A review of Australian approaches for monitoring, assessing and reporting estuarine condition: III. Evaluation against international best practice and recommendations for the future

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Abstract

In this final component of a three-part review, we present a national synthesis and evaluation of approaches for monitoring, assessing and reporting estuarine condition across Australia. Progress is evaluated against objective criteria that together provide a model of international best practice. We critically assess the limitations, inconsistencies and gaps that are evident across Australian jurisdictions, and identify common obstacles to future progress. Major strengths and successes are also highlighted, together with specific examples of best practice from around Australia that are transferable to other States and beyond. Significant obstacles to greater national coordination of monitoring and reporting practices include inconsistent spatial scales of management, pluralistic governance structures and the lack of any overarching legislation. Nonetheless, many perceptible advances have been made over the last decade across Australia in estuarine monitoring and health assessment, and there is great potential for further progress. Finally, we provide a list of recommendations to address some of the most pressing limitations and gaps, and support improved future monitoring, assessment and reporting for Australian estuaries.

Keywords Estuary, ecological status, health, monitoring, management, Water Framework Directive

1. Introduction

The implementation of the European Union (EU) Water Framework Directive (WFD) in 2000 aimed to harmonize fragmented policies for water resource management across Europe under a coordinated legislative framework. It expanded the scope of water protection to both

surface waters (i.e. rivers, lakes, coastal waters, 'transitional waters' such as estuaries and rias) and groundwater, and placed at the forefront of management the goal of protecting the ecological quality of water resources (Chave, 2001; Kallis and Butler, 2001; Hering et al., 2010). By stipulating that water management should be based on river basins, the WFD also seeks to encourage greater coordination of management by replacing systems defined by administrative or political boundaries with those focused on natural geographical and hydrological units (Moss, 2012).

Significantly, the WFD required EU Member States to achieve specific water management objectives by set dates, e.g. achieving 'good chemical and ecological status' for all estuaries and other transitional waters by 2015 (Borja et al., 2012). This has resulted in substantial changes to the assessment, monitoring and reporting of estuarine condition across Europe. The focus on ecological status has engendered a more holistic view of estuarine condition, with 'ecological status' being reflected by five biological quality elements, i.e. phytoplankton, macroinvertebrates, macroalgae, phanerogams, and fishes (Borja et al., 2012). Additionally, the need to define ecological status and the question of how best to quantify it have generated an enormous volume of research to develop and test suitable indicators (Devlin et al., 2007; Schmutz et al., 2007; Pinto et al., 2009; Birk et al., 2012; Pérez-Domínguez et al., 2012). The broad remit of the WFD has also necessitated type-specific reference conditions (Verdonschot, 2006; Hering et al., 2010) and the harmonisation or intercalibration of assessment tools and methodologies (Heiskanen et al., 2004; Birk et al., 2013; Poikane et al., 2014) to enable fair and robust comparison of estuarine status across member States.

As noted by numerous sources, Australian programs for assessing, monitoring and reporting estuarine condition are typically in stark contrast to those described above, with issues around the governance, legislative and funding arrangements for estuarine management, and a lack of appropriate tools and robust data for quantifying estuarine condition and trends (NLWRA, 2002a, b, 2008a, b; Beeton et al., 2006). Consequently, previous assessments of estuary condition across Australia have relied largely upon qualitative criteria (NLWRA, 2002b, 2008b; Beeton et al., 2006; Borja et al., 2012). Borja et al. (2012) suggested, however, that a large number of emerging projects and programs were likely to address this deficiency in the coming years. In part II of the current review (Hallett et al., submitted II), we systematically documented many of these more recent (and existing) programs, providing State-by-State summaries and supporting detailed Appendices, which now provide a sound basis for evaluating recent Australian progress in this area.

Here, in the concluding part of the review, we provide a national-level synthesis of these Australian approaches to assessing, monitoring and reporting estuarine condition and evaluate them against the objective criteria reflecting international best practice that were established in Part I (Hallett et al., submitted I). We document examples of successes, progress and best practice within Australia, as well as notable weaknesses, gaps, inconsistencies and impediments to progress. Finally, we provide some recommendations to improve future understanding and reporting of estuarine health across Australia, couched within a broader adaptive management framework.

2. Synthesis and evaluation of Australian approaches

The following sections are structured to reflect the list of criteria against which Australian approaches were evaluated (Hallett et al., submitted I). These are listed in Table 1, which provides the detailed evaluation and examples of best practice across Australia.

2.1. Context, objectives and design of monitoring programs

Marine and estuarine management worldwide is typically underpinned by some variant of the DAPSI(W)R(M) framework, a recent development of the DPSIR (Drivers–Pressures–State Change–Impact–Response) approach (Atkins et al., 2011; Wolanski and Elliott, 2015). **D**rivers are basic human needs which generate **A**ctivities; these in turn create **P**ressures, as the mechanisms that lead to **S**tate change of the natural system and **I**mpacts on human **W**elfare. The latter changes then require societal **R**esponses, which are often termed **M**easures, and may include engineering approaches or economic or legal instruments. Any successful implementation of this framework will require effective monitoring, assessment and reporting of pressures, state changes and impacts, and effective management responses that target human activities.

Variants of this framework broadly underpin estuarine monitoring and reporting throughout much of Australia (*Criterion 1)*, although the degree to which pressures (sometimes termed stressors) are explicitly quantified and communicated varies greatly among States (Table 1). New South Wales (NSW), for example, is moving towards an integrated strategy that encompasses measurements at each level of the above framework, thus enabling the outcomes of management actions to be assessed and communicated more effectively. However, quantitative data on many relevant pressures and activities are lacking for many estuaries in other States, which has critically hampered development of biotic indicators and the testing of causal relationships between pressures, estuarine state changes

and impacts on human welfare (Arundel et al., 2008; Mount, 2008). Moreover, indicators of human impacts and management responses are rarely employed (Table 1), though several planned or recent programs in Queensland aim to incorporate social and economic indicators into their reporting.

Australian estuarine management programs now commonly employ conceptual models (Fig. 1) as a basis for understanding and managing estuaries, enabling managers to identify key environmental values/assets that require protection, and the threatening processes and pressures that impact on them. This allows specific management objectives to be established, around which the supporting monitoring programs are built, and management actions to be subsequently refined as part of an adaptive approach. The adoption of adaptive management practices, involving iterative cycles of monitoring, evaluation and reporting to address specific management objectives (*Criterion 2*), is an encouraging feature of several recent initiatives across Australia, e.g. the Tamar Estuary and Esk Rivers Ecosystem Health Assessment Program in Tasmania. Most notably, the current NSW Monitoring, Evaluation and Reporting (MER) Strategy (NSW DECCW, 2010) has a strong adaptive management focus and includes a Program Performance strand to ensure management practices are constantly evaluated and improved upon (Table 1). An imperative of this strategy is that monitoring data should be promptly analysed and used adaptively to refine the sampling regime and better address the relevant pressures (Roper et al., 2011).

The international examples considered in part I of this review (Hallett et al., submitted I) highlight the importance of national and international legislation in progressing estuarine monitoring and reporting (*Criterion 3*). In contrast, Australian legislative requirements for assessing, monitoring and reporting estuarine condition are generally fragmented (State of the Environment 2011 Committee, 2011), varying greatly not only between States but often between regions within a State (Table 1). This reflects the vesting of responsibility for the environment primarily with the States under the Australian Constitution (HC Coombs Policy Forum, 2011a), which complicates the development of overarching federal legislation that encompasses all aspects of estuarine management. Resulting impediments are widely documented, and include a lack of clarity of roles and responsibilities among federal, State, regional and local agencies, complex statutory frameworks, and issues around the longevity and stability of funding mechanisms and institutional commitment in the context of political cycles at both State and Commonwealth levels (HC Coombs Policy Forum, 2011a, b). Consequently, estuarine monitoring programs in Australia tend to be relatively short term and

predominantly focussed on systems with existing major issues and high public profiles (Barton, 2003; Hirst, 2008; Table 1).

2.2. Monitoring elements and indicators

The value of holistic, ecologically-relevant approaches for measuring aquatic ecosystem condition is well-established (*Criterion 4*), underpinning legally-mandated directives for estuarine monitoring in Europe, South Africa and the USA. In Australia, several national-level documents and policies have long espoused a need to move toward a more holistic consideration of aquatic ecosystem health (ANZECC and ARMCANZ, 2000a, b). Bioassessment techniques are relatively well established in programs for monitoring river health or condition across Australia (Halse et al., 2002; Parsons et al., 2002; Bunn et al., 2010), e.g. the macroinvertebrate-based Australian River Assessment System (AUSRIVAS; www.ausrivas.ewater.com.au) (ANZECC and ARMCANZ, 2000a, b; Davies, 2000). Yet, Australia has been comparatively slow to apply bioassessment approaches to the monitoring and management of estuaries, with a persistent bias towards monitoring of physical and chemical aspects of water quality. Although this major gap was highlighted two decades ago (Harris, 1995; Norris and Norris, 1995), few such indicators have since been applied to Australian estuaries (Deeley and Paling, 1998; Barton, 2003; Hallett et al., submitted II; Table 1). Some biotic indices have recently been developed (e.g. Hallett et al., 2012; Sheaves et al., 2012; Irving et al., 2013; Warry and Reich, 2013), but their application is not yet widespread.

There is also a relative paucity of effective and timely monitoring of estuarine habitats, ecological processes and functions (Table 1), despite repeated recommendations to more fully consider the ecological complexity of estuarine condition (ANZECC and ARMCANZ, 2000a; NLWRA, 2002a). Monitoring in most jurisdictions focuses on water quality variables as a surrogate for the condition of aquatic communities and key ecological processes (ANZECC and ARMCANZ, 2000a), primarily because they are easier to monitor. However, this raises the important yet frequently unanswered question of whether such variables are truly fit for purpose as surrogates of broader ecological integrity. Appropriate indicators of biological condition must therefore be developed and implemented to verify that this is the case and to better track whether management actions that target improved water quality are translated into improved ecological health in a broader sense.

Effective estuarine monitoring programs are able to connect sources of anthropogenic stress (i.e. pressures) to their impacts on ecological condition and human well-being (Rapport

and Hildrén, 2013) by employing sensitive indicators with clear cause and effect relationships to relevant stressors and known ranges of natural variability (*Criterion 5*). The stratified design of estuarine monitoring under the NSW MER Strategy has enabled the sensitivity of phytoplankton and sediment indicators to catchment disturbance, and specifically nutrient and sediment loads, to be demonstrated (Table 1). Similarly, some of the biotic indices that have recently been developed for assessing estuarine condition in Australia (Hallett et al., submitted II) have been shown to be sensitive to the spatio-temporal changes in estuarine condition resulting from hypoxia, algal blooms or habitat degradation (e.g. Hallett et al., 2012, 2016; Irving et al., 2013). However, in many cases, establishing causal relationships between condition indicators and their ultimate drivers has been hampered by a failure to effectively quantify relevant pressures (DERM, 2012). It is important to emphasise that effective validation of indicator sensitivity and robustness is markedly more common for physico-chemical indicators than among those focused on estuarine habitats or biota.

Assessments of ecosystem condition are typically founded on the reference condition approach, whereby the relative condition (sometimes termed 'health', 'integrity', or 'status') of an ecosystem component (or 'element') is quantified by comparing values of relevant indicators to those found in comparable estuaries with the same physical characteristics, but which are relatively unimpacted by human development (Gibson et al., 2000). Establishing appropriate references or baselines is clearly essential to enable robust detection of any significant deviations in condition, and thus invoke an appropriate management response. Historical and contemporary water quality monitoring data are now frequently used to establish type-specific reference conditions for estuaries in each State or in a particular bioregion (Table 1). For example, objective statistical (e.g. percentile-based) methods are commonly applied to the data collected from undisturbed or least impacted estuaries to establish reference conditions and ecologically relevant scoring thresholds between condition classes (*Criterion 6*). These thresholds are often formalised as local/State water quality guidelines, providing clear advantages over default (e.g. ANZECC and ARMCANZ, 2000a) guideline values. In contrast, establishing reference conditions for many biotic indicators across Australia is hampered by a lack of appropriate long-term data, necessitating a more subjective, expert judgement approach to establishing reference conditions and scoring thresholds (Table 1).

One of the biggest and longest-standing issues around condition monitoring of natural resources in Australia is an inability to scale up assessment outputs for reporting at broader spatial scales (NLWRA, 2008a, b; Hallett et al., submitted II). Whilst the exemplary stratified

monitoring regime and approach for setting reference conditions in NSW estuaries ensures that all systems are assessed against a common State-wide scale to enable robust comparisons among systems (*Criterion 7*; Table 1), there is in most States little or no emphasis on standardising indicators and methods in this way. Huge differences are evident, both between and within jurisdictions, in the spatial scale of individual management units and their associated monitoring programs (i.e. from those focused on individual estuaries to those that are bioregional or State-wide), and in the degree of coordination between these programs. The result is a patchwork of different assessment methods and indicators, applicable only to specific estuaries or geographic regions. Moreover, comparison of estuarine condition between States is hindered by a lack of intercalibrated or standardised indicator thresholds, despite a requirement to assess and compare condition across Australia for national State of the Environment reporting. As a result of these disparities, monitoring outputs tend to inform management objectives at a local level, but are not integrated effectively within a hierarchical reporting framework that could also address regional, State-wide or national objectives (Table 1). Currently, inter-calibration of monitoring results among such divergent programs is not feasible; only through broader adoption of standardised, state-wide monitoring strategies such as the NSW MER are robust, broad-scale comparisons of estuary condition across Australia likely to become possible.

Numerous attempts have been made in the last decade or so to propose a common, nationwide monitoring and reporting framework (e.g. Smith et al., 2001; Kingsford et al., 2005; Mount, 2008), all of which aim to encourage greater coordination and complementarity of approaches across Australia (Hallett et al., submitted II). However, no such framework has been adopted to date, reflecting, at least in part, a lack of legislative and financial support and the complex, disparate and frequently shifting responsibilities for managing estuaries across Australia (Smith et al., 2001; Pannell et al., 2008; NLWRA, 2008b). Thus, there is a critical need for legislative, governance and funding arrangements that are more efficient, stable and coordinated (Lockwood et al., 2010; HC Coombs Policy Forum, 2011a, b). To this end, initiatives like the current NSW coastal management reform process, which aims to provide a simpler, integrated legal, policy and governance framework and the sustainable funding arrangements required to support estuary management, are an important progressive step.

2.3 Reporting, communicating and responding

Reporting of estuarine monitoring outputs has in many ways improved enormously over the last decade within Australia. Monitoring data are increasingly integrated (*Criterion 8*) and simplified to better communicate trends in estuarine condition to a wider audience (*Criterion 9*; Dennison et al., 2007). The first of these aspects is exemplified by the proposed Index of Estuarine Condition for Victoria, the Healthy Waterways program (Fig. 2) and similar recent initiatives in Queensland, and the pressure and condition indices implemented across NSW (Table 1). With respect to community reporting of estuarine condition, a range of media and approaches are now employed, including web-available report cards (Table 1; Fig. 3). However, the reporting of some condition elements (e.g. biota and habitats) is frequently based on outdated information and thus has little capacity to inform prompt management actions.

Perhaps the greatest weakness of many current Australian programs is their failure to ensure that observed declines in estuarine condition trigger practical and adaptive management responses (Hallett et al., submitted II). As part of an adaptive approach to management, limits of acceptable change (LAC) or other quantitative targets should provide a basis for determining whether management objectives have been achieved or what management response is required (*Criterion 10*; WA DoW, 2007). It is evident that considerable progress has been made across Australia towards setting relevant, specific and measurable targets for water quality (termed water quality objectives/guidelines, LAC, trigger values etc.; Table 1). Too frequently, however, while monitoring has documented a decline in estuarine condition, there has seemingly been a lack of clear and targeted management action to address that decline (Hallett et al., submitted II). The reporting of monitoring outputs must be more effectively tied to specific, timely and adaptive management actions with tangible effects on estuarine condition (HC Coombs Policy Forum, 2011b), rather than simply stimulating further monitoring. The NSW MER Strategy is attempting to address this issue by linking the scoring systems for condition and pressure indicators more directly to triggers for different management actions (Roper et al., 2011).

3. Recommendations for estuarine health assessment in Australia

Having identified numerous gaps and limitations of current Australian programs for assessing, monitoring and reporting estuarine condition, as well as specific strengths and examples of best practice nationally, we provide in Table 2 a list of recommendations for improving the future of estuarine health assessment in Australia and aligning it more closely with international best practice. In a broad sense, however, our recommendations reflect

many fundamental attributes of effective natural resource management programs and thus are applicable to ecosystem monitoring and reporting activities worldwide. Fig. 4 illustrates how these recommendations relate to an idealised policy cycle of adaptive management for estuaries, noting that the need for an iterative and adaptive approach to management is implicit and should underpin all estuarine monitoring and management activities (Allen et al., 2011; Williams, 2011). This enables evaluation of management performance and refinement of management actions (Jacobson et al., 2014), increasing the likelihood of successful outcomes for estuarine condition.

4. Conclusions

This three-part review has provided a timely, comprehensive and critical evaluation of the approaches currently employed across Australia for assessing, monitoring and reporting estuarine condition. We have identified several examples of best practice from across the country and proposed recommendations to address some of the most pressing issues and gaps that remain. Notable advances have been made over the last decade, including a move in several States towards adaptive and integrated strategies for improved evaluation and communication of management outcomes. The stratified design of monitoring programs in some States, and particularly NSW, provides a firm basis for quantifying estuarine condition and validating the sensitivity of ecosystem indicators to relevant pressures. Overall, however, Australian progress towards more coordinated and holistic estuarine monitoring schemes varies markedly among jurisdictions, with at best gradual advances in several cases. Consequently, Australia continues to lack many of the tools and data needed to effectively establish estuarine health and trends, and particularly for biota, ecological functions and processes (NLWRA, 2002a, b; Beeton et al., 2006; State of the Environment 2011 Committee, 2011). Regarding a nationally-coordinated assessment and comparison of estuarine condition, while various frameworks have been proposed (Hallett et al., submitted I), their implementation has been hampered by a lack of appropriate legislation, governance, political will and/or financial support.

It is crucial to emphasise that management of aquatic resources occurs at the interface of science and public policy, and particularly so under a federal system involving local, regional, State and national governance arrangements. Significant obstacles to future progress in Australia, as determined by this review and/or several other workers (e.g. Smith et al., 2001; HC Coombs Policy Forum, 2011a, b; State of the Environment 2011 Committee, 2011), include inconsistent spatial scales of management; pluralistic governance structures

and fragmented legislation; inadequate interaction between scientists and managers; an inability to balance competing demands and changing interests, and funding arrangements that fail to support effective long-term monitoring. It is thus relevant that Poikane et al. (2014) noted that the efficacy of policy initiatives such as the EU WFD or US Clean Water Act depends upon both the technical clarity of ecological goal statements and the political clarity of intent that is enshrined in law. In the absence of any overarching law to mandate their intent, we can only conclude that analogous Australian policy initiatives (e.g. ANZECC and ARMCANZ, 2000a, b) are destined to remain ineffective without significant changes to the legislative, funding and governance structures that support estuarine management.

In documenting many of the emerging projects and programs noted by Borja et al. (2012), the vast majority of which are only accessible through the grey literature, we have highlighted and evaluated the strengths and weaknesses of current approaches for monitoring and reporting estuarine condition across Australia. There is great potential for further progress to be made across Australia in the field of estuarine monitoring and health assessment if we address these deficiencies and pursue the above recommendations in a more coordinated and strategic manner. Furthermore, the examples of best practice that we have identified and the recommendations arising from this review are relevant for estuarine monitoring and reporting programs worldwide, and particularly for those that are subject to federal or supra-national governance arrangements.

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Figure captions

Fig. 1. Example of a conceptual ecosystem model, providing a basis for understanding and managing nitrogen dynamics in a wave-dominated estuary. © OzCoasts (Geoscience Australia) 2012, licensed under the Creative Commons Attribution 3.0 Australia licence.

Fig. 2. Example output from the web-based Healthy Waterways 2015 report card for freshwater and estuarine sections of the Lower Brisbane River (www.healthywaterways.org).

Fig. 3. Output from the 2014 Darwin Harbour Report Card (DLRM, 2014).

Fig. 4. A model of an adaptive policy cycle that is underpinned by the DAPSI(W)R(M) framework and effectively links monitoring, assessment and reporting to the management of estuaries (modified from Wolanski and Elliott, 2015).

Tables *(separate files, attached)*

Table 1

An evaluation of recent and current practices for monitoring, assessment and reporting of estuarine condition across Australia, against objective criteria established by Hallett et al. (submitted, I).

Table 2

Recommendations for improved monitoring, assessment and reporting of estuarine condition across Australia and beyond.

Table(s)

Table 1. An evaluation of recent and current practices for monitoring, assessment and reporting of estuarine condition across Australia.

Evaluation criterion [a]	Evaluation of Australian practices [b]	Examples of best practice in Australia [b]
Context, objectives and design of monitoring programs		
1. Monitoring and assessment is underpinned by the DAPSI(W)R(M) (i.e. Driver-Activity-Pressure-State Change-Impact (on Welfare)-Response (Measures) framework, or similar.	Australian monitoring and reporting is focused predominantly on *state changes*, while the underlying *drivers, activities* and *pressures* are not always quantified. The coordinated strategy of NSW, which is founded upon *a priori* assessments of catchment disturbance and the pressures and threats posed to estuaries, is atypical. For most programs, relevant pressures are frequently unquantified or are not collated and reported in a broadly accessible and compatible manner. Moreover, practical indicators of human *impacts* or management *responses* are rarely implemented.	The NSW estuary monitoring program is based on a pressure-stressor-outcome model, with comparable pressure and condition indicators among estuaries. Moreover, the Program Performance strand of the NSW Monitoring, Evaluation and Reporting (MER) Strategy (NSW DECCW, 2010) focuses on impacts and responses of human populations to management actions, including changes in community attitudes, stakeholder behaviours and management approaches that result from specific management interventions.
2. Monitoring and assessment addresses specific management objectives and forms an integral part of an adaptive management cycle.	Several recent initiatives (e.g. Attard et al., 2012) recognise the importance of effective monitoring, reporting and evaluation for the adaptive management cycle. Most States have identified and prioritised key estuarine values as management targets, e.g. in WA, Water Quality Improvement Plans identify management actions to address specific targets, and progress against these targets is to be evaluated using monitoring outputs. However, several of these Plans are yet to be implemented due to lack of funding.	As nutrients and sediments are identified as the main threats to NSW estuaries, relevant pressures and stressors (e.g. modelled estimates of nutrient and suspended solid loads and freshwater flows) are quantified for every estuary across the State. Management responses aim to modify pressures and thereby improve estuarine condition. Findings from each round of the NSW MER Strategy inform improved collection and analysis of data for subsequent State of the Catchment (SoC) reports.
3. Monitoring addresses a legislated requirement for assessing and reporting estuarine condition and trends.	Numerous pieces of State and federal legislation relate to estuarine condition, though these typically focus on particular estuaries, elements and/or activities (e.g. specific Fisheries and Water Acts). More commonly, monitoring and reporting are governed by non-statutory policies, guidelines and strategies that are vulnerable to changes in priorities, governance and funding, and for which there is little clear accountability.	NSW adopted a coordinated MER Strategy in 2006 to measure progress towards State-wide estuary condition targets. This Strategy analysed existing information, coordinates future monitoring and requires individual SoC reports to be prepared every three years (NSW DECCW, 2010).
Monitoring elements and indicators [c]		
4. Monitoring and assessment programs adopt an holistic view of ecological condition and employ relevant, cost-effective indicators of State Change, including physical and chemical water quality; sediment quality; habitats; key	Despite widespread acknowledgement of the need to include a broad range of ecological elements, monitoring and reporting of estuarine condition across much of Australia continues to be based largely on water quality. Sediment condition is rarely monitored, despite pressures threatening many estuaries nationally (e.g. siltation, contamination), although some novel indices are currently in development (WA, NSW) and regular monitoring occurs in some key systems (e.g. Derwent Estuary, Tasmania). Habitat condition and benthic invertebrates are rarely monitored, and fish-based indices have been tested and/or employed in only a few cases (WA, NSW, Victoria, NT). Indicators of	Broader, more holistic suites of ecological indicators are now employed, or will soon be implemented, in a number of key estuaries nationwide, e.g. Swan-Canning Estuary (WA), Darwin Harbour (NT), Derwent Estuary (Tasmania), Fitzroy River Estuary and Gladstone Harbour (Queensland). The NSW MER Strategy also employs a cost-effective set of condition indices across the State, which encompasses relevant elements of estuarine ecological structure and function (e.g. chlorophyll *a*, seagrass, mangrove and saltmarsh extent, and fish communities). The proposed IEC for Victoria (Pope et al., 2015) also integrates indices from six

Evaluation criterion [a]	Evaluation of Australian practices [b]	Examples of best practice in Australia [b]
flora and fauna; ecosystem processes/functions.	ecological processes and function are rare (NLWRA, 2008a), but are under development in NSW and Queensland. Lack of funding and political will are commonly cited as reasons for the scarcity of these broader indices.	themes covering multiple aspects of estuarine condition, i.e. physical form, hydrology, water quality, sediment, flora and fauna.
5. Monitoring and assessment programs employ indicators that are sensitive to changes in estuarine condition, i.e. they can detect 'signals' of anthropogenic pressure against the 'noise' of natural variability.	Many water quality indicators employed in various jurisdictions (e.g. NSW, Queensland, Tasmania) have been extensively validated to establish their sensitivity to anthropogenic pressures. In contrast, validation of biotic indices has generally been less extensive (with exceptions such as the WA Fish Community Index and components of the Victorian IEC), in part because a lack of quantification and reporting of anthropogenic pressures prevents robust testing. Establishing cause-effect relationships between key pressures and changes in condition indices will greatly enhance the diagnostic and predictive capacity of these tools.	Estuarine monitoring across NSW is stratified by level of catchment disturbance, enabling validation of index responses to anthropogenic pressures. The SA Monitoring, Evaluation and Reporting Program (MERP) seagrass habitat condition index is based on validated conceptual models of responses to stress (Irving et al., 2013). Similarly, the Fish Community Index (FCI) used to monitor the condition of the Swan-Canning Estuary (WA) has been extensively validated and shown to be sensitive to algal blooms and hypoxia and robust to the effects of natural variability (Hallett et al., 2012, 2016).
6. Appropriate reference conditions, and scoring thresholds that distinguish condition classes and/or limits of acceptable change, are established for each indicator using objective, independent data on estuarine condition or anthropogenic pressure.	Data for least impacted estuaries are now commonly used to statistically derive water quality guidelines, objectives or reference conditions for physico-chemical parameters and chlorophyll (NSW, WA, SA, Tasmania, Victoria), tailored to the specific regions and estuary types. Processes for determining reference conditions for biotic indicators (e.g. of habitats, seagrasses and fish) are less well established, and in some cases rely heavily on subjective judgement. More focus is needed on quantifying indicator responses to anthropogenic pressures in order to better establish appropriate reference conditions, scoring thresholds and limits of acceptable change (LAC).	Specific water quality objectives for each region of Darwin Harbour (NT) have been established for each estuarine condition indicator, enabling effects of human impacts to be better distinguished from natural variability (Maraud, 2013). Water quality trigger values for NSW estuaries are set using a percentile-based approach applied to data from undisturbed reference estuaries. Metrics comprising the WA Fish Community Index are scored against best-available reference conditions established using three decades of historical fish community data (Hallett et al., 2012). Scoring thresholds for this index were established from quantiles of the distribution of historical FCI scores, enabling condition to be classified as very good (A) to very poor (E) (Hallett, 2014).
7. Monitoring and assessment programs employ indicators that enable condition to be reliably compared among estuaries and allow for monitoring outputs to be 'scaled up' for reporting across multiple spatial scales, as required.	Comparing estuarine condition across broad spatial scales continues to be severely hampered by a lack of standardised approaches to monitoring and reporting. State-wide programs that permit hierarchical assessment and reporting are rare (e.g. NSW) and large disparities often exist in the degree of monitoring among estuaries, both between and within States (e.g. Victoria, Tasmania, WA, Queensland). This reflects a lack of coordination among the many and diverse programs nationwide. Consequently, it is often impossible to compare estuary condition, even within a given type in the same State or bioregion.	The NSW MER Strategy entails replicated monitoring of over 30 different estuaries (plus 10 fixed systems) per year, focussing on one of three regions on a three-year rolling cycle. This allows the calculation of condition and pressure indices for each estuary, region and for NSW as a whole. Aggregation rules ensure that reporting of condition at regional and State levels is representative and State-wide condition scores are calculated based on at least 20 estuaries across NSW. Reporting grades (A–E) for each zone/estuary are based on percentiles of all scores across the State, providing a consistent estuary health score for NSW, irrespective of the data source (Roper et al., 2011).

Evaluation criterion [a]	Evaluation of Australian practices [b]	Examples of best practice in Australia [b]
Reporting, communicating and responding		
8. Monitoring and assessment outputs are integrated for reporting and decision-making purposes.	There has been an increased focus on integrating water quality measurements into compound indices that summarise estuarine condition in a widely comprehensible manner, yet retain key information to enable analysis of trends and drivers (e.g. Birch et al., 2016). To date, there are far fewer examples of the successful integration of physico-chemical, floral and faunal condition elements into a holistic reporting framework, though this is being addressed under several recent or proposed schemes in Victoria and Queensland.	Indicators of pressures and condition for NSW estuaries are combined into integrated pressure and condition indices for SoC reporting. These indices provide a more balanced and complete assessment of ecosystem health than individual indicators alone (Roper et al., 2011). Outputs from South-East Queensland's Healthy Waterways monitoring program are also integrated into an Environmental Condition Grade, comprising measures of water quality and habitat distribution/extent.
9. Reporting of monitoring and assessment outputs is conducted at relevant time scales, utilises formats suitable for the lay person/politician, and is widely accessible and publicised.	Monitoring results are increasingly communicated to a broad audience, including key stakeholders and the public, in a concise and comprehensible report card format (e.g. A-E condition grades). Accompanying technical reports provide background information and context for interpreting monitoring results and trends. However, most Australian report cards remain strongly focused on water quality, and in some jurisdictions (e.g. WA), their publication has been delayed. In some cases, there remains a marked disconnect between monitoring and reporting timescales, and particularly for ecological elements such as habitats, seagrasses and fauna.	A growing number of local-scale programs are producing effective report cards and supporting technical documents (e.g. those for Darwin Harbour, Derwent Estuary and Tamar Estuary). The Derwent Estuary Program, for example, produces annual report cards, quarterly eBulletins and a five-yearly State of the Derwent Estuary report. Southeast Queensland's Healthy Waterways program has released annual ecosystem health report cards for 15 years, with an accompanying website (www.healthywaterways.org) that enables users to examine grades and trends in condition, request access to monitoring data and download supporting documents.
10. Monitoring and assessment outputs elicit a management response when limits of acceptable change (based on a target or thresholds) are exceeded.	Established trigger values or other LAC for water quality indicators are now common in many jurisdictions, though there are many examples of monitoring that is not effectively tied to specific, timely and relevant management responses. Exceedance of trigger values commonly invokes investigation (i.e. more monitoring) of the underlying causes, yet specific practical management interventions do not always follow. This partly reflects the 'wicked problem' (Patterson et al., 2013) posed by key drivers of estuarine decline, whose solutions may be politically and socially intractable (e.g. the widespread need for reduced nutrient inputs to estuaries). Furthermore, LAC are rarely established for elements such as habitat condition or fauna due to a lack of appropriate monitoring data, severely limiting the ability to detect and address significant declines in condition over time.	Under the SA MERP, if observed estuary condition differs from that predicted then further investigations may be undertaken to identify possible causes of the disparity and inform management actions. Continuous monitoring of dissolved oxygen informs the control of artificial oxygenation plants in the upper Swan Canning Estuary, WA, which can be triggered on an automated basis (e.g. whenever dissolved oxygen concentrations fall below 4 mg/L) to minimise the severity of hypoxia.

[a] See Hallett et al. (submitted, I) for explanation and exemplification of these attributes of international best practice.

[b] See Hallett et al. (submitted, II) for detailed descriptions of the monitoring and reporting programs on which these evaluations are based.

[c] We define **elements** as the various components of the ecosystem whose condition is of interest (e.g. water chemistry, habitats, flora, fauna). The state of these elements can be assessed and reported using **indicators**, which may be single parameters (e.g. water temperature, dissolved oxygen concentration, seagrass density) or composite indices (e.g. the Water Quality Index of Pantus and Dennison [2005]).

Table(s)

Table 2. Recommendations for improved monitoring, assessment and reporting of estuarine condition as integral constituents of an adaptive management cycle. The numbers in parentheses refer to steps in Fig. 4.

Recommendation	Required outcomes
• Ensure greater stability, continuity and coordination of the legislative, governance and funding arrangements supporting estuarine management and monitoring (1–10).	• Facilitate the broader-scale, long-term, adaptive monitoring programs that are essential to effectively measure and manage the condition of estuarine resources.
• Estuarine monitoring and management programs should align more closely with the DAPSI(W)R(M) framework, and in particular have a greater focus on quantifying and reporting the pressures that cause changes in estuarine condition, and the human responses to those changes (2,5,6,7).	• Better identify the causes of declines in condition and the optimal, most cost-effective management responses to address them.
• Pressures should be measured and reported at multiple, complementary spatial and temporal scales (2,3,5,8).	• Enable development of causal relationships between estuarine condition and pressures, robust and sensitive indicators and ecologically relevant scoring thresholds. • Better targeting of those stressors that are most relevant or amenable to management interventions. • Provide early warning of likely future impacts on currently unimpacted (i.e. pristine) systems.
• Develop and implement ecologically-relevant, holistic methods for assessing estuarine condition, including biotic indicators and measures of ecological processes and function (2,5).	• Help to determine whether current management actions are having measurable benefits for broader ecological condition (e.g. healthier habitats, biotic communities and ecosystem processes/functions).
• Combine physico-chemical, floral, faunal and other ecological condition elements into integrative indices of estuarine condition (3,4,6,8).	• Reporting focuses on integrated measures of the condition of the whole ecosystem, and/or component indicators, facilitating identification of the potential causes of observed declines in condition.
• Establish shared reference conditions and standardised procedures to enable the condition of multiple estuaries to be assessed on a common scale (4).	• Improve the robustness and comparability of monitoring and assessment schemes across large spatial scales, facilitating broad-scale management prioritisation and reporting.
• Establish relevant, quantitative threshold values/limits of acceptable change for ecological indicators, exceedance of which will trigger a management response. (4,9,10).	• More appropriate and timely management interventions designed to improve or maintain ecological condition.
• Develop coordinated and hierarchical monitoring programs that incorporate relevant indicators at local to landscape scales, and which can be aggregated or disaggregated to address local, bioregional or State management and reporting needs (5,8).	• Greater capacity for monitoring outputs to inform a broad range of management objectives.
• Where possible, monitoring programs should incorporate stratified monitoring of multiple estuaries across all types and levels of pressures/stressors (5,6,8).	• Facilitate the development of more relevant, robust and informative indicators
• Improve alignment between the timing of monitoring and reporting cycles (5,8,9).	• Enable more timely and adaptive management interventions to reduce the risk of declines in estuarine

Recommendation	Required outcomes
	condition.
• Monitoring reports should be widely accessible and comprehensible to a broad audience. Monitoring programs should also be evaluated (i.e. peer-reviewed) for scientific rigour, management relevance and cost-effectiveness (8,10).	• Better educate the broader community on estuarine condition status. • Build confidence in the science underpinning management programs.
• Where monitoring outputs indicate a decline in estuary condition beyond an established threshold or limit of acceptable change, implement appropriate, cost-effective and practical management measures aimed at tackling the pressures responsible, rather than simply more monitoring (4,6,7,9).	• Management responses provide tangible outcomes for ecosystem health. • Monitoring outputs better contribute to adaptive management, rather than simply tracking ecosystem decline.
• Adaptively refine sampling regimes and management actions in light of evaluations of monitoring data, as part of an ongoing, interative approach (5,9,10).	• Improved management actions to better maintenance or improvement in estuarine condition.

Figure(s)

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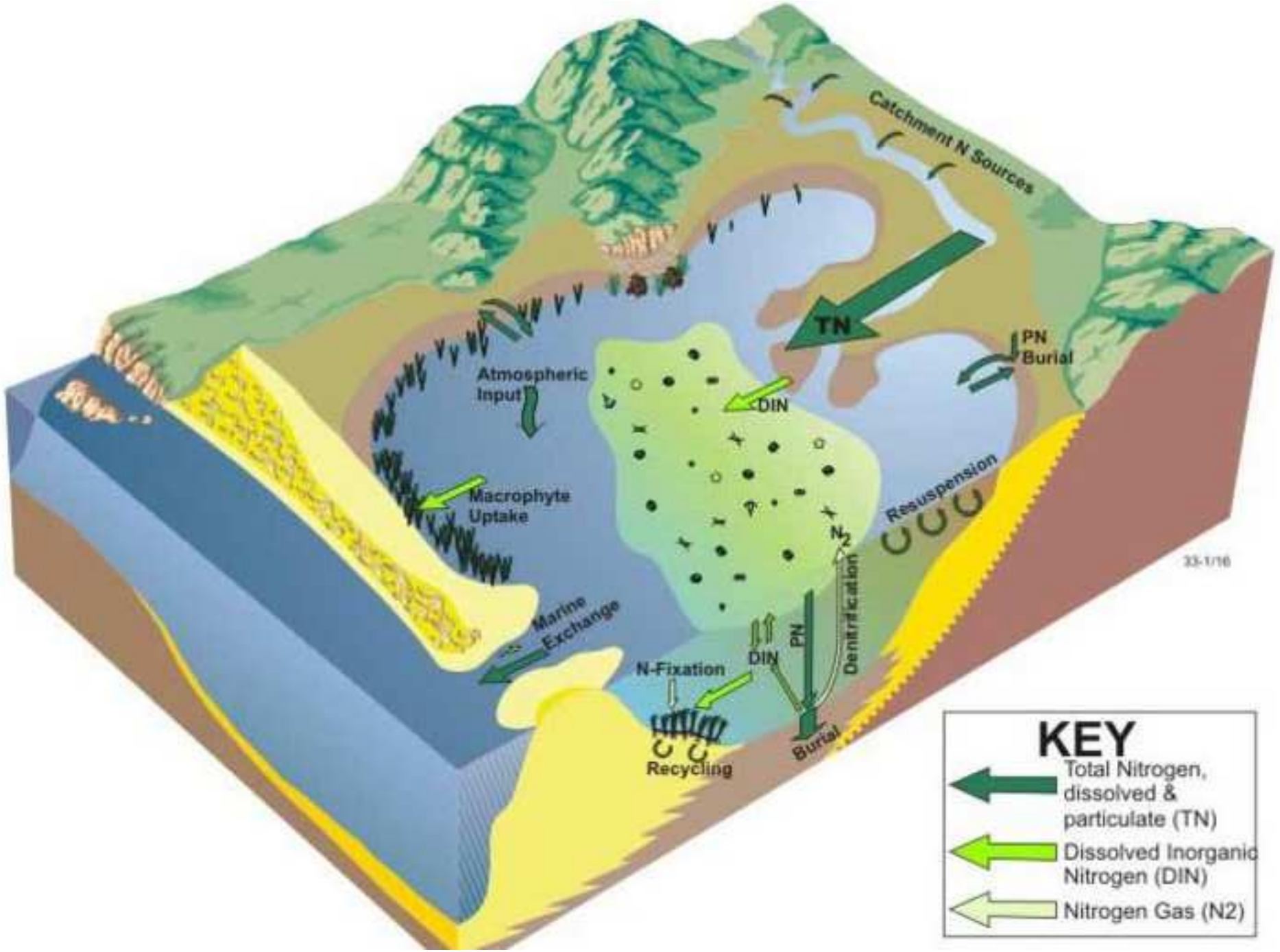

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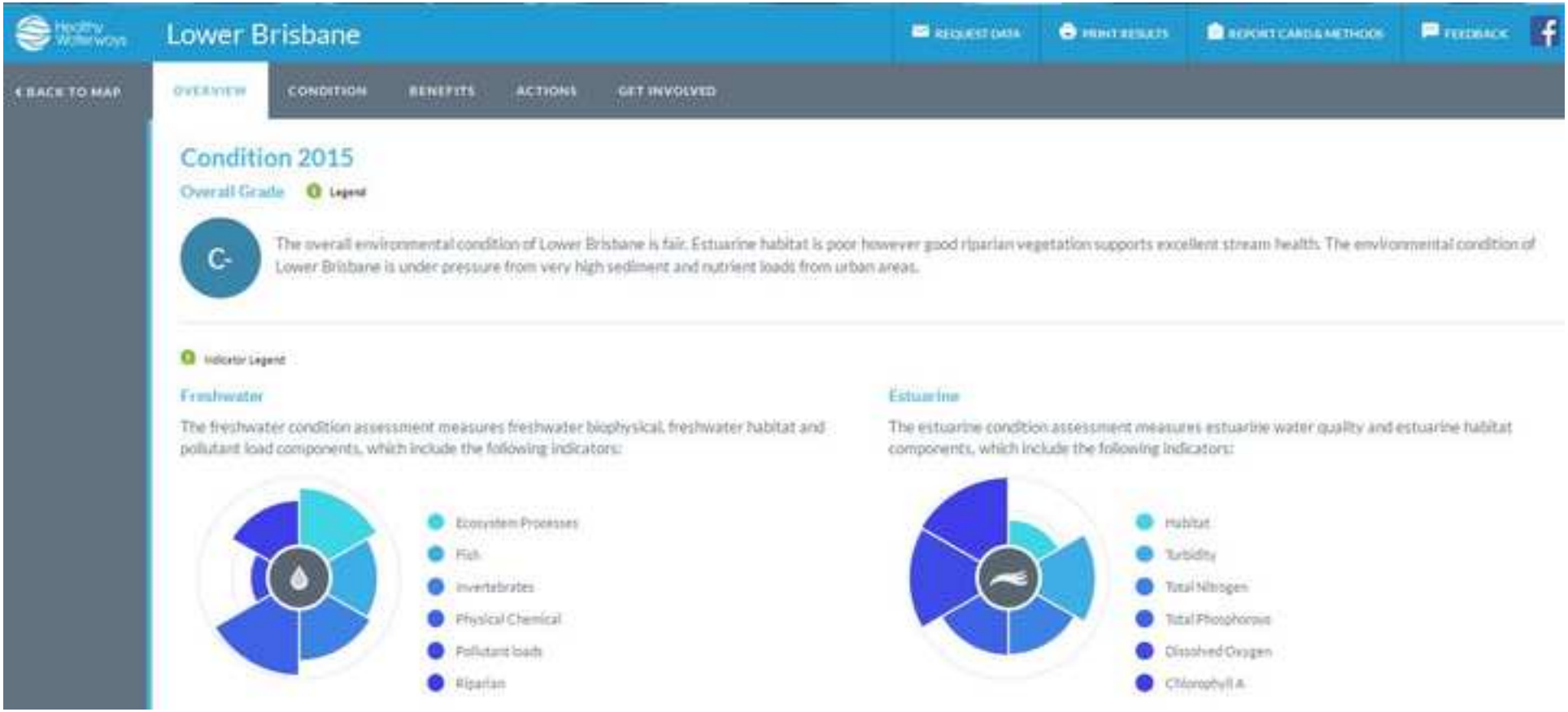

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