellates such as *Karlodinium veneficum*, have also occurred regularly in several southwestern Australian estuaries in recent decades (DoW, 2011; Adolf et al., 2015; Hallett et al., 2016). Such hypoxic and/or bloom events may result in significant fish kills (Place et al., 2012; Tweedley et al., 2014) and pose a risk to human health. Other symptoms of declining estuarine water quality include monosulfidic black oozes and hypersalinity, all of which can have significant effects on estuarine ecology (e.g. Hoeksema et al., 2006).

Current state of knowledge

Adequate monitoring programs were in place from around 2000 to 2010 for many South West estuaries including weekly to quarterly monitoring of numerous physico-chemical parameters and a range of nutrients in many South West estuaries since the mid-1990s (e.g. DoW, 2007a), and quarterly monitoring of a reduced range of parameters most South Coast estuaries (e.g. DoW, 2007b). However, these programs have been progressively eroded in recent years. In some South West estuaries only rudimentary water quality monitoring is in place, for example, quarterly monitoring of the Wellstead Estuary. There is also a recognised need to monitor additional parameters (e.g. organic nutrients, Total Suspended Solids) in South West systems (DoW, 2007b). The resulting gaps have hampered our ability to address fundamental research questions on the behaviour and ecological responses of our estuaries to human pressures (Hallett et al., submitted).

Management implications of improved knowledge

Remedial measures to address these problems are not straightforward, but would be greatly assisted by improved monitoring and reporting of estuarine condition. Monitoring data form the basis for assessing condition, developing Water Quality Improvement Plans (e.g. DoW, 2011), establishing estuary health indicators and communication products for all stakeholders and, not least, measuring the effectiveness of management actions. Baseline data are also crucial to enable the development and testing of estuary response models. Fundamentally, monitoring data allow us to develop and test our understanding of how estuarine condition responds to anthropogenic pressures and to the management actions that are implemented to mitigate these pressures.

Integrated and consistent syntheses of monitoring information need to be developed and widely communicated to stakeholders to report estuary health status and trends (Hallett et al., submitted). Annual reporting of status and trends using science-based estuary health indices in a report card format is a proven method that can engage stakeholders from the political to the local community level, as demonstrated, for example, by the Southeast Queensland Healthy Waterways Program, the Derwent Estuary program and many other such initiatives (Longstaff et al., 2010).

Table 2 Science needs for the management of Water Quality

Knowledge gap	Description	Priority*	Linked Themes
<i>Enabling priorities</i>			
Baseline water quality monitoring and reporting (nutrients, carbon etc)	Establish baseline monitoring (where gaps exist) as foundation to estuary management and scientific analyses and reporting to communicate condition and trends	H	
<i>Research priorities</i>			
Estuary metabolism and nutrient cycling	In-estuary - quantitative information on primary and secondary productivity, organic matter decomposition pathways (including sulfidic sediments), nutrient flux from the sediment, sedimentation and bioturbation, and how they respond to environmental variability	H	Sediment quality, Biota,
Phytoplankton response to drivers	Deeper understanding of the dynamics of phytoplankton, especially harmful algal blooms. Currently there is a lack of capacity in phytoplankton ecologists in local research institutions	H	Biota
Sources of water quality threats	Identification of external sources of catchment derived N, P, organic matter, and sediments to the estuarine receiving waters – needed for management because organic loading is also a key driver of estuary metabolism and overall water quality. Identification of sources and lability using advanced biogeochemical techniques such as isotopes and other assessments.	H	Land use, Freshwater hydrology

3.3 Key habitats

Importance

Estuaries typically provide a diversity of subtidal, intertidal and riparian habitats, including seagrasses, mangroves, mud and sand flats, oyster reefs, wetlands and saltmarsh. Together, these habitats fulfil many critical ecological roles and deliver crucial ecosystem services, placing estuaries among the most valuable environments globally (Costanza et al., 1997, 2014). Estuaries are essential nursery habitats for a range of faunal species (Beck et al., 2001; Sheaves et al., 2015), provide crucial support for terrestrial, freshwater and marine foodwebs (Abrantes et al., 2015) and are important sites for carbon storage (Laffoley and Grimsditch, 2009). They also protect water quality and support fisheries, food security, livelihoods and recreation (Barbier et al., 2011; Sheaves et al., 2014). The widespread degradation of estuarine habitats thus has dramatic implications for global biodiversity, ecological sustainability and human welfare and development.

Primary issues

Estuarine habitats across southwestern Australia have been dramatically altered since European settlement and continue to be threatened by numerous anthropogenic pressures (Brearley, 2005; DoW, 2011). The delivery of nutrients and sediment from cleared catchments threatens our estuarine seagrasses, and the collapse of *Ruppia* sp. meadows and development of algal blooms in the Wellstead Estuary in recent years signals a potential tipping point between ecosystem states in this system. Climate change and rising sea levels are likely to have significant impacts on riparian and saltmarsh habitats (McKee et al., 2012; Hallett et al., in prep.), whilst increasing salinisation and erosion are well-recognised as existing threats to our riparian vegetation (Pen, 1999; Calvert, 2002; Hale and Kobryn, 2009). Management needs to understand the health of key habitats as well as the modes of resilience (resistance and recovery), as described for seagrass in Kilminster et al (2015), but is also relevant for other estuarine habitats. The need for restoration of our key estuarine habitats is acknowledged (Creighton et al., 2015), yet there is a widespread lack of appropriate quantitative information to understand longer term trends and direct and evaluate the success of restoration efforts.

Current state of knowledge

There is a broad lack of comprehensive, comparable and repeated habitat surveys across most estuaries in southwestern Australia, with some exceptions such as the annual mapping of seagrass and macroalgae throughout the Peel-Harvey Estuary from the late 1970s to early 2000s and a further study in the late 2000s (e.g. Wilson et al., 1999; Pedretti et al., 2011). More recently, seagrass health indicators have been developed in the Swan-Canning estuary (Kilminster et al., 2014 and Kilminster & Forbes, 2014), and the methodology has also been trialled Leschenault and Peel-Harvey estuaries. The information that does exist is patchy, usually highly specific to a particular consulting or research project, not easily accessible

and/or undertaken at inappropriate scales for local understanding and management, e.g. Facies type mapping by the National Land and Water Resources Audit (data source and quality not well known). There is little commitment to long-term monitoring of these crucial aspects of estuarine structure and function (Hallett et al., submitted).

Management implications of improved knowledge

The lack of contemporary and comparable information on habitat extent, composition, health and resilience is a significant impediment to effective understanding and management of our estuaries. Baseline mapping and monitoring of habitat status is a fundamental requirement for both management and research purposes, and commitment to a robust and ongoing program is required. The minimum requirement would involve estuarine habitat mapping at 3-5 yearly intervals (seagrass, saltmarsh, shallow mud flats, mangroves, fringing vegetation) including, where relevant, assessments of community composition and how key fauna depend and interact with habitats (Hale, 2010; Peel Harvey Catchment Council, 2011). Such information would help identify and track declines in habitat health and/or extent, and direct subsequent efforts to restore the health of e.g. seagrasses or riparian habitats.

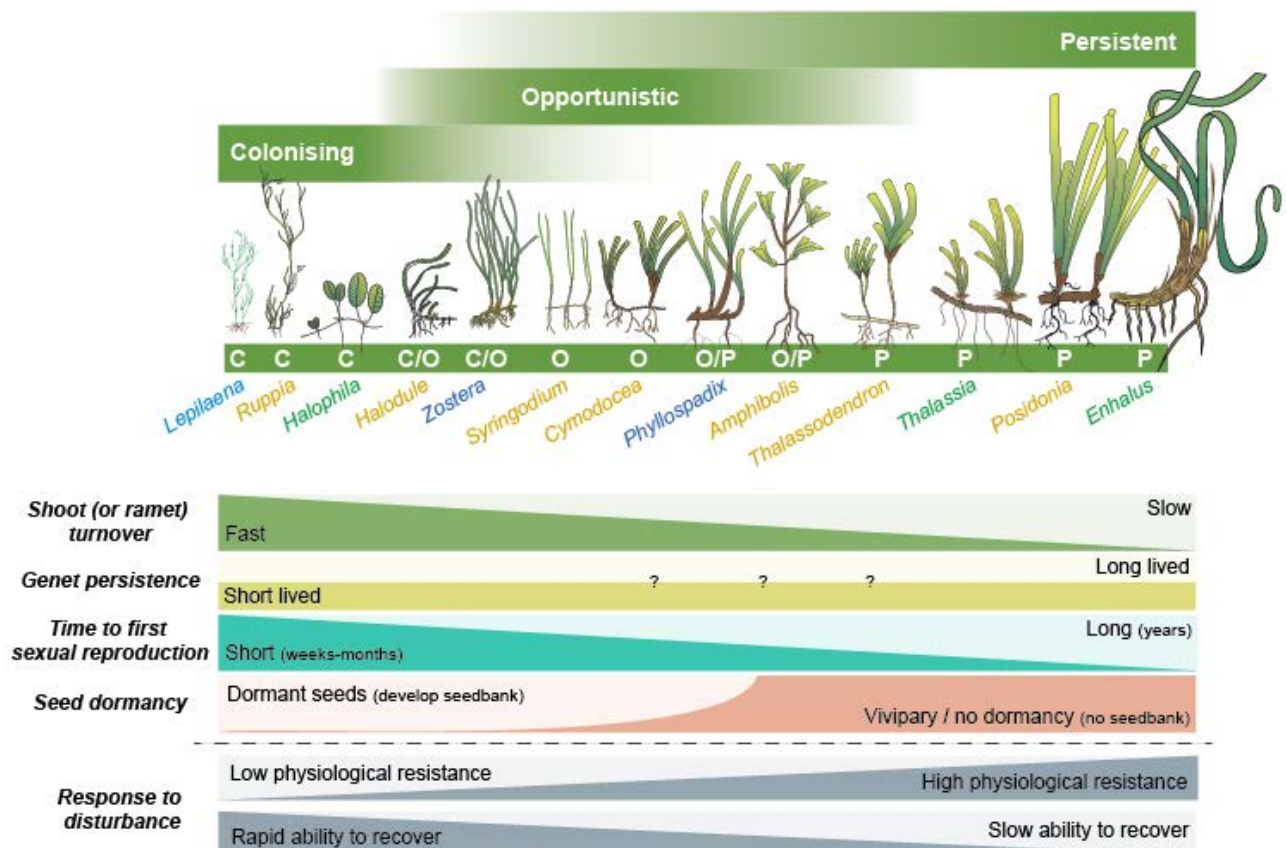


Figure 6 Seagrass species in South West estuaries are typically colonising (*Halophila* and *Ruppia*), therefore their survivability depends on maintaining the seedbank and conditions that trigger germination (diagram from Kilminster et al., 2015, used with permission).

Table 3 Science needs for the management of Key Habitats

Knowledge gap	Description	Priority*	Linked Themes
<i>Enabling priorities</i>			
Baseline - Habitat mapping	Mapping of submerged and fringing vegetation incl. shallow mudflats (3-5 year intervals), community type classification, fish and waterbird usage	H	
<i>Research priorities</i>			
Ecological function	Identify key ecological functions – e.g. seagrass, saltmarsh, mangroves as fish nursery areas, ecological connectivity, trophic links, complexity of habitat, role of SAV and riparian habitats in nutrient and carbon cycle, including carbon sequestration; physiological tolerances of key species	H	Biota, Socio-economic
Health indices	Indicators of estuarine ecosystem health, allowing for the dynamic and variable nature of estuaries	H	Socio-economic
Response to anthropogenic pressures	Impact and response of key habitats to pressures of land use change, urbanisation, water quality and quantity	M	Land Use
Restoration science	Develop understanding of restoration of estuarine habitats – including seed viability, recruitment success, reproduction bottlenecks etc.	M	
Climate change impacts on biota	Sea level rise, temperature increase and decreased flow impacts on species, processes and energy flow; resilience including potential for habitat adaptation and migration Evaluate species for increased salinisation; sea level variability	L	Biota
Invasive species	Monitoring and impact on habitats	L	Biota

3.4 Biodiversity

Importance

Estuaries are dynamic systems that harbour unique and highly adaptable biotic communities and help to support populations of marine and freshwater species (Elliott and Quintino, 2007). Aside from its intrinsic value, the maintenance of such biodiversity is essential to ensure that ecosystems function appropriately (Hooper et al., 2012; Midgley, 2012) and continue to provide ecosystem services (Basset et al., 2013). Globally, estuarine biodiversity is threatened by multiple pressures, including invasive species, habitat loss, fishing, eutrophication and pollution, altered hydrology and climate change (Kennish, 2002; Gillanders et al., 2011).

Primary issues

Hypoxia, algal blooms, deteriorating water quality and urbanisation impact the fish and invertebrate communities and other aquatic life of southwestern Australian estuaries (Wildsmith et al., 2009; Tweedley et al., 2015; Hallett et al., 2016), including iconic species such as the black swan, black bream, western school prawn and dolphins. Invasive fish and invertebrate species are established in rivers and estuaries across the region, posing a significant threat to native fish populations (Beatty et al., 2013, 2014). In addition, climate change is likely to exacerbate existing threats to biodiversity and impact the distributions, behaviour and survival of many species that inhabit our estuaries (Gillanders et al., 2011, Thompson et al., 2015; Hallett et al., in prep.).

Current state of knowledge

There is great potential for estuarine flora and fauna to be employed as indicators of estuarine health in southwestern Australia (Kilminster et al., 2014; Cottingham et al., 2014, 2015a; Hallett et al., 2016). However, to do so we need longer-term, comparable data sets on these groups to allow us to better characterise their natural variability and ecological requirements and thus understand and even predict their responses to a range of natural and human pressures (Hallett et al., submitted). Currently, and despite the presence of globally significant biotic communities in several of our estuaries (e.g. DoW, 2011), the available information for most biological groups is predominantly limited to sporadic surveys (e.g. Lane et al., 2007; Hale, 2008; Wildsmith et al., 2009), with very little regular, comparable and quantitative monitoring (Hallett et al., submitted).

Management implications of improved knowledge

Science requirements around managing Biodiversity overlap to a large degree with those under the Water Quality and Habitats themes, as the three themes represents complementary and inter-related aspects of estuarine ecological condition. One area that was consistently rated as a high priority was more efficient generation of baseline data for estuaries, and better use (accessibility and integration) of existing datasets. Such baseline

data on biodiversity would facilitate the development of robust ecosystem models, and allow us to develop biotic indicators of estuarine health (e.g. Hallett and Tweedley, 2015) and thus quantify, track and communicate future changes in estuarine health (Hallett et al., submitted). Improved understanding of species interrelationships and energy transfer through different trophic levels is crucial for managing biodiversity issues.

In addition, baseline biodiversity information is required to demonstrate that the management of significant flora, fauna and ecological communities is meeting national and international obligations. These include the *Ramsar Agreement* and *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act).



Figure 7 There is almost no information on South West estuary phytoplankton-zooplankton interactions - fundamental knowledge for understanding food web dynamics.

Table 4 Science needs for Biodiversity management

Knowledge gap	Description	Priority*	Linked Themes
<i>Enabling priorities</i>			
Baseline - biotic data	Establish baseline data for key biota (including: phytoplankton, zooplankton, benthic fauna, meiofauna, fish and waterbirds) where gaps exist	H	
<i>Research priorities</i>			
Food web understanding	Improve the quantitative/qualitative understanding of foodwebs and linkages to drivers, trophodynamics for ecological modelling	H	
Determine limits of acceptable change	Determine reference points, understand natural variability, and establish decision rules with regard to important species and Ramsar requirements	H	
Eutrophication impacts	Investigate how deoxygenation impacts on diversity/complexity	M	
Health indices	Develop indicators of change for different trophic levels	M	
Ecology of listed, target or high value species	Improve understanding of the environmental/habitat requirements of socio-economically important species, such as dolphins, black bream, prawns, crabs, waterbirds	M	
Climate change impacts	Understand the impacts of sea level rise, temperature increase and decreased rainfall on species, processes and energy flow	M	
Ecological connectivity	Connectivity – between estuarine reserves and ecosystems	L	
Efficient screening for exotic marine pests	More efficient and effective methods for early detection of exotic marine pests	L	
Contaminants	Investigate the impact of contaminants on ecosystem health, For example: Impact of mosquito spray on non-target species, wider ecosystem impacts	L	
Biodiversity measures	Explore metagenomics as a mechanism for measuring diversity	L	

3.5 Land use practices

Importance

The clearance of catchments for agricultural and urban land use has dramatically increased the loads and rates of delivery of sediment, nutrients and other pollutants to estuaries worldwide (Howarth et al., 1991; Cloern, 2001). The negative effects of these pressures on water quality and broader ecological condition (Howarth et al., 2002, 2011; Edgar and Barrett, 2000) are exacerbated by the nature of estuaries as sinks in which nutrients and pollutants may accumulate. For example, long residence times can encourage nutrients to accumulate in estuarine sediments, creating so-called legacy effects that hinder the management of eutrophication (Sharpley et al., 2014).

Primary issues

Estuaries in the South West exhibit the effects of degradation associated with catchment clearing and land use (Zammit et al., 2005; DoW, 2011). Natural characteristics of our soils and the widespread removal of catchment and riparian vegetation (Hatton et al., 2003) enhance the delivery of nutrients and sediments to our rivers from diffuse agricultural and pastoral sources, whilst urban sources have also supplied high levels of nutrients and contaminants to some of our estuaries (Rate et al., 2000; Nice and Fisher, 2011). Land use practices resulting in the disturbance of acid sulfate soils can deliver trace metals and rare earth elements to estuaries (Kilminster & Cartwright 2011, Morgan et al 2012a, and Morgan et al 2012b), with relatively unknown effects. The effects of these inputs on many of our microtidal estuaries are exacerbated by their relatively long residence times (Tweedley et al., in press), which are likely to increase further with ongoing declines in river flows attributable to climate change.

Current state of knowledge

Assessment of the impacts of land use on water quality is currently based on the expected application rate of nutrients of those land uses combined with the expected interactions between the land use, land management practices, soil type and landscape morphology. We therefore need to better quantify the effects of catchment land use practices on estuarine water quality (e.g. Wilcock et al., 2013) and broader ecological condition, necessitating appropriately-designed long-term monitoring programs and novel tools to better quantify these effects (e.g. Bricker et al., 2003).

The ARC Linkage project (LP150100451) aims to address these priority knowledge gaps in the Peel Region. The project will focus on developing a predictive decision support framework to help identify land-planning solutions that best optimise trade-offs between catchment development aspirations ('societal health') and estuarine ecological integrity and ecosystem service delivery ('estuarine health'). This will include determining the ways in which catchment inputs and internal estuarine processes interact to influence estuarine

environmental quality, and unravelling the specific nutrient source-fate pathways from different catchment land uses.

Management implications of improved knowledge

Addressing recognised knowledge gaps will enable managers to (i) better quantify the relationships between activities undertaken in a catchment, the quality of the water subsequently discharged to the estuary, and the ultimate effects on estuarine condition and ecosystem service provision, (ii) identify critical nutrient sources to help prioritise management efforts, (iii) evaluate, communicate and ultimately optimise the outcomes of management activities such as riparian habitat restoration and the implementation of Best Management Practice (BMP).

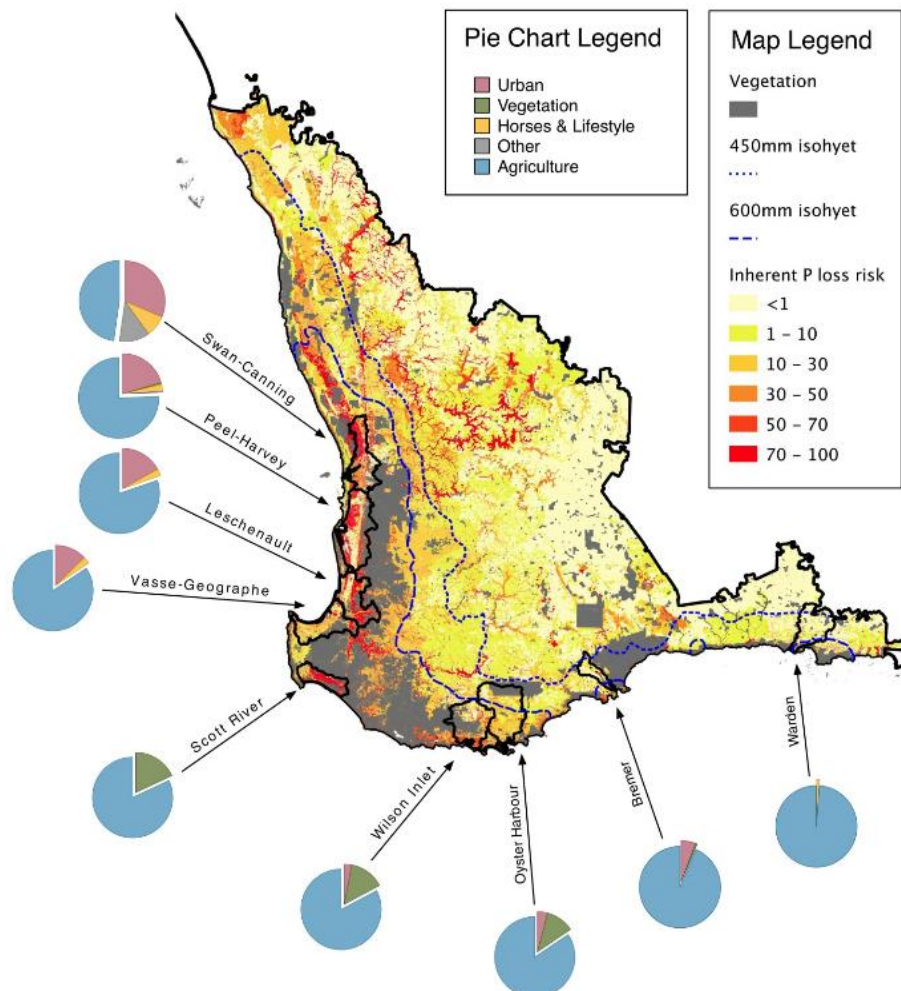


Figure 8 Phosphorus sources attributed to different land uses (pie chart) and P loss risk (map) in the South West region (derived from Van Gool et al., 2005).

Table 5 Science needs for Land Use Impacts of Estuaries

Knowledge gap	Description	Priority*	Linked Themes
<i>Enabling priorities</i>			
Baseline monitoring - land use change and impacts	Land use mapping - changes in land use are not captured on a regional scale and therefore cumulative impacts are not determined	H	
Baseline rates of sediment and nutrient run-off	Understand the natural sediment and nutrient run-off, and how land use has altered rates for different land uses on different soil types/regions	H	Water quality
<i>Research priorities</i>			
BMP soil management - urban and rural	Best practice for urban soils (new development), soil pH to optimise P requirements Innovative ways to manage new developments to avoid issues of nutrient pollution and acid release Build a knowledge base of performance assessment of current and future interventions	H	
Impact of land use changes	What will be the impact of increased urbanisation and agricultural intensification?	H	
Develop design criteria for vegetative buffers	To develop best practice guidelines for optimal nutrient trapping	M	
Urban waterways – Water Sensitive Urban Design (WSUD) needs	WSUD – links to the CRC for Water Sensitive Cities Ecological values for urban water, hydrology nutrient processes in ground water-surface water interface to improve urban water nutrient design guidelines and groundwater management	M	
Non-nutrient contaminant status and impacts	Understanding herbicide and pesticide effect on ecology (e.g. seagrasses; saltmarsh etc) Urban stormwater impacts	L	Habitat, Biota

3.6 Coastal Engineering and Port Development

Importance

Estuaries are hotspots of urban and industrial development and population growth, with 22 of the 32 largest cities in the world being located around these environments (Valle-Levinson, 2010). Consequently, estuaries are commonly subjected to the pressures associated with land reclamation, coastal engineering and the development and expansion of ports and marinas (Kennish, 2002). The ecological effects of these pressures (Erftemeijer and Lewis, 2006; Bilkovic and Roggero, 2008; Jickles et al., 2015; Kjelland et al., 2015) will be modulated by both climate change, e.g. rising sea level and increased storminess (McInnes et al., 2015), and our engineered responses to this challenge. Novel solutions and different approaches may be required to address these effects (Temmerman et al., 2013).

Primary issues

Numerous estuaries of southwestern Australia are affected by port development (e.g. the ports of Fremantle, Bunbury, Albany), dredging to maintain navigable channels (e.g. Peel-Harvey and Leschenault estuaries), artificial opening of estuary mouths (e.g. Wilson Inlet), and replacement of natural subtidal and riparian habitat with engineered structures designed to protect riverbanks (e.g. Swan-Canning Estuary). Rapidly increasing population growth (most notably in Peel Region) and the need for expansion of industrial capacity (e.g. Port of Fremantle) will magnify these stressors. Such pressures are also likely to increase with climate change, as increased storminess and sea level rise heighten the risk of flooding and demand management responses to protect urban and agricultural land use (Hallett et al., in prep.).

Current state of knowledge

The current WAMSI Dredging Science Node has dramatically improved our knowledge and understanding of dredging practices and how to mitigate their ecological effects. Nonetheless, in many of our estuaries, coastal engineering projects, including dredging, shoreline protection, harbour developments and estuary mouth openings, are progressing with a less than adequate evidence base. Basic bathymetric data has been lacking or out of date for many of our estuaries, and the management of estuary mouth openings on the south coast proceeds in many cases on an ad-hoc basis. This is being addressed for some systems (Peel-Harvey, Leschenault, Hardy and Wilson Inlets) by a Light Detection and Ranging (LIDAR) bathymetric survey scheduled for 2016 by the Department of Transport. There is also little capacity to reliably measure, and thus effectively respond to, any change in the nature and condition of our estuary foreshores, as current efforts are limited to one-off or sporadic surveys (e.g. Swan River Trust, 2008). Finally, many existing coastal engineering activities are being undertaken without adequate consideration of future climate change impacts, as the projected synergistic effects of changes in wind and wave climates and the magnitude and frequency of storm surges, together with relative sea level rise due to climate change, are

largely unknown. Current studies in this area, particularly at UWA, should be evaluated against decision-maker needs.

Management implications of improved knowledge

Addressing recognised knowledge gaps will provide managers with a more robust evidence base for managing estuarine erosion, dredging, foreshore protection, rehabilitation and mouth openings. Effective research and monitoring will help managers to quantitatively model flood risk and geomorphological responses to predicted sea level rise and storm surge impacts, thus helping to identify high and low risk areas for future development. This will allow for more informed evaluation of the potential risks, impacts, and societal benefits of future coastal development and engineering projects, as part of a cost-benefit approach to decision-making.

Table 6 Science needs for Coastal Engineering and Port Development

Knowledge gap	Description	Priority*	Linked Themes
Enabling priorities			
Baseline – bathymetry linked to topography	Establish essential baseline information for hydrodynamic modelling, habitat mapping, foreshore erosion, dredging, bar management, flushing protocols and sedimentation rates. Bathymetry data is non-existent or out-of-date, except in the Swan-Canning. Topography of surrounding land linked to bathymetric data for flood risk assessment, identification of habitat migration pathways	H	Habitat, System understanding
Research priorities			
Climate change impacts on coastal inundation patterns	Increased understanding and predictive capacity of the impact of climate change and anthropogenic activity on coastal inundation (including storm surge dynamics) to inform design criteria for coastal communities, infrastructure and urban development – high and low risk areas for edge development and risk to existing development.	H	
Bar openings - geomorphological modelling	Improve predictive capacity to understand how bar openings, sedimentation and bathymetry may change with climate change predictions	M	
Understanding the impacts of dredging and port construction and spatial planning (new development locations)	Development of best practice assumptions and criteria for modelling the transient and permanent impacts of dredging and port construction on ecosystems	M	
Foreshore erosion and sedimentation - development of best management practices	Increased understanding and modelling capability pertaining to the cause and predictability of foreshore erosion and sedimentation on estuary foreshore and infrastructure; and the development of mechanisms to avoid or mitigate the impact - cost/benefit analysis of these; determine suitability of different locations	M	
Evidence to determine flushing protocols	Investigations into acceptable/unacceptable flushing times to establish more accurate threshold values for canal developments	L	Water quality
Improved benthic rehabilitation techniques	More efficient and effective methods for benthic rehabilitation	L	

3.7 Sediment Quality

Importance

Healthy estuarine sediments play a crucial role in regulating water chemistry and supporting benthic faunal communities (Middleburg and Levin, 2009), which are a key component of estuarine foodwebs. However, estuarine sediments are strongly impacted by anthropogenic stressors such as hypoxia, organic enrichment or chemical pollution. Responses of benthic communities to these stressors include reduced species richness and diversity, increased dominance of small-bodied, tolerant and opportunist species and the loss of more sensitive taxa such as crustaceans (Pearson and Rosenberg, 1978; Warwick and Clarke, 1995; Levin et al., 2009), potentially impacting on estuarine trophic function, sediment biogeochemistry and fisheries (Rakocinski *et al.* 1997; Breitburg, 2002; Middelburg and Levin, 2009). The composition of benthic faunal communities is thus commonly used as a measure of the ecological condition of estuaries, and particularly their benthic habitats (Diaz et al., 2004).

Primary issues

Estuarine sediments throughout much of southwestern Australia contain relatively high concentrations of nutrients and organic matter, generating increased oxygen demand and contributing to hypoxia and anoxia. Under low oxygen conditions, they may release ammonia, hydrogen sulphide and/or inorganic phosphorus into the water column (Morgan et al., 2012), causing further deoxygenation and potentially fuelling algal blooms. Such sediments typically support degraded benthic macroinvertebrate communities (Wildsmith et al., 2009; Tweedley et al., 2012, 2015). Some estuarine sediments are also contaminated with organic pollutants (e.g. pesticides, herbicides, and hydrocarbons) or toxic metals (Nice and Fisher, 2011), arising from urban, industrial or agricultural land use or poorly managed development in areas with acid sulphate soils (DoW, 2011).

Current state of knowledge

In recent years DoW staff, working with Geoscience Australia, have developed ways of using information on various sediment attributes (including phosphorus binding capacity, denitrification, oxygen consumption and per cent organic matter) as an indicator of estuarine condition. As part of this work, sediment studies have been conducted in most estuaries on the south coast of WA (i.e. Wilson, Parry, Irwin, Walpole Nornalup, Torbay, Wellstead, Beaufort, Gordon and Stokes Inlets and Oyster and Princess Royal Harbours), plus the Hardy and Leschenault Inlets (DoW, 2011) and the Vasse-Wonnerup, Peel-Harvey and Swan-Canning estuaries. These studies are providing an invaluable understanding of sediment dynamics and condition, yet further work is needed to address key knowledge gaps, which include the spatial and temporal variability of nutrient cycling and its interaction with groundwater in our estuaries, and the sediment characteristics and oxygen concentrations required for colonisation by bioturbating organisms. Moreover, improved understanding is needed of the distribution and behaviour of contaminated sediments (including acid-sulphate soils and

mono-sulfidic black oozes) in our estuaries (DoW, 2011), and particularly the actions needed to mitigate their potentially harmful effects during dredging operations (Morgan et al., 2012).

Management implications of improved knowledge

Improved knowledge of sediment distributions, dynamics, and contaminants will enable managers to better quantify and identify the causes of declining sediment condition in our estuaries and help mitigate negative effects. Monitoring data will enable the best indicators of sediment health to be identified and appropriate trigger values to be established, thus ensuring, for example, that future dredging activities are designed and conducted so as to minimise negative environmental impacts.

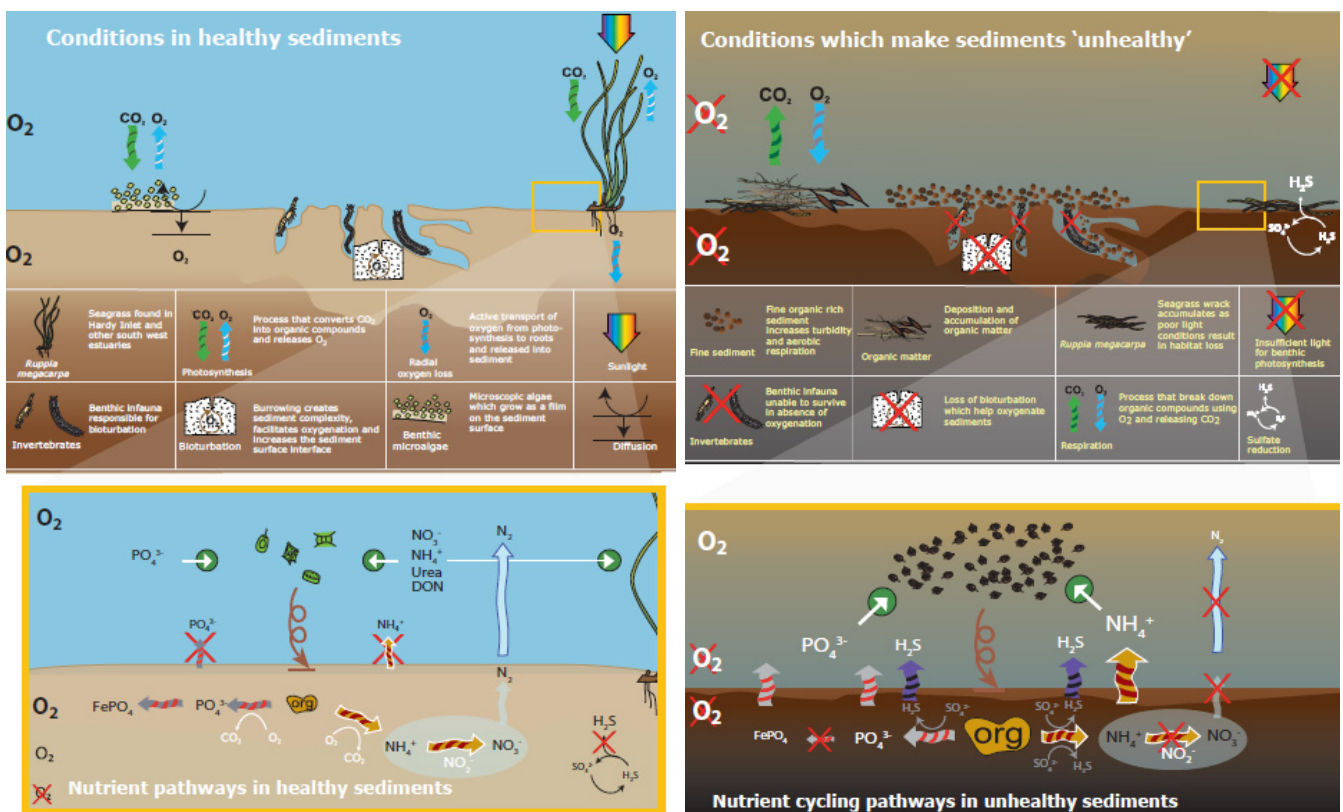


Figure 9 Persistent anoxia in sediments has significant implications for benthic habitats. There is much to understand about the recovery pathways that might be enabled by artificial oxygenation. Conceptual model from the Department of Water, (2010).

Table 7 Science needs for the management of Sediment Quality

Knowledge gap	Description	Priority*	Linked Themes
<i>Enabling priorities</i>			
Sediment understanding - sediment sources and development of a sediment health index	Sediment-water interactions directly influence water quality in SW estuaries. The determination of allocthonous and autocthonous nutrient/sediment sources is critical to guide management actions. Improved baseline monitoring data is required and a sediment health index developed.	H	Water quality
Sediment contamination	Extend knowledge (current is patchy)	L	
<i>Research priorities</i>			
Load and sources	Determine sediment and organic loads for impacts on primary productivity	M	Water quality
Sediment health indices	Metrics to track condition (spatial 3-5 yearly)	M	
Sediment - bioturbation interactions	Sediment quality impacts on bioturbation	M	
Sedimentation rates	Rates in estuaries – current and historical rates (e.g. seismic surveys)	M	
Microbial processes	Role of microbes - compound identification and process understanding	M	
Dredging – disposal, legacy and cost-effectiveness	Legacy of dredge disposal sites – contaminants and stability; where and how to dispose, what treatments can be applied – cost-effective options	M	
Acid sulfate soils, monosulfidic sediment and dredging impacts	Impacts from development, cumulative impacts on ecology and chemistry, drivers and controls on accumulation of monosulfidic sediment in estuaries (links with nutrients)	L	
Ecological impacts	Role of sulfide in limiting primary productivity (local and cumulative + threshold)	L	
Groundwater interactions	With nutrient cycling - some studies done but no certainty for management	L	
Positioning infrastructure - best practice guidelines	Compare adjacent brownfield developments with new development sites - knowledge needed to avoid remediation costs	L	

3.8 Human Health

Importance

Changes to the ecology and health of ecosystems, due to anthropogenic degradation or climate change, will have consequences for human health (Ford et al., 2015). For example, climate change may affect the distributions and behaviour of species, bringing human populations and potential disease vectors into closer proximity (McMichael et al., 2006), and is predicted to encourage the development of harmful algal blooms that can have significant, and potentially fatal, consequences for human health (Moore et al., 2008; Anderson et al., 2012). Furthermore, the widespread introduction of invasive species to areas outside their normal distribution has the potential to bring new diseases that impact human health (Crowl et al., 2008).



Primary issues

The association of mosquito-borne disease vectors for Ross River Virus and Barmah Forest Virus within 3 km of tidal salt marsh and brackish water areas presents a human health risk in the South West region, predominantly between Mandurah and Busselton (A. Jardine, pers. comm.). This risk is likely to increase with urban development in proximity to estuaries and potentially with climate change. The incidence of harmful algal blooms in South West estuaries has also risen significantly in recent decades, including notable cyanobacterial blooms that have posed a threat to human health (e.g. Atkins et al., 2001; EPA, 2008), and an increase in the frequency of dinoflagellate blooms (Brearley, 2013; Hallett et al., 2016). Health concerns associated with such blooms, including the risk of poisoning via contact or the consumption of algal neurotoxins bioaccumulated in estuarine shellfish or fish, periodically force the closure of bloom-affected estuaries to recreation and other activities.

Current state of knowledge

Pressing science needs centre around establishing the biotic and abiotic factors that are conducive to mosquito breeding, regular mapping showing risk profiles around mosquito breeding habitat, and building knowledge on the impact of pesticides on the food web, including human health impacts through ingestion and ambient spraying. Monitoring and investigation of potentially harmful algal species is required across all relevant estuaries in order to determine trends and provide public health warnings, as is currently the case for the Swan-Canning Estuary which is monitored for harmful algal blooms on a weekly basis.

Management implications of improved knowledge

Improved monitoring and understanding of the causes and dynamics of algal blooms, potential sources of toxins and contaminants (e.g. pesticides, heavy metals, faecal enterococci) and the distribution of mosquitoes will help managers to quantify and mitigate the resulting risks to human health. Again, there is a clear need to integrate datasets and provide a central repository for monitoring data and information on health risks. This would improve the evidence base on which health warnings are issued and help managers to predict future risk areas and tailor effective management actions to address existing and future problems. There is also a view that WA needs to improve expertise in a number of these areas.



Figure 10 A *Microcystis* bloom in the Swan-Canning Estuary closed the estuary to recreational activities for two weeks in January, 2000.

Table 8 Science needs for Human Health issues associated with estuaries

Knowledge gap	Description	Priority *	Linked Themes
Enabling priorities			
Baseline mapping mosquito breeding areas (to inform land use planning and interventions such as spraying).	Establish maps for high risk areas	H	
Baseline monitoring and reporting – harmful and nuisance algal blooms known toxic species	Establish monitoring and reporting programs across priority and at-risk South West estuaries, including benthic algae known to be toxic (eg <i>Lyngbya</i>)	M	Biodiversity
Research priorities			
Future human health risk areas	Identify the likely impacts from current and future development scenarios and climate change on mosquito borne viruses, contaminants patterns (including phytoplankton toxins)	H	Socio-economic, Land use
Mosquito breeding - environmental drivers	Determine local biotic/abiotic factors that are conducive to mosquito breeding and develop indicators for risk to human health	M	Water quality
Contaminants (including phytotoxins) in fish/invertebrates	Undertake contaminant analyses and reporting for popular recreational species.	M	Biodiversity
Mosquito control measures	Feasibility of aerial larvicide in urban areas Effectiveness of alternative mosquito management strategies	L	Biodiversity

3.9 Freshwater and Hydrology

Importance

Water abstraction for human use and hydrological alterations associated with climate change are major pressures on estuaries, and are likely to disproportionately impact estuarine ecosystems in Mediterranean climate regions (including southwestern Australia), which are forecast to become progressively drier with climate change. Modified hydrological cycles, including changes to the magnitude, timing and/or variability of flows and the frequency of extreme events (e.g. floods, droughts and storms), have potentially dramatic effects on water quality and estuarine communities (Wetz and Yoskowitz, 2013; Paerl et al., 2014; Dittman et al., 2015; Thompson et al., 2015).

Primary issues

The climate of southwestern Australia has been consistently drying over the last 40 years (Bates et al., 2008), due largely to a decline in winter rainfall (Delworth and Zeng, 2014); a trend that is forecast to continue under future climate change scenarios (Suppiah et al., 2007). Runoff has declined even more markedly, with up to 50% reductions in inflows to regional dams since the mid-1970s, and further reductions of up to 50% predicted by 2030 under a dry climate scenario (Silberstein et al., 2012). As rainfall may be considered a major factor controlling estuarine ecology in the region (Thompson, 2001), the resulting changes to hydrology have dramatic effects on water quality and estuarine communities (e.g. Kanandjembo et al., 2001a, b; Young and Potter, 2002; Tweedley et al., 2015).

The drainage modifications of last century were orientated towards flood management and establishing land suitable for agriculture. The legacy of these modifications has, and continues to negatively impact some of our estuaries – delivering high nutrient sediment loads and reduced transit times of freshwater to estuaries. Community expectations have evolved since modifications were made. It has become complex to address the multiple interests in these altered systems as evidenced by recent work in the Vasse-Wonnerup, Wilson and Peel region.

Current state of knowledge

The hydrology of some of our estuaries is relatively well understood (e.g Hamilton et al., 2001; Kurup and Hamilton, 2002; Hipsey et al., 2014). However, our knowledge of the future changes to freshwater flows that are likely to result from climate change is largely restricted to broad predictions (Silberstein et al., 2012). Robust models greatly assist our understanding of the impact of further changes to drainage, restoration of natural flow patterns and/or climate change scenarios on the ecological response of estuaries. Fundamentally, we have little to no quantitative understanding of the environmental flows that are required to ensure the integrity of key parts of our ecosystem, including seagrasses, invertebrates, fish and birds (EPA, 2008; DoW, 2011), and to sustain the broader ecological functioning of our ecosystems.

Management implications of improved knowledge

Addressing identified knowledge gaps will allow us to better understand the requirements and limits to resilience of key ecosystem components. For example, establishing quantitative environmental flow requirements for fish, birds etc. will help to establish specific hydrological management objectives to avoid significant impacts on these estuarine communities. Robust modelling will enable the assessment of future changes to estuarine hydrology, e.g. changes in residence times and stratification and the resulting impacts on algal blooms, hypoxia and nutrient fluxes, and will thus allow managers to better balance community expectations and ecological functioning of estuarine environments.

Table 9 Science needs for Freshwater and Hydrology

Knowledge gap	Description	Priority*	Linked Themes
<i>Enabling priorities</i>			
Groundwater inflows	Nutrient inputs from groundwater to estuary, including discharge and recharge points, and seasonality	H	
<i>Research priorities</i>			
Surface inflows to estuaries - climate change, land use and abstraction changes	How does hydrology and estuary hydrodynamics respond to change? Includes water residence times, stratification, hypoxia.	H	
Nutrient assimilation in freshwater streams	Riparian and in stream	H	
Impact of inland waterway diversion on estuaries (site-specific)	Understanding and predicting the impact of changes to volume, content and location of river discharge that results from waterway diversion (and dams) on estuaries, e.g, Vasse-Wonnerup floodgate management. What are the levels of inflows from various sources required to maintain different levels of system functionality to inform upstream water management decisions	M	

3.10 Sustaining Resources

Importance

Estuaries play a crucial role in supporting fisheries production worldwide due to their highly productive nature and importance as nursery areas for many fish and invertebrate species (Abrantes et al., 2015). However, numerous pressures may impact on estuarine fishes and their food sources (Kennish, 2002) and thus have dramatic effects on fisheries production (Breitburg, 2002).

Primary issues

Our estuaries provide invaluable feeding and nursery habitats for a wide variety of commercially and recreationally important fish and invertebrates (including cobbler, herring, blue swimmer crab and various whiting, flathead, prawn and mullet species), and also support iconic estuarine species such as black bream. Potential threats to estuary-dependent fisheries in the region include eutrophication and hypoxia (Cottingham et al., 2014; Fletcher and Santoro, 2010; Tweedley et al., 2015; Hallett et al., 2016), feral fish (Beatty et al., 2013) and loss of habitat (EPA, 2008; DoW, 2011). Climate change may also impact our estuary-dependent fisheries. For example, the predicted future closure of numerous south coast estuaries for longer periods by their sand bars is likely to reduce access for juveniles of many commercially and recreationally important marine species (Hallett et al., in prep.), representing the loss of vital nursery areas (Valesini et al., 1997). Even at present condition a decline in commercial fishing licences and reduction of some key species such as western school prawn in the Swan-Canning and Peel-Harvey estuaries has been observed (Fletcher and Santoro, 2010). This is due to a combination of the buy-back of licenses by Government and in some cases decreasing stock abundance due to deteriorating environmental conditions (e.g. Cobbler and Perth herring in the Swan-Canning Estuary).

Current state of knowledge

Despite the widely-acknowledged importance of our estuaries for supporting commercial and recreational fisheries, there is currently little to no comparable and quantitative information on the intensity of shore-based recreational fishing effort across the estuaries of the region. Similarly, data on the current size of some key fish stocks that inhabit or use estuaries are not available. Together, these gaps present a challenge to effective, evidence-based management of regional fisheries for some estuaries. Restocking or stock enhancement has been proposed, and in some cases implemented (Gardner et al., 2013; Cottingham et al., 2015b), as a potential measure to mitigate documented declines in some key estuarine species. However, in most cases, more information is needed on the requirements, threats, costs and viability of such restocking projects (Moloney et al., 2003). There is a similar need for appropriate restoration of estuarine fish habitat (Creighton et al., 2015), but currently also an insufficient evidence base to inform the design of effective restoration programs.

Management implications of improved knowledge

Better quantification of the ecological requirements, stock size and characteristics of key fisheries species, along with robust and comparable data on fishing intensity and catches across appropriate spatial and temporal scales, will help to ensure the sustainability of commercial and recreational fisheries into the future. The collection of targeted information to quantify existing and future threats to our fisheries (e.g. feral fish, habitat loss, changes to hydrology and water quality) will also be required. Habitat enhancement and/or restocking of key species should be based on appropriate quantitative evidence and supported by an evaluation of predicted socio-economic and environmental costs and benefits (Moloney et al., 2003, Lorenzen et al., 2010). Such initiatives have the potential to not only support sustainable fisheries, but also increase community engagement and environmental stewardship (Cooke et al., 2013), as exemplified by the Prawn Watch component of a current project to restock western school prawns in the Swan-Canning Estuary (<http://www.riverguardians.com/projects/prawn-watch>).

Table 10 Science needs for Sustaining Estuarine Resources

Knowledge gap	Description	Priority	Linked Themes
<i>Enabling priorities</i>			
Quantification of the recreational effort/catch and its impacts on stocks	Enhanced monitoring and assessment methods that lead to a more precise estimation of the recreational catch in key species (e.g. use of cameras) and improved understanding of its impacts on key stocks.	H	Biota
Stock size and status	Improved understanding of the size and status of key fish and invertebrate stocks.	H	
<i>Research priorities</i>			
Impact of eutrophication and different flushing/flow regimes on fisheries and developing predictive ability	Determine the impacts of water quality (linked to land use activity) and different flushing/flow regimes on the productivity and viability of specific commercial & recreational fisheries, and developing predictive ecosystem response models to forecast these impacts under future scenarios.	M	Water quality
Environmental triggers and thresholds for maintaining fish stocks	Identify and develop indicators of estuary and fish habitat health – such as water quality and key biota (e.g. benthic invertebrates).	M	Water quality, Biota
Fish biology	Improving understanding of fish movement patterns (and response to environmental drivers), basic biology (repeated at regular intervals) and trophic functioning.	L	Biota
Impact of climate change and catchment development	Understanding the likely impacts of climate change (decreased flow, increased sea level and increased temperature) and catchment development (changes in nutrient and flow regimes) on the productivity of recreationally important fisheries, and the mechanisms of why they are changing.	L	Water quality
Feral species	Improving understanding of the impact of invasive species on estuarine fish and invertebrate species.	L	Biota
Habitat enhancement opportunities for recreational species	Develop understanding of revegetation methods and opportunities for habitat enhancement structures in SW estuaries.	L	Habitat
Restocking viability	Identify the environmental, commercial and anthropogenic variables that impact on successful recruitment of restock species (black bream, mullet, western school prawns).	L	Biota
Commercial impacts of current land use practice vs management practice required to achieve healthy outcomes.		L	Land use

3.11 Socio-economic Issues in Decision Making

Importance

The management of estuarine ecosystems and their sustainable use is increasingly complex, given a growing population and the need to effectively balance ecological objectives that protect the condition of ecosystems and the services they provide, whilst simultaneously capitalising on development opportunities to support economic and societal growth (Barnard and Elliott, 2015). These competing demands frequently involve a diverse range of stakeholder opinions and may present ‘wicked problems’ (e.g. Patterson et al., 2013). Solving these problems will require more effective means of eliciting behaviour change, improved methods for public communication and engagement (Longstaff et al., 2010) and cost-benefit analyses of potential management options, including the quantification of ecosystem services (Costanza et al., 1997, 2014; Pinto and Marques, 2015).

Primary issues

Balancing economic growth and reducing pollutant loads to southwestern WA estuaries is, and will continue to be, extremely challenging. An effective cost-benefit framework is needed to achieve reasonable environmental outcomes and uses of water within the context of significant existing and future development pressures. This will require the development of quantitative and transparent decision making tools that consider a broad range of social, environmental and economic benefits provided by our estuaries, including the values of Indigenous and non-Indigenous peoples. We also need to implement more effective methods for communicating and engaging with the public (e.g. Longstaff et al., 2010) to encourage behaviour change and the adoption of sustainable practices around water use, fertiliser application, fishing etc.

Current state of knowledge

We currently lack many of the tools that are required to provide a more robust, informed and transparent basis for decision making around estuarine management. There is a need for (i) quantitative methods to better quantify the ecosystem services, social values and economic benefits that estuaries provide to a diversity of stakeholders, (ii) better communication techniques and tools to improve science-based knowledge exchange and promote community engagement, and (iii) greater understanding and implementation of proven methods to encourage behaviour change around environmental issues.

Management implications of improved knowledge

The ARC Linkage project (LP150100451 see section 4.5) aims to address some of these priority knowledge gaps in the Peel region. In addition to developing quantitative indicators of estuarine health, it will also develop indicators of the social and economic benefits of catchment development and integrate them within a broader decision support framework. The main goal of this project is to provide stakeholders with a tool for quantitatively

evaluating and optimising the environmental, ecological and socio-economic costs and benefits of different catchment development and climate scenarios. The potential future application of such a framework to other estuaries and their catchments across the South West could help bring about a broader understanding of key socio-economic issues across the region and encourage swifter progress towards sustainably developed systems, i.e. resilient estuaries that can cope with the pressures of growing economic opportunities while still delivering environmental and societal benefits. An agreed, consistent framework will provide great opportunities for effective communication and engagement with all stakeholders.



Figure 11 Multiple uses and interests in highly valued estuarine environments demands a framework to evaluate and optimise their social, economic and environmental costs and benefits.

Table 11 Science needs for Socio-Economic aspects

Knowledge gap	Description	Priority *	Linked Themes
Enabling priorities			
Science communication and engagement strategies	Develop better communication techniques/tools for science-based knowledge exchange to enable rational decision making - consistent monitoring and reporting including annual reporting of status and trends using science-based estuary health indices; estuary specific website for synthesis, documents, info etc. (especially for high interest issues such as bar openings and fisheries management).	H	Coastal Engineering, Sustaining Resources
Citizen science	Identify opportunities to contribute to baseline information	L	Biota, Coastal Engineering
Research priorities			
Determine agreed methods across South West estuaries to detail the socio-economic benefits	Ecosystem service assessment to enable balancing trade-offs - quantitatively and spatially explicit, including future scenarios and planning. Evaluate relative economic value of different land uses in catchments of at-risk estuaries. Consider local, regional and state scales - potentially identifying other sites in WA where economic benefit could be met with lesser impacts.	H	Land use
Indigenous knowledge and engagement	Identify ways to better integration Indigenous knowledge into estuary management. Further consultation is required but opportunities should be sought following the South West Native Title Settlement Agreement (2015)	H	
Behaviour change	How to get effective uptake of BMPs, especially fertiliser application change e.g State Government soil testing programs. Enabling use of mining “waste” as soil amendments – e.g. revise regulatory policies.	H	Land use
Risk assessment	Ecosystem service assessment, economic and ecological consequences of loss.	H	All
Carrying capacity	What is the sustainable capacity of the system for recreational, urban and development uses?	M	
Thresholds of community acceptance to estuary condition	Identify triggers and thresholds for various interest groups, e.g. farmers, developers, LGAs, community, fishers to better balance socio-economic use with estuarine health.	M	
Opportunities to enhance values	Identify opportunities for quality eco-tourism, recreation, signage and education.	L	
Socio-economic engagement with respect to infrastructure development	Synthesis of risks, impacts and societal benefits to aid decision-making	L	Coastal/ports
Promoting behaviour change – recreational fishing	Identify better strategies to encourage positive behaviour change in the community with respect to sustainable recreational fishing	L	Sustaining resources

3.12 System Modelling

Importance

Despite a degree of scepticism among some decision and policy makers, modelling is an increasingly integral tool for management of estuaries as it enables us to:

- i. develop and test our conceptual understanding of ecosystem behaviour
- ii. identify knowledge gaps and key research and management questions
- iii. predict responses of estuaries to future management, land use and climate change scenarios
- iv. simplify the presentation of complex data sets and concepts, thus facilitating communication with stakeholders (Ben Hamadou et al., 2011)

Successful numerical modelling relies on the process understanding captured in the model, assumptions made and the data available to it. By addressing these critical requirements, robust models may be developed that, whilst not providing a silver-bullet solution to all environmental issues, will ensure a better flow of information to decision makers. Communication of the assumptions and errors associated with the outputs of the model is critical to ensure sound decision-making.

Primary issues

Modelling underpins and is intricately linked to many of the research priorities and knowledge gaps identified through the consultation process. Thus, developing and implementing appropriate models will be crucial to address many of the aforementioned threats to estuaries. Whilst catchment and hydrodynamic estuary models have been developed for some key systems (e.g. Fig. 12), there is a need to expand and couple these with more complex biogeochemical models that will enable quantification of nutrient processing from catchment to coast and the associated responses of estuarine water and habitat quality and ultimately, higher ecology. This will help to evaluate the social, environmental and economic costs and benefits of alternative management and development options.

Current state of knowledge

Hydrodynamic and biogeochemical models have been progressed for several South West estuaries (Table 12), with recent investigations developing ecological response models to some specific questions. Nonetheless, numerous research gaps need to be addressed to expand and link these models such that they span the catchment to coast continuum and incorporate responses of estuarine water, habitats and biota. The ARC linkage project in the Peel Region (see section 4.5) aims to address this need, thereby providing a predictive decision support framework for helping to identify land-planning solutions that best optimise trade-offs between catchment development aspirations and estuarine condition and ecosystem service delivery.

Management implications of improved knowledge

Investment in the development of integrated catchment and estuarine response models was seen as a priority by the majority of the workshop participants, and is essential to help address many of the knowledge gaps identified under the previous ten themes. It is envisaged that operational estuary-catchment linked models would also facilitate the identification of future research questions related to estuary management. Such a systems-based approach, integrating physical, chemical, biotic, social and economic values of estuaries, will ultimately help to deliver timely management decisions that are based on all of the available information and consider the full range of costs and benefits associated with development.

Table 12 South West estuary and catchment models - current status.

<i>Estuaries</i>	<i>Hydrodynamic</i>	<i>Biogeochemical</i>	<i>Ecological</i>	<i>Notes</i>
Swan-Canning	Yes	Yes	In part	Tuflow FV - upstream of Narrows, extending to downstream zone
Peel-Harvey	Yes			Tuflow FV
Leschenault	Yes			SHOC
Vasse-Wonnerup	Yes			Tuflow FV - In progress

<i>Catchments</i>	<i>eWater SOURCE</i>	<i>LASCAM</i>	<i>Notes</i>
Swan-Canning		yes	planning to move to SOURCE platform
Peel-Harvey		yes	planning to move to SOURCE platform
Leschenault	Yes		
Hardy – Scott	Yes		
Hardy – lower Blackwood	Yes		

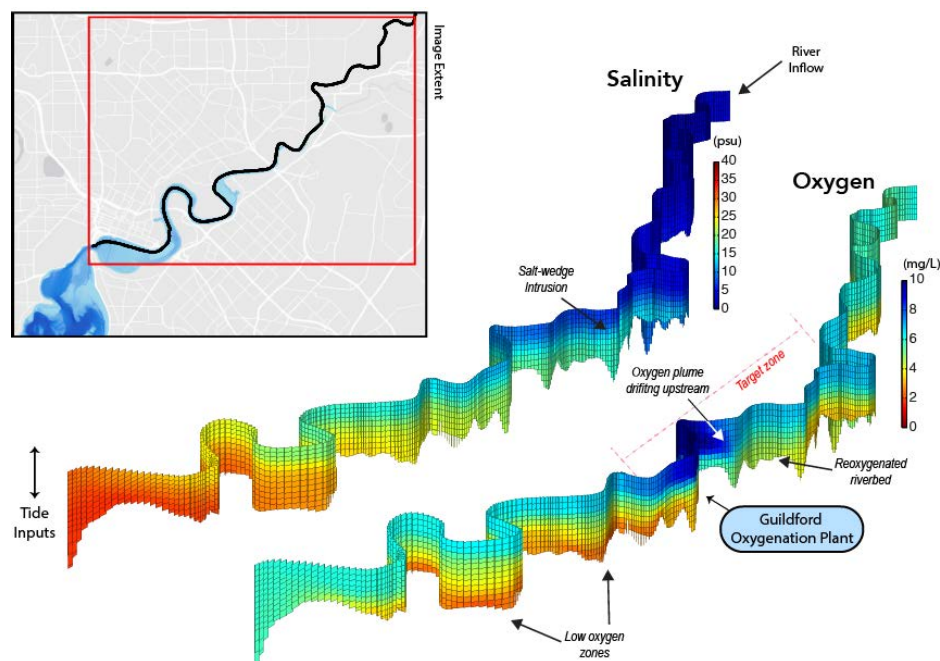


Figure 12 Modelled salinity and oxygen profiles of the upper Swan - supports management of the artificial oxygenation program (Hipsey et al., 2014).

Table 13 Science needs for Integrated System Modelling

Knowledge gap	Description	Priority*	Linked Themes
<i>Research priorities</i>			
Estuarine biogeochemical and ecological response model	Extend hydrodynamic models to include biogeochemical model. Add complexity such as ecological response in modular form as need demands and system understanding allows. Important to develop approaches for appropriate quantification of uncertainty and limits of confidence in modelled results	H	Water quality, habitats, biota
Catchment linked to estuarine response models	Develop approaches to link land use with estuary models in order to assess future development and climate change impacts on water and nutrient delivery, and subsequent estuarine response	H	Water quality, habitats, biota
Structural understanding	Identification of site-specific food web details, allowing for appropriate configuration of functional groups and the strength of biotic inter-relationships within models.	M	Biota
Trigger values	Systematic determination of trigger values based on ecosystem objectives, and definition of estuary-specific sustainable loads.	M	
Integrate Bayesian belief models into estuary models (for socio-economic drivers)	Identifying community values and key ecosystem services relevant to stakeholders in order to clearly define outputs as end points for model prediction and scenario assessment. This should allow for incorporation of expert opinion.	M	Socio-economic
Modelling habitat response	Develop models of habitat growth, requirements and response to threats	M	
Tipping points	Estuary resilience: what are the tipping points and what aspects can enhance resilience, what are the recovery pathways. This requires empirical science and scenario assessment of models of estuarine systems to explore response trajectories. What sediment/nutrient loads are ecologically viable?	M	Water quality, habitats, biota
Nutrient pathways process understanding	Nutrient cycling – source, pathways and fate. Required for model boundary conditions and internal biogeochemical algorithms, and to validate model function.	L	Water quality
Decision support tools for agricultural land use decisions	Such as - translate the Urban Nutrient Decision Outcomes tool to agricultural land use	L	Water quality
Local scale process models	As needs arise to inform the catchment scale models	L	Water quality

3.13 Synthesis of highest priorities at the regional scale

In this section we will summarise what were deemed the highest priority knowledge gaps; both enabling priorities and the research priorities. The enabling priorities are essential to support both the management needs as well as baseline scientific information for research priorities. This is not to say that the priorities rated as medium or low are irrelevant, they should still be pursued if opportunities to progress present themselves. However in the first stage we propose that at least the highest priorities be addressed; and opportunities to leverage work from the local to the regional scale be identified (the mechanism and funding structure to deliver this research will be developed as part of a separate process).

Enabling Priorities

The key enabling elements of a science-base management framework were all identified at least in part, as enabling gaps. These include:

1. *Monitoring and modelling – a stable and enduring platform*

In the case of estuaries, there has been a steady reduction in the level of monitoring over the last decade (pers. comm., DoW). This has resulted in baseline monitoring data being one of the key knowledge gaps raised by both experts and decision makers as part of this process, as shown in Section 4. The Regional Estuaries Initiative (REI), a four year State Government-funded program commenced in April 2016, has enabled the reinstatement of some essential monitoring in five of the estuaries considered in this project. It excludes the Swan-Canning and Wellstead. The Swan-Canning is well-funded for baseline water quality monitoring, however the Wellstead has largely inadequate quarterly sampling in the estuary and none in the catchment.

Delivering a strategy in relation to monitoring should consider the following steps:

- Gain commitment of all parties to share and make available data due to the public interest of estuary management.
- Review of Table 14 (below) to determine priority data that supports both operational management and critical research, and to inform preparation of a detailed monitoring program.
- Urgent investment in critical and well-known gaps.
- Mapping of all State, Commonwealth (e.g. NESP, CSIRO), community, consulting and research groups monitoring infrastructure and data (potentially through a LandGate/WALIS group using Pawsey facilities).
- Investment in capturing, QA/QC and loading of all legacy but inaccessible datasets such as those held by researchers.
- Invest both capital, capital-replacement and long-term operating costs in a monitoring program against priorities and determine long-term custodianship beyond any finite research program.

- Review the monitoring programs every five years in consideration of management needs including data for estuary systems model validation, and future research requirements.

Table 14 outlines the priority monitoring gaps that are currently limiting management and research efforts.

Table 14 Priorities for new or extension of existing monitoring

	SC	PH	LE	VW	HI	WI	WE
Estuary - water quality							
baseline biophysical and chemistry	low	high	high	high	high	high	high
Estuary - habitat mapping							
submerged and fringing vegetation	moderate	high	high	high	high	high	high
community type classification	moderate	moderate	moderate	moderate	moderate	moderate	moderate
fish usage	moderate	moderate	moderate	moderate	moderate	moderate	moderate
waterbird usage	moderate	high	moderate	high	moderate	low	low
mosquito breeding areas	moderate	high	high	high	moderate	low	low
Estuary - biodiversity							
phytoplankton	low	moderate	moderate	moderate	moderate	moderate	moderate
zooplankton	moderate	moderate	moderate	moderate	moderate	moderate	moderate
known toxic species, e.g. <i>Lyngbya</i> and benthic fauna	low	low	low	low	low	low	low
recreational fish catch	high	high	high	high	high	moderate	moderate
fish stock - size and status	high	high	high	high	high	moderate	moderate
Estuary - sediment quality							
sediment indicators	high	high	moderate	high	low	low	low
sediment quality	moderate	high	low	low	low	low	low
Sediment/ nutrient runoff							
Quantification of sources	high	high	high	high	moderate	moderate	moderate
Bathymetry							
good bathymetry linked to topography	low	high	high	high	high	high	moderate
Groundwater inflows							
Nutrient and contaminant inputs & hydrological changes	moderate	moderate	moderate	low	low	low	low
Catchment							
map changes in landuse	high	high	high	high	high	high	high
sediment and nutrient loads	moderate	moderate	moderate	moderate	moderate	moderate	moderate

Key

- high priority information gap
- moderate priority information gap
- low priority information gap

SC Swan-Canning

PH Peel-Harvey

LE Leschenault Estuary

VW Vasse-Wonnerup

HI Hardy Inlet

WI Wilson Inlet

WE Wellstead Estuary

2. Effective, frequent assessment – report on condition/trends

Report Cards are a well-demonstrated framework to accurately and consistently illustrate waterway health status as shown in South East Queensland Healthy Waterways Program (Cottingham et al., 2010). Ongoing, multi-year data also allows managers and researchers to identify and communicate key trends. The synthesis of water quality indicators into relevant biotic and abiotic indicators of health moves beyond the reporting of basic water quality parameters in reference to water quality standards. The latter is difficult for the broad range of stakeholders to interpret in terms of overall system health. There would appear to be a depth of agreement amongst local stakeholders that it is now imperative that the synthesis of monitoring data into ecosystem health indices such as a report card framework for South West estuaries is progressed.

3. Ability to inform catchment management – forecast effectiveness and intervention scenarios

There was common agreement throughout the consultative process that a modelling framework is required to allow both managers and researchers to understand how complex components of estuary systems interact and the unexpected implications of decisions to allow/restrict certain activities.

A strategy should include developing a modelling framework that:

- Is appropriate for investigating the questions that estuary managers and stakeholders are asking.
- Allows scenario testing for various land planning, direct intervention and other policy measures.
- Allows general prediction of long-term impacts of climate change including reduced flows from catchments, inundation of land/infrastructure from sea level rise and increased temperature.

4. Effective Communication

The power of effective communication cannot be underestimated. Communication facilitates engagement with all stakeholders; a common, comprehensible language (such as in report card formats) is fundamental. This can enable evidence-based responses to supersede opinion-based ones that might unduly influence the public and decision makers.

Integrated systems models are also a priority tool for the communication of complex information and demonstrating the future scenarios as a consequence of potential population, agriculture and climate change trajectories.

Research Priorities

Through this process, we have determined that the highest priority areas of research for estuary management in the South West are:

1. Estuary metabolism and nutrient cycling (Theme: Water Quality)

Within estuaries, knowledge on the transport, cycling and fate of nutrients and organic matter (including microbial pathways) is a major constraint for understanding water quality and biotic response – and indeed modelling these aspects of estuarine function. Therefore we recommend investment in **understanding estuary metabolism and nutrient cycling at appropriate time and spatial scales**. Research that focuses on rates of these processes and fundamentally what drives variability across the estuary will improve current models.

2. Ecosystem function and food web dynamics (Themes: Key Habitats and Biota)

There are critical gaps in ecosystem function that require urgent research. Management is currently making decisions without sound understanding of the ecological connectivity, role of different habitats (e.g. as fish nursery grounds), trophic interdependence and the ecological role of aquatic and fringing plants to mediate eutrophication. In some systems, where management decisions can significantly manipulate environmental conditions, understanding physiological tolerances of key species is important. Additionally, research is required to quantitatively understand **food webs** and their linkages to catchment and estuarine drivers, aspects required for ecological modelling.

3. Innovation in managing nutrient loss from catchment to estuaries (Theme: Land use)

There is also a requirement to develop **innovative ways of managing nutrient enrichment** in urban and rural areas, and also **assessing the performance of Best Management Practices (BMPs)** - both current and new interventions. In many cases, the efficacy of currently recommended BMPs has not been scientifically established. Historical drainage modifications and management need revision in consideration of current pressures - development and climate change.

4. Climate change impacts (Themes: Coastal Engineering, Habitats, Biota and Human Health)

Research on **coastal inundation patterns related to climate change** will allow informed decision-making with respect to infrastructure and coastal community development. Increased understanding and predictive capacity in this research area has a direct ability to reduce the risks and costs associated with poor planning decisions around our estuaries. Similarly, this research could assist with assessment of **future human health risk areas**, e.g. vectors of mosquito-borne viruses

associated with inundation. Both of these research areas require a consideration of current and future land development decisions.

5. *Socio-economic assessment and Indigenous knowledge (Theme: Socio-economic aspects)*

Investment in **developing agreed methodologies to assess socio-economic benefits**, in a quantitative and spatially explicit way, and one that can be used to assess costs and benefits of future scenarios and planning decisions, is also critical for effective management of our South West estuaries. There is a need to be able to express the value of estuaries and balance trade-offs associated with population growth and development. Research relating to **Indigenous knowledge and its integration into management** is required.

6. *Integrated systems modelling (Themes: all)*

Investment in **integrated system modelling** will continue the synthesis of bio-physical data and process understanding and develop predictive tools to directly support decision-making. Currently, hydrodynamic models successfully predict physical conditions, yet research is needed to adequately couple these to biogeochemical and ecological aspects within our estuaries. Research is also needed to link land use change with estuarine response in a predictive manner. A framework with agreed protocols is required to allow efficient and effective modular model development. Research on other critical knowledge gaps should be undertaken in a way that facilitates transfer and inclusion in future models.

4 Estuary-specific priorities

The priorities listed in the previous section ranked highly, largely because they are broadly applicable across all South West estuaries. In parallel, we considered seven case study estuaries singularly to determine how their priorities compared with the broader regional scale priorities identified and whether gaps exist. Some of the selected estuaries are well-studied and have been the focus of recent strategic projects such as the [Regional Estuaries Initiative \(REI\)](#), the [Perth and Peel Green Growth Plan](#) the [Vasse Geographe Strategy](#) and the [Swan Canning River Protection Strategy](#). The system-specific science needs for these systems have largely been articulated within these strategies. In the following sections the system-specific priorities are mapped against the regional-scale high priorities outlined in Section 4.13.

4.1 Swan-Canning River System



The Swan-Canning River system has a relatively long history of management focus and associated science programs. Management is currently guided by the River Protection Strategy (DPaW, 2015). Both management and scientific understanding has been supported by a 20-year water quality data set.

In addition, some strong management-researcher partnerships have been fostered. This continues to date and many of the high priority science needs identified in this document are applicable to the Swan-Canning and identified in the Swan-Canning Research Strategy (as developed by the Swan River Trust 2014).

In the 2014 review by the WA Auditor General on the health of the Swan-Canning river system, it was recommended that indicators and monitoring needed to be sufficient to report to government on the status of the river to better understand the changes that occur and to provide effective management of the river system.

ENABLING PRIORITIES	E1. Monitoring and modelling - a stable enduring platform
	<ul style="list-style-type: none"> - a high value 20 year WQ dataset exists; monitoring program in review to ensure applicability of data to management needs - habitat mapping - biotic monitoring
	E2. Effective, frequent assessment – report on condition/trend
	<ul style="list-style-type: none"> - high priority
RESEARCH PRIORITIES	E3. Ability to inform catchment management – assess and forecast effectiveness and intervention scenarios
	<ul style="list-style-type: none"> - high priority
	E4. Effective Communication
	<ul style="list-style-type: none"> - high priority
	R1. Water Quality: Estuary metabolism and nutrient cycling
	<ul style="list-style-type: none"> - deeper understanding of the response to changing environmental conditions - quantification of biotic components in trophic pathways (e.g. zooplankton, jellyfish)
	R2. Key Habitats and Biota: Ecosystem function and food web dynamics
	<ul style="list-style-type: none"> - environmental requirements for high-value species - extend understanding of contaminant levels in recreationally caught fish and invertebrates to provide better information to the community
	R3. Land use: Innovation in managing nutrient pollution
	<ul style="list-style-type: none"> - nutrient export from the catchment remains a priority; improved information on groundwater-surface water interactions, nutrient stripping and innovative soil management technologies are required - refer to CRC for Water Sensitive Cities research programs for information and status on Urban nutrient management knowledge gaps (https://watersensitivecities.org.au/content_type/resources/)
	R4. Coastal Engineering, Habitats, Biota and Human Health: Climate change impacts
	<ul style="list-style-type: none"> - Understanding changes and developing climate mitigation and adaptation strategies requires improved information on biotic habitat requirements and tolerance limits. Improved predictive capacity through modelling will assist in management of estuarine and foreshore habitat and also in managing built foreshores with better design criteria and management practice.
R5. Socio-economic aspects: Socio-economic assessment and Indigenous knowledge	
<ul style="list-style-type: none"> - improved understanding of economic value of different land uses and natural capital will assist in decision support 	
R6. All themes: Integrated systems modelling	
<p>Development of an estuarine response model is well underway but to be fully functional requires improved information on estuarine metabolism, nutrient inputs and cycling, dynamics of biota, their interaction and responses to changing environmental conditions and ecological function.</p> <ul style="list-style-type: none"> - next stage is to develop biogeochemical and ecological modules <p>Through integrated system modelling, a predictive capacity to test scenarios of land use change and interventions is a necessity, as well as ensuring the performance of interventions are monitored, assessed and communicated.</p> <p>Linking catchment and estuarine models: updating and refining and linking existing models will provide valuable decision support mechanisms for the management of key water quality and eutrophication.</p>	
Other estuary specific priorities	
<p>Health indices: the existing fish communities indices and seagrass indices requires support for ongoing monitoring and validation respectively. For a more complete picture of ecosystem health, measures should include invertebrate and microbial communities.</p> <p>Estuarine resources: the Swan-Canning supports high value recreational fisheries and while there is information about fish communities generally, the stock size and status of many key species is not well documented. Additionally, only limited data is available on the impact of recreational fishing on the stocks. More information is required in order to adequately manage these valued resources and disentangle fishing pressure from other environmental pressure. Effort should be coupled with better information on fish biology and movement patterns, and investigation of the value of restocking targeted species where appropriate.</p>	

4.2 Peel-Harvey Estuary



In 2016 The Western Australian Government released the draft Perth and Peel Green Growth Plan for 3.5 million (Green Growth Plan www.dpc.wa.gov.au/greengrowthplan) with two key goals:

- *Cutting red tape by securing upfront Commonwealth environmental approvals and streamlining State environmental approvals for the development required to support growth to 3.5 million people; and*
- *Unprecedented protection of our bushland, rivers, wildlife and wetlands through implementation of a comprehensive plan to protect our environment.*

An ARC Linkage project (see Section 4.5) that commenced in early 2016, is designed to address some of the knowledge gaps detailed in this document with respect to the Peel-Harvey estuary and its catchment. It will focus on developing the predictive decision support framework required to support social aspirations and environmental health.

The Regional Estuaries Initiative includes a number of activities in the Peel Region such as drainage management and voluntary soil testing. There are also several projects being undertaken by the Department of Water and the Peel-Harvey Catchment Council with the objective of improving water quality in the rural drainage system in the catchment.



These two initiatives representing both highly engaged management and complimentary research presents a timely opportunity to establish a best practice model of delivering science for estuary management.

ENABLING PRIORITIES	E1. Monitoring and modelling - a stable enduring platform
	<ul style="list-style-type: none"> - all baseline data referred to in Tables 2-11 and 13 bathymetry survey (LiDAR survey completed in 2016 - data needs validation) - WQ catchment/estuary monitoring extended in 2016 (https://rei.water.wa.gov.au/)
	E2. Effective, frequent assessment – report on condition/trend
	<ul style="list-style-type: none"> - high priority
RESEARCH PRIORITIES	E3. Ability to inform catchment management – assess and forecast effectiveness and intervention scenarios
	<ul style="list-style-type: none"> - high priority
	E4. Effective Communication
	<ul style="list-style-type: none"> - high priority
	R1. Water Quality: Estuary metabolism and nutrient cycling
	<ul style="list-style-type: none"> - high priority - better understanding of the estuary metabolism, nutrient cycling - quantitative information on productivity, decomposition, nutrient flux, sedimentation and bioturbation (work in this area has commenced with the ARC linkage project - LP150100451)
	R2. Key Habitats and Biota: Ecosystem function and food web dynamics
	<p>The Peel-Harvey supports high value recreational fisheries and while there is information about fish communities generally, the stock size and status of some key species is not well documented. Additionally, only limited data is available on the impact of recreational fishing on the stocks. More information is required in order to adequately manage these valued resources and disentangle fishing pressure from other environmental pressure. Effort should be coupled with better information on fish biology and movement patterns.</p>
	R3. Land use: Innovation in managing nutrient pollution
	<ul style="list-style-type: none"> - catchment source delineation and connection to management interventions, impact of organic nutrient loads on primary productivity - innovative use of soil amendments and performance assessment of these interventions - interventions in rural drainage systems
R4. Coastal Engineering, Habitats, Biota and Human Health: Climate change impacts	
<ul style="list-style-type: none"> - high priority 	
R5. Socio-economic aspects: Socio-economic assessment and Indigenous knowledge	
<ul style="list-style-type: none"> - build a decision support framework for optimising trade-offs between social aspirations and sustaining key ecosystem services (in progress - ARC Linkage Project) 	
R6. All themes: Integrated systems modelling	
<ul style="list-style-type: none"> - high priority 	
Other estuary specific priorities	
<ul style="list-style-type: none"> - dredging impacts and management options - eg. explore potential adaptations of the WAMSI dredging node findings, disposal of dredge spoil ,and consideration of dredging contaminated sediments sediment chemistry – drivers of black ooze, sediment nutrient cycling, contaminant status -options for disposal of dredging spoil 	

4.3 Leschenault Estuary

The Leschenault Estuary, located adjacent to the city of Bunbury, one of the most populous areas of the state's southwest. The population is forecast to grow from 61,000 to between 100,000 to 150,000 residents by 2031 (WAPC 2005; DoP pers. comm.). The projected urban development and intensification of land uses, such as irrigated horticulture and intensive dairies, will be close to the estuary and have the potential to increase nutrient runoff to the waterways and the estuary, unless appropriate land use planning and management measures are undertaken.

The Leschenault Estuary and associated waterways are showing signs of stress. In the estuarine portions of the Preston, Brunswick and Collie rivers and in the Leschenault estuary's northern basin, symptoms of estuary decline and collapse are evident. Excessive algal growth (including toxic species) and lack of oxygen leads to fish deaths and unpleasant odours, and these symptoms are exacerbated by low flows. Ecosystem decline also manifests as large-scale macroalgal blooms along the estuary shores. Indications are that the seagrass in the estuary is also struggling.

Dolphins are an important component of this ecosystem and are significant socio-economically through the Dolphin Discovery Centre (dolphindiscovery.com.au), tourism activities and research programs of the South West Marine Research Program (mucru.org/our-research/research-projects/south-west-marine-research-program/marine-mammal-health-project and mucru.org/our-research/research-projects/south-west-marine-research-program/marine-mammal-health-project).

The Department of water in partnership with the Leschenault Catchment Council (LCC) led the development of the Leschenault Estuary Water Quality Improvement Plan (WQIP). The WQIP presents a consolidated understanding of the water quality issues in the catchment and estuary and has identified a number of management actions supported by cost/benefit analysis (Hugues-dit-Ciles et al, 2012). Implementation of the Regional Estuaries Initiative in 2016 has reinstated critical monitoring programs in the catchment and estuary and the communication of condition and management activity has commenced with the REI website (rei.water.wa.gov.au/estuary/leschenault-estuary).

The workshop participants identified a number of priorities for the Leschenault. These have been confirmed and others added from the recently updated Condition Statement (DOW, 2015 *draft*):

ENABLING PRIORITIES	E1. Monitoring and modelling - a stable enduring platform
	<ul style="list-style-type: none"> - refer Tables 2-11 and 13 - macrophyte surveys - invertebrate monitoring - bathymetry survey (LiDAR survey completed in 2016 - data needs validation) - WQ catchment/estuary monitoring reinstated by REI
	E2. Effective, frequent assessment – report on condition/trend
	<ul style="list-style-type: none"> - high priority
RESEARCH PRIORITIES	E3. Ability to inform catchment management – assess and forecast effectiveness and intervention scenarios
	<ul style="list-style-type: none"> - high priority
	E4. Effective Communication
	<ul style="list-style-type: none"> - high priority
	R1. Water Quality: Estuary metabolism and nutrient cycling
	<ul style="list-style-type: none"> - sediment nutrient cycling studies particularly in the Collie/Brunswick rivers - groundwater influence on estuary particularly from northern agricultural land and eastern residential side; is this a significant contributor to observed macroalgal blooms? - bioturbation studies to understand the influence on sediment nutrient stores and recycling; detail role of blue swimmer crab population, are they contributing to the observed low nutrient stores in fine sediments?
R2. Key Habitats and Biota: Ecosystem function and food web dynamics	
<ul style="list-style-type: none"> - demonstrate seagrass values as habitat/ protection/food; provide evidence of importance of habitat - invertebrate studies to assess use as an indicator of estuary health 	
R3. Land use: Innovation in managing nutrient pollution	
<ul style="list-style-type: none"> -dynamics of Parkfield drain a priority given planned intensification of agriculture in vicinity and poor flushing characteristics of the northern estuary 	
R4. Coastal Engineering, Habitats, Biota and Human Health: Climate change impacts	
<ul style="list-style-type: none"> - narrowing of 'The Cut' is raising concerns about estuary-ocean exchange dynamics 	
R5. Socio-economic aspects: Socio-economic assessment and Indigenous knowledge	
R6. All themes: Integrated systems modelling	
Other estuary specific priorities	

4.4 Vasse-Wonnerup Wetland System



The Western Australian Government, through Royalties for Regions, has recently funded the *Revitalising Geographe Waterways* (<http://www.water.wa.gov.au/water-topics/rivers-and-estuaries/vasse-wonnerup-waterways-and-wetlands>) which supports the *Vasse Strategy* (<http://geocatch.asn.au/our-work/vasse-geographe-strategy/>). The **Vasse Taskforce** driving the strategy that aims to improve water quality across five key water assets - Geographe Bay catchment, Vasse-Wonnerup wetlands, Lower Vasse River, Toby Inlet and rural drainage networks.

This program is delivering on-ground works and other actions that will:

- reduce nutrients from significant sources in the catchment
- establish a sound technical basis for management
- develop a financial sustainability strategy for long-term water quality improvement
- build capacity in local water asset managers
- involve the community in establishing management objectives
- develop plans for the long-term management of key water assets

Science has a clear role in establishing the sound technical basis for management and a science advisory group has recently been formed to guide the Vasse Strategy. The science and monitoring needed in the Vasse-Wonnerup has previously been articulated both in the Ecological Character Description (WRM, 2007) and in the background document prepared by South West Catchment Council prior to funding PhD and Masters research projects on the system (Hugues dit Ciles, SWCC 2014). These are summarised below, with additional input from the science advisory group.

ENABLING PRIORITIES	E1. Monitoring and modelling - a stable enduring platform
	<ul style="list-style-type: none"> - refer Tables 2-11 and 13 - invertebrate/ crustacea monitoring - map and monitor status of fringing vegetation - improve spatial and temporal information about phytoplankton, macroalgae and submerged aquatic vegetation, including influence of water quality parameters on growth rates
	E2. Effective, frequent assessment – report on condition/trend
	<ul style="list-style-type: none"> - high priority
RESEARCH PRIORITIES	E3. Ability to inform catchment management – assess and forecast effectiveness and intervention scenarios
	<ul style="list-style-type: none"> - high priority
	E4. Effective Communication
	<ul style="list-style-type: none"> - high priority
	R1. Water Quality: Estuary metabolism and nutrient cycling
	<ul style="list-style-type: none"> - identify nutrient and carbon sources and sinks within the estuaries and determine nutrient dynamics (e.g. bioavailability, adsorption/desorption, denitrification), understand sediment role in nutrient cycling
	R2. Key Habitats and Biota: Ecosystem function and food web dynamics
	<ul style="list-style-type: none"> - extend knowledge on the interrelationships between flora and fauna in the system - physiological requirements of key biota at critical life stages - influence of wq on growth rates, of phytoplankton, macroalgae and aquatic macrophytes - understand relationships between water birds and water variables (depth, salinity etc) and understand role of wetlands for breeding
R3. Land use: Innovation in managing nutrient pollution	
<ul style="list-style-type: none"> - assessment and scalability of dairy effluent BMPs 	
R4. Coastal Engineering, Habitats, Biota and Human Health: Climate change impacts	
<ul style="list-style-type: none"> - high priority 	
R5. Socio-economic aspects: Socio-economic assessment and Indigenous knowledge	
<ul style="list-style-type: none"> - establish community values for waterways, especially to guide restoration objectives 	
R6. All themes: Integrated systems modelling	
<ul style="list-style-type: none"> - build understanding of critical processes to guide management action 	
Other estuary specific priorities	
<ul style="list-style-type: none"> - coastal engineering - improve understanding of the surge barrier operation with respect to fish movement, sediment nutrient release, water quality and phytoplankton response 	

4.5 Hardy Inlet



The Hardy Inlet is a highly valued estuary, both socially and ecologically and its condition is deteriorating. It provides important habitat for migratory and resident waterbirds and is extensively used for recreational fishing, boating and ecotourism.

As land use in the estuary's lower catchments has intensified during the past decades, symptoms of nutrient enrichment have emerged in the inlet. Algal blooms and fish kills have occurred more regularly and community concern about the inlet's health has been growing.

The Hardy Inlet water quality improvement plan (WQIP): Stage one - the Scott River catchment, focused on managing the largest source of phosphorus load to the inlet from the Scott River catchment (White, 2012). The Department of Water, in partnership with the South West Catchment Council (SWCC), is completing Stage 2 of the WQIP addressing other key sources of nutrients to the inlet, including those delivered by the Lower Blackwood catchment and the Augusta town site.

Poor water quality and potentially overfishing has led to a decrease in the abundance of key recreational fish species such as black bream in the Hardy Inlet-Blackwood River system (there is only one commercial fishing license). A restocking project by Murdoch University and Challenger Institute of Technology was undertaken to enhance black bream fish stocks. Studies have shown that restocking has contributed substantially to the recreational and commercial catches. Monitoring of environmental conditions and better data on the recreational fish take are important to assess the potential for and success of restocking programs. With an increasing number of fish stocks being closed for fishing in the marine environment, restocking estuaries may increasingly be useful to relieve some of the pressure on those stocks and provide alternative opportunities for recreational fishers.

ENABLING PRIORITIES	E1. Monitoring and modelling - a stable enduring platform
	- refer to Tables 2-11 and 13 - commitment to baseline monitoring (some has been reinstated by REI, 4 year program) - bathymetry survey (LiDAR survey completed in 2016 - data needs validation)
	E2. Effective, frequent assessment – report on condition/trend
	- high priority
RESEARCH PRIORITIES	E3. Ability to inform catchment management – assess and forecast effectiveness and intervention scenarios
	- high priority
	E4. Effective Communication
	- high priority
	R1. Water Quality: Estuary metabolism and nutrient cycling
	- high priority
	R2. Key Habitats and Biota: Ecosystem function and food web dynamics
	- high priority
	R3. Land use: Innovation in managing nutrient pollution
	- high priority
R4. Coastal Engineering, Habitats, Biota and Human Health: Climate change impacts	
- high priority	
R5. Socio-economic aspects: Socio-economic assessment and Indigenous knowledge	
- develop tools and behaviour change strategies to reduce phosphorus loads from Scott River	
R6. All themes: Integrated systems modelling	
- estuarine response model linked to catchment model to guide management scenarios	
Other estuary specific priorities	

4.6 Wilson Inlet



Wilson Inlet, adjacent to the town of Denmark, is one of the largest estuaries on the south coast and is seasonally open to the ocean. A sound science based understanding of the pressures on the estuary was established during the 1980s and 90s. This led to the development of the Wilson Inlet Nutrient Reduction Action Plan (WRC, 2003). Subsequently, the Wilson Inlet Management Strategy was developed by the Wilson Inlet Catchment Committee (WIMC, 2010).

The sandbar is opened most years by the Water Corporation in accordance with an agreed protocol primarily to mitigate against flooding of the low-lying districts. The water level, timing and location of the opening impacts multiple socio-economic and environmental aspects of the inlet. High water levels reduce the amount of wading habitat for shorebirds; longer closing times restrict the exchange of marine water which may impact on fish recruitment; and there are concerns that longer closing times increase the eutrophic symptoms. These sometimes-competing interests are exacerbated by the reduction in freshwater inflows observed in recent years.

To assist management responsibilities to mitigate flooding and optimise ecological and community needs, an estuary response model is required. The recently funded Regional Estuaries Initiative will invest in the development of an estuary model incorporating the predicted climate change scenarios - this is intended to assist decision-making, facilitate community engagement and will ultimately lead to an updated bar opening protocol. Clearly model scenarios will need to consider not only an absolute water level but also take into consideration the rainfall patterns and the key values of the inlet, e.g., flora and fauna ecosystems, social interaction and Indigenous heritage.

ENABLING PRIORITIES	E1. Monitoring and modelling - a stable enduring platform
	- refer Tables 2-11 and 13 - bathymetry survey (LiDAR survey completed in 2016 - data needs validation)
	E2. Effective, frequent assessment – report on condition/trend
	- high priority
RESEARCH PRIORITIES	E3. Ability to inform catchment management – assess and forecast effectiveness and intervention scenarios
	- high priority
	E4. Effective Communication
	- high priority
RESEARCH PRIORITIES	R1. Water Quality: Estuary metabolism and nutrient cycling
	Concurrent water quality data with estuary opening/closing to calibrate salt wedge penetration into the estuary. Define the nutrient levels from river input and sediment release
	R2. Key Habitats and Biota: Ecosystem function and food web dynamics
	- high priority
	R3. Land use: Innovation in managing nutrient pollution
	- high priority
	R4. Coastal Engineering, Habitats, Biota and Human Health: Climate change impacts
	- high priority
	R5. Socio-economic aspects: Socio-economic assessment and Indigenous knowledge
	- high priority
R6. All themes: Integrated systems modelling	
Estuary Model: Currently at initial stages for numerical model development (DoW) Sediment transport modelling – including data validation needs.	
Other estuary specific priorities	
- Once satisfied with hydrodynamic model, then a biochemical model can be initiated. This addresses the first key target for the Wilson Catchment Council, a reduction in nutrient concentrations from all sources to achieve downward trend (including catchment, rural and urban sources).	

4.7 Wellstead Estuary



Wellstead estuary, adjacent to the town of Bremer Bay, forms the western boundary of the Fitzgerald River National Park. The Fitzgerald River National Park is one of the largest and most botanically significant national parks in Australia. The park and surrounds, of which the estuary forms part, has been given international status as an International Biosphere Region.

Recent observations have shown a potential shift from a macrophyte to phytoplankton (cyanobacteria) dominated system. The dominant macrophyte was *Ruppia* seagrass and waters were generally clear; now the cyanobacteria *Synechococcus* dominates the aquatic flora creating more turbid, pumpkin soup-coloured waters.

The most recent management plan was undertaken by the Shire of Jerramungup and Department of Environment (DoE, 2006).

ENABLING PRIORITIES	E1. Monitoring and modelling - a stable enduring platform
	- refer to Tables 2-11 and 13 - very limited baseline water quality data precludes knowledge development in this area, currently quarterly monitoring in estuary and no catchment monitoring (not funded by REI)
	E2. Effective, frequent assessment – report on condition/trend
	- high priority
RESEARCH PRIORITIES	E3. Ability to inform catchment management – assess and forecast effectiveness and intervention scenarios
	- high priority
	E4. Effective Communication
	- high priority
	R1. Water Quality: Estuary metabolism and nutrient cycling
	- high priority
	R2. Key Habitats and Biota: Ecosystem function and food web dynamics
	understand cause of dynamics of observed ecological changes (shift from macrophyte to picoplankton dominated system to propose potential management actions to protect estuary values)
R3. Land use: Innovation in managing nutrient pollution	
R4. Coastal Engineering, Habitats, Biota and Human Health: Climate change impacts	
R5. Socio-economic aspects: Socio-economic assessment and Indigenous knowledge	
- high priority	
R6. All themes: Integrated systems modelling	
Other estuary specific priorities	

5 Conclusion

In the case of many of our estuaries of the South West, our aim should not be to manage the natural assets by excluding development; rather it needs to be to manage our natural assets for development, as people are an intrinsic part of these socio-economic and environmental systems. Our challenge is to manage them in the context of significant development (existing or planned) such that the important ecosystem services that they freely provide are sustained, or in some cases revitalised. For near-pristine systems, our focus of understanding should orient towards sustainability thresholds and in the case of impacted or degraded systems, it should be on how to revitalise natural ecosystem services. The socio-economic decisions being made now will determine if Australian estuaries are sustainable in 2050 and beyond (Wolanski and Ducrotoy, 2014).

Due to the complexity, multi-jurisdictions involved and interdisciplinary nature of estuaries, a collaborative and coordinated approach is essential. This will allow the aligned, complimentary and efficient use of the collective resources of many organisations and result in greater value for public investment in science; more targeted outputs from science through close work between end-users and providers; and a greater chance of innovative solutions through multi-disciplinary consideration of problems. As stated earlier in this document, our purpose is to present science priorities for estuary management irrespective of the governance arrangements, however the governance is important for the successful delivery of science needs and management actions. A collaborative structure that will facilitate the delivery of a strategic, aligned research agenda will be presented in a future document.

This report has demonstrated that both the management and research community agree that there are significant gaps in the knowledge base necessary for effective and efficient estuary management. Accepting that the demands are intense and pressures are increasing and changing, strengthening our capacity to collaborate, engage and align our interests around addressing the knowledge gaps is needed now more than ever. We envisage that having an agreed research agenda and progressing the implementation of enabling science priorities will promote better governance of estuaries and their catchments and in so doing support the communities of these regions, both socially and economically.

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APPENDICES

A. Acknowledgements

ORGANISATIONS SURVEYED

Government	DEPARTMENT OF AGRICULTURE AND FOOD, WA DEPARTMENT OF FISHERIES, WA DEPARTMENT OF HEALTH, WA DEPARTMENT OF PARKS AND WILDLIFE, WA DEPARTMENT OF PLANNING, WA DEPARTMENT OF TRANSPORT, WA DEPARTMENT OF WATER, WA SWAN RIVER TRUST (now DEPT OF PARKS AND WILDLIFE)
Research	CSIRO CURTIN UNIVERSITY EDITH COWAN UNIVERSITY MURDOCH UNIVERSITY UNIVERSITY OF WESTERN AUSTRALIA
Catchment Groups	LESCHENAULT CATCHMENT GROUP PEEL-HARVEY CATCHMENT COUNCIL SOUTH WEST CATCHMENTS COUNCIL WILSON INLET CATCHMENT COUNCIL
Peak Bodies	RECFISHWEST

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B. Key statistics of the seven case study estuaries

	Swan-Canning Estuary ¹	Peel-Harvey Estuary ²	Leschenault Estuary ³	Vasse-Wonnerup Wetlands	Hardy Inlet ^{4, 5}	Wilson Inlet ⁶	Wellstead Estuary ⁷
City/town	Perth-Fremantle	Mandurah	Bunbury	Busselton	Augusta	Denmark	Bremer Bay
Population	1,728,867	100,000	64,385	31,767	1,022	2,300	600
Population growth rate	3.5% pa	3.4% pa	1.5% pa		2.2% pa	2.4% pa	~1.5% pa
Ocean opening	Permanent opening	Permanent opening	Permanent opening	Permanent flood gate/surge barrier control	Permanent opening (natural)	Artificially opened in August to October	Natural sandbar opening every 1-3 years
Estuary surface area (km²)	40	134	27		9	48	2.5
Catchment area (km²)	2,090*	2,805*	1,889		22,500	3,400	720
Catchment: estuary ratio	52	77	70		2500	71	288
Mean annual rainfall (mm/yr)	~750	850	~750		500	765	494
Mean annual discharge (GL/year)	189 (1997–2006)	398 (1997–2007)	358 (1998–2007)		587 (2000–11)	157	14
Catchment percentage cleared (%)	56	60	52		75	60	75
% urban	33	9	3		-	-	-
% agricultural	23	51	49		-	-	-
Annual nitrogen load (t/yr)	250 (1997-2006)	818 (1997–2007)	312 (1998–2007)		445 (2000–11)	204 (2011)	-
Annual phosphorus load (t/yr)	26 (1997–2006)	135 (1997–2007)	28 (1998–2007)		18 (2000–11)	11 (2011)	-
Nitrogen reduction target (% reduction) (t/yr)	130 (49%)	-	211 (37%)		1.0 mg/L	-	-
Phosphorus reduction target (% reduction) (t/yr, or concentration)	14 (46%)	64 (53%)	5.7 (73%)		0.1 mg/L	-	-

C. Process used to determine knowledge priorities

The prioritisation framework is derived from David Pannell, an expert on priority setting for environmental research. David provided a relatively simple and robust framework for the members of the Marine Blueprint 2050 Steering Group to consider (see Pannell et al., 2013 and 2014). For the SW estuaries knowledge gaps we have used a modified version of that framework which delivers a benefit cost analysis for each identified knowledge gap/science need based on allocation of scores against, in our case, five well-tested and sensible criteria, as outlined in the table below.

Table 19 Process used to determine knowledge priorities

Criteria		Guidance on issues to consider when addressing each criteria	Scoring	Numeric
1	Importance of the issue to healthy estuaries (I)	<ul style="list-style-type: none"> • scale of the issue • economic costs or benefits related to the issue • community interest in the issue 	V. High High Moderate Low V. Low	5 4 3 2 1
2	Relevance: The relative importance of <u>new</u> information in addressing this issue? (R)	<ul style="list-style-type: none"> • Is a lack of certainty or information the greatest challenge in this area, or is it engineering feasibility, mapping or policy? If the latter then perhaps 'Low' is appropriate. • Will it address the knowledge gap? 	High Medium Low	3 2 1
3	Urgency of the information need (U)	<ul style="list-style-type: none"> • When do decision makers need the information to manage the above issue? <p>Note: This may not be for "on-ground effect", but when planners need it for planning processes for example which may be several years before a plan is implemented</p>	<5 years 5-10 years > 10 years	1 2 3
4	Certainty of research outcome (Ce)	<ul style="list-style-type: none"> • Is this area or research/monitoring experimental, or are we certain to get an outcome as the method/approach been tested previously 	High Medium Low	3 2 1
5	Costliness of research in this area. (Co)	<ul style="list-style-type: none"> • Needs expensive labs/field equipment? • Lots of remote field work? • Lots of people employed to do it? • Research needs to be continued for many years? 	High > \$1M Moderate \$100K - \$1M Low < \$100K	3 2 1
-	Adoptability of the results. (A)	<ul style="list-style-type: none"> • Systems are in place for uptake – a constant will be applied to all for this factor so the WG does not need to consider 	N/A	

Scores for each criterion are used in a metric for ranking research/knowledge gaps, as follows:

$$\text{Overall score} = I \times R \times Ce \times (1 - U/4) / Co$$

David Pannell advised the Marine Blueprint Steering Group that the structure of this metric is important. He advised to multiply the benefit-related variables, not add them and to divide by cost, not subtract it. The inclusion of U in $(1 - U/4)$ is to approximate discounting for time. For the specified time lags (<5, 5-10, >20 years) this formula is recommended as it gives a close approximation of discounting at 5% per year.

This prioritisation framework was applied to the 123 knowledge gaps across 11 management themes as identified from the initial survey results and subsequent workshop (September, 2014). Members of the working group individually assigned scores using this framework for the seven case study estuaries. The scores were assigned for each knowledge gap for each of the case study estuaries and averaged to give a regional score for all estuaries. The knowledge gaps were then ranked based on these averaged scores. Scores were reviewed by the Working Group and some revisions were made following discussion and agreement on appropriate scoring.

D. Current governance responsibilities for estuary management in southwest Western Australia

Agency / group	Responsibility
Department of Water	<p>Manages groundwater use primarily via allocation limits and groundwater licences (as regulated under the <i>Rights in Water and Irrigation Act 1914</i>).</p> <p>Is responsible for developing strategies and management plans (primarily through non-statutory Water Quality Improvement Plans) to protect the quality of estuarine waterways through a whole-of-government, catchment based approach and to protect infrastructure from flooding, and enhance the living environment for the community.</p> <p>Manages several foreshore reserves in and around Ramsar sites.</p>
Department of Parks and Wildlife	<p>Manages lands within Ramsar sites that are vested within the Conservation Commission of Western Australia under the CALM Act, including the conservation parks that fringe Estuaries. Ramsar sites of the 7 estuaries included in the current study are the Peel-Harvey Estuary and the Vasse-Wonnerup Wetland System. In addition, the Department of Parks and Wildlife are responsible for management of the Swan-Canning Riverpark under the Swan-Canning Management Act as amended (2015)</p>
Department of Fisheries	<p>Is responsible for conserving, developing and managing fish and aquatic resources. Manages and licenses commercial and recreational fishing activities within the southwest bioregions, through compliance and community education.</p> <p>Responsible for providing scientific knowledge and advice to support the conservation and sustainable use of the State's aquatic resources.</p> <p>Lead agency for aquatic biosecurity.</p>
Department of Agriculture and Food	<p>The Department of Agriculture and Food WA (DAFWA) has input into sustainable farming systems that minimise off-site impacts, i.e. management of nutrients on farm to minimise damage to waterways whilst maintaining productivity.</p>
Department of Transport	<p>Is responsible for marine safety and the provision of coastal facilities such as jetties and moorings. This includes managing designated water ski areas, launching ramps and jetties, moorings, boating prohibited areas, boating speed restrictions, navigation aids and dredging within navigable waterways.</p>
Department of Health	<p>Is responsible for responding to public health issues associated with harmful algal blooms, and mosquito-borne disease risk minimization associated with waterways. It provides advice on the suitability of natural waterways for primary and secondary contact recreational activities and administers the Western Australia Shellfish Quality Assurance Program (WASQAP).</p>
Department of Planning	<p>Is responsible for land use planning. The DoP is not an estuary manager and nor does it set policy for estuary management. In undertaking land use planning and decision making around estuaries the DoP relies upon advice provide by those State Government agencies with a direct role and expertise relevant to estuary management – the Departments of Water, Parks and Wildlife (the Swan River Trust), Fisheries, and Environment Regulation. Having said this, DoP planners are cognisant of the impacts that land development can have on estuaries and vice versa. The overall planning approach is to ensure the application of water sensitive</p>

	urban design principles at each stage of the planning system. Land use planning policy on this matter is included in a number of State Planning Policies (SPP), a Planning Bulletin (PB) and an implementation guidance document:
Local government authorities	Have land management responsibilities for conservation and recreation reserves inside or adjacent to estuarine sites. Inform and negotiate with local communities on estuarine issues such as bar opening and human health issues
Catchment Councils	Are not-for-profit, community based Natural Resource Management organisations that promote an integrated approach to catchment management and protection and restoration of the environment within estuary catchments.
Landcare Centers	Support the planning and implementation of on-ground activities conducted by Local Government, private landholders and community groups on public land e.g. revegetation, streamlining (fencing and revegetation of riparian areas), protection of bushland, weed control, litter removal and wetland enhancement
Other community groups	Groups or peak bodies also represent local community environmental and recreational interests such as BirdLife Australia and Recfishwest

E. Estuary management activities in southwest Western Australia: 20-year summary

In the South West, at-risk estuaries have been identified and actively managed over the last 20 years. The following is a summary of the management activities undertaken during this time:

- Majority of estuaries in the greater southwest from Kalbarri to Esperance have been surveyed and assessed for condition
- At-risk estuaries have been identified for more intensive study and development of action plans based on findings of integrated research programs. They are:
 - Swan-Canning – Swan-Canning Cleanup Program and Healthy Rivers Actions Plan
 - Peel-Harvey – Management Plan
 - Wilson Inlet – Wilson Inlet Nutrient Reduction Plan
 - Torbay – Watershed Torbay
 - Albany Harbours – Management plans
 - Wellstead, Stokes and Culham inlets on the south coast – Management plans
 - Vasse-Wonnerup – GeoCatch Lower Vasse River Cleanup Plan, currently the Vasse Strategy
- Development of whole of catchment partnership Water Quality Improvement Plans (WQIPs) using numerical modelling tools and identification of agricultural best practice for five estuary systems:
 - Peel-Harvey
 - Swan-Canning
 - Vasse-Geographe
 - Leschenault estuary
 - Hardy Inlet – Stage 1 Scott and Stage 2
- Recent inclusion of Avon catchment in numerical modelling approaches and identification of management actions.
- Development of understanding of estuary response to catchment pressures in SW estuaries leading to identification of key indicators of condition:
 - Water quality
 - Phytoplankton
 - microalgae
 - Sediment
 - Submerged aquatic vegetation
 - Ocean connectivity
 - River flow
- Extensive catchment and estuary monitoring to support decision making
- Development of Estuary Condition Assessment Framework taking into account range of estuaries in the South West allowing estuary Condition Reporting

- Development of an estuary report card format suitable for a range of estuaries using internationally benchmarked Water Quality Index.
- Extensive development of seagrass indicators of estuary condition now being applied to Swan-Canning, Peel-Harvey and Leschenault estuaries
- Comprehensive study of roles of sediments in estuary condition across 16 estuaries in partnership with Geoscience Australia
- Substantial progress in development of a Fish Community Health Index
- Implementation of actions plans and WQIPs to the extent that they are funded through partnership approach
- Development and implementation of River Action Plans in many catchments including substantial establishment of Riparian Zone vegetation.
- Development, testing and implementation of innovative remediation technologies such as:
 - Phoslock™
 - Bottom water oxygenation in estuaries
 - Algal floccing clays
 - Hybrid nanoclays to bind phosphorus
- Assessment of acid sulphate soil impacts on South West estuaries through extensive investigations.
- Engagement through cross agency and catchment council partnerships with landholders on best practice to improve both farm productivity and water quality in receiving waters.
- Continuing engagement with dairy industry to develop best practice in effluent management.
- Establishment of Fertiliser Action Plan and the Fertiliser Partnership as a government policy response to the need for fertiliser management leading to extensive soil testing and fertiliser management advice.
- Concerted effort by DoW, DAFWA and CSIRO to identify, characterise, test and trial soil amendments for the purpose of improving phosphorus retention of soils to benefit both farm productivity and water quality.
- Development of Best Urban Water Management Framework (BUWM) as whole of government policy so that water quality outcomes can be achieved through the planning process. Active promotion and assistance to local government in implementing the framework
- Development and update of Stormwater Manual and stormwater management practices including promotion of Water Sensitive Urban Design (WSUD)
- Essential participant relationship with CRC for Water Sensitive Cities to develop broader appreciation of urban water in which estuaries are a key component.
- Use of Drainage Water Management Plans (DWMPs) and Urban Water Management Plans in areas of urban expansion not only to manage water but also to minimise nutrient pollution.

- Development of Urban Nutrient Decision Outcomes (UNDO) tool to assist developers, local government and state agencies to minimise nutrient losses from urban developments.
- Establishment of citizen science projects such as Dolphin Watch and Prawn Watch.
- Support of localised stream restoration from drainage channels to living streams (eg. Bannister Creek) and construction of nutrient assimilation wetlands, such as Liege St wetland and Point Frazer wetlands, which are best practice examples of effective urban stormwater management for positive biodiversity and water quality outcomes.



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