The development and implementation of a hierarchal assessment scheme for the management of estuaries in New South Wales

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Declaration

I certify that this thesis entitled 'The development and implementation of a hierarchal assessment scheme for the management of estuaries in New South Wales' submitted for the degree of Master of Science (MSc.) is my own research, unless otherwise acknowledged, and that this thesis or any part therein has not been submitted for a higher degree at any other university or institution.

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Date

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Abstract

The coastal fringe of Australia is characterised by a number of estuarine environments with over 900 systems identified. Estuaries are one of the richest and diverse coastal environments, ranked among the most valuable natural resources in the world. In Australia, estuaries are biologically productive, providing key environmental, social and economic functions. As coastal populations increase, considerable pressures are exerted on estuarine environments. Despite recent improvements to estuarine management, the absence of a clear and consistent management approach and limited accountability has affected the value of estuarine management. Consequently, there is a need for a clear approach, involving the development of an effective, integrated and regionally consistent assessment of estuarine environments. This approach will guide the formation of management decisions and distribution of limited management resources. A review of existing state and national estuarine assessment schemes revealed that the value and functionality of these assessments are often limited by the inappropriate use of environmental indicators and complex management of data. Several improvements have been made in the current scheme, allowing a greater degree of reliability in the reporting of estuarine condition. These improvements include the development of a simple assessment framework, use of high-value indicators that limit confounding by natural spatial and temporal variation, reduction in the complexity of data analysis and the use of fuzzy logic in indicator evaluation. These improvements were incorporated into the development of a hierarchal assessment scheme that involved a two-tiered assessment of estuaries within New South Wales (NSW), Australia. The regional assessment scheme formed the preliminary component of estuarine evaluation, providing an initial quantitative assessment of 38 estuaries in NSW. Five classes of estuarine condition were identified: near pristine, slightly modified, modified, highly modified and severely modified. Under this scheme, estuarine systems classified as ‘severely modified’ (Dee Why Lagoon, Curl Curl Lagoon, Manly Lagoon, Sydney Estuary and Cooks River) were selected for a detailed evaluation under a local assessment scheme. Using Sydney estuary as a case study in this category, the local assessment formed the secondary component of the hierarchal scheme, providing a detailed intra-estuary assessment of catchment pressures and estuarine condition. Blackwattle/Rozelle Bay, Iron Cove, Homebush Bay and Duck River were found to be heavily degraded with water quality of particular concern in Duck River, Homebush Bay, Parramatta River and Lower Parramatta River. Sediment quality was also of significant

concern in Blackwattle/Rozelle Bay, Iron Cove and Hen and Chicken Bay. North Harbour, Upper Middle Harbour and Lower Middle Harbour were found to be in the best condition. A report card format, involving the use of letter grades, was used to present the results of the assessment schemes. The use of report cards is a valuable tool to convey scientific information in a readily understood manner to estuarine managers and members of the public. Use of letter grades also provides benchmarking and performance monitoring ability, allowing estuarine managers to set improvement targets and assesses the effectiveness of management strategies. The current hierarchal assessment scheme provides an effective, integrated and consistent assessment of estuarine health, unhindered by natural spatial and temporal variance. This scheme, involving the regional and local assessment of estuaries, provides an effective decision support tool to maximise the efficient distribution of limited management resources by identifying priority estuarine systems.

Key Terms

Estuary:

A partially enclosed coastal body of water that is either permanently or periodically open to the sea and which receives sediment from both fluvial and marine sources. The estuary contains geomorphological facies influenced by tide, wave and fluvial processes and is considered to extend from the landward limit of tidal range to the seaward limit.

Regional assessment:

Regional assessment is an inter-basin assessment of multiple estuarine systems.

Local assessment:

Local assessment is an intra-basin assessment of a single, local estuarine system.

Sydney estuary:

Sydney estuary is defined as encompassing all submerged areas to Indian Spring Low water in the estuary and includes areas of North Harbour, Middle Harbour, Sydney Harbour and the Parramatta River.

Sydney catchment:

The Sydney catchment is a drainage basin, defined by topographical boundaries whereby surface water runoff drains into Sydney estuary.

Sub-catchment:

A sub-catchment is a smaller division of catchment, defined by topographical boundaries within a larger catchment. A single catchment may comprise of many sub-catchments.

Sub-estuary:

A sub-estuary is a smaller division of an estuary. Embayments and estuary channels may be classified as subestuaries.

Compartment:

A compartment is a catchment/estuary system operating as a single entity.

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Chapter 1: Introduction

1 Introduction

Estuaries are one of the richest and diverse coastal ecosystems, providing essential environmental, social and economic functions (NLWRA, 2002). With greater than 90% of the Australian population living within 50 km of the coast (ABS, 2011), increasing population densities and urbanisation has resulted in the degradation of many of these important environments.

1.1 Defining Estuarine Environments

Numerous definitions are available to describe estuarine environments, however many of these descriptions fail to take into account features that characterise many Australian estuaries (Potter et al., 2010). To accurately describe estuarine environments within Australia, the following definition adapted from Dalrymple et al. (2010), is used in the current study:

An estuary is defined as a partially enclosed coastal body of water that is either permanently or periodically open to the sea and which receives sediment from both fluvial and marine sources. The estuary contains geomorphological facies influenced by tide, wave and fluvial processes and is considered to extend from the landward limit of tidal range at its head to the seaward limit of its mouth.

1.1.1 Classification of Estuarine Environments

Estuaries and coastal water bodies are dynamic environments in which geomorphic change may occur over a range of time scales (Roy, 1994; Harris et al., 2002). Under stable conditions, the geomorphology of coastal waterways is principally determined by the influence of wave, tide, and river energy (Ryan et al., 2003) (Figure 1).

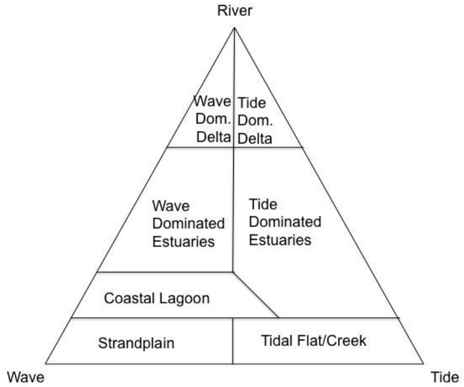


Figure 1: Ternary classification of estuaries (adapted from Dalrymple et al., 2002; Boyd et al., 2002).

A number of schemes have been developed that attempt to classify the range of physical characteristics exhibited by estuarine environments. However, the majority of these are not widely applicable, or do not characterise the nature of Australian estuaries. Ryan et al. (2003) identified several estuarine classes of Australian estuaries and coastal waterways depending on the relative influence of waves, tides, and rivers (Figure 1). Estuaries and coastal waterways may be classified into the following categories:

- Wave dominated;
- Tide dominated;
- Drowned river valley (tide and wave dominated);
- Coastal lagoons and strandplain lakes; and
- Tidal creeks.

1.2 Importance of Estuarine Environments

Estuaries are highly valuable coastal environments, ranking among the most important natural resources in the world (Smith et al., 2001). Large urban populations often occupy these environments due to significant environmental, economic and social importance.

1.2.1 Environmental Value

Estuaries are biologically productive and diverse environments, acting as the interface between terrestrial and marine environments. With high ecological and conservation value (Hutson, 2005; Birch and Hutson, 2009; Boyes and Elliot, 2006), these systems play an important role in maintaining the health of coastal ecosystems, providing essential environmental and ecosystem functions, that include:

- Provision of shelter, breeding grounds and nursery habitat for marine, estuarine and terrestrial species;
- Ability to trap sediment and gross pollutants;
- Play an important role in the recycling of nutrients and carbon; and
- Provision of suitable conditions for important ecological communities, such as saltmarsh, mangroves and seagrass beds.

1.2.2 Economic and Social Value

Estuaries also have a high social and economical value, supporting industrial, commercial and recreational activities (Burchmore, 1992; Ward et al., 1998; Boyes and Elliot, 2006). Estuaries provide:

- Sheltered deep-water access for ports, facilitating trade and ocean transport;
- Suitable areas and resources for urban and industrial development;
- Natural resources such as fisheries and aquaculture;
- Areas for tourism and recreation; and
- Aesthetic value.

1.3 Management of Estuarine Environments

In Australia, rapid, catchment-wide urbanisation and industrialisation in the 19th century may be correlated to the onset of estuarine degradation and contamination (Taylor et al., 2004). Increasing population densities and urban development have increased environmental pressures and subsequent deterioration of adjacent estuarine systems (Birch and Hutson, 2009).

Despite the importance of these natural resources, management of estuaries in Australia has historically been poor (Hutson, 2005), with limited accountability and responsibility. For example, reclamation within Sydney Estuary was considered a ‘harmless’ practice by the NSW Legislative Assembly in 1866, but came at the expense of wetlands, mangroves and other sensitive habitats (Birch et al., 2009). Estuarine environments were also regarded as a suitable location for industrial waste disposal, leading to extensive contamination of heavy metals and organic contaminants (McCready et al., 2000). The absence of a coherent management structure and lack of responsibility has led to the degradation of coastal waterways in Australia (Birch and Taylor, 2004).

Despite recent improvements in the management of estuarine environments in Australia, there is a need to effectively manage impacted estuaries to maintain vital environmental functions, as well as maintaining important social and economic services. Effective management may only be achieved through a sound understanding of the relationship between a catchment and estuary (Edgar et al., 1999). Effective and targeted management of estuaries requires rigorous, high quality, science-based information provided in such a way that it may be readily integrated into a decision-making process by natural resource managers (Hutson, 2005).

1.4 Environmental Indicators

An environmental indicator is a physical, chemical, biological or socio-economic measure, used to assess the current state and condition of the environment. Indicators provide a scientific basis for the management, planning and monitoring of estuarine environments and are key to measuring progress towards and achieving standards and targets (Barton, 2003; Bateson, 2010; Reese et al., 2008; Birch, Olmos and Lu, 2012).

It has been recognised by the scientific community that a variety of indicators derived from a multi-disciplinary approach is necessary for successful estuarine assessment and informed management (Ward et al., 1998). Many governments and management organisations have adopted the use of environmental indicators that have become an integral part of natural resource management and policy making (Bayer et al., 2008; Backer, 2008).

No single environmental indicator will unambiguously measure impacts of anthropogenic pressure on estuarine systems (Deeley and Paling, 1999). However, a holistic approach employing the use of a variety of indicators will provide an effective and relevant assessment. Care should be taken when choosing suitable environmental indicators, selecting those that minimise spatial and temporal variability and demonstrate strong causal relationships.

Effective environmental indicators should fulfil the following criteria (Bateson, 2010; Scheltinga et al., 2004; Niemi et al., 2004):

- Sensitive to aspects of environmental change;
- Reflect key components of the environment;
- Provide an early warning of potential problems;
- Easily monitored;
- Show clear causal relationships;
- Should not be affected by spatial and temporal variation;
- Easy to interpret and understand; and
- Scientifically robust.

1.4.1 Limitations of Common Environmental Indicators

It is increasingly recognised that much emphasis is being placed on irrelevant environmental indicators in estuarine assessment (Olmos and Birch, 2009; ANZECC, 2000). For indicators to communicate appropriate information they must: simplify complex information to aid communication between scientists and management, establish current environmental status and provide benchmarks and thresholds. Subsequently, there is a need to focus on indicators that provide meaningful science-based information with minimum effort and expense (Ardron, 2008).

Many indicators used in existing assessment schemes are limited in their ability to accurately assess the condition of catchment / estuary systems. These limitations, detailed below, must be acknowledged in order to provide an accurate assessment of these environments.

Spatial and Temporal Variability

A primary limitation of many environmental indicators is the potential for spatial and temporal variation to confound the result of the indicator. This natural variation may make it difficult to identify and quantify the human-induced component of change. Spatial and temporal variability may be managed to a degree through careful sample design, data collection and interpretation. However, many common indicators are effort intensive and are poor in providing reliable trend and compliance information (Magni, 2003; Birch, Olmos & Lu, 2012).Careful selection of indicators that minimise natural temporal and spatial variability is key to providing an accurate assessment of human-induced change in environmental management.

Causal Relationships

Understanding causal relationships between catchment pressures and estuarine condition is important in when selecting relevant environmental indicators to assess estuarine condition. Without a clear correlation between indicators, the selection of appropriate management actions is difficult. Use of irrelevant environmental indicators limits the value of information provided in an assessment and may incur additional cost and time.

1.4.2 Examples of Limitations within Common Environmental Indicators

Biological Indicators

Biological indices are important and valuable indicators of estuarine condition. However, due to technological, logistical and financial reasons, biological assessments are often isolated to small sample areas over short periods. Consequently, the ability of these indices to assess and record change over a range of temporal and spatial scales is inherently imprecise. Careful interpretation is important due to confounding effects of natural temporal and spatial variation.

Many estuarine assessments commonly examine the distribution and extent of mangrove, seagrass and saltmarsh habitat. These habitats, particularly seagrass communities, are susceptible, not only to natural disturbances, but are highly temporally variable in spatial extent. For example, large natural runoff events resulted in widespread decrease in seagrass distribution in Moreton Bay, Queensland (Dennison and Abal, 1999). In Western Australia Wood and Lavery (2001) observed common variables used to assess seagrass health (shoot density, canopy cover, leaf density etc.) vary seasonally and are limited in the ability to assess the health of such habitats.

Studies have also identified catchment-based impacts such as land clearing, increased sedimentation, nutrient loads and changes in catchment hydrology may be attributed to both the expansion and decline of mangrove habitat (Morrisey et al., 2007; Farnsworth and Ellison, 1997; Saintilan and Wilton, 2001). A lack of sufficient and reliable data makes identification of the human-induced component of change in mangrove extent difficult to discern, making their value as estuarine indicators questionable (McLoughlin, 1985). Detailed investigation of the relationship between habitat extent and human impacts is required for these indicators to be used with confidence.

Other common biological indices, such as species diversity and composition, abundance, nursery function and trophic integrity are also subject to natural temporal and spatial variability, as well as challenges in data collection and interpretation. Such indicators are only able to provide an approximation of condition and are hence limited in assessment of estuarine health. Appropriate selection and careful interpretation of biological indices may provide valuable information in the assessment of estuarine health. However, the availability and quality of data for Australian estuaries is limited.

Water Quality Indicators

Water quality parameters are commonly used in the assessment of estuarine condition, but the inherent variability of contaminant concentrations requires intensive sampling with higher costs and more complex interpretations (Horowitz et al., 1990; Birch et al., 1999). Water sampling may also miss many brief, but high-concentration contaminant discharges.

Similar to many biological indicators, water quality parameters are subject to natural spatial and temporal variation. Turbidity, for example, is a common water quality parameter, but may vary temporally in response to changes in rainfall, wind, tide, temperature and resuspension (Birch et al., 1999). Variation in turbidity may influence other indicators associated with suspended particulate matter, such as nutrients, dissolved oxygen and contaminants. Thus variation may be a result of natural process, making the human-induced component of change difficult to establish. Where data exists in sufficient temporal and spatial detail, water quality indices are valuable metrics of estuarine health.

1.5 Value and Use of Sedimentary Metals as Indicators

The importance of sediment chemistry in assessment of estuarine condition is widely acknowledged (Olmos and Birch, 2008; Borja and Dauer, 2008; Fairy et al., 2001; Chang, 2001). However, the evaluation of estuarine sediments is rarely applied effectively in mainstream assessment schemes. Sedimentary metal indicators, when used in a weight-of-evidence approach, are valuable tools in evaluating the health of estuarine environments.

The affinity of heavy metals and contaminants to adsorb to the fine fraction (organic and inorganic) of sedimentary material (Birch, 2003) allow sediments to faithfully record and time-integrate the environmental status of an aquatic ecosystem. An advantage of sediment-bound metals is the ability to identify the pre-anthropogenic condition and provide natural ‘background’ concentrations in sediments. These indicators provide information background condition, historical and possible future magnitude of anthropogenic change, as well as benthic risk, not confounded by natural spatial and temporal variability (Birch and Taylor, 1999; Birch and Olmos, 2008).

Sedimentary metals indicators are particularly useful in the preliminary stage of estuarine health assessment as they can provide a determination of both human impact and biological risk (Olmos and Birch 2008; 2010). Sedimentary metal indicators provide additional lines of evidence in assessment of estuary condition and provide added value to allow differentiation of estuarine ecosystem health. Subsequently, these indices have been adopted for use in the current study. Other chemical indicators such as redox and polycyclic aromatic hydrocarbons (PAH) may provide valuable environmental information, however the availability and quality of such data for Australian estuaries is limited.

1.6 Limitations of Existing State and National Estuarine Assessment Schemes

1.6.1 National Land and Water Resources Audit – Estuary Assessment (2002)

In 2002, the National Land and Water Resources Audit (NLWRA) published the first comprehensive assessment of catchments, rivers and estuaries in Australia (NLWRA, 2002). Using data already available, the audit provided a condition assessment of Australian estuaries. The assessment was conducted in two stages. Stage one involved a preliminary assessment of estuarine condition, providing an effective opportunity to identify impacted estuary systems (NLWRA, 2002). Criteria used in the preliminary assessment were largely qualitative, with emphasis placed on catchment-based indicators. Four estuary conditions were subsequently identified, e.g. near pristine, largely unmodified, modified and extensively modified.

The primary assessment was designed to provide an assessment of Australian estuaries using limited resources and available information. The effectiveness of the assessment was limited by the selection and use of environmental indicators that were largely qualitative and not supported by robust scientific data. Indicators placed emphasis on catchment processes with no delineation of catchment pressures and estuarine condition.

Subjective indicator definitions such as '*ecological systems and processes modified (e.g. loss of benthic flora and fauna*' and '*dams and impoundments, significant abstraction modifying natural flows*' were used to classify each estuary into one of the four condition categories with little or no scientific data used to demonstrate the effect of these pressures on estuarine condition. The subjective and qualitative nature of indicators used raises concern over the validity of results and correct classification of estuaries. Estuaries appear to have been assessed regardless of true catchment pressures and estuarine condition, potentially resulting in incorrect assessment of estuaries and implementation of uniformed management responses. The classification of estuarine condition by existing assessment schemes is further detailed in Chapter 2, Section 4.4.

The second stage of the Audit assessed the extent of change in modified systems using a Pressure-State-Response model. The audit utilised several condition indices that assessed parameters, such as ecosystem integrity, habitat integrity and fish condition, as well as water and sediment quality. Pressures were separately assessed through a susceptibility and utilisation index. The detailed assessment proved difficult mainly due to limited and inconsistent data due to poor availability and differences the reporting and quality of data (NLWRA, 2002).

Indicator selection was again a limiting factor in the ability of the audit to provide a realistic assessment of estuarine health. Metrics, such as seagrass and mangrove cover, diversity and abundance of fish species and water quality parameters were used as indicators of anthropogenic influence. As previously noted, such indicators are subject to confounding due to temporal and spatial variability and natural stress. Due to the scale of the Audit and methods of data collection / accessibility, these indicators are not considered to be suitable. The NLWRA understood some limitations, recognising that due to a lack of data, the audit was unable to define benchmarks to establish the extent of change for all modified estuaries (NLWRA, 2002).

Where data were available, subjective definitions for each indicator were again used to categorise an estuary into one of four condition categories (near pristine, largely unmodified, modified and extensively modified). This method raises concerns over the reliability and validity of results. In addition, the weighted ranking of each condition indicator index is largely inclined towards the ecosystem integrity index which, amongst others, predominantly uses chlorophyll *a* and turbidity data for which little information exists in detail for Australian estuaries. Despite these limitations, the NLWRA report was a key study that helped identify areas of future research and was a step forwards in the allocation of resources and management of Australian estuaries.

1.6.2 New South Wales - State of the Catchment Reports (2010)

The NSW State of the Catchments Reports - Estuaries and Coastal Lakes (NSW SOC), adopted a quantitative approach to estuarine assessment. The NSW SoC reports utilised new and existing datasets compiled under the Monitoring, Evaluation and Reporting Program (MER) to establish estuarine reference conditions and compare both pressure and condition indicators. A mix of indicator groups were adopted, representing elements of the structure, function and composition of estuarine ecosystems including; eutrophication, habitat availability and fish assemblages. Pressure indicators were separately assessed and included both catchment and estuarine indicators. Limitations identified within the SoC assessment are detailed below.

Estuary classification subgroups were defined and reference conditions established for ‘pristine’ estuaries in each estuary subgroup. A primary disadvantage of this method was that reference conditions were largely generalised for each estuary type and were not estuary specific. Subsequently, the condition of an estuary was compared to a reference estuary that may not be truly reflective of the estuary examined. Estuary specific reference conditions would be more valuable in determining the degree of disturbance in the future.

In comparison to many existing assessment schemes, the NSW SoC reports again focuses heavily on indicators (estuarine macrophytes, fish assemblages and water quality) that are confounded by temporal and spatial variability and natural stressors. Sampling programs developed as part of the MER program took steps in addressing these issues. However, a general lack of available data limited the value of these indicators in the assessment of estuarine condition. In addition, little evidence of direct correlation between pressure and condition indicators were provided with links primarily based on expert opinion, not scientific data.

Methodology used to assess indicators restricted the ability of the scheme to convey useful information to the user. Scoring followed a conventional ordinal scoring system whereby an indicator value is placed into one of several discrete categories. Some ordinal category boundaries were defined by expert option, potentially introducing uncertainty and bias into the assessment. Limitations of ordinal scoring systems are further discussed in Section 4.1.2.

In general, the NSW SoC – Estuaries and Coastal Lakes assessment provided a data-driven approach to estuarine assessment. However, due to the scale of the assessment and generalisation of reference conditions, indicators selected may have limited the value of the assessment. Through limited data availability (a condition index could not be calculated for 45% of NSW estuaries), scoring methodology and influence of temporal and spatial variability, the assessment may not be an accurate representation of estuarine condition within NSW.

1.7 Approach of the Current Study

In a novel approach to the management and identification of ‘priority’ estuarine environments in NSW, a hierarchal assessment approach was adopted in the current study. This approach, detailed in Figure 2, combines the use of a regional and local assessment scheme to facilitate the provision of targeted management and the effective distribution of limited resources.

The regional assessment scheme (Chapter 2) is a preliminary assessment of estuarine condition, designed to demonstrate the value of sedimentary metals in estuarine assessment. The scheme assesses catchment-based pressures and provides information on biological risk and the magnitude of human-induced change. Individual ‘priority’ estuaries identified through this preliminary stage may undergo further examination though a secondary, local assessment scheme.

The local assessment scheme (Chapter 3) considers an estuary and its catchment at an intra-estuary scale, utilising a suite of physical, chemical and socioeconomic indicators in a weight-of-evidence approach. The local secondary assessment identifies issue of concern at a local scale, allowing the prioritisation of site management and provision of targeted solutions.

This ‘top-down’ approach provides a decision support tool allowing for the systematic and informed allocation of resources for effective and targeted estuarine management.

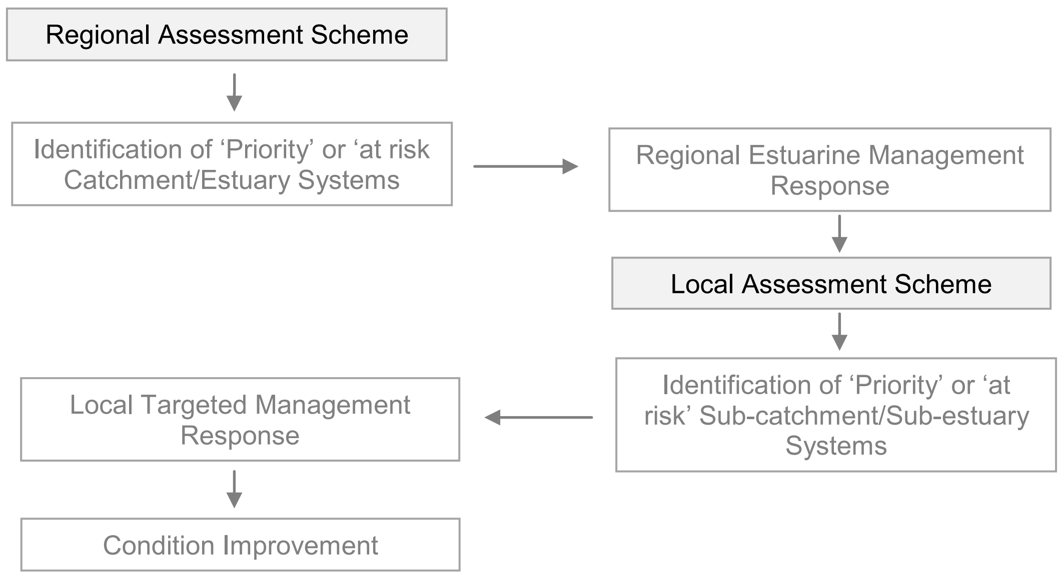


Figure 2: Hierarchal assessment approach to estuarine management.

1.8 Project Objectives

The current study aims to implement a hierarchal assessment scheme involving a preliminary regional assessment and secondary detailed assessment of catchment/estuary systems. Through use of simple assessment frameworks, maximising the use of high-value indicators, the scheme is intended to provide an effective decision support tool for estuarine managers. This tool provides science-based information for effective decision making and facilitates the efficient distribution of limited management resources to degraded estuarine environments.

The project will be achieved through completion of the following objectives:

a. Develop a hierarchal assessment scheme to identify ‘priority’ estuarine environments at a regional and local scale in NSW;

b. Identify a suite of relevant, high-value environmental indicators for the accurate assessment of estuarine condition;

c. Evaluate relationships between catchment pressure and estuarine condition;

d. Assess applications of the assessment results; and

e. Identify management implications of the assessment.

1.9 Thesis Structure

The structure of this thesis is as follows:

Chapter 1: Introduction;

Chapter 2: Regional estuarine assessment scheme;

Chapter 3: Local estuarine assessment scheme; and

Chapter 4: Conclusions.

It is acknowledged that due to intentional similarities between the regional and local assessment schemes, some repetition is expected.

Chapter 2: Regional Assessment Scheme

1 Introduction

A large proportion of the Australian population resides on the coastal fringe, resulting in significant pressures on estuarine environments (Birch and Hutson, 2009). Due to the environmental, social and economic importance of these systems, effective management is urgently required. Despite recent improvements, a lack of a clear management structure and limited accountability has restricted the effective management of Australian estuaries.

Several state and national audits have attempted to address the management of these environments through the assessment of impact on Australian estuaries. The value and functionality of these assessments were found to be often limited by inappropriate use of environmental indicators and the management of data. Due to these limitations, there is a need to develop an effective, integrated and regionally consistent assessment of estuarine health, unhindered by natural spatial and temporal variance.

There is a need to focus on indicators that provide meaningful information with minimum effort and expense (Ardron, 2008; McNie, 2007). Sedimentary metal indicators provide valuable information on human activities that affect the environment in a time-effective manner. Sedimentary metals are particularly useful estuarine assessment as they provide a determination of human impact as well as biological risk (Olmos and Birch, 2008; 2010).

The regional assessment scheme developed in the current study forms a component of a hierarchal assessment whereby limited resources can be distributed most effectively. The scheme provides an initial quantitative assessment of 38 NSW estuaries and demonstrates the value of sedimentary metals in evaluating estuarine condition.

1.1 Project Objectives

The current study has been designed specifically to assess catchment pressures and estuarine condition of catchment/estuary systems on a regional scale. This scheme, forming the preliminary assessment in a hierarchal scheme, aims to facilitate effective decision making and management and identification of 'priority' catchment/estuary systems.

The project will be achieved through the completion of the following objectives:

a. Develop a regional assessment scheme to identify 'priority' or 'at risk' estuarine environments in NSW;

b. Identify relationships between catchment pressure and estuarine condition;

c. Evaluate applications of the assessment scheme results;

d. Compare the results of the regional assessment scheme with existing state and federal estuarine audits; and

e. Identify management implications of the regional assessment scheme.

2 Methodology

2.1 Study Area

Of the 970 defined estuaries (>0.05km^2) in Australia, 130 are located on the NSW coast (NLWRA, 2002). For the purposes of the current study, 38 NSW estuaries (Figure 3 - 5; Table 1) were selected to be assessed as part of a regional report card scheme. All estuaries are located within 300 km of the Sydney CBD with Saltwater Creek to the north and Wallaga Lake to the south.

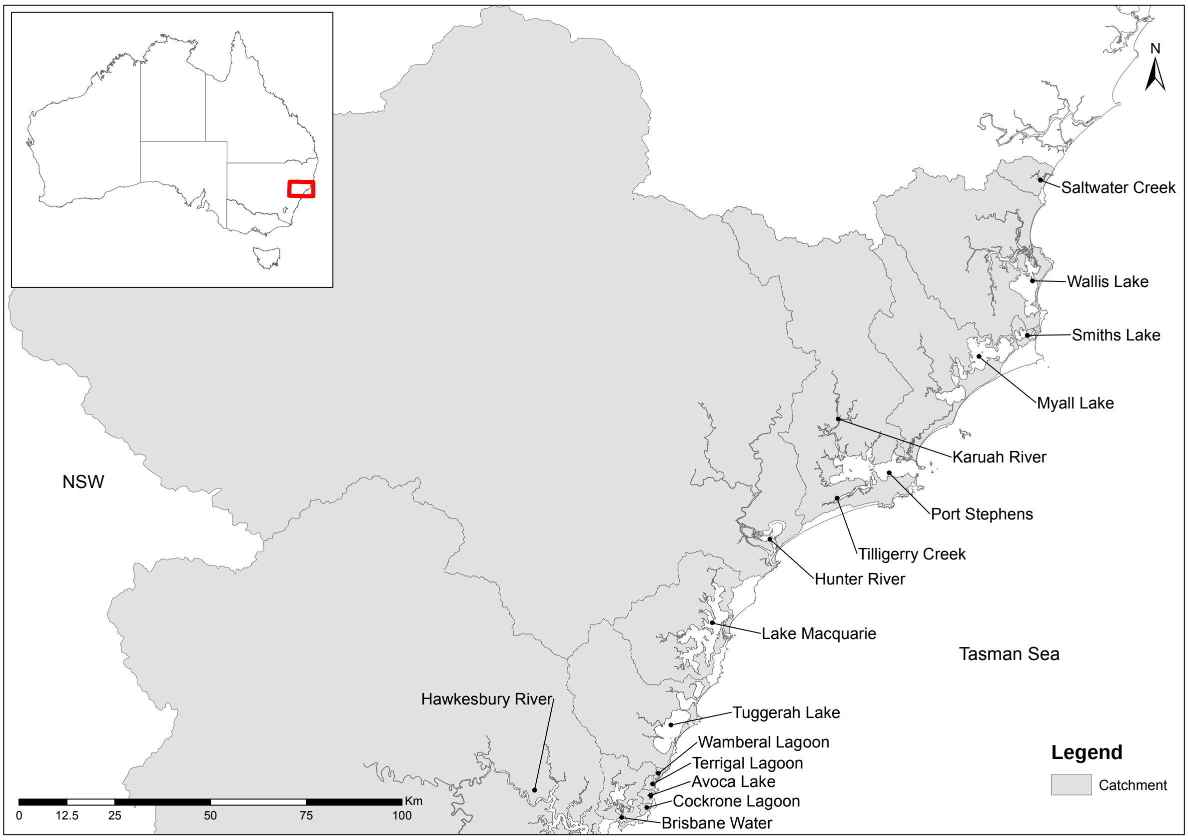


Figure 3: Estuaries assessed in the northern portion of the study area.

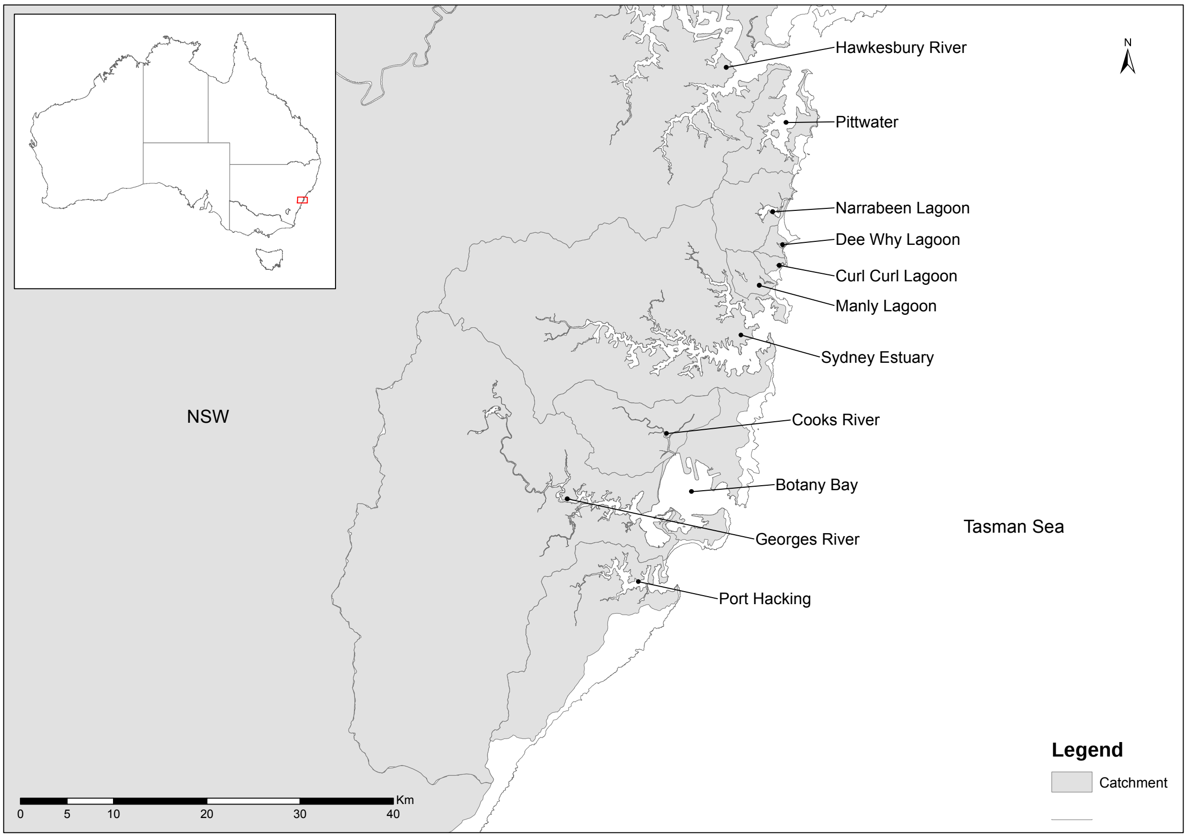


Figure 4: Estuaries assessed in proximity to the Sydney metropolitan region.

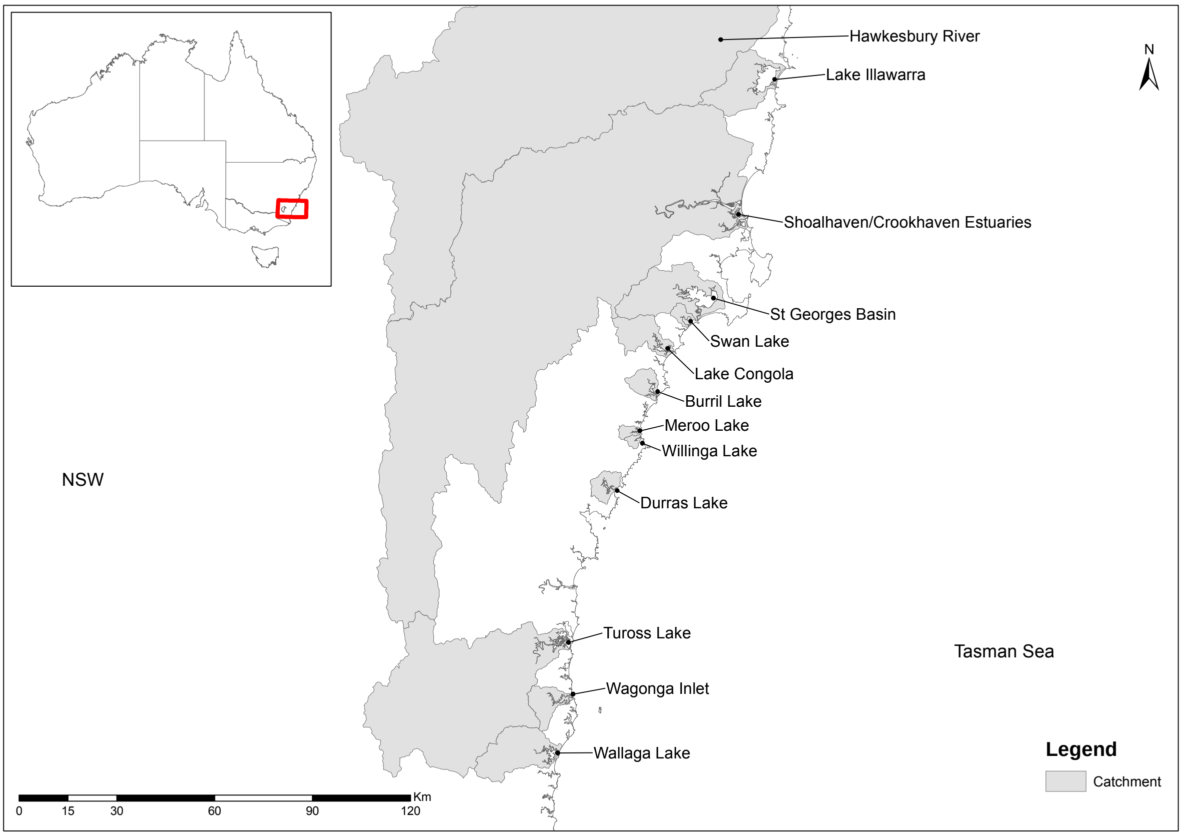


Figure 5: Estuaries assessed in the southern portion of the study area.

2.2 Catchment Selection

A total of 38 NSW estuaries were selected to be evaluated as part of the regional assessment (Table 1). Estuaries were chosen from a range of 'near-pristine' to 'extensively modified' environments, as identified in the NLWRA (2002), and encompassed a diverse array of estuary sizes, types and entrance conditions.

Table 1: Estuary classification for selected NSW estuaries assessed in the current study.

Estuary	Catchment Area (Km^2)	Estuary Area (Km^2)	Entrance Conditions*	Estuary Type*
Saltwater Creek	91.9	1.0	I	IV
Wallis Lake	1215.9	91.8	O/T	III
Smiths Lake	23.1	9.9	I	IV
Myall Lakes	815.7	109.1	I	V
Karuah River	1493.5	18.0	O	II
Port Stephens	1878.6	136.9	O	II
Tilligerry Creek	135.5	10.3	O	III
Hunter River	21377.9	55.6	O/T	III
Lake Macquarie	595.3	113.8	O/T	III
Tuggerah Lakes	715.9	80.8	I	III
Wamberal Lagoon	6.0	0.5	I	IV
Terrigal Lagoon	9.0	0.3	I	IV
Avoca Lake	11.4	0.7	I	IV
Cockrone Lagoon	6.9	0.3	I	IV
Brisbane Water	153.5	28.3	O	III
Hawkesbury River	21618.2	115.2	O	II
Pittwater	50.9	18.3	O	II
Narrabeen Lagoon	52.8	2.3	I	IV
Dee Why Lagoon	5.8	0.3	I	IV
Curl Curl Lagoon	4.4	0.1	I	IV
Manly Lagoon	17.4	0.1	I	IV
Sydney Estuary	479.8	53.3	O	II
Cooks River	103.1	1.2	O	-
Georges River	936.9	26.2	O	II
Botany Bay	1099.7	40.2	O	I
Port Hacking	164.5	11.9	O	II
Lake Illawarra	238.4	35.7	O/T	III
Shoalhaven River	7110.5	29.8	I	III
St Georges Basin	325.8	40.4	O	III
Swan Lake	26.0	4.7	I	IV
Lake Conjola	139.3	6.7	O	III
Burrill Lake	61.0	4.1	O(I)	III
Meroo Lake	19.5	1.2	I	IV
Willinga Lake	13.6	0.3	I	IV
Durras Lake	59.2	3.9	I	IV
Tuross Lake	1814.7	14.5	O	III
Wagonga Inlet	93.4	6.9	O/T	III
Wallaga Lake	264.2	9.1	O/I	III

*Adapted from Roy et al. (2001). Entrance Conditions: O=open, T=trained, I=intermittent. Estuary group types: I=oceanic embayment, II=tide dominated estuary, III=wave dominated estuary, IV=intermittently closed estuary, V=freshwater.

2.2.1 Delineation of Sub-catchments

Catchments were delineated from estuarine catchment boundaries produced by the Office of Environment and Heritage (2008). Catchment boundaries were further refined to provide a greater level of detail using 1:25,000 topographic maps developed by the Department of Lands (2001).

2.2.2 Regional Assessment Scheme Structure

Assessment Framework

Due to inherent complexities in the evaluation of multiple estuarine systems, the regional assessment scheme necessitated the need for a simple, yet effective assessment framework. Based on the Pressure-State-Response model (OECD, 1993), the framework was adapted to provide a simple yet robust regional assessment, reducing the complexity of analysis required and prioritising the use of relevant and meaningful environmental indicators.

The regional assessment framework (Figure 6) allowed the relationship between estuarine condition and catchment pressures to be examined and applied at a regional scale. The framework provided individual assessment of catchment pressure and estuarine condition, as well as an overall assessment of estuarine health.

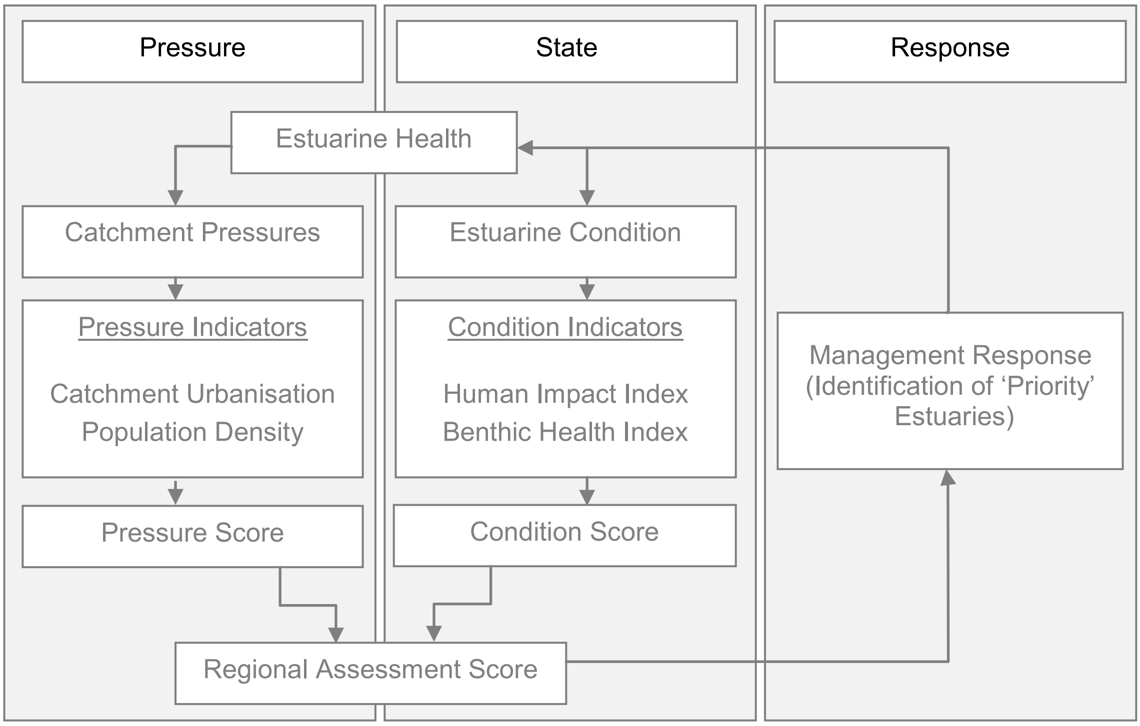


Figure 6: Regional assessment framework based on the Pressure – State – Response model.

2.3 Environmental Indicators

To identify and quantify the human–induced component of change in estuarine systems, the current study utilised high-value indicators that are not confounded by natural spatial and temporal variance. These indicators evaluate catchment pressures and estuarine condition, providing information on biological risk and the magnitude of human-induced change. The following section describes the environmental indicators used in the regional assessment.

2.3.1 Pressure Indicators

Urbanised Catchment Area

It is well understood that catchment characteristics, such as urbanisation and industrial activity, have influenced the condition of receiving basins (Birch and Taylor, 1999; Abrahim and Parker, 2002). A strong association exists between the proportion of urbanised catchment and the extent of human impact on an estuary. High dissolved and particulate phase contaminants identified in stormwater and fluvial sediment connects the catchment and estuary (Snowden and Birch, 2004), suggesting land-derived metals make an important contribution to estuarine contamination (Birch, Vanderhayden and Olmos, 2011), particularly in urbanised catchments.

Several studies note that landuse may be correlated to human-induced change and the risk of adverse biological effects in estuarine systems (Birch and Olmos, 2008; McCready et al., 2006a, 2006b; Sanger et al., 1999; Taylor et al., 2004). Birch and Olmos (2008) found a strong positive correlation between landuse and human impact, particularly with Cu, Pb and Zn. It was also observed that sediments in estuaries with more than 85% of the landuse dedicated to parkland, agriculture, and public services did not exceed sediment quality guidelines (Birch and Taylor, 1999; 2004). Sediment exceeded guidelines where >29% of landuse was dedicated to residential, commercial, and industrial activities (Birch and Olmos 2008).

Calculation of Urbanised Catchment Area

Landuse information was derived from the Australian Bureau of Statistics (ABS) Mesh Blocks (Draft) data set (ABS, 2005). Landuse data were presented in ArcGIS 10 and, using the clip function, data were extracted for the 38 study estuaries. Urbanised catchment area was expressed as a proportion of total catchment area, i.e.

$$Urbanised\ Catchment\ Area\ (\%) = \left(\frac{Urbanised\ Area}{Total\ Catchment\ Area}\right) \times 100$$

Population Density

Population density is considered an important indicator in the assessment of pressures on estuarine systems, with a close relationship observed between population density and estuarine condition (Birch and Olmos, 2011; Bricker et al., 2008; Ward et al., 1998).

Pressures exerted by population density on estuarine systems include increased metal, nutrient, litter and sediment loads, as well as sewage overflows and disturbance of riparian vegetation and estuarine biota (Roper et al., 2010). In addition, a strong and consistent correlation between population density to pollutant flux (Cu, Pb, Zn and total particulate matter) has been demonstrated for a number of urbanised catchments in NSW, Australia (Davis, 2009).

Calculation of Population Density

Population density was derived from the ABS Statistical Local Area (SLA) dataset (ABS, 2011). Population data were presented in ArcGIS Version 10 and, using the clip function, data were extracted for the 38 study estuaries.

Population densities of individual SLAs within catchment boundaries were averaged to generate a mean population density indicator value for the catchment. Population density was expressed as a mean value for a single sub-catchment i.e.

$$Population\ Density\ (people\ ha^{-1}) = \frac{\sum SLA\ population\ densities}{Number\ of\ SLAs\ in\ Catchment}$$

2.3.2 Condition Indicators

Human Impact Index (HII)

Estuarine sediments are enriched in metals throughout NSW due to increased population density and urbanisation within surrounding catchments (Birch and Olmos, 2008; Taylor, Birch and Links, 2004; Hutson, 2005). While current and historical sources of pollution continue to enrich estuarine sediments in metals and organic contaminants, recent evidence indicates that in some locations, concentrations of sediment-bound metals are decreasing due to tighter legislative controls on pollution and the gentrification of shoreline industry (Lean, 2013).

The pre-anthropogenic or pristine condition of an estuary is required to estimate the magnitude of impact caused by human activities (Birch et al., 1999). Sediment-bound metals offer a method to identify the pre-anthropogenic condition, providing natural background concentrations from unmodified pre- anthropogenic material. Background concentrations for estuaries assessed in the current study were determined using size-normalised (<62.5 μm fraction) sedimentary metals data obtained from pre-anthropogenic substrate. Background concentrations for the estuaries ranged between 3-45 μg g^{-1} for Cu, 9-43 μg g^{-1} for Pb and 20-107 μg g^{-1} for Zn (Birch and Olmos, 2008).

Birch and Olmos (2008) identified three metals (Cu, Pb and Zn) closely correlate to the suite of nine metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn), ubiquitous in estuarine environments. Further correlation was also identified between these three metals and Organochlorines (OCs), Polychlorinated Biphenyls (PCBs) and Polycyclic Aromatic Hydrocarbons (PAHs) in Sydney estuary and other Australian and international estuaries. Consequently, only these three metals (Cu, Pb and Zn) have been used in the HII to provide a simple assessment of human-induced change.

Calculation of HII

The HII assesses the magnitude and spatial extent of human-induced change on estuarine sediments by expressing surficial sediment metal concentrations over 'background' levels observed within pre-anthropogenic substrate. The HII uses the mean enrichment quotient (MEQ) of Cu, Pb and Zn for normalised sediment samples within an estuary i.e.

$$\mathrm{HII}(MEQ) = \frac{\left(\left(\frac{Cu_{Sediment}}{Cu_{Background}}\right) + \left(\frac{Cu_{Sediment}}{Cu_{Background}}\right) + \left(\frac{Cu_{Sediment}}{Cu_{Background}}\right)\right)}{3}$$

Using detailed sedimentary data obtained from the University of Sydney Environmental Geology Group (USEGG) sedimentary database, the HII was calculated for each sample location within each estuary. Individual values were averaged to generate a mean HII value for each estuary.

Benthic Health Index (HII)

Sedimentary metals may also be used as an effective indicator of biological risk through the application of sediment quality guidelines (SQGs). SQGs were initially developed in North America as a predictive tool to assess the potential toxicity of sediments to benthic organisms (Long et al., 1998; Birch and Taylor, 2000; McCready et al., 2006). These guidelines comprise effects range-low (ERL) and effects range-median (ERM) for 28 chemical concentrations associated with adverse biological effects (McCready et al., 2006). ERLs correspond to concentration below which adverse biological risk is expected rarely. ERMs represent concentrations above which biological effects are expected frequently (Long and Macdonald, 1998).

Due to a lack of sufficient data, North American ERM and ERL values have been adapted as interim SQGs (ISQGs) in Australia, as ISQG-Low and ISQG-High, respectively (ANZECC / ARMCANZ, 2000). ISQG-L is considered a threshold level that triggers the requirement for further investigative work (Olmos and Birch, 2008) and was therefore adopted in the BHI developed in the current study. Due to the predictive ability of Cu, Pb and Zn, only these metals have been used in the calculation of BHI.

The mean ISQG-L (MISQG-L) quotient was adopted in the current study to account for the presence of mixtures of chemicals that may have additive toxicity affect (Long and McDonald, 1998). The mean ISQG quotient is a valuable tool for assessing the quality of sediment in which there are complex mixtures of substances.

Calculation of BHI

The BHI assesses potential risk to benthic organisms from contaminants contained within estuarine sediments. ISQG-L values for Cu, Pb and Zn (65, 50 and 200 µg $g^{-1,}$ respectively) (ANZECC, 2000) were used to calculate the mean ISQG-L (MISQG-L) value for total sediment samples i.e.

$$\text{BHI}\ (\mathit{MISQG\text{-}L}) = \frac{\left(\left(\frac{Cu_{Sediment}}{65}\right) + \left(\frac{Cu_{Sediment}}{55}\right) + \left(\frac{Cu_{Sediment}}{200}\right)\right)}{3}$$

Using sedimentary data obtained from the University of Sydney Environmental Geology Group (USEGG) sedimentary database, the BHI was calculated for each sample location within each of the 38 subject estuaries. Individual values were averaged to generate a mean BHI indicator value for each estuary.

2.4 Correlation Matrix of Indicators

Using a non-parametric Spearman's correlation test in Microsoft Excel, a correlation matrix of indicators was created to assess covariance between indicators used in regional assessment and to further examine the relationship between pressure and condition indicators.

The Spearman correlation coefficient is a non-parametric measure of statistical dependence between two ranked values, and assesses how well the relationship between two variables may be described using a monotonic function (Corder and Foreman, 2009). For each indicator used, the raw values (X_i, Y_i) were converted to ranks (x_i, y_i), equal to the average of their positions in the ascending order of the values. The correlation coefficient (ρ) was calculated from these ranked values (Myers and Well, 2003) using the following equation:

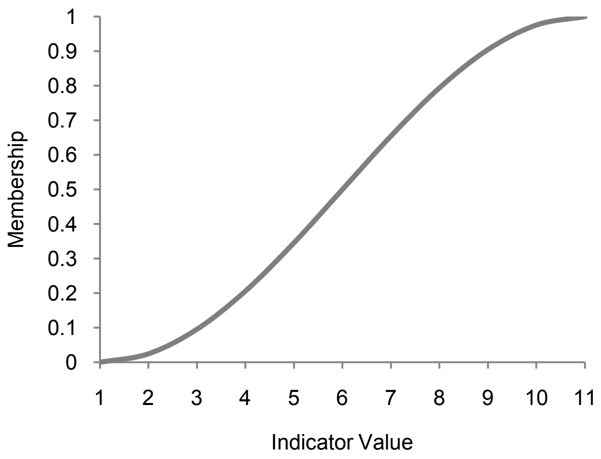
$$\rho = \frac{\sum_i (xi - \overline{x})(yi - \overline{y})}{\sqrt{\sum_i (xi - \overline{x})^2 \sum_i (yi - \overline{y})^2}}$$

Output values for the Spearman correlation coefficient range between -1 and 1, indicating a negative to positive correlation, respectively. A test of significance was undertaken on the coefficient values generated with the P value determined using a t-distribution table of critical values.

2.5 Assessment of Indicators

The current study uses the application of fuzzy logic for the assessment of indicators in the regional assessment. Fuzzy logic, in its simplest iteration, has been employed to obtain a non-linear transformation of indicator values, measured on various scales, in order to make the data comparable in a functional and readily understood common index between 0 (good) to 1 (poor).

All indicators in the current study were assessed using the sigmoidal 's-shaped' membership function (Figure 7), one of the most commonly used fuzzy set functions. Indicator values were transformed using the monotonically increasing function where a lower indicator value represented a better pressure or condition. The sigmoidal 's-shaped' curve is produced using a cosine function, which is described in Figure 7.



$$f = \cos\left(\left(\frac{data - max}{min - max}\right) \times \left(\frac{Pi}{2}\right)\right)^2$$

Where:

Data = Raw indicator value

Max = Maximum indicator value observed

Min = Minimum indicator value observed

Figure 7: Sigmoidal ‘s-shaped' monotonically increasing membership function used in the current study.

Using these functions, a fuzzy score between 0 (good) and 1 (poor) was generated for each indicator. The concept of fuzzy logic and its application is discussed in Section 4.1.2.

2.6 Calculating Assessment Scores

This section describes the calculations used in the determination of pressure, condition and final assessment scores for the NSW estuaries examined in the current study. Stages involved in the calculation of assessment scores are provided in Figure 8 and detailed below.

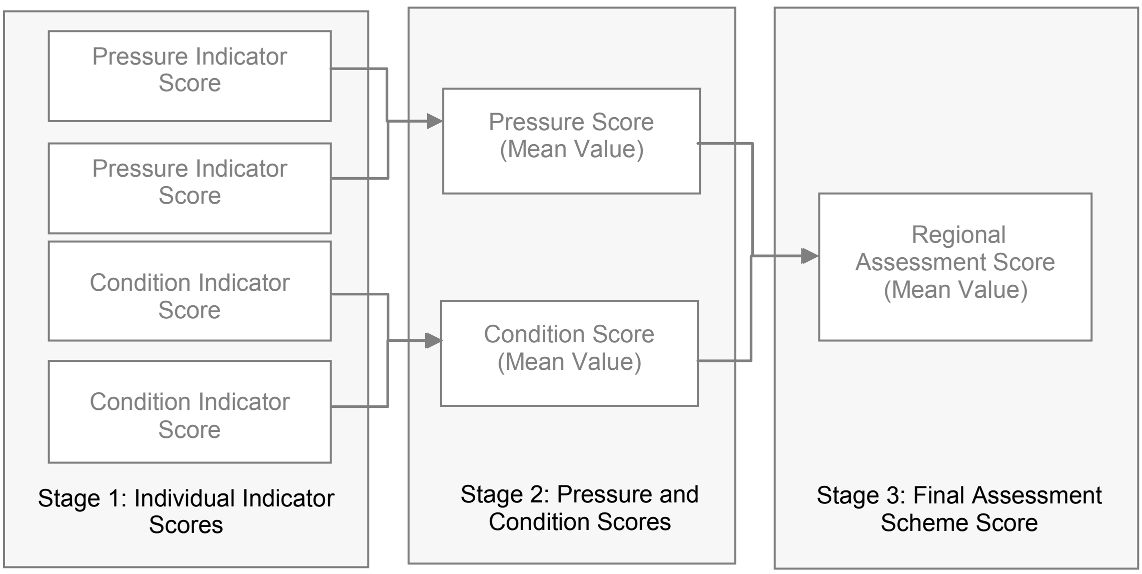


Figure 8: Calculation of regional assessment scores.

Stage 1: Calculating Indicator Scores

Individual indicators were assessed using fuzzy logic as detailed in Section 2.5 above. A ‘fuzzy score’ was generated for each estuary.

Stage 2: Calculating Pressure and Condition Scores

To calculate the pressure and condition score for each stressor category, the sum of the ‘fuzzy’ indicator scores were divided by the number of respective indicators to generate a mean indicator score for both pressure and condition i.e.

$$Pressure\ Score = \frac{\sum(Pressure\ Indicator\ Scores)}{Number\ of\ Pressure\ Indicators}$$

$$Condition\ Score = \frac{\sum(Condition\ Indicator\ Scores)}{Number\ of\ Condition\ Indicators}$$

Stage 3: Calculating Overall Estuary Scores

The final estuary assessment score was calculated by averaging the final pressure and condition score obtained for an estuary i.e.

$$Regional\ Assessment\ \ Score = \frac{(Pressure\ Score + Condition\ Score)}{2}$$

2.7 Regional Assessment Scheme Output

Results were assessed against a colour-coded scale, adapted from Gunns (2011), which ranges from 0 to 1 (good to poor condition), categorised equally into 13 condition classes. Letter grades from A+ to F (Figure 9) have been assigned to the 13 condition classes adopted in the current study. Pressure, condition and overall assessment score results may be evaluated against this scale.

<0.07	0.07-0.14	0.15-0.22	0.23-0.30	0.31-0.38	0.39-0.45	0.46-0.53	0.54-0.61	0.62-0.68	0.69-0.76	0.77-0.85	0.85-0.91	>0.91
A+	A	A-	B+	B	B-	C+	C	C-	D+	D	D-	F

Figure 9: Scoring classes for the regional assessment and associated letter grades A+ to F.

Whilst the current scheme aimed to minimise the categorisation of data, the use of letter grades in a report card format required the classification of results as per Figure 9. Despite this limitation, the categorisation of final scores acts to minimise information loss and maintain data integrity, preserving the accurate assessment of estuarine condition.

3 Results

The following section details the results of the regional assessment scheme. Implications of results for the regional assessment scheme are examined in Section 4 of this chapter.

3.1 Indicator Correlation Matrix

Results of the non-parametric Spearman's correlation test revealed condition indicators show a significant co-variance (P<0.05) with pressure indicators used in the current study (Table 2). Results indicated a strong relationship between catchment urbanisation, population density and the magnitude of human induced change and benthic health.

Table 2: Correlation coefficients for indicators used in the regional report card.

		Condition Indicators	
		Human Impact Index (HII)	Benthic Health Index (BHI)
Pressure Indicators	Catchment Urbanisation	0.79	0.66
	Population Density	0.82	0.77

Bivariate plots show that BHI was strongly related to the proportion of urbanised catchment area (R^2 = 0.607) (Figure 10-A) and population density (R^2 = 0.609) (Figure 10-C). A similar relationship was demonstrated by the proportion of urbanised catchment area and HII (R^2 = 0.632) (Figure 10-D) with a slightly weaker relationship between population density and HII (R^2 = 0.513) (Figure 10-B).

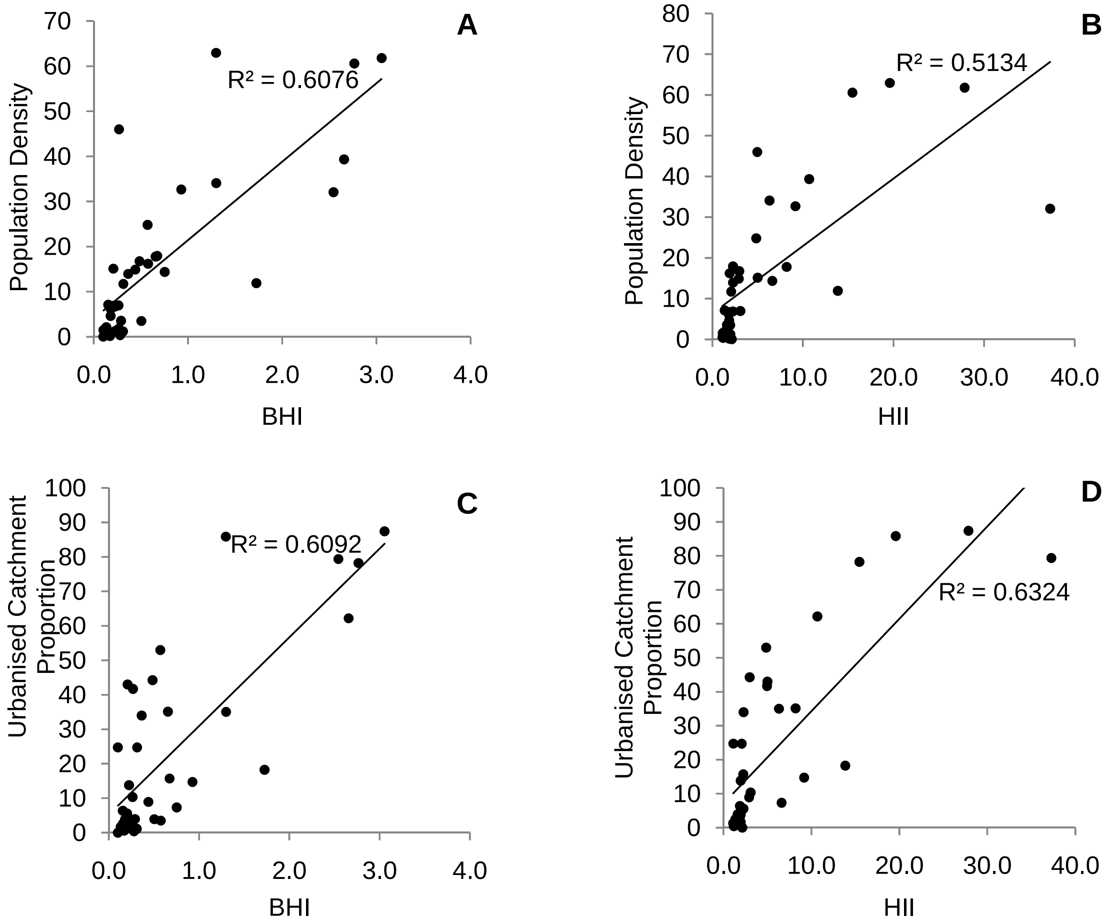


Figure 10: Bivariate plots of catchment pressure and estuarine condition indicators. A. Population density and Benthic Health Index (BHI), B. Population Density and Human Impact Index (HII), C. Proportion of urbanised catchment and Benthic Health Index (BHI), D. Proportion of urbanised catchment and Human Impact Index (BHI).

3.2 Regional Assessment Results

Results of the regional assessment are detailed below and summarised in Table 3 and Figure 14 - 16. Detailed results, including the calculation of scores, are presented in Appendix A.

Table 3: Assessment results for NSW estuaries assessed in the current study.

Estuary	Pressure Score / Report Card Grade	Condition Score / Report Card Grade	Regional Assessment Score / Report Card Grade
Saltwater Creek	0.09 A	0.00 A+	0.05 A+
Wallis Lake	0.02 A+	0.00 A+	0.01 A+
Smiths Lake	0.01 A+	0.00 A+	0.00 A+
Myall Lakes	0.00 A+	0.00 A+	0.00 A+
Karuah River	0.00 A+	0.00 A+	0.00 A+
Port Stephens	0.01 A+	0.00 A+	0.01 A+
Tilligery Creek	0.04 A+	0.00 A+	0.02 A+
Hunter River	0.07 A	0.09 A	0.08 A

Estuary	Pressure Score / Report Card Grade		Condition Score / Report Card Grade		Regional Assessment Score / Report Card Grade	
Lake Macquarie	0.09	A	0.43	B-	0.26	B+
Tuggerah Lakes	0.08	A	0.02	A+	0.05	A+
Wamberal Lagoon	0.22	B+	0.01	A+	0.12	A
Terrigal Lagoon	0.31	B	0.02	A+	0.16	A-
Avoca Lake	0.13	A	0.01	A+	0.07	A
Cockrone Lake	0.03	A+	0.01	A+	0.02	A+
Brisbane Water	0.34	B	0.02	A+	0.18	A-
Hawkesbury	0.08	A	0.03	A+	0.06	A+
Pittwater	0.24	B+	0.09	A	0.16	A-
Narrabeen Lagoon	0.50	C+	0.04	A+	0.27	B+
Dee Why Lagoon	1.00	F	0.44	B-	0.72	D+
Curl Curl Lagoon	0.75	D+	0.96	F	0.86	D-
Manly Lagoon	0.75	D+	0.56	C	0.65	C-
Sydney Estuary	0.98	F	0.66	C-	0.82	D
Cooks River	1.00	F	0.92	F	0.96	F
Georges River	0.46	C+	0.20	A-	0.33	B
Botany Bay	0.65	C-	0.02	A+	0.33	B
Port Hacking	0.30	B+	0.15	A-	0.22	A-
Lake Illawarra	0.13	A	0.05	A+	0.09	A
Shoalhaven Estuary	0.01	A+	0.00	A+	0.01	A+
St. Georges Basin	0.02	A+	0.00	A+	0.01	A+
Swan Lake	0.00	A+	0.00	A+	0.00	A+
Lake Conjola	0.00	A+	0.00	A+	0.00	A+
Burrill Lake	0.01	A+	0.02	A+	0.01	A+
Meroo	0.00	A+	0.00	A+	0.00	A+
Willinga	0.00	A+	0.00	A+	0.00	A+
Durras Lake	0.00	A+	0.00	A+	0.00	A+
Tuross Lake	0.00	A+	0.00	A+	0.00	A+
Wagonga Inlet	0.01	A+	0.01	A+	0.01	A+
Wallaga Lake	0.00	A+	0.01	A+	0.01	A+

Final Regional Assessment Results

Table 3 and Figure 14 - 16, show final assessment scores ranged between 0.00 (Willinga Lake) and 0.96 (Cooks River) (grade A+ to F, respectively). The mean assessment value was 0.17 (A-). Approximately 58% of estuaries assessed received a final assessment grade of A+, with 8% and 10% receiving A and A- , respectively. The remaining 24% of estuaries returned grades of B+ and lower. Five estuaries located within the Sydney region returned the poorest overall assessment scores (Figure 11). Curl Curl Lagoon (0.86) and Cooks River (0.96) returned the lowest grade of D- and F, respectively. The three remaining estuaries received grades of C-, D+ and D (Manly Lagoon 0.65, Dee Why Lagoon 0.72 and Sydney estuary 0.82 respectively).

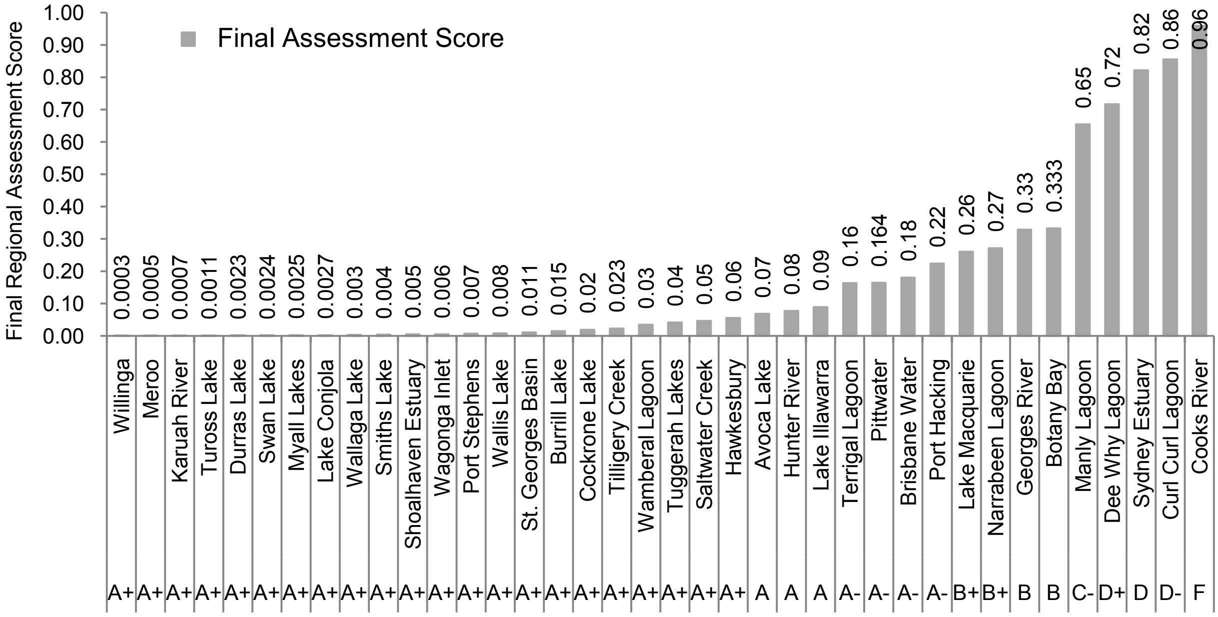


Figure 11: Final regional assessment scores and letter grades.

Regional Pressure Results

Pressure scores were generally poorer than overall results with a mean score of 0.21 (A-). Scores ranged between 0.00 and 1.00 (grade A+ to F respectively). Approximately 50% of estuaries assessed received a final pressure grade of A+, with 18% receiving a grade of A. The remaining 32% of estuaries returned grades of B+ and lower. Dee Why Lagoon and Cooks River returned the highest pressure score with 1.00 (F), followed Sydney estuary (0.98 F), Manly Lagoon and Curl Curl Lagoon both with 0.75 (D+) (Figure 12).

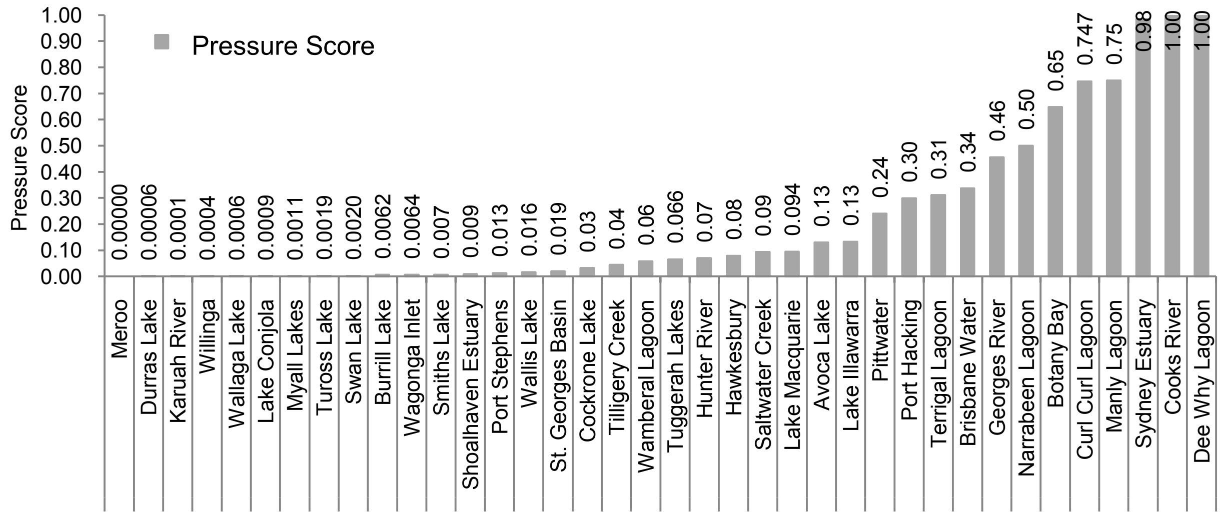


Figure 12: Regional pressure scores and letter grades.

Regional Condition Results

Condition scores were generally lower than pressure scores with a mean value of 0.13 (A). Scores ranged between 0.00 and 0.96 (grade A+ to F, respectively). Approximately 74% of estuaries received a final condition grade of A+, with 11% each receiving a grade of A and A-. The remaining 15% of estuaries returned grades of B- and lower.

Curl Curl Lagoon and Cooks River returned the poorest condition score with 0.96 (F) and 0.92 (F) respectively. This was followed by Sydney estuary (0.66 F), Manly Lagoon (0.56 C), Dee Why Lagoon with 0.44 (B-) and Lake Macquarie (0.43 (B-) (Figure 13).

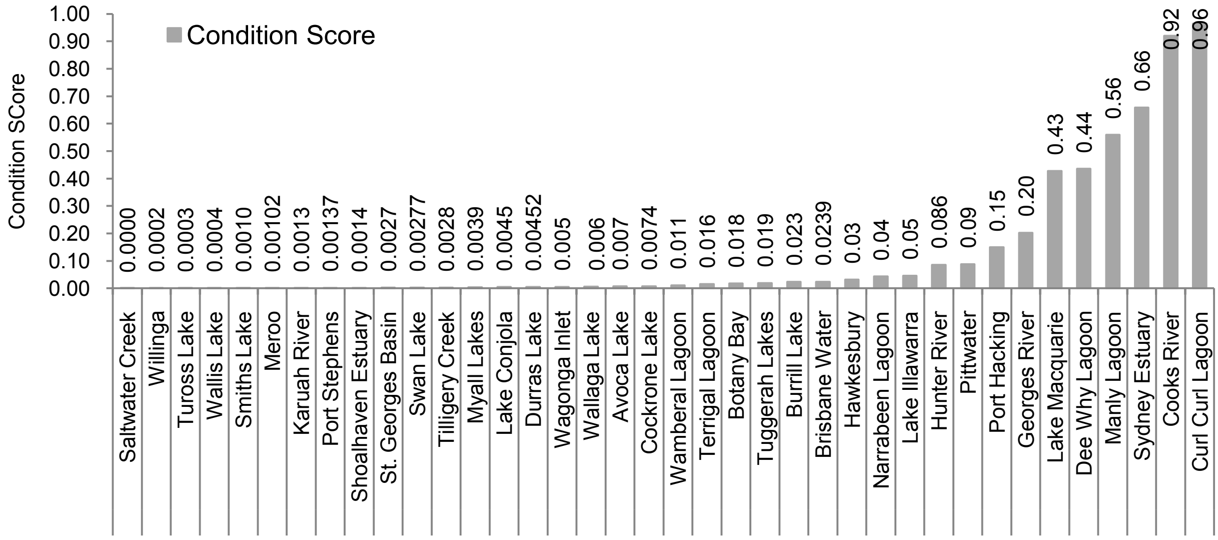


Figure 13: Regional condition scores and letter grades.

3.2.1 Geographical Distribution

Eight of the nine poorest scoring estuaries are located within the Sydney region (Figure 15), with scores generally improving with distance away from the urban centre (Figure 14 - Figure 16). In addition, estuaries south of Sydney were observed to have better assessment scores than those located north of Sydney. In comparison to surrounding estuaries, Lake Macquarie (Figure 14) returned a significantly lower final assessment score of B+.

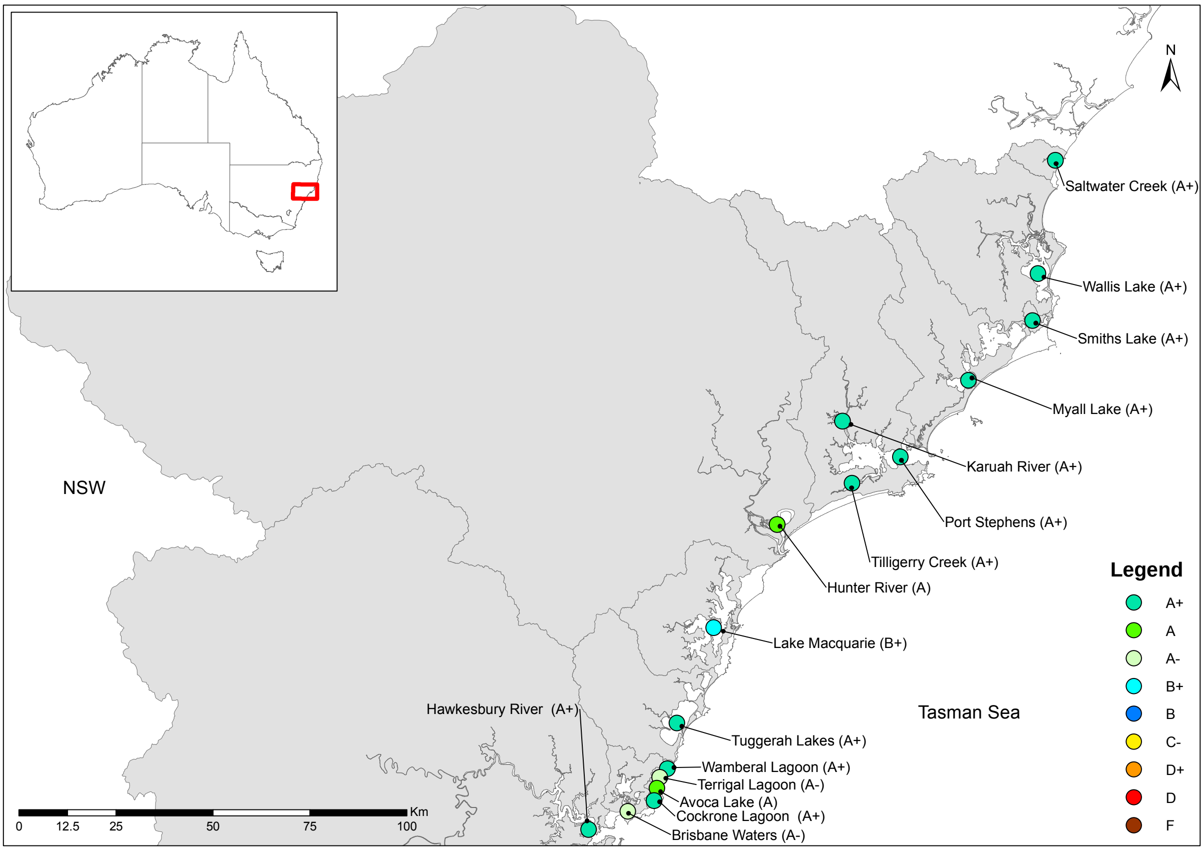


Figure 14: Final regional assessment results for northern estuaries.

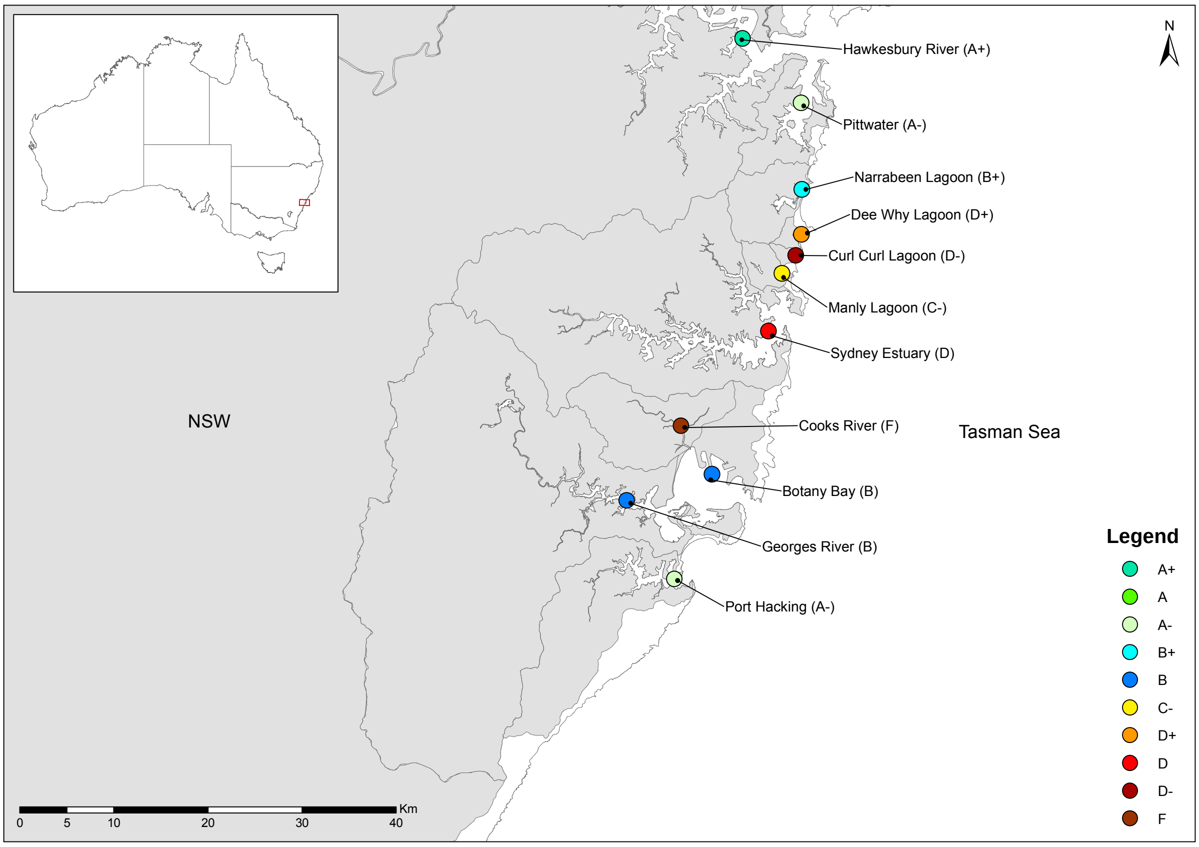


Figure 15: Final regional assessment results for Sydney metropolitan estuaries.

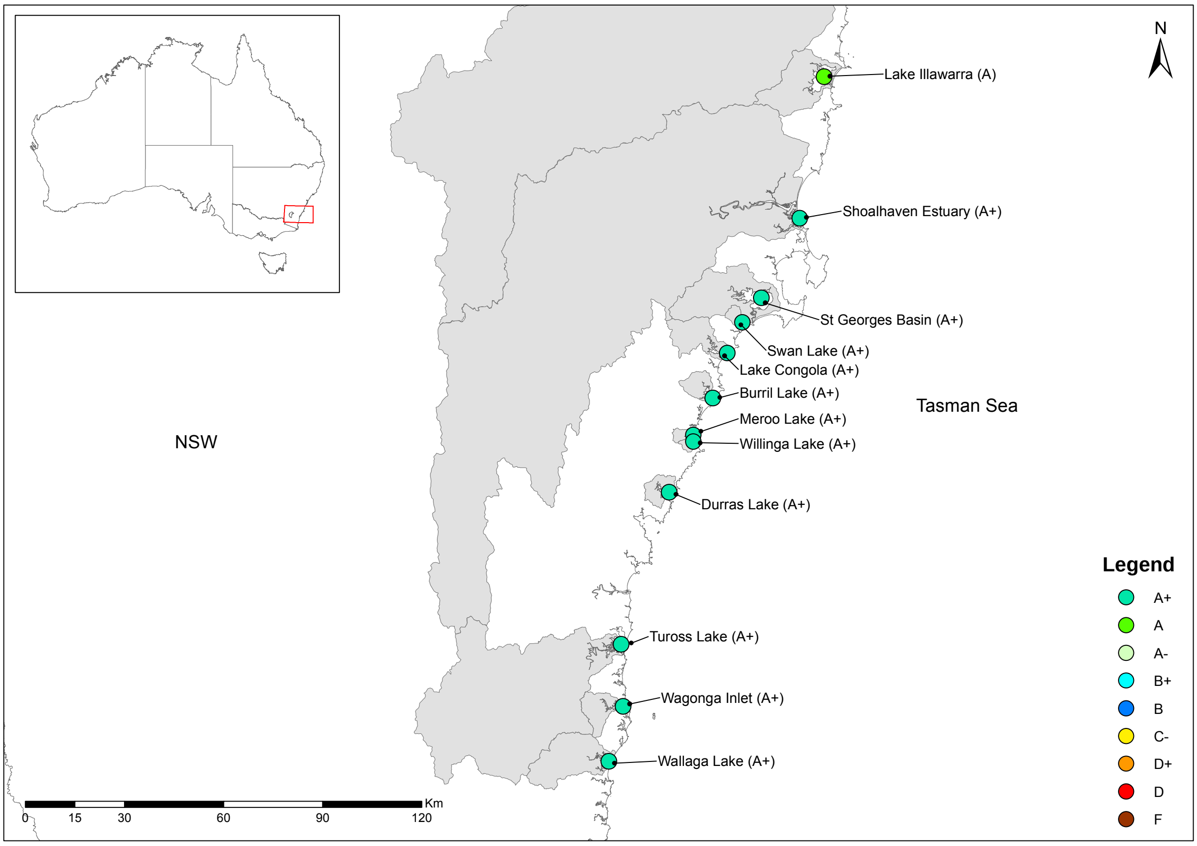


Figure 16: Final regional assessment results for southern estuaries.

4 Discussion

4.1 Development of the Regional Assessment Scheme

4.1.1 Development of the Assessment Framework

The regional assessment scheme was developed as a preliminary assessment in a hierarchal assessment scheme, designed to maximise the efficient use of limited management resources. Recognising limitations of exiting estuarine assessment schemes, the regional framework developed in the current study improved the assessment and transfer of scientific data, with results reflective of actual estuarine condition.

Framework Structure

Due to the scale of the assessment and inherent complexities in the evaluation of multiple estuarine systems, a simple yet effective assessment scheme was required. To achieve this requirement, an assessment framework was developed around a simplified 'Pressure-State-Response' model (OECD, 1993). The framework reduced the complexity of analysis required and prioritised the use of relevant and meaningful environmental indicators.

The framework, detailed in Section 2.2.2, can provide estuarine managers and end users with the ability to identify catchment/estuary systems where further investigation and management would be required. The structure of the scheme and indicators used would allow the assessment to be undertaken over longer time intervals to minimise time and other burdens associated with current intensive annual assessment schemes.

Emphasis on High-Value Environmental Indicators

High-value environmental indicators were employed to maintain the simplicity of the regional assessment whilst providing accurate science-based information. Sedimentary metal indicators were used due to their value in the preliminary stage of estuarine assessments and ability to provide information on both human impact and biological risk.

Fuzzy Logic and Data Management

The present regional assessment abandons the traditional 'ordinal' scoring of indicators and replaces it with the concept of fuzzy logic. To assess estuarine indicators, fuzzy logic was used to minimise the transformation of data, reducing information loss and maintaining data integrity. The application of fuzzy logic is further discussed in below.

4.1.2 Indicator Assessment and Data Management

Ordinal Assessment, Bivalence and 'Crisp' Sets

Traditionally, estuarine assessment schemes have typically used an ordinal scoring system to categorise environmental data and assessment of environmental indicators. In these systems, indicator values are placed within one of several discrete assessment categories defined by a 'crisp' set of boundaries which may be either statistically or arbitrarily defined. In fuzzy set theory, 'crisp' sets are defined as a conventional set, whereby the degree of membership of any value is either 0 or 1, true or false (Goble, 2001; Hellmann, 2001). Crisp sets are governed by use of bivalent logic which states that an element within a set has either full membership or nil membership (Tomassi, 1999; Hürlimann, 2009; Béziau, 2003).

Table 4 demonstrates the application of ordinal scoring and 'crisp' sets in the assessment of environmental indicators. Under a conventional five-point ordinal scoring systems, raw values would be transformed as shown below.

Table 4: Conventional ordinal scoring using 'crisp' data sets.

Raw observation (%)	Ordinal score	Description
0 - 5	1	Very Good
>5 - 10	2	Good
>10 - 20	3	Moderate
>20 - 40	4	Poor
>40	5	Very Poor

Table 4 demonstrates not only that there is a considerable loss of information value in the transformation process, but small differences between two individual measurements may result in them being placed into different categories, with significant implications for their interpretation. For example, little difference exists between a value of 9.8%, and one of 10.2%, however, if the two measurements were made on successive occasions, the ordinal scoring method would indicate a significant decline in condition. Similarly, a measurement of 39.95% would effectively conceal the true condition as the assessment score would be four on a five-point scale.

In addition, the categorisation of data in traditional assessment schemes occurs in the initial stage of indicator assessment. Information lost by forcing data into a set of discrete classes is carried throughout the remaining assessment process, potentially compounding the effect of information loss, influencing results of the scheme and management decisions based upon them.

Ordinal scoring was trialled by Gunns (2011), using an ordinal scale from 1 – 5 (good to poor). It was determined that results generated did not reflect true conditions within the Sydney catchment/estuary system. Fuzzy logic was trialled and adopted by Gunns (2011), as a method to improve the accuracy and precision of indicator assessment and to preserve information value.

Application and Use of Fuzzy Logic

When dealing with complex and imprecise systems, such as estuarine environments, the coarse categorisation of data is not reflective of real-world conditions where no sharp distinctions may be defined (Zadeh, 2008). Using estuarine condition as an example, there is no sharp cut-off between good and poor condition, rather a gradual transition between the two (Gunns, 2011).

Fuzzy set theory and fuzzy logic allows intermediate values to be defined between conventional evaluations like true/false, yes/no (Hellmann, 2001). A fuzzy set is defined as a set without crisp boundaries, characterised by a continuous membership grade that ranges from 0 (non-membership) to 1 (full membership) i.e. to what degree does a variable belong in a specified set (Chapman, 2010; Eastman, 2003; Hellmann, 2001).

Fuzzy logic is employed in the current study to obtain a non-linear transformation of indicator scores, measured on multifarious scales, to make them all comparable on a single scale. For example, in evaluating the condition of a particular environmental indicator, a fuzzy membership function may be defined, such that a value of 1 has a membership of 0 (good condition), and a value of 10 has a membership of 1 (poor condition). Between 1 and 10, the fuzzy membership of an indicator value gradually increases on a scale from 0 to 1 (Figure 17). This is in contrast with the classic crisp set, used in ordinal scoring, which has a distinct boundary at 5 between good and poor condition. Using fuzzy membership functions in the assessment of indicators, the information value of data is retained throughout the assessment process, thus producing accurate and meaningful results.

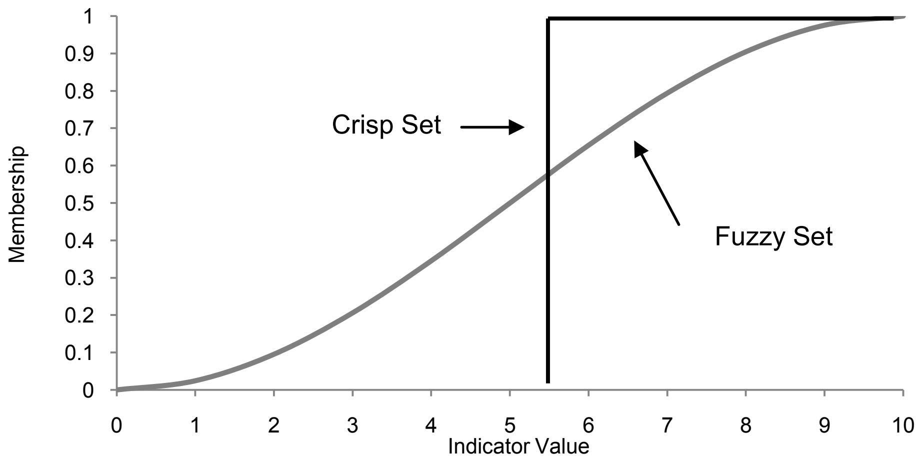


Figure 17: Comparison between 'fuzzy' and 'crisp' membership functions.

It would be expected, when assessing the health and condition of catchment/estuary systems, few results would be located towards the extreme ends of the assessment range, i.e. towards 0 or 1 where the datum would be classified either as pristine, or extensively degraded. The majority of results would be expected to fall around the middle of this range. The Sigmoidal or 's-shaped' fuzzy membership function (Figure 7) is one of the most commonly used functions in the application of fuzzy set theory (Chapman, 2010; Eastman, 2003) and has been applied in the current study to attain the finest differentiation in the mid-range values. Thus providing a greater level of differentiation between indicators scores and allowing variances between catchment/estuary systems to become apparent.

Use of Indicator Weightings

Indicator weightings are often used in assessment schemes to differentiate indicators based on their perceived value in determining catchment pressure and estuarine condition. Weightings are an arbitrary value applied to indicator scores to increase or decrease their value and thus their influence in determining the overall pressure or condition score for an estuary.

Use of indicator weights in estuarine report cards was investigated by Gunns (2011) through the use of the Delphi method (Gordon, 2004). Results of the study revealed a strong central tendency of weights, indicating a conservative bias of the respondents, and provided little differentiation between the results of each catchment/estuary system. Comparison between weighted and unweighted results revealed that weighted indicators produced misleading results, inferring little variation between the conditions of catchment/estuary systems assessed

Given the results of Gunns (2011), indicator weightings were not adopted in the current study. In future studies, weightings may be selected through a more detailed scientific consensus, or assigned by an individual or management authority. If an individual or management authority does select this method, the user must be aware of the potential implications of these decisions in biasing the results of the assessment.

4.2 Relationships between catchment pressures and estuarine condition

4.2.1 Indicator correlation

Association between catchment development and estuarine condition has been observed locally and internationally (Abrahim and Parker 2002; Birch and Taylor 1999; Walters et al. 2003). This relationship has been demonstrated in the current study with a strong correlation (P=<0.05) identified between the regional pressure and condition results (R^2=0.6405) (Figure 18).

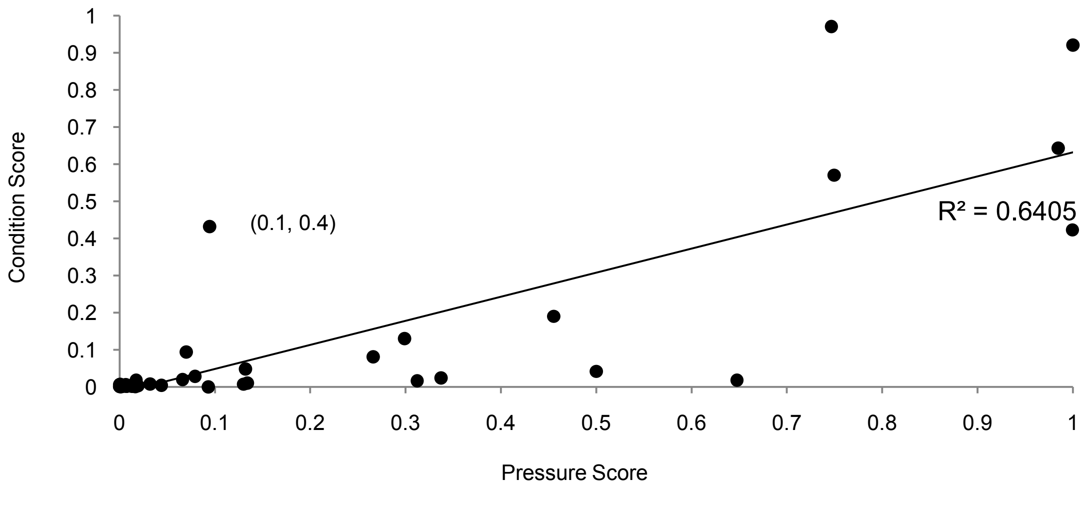


Figure 18: Correlation between regional pressure and condition assessment scores.

Correlation established between catchment pressure and estuarine condition reveals the value of sedimentary metal indicators in representing the condition of the estuary and the role population density and catchment urbanisation play in influencing the health of estuarine systems. A significant outlier, located at 0.1, 0.4, represents the Lake Macquarie estuary. The nature of this outlier is discussed in greater detail in Section 4.3.1.

4.2.2 The influence of catchment pressures on estuarine condition

Catchment pressures, including population density and urbanised catchment area correlate positivity and significantly with both the HII and BHI (Table 2). However, these pressures are not consistently related to estuarine condition as demonstrated in Figure 19 – 20. Results of the regional assessment indicate that combined high population density and catchment urbanisation is not always related to an elevated HII (Figure 19). For example, Narrabeen Lagoon, Botany Bay and Georges River have relatively high catchment pressures, yet these estuaries demonstrate comparatively low HII scores. Clearly, urbanisation and population density are not the only factor controlling HII in these estuaries. Manly Lagoon demonstrates a similar association, although this is likely attributed to recent dredging and remediation of sediments (Cardno, 2010).

Impacted estuaries with high BHI values, e.g. Curl Curl Lagoon, Manly Lagoon, Sydney estuary and the Cooks River (Figure 20), demonstrate a strong relationship with catchment pressures. However, high population density and catchment urbanisation is not always associated with a high BHI. For example Botany Bay and Dee Why Lagoon demonstrate comparatively low BHI values which may be attributed to the coarse nature of estuarine sediments (<39% fine fraction) and possible remobilisation and removal of fine surficial sediment as a consequence of enhanced flushing. High catchment urbanisation / low population density observed in Brisbane Water and Narrabeen Lagoon, suggest the BHI in these estuaries is influenced by localised areas of intense urbanisation within the catchment. Pittwater has a high BHI in comparison to catchment pressures, reflecting heavy metal contamination associated with one of the highest recreational boating densities in Australia (WBM, 2006).

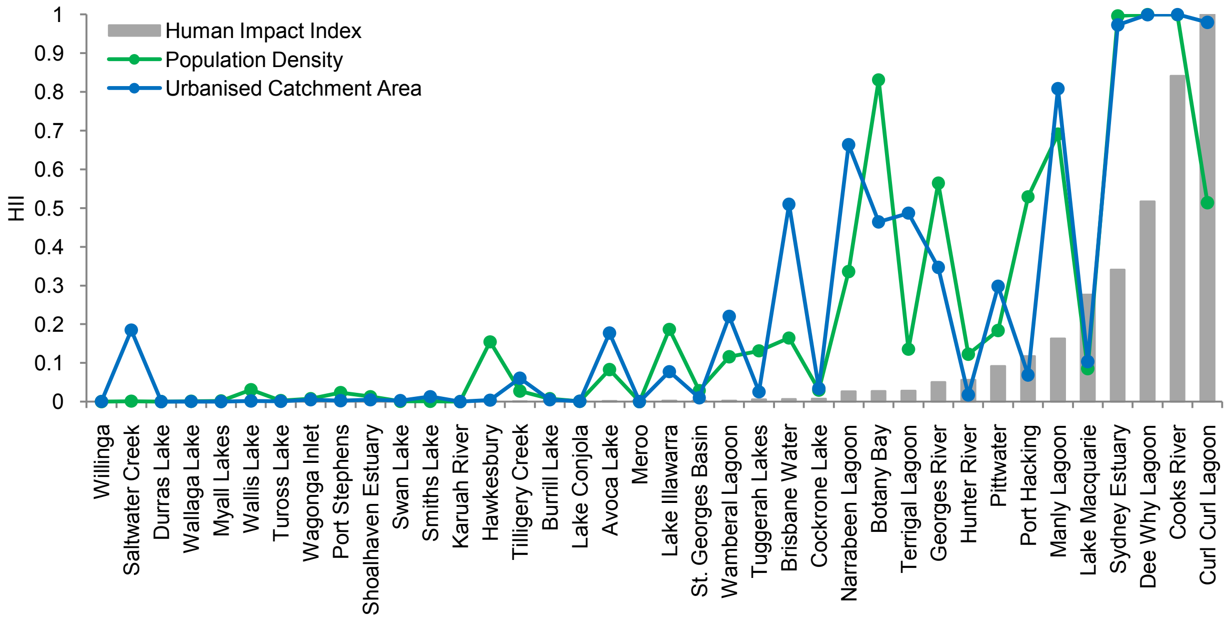


Figure 19: Relationship between regional HII and pressure indicators.

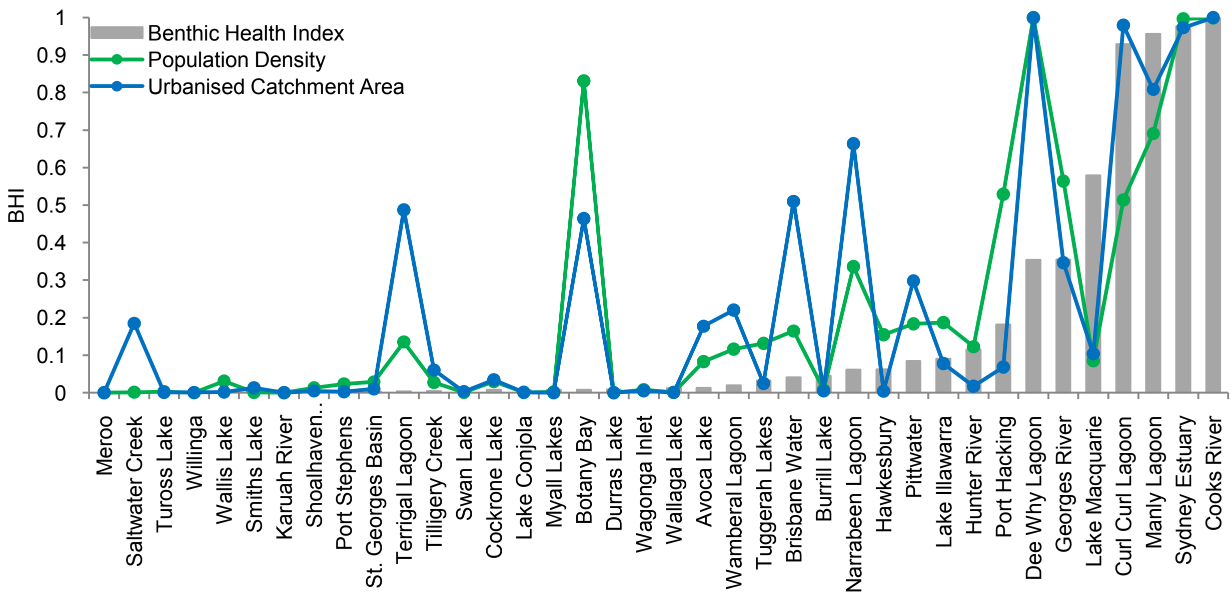


Figure 20: Relationship between regional BHI and pressure indicators.

4.3 Application of the Scheme in the Assessment of Estuarine Condition

4.3.1 Application and Use of Assessment Results

Results of the regional assessment scheme may be used in various applications in order to convey information on the condition of catchment/estuary systems. Information may be used to:

- Generate report cards, as undertaken in the current study;

- Categorise the condition of estuaries in a regional context;
- Determine evolutionary trends of estuaries in response to human impact; and
- Provide a weight-of-evidence approach to estuarine assessment.

Development of Report Cards

As demonstrated in the current study, results of the regional assessment scheme may be used to generate a report card for individual catchment/estuary systems. Report cards are an important decision support tool for estuarine managers to prioritise estuary management, identify issues and areas of concern and allow for the condition of a catchment/estuary system to be assessed.

Report cards are also a valuable method to convey information in a simplistic and readily understood manner to natural resource managers, members of the public and interested stakeholders. They provide a method of summarising the assessment of an estuary in a way that provides concise, interesting and relevant content (both graphical and written) in an easily read form. The Health-e-Waterways Report Card (SEQ Healthy Waterways 2013) is an example of successful report card that provides interesting and relevant content in both interactive online and printed formats.

The application and use of the report cards in the current study is detailed in Section 2.7 of this chapter.

Categorisation of Estuaries

As noted in Section 4.2.1, a strong correlation (R^2=0.6405) exists between pressure and condition scores of estuaries assessed in the current study. Consequently, when presented in a bivariate plot, estuaries may be grouped into five distinct categories (Figure 21).

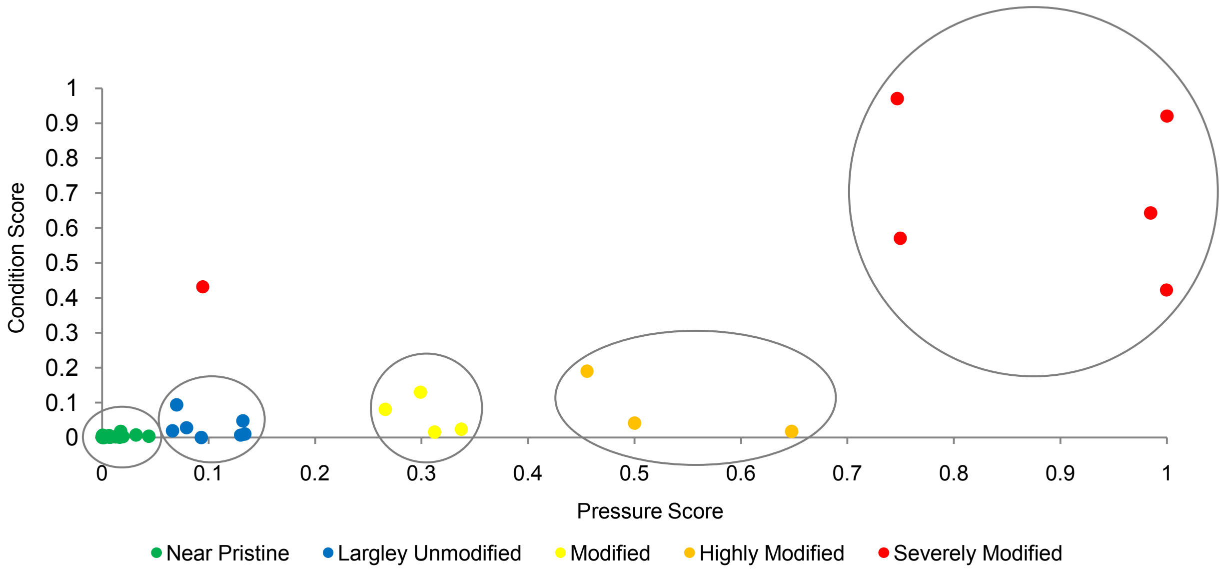


Figure 21: Determination of condition classes based on the relationship between catchment pressures and estuarine condition.

These categories, shown Figure 21, represent five classes of estuarine condition (Table 5). Description of the classes from ‘near pristine’ to ‘severely modified’, have been adapted from the NLWRA (NWLRA 2002) and aim to represent the condition of the catchment/estuary system in response to anthropogenic impacts.

Table 5: Five condition classes for the regional classification of NSW estuaries.

Condition Category	Regional Assessment Score	Description
1	0 – 0.01	Near Pristine
2	>0.01 – 0.05	Largely Unmodified
3	>0.05 – 0.2	Modified
4	>0.2 – 0.5	Highly Modified
5	>0.5 – 1	Severely Modified

Each of the 38 estuaries assessed were grouped according to the five condition classes and are presented in Table 6. The outlying data point (Lake Macquarie [0.1, 0.4]), has been classified as ‘severely modified’ due to the specific nature of anthropogenic influence within the catchment. This is discussed in greater detail in Section 4.3.1.

Table 6: Regional classification of NSW estuaries assessed according to Table 5.

Estuary	Condition Class	Estuary	Condition Class
Saltwater Creek	1 - Near Pristine	Curl Curl Lagoon	5 - Severely Modified
Wallis Lake	1 - Near Pristine	Manly Lagoon	5 - Severely Modified
Smiths Lake	1 - Near Pristine	Sydney Estuary	5 - Severely Modified

Estuary	Condition Class	Estuary	Condition Class
Myall Lakes	1 - Near Pristine	Cooks River	5 - Severely Modified
Karuah River	1 - Near Pristine	Georges River	4 - Highly Modified
Port Stephens	1 - Near Pristine	Botany Bay	4 - Highly Modified
Tilligerry Creek	2 - Largely Unmodified	Port Hacking	4 - Highly Modified
Hunter River	2 - Largely Unmodified	Lake Illawarra	2 - Largely Unmodified
Lake Macquarie	4 - Highly Modified	Shoalhaven River	1 - Near Pristine
Tuggerah Lakes	2 - Largely Unmodified	St Georges Basin	1 - Near Pristine
Wamberal Lagoon	2 - Largely Unmodified	Swan Lake	1 - Near Pristine
Terrigal Lagoon	3 - Modified	Lake Conjola	1 - Near Pristine
Avoca Lake	2 - Largely Unmodified	Burrill Lake	2 - Largely Unmodified
Cockrone Lagoon	2 - Largely Unmodified	Meroo Lake	1 - Near Pristine
Brisbane Water	3 - Modified	Willinga Lake	1 - Near Pristine
Hawkesbury River	2 - Largely Unmodified	Durras Lake	1 - Near Pristine
Pittwater	3 - Modified	Tuross Lake	1 - Near Pristine
Narrabeen Lagoon	4 - Highly Modified	Wagonga Inlet	1 - Near Pristine
Dee Why Lagoon	5 - Severely Modified	Wallaga Lake	1 - Near Pristine

Identification of evolutionary trends

A strong correlation (R^2=0.6405, p<0.05) between catchment pressure and estuarine condition suggests an inverse relationship exists whereby estuary condition decreases as catchment pressures increase. This concept is widely accepted, with environmental degradation seen as an inevitable consequence of industrial and urban development (Taylor et al., 2004; Reish et al., 1998).

Relationships between catchment pressures and condition identified in the current study (Figure 19 - Figure 20), suggest that the contemporary condition of an estuary is not only a function of current catchment pressures, but also historical catchment changes, sediment characteristics and remediation activity. Estuarine morphodynamics and flushing attributes may play a role in influencing the condition of an estuary, however a relationship between estuarine condition and estuary type was not observed in the current study. Results of the regional assessment may be used to infer and predict evolutionary trends of a catchment/estuary system in response anthropogenic impacts.

Evolution of Catchment/Estuary Systems with an Extensive History of Industrialisation and Urbanisation

Results of the regional assessment show that catchment/estuary systems with an extended history of industrial activity and urbanisation are generally characterised by high catchment pressures and poor estuarine conditions. These estuaries, located within close proximity to Sydney, include Dee Why Lagoon, Manly Lagoon, Sydney estuary, Curl Curl Lagoon and Cooks River. Results may be used to infer how estuarine condition has evolved from 'near pristine' to 'severely modified' in response to historical changes within the catchment. These results have been used to explain historical trends in the following case studies.

Case study: Sydney estuary

Sydney estuary has a history of environmental degradation and contamination, associated with intense urbanisation and industrialisation during the 19th and 20th centuries (Taylor et al., 2004). The evolution of urbanisation and landuse within the Sydney catchment has been investigated and documented by Lean (2013) for seven time slices from 1788 to 2010. In 1892, approximately 13% of the catchment was urbanised with residential (2%) and roads (9%) the dominant landuse. Industrial activity only accounted for 1% of the catchment area. Between 1892 and 1936, urbanisation within the catchment increased to 38% with the proportion of industrial landuse growing to 2%. During this time shore-based industry became prevalent. From 1936 to 1978 industrial landuse increased to 4% of the catchment and occupied 32km of the estuary foreshore (Lean 2013). Since the approximate maximum industrial activity in the 1970s, industrial landuse within the catchment decreased to 2%, occupying 9 km of the shoreline in 2010. Industrial areas have replaced by larger commercial centres and residential developments. In 2010, 77% of the catchment was urbanised, making it one of the most heavily urbanised catchments in the world (Birch, Lee and Churchill 2013).

Evolution of landuse within the Sydney catchment may be correlated to sediment contamination within the estuary. Onset of contamination has been closely linked to rapid urbanisation and industrialisation within the catchment during the early to mid 20th century (Taylor, Birch and Links 2004). Maximum sedimentary metal concentrations coincide with the highest industrial activity within the catchment in the 1970s (Taylor et al., 2004). High levels of contamination away from stormwater discharge points provides further evidence the role of industrial pollution played contamination during the industrialisation and urbanisation of the Sydney catchment (Birch et al., 2013).

Relocation of shore-based industry and introduction of pollution control legislation, including the *Pollution Control Act 1970* and *Clean Water Act 1972* has seen a decrease in sediment contamination in areas of the estuary (Taylor et al., 2004; Birch et al., 2013). Despite a reduction of industrial pollution, studies show contamination is still persistent within the harbour with stormwater derived pollutants replacing industrial activity as the dominant source of contamination to the estuary (Birch et al., 2013; Birch, Vanderhayden and Olmos, 2010).

As shown in Figure 19 – 20, assessment results for Sydney Estuary show high pressure and condition scores, reflecting the nature of the catchment and its industrial history. Similar patterns are observed within the results for Dee Why Lagoon, Manly Lagoon, Curl Curl Lagoon and Cooks River, which all demonstrate a history of industrial activity and intensive urbanisation.

Case Study: Lake Macquarie

Results of the regional assessment indicate that the contemporary condition of Lake Macquarie has been influenced by a single historical pollution point source, as indicated by a low catchment pressure score and comparatively high condition score. The condition score of the estuary has been largely driven by the refining of Cd, Pb, and Zn at the Cockle Creek Smelter. Commencing operation in 1897, waste effluent from the smelter was dispersed into Cockle Creek, in the northern portion of the estuary, until the 1970s when a sludge treatment facility was installed (Spurway, 1982). Despite treatment, wastewater and material stockpiles continued to contribute contaminants to the creek and the estuary until the smelter was closed in 2003 (Willmore et al., 2006). Consequently, significant concentrations of Cd, Cu, Pb and Zn are observed within surficial sediments in the northern portion of Lake Macquarie (Birch and Olmos 2009).

Similar to Sydney estuary, industrial contamination has historically been the primary source of pollution within Lake Macquarie. However, the shutdown of the Cockle Creek Smelter and increasing urbanisation and population density within the catchment has seen stormwater become the dominant source of contamination. A study by Birch and Olmos (2009) provides evidence of this trend, with an overall improvement in sediment quality observed in the northern part of the estuary affected by the Cockle Creek Smelter between 1979 and 2003. An increase in surficial Cu concentrations was also identified across the whole estuary, possibly reflective of the influx of contamination from current stormwater derived sources.

The Hunter River exhibits similar characteristics whereby industrial landuse (port facilities) may be linked to a disproportionate variation between estuarine condition and catchment pressures (Figure 19). In response to changing landuse, the source of contamination in these estuaries generally follows the historical trend: natural background influx > industrial point sources > stormwater derived contamination.

Evolution of Catchment/Estuary Systems with a Recent History of Urbanisation

Results of the regional assessment have demonstrated catchment/estuary systems with a recent history of urbanisation are characterised by moderate to high catchment pressures and good estuarine conditions. These estuaries include Narrabeen Lake, Avoca Lagoon, Wamberal Lagoon, Terrigal Lagoon, Tuggerah Lake and Brisbane Water. In general, these estuaries have recent history of urbanisation, primarily dominated by commercial and residential developments. Consequently, the source, type and migration pathways of contaminants differ from those with a history of industrial use and intense urbanisation.

Case Study: Brisbane Water

Brisbane Water has a relatively recent history of urbanisation, with expansion of residential and commercial areas occurring during the mid 20^{th} century. Due to its location away from Sydney, the estuary was spared from intensive industrial activity and associated contamination. Today, Brisbane Water is predominantly characterised by agricultural and parkland land uses with residential (27%), commercial (4%) and industrial (1%) land uses accounting for the urbanised area of the catchment (Olmos and Birch 2008).

An investigation of sediment quality within Brisbane Water on the NSW Central coast by Olmos and Birch (2008), identified creeks draining urbanised portions of the catchment were the main source of contamination to the estuary. Residential land uses were found to contribute the highest heavy-metal loading for most of the estuary. The results of Olmos and Birch (2008) in conjunction with the regional assessment scheme, demonstrate that without an extensive history of urbanisation and intense industrialisation, stormwater derived contamination is the primary source of pollution to an estuary. Similar trends are also observed within Narrabeen Lake, Avoca Lagoon, Wamberal Lagoon, Terrigal Lagoon and Tuggerah Lake which lack a history of intensity industrial activity. Botany Bay exhibits a similar relationship between catchment pressures and estuarine condition, however this is likely attributed to the coarse nature of the sediments (12.5% mean fine fraction) limiting the ability of contaminants to be adsorbed and retained.

4.3.1.1 Other Applications

Results of the regional assessment scheme may also be used within other estuarine or environmental assessment schemes when used in conjunction with other indicators in a weight-of-evidence approach to environmental and estuarine management.

4.4 Comparison to state and national assessment schemes

The regional assessment scheme considers the benthic risk and magnitude of human-induced change of sediments as a consequence of catchment urbanisation and population density. Because the methodology and criteria used to assess ecosystem condition in the NLWRA Audit and NSW SoC Reports comprise a range of catchment and estuary attributes, results of the schemes may not necessarily covary. Nevertheless, similarities and differences in outcomes of the three approaches will provide insight into the importance of the assessment methodology and use sedimentary metal as indicators in the current regional scheme.

4.4.1 National Land and Water Resources Audit (2002)

To facilitate comparison between the current regional assessment scheme and the NLWRA, 5 classes of estuarine condition in the current study were consolidated into 4 categories by combining groups 1 and 2 (near pristine and largely unmodified).In general, little similarity exists between the results of the national audit and the current regional assessment (Figure 22), with results of the current scheme indicating estuaries assessed are in better condition than indicated by the national audit. However, some agreement between the two schemes is noted between five ‘extensively modified’ (Manly Lagoon, Curl Curl Lagoon, Dee Why Lagoon, Sydney estuary and Cooks River) and four ‘near pristine’ estuaries (Willinga Lake, Meroo Lake, Karuah River and Tuross Lake).

As detailed in Section 1.6.1, the NLWRA relies heavily on environmental indicators that are not only limited by natural spatial and temporal variation, but also poor data availability. Reliance on existing data sets varying in quality and age severely restricted the effectives of indicators to provide a reliable and accurate assessment of estuarine condition. Use of water quality and biological indices, obtained from pre-existing data sets, do little to address natural spatial and temporal variation and further hindered the audit. In addition, subjective pressure indicators, such as 'recreational fishing' and 'yachting and boating' demonstrated little relationship with the actual condition and health of an estuary. Data management and indicator assessment techniques adopted in the NLWRA again acted to introduce uncertainty and bias into the assessment. Use of ordinal scoring, weightings and subjective indicator scoring methods confounded assessment results and may have resulted in improper assessment of estuarine condition.

The current regional assessment addresses the shortcomings of the NLWRA, simplifying the assessment framework and utilising high value pressure and condition indicators in a data-driven approach. Use of sedimentary metals provides an effective method to assess estuarine condition (see Section 1.5), providing information on biological risk and magnitude of human-induced change. Data in the current scheme was not forced into several discrete categories, but rather transformed on a linear scale using fuzzy logic, minimising information loss and improving the accuracy of the assessment.

Assessment of estuarine condition by the audit (Figure 22) identified a number of extensively modified estuaries (n=17). In comparison to the current study, only five estuaries considered to be 'extensively modified' (see Table 5 and 6) would require further assessment, thus improving the quality and efficiency of management responses.

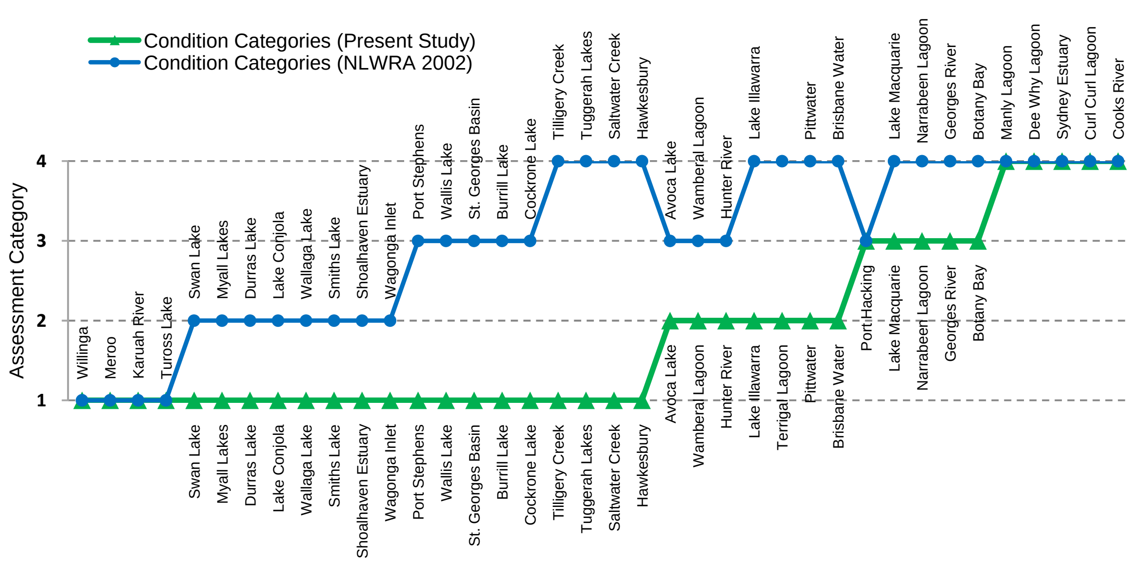


Figure 22: Comparison of the NLWRA and regional assessment scheme results developed in this study.

4.4.2 NSW State of the Catchments (2010)

A combined assessment of estuarine pressure and condition was not undertaken in the NSW SoC reports. Therefore, in order to facilitate comparison, separate pressure and condition results of the current scheme were grouped into 5 categories and compared to the NSW SoC reports. NSW SoC assessment values were subsequently reversed to reflect scoring used in the regional assessment scheme. While some comparisons may be drawn between several estuaries in the NSW SoC reports and regional assessment, little similarity exists between results.

Results show a conservative bias in the NSW SOC report card (Figure 24 - Figure 23) with pressure and condition scores generally 'good/low' to 'fair/moderate' (category 2 and 3 respectively). No estuaries were assessed to have very high pressure or very poor condition, with the exception of Manly Lagoon. The central tendency of pressure and condition results suggests a conservative bias has been introduced through weighted indicators.

Similar to the NLWRA, the NSW SoC reports relied heavily on biological environmental indicators that are not only influenced by natural spatial and temporal variation, but have limited data availability (only 45% of NSW estuaries assigned a condition score). Reliance on these indicators confounded by natural variation restricted the ability to provide a reliable and accurate assessment of estuarine condition. In comparison to the NSW SoC, the current assessment limited the number of indicators used, improving the method of indicator assessment to improve the accuracy of the assessment and the value of the scheme to natural resource managers.

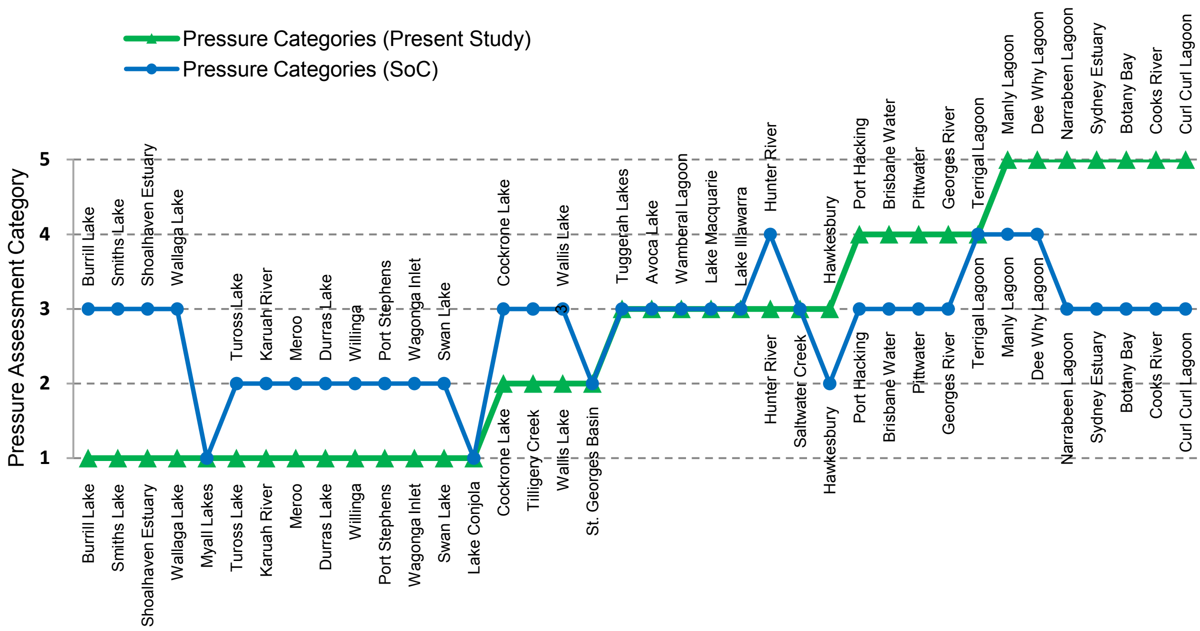


Figure 23: Comparison of the SoC pressure and regional assessment scheme pressure results developed in this study.

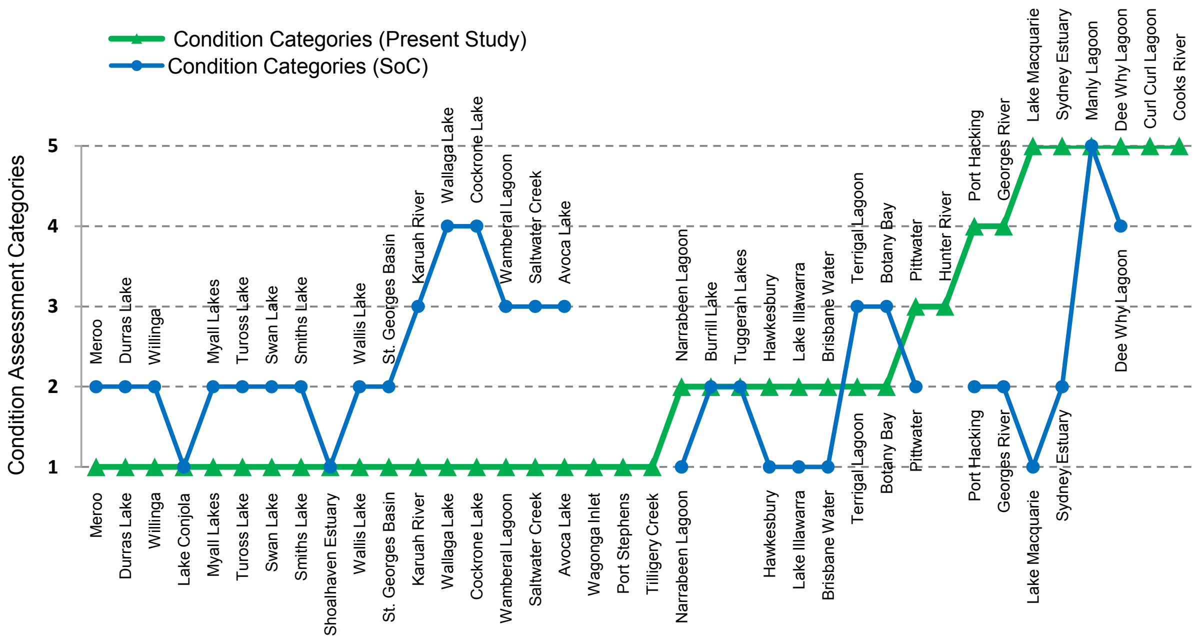


Figure 24: Comparison of the SoC condition and regional assessment scheme condition results developed in this study.

4.5 Management Implications

As coastal urbanisation and populations increase, considerable pressures are being exerted on estuaries in Australia (Hutson, 2005). The absence of a consistent regional management structure and limited responsibility has intensified the degradation of these coastal environments (Birch and Taylor, 2004).

The current regional assessment scheme provides the ability to rapidly identify ‘priority’ catchment/estuary systems, but also assists natural resource managers and decision makers in the prioritisation of estuaries, benchmarking, performance monitoring and the allocation of limited management resources. For example, five estuaries identified as ‘extensively modified’ (Manly Lagoon, Dee Why Lagoon, Sydney estuary, Curl Curl Lagoon and Cooks River), may be prioritised by managers for further assessment and evaluation as per the local assessment scheme detailed in Chapter 3.

The value of the assessment scheme may be further enhanced through the application and use of a report card format that conveys high quality technical information in a simplistic and readily understood manner to the public. Use of letter grades provides estuarine managers with a tangible method of setting improvement targets and to determine appropriate management actions through which the condition of the catchment/estuary system may be improved. Value and progress of the estuarine management strategies may also be tracked and assessed using this format.

5 Conclusions

For countries like Australia where >90% of the population resides within the coastal fringe, the effective management of coastal and estuarine resources is an important socio-political issue. Pressures exerted on these estuarine environments require that effective management is urgent and high priority. Historically, a lack of a clear management structure, as well as limited responsibility and accountability has resulted in an often disjointed and ad-hoc approach to estuarine management.

Accurate and reliable science-based information is required to provide the tools and techniques to adequately assess the condition of estuarine environments and to guide appropriate management strategies. The objective of the current study was to develop a framework for the regional assessment of NSW estuaries and demonstrate the value of sedimentary metal indicators in estuarine assessment.

Several state and national assessment schemes have attempted to quantity the level of impact on Australian estuaries. However, the use of indicators and complex data management has limited the value and functionality of these assessments. Recognising the limitations of existing estuarine assessments, the current regional assessment scheme was developed as a preliminary assessment in a hierarchal scheme, designed to provide high quality accurate scientific information to natural resource managers.

In the current study, pressure indicators show population density and catchment urbanisation to be significantly related to the enrichment and biological risk of sedimentary metals in 38 estuaries in NSW. However, some coastal waterways show a varying relationship between pressure and condition indices due to historical and current landuse activities, remedial activities and the physical nature of sediments. Estuarine morphodynamics and hydrology may also play a role in determining the present condition of an estuary, however no signification relationship between sedimentary metals and estuary type was identified. Sedimentary metal indicators are unique in providing accurate information on the magnitude of human-induced change, as well as biological risk not confounded by natural and temporal stress. The value of sedimentary metal indicators in assessment and ranking coastal waterways is demonstrated in the current study.

In addition to the generation of report card grades and identification of historical trends, results of the assessment have also been used to identify five classes of estuarine condition;

severely modified (n=5), highly modified (n=5), modified (n= 3), largely unmodified (n=9), near pristine (n=16). Estuarine condition was found to decrease in proximity to large urban centres, with the exception of Lake Macquarie due to a single local industrial point source. To improve the efficient use of management resources, estuaries identified as ‘severely modified’ would be subject to further assessment under the local assessment scheme detailed in Chapter 3.

The assessment scheme developed is an effective, integrated and regionally consistent assessment of estuarine health, unhindered by natural spatial and temporal variance. The scheme may be used to construct baseline data against which future trends may be assessed and management strategies judged. This scheme maximises the efficient use of limited management resources in an effective manner.

1 Introduction

Sydney estuary is surrounded by one of the most extensively urbanised and densely populated catchment in Australia (Birch and Taylor, 1999) and is considered to be one of its most polluted waterways (Taylor et al., 2004). Historically, ineffective and uninformed management of this important natural resource has led to the degradation of this catchment/estuary system.

For several decades, Sydney estuary has been the focus of environmental research (Birch and Taylor, 1999; 2000; 2004; Birch and Hutson, 2009), however the wealth of information gathered from these studies is only now being incorporated into management of the estuary and catchment. This high-quality scientific data should be evaluated in a way that it may be readily integrated in the decision-making process as an effective decision support tool for environmental managers.

In recent years, there has been a trend towards the development and use of estuarine assessment schemes as a decision support tool in the effective management of estuarine environments (DECCW, 2010; Dauvin et al., 2008; EcoCheck., 2010). These schemes offer a method by which high-quality environmental data may be converted into a readily understandable and communicable format, providing science based information for effective and informed management decisions.

Assessment schemes have been developed for several Australian and international estuaries (Drewry, 2010; DECCW, 2010; SEQ Healthy Waterways, 2010; EcoCheck, 2010). Whilst fulfilling the purpose for which these schemes were designed, their accuracy and effectiveness is often limited as a result of their structure, function and/or content.

Consequently, there is a need for the development of a comprehensive, effective and accurate assessment methodology that provides detailed information on a local scale for urbanised catchment/estuary systems. The development of such a scheme will guide estuarine managers in the formation of effective management decisions, as well as assisting in site prioritisation, goal setting, performance monitoring for the sustained improvement in estuarine condition.

1.1 Project Objectives

The current study, using Sydney Estuary as a case study, is the first to implement a detailed, local assessment scheme, designed specifically to assess catchment pressures and estuarine condition of 'severely modified' catchment/estuary systems. This scheme aims to facilitate the provision of science-based information for effective decision making and management of degraded estuarine environments.

The project will be achieved through the completion of the following objectives:

a. Develop a local assessment scheme to evaluate the condition of an urbanised catchment/estuary system (Sydney estuary);

b. Identify relationships between catchment pressure and estuarine condition;

c. Identify priority sub-catchment/sub-estuary systems for further assessment and management; and

d. Identify management implications of the local assessment scheme.

2 Methodology

2.1 Study Area

Sydney estuary, located on the central New South Wales coast (Figure 25), is a tide-dominated, drowned river valley with variable bathymetry (Birch et al., 2008). The estuary is surrounded by a highly-urbanised catchment (>80%) of 480 km^2, supporting a population of approximately 2.5 million people (Birch and Taylor, 1999). Sydney estuary is referred to in the current study as encompassing all submerged areas to Indian Spring Low water (McLoughlin, 2000, cited in Birch et al., 2009) rather than the customary ‘Port Jackson’ or ‘Sydney Harbour’, which are spatially restricted.

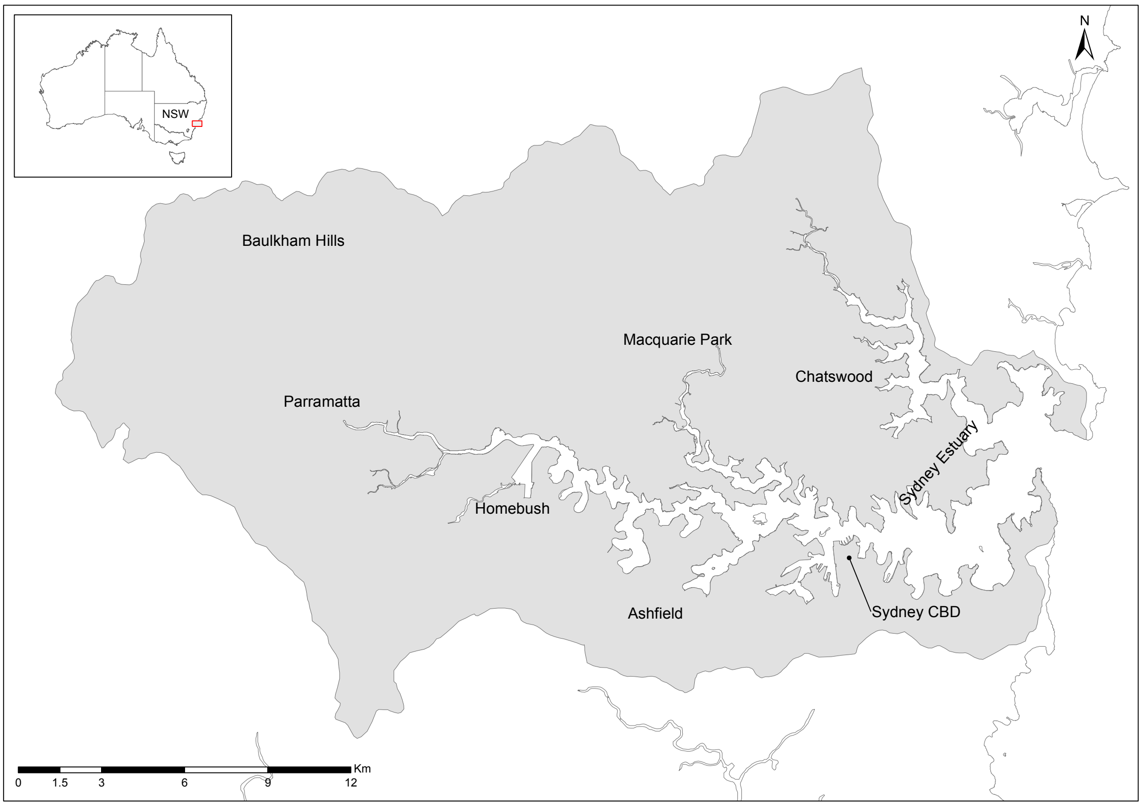


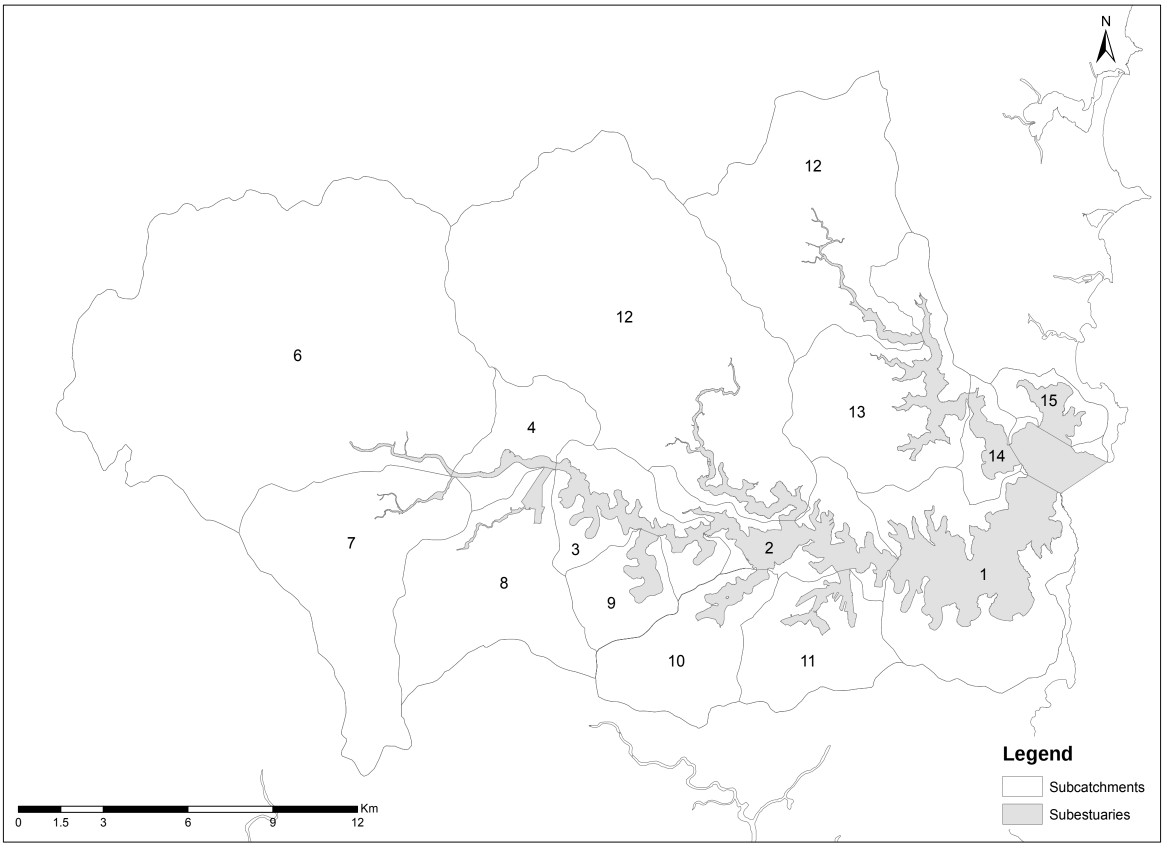
Figure 25: The Sydney estuary.

The estuary (50 km^2) is well mixed under dry and low-precipitation conditions, but becomes temporarily stratified during infrequent, high-precipitation events (>50 mm day^{-1}) (Lee and Birch, 2012, Birch et al., 2009). Flushing rates range from less than 1 day at the mouth to 255 days in the upper reaches (Das et al., 2000).

Sydney estuary has an extensive history of environmental degradation with the onset of contamination during the 19th century associated the rapid increase of urbanisation and industrialisation within the catchment (Taylor et al., 2004). Legacy contamination and stormwater discharge from urban areas continues to influence the health and condition of Sydney estuary.

2.2 Delineation of Sub-catchments

Sub-catchments of the Sydney estuary were originally derived from Cruickshank (2006) who delineated fifteen individual sub-catchments (Figure 26) using 1:25,000 topographic maps produced by the Departments of Lands (2001). Sub-catchments have been defined on the basis of elevation rather than drainage infrastructure (stormwater distribution). All fifteen sub-catchment/sub-estuary systems that define the Sydney estuary catchment have been assessed as part of the present study.



1. Lower Estuary	6. Parramatta River	11. Blackwattle / Rozelle Bay
2. Middle Estuary	7. Duck River	12. Upper Middle Harbour
3. Upper Estuary	8. Homebush Bay	13. Central Middle Harbour
4. Lower Parramatta River	9. Hen and Chicken Bay	14. Lower Middle Harbour
5. Lane Cove	10. Iron Cove	15. North Harbour

Figure 26: Sub-catchment/sub-estuary systems of Sydney Estuary (after Gunns, 2011).

The sub-catchment/sub-estuary systems of Sydney estuary are provided in a schematic diagram (Figure 27). The schematic demonstrates the overall structure and function of water movement and sediment transport within the waterway and relationships between individual sub-catchment/sub-estuary systems.

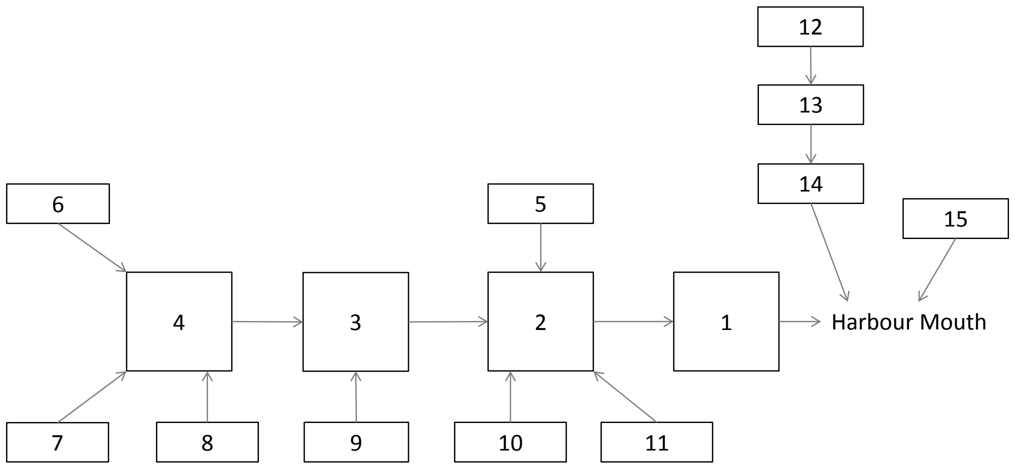


Figure 27: Schematic diagram of sub-catchment/sub-estuaries of Sydney estuary (after Gunns, 2011).

2.3 Report Card Structure

2.3.1 Framework

The assessment framework employed in the current study (Figure 28) is an evolution of the framework developed by Gunns (2011). Developed in consideration of the Pressure-State-Response model, the present framework provides a much improved method by which causal relationships between pressures and condition may be evaluated and factors that influence estuarine health may be identified.

The scheme developed in Gunns (2001) was a 'pilot' study of four sub-catchment/sub-estuary systems within Sydney estuary. The scheme was designed to test a range of different assessment methodologies and indicators to provide the most accurate evaluation of estuarine systems. The present local scheme draws upon the finding of Gunns (2011), making several improvements to the assessment framework, e. g. removing the evaluation of driving forces or 'stressors', as well as the separate assessment temporal change, which were included in the original assessment. These changes were aimed at simplifying the report card structure, ensuring the use of high-quality, scientific data and minimising duplication of environmental indicators. Separate assessment of sediment quality and water quality condition indicator groups (Figure 28) were introduced in the current assessment to provide a greater degree of functionality and understanding of estuarine condition.

The present framework allows for a detailed assessment of catchment pressures and estuarine condition, guiding informed management responses and decisions. Appropriate management responses would, in turn, lead to an improvement in the overall condition of an estuarine system.

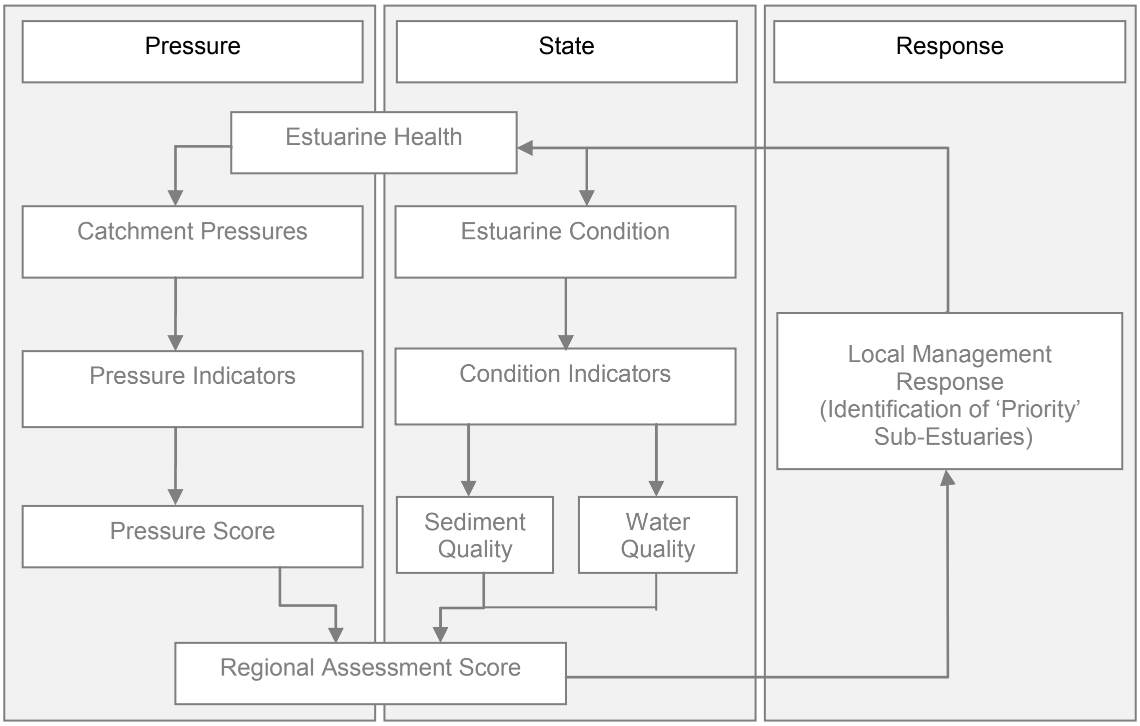


Figure 28: Local report card framework based on the Pressure – State – Response model.

2.4 Environmental Indicators

The current study uses pressure and condition indicators to evaluate the activities, actions and processes that may impact the condition of the estuary. The following section defines environmental indicators for the local assessment.

2.4.1 Pressure Indicators

Urbanised Catchment Area

It is well understood that catchment characteristics, such as urbanisation and industrial activity, have influenced the condition of receiving basins (Birch and Taylor, 1999; Abrahim and Parker, 2002). This indicator is described in greater detail in Chapter 2 Section 2.3.1.

Calculation Urbanised Catchment Area

High-resolution landuse information for the Sydney Estuary was derived from Cruikshank (2006) who produced a landuse use map based on the Australian Bureau of Statistics Mesh

Blocks (draft) data set (ABS, 2005) and transport infrastructure from the Department of Property Information (2000).

Using ArcGIS 10, the landuse layer of Cruikshank (2006) was refined in the present work using cadastral information provided by the Land and Property Information (2012), current high-resolution aerial imagery (NearMap, 2012), as well as the 'street view' function in Google Maps.

High-resolution landuse data were extracted for the 15 sub-catchments using the 'Clip' function in ArcGIS. Urbanised catchment area was expressed as proportion of total catchment area i.e.

$$Urbanised\ Catchment\ Area\ (\%) = \left(\frac{Urbanised\ Area}{Total\ Catchment\ Area}\right) \times 100$$

Population Density

Population density is considered an important indicator in the assessment of 'pressures' on estuarine systems, with a close relationship between population density and estuarine condition (Birch and Olmos, 2011; Bricker et al., 2008; Ward et al., 1998). Pressures exerted by population density on estuarine systems include increased metal, nutrient, litter and sediment loads, as well as sewage overflows and disturbance of riparian vegetation and estuarine biota (Roper et al., 2010). This indicator is described in greater detail in Chapter 2 Section 2.3.1.

Calculation of Population Density

Population density information was derived from the Australian Bureau of Statistics Statistical Local Area (SLA) dataset (ABS, 2011). Population data were presented in ArcGIS 10 and, using the 'Clip' function, data were extracted for the 15 sub-catchments.

Population densities within a sub-catchment were averaged to generate a mean population density value i.e.

$$Population\ Density\ (people\ ha^{-1}) = \frac{\sum SLA\ population\ densities}{Number\ of\ SLAs\ in\ Catchment}$$

Estuary Reclamation

Sydney has an extensive history of harbour development with reclamation of the estuary commencing soon after European colonisation. To date, a total of 1135 ha or 22% of the estuary has been in-filled (Murray, 2003; Birch et al., 2009). Reclamation was not limited to port activities, but also undertaken at the heads of embayments in an effort to improve the appeal of harbour foreshores and to create recreational and residential areas close to the water (Birch, 2006, Birch et al., 2009).

Reclamation was initially regarded as a 'harmless' procedure (NSW Legislative Assembly 1866, cited in Birch et al., 2009), however, estuary foreshores were reclaimed at the expense of mudflat, wetland, mangrove, seagrass and saltmarsh ecosystems (Birch et al. 2009; McLoughlin, 2000). In addition to estuarine ecological effects, reclamation has been shown to reduce the tidal prism, tidal flushing and water velocity, with an estimated 9 million cubic meters of water lost each tidal cycle (Birch, 2006). A reduction in water movement can influence the build-up of contaminants and increase sedimentation within the estuary (Birch et al., 2009).

It is also recognised that leachates from waste materials and dredge spoil used as infill material may also act as a source of contamination to estuarine environments (Birch and Taylor, 1999; Irvine and Birch, 1998, Birch, 2006). Tidal pumping and rainwater percolation has been shown to actively release metals from infill material and acts as a primary source of contamination to Sydney estuary (Suh et al., 2003a, b; Suh et al., 2004; Birch et al., 2004 and Birch et al., 2009).

Calculation of Estuary Reclamation

This indicator aims to reflect the potential effect that foreshore reclamation has had on hydrologic and ecological functioning within Sydney estuary, as well as providing an indication of potential risk of estuarine contamination from infill material.

Using the clip function in ArcGIS v10, Sydney estuary reclamation polygons, derived from Murray (2003), were clipped to individual sub-catchment/sub-estuary boundaries. Reclaimed areas were expressed as proportion of original estuary area i.e.

$$Reclaimed\ Area\ (\%) = \left(\frac{Reclaimed\ Area}{Total\ Original\ Area}\right) \times 100$$

Condition of Riparian Vegetation of Creeks and Rivers

This indicator is derived from the Sydney Metropolitan Catchment Management Authority (SMCMA) 'Waterways Health Strategy', which aimed to prioritise and monitor progress to protect and rehabilitate the waterways of Sydney (Earth Tech, 2007). A riparian vegetation condition assessment of creeks and rivers, conducted as part of the waterways assessment, formed the basis of this indicator.

Calculation of Riparian Condition

This indicator reflects the ability of riparian vegetation to reduce pollutants (sediment, pathogens, metals and nutrients) entering catchment creeks and rivers.

Following the methodology used in the Waterways Health Strategy (Earth Tech, 2007), this indicator examines riparian vegetation of catchment creeks and rivers of the Sydney estuary which are classified into one of nine condition classes (Table 7).

Table 7: Condition classes used to assess the condition of riparian vegetation.

Condition Value	Condition Class	Description
1	Near Intact	Inside Reserve
2	Near Intact	Outside Reserve
3	Good Condition	High Recovery Potential
4	Good Condition	Moderate Recovery Potential
5	Moderate Condition	Good/Moderate Vegetation Cover
6	Moderate Condition	Little/No Vegetation Cover
7	Degraded Condition	Good/Moderate Vegetation Cover
8	Degraded Condition	Little/No Vegetation Cover
9	No vegetation/Flood Control/Recreation	

A length-weighted pressure score was developed in the present work, combining the value of each condition class (1-9) with the proportion that value represents of the total length of creeks and rivers within the sub-catchment i.e.

$$Riparian\ Condition\ Score = \sum (Condition\ Value\ \times proportion\ length)$$

A total riparian condition score, 1 to 9 (good to poor condition), was generated for each sub-catchment.

Enrichment of Metals in Catchment Soils

Enrichment is defined as the extent to which soil metal concentrations exceed geochemical background or pre-anthropogenic concentrations (Birch et al., 2010) and provides a direct measure of human-induced change. As metals are not biodegradable and are poorly mobile, catchment soils are often enriched in trace metals.

Enrichment of metals in urban soils is expressed as an enrichment factor (EF) and is related to intensity and type of landuse. The enrichment factor is expressed as current surficial concentrations over pre-anthropogenic or 'background' concentration with an EF greater than 1.5 times background concentrations, considered to be indicative of human influence (Birch and Olmos 2008).

Birch et al. (2010) demonstrated that in the Sydney catchment, the highest EF for Cu was found in industrial areas with areas adjacent to main roads showing maximum enrichment for Pb and Zn. Parkland and open space landuse showed the lowest enrichment for all three metals.

Calculation of Metal Enrichment

This indicator assesses the magnitude and spatial extent of human-induced change on catchment soils by expressing soil metal concentrations over 'background' levels recorded. Background concentrations for Cu, Pb and Zn in Sydney estuary catchment soils were estimated at 9, 16±3.5 and 17±6.3 µg g^{-1} respectively (Vanderhayden, 2007).

This indicator uses the combination of Cu, Pb and Zn to calculate a Mean Enrichment Quotient (MEQ). The MEQ for is calculated from size normalised soil samples within a sub-catchment i.e.

$$MEQ = \frac{\left(\left(\frac{Cu_{Soil}}{Cu_{Background}}\right) + \left(\frac{Pb_{Soil}}{Cu_{Background}}\right) + \left(\frac{Zn_{Soil}}{Cu_{Background}}\right)\right)}{3}$$

Using soil data derived from Vanderhayden (2007), the MEQ was calculated for each sample location within each of the 15 sub-catchments (total 491 samples). Individual values were averaged to generate a mean MEQ value for each sub-catchment.

Metal Yield

This indicator uses the mass of contaminants generated per unit area of catchment per year (yield). Soil contamination may influence metal yields and if transported into the adjacent estuary in surface runoff, may affect the condition of sediments, water quality and estuarine biota.

Contaminants in stormwater are generated by a range of landuse types (Fletcher et al. 2004) with Cu, Pb and Zn commonly elevated in soils, sediment and biota in the Sydney catchment/estuary system. Influenced by anthropogenic activity, these metals have been widely used to assess impacts of human-induced changed.

Sub-catchment yield (kg km^2 yr^{-1}) allows for direct comparison of loadings in respect to sub-catchment size and can be helpful in identifying catchments that generate high contaminant loads.

Calculation of Metal Yield

This indicator uses yield data from Lean (2013) who calculated the yield values for Cu, Pb and Zn for the 15 Sydney estuary sub-catchments assessed. Lean (2013) calculated loading values for each sub-catchment using the simple empirical model (EPA, 2001) and pollutant Event Mean Concentrations (EMCs) from Fletcher et al. (2004).

Yield values for each sub-catchment were calculated using the following formula:

$$Catchment\ Yield\ (kg\ km^2\ yr^{-1}) = \frac{Total\ Subcatchment\ Yield\ (kg\ yr^{-1})}{Subcatchment\ Area\ (km^2)}$$

Nutrient Yield

The supply of nutrients (Nitrogen and Phosphorous) from the catchment to the adjacent estuary is an important indicator of anthropogenic pressures placed on these (ANZECC 2000). In urbanised catchments, a significant proportion of nutrients are derived from wastewater discharges or diffuse runoff as a consequence of human pressures. Generally, the highest yields of nutrients are from urban areas with lower yields from agricultural and forested areas (Campbell and Doeg, 1989; Ward et al., 1998).

In the Sydney catchment, elevated concentrations of nutrients in receiving waters are generally associated with stormwater discharges and sewer overflows during high-rainfall periods (Birch, Eyre and Taylor, 1999).

Calculation of Nutrient Yield

This indicator uses nutrient data from Lean (2013) who calculated yield values for Total Nitrogen (TN) and Total Phosphorous (TP) for the 15 Sydney estuary sub-catchments assessed. Lean (2013) calculated loading values for each sub-catchment using the simple empirical model (EPA, 2001) and pollutant Event Mean Concentrations (EMCs) from Fletcher et al. (2004).

Yield values for each sub-catchment were calculated using the following formula:

$$Catchment\ Yield\ (kg\ km^2\ yr^{-1}) = \frac{Total\ Subcatc\ hment\ Yield\ \ (kg\ yr^{-1})}{Subcatc\ hment\ \ Area\ \ (km^2)}$$

2.4.2 Condition Indicators

2.4.2.1 Sediment Quality Indicators

Benthic Health Index (BHI)

Sedimentary metals may also be used as an effective indicator of biological risk through the application of sediment quality guidelines (SQGs). These guidelines comprise effects range-low (ERL) and effects range-median (ERM) for 28 chemical concentrations associated with adverse biological effects (McCready et. al 2006). Due to a lack of sufficient data, North American ERM and ERL values have been adapted as interim SQGs (ISQGs) in Australia, as ISQG-Low and ISQG-High, respectively (ANZECC 2000).

The mean ISQG-L (MISQG-L) quotient was adopted in the current study as it is a valuable tool for assessing the quality of sediment in which there are complex mixtures of substances. This indicator is described in greater detail in Chapter 2 Section 2.3.2.

Calculation of BHI

The BHI was calculated using the method detailed in Chapter 2 Section 2.3.2, for each sample location within each of the 15 sub-estuaries. Individual values were averaged and a mean BHI value generate for each sub-estuary.

Human Impact Index

The pre-anthropogenic or pristine condition of an estuary is required to estimate the magnitude of impact caused by human activities (Birch et al., 1999). Sediment-bound metals provide a method to identify the pre-anthropogenic condition, providing natural background concentrations from unmodified pre-anthropogenic material. Background concentrations of sedimentary metals in Sydney Estuary are 12, 20 and 48 µg g^{-1}, for Cu, Pb and Zn respectively (Birch and Taylor 1999).

Birch and Olmos (2008) identified three metals (Cu, Pb and Zn) closely correlate to the suite of nine metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn). Consequently, only these three metals (Cu, Pb and Zn) have been used in the HII to simplify the assessment of human-induced change. This indicator is described in greater detail in Chapter 2 Section 2.3.2.

Calculation of HII

The HII value was calculated using the method detailed in Chapter 2 Section 2.3.2 for each sample location within each of the 15 sub-estuaries. Individual sample values were averaged to generate a mean HII value for each sub-estuary.

Water Quality Indicators

Water quality indices are common among estuarine assessment schemes and are frequently relied on as a primary tool to evaluate the condition of an estuary (NLWRA, 2002; DECCW, 2010). Whilst there are inherent difficulties in the collection, analysis and interpretation of water quality data to discern the influence of human activities, water quality indices have been included in the local assessment scheme due to the availability of high-quality data for the Sydney estuary. Water quality indices are further discussed in Chapter 1 Section 1.4.2.

Water quality parameters assessed are those influenced by human activity and of particular concern in urbanised estuarine systems (ANZECC, 2000). Parameters include; chlorophyll-a (chl *a*), Dissolved Oxygen (DO), turbidity and nutrients (Total Nitrogen and Total Phosphorous).

*Chlorophyll a (*Chl *a)*

Chl *a* is often used as a general indicator of plant biomass due to the presence of chl *a* in plants, algae and cyanobacteria (ANZECC, 2000; Brando et al., 2006). Increased levels of Chl a in the water generally indicates that plants, algae or cyanobacteria are growing and can indicate if a water body has become eutrophic. Chl *a* may also be used as a surrogate for nutrient pollution within a water body (ANZECC, 2000; Scanes et al., 2007).

Elevated nutrient loads associated with catchment urbanisation is considered a primary factor in the elevation of chl *a* in a water body (Cruikshank 2006). Chl *a* should be used with caution as there is not always a clear relationship between chl *a* concentration and plant biomass due to species variation and varying physiological conditions (ANZECC, 2000; Bolwes, 1982).

Dissolved Oxygen (DO)

Concentration of DO within a water body reflects the equilibrium between oxygen-consuming processes and oxygen releasing process (ANZECC, 2000; Best et al., 2007). Biodegradable organic matter, such as sewage effluent and plant material, which are readily available to microorganisms, may have a considerable impact on dissolved oxygen levels. These organisms utilise dissolved oxygen when decomposing organic matter reducing DO concentrations (Connell and Miller, 1984; ANZECC, 2000).

Low DO concentrations can significantly affect aquatic organisms that rely on optimal concentrations for efficient functioning. Low DO concentrations at the sediment-water interface can also control the flux of nutrients, metals and other compounds into the water column. Toxicity of some substances, such as Cu, Pb, Zn, cyanide, hydrogen sulphide and ammonia can also increase with low DO due to physiological changes in gilled organisms, affecting the rate of respiratory flow and thus the concentration of toxins on the gill surface (Lloyd, 1961; Davis, 1975; ANZECC, 2000).

DO, as an indicator of human impact, should be used with caution as concentrations within a water body may be highly dependent on temperature, salinity, biological activity and rate of transfer from the atmosphere. Consequently, concentrations may vary widely over a 24 hr period (ANZECC, 2000).

Turbidity

Turbidity is the presence of suspended particulate matter and colloidal material (silt, clay, phytoplankton and other detritus) in a water body (ANZECC, 2000). Turbidity is largely controlled by natural factors, such as tidal movement, rainfall, temperature and resuspension by wind and wave action (Birch et al., 1999). However human influences such as urbanisation, catchment clearing, erosion and waste water discharges may introduce fine suspended sediments into the estuary (ANZECC, 2000). Additional factors, such as vessel movements, moorings and dredging can influence turbidity through resuspension and remobilisation of sediments.

A significant impact of increased suspended particulate matter is a reduction in light availability, influencing primary production and disrupting trophic functioning (Heap et al., 2001). Other impacts may include the mechanical and abrasive impairment of gilled organisms, disruption of community structure, succession of exotic weeds and smothering of benthic organisms and habitat (ANZECC, 2000).

Nutrients (Total Nitrogen, Total Phosphorous)

Concentrations of nitrogen (N) and phosphorous (P) in the water column can be used to indicate how eutrophied a water body is and its susceptibility to nuisance plant growth (NRC, 2000; Alderson et al., 2002). Activities, such as sewage discharge, industrial and agricultural wastewater and fertiliser runoff can supply excess nutrients in receiving waters.

Excess nutrients may cause eutrophication, stimulate nuisance growth of aquatic plants, increase oxygen demand through decomposition of organic matter and can potentially lead to a reduction in dissolved oxygen (Boyton et al., 1996). Algal blooms and nuisance plant growth may also limit the recreational and economic value of estuaries due to restricted use of the waterway (Alderson et al., 2002; ANZECC 2000).

In Sydney estuary, N and P concentrations can exceed ANZECC guidelines and with blooms of blue-green algae common in the upper reaches of the estuary (Birch, Eyre and Taylor, 1999).

Calculation of Water Quality Indices

Twelve months of water quality data were provided by Harrison (University of Sydney unpublished data, 2013) for the calculation of these indicators. Water samples were collected on a weekly basis from 29 locations within Sydney estuary with two depths sampled; 0.3 m below the surface and 0.3 m above the sea bed. Due to data availability, only shallow water data was used in the current assessment.

Chl *a* was analysed by the spectrophotometric method according to the Standard Methods 10200 H (APHA, 1998) including the correction for phaeophytin-a by acidification, on a Hitachi U-2000 dual beam spectrophotometer. Determination of TN and TP was conducted using a persulfate digestion according to Method 4500-N C. Persulfate Method (APHA, 1998). Final concentrations of N and P were determined by flow injection analysis on a LaChat FIA. Turbidity (NTU) and DO (%) were measured in situ using a YSI model 6600 V2 sonde.

Water quality data was compared to trigger values defined in the ANZECC (2000) guidelines for estuaries in south-east Australia (Table 8). The proportion of samples exceeding the trigger value for a given parameter was used to provide an indicator of overall water quality within each sub-estuary.

A percentage value for each sub-estuary was calculated using the following formula:

$$Proportion\ of\ Samples\ Excceding\ Trigger\ \ (\%) = \left(\frac{\sum(Samples\ Excceding\ Trigger)}{Number\ of\ Samples}\right) \times 100$$

Table 8: ANZECC and ARMCANZ (2000) water quality trigger values for SE Australian estuaries.

Water Quality Parameter	Guideline Trigger Value*
Chlorophyll a (µg L^{-1})	4
Total Nitrogen (µg L^{-1})	300
Total Phosphorous(µg L^{-1})	30
Dissolved Oxygen (%)	Upper: 110 Lower: 80
Turbidity (NTU)	10

** ANZECC (2000) trigger values for SE Australian estuaries.*

2.5 Correlation Matrix of Indicators

Using the non-parametric Spearman's correlation test, a correlation matrix of indicators was created to assess covariance between indicators used in local assessment and to further examine the relationship between pressure and condition indicators. Use of the Spearman's correlation test is detailed in Chapter 2, Section 2.4.

Results of the correlation test are provided in Section 3.1 of this chapter.

2.6 Assessment of Indicators

The assessment of indicators uses the same fuzzy logic assessment methods as the regional assessment scheme which is detailed in Chapter 2, Section 2.5.

2.7 Calculating Assessment Scores

This section describes the calculations used in determination assessment scores for the 15 sub-estuaries examined. Stages involved in the calculation of assessment scores are provided in Figure 29 and detailed below.

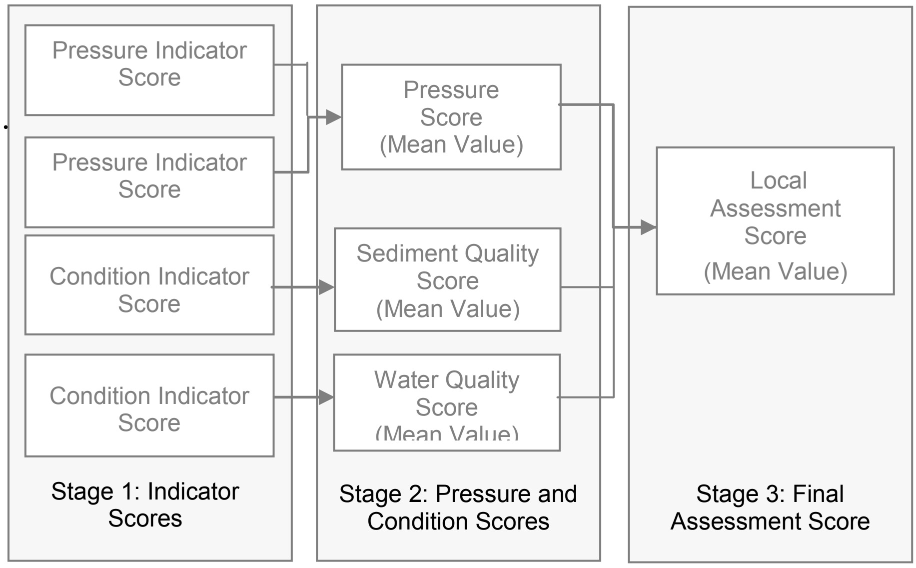


Figure 29: Calculation of assessment scores for the regional assessment.

Stage 1: Calculating Indicator Scores

Individual indicators were assessed using fuzzy logic as where individual indicator values were transformed so that a 'fuzzy' score between 0.00 (good) and 1.00 (poor) was generated for each indicator.

Stage 2: Calculating Pressure and Condition Score

To calculate pressure and condition scores, the sum of 'fuzzy' indicator scores was divided by the number of respective indicators to generate a mean indicator score i.e.

$$Pressure\ Score = \frac{\sum(Pressure\ Indicator\ Scores)}{Number\ of\ Pressure\ Indicators}$$

$$Sediment\ Quality\ Condition\ Score = \frac{\sum(Sediment\ Indicator\ Scores)}{Number\ of\ Sediment\ \ Indicators}$$

$$Water\ Quality\ Condition\ Score = \frac{\sum(Water\ Quality\ Indicator\ Scores)}{Number\ of\ Water\ Quality\ Indicators}$$

Stage 3: Calculating Overall Estuary Scores

The final sub-catchment/sub-estuary assessment score was calculated by averaging the final pressure and condition scores i.e.

$$Local\ Assessment\ Score = \frac{(Pressure\ Score + Water\ Quality\ Score + Sediment\ Quality\ Score)}{3}$$

2.8 Assessment Scheme Output

In line with the regional assessment scheme detailed in Chapter 2, a letter grade format has been selected to present the results of the local assessment scheme. The letter grade output is detailed in Chapter 2, Section 2.7.

3 Results

3.1 Indicator Correlation Matrix

Results of the non-parametric Spearman's correlation test revealed sediment quality indicators generally show a significant correlation (*P*<0.05) with pressure indicators (Table 9). However, sediment quality was not significantly related to TN yields with BHI and population density demonstrating little covariance (R^2=0.271).

Water quality indicators generally showed little correlation with pressure indicators with the exception of estuary reclamation, which showed significant correlation with all water quality indices (Table 9). In addition, Chl *a* had a strong correlation to catchment urbanisation and riparian health. Total phosphorus showed covariance with riparian health and soil metal enrichment.

Table 9: Correlation coefficients for indicators used in the local report card*.

		Condition Indicators						
		Human Impact Index (HII)	Benthic Health Index (BHI)	Total Nitrogen	Total Phosphorous	Turbidity	Chlorophyll *a*	Dissolved Oxygen
Pressure Indicators	Catchment Urbanisation	**0.625**	**0.611**	-0.070	0.243	-0.173	**0.442**	-0.178
	Population Density	**0.571**	0.271	-0.488	-0.358	-0.373	0.137	-0.507
	Riparian Health	**0.621**	**0.820**	0.129	**0.508**	-0.041	**0.576**	-0.334
	Estuary Reclamation	**0.504**	**0.800**	**0.668**	**0.852**	**0.523**	**0.485**	**0.444**
	Soil Metal Enrichment	**0.754**	**0.907**	0.264	**0.591**	0.162	0.657	0.115
	Metal Yield	**0.525**	**0.314**	-0.698	-0.300	-0.558	0.205	-0.686
	Total Nitrogen Yield	0.275	0.068	-0.687	-0.450	-0.489	0.000	-0.465
	Total Phosphorous Yield	**0.546**	**0.418**	-0.485	-0.210	0.113	-0.129	-0.416

**indicators showing a significant correlation (P<0.05) shown in bold.*

3.2 Local Assessment Results

The following section details the results of the regional assessment scheme. Complete results for the sub-catchment/sub-estuary systems assessed are contained in Appendix B.

Results of the local assessment are summarised in Table 10 and in Figure 31 - Figure 37.

Table 10: Summarised assessment results for Sydney estuary.

Sub-estuary	Pressure Score / Report Card Grade		Water Quality Score / Report Card Grade		Sediment Quality Score/ Report Card Grade		Final Assessment Score / Report Card Grade	
Lower Estuary	0.65	C-	0.10	A	0.15	A-	0.38	B
Middle Estuary	0.56	C	0.06	A+	0.38	B	0.35	B
Upper Estuary	0.50	C+	0.48	C+	0.47	C+	0.49	C+
Lower Parramatta River	0.40	B-	0.69	D+	0.29	B+	0.49	C+
Lane Cove River	0.28	B+	0.52	C+	0.15	A-	0.34	B
Parramatta River	0.35	B	0.72	D+	0.19	A-	0.46	C+
Duck River	0.44	B-	0.86	D-	0.47	C+	0.60	C
Homebush Bay	0.53	C+	0.78	D	0.49	C+	0.62	C-
Hen And Chicken Bay	0.47	C+	0.44	B-	0.90	D-	0.52	C+
Iron Cove	0.76	D+	0.34	B	0.93	F	0.63	C-
Blackwattle / Rozelle Bay	0.96	F	0.24	B+	1.00	F	0.71	D+
Upper Middle Harbour	0.12	A	0.31	B	0.04	A+	0.18	A-
Central Middle Harbour	0.35	B	0.16	A-	0.49	C+	0.31	B
Lower Middle Harbour	0.39	B-	0.01	A+	0.00	A+	0.20	A-
North Harbour	0.18	A-	0.01	A+	0.07	A	0.10	A

3.2.1 Final Local Assessment Results

Final assessment scores (Table 10 and Figure 30 - Figure 31) were generally well distributed with values ranging from 0.10 (North Harbour, A) to 0.71 (Blackwattle/Rozelle Bay, D+). The mean final assessment score for Sydney estuary was 0.43 (B-). North Harbour (0.10), Upper Middle Harbour (0.18) and Lower Middle Harbour (0.20) returned the assessment scores with grades ranging between A and A- respectively. Four sub-estuaries returned the poorest overall assessment scores (Figure 31) with Blackwattle/Rozelle Bay (0.71) and Iron Cove (0.63) returning the lowest grade of D+ and C- respectively. Duck River (0.60) and Homebush Bay (0.62) both received a grade of C. Of remaining sub-estuaries assessed, four received a grade of B (Central Middle Harbour [0.31], Lane Cove River [0.34], Middle Estuary [0.35] and Lower Estuary [0.38]). Parramatta River (0.46), Lower Parramatta River

(0.49), Upper Estuary (0.49) and Hen and Chicken Bay (0.52) all returned a grade of C+ (Figure 31).

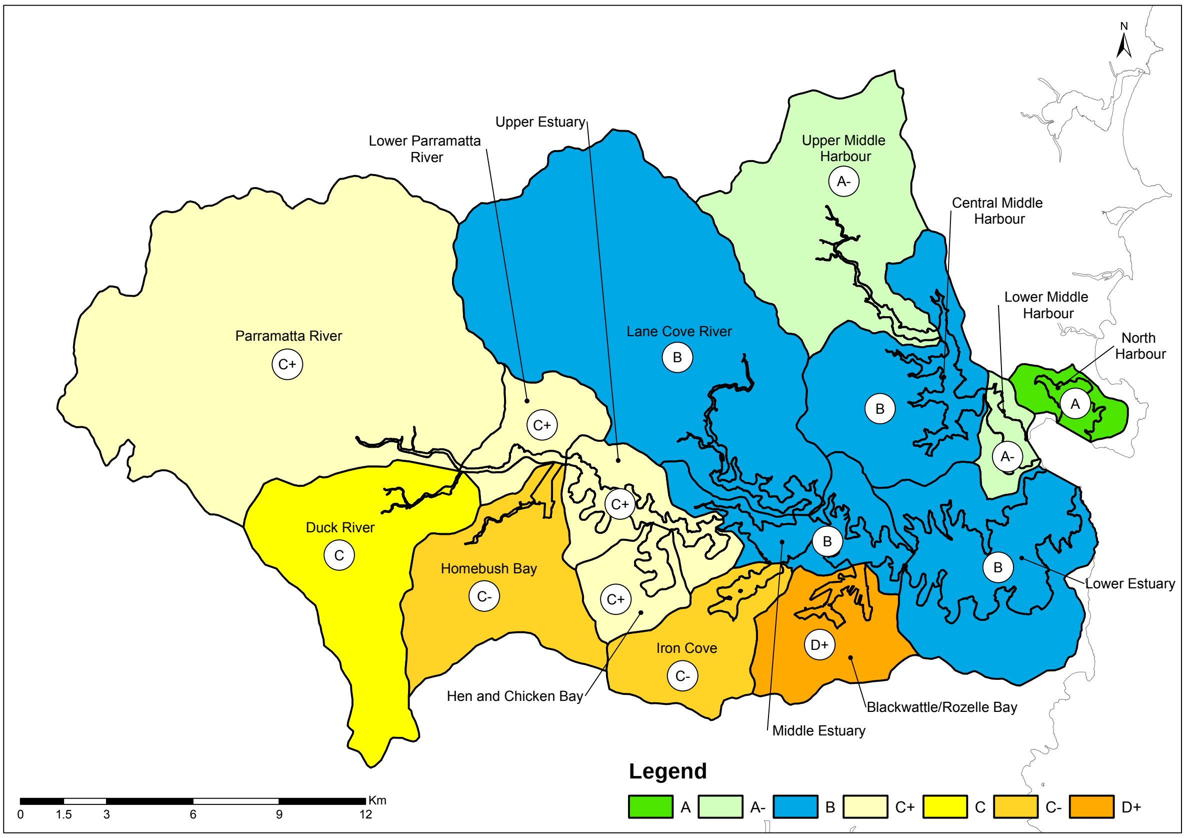


Figure 30: Final assessment grades for the Sydney estuary.

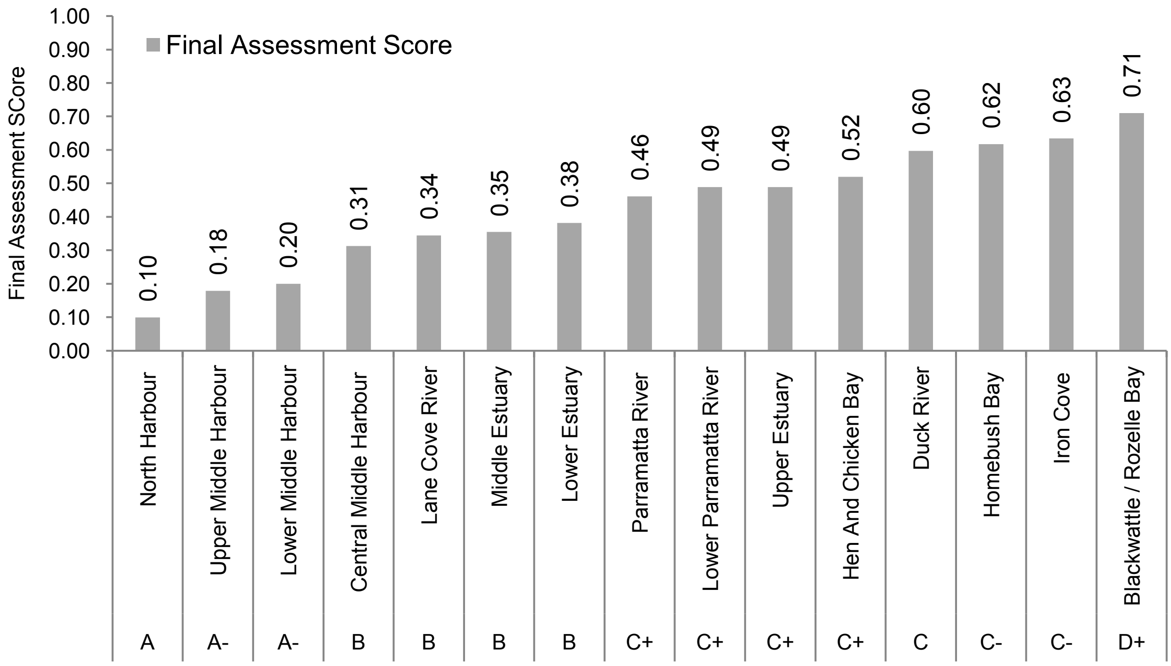


Figure 31: Final local assessment scores and letter grades.

Pressure scores ranged between 0.12 (Upper Middle Harbour, A) and 0.96 (Blackwattle/Rozelle Bay, F) (Table 10 and Figure 32 - Figure 33). Sydney estuary returned a mean pressure score of 0.46 (C+). Upper Middle Harbour and North Harbour had the lowest catchment pressures with scores of 0.12 (A) and 0.18 (A-), respectively. Blackwattle/Rozelle Bay had the highest catchment pressures in the Sydney Estuary with a score of 0.96 (F), significantly greater than the next highest sub-catchment, Iron Cove, with 0.76 (D+). Remaining sub-catchments were relatively well distributed between B+ and C-. Approximately 40% returned a grade between 0.28 and 0.44 (B+ to B-) with 33% returning a grade between 0.47 and 0.76 (C+ to C-), respectively (Figure 32-Figure 33).

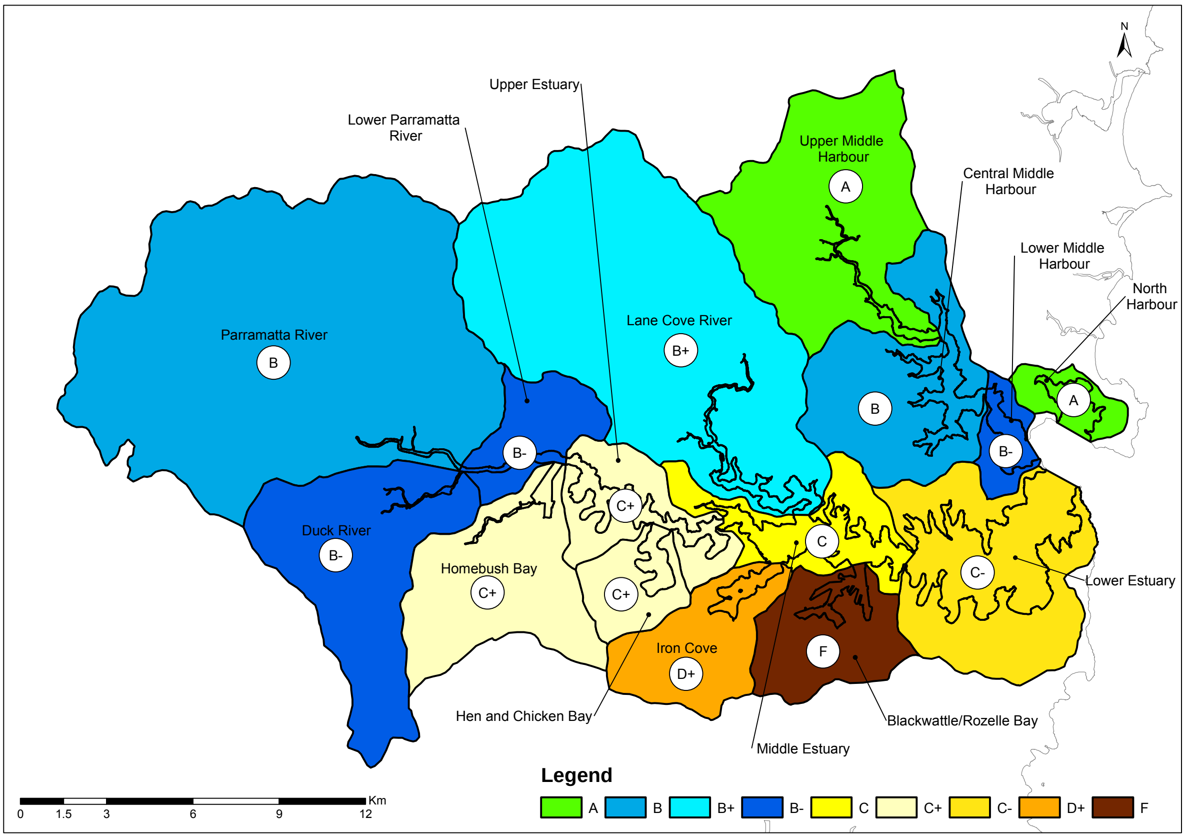


Figure 32: Final pressure grades for the Sydney estuary.

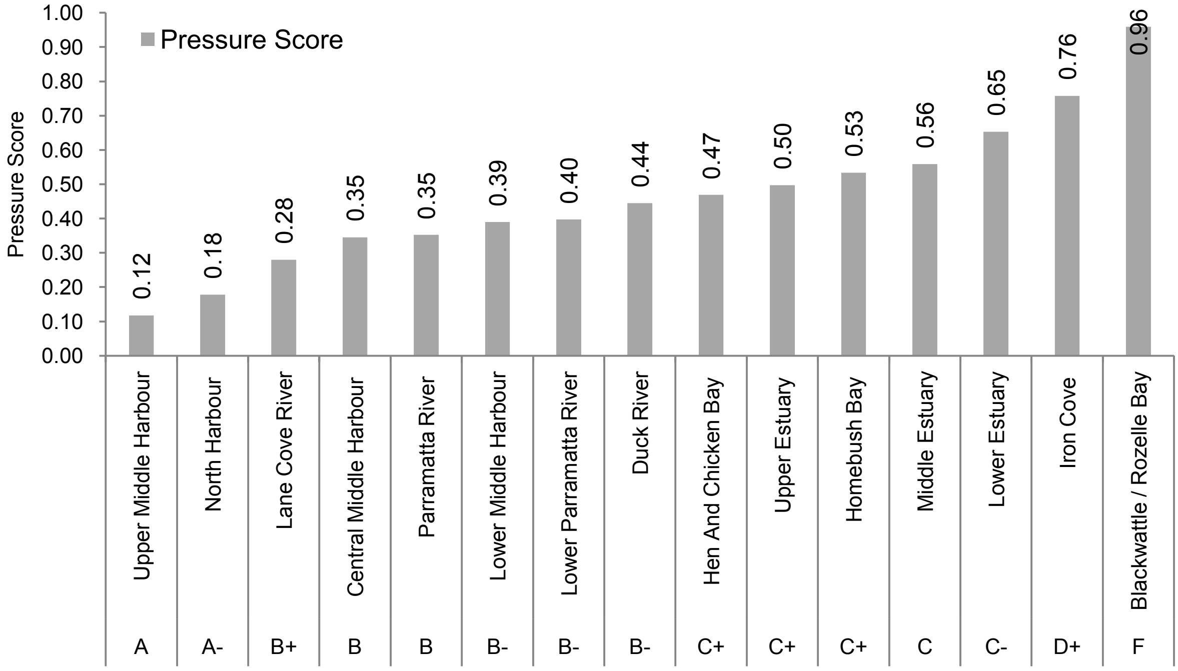


Figure 33: Final pressure scores and letter grades for the Sydney estuary.

3.2.2 Condition Results

3.2.2.1 Water Quality

Water quality decreased away from the estuary mouth (Figure 34) with poorest conditions recorded in Duck River (0.86, D-) followed by Homebush Bay (0.78, D) Parramatta River (0.72, D) and the Lower Parramatta River (0.69, D). Sub-estuaries located within proximity to the estuary mouth (Figure 34), i. e. North Harbour (0.01) Lower Middle Harbour (0.01), Middle Estuary (0.06) all returned grades of A+ followed by Lower estuary (0.10) and Central Middle Harbour (0.16) with scores of A and A, respectively (Figure 35). The remaining sub-estuaries returned scores ranging between 0.24 (B+) and 0.52 (C+) (Figure 34 and 33).

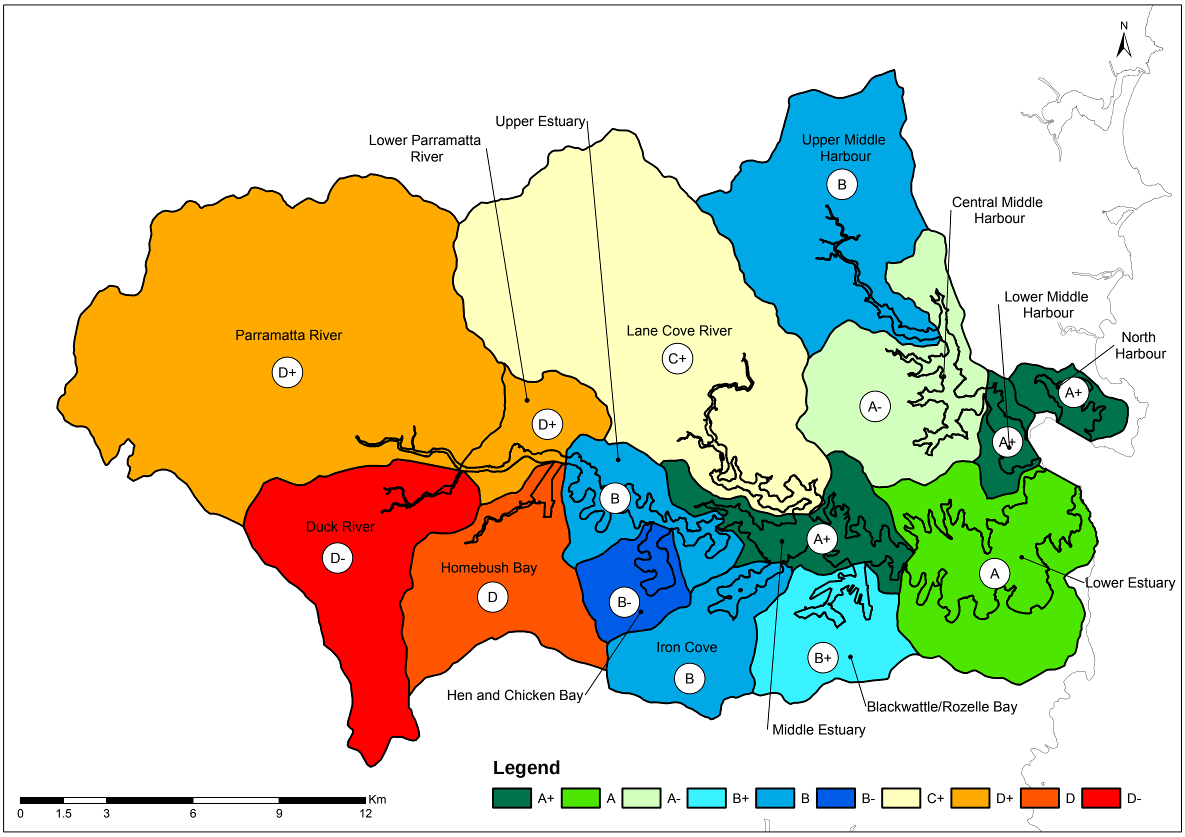


Figure 34: Final water quality grades for the Sydney estuary.

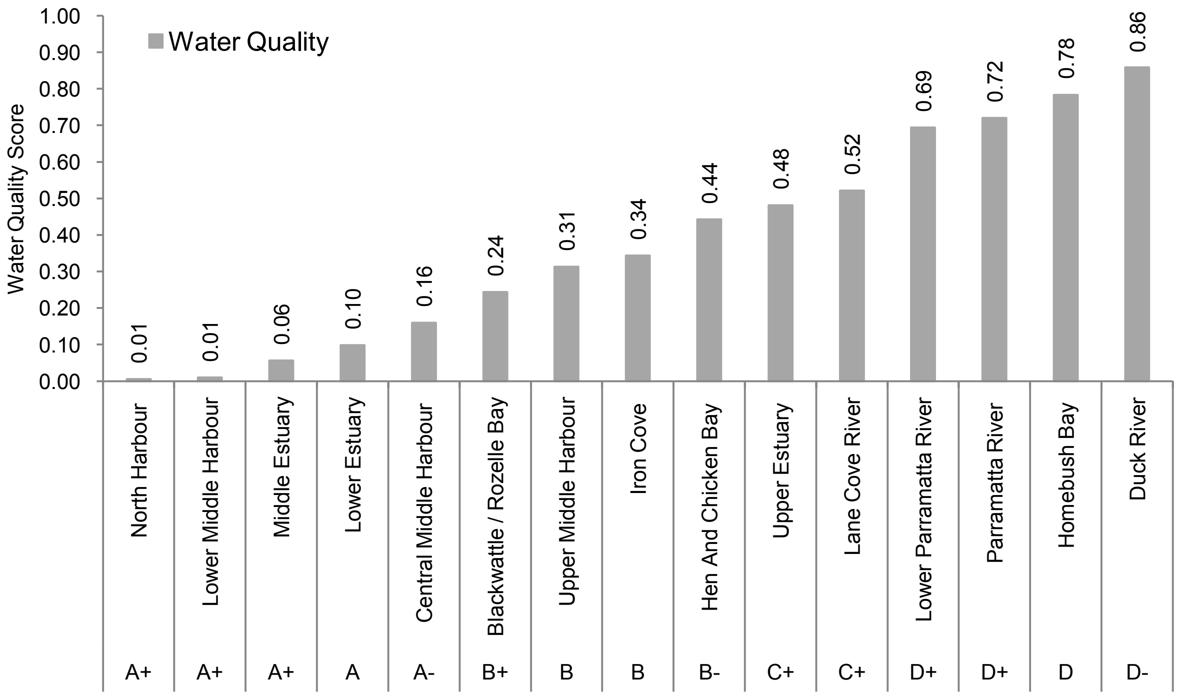


Figure 35: Final water quality scores and letter grades for the Sydney estuary.

3.2.2.2 Sediment Quality

Sediment quality results were highly variable, with scores ranging between 0.00 (A+) in Lower Middle Harbour and 1.00 (F) in Blackwattle/Rozelle Bay (Table 10 and Figure 36 - Figure 37). Three sub-estuaries (Blackwattle/Rozelle Bay, Iron cove and Hen and Chicken Bay) returned significantly higher sediment condition results in comparison to other sub-estuaries, with scores of 1.00 (F), 0.93 (F) and 0.90 (D-), respectively. Central Middle Harbour returned the next highest score of 0.59 (C). Lower Middle Harbour and Upper Middle Harbour had the best sediment quality, both returning scores of 0.00 (A+) and 0.04 (A+). Four other estuaries (North Harbour, Lower Estuary, Lane Cove River and Parramatta River) returned scores with 0.07 (A), 0.15 (A-), 0.15 (A-) and 0.19 (A-), respectively. Remaining sub-estuaries ranged between B+ and C+ (Figure 37).

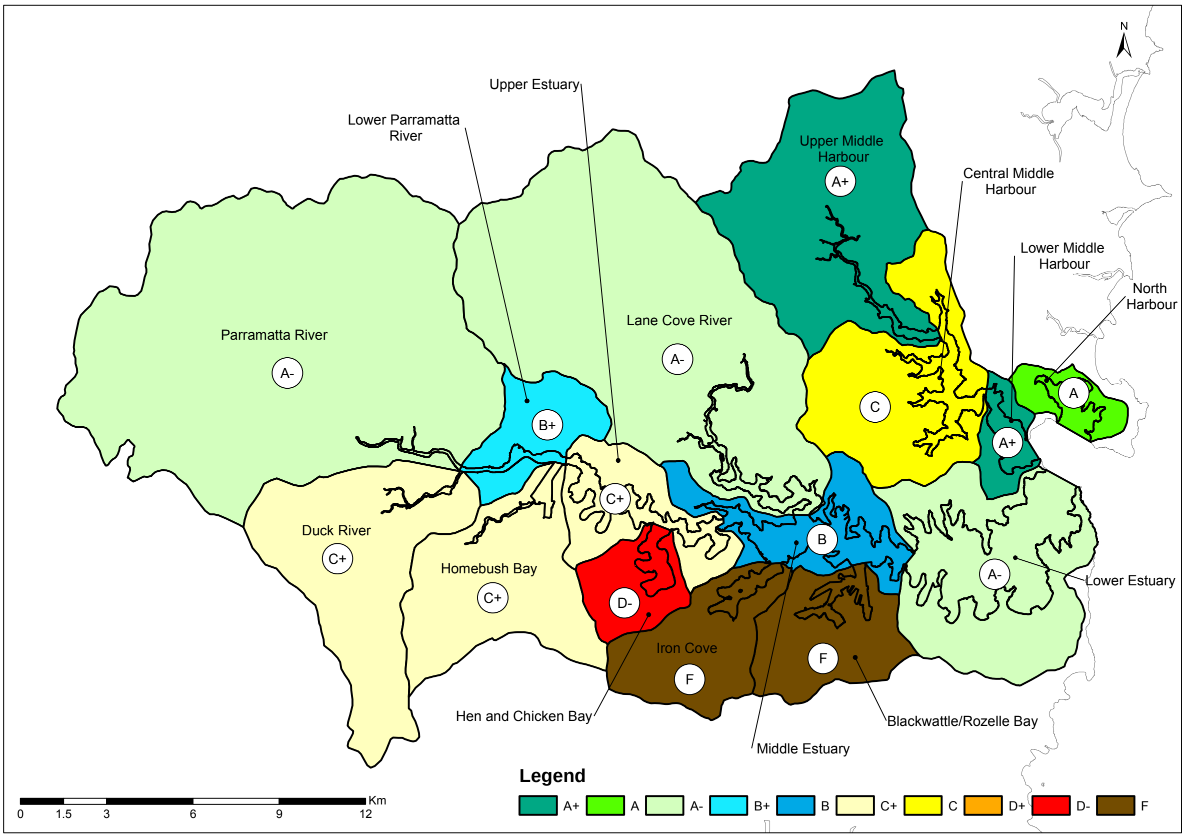


Figure 36: Final sediment quality grades for the Sydney estuary.

Figure 37: Final sediment quality scores and letter grades for the Sydney Estuary.

4 Discussion

4.1 Development of the Local Assessment Scheme

4.1.1 Development of the Assessment Framework

The local assessment scheme was developed as a secondary, detailed assessment tool in a hierarchal scheme, evaluating ‘severely modified’ estuarine systems identified in the regional assessment (Chapter 2). The scheme was designed to provide a comprehensive understanding of relationships between catchment pressures and estuarine condition at a local scale.

Recognising limitations of indicators used in existing state and national assessment schemes, the local framework maximises the use of high-value environmental indicators. This scheme provides relevant and meaningful information to estuarine managers and allows for the fine scale assessment of estuarine condition. The current scheme centres on the internal assessment of Sydney estuary whereby individual sub-catchment/sub-estuary systems are compared to each other rather than external reference sites. This method facilitates the development and implementation of realistic management options and goals specific to the Sydney estuary.

Framework Structure

The framework, developed around a simplified ‘Pressure-State-Response’ model (OECD 1993), mirrors that of the regional assessment and is capable of providing a robust and detailed local assessment of estuarine condition. The framework reduces the complexity of indicator analysis required, maintains information value and prioritises the use of relevant and meaningful environmental indicators. The structure allows catchment pressures and estuarine condition indicators to be evaluated individually and as a whole with functionality and value of the scheme improved by the individual assessment of sediment quality and water quality. The framework allows estuarine managers with the ability to identify specific areas and issues of concern within the estuary and prioritise management in these areas.

Use of Relevant High-Value Indicators

A selection of high-value physical, chemical and socioeconomic indicators were chosen to provide accurate and robust assessment of Sydney estuary. These indicators were required to have:

- Suitable data availability;
- Fine-scale spatial resolution;
- Clear causal relationships between catchment pressure and estuarine condition; and
- Relevance to environmental issues within the estuary.

Sediment Quality Indicators were chosen due to high levels of sediment contamination identified within the estuary (Birch et al, 2004, Olmos and Birch, 2008; Birch and Taylor, 1999). These indicators are valuable in the assessment of estuarine condition due to the ability to provide information on both the magnitude of human impact and biological risk within an estuary.

Water quality within Sydney estuary is generally good, except during high precipitation events where rapid increases in freshwater discharge can cause temporary stratification (<44 days) within the estuary (Lee and Birch, 2012). Stormwater constituents, including sediment, nutrients and particulate and dissolved contaminants can result in short-term reduction in water quality (Lee and Birch, 2012; Farmer and Graham, 1999; Barry et al., 1999). Although the degree of human influence is difficult to discern, water quality indicators are an important indicator of estuarine condition. The provision of high quality data allowed water quality indices to be used with confidence in local assessment.

Use of Biological Indicators

Due to technological, logistical and financial reasons, biological assessments are often limited in their ability to assess and record change over a range of temporal and spatial scales. Confounding effects of natural temporal and spatial variation mean careful interpretation of biological indices is important in order to identify the human-induced component of change. Limitations of biological indices in estuarine assessment are discussed in Section 1.4.2.

The composition of intertidal biota was considered to be used in the local assessment scheme however it was subsequently excluded due to poor data availability and spatial resolution. A dedicated sampling program specifically designed for inclusion in a report scheme would be required to minimise the confounding effect of natural spatial and temporal variation. Relevant and robust biological indicators would complement the existing suite of indictors used in the assessment and may include bioaccumulation / enrichment of metals in sessile filter feeders such mussels and oysters.

Other biological indicators including fish assemblages as well as mangrove, seagrass and saltmarsh extent have the potential to be used in the current scheme. If these indicators are to be used with confidence, detailed investigation involving a comprehensive sampling strategy would be required to address spatial and temporal variability and to discern the influence of anthropogenic activity.

Spatial Variation of Conditions

Whilst the local assessment provides an average condition for a particular sub-estuary, the quality of sediment and water can vary spatially. Excluding industrial or known historical point sources, trace metals generally increasing towards the heads of embayments, with highest concentrations identified in proximity to stormwater discharge points (Birch and Taylor; 1999; Barry et al., 2000; Birch et al., 2013). Water quality is also highly spatially variable and can be associated with waste water discharge points, sewage over flow locations or in constricted embayments within a sub-estuary (Lee and Birch, 2012). The local assessment developed in the current study does not provide this level of differentiation; rather it has been designed as a tool to guide the prioritisation of estuaries for further research to identify specific areas of concern and to develop appropriate management strategies.

4.1.2 Indicator Assessment and Data Management

The current assessment abandons the traditional 'ordinal' scoring of indicators, adopting instead the concept of fuzzy logic. Fuzzy logic was used to minimise the transformation of data, reducing information loss whilst maintaining data integrity. Fuzzy logic was employed to obtain a non-linear transformation of indicator scores, measured on multifarious scales, to make them all comparable on a single scale.

An investigation of indicator weights by Gunns (2011) found that conservative bias was introduced into the assessment through the use of weighted indicator scores. This bias resulted in the distortion of results and the misrepresentation of estuarine condition. Given these findings, indicator weights were not applied in the current study. Indicator assessment and data management techniques employed in the local assessment scheme are previously discussed in Chapter 2, Section 4.1.2.

4.2 Relationships between catchment pressure and estuarine condition

4.2.1 Indicator Correlation

Unlike the regional scheme, results of the local assessment suggests little correlation exists between the catchment and its associated estuary (R^2=0.0581) (Figure 38 A). However, as shown in Figure 38 B, this relationship is largely driven by poor covariance between water quality and pressure results (R^2=0.0021).

Association between catchment pressures and water quality (Figure 38 B), suggests catchment based pressures are not the only factor controlling water quality within the Sydney estuary. Other factors such as flushing rates and estuary morphodynamics may influence water quality and are further discussed in Section 4.3 of this chapter. In agreement with the regional assessment, a significant correlation exists between catchment pressure and sediment quality (R^2=0.5414) (Figure 38 C). This relationship demonstrates the value of sedimentary indicators in representing the condition of the estuary and role of human induced pressures in influencing the health of estuarine systems.

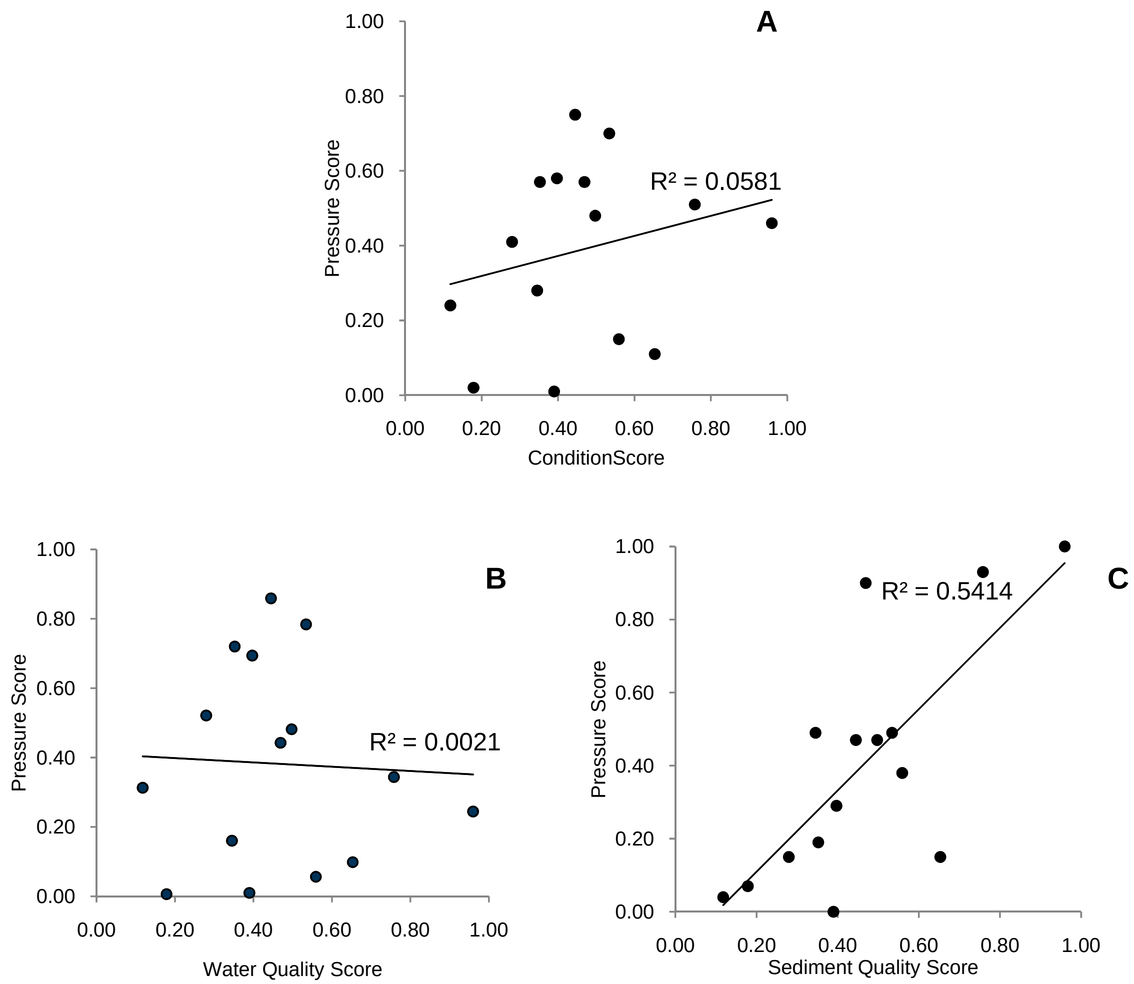


Figure 38: Bivariate plots of catchment pressure condition results. **A**. Pressure and condition results, **B**. Pressure and Water Quality Results, **C**. Pressure and sediment quality results.

4.3 Influence of catchment pressures on estuarine condition

Correlation between catchment pressure and estuarine condition may be used as a method of determining the influence of anthropogenic impacts and understanding causal relationships between a catchment and estuary. Results of the assessment may also be used to infer how historical catchment changes have influenced the current condition of an estuary.

Sediment Quality

Catchment pressures correlate positively and significantly (R^2=0.5414) with sediment quality indicators (Table 9 and Figure 38 C). However, these factors are not always consistently related, as shown in Figure 39.

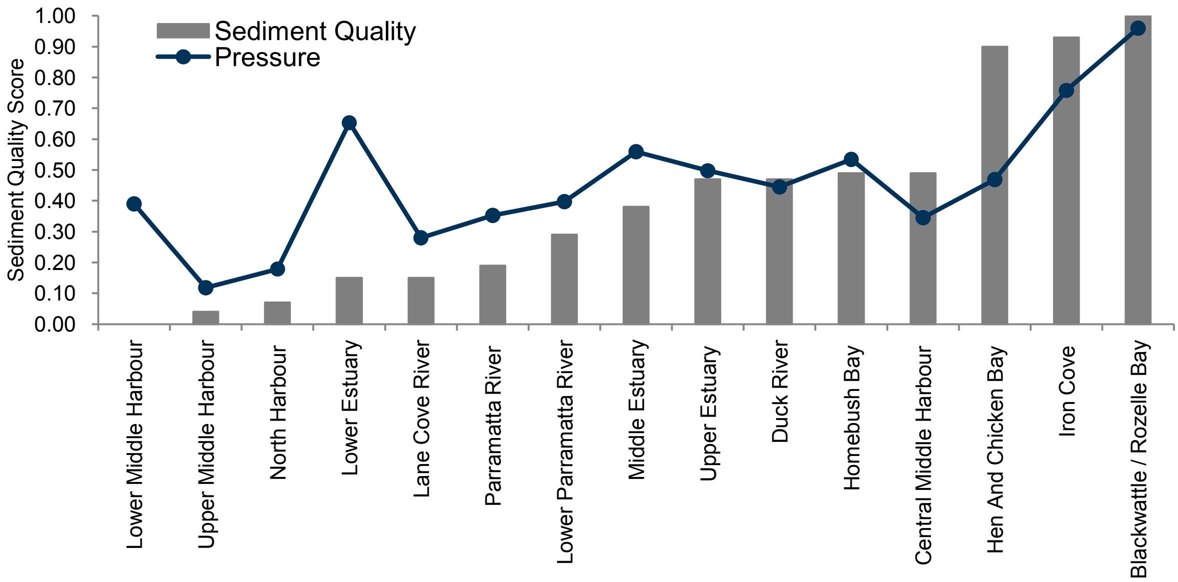


Figure 39: Relationship between sediment quality and catchment pressures.

Lower Middle Harbour and Lower Estuary have high catchment pressure scores in comparison to low sediment quality scores indicating catchment-based pressures are not the only factor controlling the quality of sediments in these sub-estuaries. This inverse relationship is likely attributed to the coarse nature of sediments within Lower Middle Harbour and Lower Estuary (<36% and <43% fine fraction, respectively) which limits the ability of contaminants be adsorbed and retained. Increased flushing rates, vessel movements and dredging activity may also result in the remobilisation and removal of fine surficial sediment and the lowering of metal concentrations.

Conversely, Central Middle Harbour, Iron Cove, Hen and Chicken Bay and Blackwattle/Rozelle Bay demonstrate higher sediment quality scores in comparison to catchment pressures. Located within close proximity to the Sydney CBD, sediment quality scores within these sub-estuaries is likely attributed to historical catchment use, which was dominated by industrial activity. Earliest industrial activity in Sydney was located close to the present CBD (Taylor et al., 2004). Three bays (Blackwattle, Rozelle and Cockle Bay) were the first to be urbanised with the establishment of several metal foundries, tanneries and other small industries during the 1800s (Taylor et al., 2004; Links, 1998; Lean, 2013). Significant economic development after 1860 led to rapid urbanisation and industrialisation of Sydney catchment between 1870 and 1917, which spread west to encompass Iron Cove and Hen and Chicken Bay and Homebush Bay (Taylor et al., 2004, Lean, 2013). The rapid increase in manufacturing activity within these catchments at the turn of the century coincides closely with increased trace metal concentrations in subsurface sediments.

Residual contamination from historic fill material, industrial activity and landfills located within these catchments continues to influence contamination within the estuary (Taylor et al., 2004).

The onset of contamination in Blackwattle, Rozelle and Cockle Bays occurred from 1866 - 1876, which closely approximates to the onset of metal usage within the catchment (Taylor et al., 2004). Maximum trace metal concentrations in these embayments are observed from 1950 to 1980, associated with maximum industrial activity within the catchment (Taylor et al., 2004). Metal concentrations generally decrease after this period due to a decline of shore-based industries in the catchment. Birch et al., (2013) notes in some areas of these bays, surficial sediments remain highly enriched (>50 times background concentrations).

Central Middle Harbour, whilst not extensively urbanised or industrialised during this early period, demonstrates the impact of localised and intensive industrial activity on the condition of the estuary. Significant Cr contamination within Central Middle harbour is associated with establishment of tanneries in the catchment in 1869 (Birch et al., 2013, Taylor et al., 2004). Centred near Scotts Creek, tanneries operated in the area up to 1992 (Birch et al., 2013). The onset Cr contamination, a major ingredient in the tanning process, began in 1907 with maximum concentrations (4000 mg kg-1) observed in 1923 (Birch et al., 2013). Surficial sediment is still highly enriched in comparison to regional levels, suggesting a residual source of Cr to the estuary, perhaps by remobilisation of fluvial material. The presence of a historic industrial and domestic landfill in Flat Rock Gulley, Central Middle Harbour, may also be acting as a source of residual contamination to the estuary due to the strong increase of Cr, Cu, Pb and Zn at the mouth of Flat Rock Creek in Long Bay (Birch et al, 2013).

Water Quality

As previously demonstrated, little correlation exists between water quality indices and catchment pressures in Sydney estuary (Table 9 and Figure 38). Figure 40 again reveals this relationship suggesting water quality is largely influenced by factors other than those used to assess catchment pressures in the current scheme. This association suggests that flushing rates may be a significant influence on water quality within the estuary with water quality declining away from the estuary mouth. In general, the poorest water quality was observed in Duck River, Homebush Bay, Parramatta River and Lower Parramatta River in upper reaches of the estuary. Water quality in these sub-estuaries was primarily influenced by poor DO and nutrients (TN/TP) values and to a lesser extent by turbidity and chl *a*. A correlation between estuary reclamation and water quality also suggests that a reduction in the tidal prism, tidal flushing and water velocity may result in a build-up of contaminants. Conversely, sub-estuaries located within proximity to the harbour mouth, i. e. North Harbour, Lower Middle Estuary, Middle and Lower Estuary, demonstrate the best water quality with few samples exceeding ANZECC (2000) criteria.

Catchment pressures are likely to play a greater role in the quality of water during high-rainfall events where stormwater runoff containing sediment, organic material and particulate and dissolved phase contaminants are discharged into the estuary. These freshwater pulses are generally short lived with contaminates rapidly removed from the estuary (Lee and Birch, 2012). Water sampling may miss these brief, high-concentration contaminant discharges making the influence of catchment pressures difficult to discern.

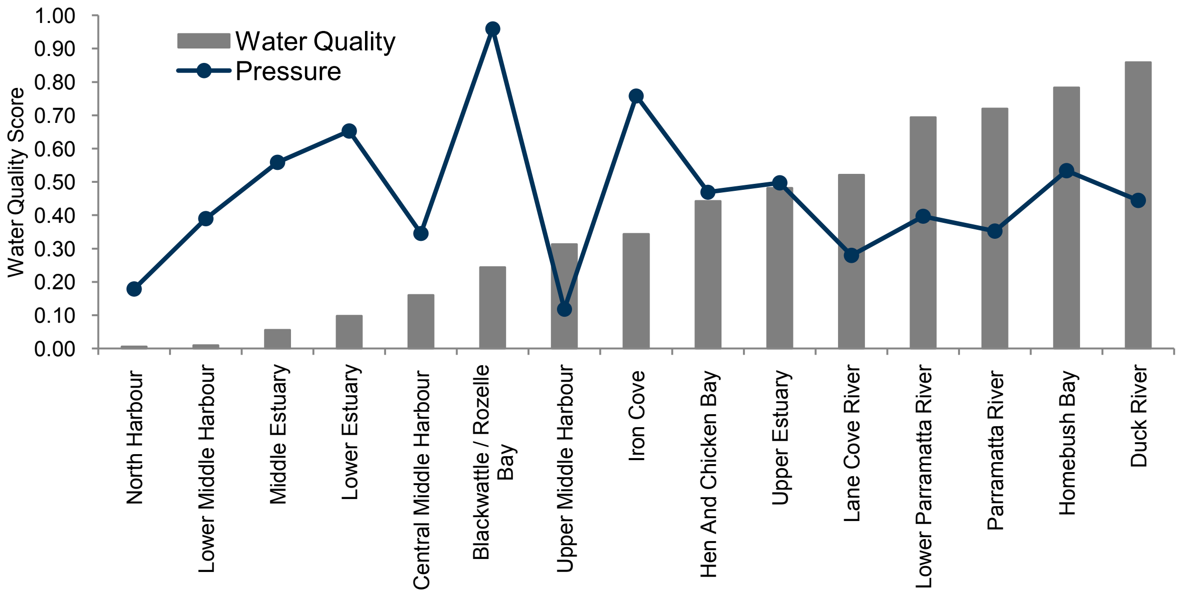


Figure 40: Relationship between water quality and catchment pressures.

4.4 Identification of Priority Sub-catchment / Sub-estuary Systems

Based on the assessment grades of the local assessment scheme, each sub-catchment/sub-estuary has been assigned a management priority classification according to the following scheme:

- Low Priority (A+ to A-);
- Medium Low Priority (B+ to B-);

- Medium High Priority (C+ to C-); and
- High Priority (D+ to F).

Management priorities for the 15 sub-catchment/sub-estuary systems are provided in Table 11.

Table 11: Management priorities derived for Sydney estuary.

Sub-estuary	Overall Priority	Sediment Quality Priority	Water Quality Priority
Duck River	High	Medium High	High
Homebush Bay	High	Medium High	High
Iron Cove	High	High	Medium Low
Blackwattle / Rozelle Bay	High	High	Medium Low
Upper Estuary	Medium High	Medium High	Medium High
Lower Parramatta River	Medium High	Medium Low	High
Parramatta River	Medium High	Low	High
Hen And Chicken Bay	Medium High	High	Medium Low
Lower Estuary	Medium Low	Low	Low
Middle Estuary	Medium Low	Medium Low	Low
Lane Cove River	Medium Low	Low	Medium High
Central Middle Harbour	Medium Low	Medium High	Low
Upper Middle Harbour	Low	Low	Medium Low
Lower Middle Harbour	Low	Low	Low
North Harbour	Low	Low	Low

4.5 Management Implications

In Australia, considerable pressures are being exerted on estuaries in urbanised catchments due to increasing coastal populations (Hutson, 2005). Despite recent improvements, the lack of a clear, consistent management approach has limited the effectiveness of estuarine management and has led to the degradation of these important coastal environments (Birch and Taylor, 2004).

Application of the current local assessment scheme provides estuarine managers with a tool to assist in the identification of 'priority' sub-catchment/sub-estuary systems, as well as areas and issues of concern. This is achieved through a multi-tiered assessment of individual sub-catchment/sub-estuary systems that evaluates catchment pressures and estuarine condition, including sediment and water quality.

An ability to prioritise estuarine management improves the efficiency of management actions and facilitates the development of effective, appropriate and targeted long-term management strategies. An understanding of the relationships between catchment pressures and estuarine condition may also be used to identify the source and pathways of contamination to an estuary, allowing appropriate management actions to be developed.

The value of the local assessment scheme may also be enhanced through the use of a letter grade format which conveys scientific information and key beneficial information in a readily-understood manner to the public. The use of letter grades also provides benchmarking and performance monitoring ability, allowing estuarine managers to set improvement targets and assesses the progress of management strategies. Letter grades have proved successful in informing the public in an easily recognised and understandable form (SEQ Healthy Waterways, 2013).

Results generated from the local assessment have demonstrated the ability of the scheme to provide a reliable assessment of estuarine condition. Its use as a decision support tool would provide the basis of informed management decisions, advancing the efficient management of urbanised estuarine environments.

5 Conclusion

Estuarine environments in Australia and worldwide, particularly those in urban areas, are frequently degraded by a history of modification and contamination. Due to the importance of estuarine environments for environmental, social and economic functions, appropriate management is critical. Historically, limited responsibility, accountability and lack of a defined management structure have restricted the effectiveness of estuarine management in Australia.

The current local assessment scheme was developed as a secondary assessment in a hierarchal assessment scheme, designed to provide reliable, science-based information to facilitate the efficient and effective allocation of limited management resources in ‘severely modified’ NSW catchment/estuary systems. The current study addressed a number of limitations identified in existing assessment schemes, using high-value environmental indicators to minimise confounding by temporal and spatial variability. Careful selection of indicators, coupled with the simplistic transformation of data using fuzzy logic, ensured the generation of accurate and reliable results, reflective of real-world conditions.

The development of a robust assessment framework, with an emphasis on causal relationships between catchment pressures and estuarine conditions, may be used as a method of determining the relative influence of anthropogenic impact. The separate assessment of water quality and sediment quality allows for differentiation and targeted management of these specific issues.

Indicator weightings have potential to be used in estuarine assessment schemes. However, as demonstrated by Gunns (2011), the use of indicator weights was found to distort the results of the current assessment. Indicator weights were therefore excluded from the present assessment of Sydney estuary. Weightings may be applied to the current scheme at any time by however their ability to distort the results of the assessment should be recognised.

Overall results of the local assessment identified Blackwattle/Rozelle Bay, Iron Cove, Hen and Chicken Bay and Homebush Bay as the most heavily impacted and were designated ‘high priority’ for management action. These sub-estuaries are located within proximity to the Sydney CBD and have an extensive history of urbanisation and industrial activity. North Harbour, Upper Middle Harbour and Lower Middle Harbour were in the best condition and were designated ‘low priority’.

Management priorities varied for water quality and sediment quality with Duck River, Homebush Bay, Parramatta River and Duck River classified as ‘high priority’ due to poor water quality. Whereas Blackwattle/Rozelle Bay, Iron Cove and Hen and Chicken Bay were designated as ‘high priority’ due to high levels of sediment contamination.

The local assessment scheme developed in the current study provides estuary managers and decision makers with the ability to prioritise site management, identify issues and areas of concern and allow goal setting and performance monitoring. This assessment scheme is a unique and effective decision support tool that will assist in the successful and efficient management of severely modified estuaries and potentially the management of degraded estuarine systems worldwide.

Chapter 4: Conclusions

1 Conclusions

Estuarine environments in Australia and worldwide, particularly those associated with large-urban areas, are often degraded as a consequence of significant anthropogenic pressures. As one of the richest and most diverse coastal environments, estuaries provide key environmental, social and economic functions. As coastal populations increase, considerable pressures are exerted on estuaries making appropriate management of these sensitive environments essential. The current study has developed a hierarchal scheme, involving both a regional and local assessment. The scheme is a tool to provide accurate, science-based information to facilitate the efficient and targeted allocation of limited management resources.

A review of state and national estuarine assessment schemes revealed the value of these schemes is often limited by the structure of the assessment, selection of environmental indicators and the management of data. To facilitate effective and targeted allocation of management resources, there must be an effective, integrated and regionally consistent approach to estuarine assessment and management. To address these issues, the current scheme makes several improvements to provide an accurate and reliable assessment of estuarine condition.

A primary limitation of many environmental indicators is the potential for confounding as a consequence of natural spatial and temporal variance. This natural variation makes it difficult to identify and quantify the human-induced component of change. Consequently, high-value environmental indicators, not confounded by natural spatial and temporal limitations, were employed in the current study to provide accurate and reliable science-based information.

Traditional ordinal methods of indicator assessment were abandoned, with fuzzy logic successfully applied in the current scheme. The use of fuzzy logic provided a simple and effective method of indicator assessment whilst maintaining information value and data integrity through the assessment process.

Indicator weightings have been previously used in estuarine assessment schemes. However, the use of indicator weights may act to distort the results of the assessment as a consequence of bias introduced in the determination of weighted values. Indicator weights were therefore excluded from the current scheme. Weightings may be applied to the current scheme, however the ability of weighted scores to misrepresent assessment results should be recognised.

The frameworks developed for the regional and local assessment scheme were based on the Pressure-State-Response model and provided a simple, yet robust assessment of estuarine condition. The regional and local frameworks were designed to maximise the use of high-value environmental indicators and provided a method by which causal relationships between catchment pressures and estuarine condition may be identified. Coupled with the simplistic transformation of data using fuzzy logic, the regional and local assessment schemes provided a robust and relevant assessment of estuarine condition.

The regional assessment scheme formed the preliminary component of estuarine assessment, providing an initial quantitative assessment of 38 estuarine in central NSW. Five classes of estuarine condition were identified: near pristine, slightly modified, modified, highly modified and severely modified. Estuarine systems classified as 'severely modified' (Dee Why Lagoon, Curl Curl Lagoon, Manly Lagoon, Sydney Estuary and Cooks River) in the regional assessment were selected for detailed evaluation under a local assessment scheme, with Sydney estuary used as a case study for systems in this category.

The local assessment formed the secondary component of the hierarchal scheme, providing a detailed intra-estuary assessment of catchment pressures and estuarine condition. The local assessment of Sydney estuary revealed that Blackwattle/Rozelle Bay, Iron Cove, Homebush Bay and Duck River were heavily degraded with water quality being of particular concern in Duck River, Homebush Bay, Parramatta River and Lower Parramatta River. Poor sediment quality was identified in Blackwattle/Rozelle Bay, Iron Cove and Hen and Chicken Bay. North Harbour, Upper Middle Harbour and Lower Middle Harbour were found to be in the best condition.

Results of the assessments were presented in a report card format using letter grades to indicate the relative condition of an estuarine system. The use of report cards is a valuable tool to convey scientific information in a readily understood manner to estuarine managers and members of the public. Letter grades also provide benchmarking and performance monitoring ability, allowing estuarine managers to set improvement targets and assesses the effectiveness of management strategies.

The absence of a consistent management structure and lack of accountability has historically limited the effectiveness of estuarine management in Australia and has led to the degradation of these coastal environments. Consequently, there is a need for a consistent management approach, involving the development of an effective assessment of estuarine environments to guide estuarine managers in the formation of effective management decisions and to facilitate the efficient distribution of limited management resources. The hierarchal assessment scheme developed in the current study is an effective, intergraded and consistent assessment of estuarine health, unhindered by natural spatial and temporal variance. This scheme, involving the regional and local assessment of estuaries, is a valuable decision support tool, improving the targeted and effective management of Australian estuarine environments

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Appendix A

Regional Assessment Scheme Score Card

AVOCA LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	24.17	0.18	A+
	Population Density (people/Ha)	62.96	0.03	11.73	0.08	
				Pressure Score	0.13	
Condition	Benthic Health Index	3.05	0.10	0.31	0.01	A+
	Human Impact Index	37.28	1.11	2.08	0.00	
				Condition Score	0.01	
				Assessment Score	0.07	A+

BOTANY BAY - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	41.70	0.46	C-
	Population Density (people/Ha)	62.96	0.03	45.99	0.83	
				Pressure Score	0.65	
Condition	Benthic Health Index	3.05	0.10	0.27	0.01	A+
	Human Impact Index	37.28	1.11	4.96	0.03	
				Condition Score	0.02	
				Assessment Score	0.33	B

BRISBANE WATER - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	44.25	0.51	B+
	Population Density (people/Ha)	62.96	0.03	16.76	0.16	
				Pressure Score	0.34	
Condition	Benthic Health Index	3.05	0.10	0.49	0.04	A+
	Human Impact Index	37.28	1.11	2.98	0.01	
				Condition Score	0.02	
				Assessment Score	0.18	A

BURRIL LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	3.91	0.00	A+
	Population Density (people/Ha)	62.96	0.03	3.50	0.01	
				Pressure Score	0.01	
Condition	Benthic Health Index	3.05	0.10	0.50	0.05	A+
	Human Impact Index	37.28	1.11	1.96	0.00	
				Condition Score	0.02	
				Assessment Score	0.01	A+

COCKROAN LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	10.35	0.03	A+
	Population Density (people/Ha)	62.96	0.03	6.96	0.03	
				Pressure Score	0.03	
Condition	Benthic Health Index	3.05	0.10	0.26	0.01	A+
	Human Impact Index	37.28	1.11	3.08	0.01	
				Condition Score	0.01	
				Assessment Score	0.02	A+

COOKS RIVER - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	87.39	1.00	F
	Population Density (people/Ha)	62.96	0.03	61.79	1.00	
				Pressure Score	1.00	
Condition	Benthic Health Index	3.05	0.10	3.05	1.00	F
	Human Impact Index	37.28	1.11	27.85	0.84	
				Condition Score	0.92	
				Assessment Score	0.96	F

CURL CURL LAGOON - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	79.38	0.98	D+
	Population Density (people/Ha)	62.96	0.03	32.05	0.51	
				Pressure Score	0.75	
Condition	Benthic Health Index	3.05	0.10	2.54	0.93	F
	Human Impact Index	37.28	1.11	37.28	1.00	
				Condition Score	0.96	
				Assessment Score	0.86	D-

DEE WHY LAGOON - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	85.85	1.00	F
	Population Density (people/Ha)	62.96	0.03	62.96	1.00	
				Pressure Score	1.00	
Condition	Benthic Health Index	3.05	0.10	1.30	0.35	B-
	Human Impact Index	37.28	1.11	19.59	0.52	
				Condition Score	0.44	
				Assessment Score	0.72	D+

DURRAS LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	0.44	0.00	A+
	Population Density (people/Ha)	62.96	0.03	0.32	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.28	0.01	A+
	Human Impact Index	37.28	1.11	1.19	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

GEORGES RIVER - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	35.02	0.35	B-
	Population Density (people/Ha)	62.96	0.03	34.07	0.56	
				Pressure Score	0.46	
Condition	Benthic Health Index	3.05	0.10	1.30	0.36	A-
	Human Impact Index	37.28	1.11	6.32	0.05	
				Condition Score	0.20	
				Assessment Score	0.33	B+

HAWKESBURY RIVER - SCORING						
	Indicator	Max		Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	3.51	0.00	A
	Population Density (people/Ha)	62.96	0.03	16.21	0.15	
				Pressure Score	0.08	
Condition	Benthic Health Index	3.05	0.10	0.58	0.06	A+
	Human Impact Index	37.28	1.11	1.92	0.00	
				Condition Score	0.03	
				Assessment Score	0.06	A+

HUNTER RIVER - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	7.34	0.02	A+
	Population Density (people/Ha)	62.96	0.03	14.36	0.12	
				Pressure Score	0.07	
Condition	Benthic Health Index	3.05	0.10	0.75	0.12	A
	Human Impact Index	37.28	1.11	6.62	0.06	
				Condition Score	0.09	
				Assessment Score	0.08	A

KARUAH RIVER - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	0.61	0.00	A+
	Population Density (people/Ha)	62.96	0.03	0.16	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.17	0.00	A+
	Human Impact Index	37.28	1.11	1.88	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

LAKE CONJOLA - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	1.64	0.00	A+
	Population Density (people/Ha)	62.96	0.03	1.26	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.26	0.01	A+
	Human Impact Index	37.28	1.11	1.98	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

LAKE ILLWARRA - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	15.70	0.08	A
	Population Density (people/Ha)	62.96	0.03	17.93	0.19	
				Pressure Score	0.13	
Condition	Benthic Health Index	3.05	0.10	0.67	0.09	A+
	Human Impact Index	37.28	1.11	2.27	0.00	
				Condition Score	0.05	
				Assessment Score	0.09	A

LAKE MAQUARIE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	18.24	0.10	A+
	Population Density (people/Ha)	62.96	0.03	11.90	0.09	
				Pressure Score	0.09	
Condition	Benthic Health Index	3.05	0.10	1.73	0.58	B-
	Human Impact Index	37.28	1.11	13.86	0.28	
				Condition Score	0.43	
				Assessment Score	0.26	B+

MANLY LAGOON - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	62.18	0.81	D
	Population Density (people/Ha)	62.96	0.03	39.34	0.69	
				Pressure Score	0.75	
Condition	Benthic Health Index	3.05	0.10	2.66	0.96	C
	Human Impact Index	37.28	1.11	10.68	0.16	
				Condition Score	0.56	
				Assessment Score	0.65	C-

MEROO LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	0.00	0.00	A+
	Population Density (people/Ha)	62.96	0.03	0.03	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.10	0.00	A+
	Human Impact Index	37.28	1.11	2.15	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

MYALL LAKES - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	0.90	0.00	A+
	Population Density (people/Ha)	62.96	0.03	1.82	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.27	0.01	A+
	Human Impact Index	37.28	1.11	1.35	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

NARRABEEN LAGOON - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	52.98	0.66	B-
	Population Density (people/Ha)	62.96	0.03	24.81	0.34	
				Pressure Score	0.50	
Condition	Benthic Health Index	3.05	0.10	0.57	0.06	A+
	Human Impact Index	37.28	1.11	4.86	0.03	
				Condition Score	0.04	
				Assessment Score	0.27	B+

PITTWATER - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	35.12	0.35	A-
	Population Density (people/Ha)	62.96	0.03	17.77	0.18	
				Pressure Score	0.27	
Condition	Benthic Health Index	3.05	0.10	0.66	0.08	A
	Human Impact Index	37.28	1.11	8.20	0.09	
				Condition Score	0.09	
				Assessment Score	0.18	A

PORT HACKING - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	14.74	0.07	B+
	Population Density (people/Ha)	62.96	0.03	32.67	0.53	
				Pressure Score	0.30	
Condition	Benthic Health Index	3.05	0.10	0.93	0.18	A
	Human Impact Index	37.28	1.11	9.17	0.12	
				Condition Score	0.15	
				Assessment Score	0.22	A-

PORT STEPHENS - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	2.86	0.00	A+
	Population Density (people/Ha)	62.96	0.03	6.16	0.02	
				Pressure Score	0.01	
Condition	Benthic Health Index	3.05	0.10	0.18	0.00	A+
	Human Impact Index	37.28	1.11	1.83	0.00	
				Condition Score	0.00	
				Assessment Score	0.01	A+

SALTWATER CREEK - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	24.73	0.18	A+
	Population Density (people/Ha)	62.96	0.03	1.51	0.00	
				Pressure Score	0.09	
Condition	Benthic Health Index	3.05	0.10	0.10	0.00	A+
	Human Impact Index	37.28	1.11	1.14	0.00	
				Condition Score	0.00	
				Assessment Score	0.05	A+

SHOALHAVEN RIVER - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	3.85	0.00	A+
	Population Density (people/Ha)	62.96	0.03	4.62	0.01	
				Pressure Score	0.01	
Condition	Benthic Health Index	3.05	0.10	0.18	0.00	A+
	Human Impact Index	37.28	1.11	1.86	0.00	
				Condition Score	0.00	
				Assessment Score	0.01	A+

TILLIRGERY CREEK - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	13.80	0.06	A+
	Population Density (people/Ha)	62.96	0.03	6.70	0.03	
				Pressure Score	0.04	
Condition	Benthic Health Index	3.05	0.10	0.22	0.00	A+
	Human Impact Index	37.28	1.11	1.96	0.00	
				Condition Score	0.00	
				Assessment Score	0.02	A+

TUGGERAH LAKES - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Catchment Landuse Index (Index)	87.39	0.00	8.92	0.03	A
	Population Density (people/Ha)	62.96	0.03	14.88	0.13	
				Pressure Score	0.08	
Condition	Benthic Health Index	3.05	0.10	0.44	0.03	A+
	Human Impact Index	37.28	1.11	2.92	0.01	
				Condition Score	0.02	
				Assessment Score	0.05	A+

TUROSS LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	1.65	0.00	A+
	Population Density (people/Ha)	62.96	0.03	2.17	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.13	0.00	A+
	Human Impact Index	37.28	1.11	1.51	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

WAGONGA INLET - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	3.94	0.01	A+
	Population Density (people/Ha)	62.96	0.03	3.56	0.01	
				Pressure Score	0.01	
Condition	Benthic Health Index	3.05	0.10	0.29	0.01	A+
	Human Impact Index	37.28	1.11	1.61	0.00	
				Condition Score	0.01	
				Assessment Score	0.01	A+

WALLAGA LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	1.13	0.00	A+
	Population Density (people/Ha)	62.96	0.03	1.20	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.37	0.02	A+
	Human Impact Index	37.28	1.11	1.28	0.00	
				Condition Score	0.01	
				Assessment Score	0.01	A+

SMITHS LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	6.37	0.01	A+
	Population Density (people/Ha)	62.96	0.03	1.11	0.00	
				Pressure Score	0.01	
Condition	Benthic Health Index	3.05	0.10	0.16	0.00	A+
	Human Impact Index	37.28	1.11	1.88	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

ST GEORGES BASIN REPORT CARD - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	5.57	0.01	A+
	Population Density (people/Ha)	62.96	0.03	6.86	0.03	
				Pressure Score	0.02	
Condition	Benthic Health Index	3.05	0.10	0.20	0.00	A+
	Human Impact Index	37.28	1.11	2.28	0.00	
				Condition Score	0.00	
				Assessment Score	0.01	A+

SWAN LAKE - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	3.04	0.00	A+
	Population Density (people/Ha)	62.96	0.03	1.30	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.23	0.00	A+
	Human Impact Index	37.28	1.11	1.87	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

SYDNEY ESTUARY - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	78.20	0.97	F
	Population Density (people/Ha)	62.96	0.03	60.58	1.00	
				Pressure Score	0.98	
Condition	Benthic Health Index	3.05	0.10	2.76	0.98	C-
	Human Impact Index	37.28	1.11	15.46	0.34	
				Condition Score	0.66	
				Assessment Score	0.82	D

TERRIGAL LAGOON - SCORING						
	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	42.97	0.49	A-
	Population Density (people/Ha)	62.96	0.03	15.12	0.14	
				Pressure Score	0.31	
Condition	Benthic Health Index	3.05	0.10	0.21	0.00	A+
	Human Impact Index	37.28	1.11	5.00	0.03	
				Condition Score	0.02	
				Assessment Score	0.16	A

WALLIS LAKE - SCORING

	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	2.52	0.00	A+
	Population Density (people/Ha)	62.96	0.03	7.11	0.03	
				Pressure Score	0.02	
Condition	Benthic Health Index	3.05	0.10	0.15	0.00	A+
	Human Impact Index	37.28	1.11	1.36	0.00	
				Condition Score	0.00	
				Assessment Score	0.01	A+

WAMBERAL LAGOON - SCORING

	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Catchment Landuse Index (Index)	87.39	0.00	33.99	0.33	B+
	Population Density (people/Ha)	62.96	0.03	13.95	0.12	
				Pressure Score	0.22	
Condition	Benthic Health Index	3.05	0.10	0.37	0.02	A+
	Human Impact Index	37.28	1.11	2.29	0.00	
				Condition Score	0.01	
				Assessment Score	0.12	A

WILLINGA LAKE - SCORING

	Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure	Urbanised Catchment Area (%)	87.39	0.00	1.33	0.00	A+
	Population Density (people/Ha)	62.96	0.03	0.54	0.00	
				Pressure Score	0.00	
Condition	Benthic Health Index	3.05	0.10	0.14	0.00	A+
	Human Impact Index	37.28	1.11	1.11	0.00	
				Condition Score	0.00	
				Assessment Score	0.00	A+

Appendix B

Local Assessment Scheme Results

1 - LOWER ESTUARY							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	80.67	0.75	C-
		Population Density (people/Ha)	139.95	19.93	95.24	0.69	
		Metal Enrichment in Catchment Soils	12.52	2.84	6.42	0.30	
		Creek and River Riparian Health (Index)	9.00	2.54	8.77	1.00	
		Estuary Reclamation (%)	74.16	1.48	5.21	0.01	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	134.48	0.66	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1778.79	0.98	
		TP Yield (Kg/Km2/Year)	318.7	146.6	272.90	0.84	
					Pressure Score	0.65	
Condition	Water Quality	Water Quality - TN	100.00	18.18	39.47	0.16	A
		Water Quality - TP	100.00	9.09	36.84	0.21	
		Water Quality - Turbidity	54.55	0.00	0.00	0.00	
		Water Quality - Chlorophyll-a	71.43	0.00	9.52	0.04	
		Water Quality - DO	83.33	0.00	15.00	0.08	
					Water Quality Score	0.10	
	Sediment Quality	Benthic Health Index	5.46	0.45	1.70	0.15	B+
		Human Impact Index (HII)	27.59	6.67	11.91	0.15	
					Sediment Quality Score	0.15	
					Overall Condition Score	0.11	A-
					Assessment Score	0.38	B-

2 - MIDDLE ESTUARY							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	83.01	0.83	C
		Population Density (people/Ha)	139.95	19.93	60.90	0.26	
		Metal Enrichment in Catchment Soils	12.52	2.84	6.49	0.31	
		Riparian Health (Index)	9.00	2.54	6.53	0.68	
		Estuary Reclamation (%)	74.16	1.48	9.94	0.03	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	132.13	0.61	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1716.40	0.96	
		TP Yield (Kg/Km2/Year)	318.7	146.6	266.30	0.79	
					Pressure Score	0.56	
Condition	Water Quality	Water Quality - TN	100.00	18.18	18.75	0.00	A+
		Water Quality - TP	100.00	9.09	28.13	0.10	
		Water Quality - Turbidity	54.55	0.00	3.03	0.01	
		Water Quality - Chlorophyll-a	71.43	0.00	12.50	0.07	
		Water Quality - DO	83.33	0.00	16.67	0.10	
					Water Quality Score	0.06	
	Sediment Quality	Benthic Health Index (BHI)	5.46	0.45	2.75	0.44	C+
		Human Impact Index	27.59	6.67	14.81	0.33	
					Sediment Quality Score	0.38	
					Overall Condition Score	0.15	A-
					Assessment Score	0.35	B-

3 - UPPER ESTUARY							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	79.55	0.71	C+
		Population Density (people/Ha)	139.95	19.93	43.27	0.09	
		Metal Enrichment in Catchment Soils	12.52	2.84	9.02	0.71	
		Riparian Health (Index)	9.00	2.54	9.00	1.00	
		Estuary Reclamation (%)	74.16	1.48	13.38	0.06	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	109.12	0.10	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1576.40	0.90	
		TP Yield (Kg/Km2/Year)	318.7	146.6	222.20	0.41	
					Pressure Score	0.50	
Condition	Water Quality	Water Quality - TN	100.00	18.18	54.55	0.41	C+
		Water Quality - TP	100.00	9.09	90.91	0.98	
		Water Quality - Turbidity	54.55	0.00	5.88	0.03	
		Water Quality - Chlorophyll-a	71.43	0.00	57.14	0.90	
		Water Quality - DO	83.33	0.00	15.79	0.09	
					Water Quality Score	0.48	
	Sediment Quality	Benthic Health Idex (BHI)	5.46	0.45	3.30	0.61	C-
		Human Impact Index	27.59	6.67	14.74	0.32	
					Sediment Quality Score	0.47	
					Overall Condition Score	0.48	C+
					Assessment Score	0.49	C+

4 - LOWER PARRAMATTA RIVER							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	65.96	0.16	B-
		Population Density (people/Ha)	139.95	19.93	38.82	0.06	
		Metal Enrichment in Catchment Soils	12.52	2.84	5.25	0.15	
		Riparian Health (Index)	9.00	2.54	8.45	0.98	
		Estuary Reclamation (%)	74.16	1.48	57.12	0.87	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	99.67	0.01	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1335.80	0.74	
		TP Yield (Kg/Km2/Year)	318.7	146.6	199.40	0.21	
					Pressure Score	0.40	
Condition	Water Quality	Water Quality - TN	100.00	18.18	90.91	0.97	D+
		Water Quality - TP	100.00	9.09	100.00	1.00	
		Water Quality - Turbidity	54.55	0.00	54.55	1.00	
		Water Quality - Chlorophyll-a	71.43	0.00	0.00	0.00	
		Water Quality - DO	83.33	0.00	41.67	0.50	
					Water Quality Score	0.69	
	Sediment Quality	Benthic Health Index (BHI)	5.46	0.45	2.76	0.44	C+
		Human Impact Index	27.59	6.67	11.97	0.15	
					Sediment Quality Score	0.29	
					Overall Condition Score	0.58	C
					Assessment Score	0.49	C+

5 - LANE COVE RIVER							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	74.17	0.48	B+
		Population Density (people/Ha)	139.95	19.93	33.15	0.03	
		Metal Enrichment in Catchment Soils	12.52	2.84	4.78	0.10	
		Riparian Health (Index)	9.00	2.54	5.26	0.38	
		Estuary Reclamation (%)	74.16	1.48	14.20	0.07	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	105.47	0.06	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1437.40	0.81	
		TP Yield (Kg/Km2/Year)	318.7	146.6	211.70	0.31	
					Pressure Score	0.28	
Condition	Water Quality	Water Quality - TN	100.00	18.18	60.00	0.52	C+
		Water Quality - TP	100.00	9.09	92.31	0.98	
		Water Quality - Turbidity	54.55	0.00	3.03	0.01	
		Water Quality - Chlorophyll-a	71.43	0.00	43.48	0.67	
		Water Quality - DO	83.33	0.00	38.03	0.43	
					Water Quality Score	0.52	
	Sediment Quality	Benthic Health Index	5.46	0.45	2.15	0.26	A
		Human Impact Index	27.59	6.67	9.14	0.03	
					Sediment Quality Score	0.15	
					Overall Condition Score	0.41	B
					Assessment Score	0.35	B

6 - PARRAMATTA RIVER							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	79.79	0.71	B
		Population Density (people/Ha)	139.95	19.93	32.41	0.03	
		Metal Enrichment in Catchment Soils	12.52	2.84	6.84	0.37	
		Riparian Health (Index)	9.00	2.54	6.48	0.67	
		Estuary Reclamation (%)	74.16	1.48	15.24	0.09	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	99.48	0.01	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1319.50	0.73	
		TP Yield (Kg/Km2/Year)	318.7	146.6	200.40	0.22	
					Pressure Score	0.35	
Condition	Water Quality	Water Quality - TN	100.00	18.18	100.00	1.00	D+
		Water Quality - TP	100.00	9.09	87.50	0.95	
		Water Quality - Turbidity	54.55	0.00	33.33	0.67	
		Water Quality - Chlorophyll-a	71.43	0.00	0.00	0.00	
		Water Quality - DO	83.33	0.00	75.00	0.98	
					Water Quality Score	0.72	
	Sediment Quality	Benthic Health Index	5.46	0.45	2.34	0.31	B+
		Human Impact Index	27.59	6.67	10.22	0.07	
					Sediment Quality Score	0.19	
					Overall Condition Score	0.57	C
					Assessment Score	0.46	B-

7 - DUCK RIVER							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	85.15	0.90	B-
		Population Density (people/Ha)	139.95	19.93	44.53	0.10	
		Metal Enrichment in Catchment Soils	12.52	2.84	7.39	0.45	
		Riparian Health (Index)	9.00	2.54	8.47	0.98	
		Estuary Reclamation (%)	74.16	1.48	15.24	0.09	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	104.73	0.05	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1341.30	0.74	
		TP Yield (Kg/Km2/Year)	318.7	146.6	203.90	0.25	
					Pressure Score	0.44	
Condition	Water Quality	Water Quality - TN	100.00	18.18	100.00	1.00	D-
		Water Quality - TP	100.00	9.09	100.00	1.00	
		Water Quality - Turbidity	54.55	0.00	27.27	0.50	
		Water Quality - Chlorophyll-a	71.43	0.00	50.00	0.79	
		Water Quality - DO	83.33	0.00	83.33	1.00	
					Water Quality Score	0.86	
	Sediment Quality	Benthic Health Index (BHI)	5.46	0.45	2.86	0.47	C
		Human Impact Index	27.59	6.67	16.64	0.46	
					Sediment Quality Score	0.47	
					Overall Condition Score	0.75	D
					Assessment Score	0.60	C

8 - HOMEBUSH BAY							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	73.89	0.47	C+
		Population Density (people/Ha)	139.95	19.93	53.15	0.18	
		Metal Enrichment in Catchment Soils	12.52	2.84	7.54	0.48	
		Riparian Health (Index)	9.00	2.54	8.79	1.00	
		Estuary Reclamation (%)	74.16	1.48	74.16	1.00	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	107.19	0.08	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1372.60	0.77	
		TP Yield (Kg/Km2/Year)	318.7	146.6	211.50	0.31	
					Pressure Score	0.53	
Condition	Water Quality	Water Quality - TN	100.00	18.18	90.91	0.97	D
		Water Quality - TP	100.00	9.09	100.00	1.00	
		Water Quality - Turbidity	54.55	0.00	27.27	0.50	
		Water Quality - Chlorophyll-a	71.43	0.00	50.00	0.79	
		Water Quality - DO	83.33	0.00	50.00	0.65	
					Water Quality Score	0.78	
	Sediment Quality	Benthic Health Index (BHI)	5.46	0.45	3.48	0.66	C+
		Human Impact Index (HII)	27.59	6.67	14.68	0.32	
					Sediment Quality Score	0.49	
					Overall Condition Score	0.70	C-
					Assessment Score	0.62	C

9 - HEN AND CHICKEN BAY							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	83.74	0.85	C+
		Population Density (people/Ha)	139.95	19.93	43.96	0.10	
		Metal Enrichment in Catchment Soils	12.52	2.84	7.24	0.43	
		Riparian Health (Index)	9.00	2.54	9.00	1.00	
		Estuary Reclamation (%)	74.16	1.48	32.50	0.39	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	121.07	0.34	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	159.60	0.00	
		TP Yield (Kg/Km2/Year)	318.7	146.6	249.10	0.65	
					Pressure Score	0.47	
Condition	Water Quality	Water Quality - TN	100.00	18.18	45.45	0.25	B-
		Water Quality - TP	100.00	9.09	100.00	1.00	
		Water Quality - Turbidity	54.55	0.00	0.00	0.00	
		Water Quality - Chlorophyll-a	71.43	0.00	60.00	0.94	
		Water Quality - DO	83.33	0.00	8.33	0.02	
					Water Quality Score	0.44	
	Sediment Quality	Benthic Health Index (BHI)	5.46	0.45	4.52	0.92	D+
		Human Impact Index	27.59	6.67	22.77	0.87	
					Sediment Quality Score	0.90	
					Overall Condition Score	0.57	C
					Assessment Score	0.52	C+

10 - IRON COVE							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	91.78	1.00	D+
		Population Density (people/Ha)	139.95	19.93	54.00	0.19	
		Metal Enrichment in Catchment Soils	12.52	2.84	12.52	1.00	
		Riparian Health (Index)	9.00	2.54	9.00	1.00	
		Estuary Reclamation (%)	74.16	1.48	29.47	0.32	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	136.77	0.71	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1791.60	0.98	
		TP Yield (Kg/Km2/Year)	318.7	146.6	276.70	0.86	
					Pressure Score	0.76	
Condition	Water Quality	Water Quality - TN	100.00	18.18	27.27	0.03	B
		Water Quality - TP	100.00	9.09	100.00	1.00	
		Water Quality - Turbidity	54.55	0.00	0.00	0.00	
		Water Quality - Chlorophyll-a	71.43	0.00	40.00	0.59	
		Water Quality - DO	83.33	0.00	16.67	0.10	
					Water Quality Score	0.34	
	Sediment Quality	Benthic Health Index	5.46	0.45	4.79	0.96	F
		Human Impact Index	27.59	6.67	23.33	0.90	
					Sediment Quality Score	0.93	
					Overall Condition Score	0.51	C
					Assessment Score	0.63	C-

11 - BLACKWATTLE / ROZELLE BAY							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	92.72	1.00	F
		Population Density (people/Ha)	139.95	19.93	139.95	1.00	
		Metal Enrichment in Catchment Soils	12.52	2.84	11.55	0.98	
		Riparian Health (Index)	9.00	2.54	9.00	1.00	
		Estuary Reclamation (%)	74.16	1.48	47.42	0.70	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	159.75	1.00	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1946.60	1.00	
		TP Yield (Kg/Km2/Year)	318.7	146.6	318.70	1.00	
					Pressure Score	0.96	
Condition	Water Quality	Water Quality - TN	100.00	18.18	40.00	0.17	B+
		Water Quality - TP	100.00	9.09	60.00	0.59	
		Water Quality - Turbidity	54.55	0.00	0.00	0.00	
		Water Quality - Chlorophyll-a	71.43	0.00	30.77	0.39	
		Water Quality - DO	83.33	0.00	14.29	0.07	
					Water Quality Score	0.24	
	Sediment Quality	Benthic Health Index	5.46	0.45	5.46	1.00	F
		Human Impact Index	27.59	6.67	27.59	1.00	
					Sediment Quality Score	1.00	
					Overall Condition Score	0.46	C+
					Assessment Score	0.71	D+

12 - UPPER MIDDLE HARBOUR							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	56.66	0.00	A
		Population Density (people/Ha)	139.95	19.93	19.93	0.00	
		Metal Enrichment in Catchment Soils	12.52	2.84	3.41	0.01	
		Riparian Health (Index)	9.00	2.54	2.54	0.00	
		Estuary Reclamation (%)	74.16	1.48	5.08	0.01	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	95.71	0.00	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1352.10	0.75	
		TP Yield (Kg/Km2/Year)	318.7	146.6	194.20	0.18	
					Pressure Score	0.12	
Condition	Water Quality	Water Quality - TN	100.00	18.18	45.45	0.25	B
		Water Quality - TP	100.00	9.09	45.45	0.35	
		Water Quality - Turbidity	54.55	0.00	0.00	0.00	
		Water Quality - Chlorophyll-a	71.43	0.00	7.14	0.02	
		Water Quality - DO	83.33	0.00	70.83	0.95	
					Water Quality Score	0.31	
	Sediment Quality	Benthic Health Index (BHI	5.46	0.45	0.75	0.01	A
		Human Impact Index	27.59	6.67	10.49	0.08	
					Sediment Quality Score	0.04	
					Overall Condition Score	0.24	A-
					Assessment Score	0.18	A-

13 - CENTRAL MIDDLE HARBOUR		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	73.93	0.47	B
		Population Density (people/Ha)	139.95	19.93	54.75	0.19	
		Metal Enrichment in Catchment Soils	12.52	2.84	5.73	0.20	
		Riparian Health (Index)	9.00	2.54	4.77	0.27	
		Estuary Reclamation (%)	74.16	1.48	6.98	0.01	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	95.71	0.00	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1659.40	0.94	
		TP Yield (Kg/Km2/Year)	318.7	146.6	252.80	0.68	
					Pressure Score	0.35	
Condition	Water Quality	Water Quality - TN	100.00	18.18	36.36	0.12	A-
		Water Quality - TP	100.00	9.09	42.42	0.30	
		Water Quality - Turbidity	54.55	0.00	3.03	0.01	
		Water Quality - Chlorophyll-a	71.43	0.00	13.33	0.08	
		Water Quality - DO	83.33	0.00	30.56	0.30	
					Water Quality Score	0.16	
	Sediment Quality	Benthic Health Index (BHI)	5.46	0.45	2.38	0.32	C+
		Human Impact Index	27.59	6.67	22.30	0.85	
					Sediment Quality Score	0.59	
					Overall Condition Score	0.28	B+
					Assessment Score	0.31	B

14 - LOWER MIDDLE HARBOUR		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	78.37	0.66	B-
		Population Density (people/Ha)	139.95	19.93	40.63	0.07	
		Metal Enrichment in Catchment Soils	12.52	2.84	2.84	0.00	
		Riparian Health (Index)	9.00	2.54	5.00	0.32	
		Estuary Reclamation (%)	74.16	1.48	1.48	0.00	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	125.42	0.44	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1706.40	0.96	
		TP Yield (Kg/Km2/Year)	318.7	146.6	251.80	0.67	
					Pressure Score	0.39	
Condition	Water Quality	Water Quality - TN	100.00	18.18	18.18	0.00	A+
		Water Quality - TP	100.00	9.09	18.18	0.02	
		Water Quality - Turbidity	54.55	0.00	0.00	0.00	
		Water Quality - Chlorophyll-a	71.43	0.00	0.00	0.00	
		Water Quality - DO	83.33	0.00	8.33	0.02	
					Water Quality Score	0.01	
	Sediment Quality	Benthic Health Index	5.46	0.45	0.45	0.00	A+
		Human Impact Index	27.59	6.67	6.67	0.00	
					Sediment Quality Score	0.00	
					Overall Condition Score	0.01	A+
					Assessment Score	0.20	A-

15 - NORTH HARBOUR							
		Indicator	Max	Min	Indicator Value	Fuzzy Score	Grade
Pressure		Urbanised Catchment Area (%)	92.72	56.66	61.16	0.04	A-
		Population Density (people/Ha)	139.95	19.93	62.38	0.28	
		Metal Enrichment in Catchment Soils	12.52	2.84	2.85	0.00	
		Riparian Health (Index)	n/a	n/a	n/a	n/a	
		Estuary Reclamation (%)	74.16	1.48	2.38	0.00	
		Average Cu, Pb, Zn Yield (Kg/Km2/Year)	159.75	95.71	107.28	0.08	
		TN Yield (Kg/Km2/Year)	1946.6	159.6	1501.40	0.85	
		TP Yield (Kg/Km2/Year)	318.7	146.6	146.60	0.00	
					Pressure Score	0.18	
Condition	Water Quality	Water Quality - TN	100.00	18.18	27.27	0.03	A+
		Water Quality - TP	100.00	9.09	9.09	0.00	
		Water Quality - Turbidity	54.55	0.00	0.00	0.00	
		Water Quality - Chlorophyll-a	71.43	0.00	0.00	0.00	
		Water Quality - DO	83.33	0.00	0.00	0.00	
					Water Quality Score	0.01	
	Sediment Quality	Benthic Health Index (BHI)	5.46	0.45	0.70	0.01	A+
		Human Impact Index	27.59	6.67	11.49	0.13	
					Sediment Quality Score	0.07	
					Overall Condition Score	0.02	A+
					Assessment Score	0.10	A