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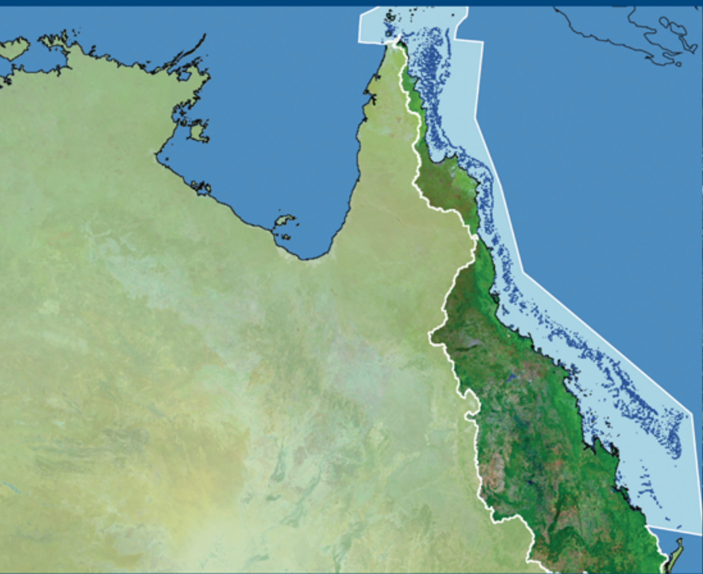

Review of existing approaches used to develop integrated report card frameworks and their relevance to catchments draining to the Great Barrier Reef

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The Marine and Tropical Sciences Research Facility (MTSRF) is part of the Australian Government's Commonwealth Environment Research Facilities programme. The MTSRF is represented in North Queensland by the Reef and Rainforest Research Centre Limited (RRRC). The aim of the MTSRF is to ensure the health of North Queensland's public environmental assets – particularly the Great Barrier Reef and its catchments, tropical rainforests including the Wet Tropics World Heritage Area, and the Torres Strait – through the generation and transfer of world class research and knowledge sharing.

This report is available for download from the Reef and Rainforest Research Centre website.
Visit http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_7.html

Cover Photograph

Burdekin River, Rebecca Bartley

Executive Summary

A key deliverable of the MTSRF program is the development of an integrated report card framework (IRCF) for reporting on condition and trends in catchment and marine health of the GBR and Torres Strait regions. The broad objective of Project 3.7.7 (*Conceptual and statistical framework for the water quality component of the integrated report card*) is to provide the science and statistical framework for integration of outputs from other MTSRF projects, which includes the development of methods for a multi-scale regionalisation, testing the suitability of various indicators and for a multimetric presentation of data.

The purpose of this first milestone report is to:

(1) Provide a review of relevant report card approaches from national and international report card programs;
(2) Raise awareness as to some of the issues and requirements for developing a report card for the GBR region;
(3) Provide some principles and an approach on how to proceed with developing a report card for the GBR region;
(4) Outline our research plan for the completion of the first year contract for this project.

While there is no formal definition of a report card, in this document we define an integrated reporting framework (IRCF) as '*a scientifically valid approach for the integration and presentation of operational monitoring data in an accessible format for adaptive ecosystem management'*. This definition captures the challenge of designing a report card to represent ecological condition that aims to statistically summarise a diverse range of data sources from a complex environment into a simplified form that remains scientifically valid. This definition also reflects the role that integrated report frameworks play within an adaptive management framework which involves ongoing monitoring and assessment. It also highlights the challenge of ensuring that the integrated components not only represent tools that managers can use, but are transparent to the scientific community and other stakeholders that require the detail underlying the report card grade. This places emphasis on the science behind the grade itself and its development.

From our review of the literature a general framework for report card development is presented. The following points are made in relation to the general principles resulting from our review, as well as the implications for the development of a Great Barrier Reef (GBR) Integrated Report Card Framework (IRCF):

1) **Define the scope and objectives** of the program, and establish what resources are available.

The scope of the IRCF must suit the available resources and time-frame. The goals and scope of the IRCF should be established as quickly as possible in order to guide subsequent stages. An overly ambitious or poorly defined scope will make it difficult to implement subsequent development stages. Existing data sets/monitoring programs may not be ideal given the requirements of the IRCF. Goals and scope of the IRCF may have to be revisited if they are to be constrained by available data;

Implications for the GBR IRCF:

It is clear from the case studies presented in this report, with the exception of the millennium assessment, that no other studies have attempted to bring together environmental condition reporting across an area as large as the GBR and Torres Strait (~ 767 000 km^2) with such a diversity of habitats, and drivers / issues to be considered. Furthermore issues of data paucity, particularly in the Cape York catchments will be an issue.

We believe, however, that the right policy and institutional drivers are in place to move the development phase forward for addressing water quality issues in the GBR. The Reef Water Quality Protection Plan (RWQPP) and the recent formation of the Reef Water Quality Partnership — as is a collective representation of end-users— are important for providing the articulation of

the objectives, issues, scope, resolution and style of reporting that will be required. This is important for specifying the science required for the development of the framework for water quality related issues. For biodiversity and conservation issues both terrestrially, and in the marine environment, these needs are not as well defined.

Some IRCFs reviewed in this report have strong socio-economic (human use / governance components), while others ignore these entirely in favour of validated measures of environmental and ecological integrity. This is a decision-point to be resolved early in the GBR IRCF development. If the focus of the IRCF is ecological, it is worth considering avoiding socio-economic reporting (at least in the early years) to avoid distracting from the primary goal. Reporting on management actions is a separate matter, and may be considered in another program.

2) **Understand the system**, drawing together and documenting all relevant theoretical and empirical knowledge, as well as expert opinion.

Conceptual frameworks and conceptual models play an important role here. Establishing the relationships between drivers, stressors and ecological impact is facilitated by explicit conceptual models of specific biophysical dynamics. An IRCF should encompass both the human and bio-physical system, and provide clear direction in terms of management actions. Adherence to an appropriate and well-supported conceptual framework will assist here. An entire-system approach is particularly important, and the relationships between anthropogenic stressors, pollutant vectors, environmental conditions and ecological responses should be made explicit.

Implications for the GBR IRCF:

A conceptual framework establishing the types of indicators to be reported and their degree of connectedness and causality need to be agreed. Possible models include the traditional pressure-state-response approach as used in SoE reporting, the pressure-vector-condition currently being developed by the Queensland Government for its Stream and Estuary Assessment Program (SEAP), the Millennium Ecosystem framework which focuses on the linkages between ecosystem services and human wellbeing.

Establishing causality between pressure-vector-response indicators — particularly for ecological and socio-economic issues has generally been poorly addressed by most report cards to date. We believe, however, that the main research challenge for the MTSRF Report card should be the development of a coherent longitudinal integration of various habitats and their indicators, from the top of the catchment through flood plains and estuaries and onto the inner and outer reef.

Working groups of experts need to be set up and tasked with documenting the key dynamics and relationships of the biological, chemical and physical properties of the system early in the IRCF design process. These conceptual models guide and justify the subsequent processes of indicator selection, regionalisation and indicator integration.

3) **Establish a measurement framework** that will address the constructs defined in Phase 1 in terms of the systems identified in Phase 2. This will include the definition of spatial reporting units (that should be scaleable), and the choice of indicators and their benchmarks.

Implications for the GBR IRCF

A multi-scale regionalisation needs to be developed that will ultimately be a pragmatic compromise between the reporting units already determined through administrative arrangements, and the use of biophysical data of landscape attributes to determine a regionalisation capable of meeting a hierarchy of reporting needs. Consideration of hydrological dynamics and stream connectivity will be important for determining the areas of human use that impact a given aquatic location and can form the basis for a multi-scale spatial classification.

This will be a major component of ongoing research and will need to consider the following:

❖ latitudinal climate and landscape variation,

- definition and delineation of habitats,
- scales of variability (spatial and temporal) that occur within a patterned hierarchy of habitat and bioregion,
- Identifying regions of minimal human disturbance that can be used to define appropriate benchmark reference conditions and thresholds-of-concern,
- Establishing human disturbance gradients would that can be used for validation of indicators, reference conditions, and regionalization schemes.

Possible approaches to regionalization may include:

- the use of landscape attributes or biological attributes singly or in combination,
- Clustering frameworks, with independent reference criteria for each cluster which may also be compared to model-based approaches. The influence of non-anthropogenic factors on indicators may be modelled and accounted for explicitly,
- Remote sensing methods will also be a great use in defining bioregions and mapping habitat extent,
- The use of expert opinion to help guide the selection of attributes and the identification of regional boundaries, especially for the reporting regions will be beneficial; a number of methods have been developed in Queensland already for applying expert opinion that can be readily adopted.

It is often possible to refer to national or international guidelines to determine reference levels for physical indicators (e.g. pertaining to water quality). Other indicators (biotic indicators in particular) will demand a process of reference level determination that is strongly related to the regionalisation scheme. All indicators will demand evaluation with respect to criteria described in this document, such as specificity, responsiveness and economy. The Queensland Water Quality Guidelines provide a framework for determining these objectives but the current values set for wet and dry tropical regions are based on very sparse data.

4) **Establish an integration and reporting framework** that will integrate and present the data generated in Phase 3 in a valid manner.

The organisation of the IRCF should be hierarchical, reporting at multiple levels of detail with regards to spatial, temporal and indicator specificity. This appears the ideal approach to accomplish the parallel goals of providing both transparency and methodological rigour.

The choice of how to integrate multiple indices can range from simple methods of averaging, or reporting the percent of sites and /or times an indicator meets a specified objective, through to more complex methods where individual indicators may be either weighted, normalised to a common metric or interpolated over spatial or temporal reporting units. One of the major shortcomings of most of the methods reviewed is that they have no or very crude representations of uncertainty. This is issue will be evaluated as part of future work undertaken in 3.7.7. Recommendations about the strengths and limitations of each approach and the scope of works required for development and implementation will be discussed more fully in milestone subsequent reports. Internet presentation is recommended to maximise accessibility to the public. The use of active and interactive PDF technologies is of particular value.

Review of Progress against milestone and further needs

The draft review of approaches is more or less complete, although discussion with endusers will sharpen the focus of the review and the foundation principles for a MTSRF Report Card framework. In section 4 of this report we detail a plan for completion of the remaining milestones. For milestones 2 and 3 we will focus on the aquatic condition of water bodies in the Tully catchment and adjacent coastal areas to further define issues relating to regionalisation and testing methods for integration of indicators.

Significant risks to the completion of our project deliverables are:

(1) *Lack of specification on report card definition*. These need to be articulated by endusers with advice from MTSRF scientists. We understand that the QEPA recently commissioned by the Reef Water Quality Partnership with funding from the Department of Environment and Water to articulate the report cards needs for water quality. Key questions we require resolution of are:

- Who are the other end-users of the report card components that encompass biodiversity and conservation issues in marine and terrestrial regions of the GBR and Torres Strait??
- What are the spatial reporting units? Catchments, NRM regions, Local Government boundaries?
- How frequently is the report card to be produced?
- Should the report card report on ambient condition, event condition or both? Should drivers and responses also be reported?
- What are the key habitats to be reported on? Freshwater, estuarine, marine?

(2) *Access to data and outputs from other MTRSF indicator projects and other institutions*.

The intention of project 3.7.7 is not to undertake statistical analyses or interpret data from other MTSRF indicator projects; rather it is to establish methods for the multimetric integration. To progress project 3.7.7 we need input from the other MTSRF programs on the following issues:

- A conceptual understanding of how the various biophysical and social systems work;
- The identification of any ‘thresholds of concern’ within these systems;
- A summary list of potential ‘indicators’ (based on the above points);
- An understanding of the standard methods used to measure/define these attributes;
- An idea of the spatial and temporal variability of these attributes;
- Data sets that show the spatial and temporal distribution of these data;
- If none of the above exist, then a description of any plans to investigate these issues as part of the MTSRF program.

Additionally there are issues relating to data access, licensing and intellectual property that sits outside of MTSRF, however, we seek advice on:

- Who is in charge of collating the data? As well as the storage and management of the various data sets to be included in the IRCF? Who is organising the current legal data sharing arrangements/agreements?
- How do other existing programs such as SEAP, Marine monitoring (GBRMPA/AIMS) and ambient and event monitoring programs (QEPA and QNRW) fit in with the MTSRF program? And who is responsible for sharing the data from these programs?

We seek answers to these questions as soon as possible so that progress can be made towards the next milestones for the IRC project.

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Acronyms and Abbreviations

ANZECC	Australian and New Zealand Environment Conservation Council
CBP	Chesapeake Bay Program
CCME	Canadian Council of Ministers for the Environment
CSMC	Cockburn Sound Management Committee
DEH	Department of Environment and Heritage
DPSIR	Drivers-Pressure-State-Impact-Response
EC	Environment Canada
ECEGM	Ecological condition of estuaries in the Gulf of Mexico
EcoHplot	Ecosystem Health Plot
EHMP	Ecosystem Health Monitoring Program
EMP	Environmental Monitoring Program
EPA	Environmental Protection Agency
GBR	Great Barrier Reef
GRR region	Represents all of the catchments draining to the GBR and associated receiving waters
GDM	Generalised Dissimilarity Modelling
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GINRF	Gippsland Integrated Natural Resources Forum
IBI	Index of Biotic Integrity
IISD	International Institute for Sustainable Development
IRC	Integrated Report Card
IRCF	Integrated Report Card Framework
IWC	International Water Centre
MBWCP	Moreton Bay Waterways and Catchments Partnership
MEWG	Monitoring and Evaluation Working Group
NCC	Newcastle City Council
OECD	Organisation for economic co-operation and development
PSR	Pressure-State-Response
SFBI	San Fancisco Bay Index
SFEI	San Francisco Estuary Institute
SoE	State of the Environment
TAI	The Australian Institute
TBI	The Bay Institute
WADE	Western Australia Department of Environment
WAEPA	Western Australia Environmental Protection Agency
WQI	Water Quality Index
WRI	World Resources Institute

1. Introduction

1.1. About this report

The MTSRF Program has a strong focus on the integration of information to enable effective reporting on the status and trends of the health of the Great Barrier Reef, Wet Tropics rainforest, catchment water quality and the Torres Strait region.

Development of an Integrated Report Card Framework (IRCF) is to be one of the primary tools for the integration of information resulting from the MTSRF program, as well as data from other regional, state and federal initiatives. As such the development of IRCF will actively involve some 23 MTSRF projects as well as strong engagement with endusers from a number of regional state and federal natural resources management agencies and industry.

MTSRF project, 3.7.7. (*Conceptual and statistical framework for the water quality component of the integrated report card)*, has the broad objective of developing a scientifically robust framework to support the production of report card(s) that integrate biophysical and socio-economic data from indicators that represent the drivers, vectors and responses in tropical aquatic landscapes of the GBR and Torres Strait Regions to support informed adaptive management of these landscapes.

The current phase 1 contract encompasses the design and principles of an IRCF. The framework needs to be broad enough to accommodate inputs from a range of programs, however, it has been agreed that water quality will be the initial focus and the priority of other programs to be determined. This draft report fulfils the first of four reporting milestones in the current contract. It presents:

1. A draft review on existing approaches to an environmental condition reporting; and
2. A revised plan for the conduct of activities to be reported on under this project including an outline of issues with respect to regionalisation, selection of indicators, data integration and visualization.

Subsequent milestones in this contract will report:

- A recommended approach to developing a statistically robust regionalization for the GBR and present results from a pilot implementation for a trial catchment;
- Initial indicators for inclusion and a process for trialling other candidate indicators;
- A recommended framework and activities for IRCF development.

In preparing this report we reviewed 8 specific cases studies from around Australia and overseas that have developed environmental condition reporting frameworks (Table 1). Key attributes of these case studies are summarised in Appendix 1;

➢
➢ **Table** A1.1 highlights specific details about each program, its purpose, the objectives and the geographic extent of each of these programs.
➢

Table A1.2 summarises the presentation styles used by each program including the method by which final scores were derived, the graphical format, visualisation of report card grades, extent of web delivery, the intended audience and the reporting frequency.

- **Table A1.3** outlines the partnership arrangements for each program and the data management structures that are put in place.
- **Table A1.4** summarises the indicators used and provides a short overview of the associated monitoring programs for each reporting framework.
-

Table A1.5 details a number of aspects of IRCF integration including indicator scaling, spatial and temporal integration of indicators and regionalisation

Table 1. Summary of case studies investigated for the review

Name	Overview
Australia	
South east Queensland Ecosystem Health Report Card *Healthy Waterways SEQ* www.ehmp.org	The annual SEQ EHMP report card presents an easy-to-understand snapshot of the health of the region's fresh, estuarine and marine environments. Ratings are assigned to each water body to communicate progress in improving waterway health of the region, to stakeholders (govt, industry, community). Provides insights into issues affecting waterways and the effectiveness of catchment management practices
Gippsland Natural Resources Report Card *Gippsland Integrated natural resources forum* www.ginrf.org.au	This report card rates the condition (A-F) of natural resources (assets) of the Gippsland Region including waterbodies, forests, energy resources, ranges, lifestyles (coastal living) against water, biodiversity and air values, as well as Stewardship, a 5 star measure of care and management of the natural asset by the entrusted govt. bodies, industry and the community.
State of Cockburn Sound *Cockburn Sound Management* www.environment.wa.gov.au/portal/page	This report card is primarily concerned with directing management actions in order to protect the stated environmental values of Cockburn Sound (~150 km^2). Emphasis is on co-ordinated, integrating and reporting information from regional monitoring programs to legislature. Primarily a report to parliament to provide advice on sustainable development and to a management framework for declaring and protecting the values of the Sound.
International	
State of Southland's Coastal Marine Environment (NZ) Environment Southland – NZ www.ara.org.nz	A web-based SoE report s using the Pressure-State-Response framework for SoE reporting on the marine and coastal assets of the Southland region (~34000 km^2). Focuses on reporting on 'shared management goals', that sit within broad themes. Biodiversity, Cultural Heritage, Natural Hazards, Resource Quality, Use and Development, Public Access, Navigation Safety, Landscapes and Natural Features. Freshwater, Land and Air covered in separate reports.
Regional Rivers Monitoring Program (NZ) Environment Waikato Regional Council www.ew.govt.nz/	Reports information from routine monthly monitoring of water quality at 100 freshwater locations across the freshwater Waikato region (25000 km2). Reports summary statistics, trends and simple grading (satisfactory or excellent, based on compliance with water quality guidelines and Standards.
Chesapeake Bay Health and Restoration Assessment *Chesapeake Bay Program (Watershed Partnership* www.chesapeakebay.net	This report card provides a clear and concise synopsis of Chesapeake Bay health and the on-the-ground restoration efforts taking place across this vast watershed (165800 km^2) which crosses 6 US states. Part one concentrates on grading ecosystem health of priority areas (Water Quality, Habitats & Lower Food Web, Fish & Shellfish) and their indicators are rated according to the percent of goal achieved. Part two rates restoration efforts (Reducing Pollution, Restoring Habitats, Managing Fisheries, Protecting Watersheds, Fostering Stewardship) relative to goals defined by the Bay states' river-specific cleanup plans and are expressed as the percent of goal achieved.
San Francisco Bay Index **The Bay Institute** www.bay.org	Reports and summarises water quality information on the sub-bays / inlets of San Francisco Bay (4160 km^2) from a number of monitoring programs, Focus on identifying issues, exploring causes, and identifying management options.
Pulse of the Estuary: San Francisco Estuary Institute www.sfei.org	A 'classic' report card presentation providing a picture of the ecological condition of the San Francisco bay as a whole Reporting considering the broader watershed (~70,000 km^2). Provide information that supports; stronger protections for endangered species and habitats; improved water quality; reform of water resources management; ecological restoration

1.2. Intended audience

The intention of this report is to provide a general review of the approaches taken to develop environmental report cards that can then be used to inform a debate among end-users and other MTSRF programs as to the foundation principles, scope and resourcing of a GBR report card. As such the review is necessarily broad, although we highlight relevant issues and questions that will need to be addressed in the development and implementation of the GBR IRCF.

This report does not provide all of the answers, instead, it provides a series of points for consideration by the wider MTSRF program. This project is providing the science framework around the development of report card and relies implicitly on inputs from other MTSRF projects (as well as other existing state and federally funded projects) in the development and trialling of: (1) proposed indicators; (2) a regionalisation process; (3) data integration methods; and (4) a visualisation approach.

1.3. Background and rationale for this work

There has been significant land management change in catchments draining to the Great Barrier Reef (GBR) since European settlement in 1850. As a result of this change, sediment, nutrient and contaminant loads from these catchments have increased (Neil et al., 2002; McCulloch et al., 2003), and recent research suggests that these increased loads are now having a detrimental effect on coral reef systems (Fabricius, 2005; Fabricius et al., 2005). In an effort to reduce this impact, the Reef Water Quality Protection Plan (RWQPP) was signed by the Queensland and Federal Governments in October 2003 with the overall aim of 'halting and reversing the decline in water quality entering the reef within 10 years'.

To facilitate the implementation of the RWQPP, a number of environmental monitoring projects have been initiated including a marine monitoring program (Haynes et al., 2005), estuarine monitoring (Haynes et al., 2005) and an assessment of the condition of rivers and streams (Negus and Marsh, 2006). At present, however, no framework exists that allows for the integration and evaluation of the individual projects so that catchment and reef health can be systematically evaluated and reported across the entire GBR region (freshwater, estuarine and marine). In addition, many of the agencies responsible for collecting and analysing this data have often struggled with the issues and methods required for the appropriate integration of various indicators. As a result, there is a strong need for statistical methods that focus on the experimental design, collection, manipulation, integration and visualisation of the data which is generated from these programs. The results then need to be put into a form that is appropriate for management authorities and the community to interpret (Vos et al., 2000). Examples of applicable statistical methods include (but are not restricted to); validating indicators with respect to the human disturbance gradient, estimating confidence intervals for combined variables, multivariate clustering of sites, modelling of natural and anthropogenic contributions to variation in indicators, and helping determine appropriate critical reference levels given the distribution of reference and target sites. To date, there is no single publication that captures this information.

1.4. Report outline

This report is presented in four main sections:

- Section 0 provides a review of relevant report card approaches from national and international report card programs, and outlines some of the issues and requirements for developing a report card for the GBR region;
- Section 0 provides a synthesis and list of general recommendations that need to be considered for the development of a report card framework for the GBR region; and
- Section 0 outlines a process and pathway of activities for completion of this project for the remainder of this financial year.

2. Review of approaches to developing a report card

2.1 Definition and context

Environmental integrated report cards are increasingly being used around the world to define and measure progress towards environmental sustainability. Report cards can be an effective community and stakeholder communication and engagement tool and when used effectively, can be a key driver in galvanising community and political commitment and action. There are numerous examples of reporting frameworks. For instance, in Australia, State of the Environment (SoE) reporting has been required by statute since 1993 with reports from local authorities, regional bodies and state government agencies outlining the condition and trend of river systems within their respective regions. (GINRF, 2006; IWC, 2006; WADE, 2005; Richmond Valley, 2004; Mason et al, 2003; MBWCP, 2006; WAEPA, 2002). The Chesapeake Bay Program (CBP) (CBP, 2006) and the San Francisco Bay Index (SFBI) (TBI, 2005) are examples of ongoing IRCF programs with documented frameworks that aim to target and monitor intensive management efforts to improve water quality in these regions, while the San Francisco Estuary Institute (SFEI, 2006), reported to the public on the regional monitoring program for the area. Other overseas programs include an integrated report of the ecological condition of estuaries in the Gulf of Mexico (ECEGM, 1999), a 'State of the Nation's Ecosystems' report (Heinz, 2002) and the 'State of the Great Lakes' (EPA&EC,1995) in the United States.

Figure 1 illustrates the relationship of an IRCF to other key groups and programs and highlights the importance of community and stakeholder engagement. Past experience has shown that government organisations are willing to devote time and resources to develop and implement a report card because of the central role that they are seen to play both in informing management decisions and in providing an interface between environmental managers, stakeholders and the community. For instance, reducing nutrient loads in Chesapeake Bay (Harwell et al. 1999) or the Great Barrier Reef (GBR) in Australia cannot be accomplished without the participation of local farmers at the landscape scale, highlighting the important role community groups take.

Figure 1 also serves to illustrate the relationships between the IRCF— which we are primarily concerned with in this review—and operational monitoring programs which collect the required data. Whereas the focus of a monitoring program is the design and implementation of an effective sampling regime in order to maximise the information generated, an integrated report card differ in that they are primarily concerned with the valid integration and concise presentation of a range of heterogenous data sources. Furthermore, an integrated reporting framework will typically make use of existing monitoring data and/or will collaborate with concurrent efforts to guide the sampling process.

Integrated reporting frameworks operate on a broad scale and may comprise a number of components which are formed from integrating over multiple indices. Muiltimetric indexes are not new; we are already familiar with the index of leading economic indicators the consumer price index, the Dow Jones industrial average that describe the economic environment (Paul 2003). Although considered similar to established multi-metric indices, such as the well-known Index of Biotic Integrity (IBI) (Karr, 1981), IRCFs tend to have a broader focus, taking into consideration ecological integrity, the quality and extent of habitats, physical and chemical measures, and impact on human use of these resources (Paul, 2003).

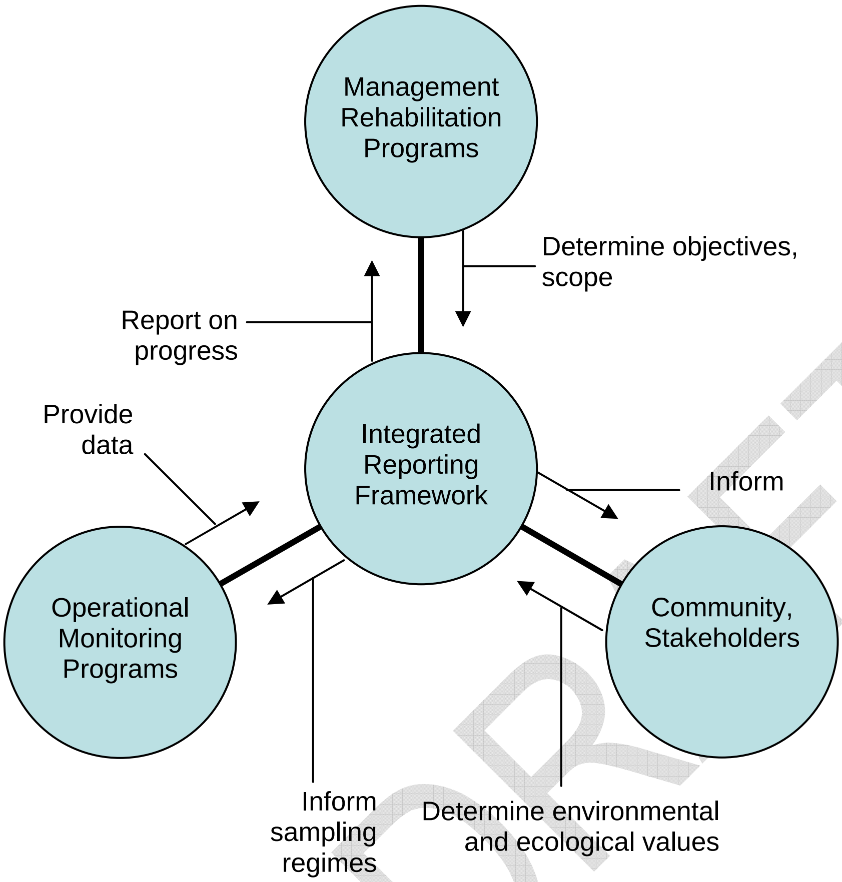


Figure 1. A conceptual diagram showing the relationship of an IRCF to other key groups and programs.

Although there is no formal definition an integrated report card (IRC) we can define a number of principles that should underpin a report card. It should:

- Be simple to understand, yet be underpinned by sound, quality-assured science;
- Integrate a range of data types and have indicators that have a sound conceptual basis;
- Harness existing long-term data collection systems enabling trends to be identified;
- Incorporate model outputs from catchment, hydrological, ecological and social models;
- Provide information not only on resource condition, but also on causality and management options;
- Support evaluation of the effectiveness of actions from sub-regional to landscape scales;
- Include social and economic dimensions to inform decision frameworks;
- Identify, address and incorporate knowledge gaps in our understanding;
- not only detect change in indicators of environmental health, but to diagnose causes and the system interactions among causes so as to provide useful feedback to support adaptive management responses.

For the purposes of this review we have adopted the following operational definition. An integrated report card (IRCF) is '*a scientifically valid framework for the integration and presentation of operational monitoring data in an accessible format for adaptive ecosystem management*'.

This definition captures the challenge of designing a report card for ecological condition that aims to statistically summarise a diverse range of data sources from a complex environment into a simplified form that remains scientifically valid. This definition also reflects the role that integrated report frameworks play within an adaptive management framework which involves ongoing monitoring and assessment (see Figure 1).

While acknowledging that each reporting framework addresses issues specific to a given region and a given set of environmental impact issues, we can summarise the key aspects of IRCFs applicable to most applications. These are summarised in Table 2. The first column captures the main characteristics of a report card, while the second column highlights the scientific contribution provided as part of the overall framework.

A general framework for report card development is captured in Figure 2, which outlines four sequential phases of the reporting process. The process is characterised by the close collaboration of scientists and decision-makers (Harwell et al., 1999) and at each phase there is scope for refinement through feedback loops. Note, this framework for report card development incorporates detail from Harwell et al. (1999), Smith & Storey (2001), Bunn & Smith (2007) and Negus & Marsh (2006).

The tasks outlined within each phase represent a non-exhaustive list. This is intended to be indicative of the tasks that need to be accomplished for most IRCFs. The phases in Figure 2 are relatively intuitive but we outline them briefly below for clarity. A discussion of each is presented in the sections that follow.

1. Define the scope and objectives of the report, and establish what existing resources are available.
2. Understand the system, drawing together and documenting all relevant theoretical and empirical knowledge. Conceptual frameworks and conceptual models play an important role here.
3. Establish a measurement framework that will address the constructs defined in Phase 1 in terms of the systems identified in Phase 2.
4. Establish an integration and reporting framework that will integrate and present the data generated in Phase 3 in a valid manner.

Table 2. Key characteristics of a report card and scientific contributions to its development.

Key Characteristics of a Report Card
Provide targeted information concerning anthropogenic impact on environmental or ecological assets.
Integrate multiple and heterogeneous data sources with spatial and temporal replication into global reports of natural assets (in terms of a conceptual framework such as the pressures, vectors[1], and condition of the assets).
Be presented in a format accessible to those with a non-technical background
Be supported by rigorous scientific and technical work demonstrating that the integration methods are valid.

Scientific Contribution
Conceptual frameworks and models that illuminate the key constructs and dynamics of the environmental and ecological systems
The methods to design, conduct, select and analyse measurements that are valid, reliable and efficient
Methods for integration, combination, and standardisation of measures into meaningful higher-order summaries
Identification of the source of observed ecological changes; natural, anthropogenic, and those that result from management actions
Assistance in the evaluation of potential management actions by evaluating their likely ecological impact
Critical evaluation as to the validity of measurement, scaling and integration methods.

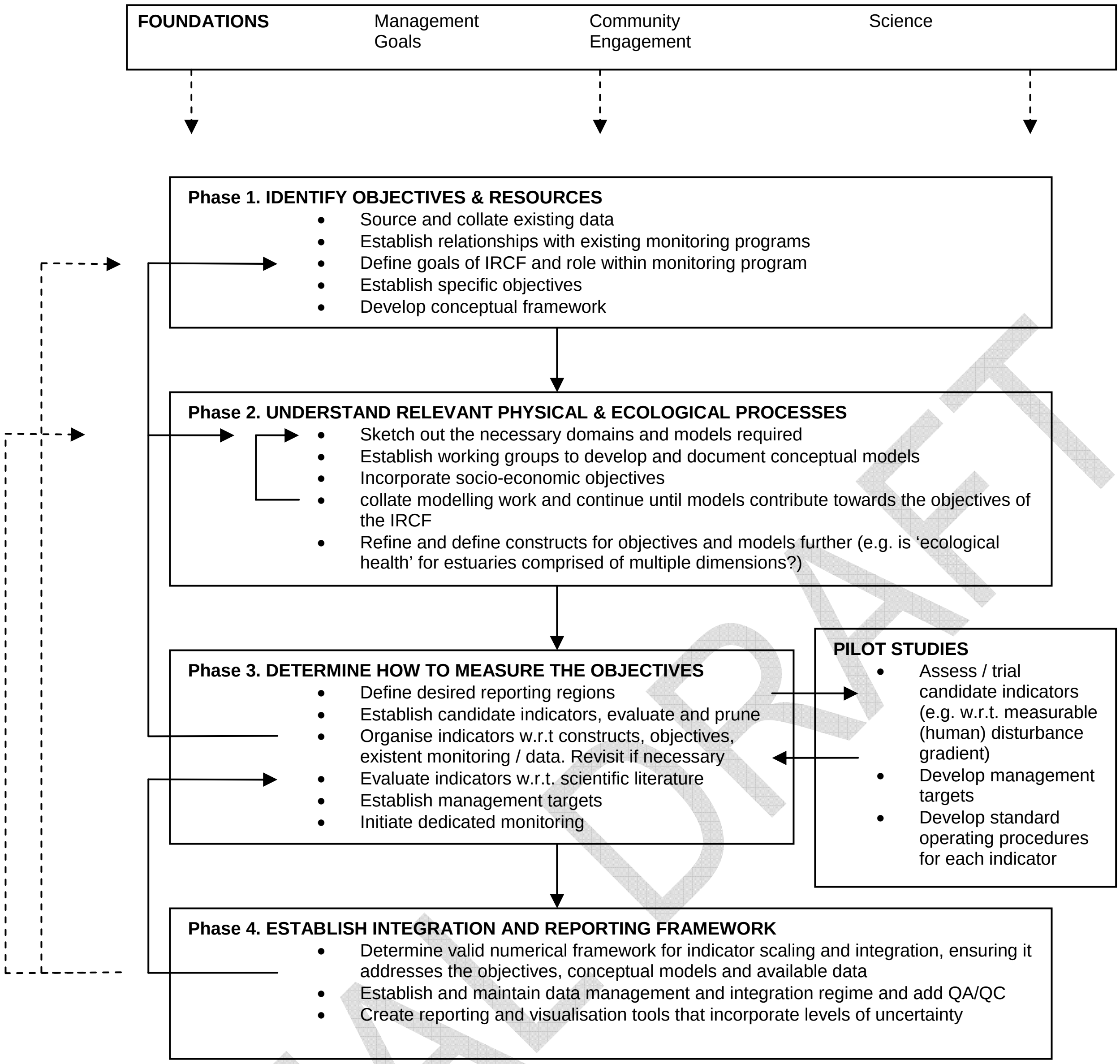


Figure 2: Phases outlining the development of an integrated reporting framework.

2.2 Phase 1: Identifying Objectives and Resources

In Phase 1 of the reporting process the objectives and goals of the report card are set. The goals may be based on ecological criteria that focus on protecting and restoring habitats, physical criteria where the aim is to prevent unacceptable levels of nutrient contamination or alternatively, socio-economic criteria where recreational experience and tourism is aimed to be enhanced or protected. Although the motivation may vary from region to region, in general these objectives are initiated either because there is:

- a consensus that human activities are leading to an unacceptable level of impact to a valued environmental resource,
- a resolution to implement a management program to alleviate impact and to rehabilitate the resource, or
- a recognised need for a monitoring and reporting framework to provide direction to the management program and to inform officials, stakeholders, and the community with respect to progress towards management goals.

The scope of the IRCF should suit the available resources. A scope that is poorly defined, too broad, or too ambitious will result in difficulties in achieving good results at subsequent phases. Scope definition should be clear, directed and simple, (where possible). The time and resources required for complete development of an IRCF and associated EMP structures should also not be under-estimated.

An example of a reporting framework that has achieved this is the Ecosystem Health Monitoring Program (EHMP) in South East Queensland, Australia. This was built upon a previous program that had been initiated in 1995. The framework was produced in 1998 followed by its first release in 2000 (MBWCP, 2006). In this program the goal of the management partnership was to identify waterways and catchments characterised by healthy ecosystems that support lifestyles in the region. The purpose of the EHMP is to measure the health of aquatic ecosystems in the region in terms of their biological, physical and chemical characteristics. The success of the EHMP is to a large extent the outcome of (a) nominating and maintaining a limited number of clear and specific objectives early in the program's development, and (b) establishing the scientific framework for tackling these objectives in a rigorous manner.

Occasionally, the use of existing data sources, rather than initiating a dedicated EMP can reduce, but not eliminate the significant development period required. The use of existing data on an ad-hoc basis will, in general, fail to fully satisfy the objectives of an IRF. Thus, the Gippsland Integrated Natural Resources Forum report card (GINRF, 2005) does exceptionally well at collating and presenting existent data but lacks some cohesion and scientific interpretability due to not having scope to establish and coordinate significant dedicated monitoring.

2.3 Phase 2: Understanding Physical and Ecological Processes

Conceptual modelling plays two roles in the IRCF framework shown in Figure 2. The first represents a broad understanding of the human-biophysical system (Maddox et al.,1999; Manley et al., 2000). This is often referred to as the *conceptual framework.* The second is one that is more specific and appears at the local level. This is often referred to as the *conceptual model,* which aims to identify components, processes and factors that drive the ecological health gradient. These types of models highlight how healthy ecosystems function and how processes respond to disturbance. They can also be useful for identifying possible management actions for rehabilitation (Bunn & Smith, 2007).

2.3.1 Conceptual Frameworks

There are a range of broad conceptual frameworks relevant to IRCF design, that despite differences in presentation and language all generally encompass representations of the condition of system, the pressures or drivers causing the change in condition and responses which can variously represent eith ecological consequences or management interventions .

Traditional Pressure-state Reponse models (PSR) outlined in Friend & Rapport (1979), form the basis of much of the State of Environment Reporitng (SOE) that occurs around Austrlalia. A variation of the PSR model variation is the drivers-pressure-state-impact-response (DPSIR) model highlighted by Jesinhaus (1999) and advocated by the European Environment Agency.

A weight of evidence approach, outlined in Downes et al. (2002) and recommended in the ANZECC guidelines (ANZECC 2000) uses a the 'total system' conceptual framework (Turner et al. 1998) is related to principles of adaptive management and informs subsequent stages in IRCF development. For example, this approach highlights the need to expend monitoring effort to assess the system at various points in the human-environmental interactive system. That is, indicators targeting human pressures (such as land clearing), vectors (such as water quality) and conditions (of natural assets).

Recently a pressure-vector-condition (PVC) framework has been adopted by Queensland Agencies for the implementation of the Stream and Estuary Assessment Program (SEAP) shown diagrammatically in figure 3. Here the pressure component reflects the natural and human influence to disturbance, the vector component reflected the hydrology and water quality and condition refers to aquatic organisms such as fish and macroinvertebrates (e.g. Negus & Marsh, 2006).

The Millenium Ecosystem Assessment (MEA) is a more recent framework that focuses on the linkages between ecosystem services and human wellbeing (Figure 4). This conceptual framework places human well-being as the central focus for assessment, while recognizing that biodiversity and ecosystems also have intrinsic value and that people take decisions concerning ecosystems based on considerations of well-being as well as intrinsic value. It assumes a dynamic interaction exists between people and ecosystems, with the changing human condition serving to both directly and indirectly drive change in ecosystems and with changes in ecosystems causing changes in human well-being. At the same time, many other factors independent of the environment change the human condition, and many natural forces are influencing ecosystems.

2.3.2 Conceptual Models

Establishing the relationships between drivers, stressors and ecological impact is facilitated by explicit conceptual models of specific biophysical dynamics. Conceptual models may take the form of qualitative narrative descriptions of relationships or a box and arrow flow-diagram. Sufficiently complex and exact conceptual models may even involve a mathematical treatment of the system. However, the most common and effective form of conceptual model is probably a hybrid graphical, text and arrow diagram (e.g. Figure 4 to Figure 6).

Conceptual models are extremely useful at highlighting the current understanding of core issues associated with anthropogenic stress on ecosystem processes. They may evolve and update as knowledge changes. The hypothesised relationships depicted in the conceptual models direct the design of pilot studies and the selection of indicators. For example, the influx of nutrients and sediments due to agriculture and clearing of vegetation may be thought to primarily act to reduce water quality, which then leads to a decrease in macroinvertebrate species composition. Indicators based on measures of land-use, riparian vegetation, various water quality indicators, and biotic indices of species composition and richness might then be recommended. A pilot study involving these indicators might be undertaken to confirm the existence and strength of these relationships. This is highlighted in Figure 4. Figure 5 illustrates the spatial connectivity of habitats and the effects of upstream processes on downstream systems. Similarly, Figure 6 represents the changes in nutrient and primary productivity processes that occur as a function of riverine input under low flow, intermediate and flood conditions.

BOX 2. Millennium Ecosystem Assessment Conceptual Framework

Changes in factors that indirectly affect ecosystems, such as population, technology, and lifestyle (upper right corner of figure), can lead to changes in factors directly affecting ecosystems, such as the catch of fisheries or the application of fertilizers to increase food production (lower right corner). The resulting changes in the ecosystem (lower left corner) cause the ecosystem services to change and thereby affect human well-being. These interactions can take place at more than one scale and can cross scales. For example, a global market may lead to regional loss of forest cover, which increases flood magnitude along a local stretch of a river. Similarly, the interactions can take place across different time scales. Actions can be taken either to respond to negative changes or to enhance positive changes at almost all points in this framework (black cross bars).

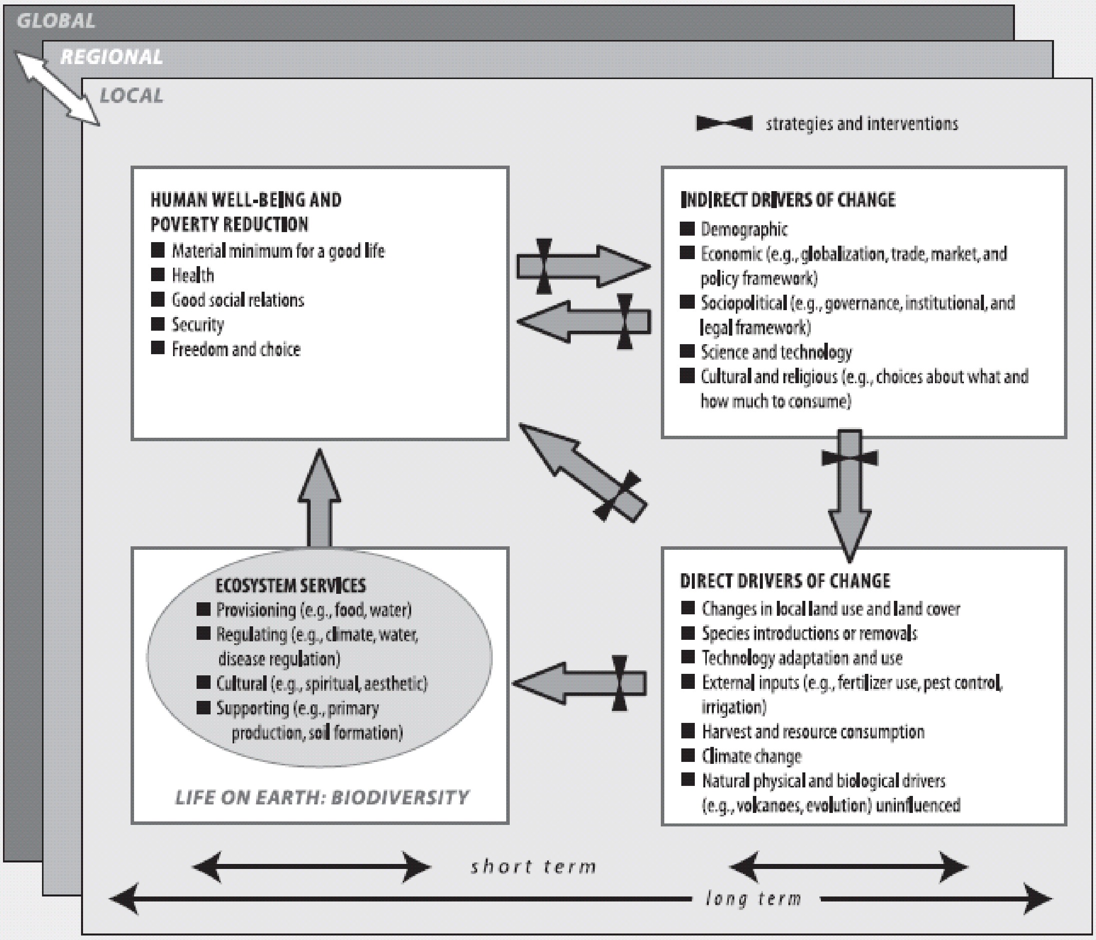


Figure 3. Conceptual Framework of the Millennium Ecosystem Assessment (from MEA 2006).

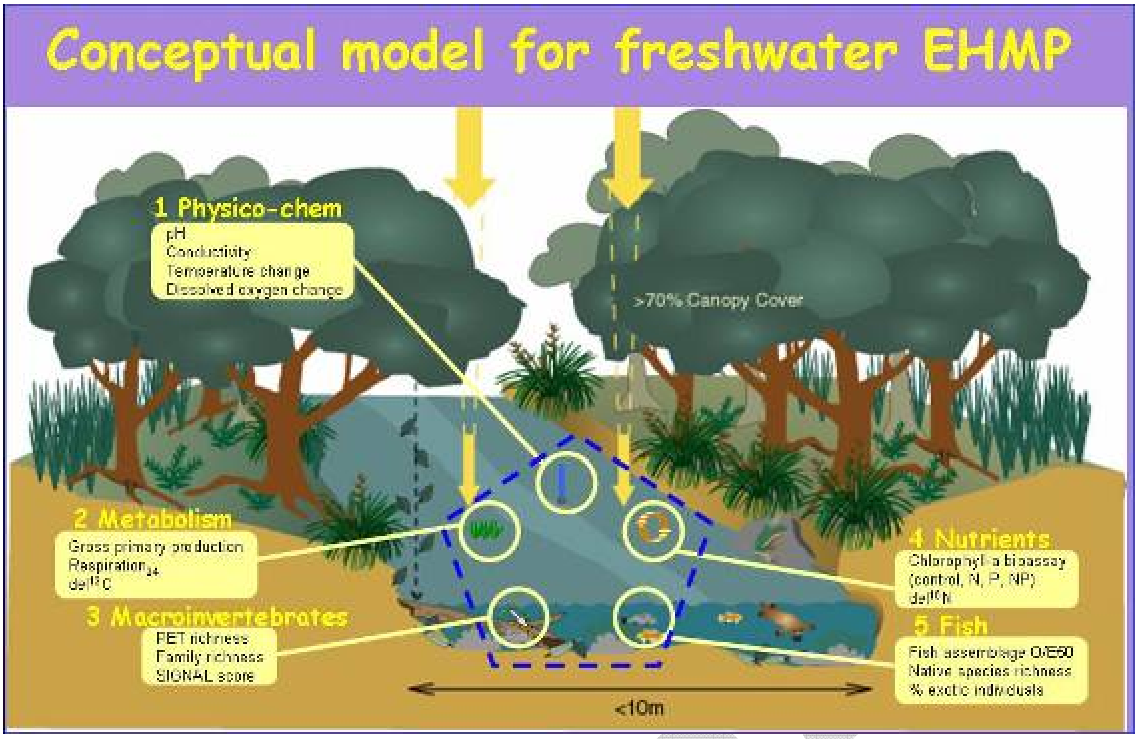


Figure 4: Example of the conceptual model used to define indicators in the EHMP study (EHMP: 2006).

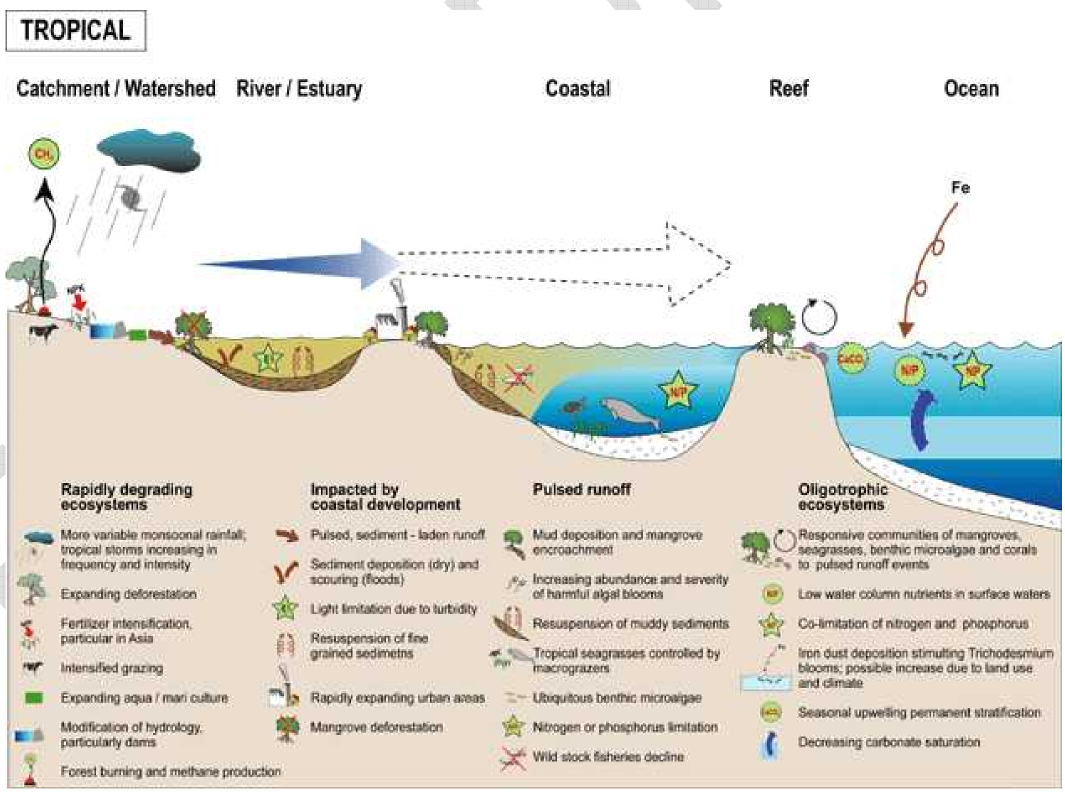


Figure 5: Example of a conceptual model diagram describing a tropical catchment-estuarine-coastal-reef-ocean system (Source: Bill Dennison)

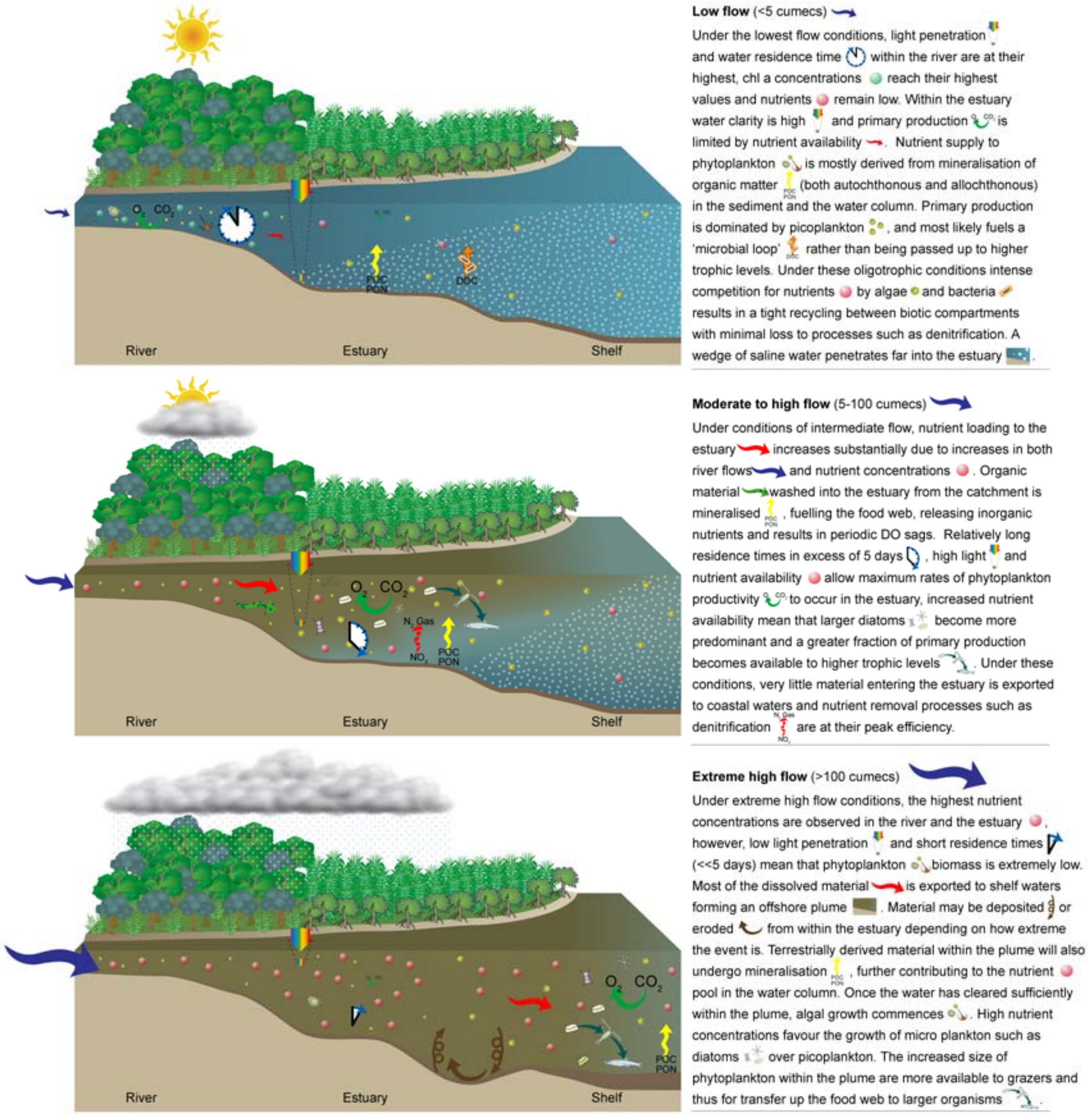


Figure 6. Conceptual diagram of nutrient processing in a wet tropics estuary under different flow conditions (Source: Steven unpublished)

2.4 Phase 3: Determine How to Measure the Objectives

Once the objectives have been defined, a process of identifying reporting regions (or regionalisation) is required followed by indicator development and selection. Each of these processes will be outlined in sections below.

2.4.1 Regionalisation

Regionalisation (or bioregionalisation) are terms used to reflect the process of sub-dividing a region into one or more homogeneous sub-regions or groups based on data that reflects differences in environmental and/or biological characteristics amongst regions. In the literature, regionalisation has been applied within three broad contexts: (1) derivation of the sampling design (Marshall et al., 2006; Smith et al., 2001), (2) identification of reference condition (Marshall et al., 2006; Negus & Marsh, 2006; Smith et al. 2001; Simpson & Norris, 2000), and (3) reporting (Accad et al., 2005; Pullar et al., 2005; Rochester et al., 2004). Note, although discussed separately below, regionalisation for these three areas of interest may also be developed in parallel.

Regionalisation for Sampling Design Purposes

Construction of a sampling design requires some stratification or “regionalisation” of the area of interest prior to selecting sampling points to ensure that the variability across the region can be adequately accounted for at the analysis stage. Here, the variability may be due to spatial, biological or environmental factors.

As highlighted by Marshall et al. (2006) if the natural variability across a region is moderately high, assessment of ecological condition at that same spatial scale becomes difficult to disentangle. This occurs because at the time of analysis, there is no sensible way of incorporating information on the source of the variability within the region. In these instances, it is clear that the sampling framework needs to consider the source of the variability initially. In doing so, however, care must be taken to ensure that an increase in the complexity of the sample design does not result in complexity at the modelling stage as highlighted by Negus & Marsh (2006).

Regionalisation for Identifying Reference Condition

Although regionalisation is used to cluster sites for sampling purposes, it has also been implemented with the aim of identifying sites in reference condition (Marshall et al. 2006; Negus & Marsh, 2006; Simpson & Norris, 2000; Wright, 2000). Here, reference condition refers to sites that have been subjected to minimal anthropogenic impact.

Reference sites become important when setting targets for indicators as values for a particular indicator in one region may be quite different in another. Negus and Marsh (2006) give an example of this for the Burnett-Mary and show how combining reference datasets from two regions exhibiting quite different ecosystems is not meaningful and therefore should be avoided.

Alternative approaches presented by Wallin et al. (2003) suggest defining reference condition using data from monitoring sites, predictive modelling and historical data in conjunction with expert information. They also highlight the advantages and disadvantages of each approach. For example, reference condition based on predictive modelling approaches are only valid for the region that the model was developed on and expert judgement applied in these situations can present biases which may hinder the regionalisation process entirely.

Regionalisation for Reporting

In the context of reporting, regionalisation attempts to break the region into ecologically meaningful, reporting frameworks (or spatial reporting units), representing a level at which stakeholders and community groups can engage in effectively. Often the regionalisation that is used for sampling and identifying reference condition is also the same one used for reporting (Negus & Marsh, 2006). However this may not necessarily be the case for all reporting frameworks as one may wish to keep the broader regional boundaries for reporting to stakeholder and community groups separate from those that attempt to identify reference condition.

For many of the broad scale studies summarised in
Table A1.1-

Table A1.5, regionalisation has evolved from clustering data which describes the climate, geology, soil type and topography of a region or from expert opinion or a combination of both (IWC, 2006; Pantus & Dennison, 2005; Smith et al., 2001). In these examples, the expert opinion can inform on the regional boundaries directly or it may help to identify appropriate variables that should be used in the multivariate analysis which defines the regionalisation. The former approach is one that was adopted by Rochester et al. (2004). Other studies have solely relied on using expert opinion to break up the region into reporting boundaries. These can be based on political boundaries or ecosystem types for example (Pawley et al., 2003; Sainsbury et al., 2003; Clark et al., 2002).

Approaches to Regionalisation

Whether the basis for the regionalisation is for designing a sampling regime, identifying reference condition or reporting on condition and trend there are a consistent suite of approaches that have been used in the literature targeted specifically at regionalising an area.

In terms of the attributes that are included in the regionalisation, two approaches have been consistently identified and discussed in the literature. The first, as highlighted by Marshall et al. (2006) can be thought of as a "top down" approach, where landscape drivers such as geology and soil type, site and climate variables are used to define regions with similar landscape characteristics. Applications of this approach include the work by Kuhnert et al. (2004) and Smith et al. (2001). The second uses a "bottom up" approach, which uses biological data to base the regional boundaries on, where the biological information may consist of fish or macroinvertebrates for example.

There is some debate about which approach to use. For aquatic based applications, biological variables are more appropriate as they consider drainage boundaries within the region (Marshall et al., 2006). However there are many examples which advocate the former approach and use landscape attributes to segregate the region of interest (Pantus & Dennison, 2005; Smith et al. 2001).

More recent advances have attempted to consider using the biological and environmental characteristics of the landscape to cluster or classify a region. While most have been developed in a supervised learning framework (De'ath, 2002; Kuhnert, 2003), that is, where the response variable is related to a set of inputs through some type of model, a few approaches have implemented an unsupervised classification (Ferrier & Guisan, 2006; ter Braak, 1986; Ferrier et al., 2002; Harch et al., 1996; Gower, 1971). Here, unsupervised learning refers to only having a set of inputs available for classification and no response with which to drive the classification process. Of these, the most recent approach outlined by Ferrier et al. (2002) and discussed in Ferrier & Guisan (2006) seems promising as it attempts to identify spatial pattern in the distribution of biodiversity at a broader level through generalised dissimilarity modelling or GDM. Care must be taken, however, when interpreting regions as the method will attempt to segregate regions based on a mixture of anthropogenic and non-anthropogenic impacts. Clearly more research is required to examine the results from this type of analysis in a reporting, reference condition and sampling framework, which are three areas that will be examined more closely in future work defined for the GBR.

Irrespective of whether a regionalisation is based on biological data, landscape attributes or a combination of both, a number of approaches have been used to construct the regional boundaries. These are described below.

Constructing Regional Boundaries

Earlier approaches to constructing regions relied heavily on expert opinion to draw boundaries with some reference to the raw data (Omernik, 1987). In this approach, maps of landscape attributes were overlayed on top of one another to determine visually, where the boundaries should lie. Although rather subjective, similar processes to this are still being implemented today (Sainsbury et al., 2003).

More recent approaches have used pattern analysis techniques such as clustering and ordination analysis that are extensively described in standard statistical texts (Digby & Kempton, 1987; Gauch, 1982; Mardia et al., 1979). See Marshall et al. (2006) and Simpson and Norris (2000) for applications of these approaches to biological datasets. Although simple to implement, these approaches can be ad-hoc, exploratory in nature and may be dependent on the similarity/dissimilarity metrics used. Furthermore, these approaches result in a "hard" style of clustering, where the number of clusters is subjectively chosen according to the pattern identified by the specific metric used. In many instances the number of clusters is not obvious and sites reflected by one or more clusters will be allocated to a cluster randomly.

An alternative approach to clustering is the “soft” style of clustering where sites obtain a probability of membership given a suite of modelled environmental attributes. This is often referred to as model based clustering (Kuhnert 2003; Fraley & Raftery, 2002). Recent examples of this approach use a combination of expert opinion and clustered environmental attributes (modelled in a Bayesian framework) to construct regional boundaries with respect to management constraints (Rochester et al., 2004; Accad et al., 2005; Pullar et al., 2005).

2.4.2 Indicator Selection

Overview

In general, a wide range of potential physical, chemical and biotic indicators may apply to particular IRCF goals for any given region (MWEG, 2006). Paul (2003) notes that indicators used should respond to anthropogenic and/or natural stress, and that an independent selection and testing process is necessary.

Indicator selection and organisation is largely guided by the overall conceptual model adopted (e.g. see Figure 7). For example, the State of the Great Lakes (EPA/EC, 1995) report explicitly adopts a pressure-state-human activities (response) framework for guiding indicator selection. Indicator selection was undertaken using expert elicitation (EPA/EC, 1995), considering indicators that had been used previously both in and out of the region. Indicator screening took place according to three criteria: the degree to which each indicator was necessary, sufficient, and feasible. For the Great Lakes, the principle aim was to adopt the minimum number of indicators sufficient to measure the dimension of interest. In a supporting document (Pawley, 2000) to the SFBI, the multi-metric approach is discussed in terms of its ability to demonstrate how actions affect ecosystem structure, processes and associated stressors within the adopted conceptual framework.

It should be emphasised that an IRCF will generally not place emphasis on reporting on individual indicators (though there are exceptions, for instance Cockburn Sound (CSMC, 2005)). As an alternative, indicators are organised into broad groupings (i.e. components) and the integrated measure is reported. To achieve this, the appropriate organisation of indicators into meaningful groupings becomes essential.

The criteria for indicator selection are many and varied. Much of the decision making needs to rest with the scientists who have local expert knowledge. In the context of the IRCF, however, indicators need to be evaluated in terms of the extent to which they contribute to the IRCF objectives defined in Phase 1 and how relevant they are to the conceptual model defined in Phase 2. They need to be well defined and have sound scientific meaning. Indicators also need to be readily understood, have a sound and practical measurement process and be cost-effective to use. In summary, the factors which should be considered in the selection of indicators consist of:

- *surrogacy*: cheaper or more easily obtained indicators in place of costly ones
- *specificity*: indicators specifically responsive to stressor
- *reliability*: the signal-to-noise ratio of the measurements
- *validity*: the indicator to be closely related to the valued resource
- *independence*: highly correlated indicators to be avoided
- *responsiveness*: responding quickly to stressors (Harwell, 1999).

It will often be the case that indicators that are direct measures of the condition of the valued resource will have good intrinsic validity, but may be slow to respond, do not highlight the processes or vectors contributing to the effect, and may be more expensive, and non-specific (i.e. are confounded by human and non-human impacts) (Harwell, 1999; Gentile et al., 1993). While it is more difficult to link indicators that target impacts, conditions or vectors directly related to the valued response may satisfy other important indicator inclusion criteria such as being highly responsive, efficient or specific. The indicators also need to be flexible enough to be altered if/when new process understanding or data describing the system at risk becomes available.

Since the goal of monitoring strongly determines the criteria for indicator selection, indicator selection for IRFs may be different in some respects to that of EMPs. For example, because of the IRF perspective of grading the state of the entire system, indicators that relate to broad, independent dimensions of ecological health are preferred. An arbitrary EMP that, for example, targets a single environmental issue or scientific investigation, may have a much more narrow focus.

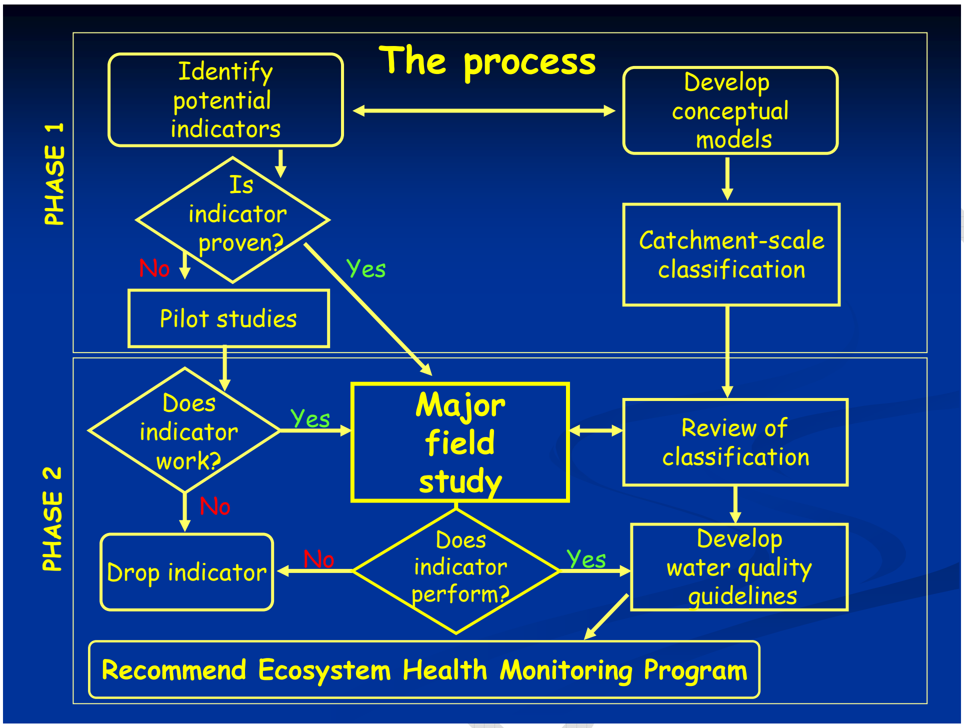


Figure 7: Indicator selection processes in the EHMP program in South East Queensland (Smith et al, 2001)

Calculation of a Single Indicator and Indicator Development

The calculation of a single indicator demands careful consideration. As an example, consider the calculation of a biotic indicator (percent abundance of taxa) in the Chesapeake Bay reporting framework (CBP 2000) in **Table 3**. In this table we see that there are a number of steps required to produce the final indicator score ranging from the calculation of the number of organisms in each sample to dividing the total by the number of replicate samples.

Table A1.4 summarises the organisation and selection of indicators across a number of case studies nationally and internationally. The Ecosystem Health monitoring program (EHMP 2006) is one example where the components of ecosystem health representing physical, chemical, fish, macroinvertebrates, nutrients and ecosystem processes were based on a pilot study and scientific analysis (Smith & Storey, 2001). Appropriate identification and justification of the components that made up *aquatic ecosystem health* helped deal with decision points in later conceptual stages, such as the presentation format used. A broad range of indicators were considered during a pilot study that assessed the utility of each predictor in predicting the human disturbance gradient (Fellows et al., 2006; Udy et al., 2006). This directly linked the components and integrated grades with the stated aims of the EHMP, which was to assess the degree of human impact on aquatic ecosystems.

Table 3: An example of the specification of a single biotic indicator from the Chesapeake Bay program (CBP 2000).

	Calculate Percent Abundance of Pollution Indicative Taxa:
Step 1	Calculate no. organisms in each sample per square metre.
Step 2	Sum total abundance over stations, sample dates and sample numbers
Step 3	Sum abundance of pollution-indicative organisms over stations, sample dates and samples
Step 4	Divide abundance of pollution-indicative taxa by total abundance
Step 5	Sum ratios by stations and sample dates
Step 6	Divide grand sum by number of replicate samples and multiple by 100

In other examples, indicator development was based around assessment questions that directly targeted particular aspects of ecological health (Thomson & Marshall, 2004). In the example presented by Thomson and Marshall (2004), one or more questions were organised into primary indicators, such as 'water quality', which were then grouped into broader dimensions. In a third example (TBI, 2005), indicators used ranged from those representing biological integrity, program performance indicators and compliance indicators to diagnostic indicators for identified relationships and vectors in the system (Pawley, 2000).

Socio-economic and Governance Indicators

Many programs incorporate socio-economic and governance indicators into the reporting framework. Socio-economic criteria relate to aspects of environmental quality that are primarily relevant to human use, rather than ecological importance while governance relates to the efficacy of environmental management programs. A number of programs directly incorporate socio-economic and management effectiveness components into their reports. For example, the SFEI has three primary dimensions which indicators are classified in to: *estuary habitats*, *biological resources* and *human use and governance* (Thompson & Gunther, 2004). The GINRF (2005) incorporates a *stewardship* component while the Bay Institute's SFBI includes a *Fishable-Swimmable-Drinkable* index. Cockburn Sound (WADE, 2005) incorporates human-use components, such as 'seafood safe for eating'.

Socio-economic and governance components of an IRCF should be handled with care. If the purpose of the management program is to improve the quality of environmental assets for human use, then it is appropriate to include socio-economic measures. However, there should be no implication that socio-economic measures may be taken as a surrogate for true ecological measures as there is often little or no relationship between them. For example, the establishment of a litter-free beach may be a source of satisfaction to human communities but will have little relevance to benthic communities if the area is subject to high levels of suspended sediment and nutrients.

Governance components should also be treated cautiously. On one hand they may be useful immediate indicators of positive management efforts, particularly since there may be a significant lag before the effects of these efforts appear in ecological measures. On the other, they are open to abuse by authorities who may be effective at creating the appearance of dynamic action, without the reality of having done so. The effectiveness of programs such as EHMP have been the result of having direct focus on scientific estimates of ecological health.

Finally, while an IRCF is primarily a scientific document, its function is that of a communication interface between community, public, and technical domains. Practitioners should ensure that social and political issues associated with IRCFs are not seen to undermine the scientific validity of the reporting.

2.5 Phase 4: Indicator Integration and the Reporting Framework

2.5.1 Indicator Integration

Multi-metric indicators are now accepted as the preferred method for evaluating the ecological health and integrity of an aquatic environmental resource (ANZECC, 2000a). The suite of indicators selected should also span multiple aspects of ecosystem health, such as organisation (e.g. biodiversity, species composition), processes (e.g. primary production rates) or direct measures of disturbance (such as riparian cover loss) (Rapport et al., 1998; Bunn & Davies, 2000). Whilst there are usually a large number of possible indicators and objective selection of indicators from the total set is a significant task in itself, there has been relatively few examples of an objective comparative approach (Bunn & Smith, 2007; Bunn, 1995). However, validated indicator selection has been performed for marine (Addison & Clarke, 1990) and freshwater (Bunn & Smith, 2007; MBWCP, 2006) ecosystems.

The key to constructing any multi-metric index is to ensure that it provides information that supports environmental decision making (Jackson et al., 2000). For the IRCF to be effective, it is critical that early and sustained engagement takes place with end-users to ensure that the questions being answered are in fact the questions being asked (Paul, 2003). The deliverables of an IRCF will in general represent a combination of information stakeholders require to modulate management programs and information required to report on progress to the community and stakeholders. Despite contributions from multiple interests, the goals and scope of the IRCF should remain explicit and targeted.

Before integration of indicators can occur, indicators must usually be transformed to a common grading scheme (e.g. 1-5 ranging from very poor to excellent). The nomination of critical values (which may be management target values or related to minimally-impacted site reference values) is naturally critical during this stage. The previous discussion of regionalisation for determining reference condition is therefore relevant here. From a scientific point of view, the act of transformation to a common grading scheme and integration may sometimes be less than satisfactory. While transformation must be justified and defensible as much possible, some degree of arbitrariness may need to be tolerated.

Some IRFs, such as the GINRF (2006), rely extensively on expert judgement rather than numerical methods for performing synthesis of multiple indicators. While a numerical integration framework is generally to be preferred, where resources do not permit a well-validated a defensible numerical framework, the use of expert judgement may produce more reliable results.

Methods for indicator integration are not new (Ott, 1978). The IRCF is based on a hierarchy in which data is progressively aggregated in a bottom-up process. The particular algorithms used for weighting and aggregation are at present relatively arbitrary and require development (Harwell et al., 1999). However it is clear that aggregation and explicit or implicit weighting schemes must be developed through consultation with experts in the specific field. Grinter (2004) provides some examples of the transformation of indicators to reporting scales with respect to reference levels.

We summarise the approach of Paul (2003) in **Table 4** for integrating indicators as an example of how integration is achieved in a reporting framework. From here the integration scheme can proceed in different ways depending on the regionalisation scheme and the reporting and presentation format required. Broader indices can be integrated into overall regional ecological health scores. Alternatively, they can be integrated initially over sub-regions. Regardless of the specific integration method chosen, the final data structure represents a hierarchical tree, with the total health of the entire region at the apex and individual indices for local zones forming at each of the leaves.

Table 4: Indicator integration as outlined by Paul (2003).

1	Select individual indicators for the combined index
2	Calculate index values. Consistent simplification of information contained in each indicator performed for each indicator via thresholds (Paul et al., 2000) (e.g. above standard / below standard / significantly below standard), resulting in (e.g. a 1-3 or 1-5 scale). With division according to reporting regions, this results in a region / indicator table.
3	Integrate individual indicators (e.g total nitrogen) over space $WI = \frac{\sum_{i=1}^{n} w_i I_i}{\sum_{i=1}^{n} w_i}$ where w_i accounts for different spatial extents of resources.
4	Integrate over time. This is usually necessary to address natural variability (e.g. seasonal, weather patterns) and other sources of measurement uncertainty.
5	Average within components (e.g. combine fish, macrobenthos, macroinvertebrates, non-native species indices) to generate component score (e.g. 'living resources').

A concern when performing indicator integration via averaging is the potential for a good overall value to mask low values for a particular component or index (Ott, 1978; Paul, 2003). This may be avoided by using a non-linear combination scheme such as setting the combined score to be to minimum of its constituent indices (Ott, 1978). More complex integration methods are naturally possible, but need to be weighed against possible difficulty in interpretation. We note that the organisation of indicators into components in itself is a form of weighting scheme. That is, if component A contains seven indicators and component B contains four indicators, the indices in component A are implicitly weighted less than those in B when considered at the component level. Appropriate definition of components to represent independent dimensions of environmental health of approximately equal importance will therefore resolve some issues regarding indicator weighting.

Different integration methods may be appropriate for different habitats or classes of reporting. The different approaches taken to multimetric integration of freshwater and estuarine / marine components of the SEQ EHMP illustrates this point (e.g. Figures Figure 8 and Figure 9). While partly this is the result historically different development approaches, these differences are also a consequence of the different environments being assessed and the scales of variability and the resources to undertake the assessments.

Assessment of Reference Condition

Reference levels define the scale at which the indicators of ecological or environmental health are evaluated. For IRCFs the issue of scaling the integrated components and final grades must also be considered. Reference levels and scaling have a major impact on the interpretation given to the report card grades. That is, they represent a major factor in determining the degree to which management targets have been met. In IRCFs, these topics are connected with the issue of (numerical) indicator integration, in which the contribution of each indicator to the broader components is explicitly or implicitly specified.

Reference values are playing an increasingly important role in environmental monitoring (Bunn & Smith, 2007; Davies, 1994; Reynoldson et al., 1997). For instance in ANZECC (2000), a greater emphasis is placed on the use of reference sites. These guidelines state that measures and values for biological and chemical indicators (particularly those that relate to stress) from suitable local reference waters should be used as benchmarks for assessing and maintaining biological diversity at a given site. Hughes (1995) discusses the use of reference conditions to establish acceptable environmental benchmarks.

Classes of indicator differ with respect to the degree to which universal reference levels may be established. It is often possible to refer to national or international guidelines to determine reference levels for physical indicators (e.g. pertaining to water quality). Due to the natural variation in ecological composition, biotic indicators such as indices of assemblage diversity may pertain only to a local region with particular physical characteristics (GESAMP, 1995). Despite this, in Australia the Monitoring and Evaluation Working Group (MEWG, 2006) has developed reference levels for a broad range of indicators, with similar efforts in other countries. The MEWG recommendations for indicators and reference levels for aquatic systems include physical (e.g. water quality measures, riverine structure and habitat integrity, changes to natural hydrologic regimes) and biotic indicators (e.g. fish, riparian vegetation, macroinvertebrates, and diatoms). If indicators vary with respect to natural factors, there may be considerable difficulty in establishing reference levels that are not confounded by non-anthropogenic effects (Beyers, 1998). In these cases pilot studies determining reference levels for minimally impacted sites may be considered. For example, Ward and Hutchings (1996) considered a range of several locally applicable bioindicators (polychaete, molluscs and crustaceans) to assess the effects of metal pollution.

Despite these challenges, the methods of applying the referential approach (i.e. valid scaling of measurements with an empirically determined range for healthy sites) have developed in sophistication (Chessman, 2006) and are commonly used.

Case Studies of Indicator Integration and Assessment

Table A1.5 in **Appendix 1** summarises the approaches used for integrating indicators across a broad range of monitoring programs. Cockburn Sound is one case study where the management program relies heavily on a suite of quality criteria, derived with community involvement. In their monitoring program, reference standards were used (WAEPA, 2002). A bench-marking process was also adopted to integrate the very large set of potential indicators, weighted with respect to ecological risk, with the aim of presenting a clear summary of the overall health of the region (WADE, 2005) as well as sub-regions within the Sound (for example, Jervoise Bay). Multi-metric components were employed in the Cockburn Sound monitoring program of which the most significant indicators were sediment tributyltin levels, seagrass health, chlorophyll a and light attenuation.

Several reporting frameworks, including the EHMP project in South East Queensland, develop condition ratings based on the percentage of sites and samples within a site or region that exceed defined criterion levels (Grinter, 2004). The EHMP (MBWCP, 2006) and CBP (2006) also detail methods for this approach in which integration over space and scaling with respect to reference levels take place in a single step.

A framework for sourcing, organising, scaling and integrating all indicators must be established For example, the SFBI (TBI, 2005) sourced data from a number of government departments, institutions and in-house monitoring effort (e.g. establishment of water quality monitoring stations). Indicators consisted of a variety of habitat extents, and a suite of specific water quality measurements. Water quality indicators were calculated with respect to national water quality standards. In this respect, the SFBI was typical of the IRCFs surveyed, establishing numerical frameworks for assessing components (such as water quality) in terms of a ratio of instances in which indicators were above threshold to the total number of measurements. The SFBI adopted methods developed by the British Columbia Ministry of the Environment, Lands and Parks (Zandbergen & Hall, 1998) for integrating indicators with respect to water quality standards (i.e. thresholds). Indicators such as ‘habitat extent’ (of, e.g. mangrove cover) were assessed with respect to pre-European settlement extent.

The EHMP established reference levels based on minimally impacted sites (such as macroinvertebrate community composition) and with respect to local water quality objectives (see MBWCP, 2006). The reference levels used by the CBP were developed with respect to the concept of total maximum daily load (CPB, 2006), which estimates the maximum levels of pollutants a water body can absorb and still meet water quality standards. Critical levels were determined in cooperative approach with respect to statutory guidelines and the scientific literature. An important contribution of the CBP was to model and explicitly link delivered loads of nutrients and sediments with resultant levels oxygen, water clarity and chlorophyll. Combined with an understanding of the tolerances of various biota such as fish, crabs and bay grasses to these environmental stressors, this systemic approach provided clear direction in setting pollutant targets.

We present one final example of indicator integration in Appendix 2, which is a detailed exposition of the Canadian Council of Ministers for the Environment (CCME) Water Quality Index (WQI) (CCME, 2001; Zandbergenn & Hall, 1998). From the perspective of IRCF development, it represents a general and well documented framework for indicator integration. In addition, we present a modification to this approach which considers a third dimension, space in the calculation of this metric.

2.5.2 Visualisation and Reporting

A key objective of an Environmental Monitoring Program is to provide accurate and concise information about the current status and trends of environmental condition (Paul et al., 2000; Kiddon et al., 2003; Johnson, 2006). Although the presentation of the results is critical for communication, most EMP planning tends to focus on monitoring and analysis, while the format is often an afterthought (Johnson, 2006). In an IRCF context, EMP results are not considered useful if the information cannot be effectively communicated to community stakeholders, managers, the media, and policy makers effectively (Johnson, 2006).

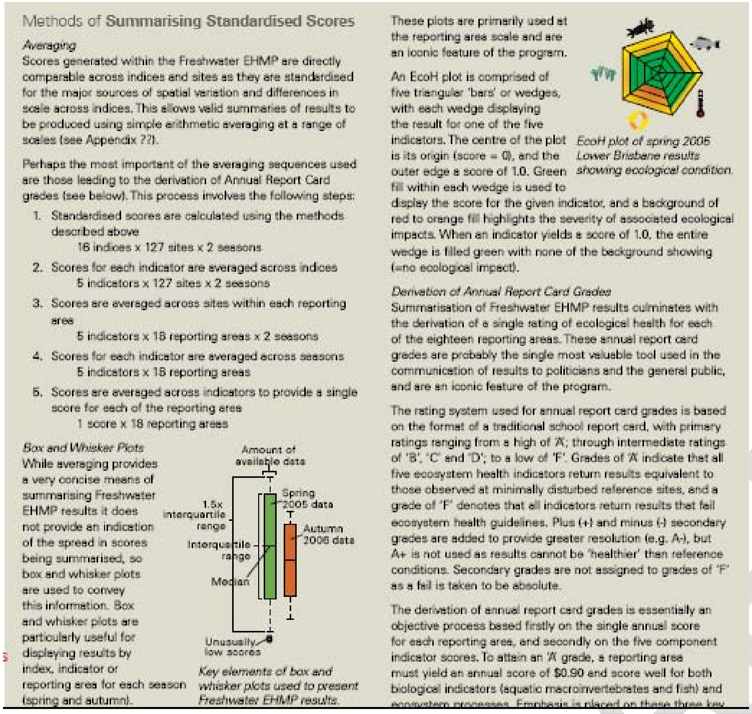
The report card must provide information at several levels of detail to meet the needs and expectations of the entire audience (Auricht, 2004; IISD, 2006; EHMP, 2006; McKane, 2003). A well-planned report card can successfully convey this information within one or two pages (McKane, 2003; CSMC, 2005; CBP, 2006; EHMP, 2006; IISD, 2006). For example, the EHMP monitoring program produces annual catchment report cards (Figure 8 and Figure 9) that contain a letter grade for ecosystem health, information about each indicator index, and a data summary showing the relative condition of the individual indicators (EHMP, 2006). In addition, the one-page report card is followed by a short summary of the catchment condition accompanied by the data, which are provided in the appendices. Multiple levels of information provide the reader with a general estimate of ecological health at-a-glance and also offer a more in-depth description for those that require that level of detail (see **Table 5**). A report card is also considered more credible if readers are able to easily obtain a more thorough understanding of the overall condition score (Johnson, 2006).

It is difficult to present multiple levels of information in a concise, straightforward, and intuitive manner (Auricht, 2004). Some monitoring programs present their results as lengthy reports (Heinz, 2002), but excessive text makes it difficult to interpret the results. Instead, an IRCF should include a careful balance of numbers, symbols, colours, maps, graphics, and text to communicate successfully with the audience (Tufte, 1983; Brewer, 1999). What follows is a summary of the ways in which these tools have been used to effectively communicate the results of an EMP.

Ecological health values are generally summarised and presented as ordinal data or ratios of variables. It is common to see scores categorized as poor, fair, good, or excellent condition (WRI, 2000; IISD, 2006; National Land and Water Resources Audit; McKane, 2003; Paul et al., 2000; Kiddon et al., 2003). Other IRCFs report values as either a percentage of areas affected by problem conditions (EPA, 1999), percentage of an area in compliance with standards (EHMP, 2006), or percentage of the management goal achieved (CSMC, 2005). These summaries are useful because the reader has an innate understanding of the difference between a good and bad score or a 95% versus 20% score, respectively. In some cases raw scores are provided, but they are generally presented in conjunction with a symbol (TBI, 2005) or a colour (Kiddon et al., 2003) to make them simpler to understand.

Colour can be used to quickly communicate ecological health scores. A logical progression of colour, such as a gradual change from blue to red or light to dark is most appropriate for continuous or ordered data, while different colours are more appropriate for categorical differences (Brewer, 1999). Colours can also have intuitive meaning, such as the ‘stop light’ approach used in the Cockburn Sound report card (CSMC, 2005). For example, it is common to associate green with ‘go’ or ‘good’ and red with ‘bad’ or ‘stop’. When colour associations are used appropriately, they help to give the reader a general understanding of ecological health (EPA, 1999; Paul et al., 2000; Kiddon et al., 2003; McKane, 2003; CSMC, 2005; EHMP, 2006; IISD, 2006).

Symbols are an integral part of a report card and are used in a variety of ways. Complex ecological indicators, such as the SIGNAL score (the average sensitivity score of taxa present in samples) used by the EHMP (2006) are represented using symbols, such as an insect, to make them simpler for a non-scientific audience to understand and interpret. Symbols, such as report card grades A to F, are commonly used to communicate ecological condition scores in a straightforward manner (TBI, 2005; EHMP, 2006; GINRF, 2006). In addition to a letter grade, the Gippsland Integrated Natural Resources Forum includes a stewardship rating, represented using a scale of 1 to 5 stars (GINRF, 2006). Other symbols, such as success meters, have also been used (CBP, 2006). In addition, the size of the symbol can vary proportionally with the importance of the issue being described by the indicator (IISD, 2006). Although all of these symbols are familiar to the reader and easy to understand, some information is lost by generalising. A combination of a letter grade and a score (TBI, 2005) or a colour and a score (Kiddon et al., 2003) enable the reader to perceive further differences when two indicators have the same symbol or category.



Methods of **Summarising Standardised Scores**

Averaging

Scores generated within the Freshwater EHMP are directly comparable across indices and sites as they are standardised for the major sources of spatial variation and differences in scale across indices. This allows valid summaries of results to be produced using simple arithmetic averaging at a range of scales (see Appendix ??).

Perhaps the most important of the averaging sequences used are those leading to the derivation of Annual Report Card grades (see below). This process involves the following steps:

1. Standardised scores are calculated using the methods described above
   16 indices x 127 sites x 2 seasons
2. Scores for each indicator are averaged across indices
   5 indicators x 127 sites x 2 seasons
3. Scores are averaged across sites within each reporting area
   5 indicators x 18 reporting areas x 2 seasons
4. Scores for each indicator are averaged across seasons
   5 indicators x 18 reporting areas
5. Scores are averaged across indicators to provide a single score for each of the reporting area
   1 score x 18 reporting areas

Box and Whisker Plots

While averaging provides a very concise means of summarising Freshwater EHMP results it does not provide an indication of the spread in scores being summarised, so box and whisker plots are used to convey this information. Box and whisker plots are particularly useful for displaying results by index, indicator or reporting area for each season (spring and autumn).

Key elements of box and whisker plots used to present Freshwater EHMP results.

These plots are primarily used at the reporting area scale and are an iconic feature of the program.

An EcoH plot is comprised of five triangular 'bars' or wedges, with each wedge displaying the result for one of the five indicators. The centre of the plot is its origin (score = 0), and the outer edge a score of 1.0. Green fill within each wedge is used to display the score for the given indicator, and a background of red to orange fill highlights the severity of associated ecological impacts. When an indicator yields a score of 1.0, the entire wedge is filled green with none of the background showing (=no ecological impact).

EcoH plot of spring 2005 Lower Brisbane results showing ecological condition.

Derivation of Annual Report Card Grades

Summarisation of Freshwater EHMP results culminates with the derivation of a single rating of ecological health for each of the eighteen reporting areas. These annual report card grades are probably the single most valuable tool used in the communication of results to politicians and the general public, and are an iconic feature of the program.

The rating system used for annual report card grades is based on the format of a traditional school report card, with primary ratings ranging from a high of 'A'; through intermediate ratings of 'B', 'C' and 'D'; to a low of 'F'. Grades of 'A' indicate that all five ecosystem health indicators return results equivalent to those observed at minimally disturbed reference sites, and a grade of 'F' denotes that all indicators return results that fail ecosystem health guidelines. Plus (+) and minus (-) secondary grades are added to provide greater resolution (e.g. A-), but A+ is not used as results cannot be 'healthier' than reference conditions. Secondary grades are not assigned to grades of 'F' as a fail is taken to be absolute.

The derivation of annual report card grades is essentially an objective process based firstly on the single annual score for each reporting area, and secondly on the five component indicator scores. To attain an 'A' grade, a reporting area must yield an annual score of ≥0.90 and score well for both biological indicators (aquatic macroinvertebrates and fish) and ecosystem processes. Emphasis is placed on these three key

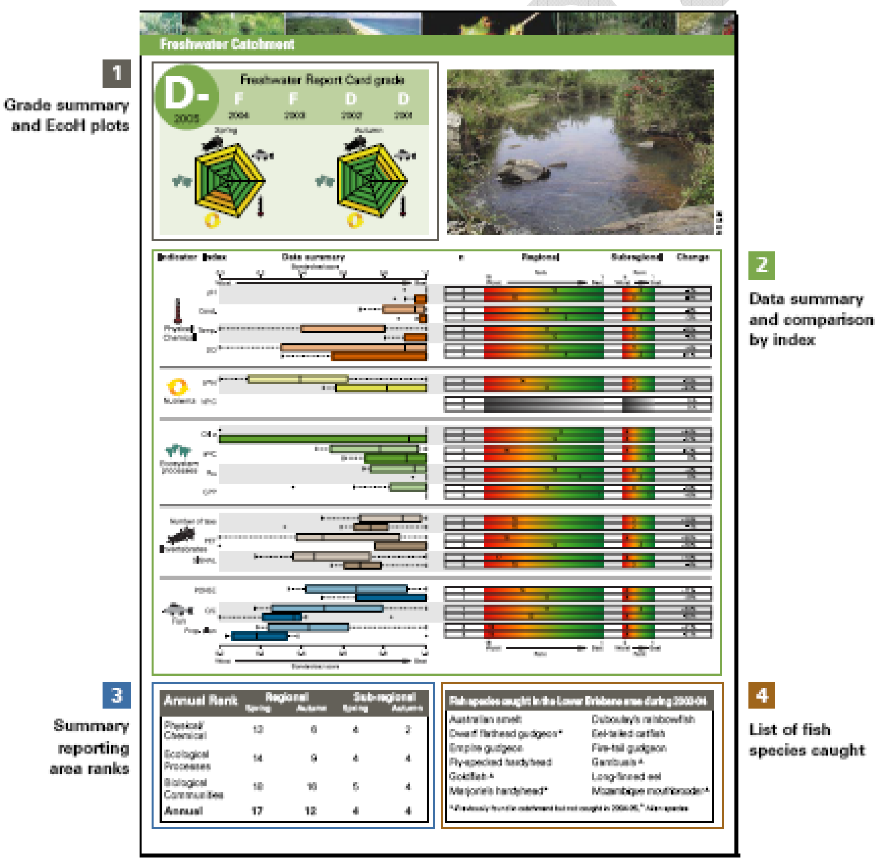


Figure 8: (A) Derivation and (B) visual presentation of EHMP Freshwater EcoH plots which provide information about the overall ecological health as well as the condition of indices and individual indicators. Figure from EHMP (2006).

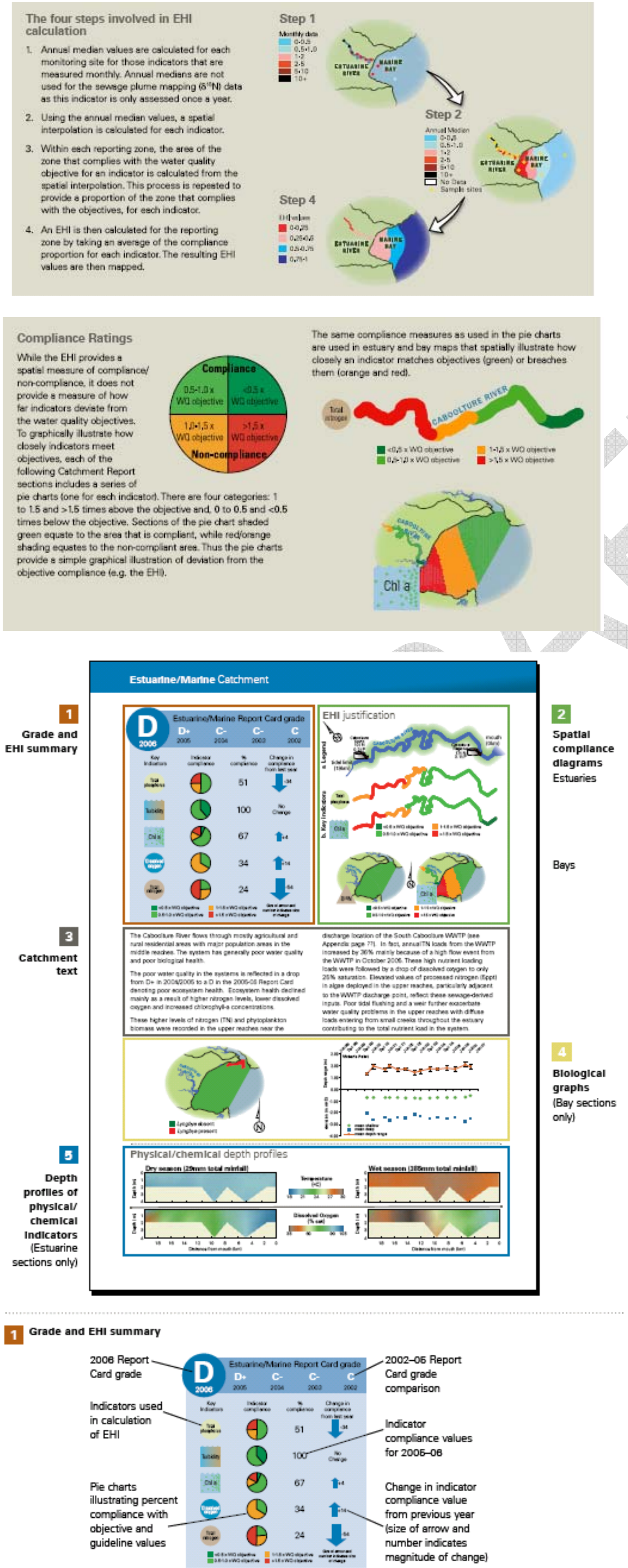


Figure 9: Derivation of the Ecological Health Index (EHI) and compliance ratings and visual presentation for the EHMP Estuarine / Marine Program (EHMP 2006).

Trend is an important component of an IRCF (Pantus & Dennison, 2005), which can also be represented using a symbol. For example, one simple representation of trend method is to include the letter grade or score for past reporting cycles (EHMP, 2006). Alternatively, a report card produced by the Australian Institute and the Newcastle City Council (TAI & NCC, 2000) used happy, neutral, and sad faces to represent the direction of the trend. A more intuitive method is to use arrows to show whether conditions are improving, remaining neutral, or declining (EHMP, 2006; WRI, 2000; TBI, 2005), while the size of the arrow can symbolize the magnitude of the change (EHMP, 2006). Trends can also be represented using graphics, such as line graphs or bar charts (Johnson, 2006; CBP, 2006; EHMP, 2006), to provide a more quantitative estimate of trend. It is important to keep in mind, however, that the current EPA water quality monitoring data (1992-2002) for the GBR catchments were unable to show any consistent long term trend across the region (Cox et al., 2005), and therefore it may be that new monitoring programs will need to be established specifically target trend analysis.

Maps provide a valuable tool for reporting condition across a geographic area. Many report cards include a map of the reporting area, but provide the ecological condition in a non-spatial format, such as a table (Paul et al., 2000; Kiddon et al., 2003). This makes it difficult for the reader to compare adjacent regions or regions with similar characteristics, such as elevation. When a map with condition ratings is provided it enables the reader to quickly identify spatial patterns in the condition and may help to identify potential sources of degradation (GINRF, 2006; EHMP, 2006; CBP, 2006; IISD, 2006).

There are many different combinations of numbers, colours, symbols, and graphics that can be used to produce an effective IRCF. However, there are a few key aspects that must be achieved in order to be successful. A reader with little scientific or environmental familiarity must be able to rapidly obtain and understand an accurate estimate of ecological condition. Multiple levels of information must be provided to satisfy the needs of a more scientifically-savvy audience. Finally, the report card is in many ways is the “face” of the monitoring program. Therefore, it must be accurate, the material relevant, and the entire product of high quality (Tufte, 1983).

To a large degree, the needs and demands of end-users and stake-holders will determine the qualities of the information that is reported. For example, the degree of spatial and temporal resolution (i.e. the size and number of defined regions, and the intervals between successive measurement and reporting) may be significantly determined by end-user needs. The use of a sophisticated and complex reporting format, in terms of the number and detail of attributes reported, should be balanced against the need for clarity and transparency. The most common approach in the case studies reviewed here is to present a total combined grade for the entire region, combined grades for subregions, and component grades for each subregion. Some presentation of historical trends at a long and short timescale is also to be recommended. Presentation of many IRCFs is provided on internet sites, which increases availability to the community, and allows for HTML techniques such as nesting information in a hierarchical format. The GINRF, for example, incorporates active code in PDF documents that provides extra information on portions of a map with mouse hovering. This provides a user-friendly method for providing extra information on local geographic areas on demand.

We recommend the implementation of a website that reflects the hierarchical organisation of the IRCF itself, with the main message presented at the top, with more technical information available deeper in the hierarchy.

Table 5. Reporting methods used in the SEQ Monitoring program.

The SEQ EHMP program provides three levels of data reporting in addition to providing a common data base manager, data storage and retrieval function. While it is anticipated that the institutional arrangements to undertake the reporting tasks will be different in the GBR, it is likely that the same three forms of reporting will be required to provide for a dynamic monitoring program capable of responding to management needs. The three important reporting levels are:

1. **Annual report card**. This is a synthesis document, similar to an executive summary, that makes the monitoring data easy to understand and accessible to the majority of the community. In addition to increasing public awareness on issues relating to the ecological health of our waterways, the report cards provides a stimulus to synthesis and review the monitoring data on an annual basis.
2. **Annual technical report**. The annual technical report provides more detail than is available in the annual report card on specific aspects of ecosystem health and various subcatchments. The technical report has been developed specifically for use by NRM officers in Councils and State agencies. It will also be relevant to others with scientific backgrounds including stakeholder groups. This report still provides synthesised data and often incorporates the current reporting year with patterns observed in previous years. As the program matures this report is also the appropriate place to publish trend analysis. The content of this report will depend on stakeholder needs.
3. **Monthly or regular data updates**. In addition to the annual synthesise (above) it is important that a monitoring program provide more regular updates of conditions so that managers can respond to atypical declines in ecosystem health. This is achieved in SEQ by providing a monthly report via email, within 6 weeks of data collection. This report is released as quality controlled data presented in a standard format so that people become familiar with interpreting the data, but it does not consume a large amount of personnel time to prepare.

Obviously the frequency of reporting and presentation of data will depend on the frequency of data collection. But it is important that a relatively automated system is established to ensure that all stakeholders receive a synthesised and easy to understand report on monitoring data as soon as possible after laboratory analyses and QA/QC checks are complete.

2.6 Discussion

The IRCFs considered here illustrate the distinction between programs that are designed to provide technical reporting and rigorous monitoring of the biophysical state of a particular ecological resource, and those that aim to provide a more general and descriptive summary of the environmental state with respect to social factors. We shall close with a consideration of the dimensions in which IRCFs vary, and incorporate recommendations for those considering IRCF development.

Some IRCFs reviewed here have strong socio-economic (human use / governance components), while others ignore these entirely in favour of validated measures of environmental and ecological integrity. This is a decision-point to be resolved early in the IRCF development. If the focus of the IRCF is ecological and scientific, it is worth considering avoiding socio-economic reporting in order to avoid distracting from the primary goal. Reporting on management actions is a separate matter, and is probably appropriate in most circumstances.

IRCFs differ significantly in the resources and time allocated to their development. A well presented IRCF is not necessarily backed up by strong and defensible science. Because of the complexity of the human-environment-ecological system, a defendable IRCF demands significant time and resources to implement properly.

IRCFs vary with respect to the degree they source existing data or are associated with a dedicated EMP, or management / rehabilitation program. It is recommended that the potential to leverage existing data sources be investigated in the early stages of IRCF development. However, existing and ongoing data sources will generally provide only part of the information needed by an IRCF. Significant dedicated operational monitoring will generally be needed, and should be budgeted for.

The scope of IRCFs varies considerably, in terms of geographic extent, habitats / ecologies considered, dimensions (e.g. whether human impact, impact vectors are assessed directly), and the range of components identified. In general, a highly focused IRCF with specific objectives and a well developed conceptual model will be more likely to meet its goals.

Most IRCFs considered are highly quantitative frameworks, although proper reporting and justification of the computational methods used is sometimes lacking. IRCFs which lack justification and technical specification of the quantitative framework used are open to being characterised as an exercise in public-relations. The term IRCF has been used previously to describe both attempts to broaden tradition economic measures of community wellbeing, as well as to describe the scientific approach to valid estimation of global measures of ecological and environmental health. This has the potential to cause confusion in the future development of IRCF methodology.

Regionalisation can play a role through all stages of development of an integrated report card. It can help identify appropriate sites to sample for a monitoring framework to capture the variability in the data. It can be used to identify reference sites and finally, regionalisation can be developed for a reporting framework. Depending on the objectives set, the regionalisation may be the same for each part of the reporting process.

In the GBR, we do not have the luxury of a monitoring program. Therefore we are reliant on the data already collected in each of its catchments. We do have the capacity however, to develop a regionalisation to examine reference condition and determine whether indicators are homogeneous within each region.

3. Principles and Issues for Developing a MTSRF Report Card

It is clear from the case studies presented in the preceding section that with the exception of the millennium assessment no other studies have attempted to bring together environmental condition reporting across an area as large as the GBR and Torres Strait (~ 767 000 km^2) with such a diversity of habitats, and drivers / issues to be considered. Furthermore issues of data paucity, particularly in the Cape York catchments will be an issue. Therefore, we will need to learn from previous studies where-ever possible, and in some cases new techniques will be required.

However we believe the right policy and institutional drivers are in place to move forward on the development phase for addressing the water quality issues. The Reef Water Quality protection plan and the recent formation of the Reef Water Quality Partnership — as a collective representation of endusers — are important for providing the articulation of the objectives, issues, scope, resolution and style of reporting that will be required to specify the science required for the development of the framework.

3.1 General principles and Issues

In the preceding review we identified a broad framework (Figure 2) of the key steps in developing a report card. In this section we summarise some the 'lessons learned' in previous IRCF practice to identify general principles that could apply to a MTSRF report card and the science, institutional and operational issues that will need to be addressed through the MTSRF.

3.1.1 Governance

- All significant IRCF case studies considered incorporated a dedicated institute for overseeing development and implementation of the program. Splitting resources and responsibilities between multiple agencies introduces significant co-ordination and communication overhead;
- Establishing an effective data management structure is critical. This is because an IRCF will generally incorporate vast amounts of data from a range of existing and dedicated operational programs.

3.1.2 Goals and scope

- The scope of the IRCF must suit the available resources and time-frame. An overly ambitious or poorly defined scope will make it difficult to implement subsequent development stages;
- An IRCF should include both the human and biophysical system, and provide clear direction in terms of management actions;
- A conceptual framework for establishing the types of indicators to be reported and their degree of connectedness and causality need to be agreed. Possible models include the traditional pressure-state-response approach as used in SoE reporting, the pressure-vector-condition currently being developed by the Queensland Government for its Stream and Estuary Assessment Program (SEAP), the Millennium Ecosystem framework which focuses on the linkages between ecosystem services and human wellbeing.

3.1.3 Conceptual framework and models

- Working groups of experts need to be set up and tasked with documenting the key dynamics and relationships of the biological, chemical and physical properties of the system. Sub-regions or special ecological resources may require more detailed and specific models. Documented work here provides the guidance and justification for subsequent indicator selection and organisation;

- The IRCF should make explicit the relationships between anthropogenic stressors, pollutant vectors, environmental conditions and ecological responses. Each class of indicator has its own strengths and weaknesses. IRCF components and indicators would ideally be drawn from each of these categories. This helps make an explicit connection between achieving management targets and gains in ecological health.

3.1.4 Indicator selection and organisation

- Socio-economic and governance components are critical components, however, their incorporation has sometimes resulted in diffusing the central message around condition and trend reporting. If the focus of the IRCF is primarily ecological health, we recommend they be handled with care;
- Determination of appropriate objective levels for indicators can mean the difference between a 'D' and an 'A' in the final report. Validating objective levels is a significant challenge that needs to be addressed in conjunction with the regionalisation and indicator selection and integration schemes;
- Due to the high intra- and inter-annual variability in water quality parameters within the GBR catchments, it will be important to define the flow conditions and field and analysis methods used to collect the indicators, so that there is consistency in reporting;
- It must be recognised that existent data sets / monitoring programs will not be ideal given the requirements of the IRCF. Goals and scope of the IRCF may have to be revisited if they are to be constrained by available data.

3.1.5 Regionalisation

- Use landscape attributes not subject to anthropogenic disturbance to develop the regionalisation across the GBR and compare with more recent approaches that model the biological and environmental attributes together in a clustering framework;
- Adopt a model based approach to clustering and develop a method (if possible) that identifies regions that map closely to hydrological features across the catchment;
- Clustering for the purpose of establishing reference levels may not be necessary (or justified, given the data). Consider modelling and accounting for the relationship between non-anthropogenic affected attributes and indicators on the entire data set;
- Use expert opinion to help guide the selection of attributes and the identification of boundaries as outlined in Rochester et al. (2004).

3.1.6 Indicator integration

- Indicators are combined after being standardized to a common scale (ranging, in general, from unacceptable / high impact to acceptable / zero impact);
- For a given class of indicators, integration simultaneously over time and space (within reporting zones) appears to be the most elegant method of accomplishing this operation;
- A general framework for numerical integration with some acceptance in the scientific literature should be nominated and then adapted to the specific integration needs of the report. The expanded CCME WQI strikes a good balance between transparency, interpretability, and sensitivity;
- Most studies transformed data into acceptable / unacceptable, hard thresholding scheme. While transparent, this approach lacks sensitivity. If sufficient information on indicators is available, consider adopting a soft-thresholding scheme (e.g. via the logistic function) that incorporates the expected sensitivity of an ecosystem to an indicator exceeding threshold.

3.1.7 Reporting and presentation

- The organisation of the report should be hierarchical, reporting at multiple levels of detail with regards to spatial, temporal and indicator specificity;

- The report will almost certainly include:
  - an overall ‘report-card’ summarising the state of the system with respect to objectives and broad components (combinations of indicators),
  - geographically specific report-cards for each of the reporting regions (catchments, estuaries, marine zones),
  - maps annotated with symbols indicating indicator compliance at specific locales / monitoring sites,
  - analysis and interpretation at varying levels of detail and complexity with reference to the conceptual models.
- Internet presentation is recommended to maximise accessibility to the public. Apart from the advantage of increased access, a hierarchical system of web-links allows readers to easily navigate to the global reports, but also to access detailed methodological information if desired;
- Active PDF technologies such as that used by the GINRF are a relatively new approach to presenting data in a graphical and interactive format. New technologies such as this should play a major role in effectively communicating scientific information.

4. Operational Issues and Proposed Work Plan

The following issues are raised principally in defining the objectives of the program, including the testing and incorporation of indicators and the operational testing of indicators.

4.1 Indicator development and testing

The GBR and Torres Strait is faced with the challenges of changing catchment runoff and loads due to land and water use, impacts of climate change ranging from bleaching and acidification to changing ocean circulation, and managing sustainable use and enjoyment of marine resources. Therefore the choice of indicators for a report card needs to accommodate this range of impacts.

In this report we do not define the indicators to be used in the GBR report card. Instead, we outline a range of issues that need to be taken into consideration when choosing indicators. Some of the issues are outlined below:

- Selection of indicators need to be in conjunction with conceptual model development of how the systems works;
- Multiple indices are required to report effectively, there is no magic single bullet;
- The indicators chosen need to reflect the connectivity between the catchments and marine (reef) environments;
- Where possible, the indicators need to be based on 'thresholds of concern';
- Indicators need to be mindful of time frames and lags between land condition change and water quality;
- The indicators may need to be chosen from monitoring programs that were initially set up for a different purpose, and hence the data may not be at the correct scale or resolution';
- Existing monitoring programs or future monitoring programs will only ever be able to cover a small proportion of the total GBR catchment area and therefore some gross assumptions will need to be made regarding the ability to extrapolate the results;
- The indices need to represent different parts of the pressure, vector, condition, response spectrum;
- The indicators are likely to come from a range of agencies and there may be different lab or field methods for measuring the indices. Consistency in data measurement and analysis techniques will be important;
- The indicators need to flexible as they may change over time as you process understanding becomes available;
- need to define the different indicator groups (e.g. water quality, habitat, reef health, socio/economic issues)
- Modelling outputs such as catchments loads can also be considered as potential indicators.

To progress the report card framework we need input from the other MTSRF programs on the following issues:

- A conceptual understanding of how the various biophysical and social systems work;
- The identification of any 'thresholds of concern' within these systems;
- A summary list of potential 'indicators' (based on the above points);
- A understanding of the standard methods used to measure/define these attributes;
- An idea of the spatial and temporal variability of these attributes;
- Data sets that show the spatial and temporal distribution of these data;
- If none of the above exist, then a description of any plans to investigate these issues as part of the MTSRF program

We realise that the above list of factors is unlikely to exist for any one catchment in the GBR for either biophysical or social data sets. Therefore we suggest that there is a need for an operational monitoring program to be set up in conjunction with the other field programs MTSRF programs. A pilot catchment may be a good way of testing a range of data collection and integration issues. The data collected can then be tested using a multi-scale environmental classification system or similar approach (e.g. Snelder and Biggs, 2002). Consideration of hydrological dynamics and stream connectivity will be important for determining the areas of human use that impact on a given aquatic location and can form the basis for a multiscale study which would consider issues of:

- latitudinal climate and landscape variation,
- definition and delineation of habitats,
- scales of variability (spatial and temporal) that occur within a patterned hierarchy of habitat and bioregion.
- Identifying regions of minimal human disturbance that can be used to define appropriate benchmark reference conditions and thresholds-of-concern
- Establishing human disturbance gradients would that can be used for validation of indicators, reference conditions, and regionalization schemes.

4.2 Defining the Endusers

Although the general relationship between the various water quality programs operating within the GBR region have been loosely defined and related (see Figure 10), there are still a number of outstanding issues and questions that need to be resolved by the MTSRF management and various partners for further progress to be made on the report card project.

Table 6 outlines a number of questions that CSIRO requires answers to, to assist us in moving forward with the IRC framework development. We seek answers to these questions as soon as possible so that progress can be made towards the next milestones for the IRC project.

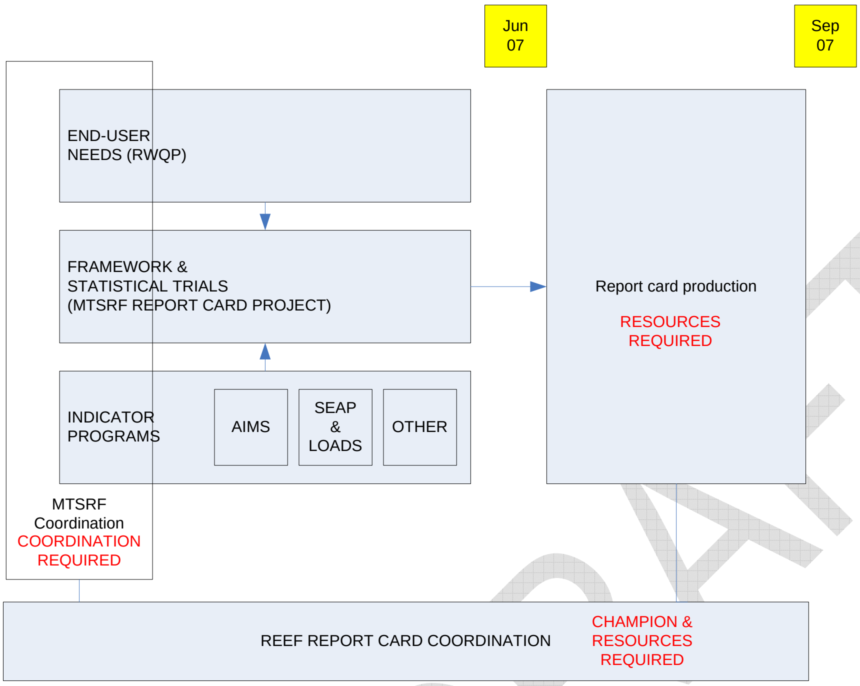


Figure 10. MTSRF report card project coordination and resourcing requirements.

Table 6: List of questions for the MTSRF management team and associated report card groups to resolve.

1. Who are the end-users of the report card?
2. What are the key reporting needs? Federal, State, Local Government or all of the above?
3. Who is developing the conceptual models for the project and when will they be completed?
4. Based on the development of the conceptual models, who is selecting the relevant indicators to be included in the IRC?
5. What are the spatial reporting units? Catchments, NRM regions, Local Government boundaries?
6. How frequently is the report card to be produced?
7. Should the report card report on ambient condition, event condition or both? If so, who has this data and is it of the same standard?
8. What are the key habitats to be reported on? Freshwater, estuarine, marine?
9. The Tully and Fitzroy have been chosen as pilot study areas. Is this appropriate?
10. Who is in charge of data storage and management of the various data sets to be included in the IRC? Who is organising the current legal data sharing arrangements/agreements?
11. How do other existing programs such as SEAP, Marine monitoring (GBRMPA/AIMS) and ambient and event monitoring programs (QEPA and QNRW) fit in with the MTSRF program? And who is responsible for sharing the data from these programs?
12. The timeframes of this process do not seem realistic (particularly if end-user engagement is important), are there options for altering what has been promised?

4.3 Work plan for completion of 2006-07 Contract

Table 7 describes the proposed timeline of activities for the IRC framework team between now and June 2007 when the final report providing a recommended framework and activities for IRCF development is due (see

Table 8).

Having reviewed the literature and made an assessment of the principle issues underpinning the development of an IRCF, we will now focus on:

(1) trialling a bioregionalisation of water quality issues in the Tully catchment, extending longitudinally from the upper catchment freshwater to the Reef;
(2) Reviewing and recommending initial indicators for inclusion and a process for trialling other candidate indicators developed through the MTRSF indicator projects;

While there have been some inevitable delays with contracts, data acquisition, enduser definition and coordination of this project with other MTSRF projects also contributing to the IRC, we feel confident we can deliver on the specified contract. However we wish to highlight the following issues with respect to the project timelines and scope of the project:

❖ We are going to start the initial data mining exercise on the Tully catchment unless otherwise instructed as much of the spatial data assessment has been carried out for this catchment (see Bruce and Kroon, 2006) which facilitates data acquisition;
❖ We intend to work with data that is easy to acquire, in the correct format (i.e. no major GIS data processing is required) and where data sharing licences already exist. Given the timeframes associated with this project we do not have time to actively chase data that is not in the correct format or which we need to develop new data sharing agreements for;
❖ We will move ahead with our testing of the different approaches for regionalisation and indicator integration without finalised conceptual models and rigorous indicator selection. This means, however, that the results we produce will represent 'examples' only and will need to be revised in subsequent years once the conceptual models and indicators are developed and agreed upon by all parties;
❖ There may be value in linking the rainforest regionalisation work being undertaken in 1.2.1 with our regionalisation work of the Tully to provide a more complete catchment to reef regionalisation that identifies the underlying connectivity and scaling issues;
❖ It is also worth noting that due to the 'water crisis' in the Murray Darling Basin (MDB), some of the CSIRO staff allocated to this project have been asked to give priority to MDB projects in the coming 6-12 months. This has a relatively minor implications for the MTSRF program, however, it has some potential for slightly delaying some aspects of this project.

Table 7: Outline of activities for CSIRO towards the IRC MTSRF project between now and June 2007.

#	Activity	Jan	Feb	March	April	May	June
1	Literature review of different IRC approaches						
2	Acquire potentially useful data sets for the Tully catchment						
3	Conduct a data mining exercise to see what data is useful and present report 2 as described in Table 8						
4	Decide on a set of test indictors that can be used for the trial data set						
5	Test clustering methods and regionalisation approaches on available data. Describe methods in Report 3 as described in Table 8						
6	Based on the above steps recommend some options for regionalisation and visualisation for the final report card						
7	Final (Report 4) submission: • Outline of initial framework and report card shell. • Present the recommended regionalization. • Recommend options for visualisation						

	of the reported condition and trend. • List of mature indicators and developmental indicators. • Outline spatial and temporal monitoring strategies for indicators. • Issues relating to data integration. Recommended framework for development and implementation in Years 2 to 4.						

Table 8: Contracted milestones for the MTSRF IRC project

For 2006/2007 Outputs Only	
Milestones – all CSIRO Responsibilities	**Date**
Signing of contract	
Report 1 submission: • Draft Report on existing approaches to an environmental condition reporting. • Revised plan for conduct of activities to be reported on under this project including an outline of issues with respect to regionalisation, selection of indicators, data integration and visualisation, and communication activities plan for Year 1.	28 Feb 2007
Report 2 submission: Progress report on: • Regionalisation methods, outlining issues with respect to collation and extraction of data, identification of important variables, clustering methods and progress with pilot area regionalisation. • Trialing of candidate water quality indicators considering: conceptual models, spatial and temporal characteristics, logistics of data collection with a focus on representativeness, redundancy, responsiveness to drivers.	27 Apr 2007
Report 3 submission: • Draft report recommending indicators of common relevance to end-users and researchers, boundaries of thresholds of concern for indicators, management pathways of relevance to indicators/thresholds, availability of datasets, to be potentially used in the prototype report card. • Identification of indicators requiring development. • Outline statistical issues to be addressed for pilot indicators.	31 May 2007
Transfer information to Projects 1.1.5 and 1.3.5	
Report 4 submission: • Outline of initial framework and report card shell. • Present the recommended regionalization. • Recommend options for visualisation of the reported condition and trend. • List of mature indicators and developmental indicators. • Outline spatial and temporal monitoring strategies for indicators. • Issues relating to data integration. • Recommended framework for development and implementation in Years 2 to 4.	11 Jun 2007

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Appendix 1: Summary Tables of Case Studies in Report Card Development

Table A1.1: Overview of the key programs that produced an integrated report card. Data collated jointly by the Environmental Protection Agency and CSIRO.

Name	Organisation	Internet URL	Contact Details	Overview	Purpose / objectives of report	Geographic scale
Ecosystem Health Report Card	Healthy Waterways SEQ	www.ehmp.org	Paul Maxwell QEPA 3362 9303 Eva Abal	Presents an easy-to-understand snapshot of the health of the region's fresh, estuarine and marine environments of SE QLD. Ratings are assigned to each catchment.	To communicate progress in improving waterway health of the region, to stakeholders (govt, industry, community). Provides insights into issues affecting waterways and the effectiveness of catchment management practices.	Large-scale regional program. Covers 18 major catchments, 18 estuaries and Moreton Bay. Extends 22672km2 including World heritage listed areas, significant wetlands, sand islands, etc.
Gippsland NR Report Card	Gippsland Integrated natural resources forum	www.ginrf.org.au	Carol Jeffs GINRF 16 Hotham st Traralgon VIC (03) 5175 7800 carol.jeffs@ginrf.org.au	Rates Gippslands Natural resources (assets) according to Condition (A-F Measure of land, water, biodiversity and air values of the natural asset and offsite impacts) and Stewardship (5 star measure of care and management of the natural asset by the entrusted govt. bodies, industry and the community)	1) Foster the strategic integration of NRM 2) Provide credible, independent and regular evaluation of NRM in Gippsland 3) Cultivate strong regional identity for Gippsland based on NRM	Large-scale, covers whole Gippsland region (30000km2). 'Assets' are not limited to waterbodies, but rather include forests, energy resources, aquifiers, ranges, lifestyles (coastal living).
Chesapeake Bay Health and Restoration Assessment	Chesapeake Bay Program (Watershed Partnership)	www.chesapeakebay.net	Bill Dennison Dennison@umces.edu	Part one concentrates on grading ecosystem health. Priority areas (Water Quality, Habitats & Lower Food Web, Fish & Shellfish) and their indicators are rated according to the percent of goal achieved. Part two focuses on restoration efforts. Five broad areas (Reducing Pollution, Restoring Habitats, Managing Fisheries, Protecting Watersheds, Fostering Stewardship) and associated efforts are compared to goals defined by the Bay states' river-specific cleanup plans and are expressed as the percent of	Provides watershed residents a clear and concise synopsis of Chesapeake Bay health and the on-the-ground restoration efforts taking place across its vast watershed. The draft report is divided into two parts and marks the first step in a three-year plan to expand and improve the Bay Program's annual reports on the Bay. Future assessments will integrate mapping components to detail geographic variations in Bay and watershed health with the overall goal of helping watershed residents better understand conditions in their part of the Bay watershed.	Very large area of around 165800km2. Crosses 6 US states. Cbay is the largest estuary in N.America.

Name	Organisation	Internet URL	Contact Details	Overview	Purpose / objectives of report	Geographic scale
				goal achieved.		
State of Southland's Coastal Marine Environment	Environment Southland - NZ	www.ara.org.nz	Scott Crawford	Web-based SoE report that moves away from simply reporting on condition, instead focussing on 'shared management goals' for the Coastal and Marine environment, that sit within broad themes. Goals from each theme are reported against using the Pressure-State-Response framework for SoE reporting. Themes include Biodiversity, Cultural Heritage, Natural Hazards, Resource Quality, Use and Development, Public Access, Navigation Safety, Landscapes and Natural Features. Freshwater, Land and Air covered in separate reports.	To measure the state of things as they are now, compared to the way the Southland community would ideally like them to be. To document the pressures on the Southland environment, and identify ways the community and environmental management agencies can respond positively to those (often conflicting) pressures, to achieve the best result for the shared coastal marine environment.	Quite large regional program 34000km2. Covers Marine and Coastal only but with a major human focus.
Regional Rivers Monitoring Programme - Data Report	Environment Waikato Regional Council - NZ	www.ew.govt.nz/	Paul Smith Environment Waikato POBox 4010 Hamilton NZ ph 0800 800 401	Provides info on the routine monthly monitoring of water quality at 100 locations across the Waikato region. Reports summary statistics, trends and simple grading (satisfactory or excellent, based on compliance with WQ (phys, chem.. & microbio.) Guidelines and Standards for freshwater.	To determine current WQ condition, the reasons behind it, trends and pressures. As well as inform management responses	Reasonably large scale regional program. Region covers 25000km2 however it does not incorporate marine and coastal areas.
Pulse of the Estuary: Monitoring and Managing Water Quality in the San Francisco Estuary	San Francisco Estuary Institute	www.sfei.org	San Francisco Estuary Institute 2nd Floor 7770 Pardee Lane Oakland, CA 94621	Focus on water quality, and specific trace element levels. Reports and summarises information from associated monitoring program, updates on management activities, and specific 'features' on specific issues: water quality, PCB contamination, phytoplankton levels, pyrethroid insecticide levels. Focus on identifying issues,	To make the most important information generated each year on water quality in the Estuary accessible to water quality managers, decision-makers, scientists, and the public.	Study region includes most sub-bays / inlets of the estuary, making a total of 4160 square kilometres

Name	Organisation	Internet URL	Contact Details	Overview	Purpose / objectives of report	Geographic scale
				exploring causes, and identifying management options.		
The Bay Institute Ecological Scorecard (San Francisco Bay Index)	The Bay Institute	www.bay.org	Grant Davis Executive Director (415) 506-0150 ext.26 The Bay Institute 500 Palm Drive Novato CA	A concern for the entire aquatic ecology connected with the region's bay, estuarine, and riverine areas. A 'classic' report card presentation providing a picture of the ecological condition of the bay as a whole.	Provide information that supports; stronger protections for endangered species and habitats; improved water quality; reform of water resources management; ecological restoration	Study region includes the estuary and the much broader watershed. Total area 70,000 square km, although actual area studied much smaller since only aquatic areas monitored.
State of Cockburn Sound	Cockburn Sound Management Council	portal.environment.wa.gov.au /portal/page?_pageid= 513,5414777& _dad=portal &_schema=PORTAL	Shop 1/15 Railway Terrace, Rockingham Beach WA 6168 +61-8-9591 3837	The report card is primarily concerned with directing management actions in order to protect the stated environmental values of the Sound. Emphasis is on co-ordinated, integrating and reporting information from regional monitoring programs to legislature.	Primarily a report to parliament to provide advice on sustainable development and to a management framework for declaring and protecting the values of the Sound.	Approx 150 square km incorporating Cockburn Sound itself

Table A1.2: Presentation of the report card for six case studies. Data collated jointly by the Environmental Protection Agency and CSIRO.

Name	Final Score Representation	Graphical Format	Web Delivery	Visualisation Methods	Audience	Frequency
Ecosystem Health Report Card	Final grades range from 'A' to 'F'. For Marine & Estuarine, Final EHI score calculates avg. % compliance across five parameters	Report card overview is an A4 10 page full colour pamphlet. Supported by a more detailed technical report of around 140pp - also full colour. Characterised by exceptional presentation methods, particularly with maps	Both EHMP and Healthy Waterways have dedicated websites. All results are posted on EHMP website in a non-interactive manner. Results are displayed by Catchments or an overview of parameter results are presented separated into Freshwater and Marine for the entire study area	Uses 'EcoH' pentagonal plots to depict condition of 5 indicator types in freshwater ecosystems. Uses pie charts and colour coded spatial illustrations (on maps) to depict compliance ratings for each indicator in marine and estuarine environs.	Stakeholders (local , state govt. research orgs, industry groups) and community.	Annual
Gippsland NR Report Card	Final grades range from 'A' to 'F'	Report Card is a simple A3 double sided, full colour sheet. One side has a simple but visually effective conceptual model style map with assets marked and ratings shown. 80page no frills companion doc also produced that goes into more detail about the ratings.	Report displayed using interactive PDF on the GINFR website. Initially the full Gippsland Report Card map is displayed. Each asset on the map has a link to a more detailed 3 page section describing that asset and it's scores. This information is not available in the normal PDF download for print purposes. Index of Stream Condition).	No visual representations of data in technical report. Interactive PDF report card provides star ratings on stylised regional map	GINRF, State and Fed Govt., Investors, Gippsland community, Vic Community	Annual
State of Southland's Coastal Marine Environment	F NA as no 'scoring' as such	Almost entirely web-based delivery. With a very small printed companion brochure (not available on site).	Almost entirely web-based delivery through a multilayered hierarchical site. Site houses an extensive amount of information, possibly to much, however navigational aids (hierarchical menu) allow the user to know their location in the site at all times. No interactive content, but site is attractive.	No visual representations of data.	The citizens of the Southland	Not established
Regional Rivers Monitoring Programme – Data Report	Summary stats for each parameter and location are presented. For each set guideline, two values are presented, the more stringent of which will	No frills report of around 30-40pp. Data presented in tables and TN, TP, Black disk, Dissolved colour presented using spatial contour plots and 5	Report available for download from the Environment Waikato site.	TN, TP, Black Disk and Dissolved Colour represented using spatial contour plots based on 5 year median values. No other visual representation of data.	Local govt., env. Managers.	Annual

Name	Final Score Representation	Graphical Format	Web Delivery	Visualisation Methods	Audience	Frequency
	indicate 'excellent' water. Stats are then assessed against the set guidelines to measure whether they fall into Satisfactory or Excellent compliance.	year medians. No interpretation of results.				
Pulse of the Estuary: Monitoring and Managing Water Quality in the San Francisco Estuary	Reporting of % goal compliance with water quality objectives and individual indicator targets. Reporting of historical data and trends. Integrated grades not presented.	Professionally laid out 80 page report with maximum accessibility in mind. 'Features' focusing on issues of primary importance to the estuary.	Report available for download as PDF. Site contains numerous databases and dynamic sources of information e.g. EcoAtlas	Conceptual models graphically illustrating e.g. contaminant pathways through food web used extensively. 'Bubble' plots on geographic maps illustrating pollution levels at individual sites. Interpolated contour maps also used. Colour-coded symbols on maps illustrating geo-spatial locations where trace elements exceeded thresholds. Extensive plotting of time series trends using bar, line graphs.	Broad: water quality managers, decision-makers, scientists, and the public.	Annual
The Bay Institute Ecological Scorecard (San Francisco Bay Index)	Report of grade point scores (e.g. B+) which are generated via transparent algorithms. Scores are provided for the bay as a whole rather than for sub-regions. Generation of grades via transformation 0-100 scale done by comparison with % of objectives achieved.	Professionally laid out reports in brief (2 page) and more detailed (15 pages) versions. Technical appendix (31 pages) also published.	PDF documents available via website.	Little of note in terms of visualisation methods	Citizens of the Bay region	Every two years
State of Cockburn Sound	A 'traffic light' scheme for presenting data in terms of the management response required was adopted. Three categories: green - monitor (below guideline), yellow -	Professionally formatted report card incorporating direct presentation of indicators (e.g. seagrass extent) along with 'grade' and supporting text for	PDF documents available on the website, which also has significant background information, maps, etc.	Apart from the 'traffic light' approach, the most interesting visualisation method was the use of different coloured symbols (e.g. green stars) on a map of the Sound to indicate indicator exceedance or otherwise for a particular monitoring site.	Formally, the State Parliament of WA. Implicitly, the audience is also the public and stakeholders.	Annual

Name	Final Score Representation	Graphical Format	Web Delivery	Visualisation Methods	Audience	Frequency
	(above guideline) investigate and where appropriate take action, red - (above standard) initiate management response.	each of the management zones. Annotated maps also provided with symbols indicating indicator state for each monitoring site. Detailed discussion on focus topics (e.g. mussel farming) along with analysis of the overall health of the bay.		Represents direct presentation of data yielding transparent results.		
Chesapeake Bay Health and Restoration Assessment	As % of goal achieved	Part one 12 pages, Part two 16 pages. Full colour, very nicely presented. Percentage goals presented visually using bars, while trends for some indicators are illustrated using simple plots that display the goal. No supporting technical report, as such.	Multilayered website provides detailed info on all data (including raw) and methods and interpretation/discussion of results. Actual report card appears as downloadable PDF. Very large amount of information on the site, however search capabilities make finding info simple.	Most parameters represented using single bar showing % towards goal achieved and then % of goal achieved over time. Dissolved oxygen visualised spatially using a map with different levels of DO displayed using different colours; DO displayed according to depth in the water using the same colour legend as map but represented as a 'side view' using a graph; colours used in sideview graph and map relate to oxygen needs of key species; these needs are displayed well using images of the species plotted against mg O2 needed, which is represented by the colours used in the graphs/maps.	Citizens of Chesapeake Bay	Annual - with a 3 yearly assessment that helps remove the impacts of annual weather-driven events

Table A1.3: Partnership arrangements for each investigated program.

Name	Partners	Data management
Ecosystem Health Report Card	Local councils, State govt., Industry, Universities, CSIRO (26 in total). Marine and Estuarine monitoring, interpretation and report writing - EPA Freswater monitoring, interpretation and report writing - NRW Report production - Healthy Waterways	Monitoring & Analyses undertaken by state agencies according to national standards. Methods developed by leading research agencies (csiro). Advice and analyses provided by research orgs (unis). Scientific dvice also provided by Scientific Expert Panel. Data managed by EPA&HW in form of database (QWD) that can be accessed for free by all stakeholders plus students/researchers. Consultants can access data for a nominal fee. Proposed management actions posted online in the Management Actions Tracking Database.
Gippsland NR Report Card	Federal, state & local govt.s, community NRM groups, research orgs, industry (48 in all)	No mention - Further information required. Suspect, that consultant is called upon to complete report by acquiring data from a variety of sources.
Chesapeake Bay Health and Restoration Assessment	Federal/State govt., Research orgs, Industry, Community (large #)	Data Management and Quality Assurance are governed by a number of dedicated workgroups. A Memoranda of Agreement has been signed by monitoring partners and specifies the development of a Chesapeake Information Management System (CIMS), which is an organised, distributed library of information and software tools designed to increase basin-wide public access to Chesapeake Bay information. The CIMS includes a variety of online databases, metadatabases and interactive tools. A great deal of effort has gone into the data management strategy /cims/index.htm. Quality Assurance is goverened by a dedicated program that monitors and tracks several environmental data sets. Guidlines are provided for data collection and analyses, with methods from different areas of study determined by sub-committee workgroups.
State of Southland's Coastal Marine Environment	5 partners (regional govt. bodies, local councils, maori resource management group)	Not discussed - need further information
Regional Rivers Monitoring Programme - Data Report	none mentioned	Collection, transport and storage of samples, methods of data verification and quality assurance fall under EW's ISO:2000 standard. Analyses are performed only at accredited labs. All data collected is stored in EW's WQ archiving database.
Pulse of the Estuary: Monitoring and Managing Water Quality in the San Francisco Estuary	San Francisco Regional Water Quality Control Board	Over 400 technical reports detailing methods and practices for dedicated EMP. Scientific standards for data collection well described and much data is available on the web site.
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The Bay Institute Ecological Scorecard (San Francisco Bay Index)	Partnership for a Healthy Bay	Perhaps due to the fact that data from existing EMPs is sourced, little information is provided regarding sampling methodology or management methods.
State of Cockburn Sound	12 Organisations (mainly government) involved in contributing data to the EMP. No specific collaborating organisations. Direct mandate from, and responsibility to state government (WA)	Aim is to consolidate data collected as part of the program into a single, publicly accessible database. Experimental and laboratory methods according to scientific standards and well documented.

Table A1.4: Summary of indicators and the monitoring program implemented for each program. Data collated jointly by the Environmental Protection Agency and CSIRO.

Name	Indicators used	Monitoring Program(s)
Ecosystem Health Report Card	**Freshwater**: PhysChem (pH, Conductivity, Temp - max & diel, DO - min & diel), Nutrients (Nitrogen stable isotopes, Nutrient bioassay) Ecosystem Processes (Algal growth, Carbon Cycling, Respiration and Gross Primary Producation) Aquatic Macroinvertebrates (No. of Macroinvertebrate taxa, PET, SIGNAL) Fish (PONSE - proportion of native species expected, Observed to Expected species (0/E50), Proportion of Alien Fish Species). ** Rainfall and wind also measured. **Marine/Estuarine:** Water Quality (N, P, DO, Chl-a, Water clarity (secchi, turbidity)), Coral monitoring, Seagrass depth range, Seagrass species and density, Nutrient processing, Lyngbya monitoring, Processed nitrogen tracking). **Management Responses:** (N Loads, P Loads, Sediment Loads, Land use)	Dedicated monitoring program. Freshwater 127 sites monitored twice a year (spring&autumn) Marine & estuarine 254 sites monitored monthly Driven by a number of collaborating agencies.
Gippsland NR Report Card	Condition indicators are divided into themes (Land, Water, Biodiversity and Air). Water condition indicators include Defined Environmental Flows, pH, P, EC, N, DO, Turbidity, Temp, Macroinvertebrates, Fish stocks, Extent and Condition of regionally significant wetlands.	No mention of monitoring in RC companion document. Will need to make contact to discuss this.
Regional Rivers Monitoring Programme - Data Report	DO (conc), D)(%sat) pH, Clarity (turbidity, Black disk (secchi)) Ammoniacal-N, Temp, Conductivity, Filtered absorption (at 340,440,780nm), Nutrients (N03,N+, N02, N, NH4, N, TKN), Microbiological [E.coli, Faecal coliforms & Enterococci (measured quarterly at 74 sample locations only)]	100 locations distributed evenly across Waikato region are sampled monthly. Sites in the region divided into 7 WQ zones as determined by expert panel. 5 extra locations are reported annually.
Pulse of the Estuary: Monitoring and Managing Water Quality in the San Francisco Estuary	Trace elements (mercury levels (fish tissue / suspended / sediment), PCBs, Selenium, Cynide, Copper & Nickel, pyrethroid insecticides) phytoplankton biomass. Impact factors such as human population levels, chemical use levels, and in-bay disposal of dredged material also considered.	Dedicated regional monitoring program managed by same institute.
Chesapeake Bay Health and Restoration Assessment	**Water Quality:** DO, Mid-channel Water Clarity, Chlorophylla, Chemical Contaminants (PCBs in white perch), River Flow and Nitrogen Loads reaching the bay. DO, Water Clarity and Chl-a rated over 3 year period as well as annually. **Habitats and Lower Food Web:** Bay Grass Abundance, Phytoplankton (Index of Biotic Integrity), Bottom Habitat (Benthic index of Biotic Integrity), Tidal Wetlands. **Fish and Shellfish**: Blue Crab Abundance, Striped Bass Abundance (Spawning Female Biomass), Native Oyster Abundance (biomass), Shad Returning to the Susquehanna River. **Reducing Pollution:** Wastewater Pollution Controls (N&P), Agricultural Pollution Controls (N,P&Sediment), Urban/Suburban Lands and Septic System Pollution Controls, Air Pollution Controls. Restoring **Habitats:** Bay Grasses Planted, Wetland restoration, Opening Rivers to Migratory Fish, Oyster reef restoration. **Managing Fisheries**: Single-species management, Multi-species management, Ecosystem-based management. For 5 species. **Protecting Watersheds:** Riparian Forest Buffers Planted, Watershed Land Preservation, Watershed Management Plans Developed.	The Chesapeake Bay Monitoring Program, begun in 1984 is a Bay-wide EPA/state cooperative effort. Comprising over 165 stations below the fall line*, the program combines efforts of Maryland, Pennsylvania, Virginia, the District of Columbia, several federal agencies, 10 institutions, and over 30 scientists. Nineteen physical, chemical and biological characteristics are monitored 20 times a year in the mainstem and many tributaries. A volunteer citizen monitoring program was started in 1985. Chl-a monitored weekly and monthly using remote sensing technology. Monitoring of weather-based events is also commonplace.
The Bay Institute Ecological Scorecard (San	**Water Quality:** Trace elements, PCBs, PAHs, dissolved oxygen, sediment **Habitat Extent:** tidal wetlands, tidal flat habitat, seasonal wetland habitat, riparian habitat, non-tidal diked wetlands,	Data sourced from multiple porgrams: e.g. San Francisco Estuary Regional Monitoring Program

Name	Indicators used	Monitoring Program(s)
Francisco Bay Index)	salt ponds **Freshwater inflow:** annual inflow, water year type, change in spring flow, seasonal variation, change in peak flow, **Food web:** chlorophyll a, rotifer abundance, % native copepod abundance, native mysid, averafe zooplankton size **Fish index:** abdundance, diversity, % native species, sensitive species **F-S-D:** Catchable fish, edible fish, swimmable, drinkable	for Trace Elements, California Department of Fish and Game (CDFG) Commercial Passenger Fishing Vessel database, Neomysis and Zooplankton Sampling Program
State of Southland's Coastal Marine Environment	**Biodiversity:** includes shellfish and fish stocks, populations of marine mammals, and information indicating species under threat of extinction. **Water Quality (public health)**: % of monitored beaches in each of the grades, ranging from Very Good to Very Poor; the number of times guidelines for safe levels of bacterial contamination are exceeded;% of monitored shellfish sites that exceeded water quality guidelines for safe shellfish gathering. **Use & Development:** number of resource consents or permits issued for use and development activities; community participation-voter turn-out at local authority elections, compared to the national average. **Landscapes & Natural features:** number of protected areas created to protect valued and distinctive landscape values; the number of significant geological features that are in reserves or protected areas.	Not discussed
State of Cockburn Sound	Indicators organised in hierarchical framework derived from ecological values **ECOSYSTEM HEALTH** Physical and Chemical: Chlorophyll 'a', Light Attenuation, Dissolved Oxygen, Temperature, Salinity ,pH Biological measures: Algal Growth Potential (Periphyton), Phytoplankton Biomass (Activity) Chlorophyll 'a', Seagrass: Shoot density, Depth limits Toxicants in water: Organics, Pesticides, Herbicides and Fungicides, Surfactants, Hydrocarbons, Miscellaneous/Others Toxicants in sediments: Organometallics (e.g. TBT) **SAFE SEAFOOD FOR EATING** Biological contaminants: Thermotolerant faecal coliform levels in water, Thermotolerant faecal coliform levels in seafood flesh, Algal Biotoxins Chemical contaminants in Seafood Flesh: Metals, Organic Chemicals **CLEAN WATER FOR SWIMMING AND BOATING** Biological measures: Bacterial Enterococci (swimming), Bacterial Enterococci (boating), Toxic algae, Physical measures: pH, water clarity, Radialogical: Gross alpha and beta activity Toxicants in water:	Targeted monitoring programs initiated by CSMC associated with report card (e.g. groundwater quality, tributyltin contamination in 2006). Most data gathering conducted by a range of government and non-government organisations. CSMC runs an EMP designed to co-ordinate, organise, and make accesible the data.

Table A1.5: Integration of indicators and report card development. Data collated jointly by the Environmental Protection Agency and CSIRO.

Name	Ecosystem Health Report Card	Gippsland NR Report Card
Overall integration framework & Comments	Quite sophisticated, using sound statistical techniques to calculate indices. Final scores subject to some degree of expert judgement. Large number of sample sites.	Scoring method is quite complex, but based on expert judgement rather than numerical integration system. Expert judgement process used in lieu of fixed guidelines/targets/objectives except insofar as individual indicators have associated scaling systems.
Indicator selection	Done through pilot studies, and assessment WRT components grouping, redundancy, relationship with the human disturbance gradient.	Done according to expert judgement based on what data sources are available for a particular resource in the last reporting period. Indicators organised according to themes (biodiversity / air land / water).
Indicator scaling / reference levels / thresholds	**Marine and Estuarine** Set with respect to SEQWRMS (2001) objectives. Thresholding in terms of meeting or exceeding objective. **Freshwater** Index values compared against guidelines to derived standardized scores (0-1) indicating healthy / unhealthy. Extensive development of reference levels WRT minimally impaired sites. Stratified random selection for reference and test sites used.	A combination of expert judgement with reference to scaling levels associated with indicators (such as Index of Stream Condition).
Interpolation, spatial and temporal integration	Linear and 2D interpoloation of physical / chemical readings performed for stream and marine areas, respectively. **Marine** spatial interpolation was performed at a cell resolution of approx. 0.5km square. calculated. **Estuarine** Linear interpolation used in estuaries with segments in the 100s of metres. % of total area in each reporting zone or % of stream length that meets or exceeds SEQWRMS (2001) objectives calculated. **Freshwater** integration within catchments: standardized scores averaged across sites and seasons.	Spatial integration done with respect to reporting regions. No interpolation
Indicator integration	**Freshwater:** 18 indices calculated per site, values compared to guidelines and standardised to a value between 0 & 1, scores averaged across indice combinations, sites and seasons, results displayed visually **Marine & Estuarine:** Annual median calculated for WQ parameters at each site, spatial interpolation used to create maps, calculated total surface water area(marine)/total stream length (est) that meets or exceeds the objective(%), Final EHI score calculates avg % compliance accross five parameters	Done non-numerically by expert judgement according to available evidence **Condition Rating** 1) Decide on weighting of condition themes for asset/resource 2) Decide on indicator weightings within each theme 3) Rate asset's performance against each indicator (Excellent=3, Good=2, Poor=1) 4) Determine relative performance out of possible score. 5) Multiply this by indicator weighting. 6) Total scores for each theme.7) Moderate for broad weightings decided in 1. 8) Determine rating (below50=F, 50-59=D, 60-75=C, 76-90=B, 91-100=A). **Stewardship Rating:** measured against 4 phases of adaptive management cycle (Plan, Implement, Evaluate, Improve).
Spatial reporting unit	**Freshwater:** With respect to catchment **Marine:** with respect to each estuary **Estuarine:** with respect to broad marine zone, e.g. inner or outer sections of bays.	Done with respect to the natural asset of significance. Natural assets varied with respect to their spatial definition (e.g. a particular national park or lake region)
Site clustering / stratification	**Freshwater:** sites organised into four groups: Upland; Lowland North coast and South Coast	None specified. Reporting units specified a priori.

Table A1.5 (cont.)

Name	Chesapeake Bay Health and Restoration Assessment	State of Southland's Coastal Marine Environment	Regional Rivers Monitoring Programme - Data Report
Overall integration framework & Comments	Integration methods quite transparent. Provides a useful guide as to progress towards goals. Scoring method mathematically based on latest data, leaving no place for political intervention in scoring system. Program on the whole is complex but well organised and very thorough. Excellent documentation and provision of publically available data.	Quite sophisticated, in that it a large amount of information is provided. However, it does not explicitly show any data or calculations.	Scoring method is a fairly simple guideline assessment. No break down into overall (grouped) grades.
Indicator selection	Evaluated 82 indicators based on five functions: Condition, Evaluate, Diagnostic, Communicate and Future (Hershner et al 06). Indicators used had to be consistent with previous assessment work. Indicators selected progressively by scientific advisory comittrees. The adoption of a large number of indicators, over time, into the CBP monitoring led to a relatively ad hoc survey design. Few common sampling locations are utilized for more than one indicator. Final IRCF attempted to address these issues.	Survey done to identify possible indicators from existing databases. Attempts to select indicators that are credible, sensitive, practical and relevent.	NA / not reported
Indicator scaling / reference levels / thresholds	Scaling of water quality measurements done with respect to WQ goals. % area in attainment used as an intermediate variable. Attempts made to account for exceedance of thresholds due to natural events. Detailed modelling of such criteria as light attenuation. Scaling of variables generally in terms of relative frequency of times statutory guidelines exceeded. Median value at each station for each month recorded. Seasonal median calculated Seasonal medians for each salinity zone used as threshold Seasonal medians of each station compared to appropriate threshold to pass or fail. Percent of stations within a segment passing threshold is then weighted by the segment's area in regional breakout.	Done mainly with respect to national and international water quality standards. Biotic indicators used (e.g. Macroinvertebrate Community Index) reported w.r.t. index-specific reference levels	NA / not reported
Interpolation, spatial and temporal integration	Extensive volumetric (1km x 1km x 1m depth resolution), 2D, and linear interpolation involved in calculations. See e.g. http://www.chesapeakebay.net/cims/interpolator.htm	Scientific methods and use of data to measure indicator performance are not divulged. Rather reporting is based around dialogue on the PSR aspects of each of the themes.	Spatial interpolation done over water bodies for several indices (e.g. secchi depth), but only for visualisation purposes
Indicator integration	Scores for each indicator are averaged and compared to goal/objective. Scores are allocated to individual indicators covering bay as a whole - not catchment-based.	NA. Indicator values reported for each sampling site directly on a map.	NA / not reported
Spatial reporting unit	Approx 16 reporting regions: rivers and bays. In tech docs they note that in early stages of the program did not have sufficient geographic resolution of reporting. In 2006 version discrete areas of bay used for reporting. Aligned, where possible, to tributory strategy boundaries and other strata (such as IBI).	Done with respect to the natural asset of significance. Natural assets varied with respect to their spatial definition (e.g. a particular national park or lake region)	NA / not reported
Site clustering / stratification	Similar water bodies grouped.	None reported.	NA / not reported

Table A1.5 (cont.)

Name	Pulse of the Estuary: Monitoring and Managing Water Quality in the San Francisco Estuary	The Bay Institute Ecological Scorecard (San Francisco Bay Index)	State of Cockburn Sound
Overall integration framework & Comments	Integration methods not applicable. Although information presented is integrated into a total picture of the bay verbally, numerical integration of different indices not performed.	Numerical integration methods reported and transparent. In some cases (e.g. water quality) quite sophisticated integration of multiple aspects of measurements with respect to standards. Conversion to a 0-100 scale followed by discretization into a 5-point scale.	Based on determining the key environmental values associated with the sound, establishing indicators for each, and integrating over stations and indicators on a 'all stations must meet standard' principle.
Indicator selection	Indicators selected according to stated goals and objectives of the program (intrinsic interest) rather than for the purpose of measuring a global construct.	Iterative indicator development as part of an adaptive management process. Indicator selection done by forming an expert scientific panel with local expertise.	Apart from the fact that selected indicators are derived from the 'environmental values' associated with the resource, cannot determine more formal methods for indicator selection.
Indicator scaling / reference levels / thresholds	Calculation, for each sampling period and contaminant, the percentage of samples that met water quality guidelines and objectives.	Reference Water quality assessed with respect to number of WQ indicators that exceeded national quality standards. Amount by which they exceed standards also considered. Indicators such as 'habitat extent' and 'chlorophyl a' standardised with respect to % historical extent / historical levels.	A two-tier system of thresholds has been adopted: guidelines and standards. Whether an indicator meets these threshold relate directly to the 'traffic light' that is reported. These are based on established "Environmental Quality Guidelines".
Interpolation, spatial and temporal integration	Temporal integration done by averaging measurements (in seasonal or annual increments)	Data collapsed over each of the Bay's 4 sub-regions (embayments), but also averaged over all stations for calculation of total score.	No interpolation reported. Spatial integration occurs as all monitoring stations in each reporting zone are considered as a group.
Indicator integration	Calculation of each indicator incorporated three different measurements (metrics): 1. number of variables whose objectives are not met (Scope) 2. frequency with which the objectives are not met (Frequency) 3. amount by which the objectives are not met (Amplitude)(method adopted by CCME)	After establishing reference conditions and converting each index to a 'grade point average', indicators were combined by averaging.	If any indicator does not meet standard in a reporting region, the respective 'traffic light' is activated. Maps provided to support report cards, with similar red-yellow-green symbols indicating state at individual monitoring stations.
Spatial reporting unit	No explicit division into reporting regions. Data presented either for the estuary as a whole, or direct reporting of monitoring results at each station on a map. Integration of data for presentation done varying with the topic considered, but usually according to bay / inlet.	For the report-card proper, reporting is made for the Bay as a whole with no sub-divisions. Mention is made of integration within 4 sub-bays ('embayments') in supporting technical material.	Reporting made according to three divisions of the Cockburn Sound area: the broad central region of the bay (classified high protection area) was reported on separately from mainland or island coastal regions (classified medium protection areas). Further, Jervoise Bay was (also a medium protection area) was considered separately.
Site clustering / stratification	No explicit division of study area into subregions.	Some mention of ecological zones in literature on development of the index, but unclear how/if this affects index calculation.	Differential standards for objectives have been set with respect to the level of human use in the local region. .

Appendix 2: A General Framework for Indicator Integration

Indicator scaling with respect to reference levels is integral to indicator integration. That is, variables must be transformed to the same metric before being integrated or expressed in terms of exceeding thresholds.

The CCME WQI (CCME, 2001; Zandbergenn & Hall, 1998) considers three factors where indicators can exceed thresholds: (1) *scope* (the proportion of distinct indicators that exceed threshold), (2) *frequency* (proportion of failed tests) and (3) *amplitude* (degree to which failed tests exceed threshold). The WQI is calculated by a normalised sum of these factors *F*

$$WQI = \frac{\sqrt{F_1^{\,2} + F_2^{\,2} + F_3^{\,2}}}{1.732}$$

which is scaled to lie in the range 0-100 by the denominator. In this expression F_1 and F_2 are simple proportions:

$$F_1 = 100 \times \frac{\text{\# failed indicators}}{\text{total \# indicators}},$$

$$F_2 = 100 \times \frac{\text{\# failed tests}}{\text{total \# tests}}.$$

Given I failed, let t_i be the i^{th} test that fails, and o_j be the water quality objective criteria for the j^{th} indicator. Then the normalised excursions are

$$e_i = \begin{cases} \dfrac{t_i}{o_j}\text{-1 if the criteria is } t_i < o_j \\ \dfrac{o_j}{t_i}\text{-1 if the criteria is } o_j < t_i \end{cases},$$

and the third factor is given by

$$F_3 = \frac{\bar{e}}{.01\bar{e} + .01}$$

with $\bar{e} = \frac{1}{I}\sum_i^I e_i$. Here, the term excursions refers to the reading at a site which exceeds the threshold for that indicator.

As a general framework, the most attractive feature of the CCNE's WQI is its equal weighting of each of the factors with respe ct to thresholds or objectives. Thus, all other aspects being equal, threshold excursion occurring over a number of indicators produces a worse index score than excursions restricted to a single indicator. Excursions occurring more frequently (i.e. distributed over a larger number of tests) tends to produce a worse indicator. Finally, given a fixed number of excursions, poorer *WQI* scores are generated when excursions exceed threshold by a higher degree. Each of these aspects related to tests exceeding threshold is weighted equally in the final calculation.

The above expression only considers the proportion of failed tests, which implicitly assumes that each test provides information about the state of the entire region over the length of time monitoring took place. However, for a given reporting region, tests tend to be distributed in both space and time.

A possible extension to this metric is one that incorporates a three dimensional assessment of a score that takes into account both space and time. If we assign each point in the three dimensional space (two dimensions for space and the third for time) to be in the same state as its nearest neighbour it is possible to define the following expression

$$F_4 = \frac{\text{Volume of failed region}}{\text{total Volume}}$$

with

$$WQI_B = \frac{\sqrt{F_1^{\ 2} + F_2^{\ 2} + F_3^{\ 2} + F_4^{\ 2}}}{2}.$$

This approach would be most suitable for natural two dimensional regions such as marine zones. For rivers, which may be abstracted as having a linear extent, F_4 can be implemented in 2D.