THE HEALTH OF LAKE ILLAWARRA - A STATUS REPORT

R.J. Morrison and R.J. West

Oceans and Coastal Research Centre, Environmental Science
University of Wollongong, NSW 2522, AUSTRALIA

ABSTRACT

Lake Illawarra is a coastal water body in south-eastern Australia that has been dramatically influenced by human activities. This paper attempts to assess the current status of the Lake from an ecological health perspective. The issues associated with defining ecosystem health and the selection and use of indicators are discussed. Lake Illawarra is, geomorphologically, a middle-aged estuary, which, in terms of responding to recent stresses, is in reasonably good condition. Detailed analysis of current stresses and their possible impacts is difficult due to the nature of most of the available information Much of the data has come from short-term studies using a variety of techniques, making historical comparisons difficult. Nevertheless, indications of ongoing stress are apparent. Information gaps have been identified, and recommendations for future assessments of the condition of the Lake are presented.

INTRODUCTION

Lake Illawarra is a coastal water body that has been significantly affected by human activities within the Lake itself as well as in its catchment, especially in the period post 1800. Its current ecological status has been described as:

- ‘High natural sensitivity (risk), with a modified catchment condition and severely affected lake condition’ (New South Wales Healthy Rivers Commission, 2002)
- ‘Overall the environmental health of Lake Illawarra appears to vary due to seasonal variations and influxes of elevated catchment nutrients following heavy rain’ (WBM, 2003).

Describing the ecological status (or health) of a lake and its catchment is difficult, as ‘health’ will vary over time and different people (e.g., ecologists, coastal engineers, geomorphologists, fishers, swimmers) have different perceptions of what constitutes a healthy system. In addition, the response to queries on the status of ecosystems will vary with the specific question that is asked. Thus, we are dealing with a complex issue, where definitions are somewhat subjective and the information base is limited.

This paper provides a review of selected information about Lake Illawarra and its catchment, in an attempt to assess the current status of the system, the impacts of current management activities and also to indicate where new problems may arise.

DEFINING HEALTH OF AN ECOSYSTEM

The concept of ecosystem health is the subject of controversy and debate, and the definition is extremely difficult because of the high degree of subjectivity associated with the concept. The first significant attempt to discuss ecosystems in a comparative way to human health was by Rapport *et al.* (1979). Such comparisons are difficult as many components of both human and ecosystem health can be highly subjective, and the use of the 'health' description has been criticised by several authors (e.g., Wicklum and Davies, 1995; Coates *et al.*, 2002). Nevertheless, using analogies to human health can be a useful initial assessment of ecosystem condition (Deeley and Paling, 1999; Wells, 2003)

Examination of the literature on the use of the term 'ecosystem health' shows that many authors have attempted to define this term and to suggest mechanisms for quantifying the situation. Some of the definitions/descriptions are outlined below:

- Rapport *et al.* (1979) stated that 'the corresponding ecological concept to health might be ecosystem persistence, or ecological resilience. Presumably this property can be assessed using a range of indicators. Candidate vital indicators include primary productivity, nutrient turnover rates, species diversity, and the ration of community production to community respiration';
- Constanza (1992) presented 6 conceptual attributes comprising the definition of ecosystem health – homeostasis; absence of disease; diversity or complexity; stability or resilience; vigour or scope for growth; balance between system components;
- Fairweather (1999) considered that 'it is unclear which ecological changes mean a decline in health or even what represents good health';
- Deeley and Paling (1999) stated that 'ecosystem health should involve the maintenance of the structural and functional attributes of the system'. There should be an absence of ecosystem stress symptoms (that also have then to be defined). Boesch and Paul (2001) used similar comments;
- ANZECC (2000) used the Schofield and Davies (1996) definition of ecological integrity as a measure of ecosystem health. Ecological integrity is the ability of an aquatic ecosystem to support and maintain key ecological processes and a community of organisms with a species composition, diversity and functional organization as comparable as possible to that of the natural habitats within a region;
- Haskell *et al.* (1992), reporting on the outcomes of workshops on ecosystem health, stated that the conclusion was that 'an ecological system is healthy and free of distress syndrome if it is stable and sustainable – that is, if it is active and maintaining its organization and autonomy over time, and is resilient to stress';
- Wells (2003) suggested that 'a healthy marine environment requires individuals (ecologically, individual organisms) with signs of wellness and productivity, based on vital signs, and the absence of obvious disease or lack of function'.

In addition to the problems of definition, other difficulties in dealing with the issue of assessing ecosystem health include:

- There is further disagreement on methods and processes of evaluating 'ecosystem health' – this is a feature associated with the complexity of ecosystems, and the fact that the whole field is one that is rapidly developing/changing;
- Ecosystems are constantly evolving and many only reach

quasi-equilibrium for relatively short periods of geological time;
- Ecosystems are dynamic (continuously changing) and have a certain capacity to resist ‘stress’ and return to ‘normal’ after perturbation
- Certain parameters, especially in coastal ecosystems, show a high degree of variability depending on the season, rainfall, etc.

Thus, in considering the health of an ecosystem, we are trying to assess something that cannot be accurately defined for a system that is continually changing – an almost impossible situation! Nevertheless, some progress can be made.

Assessing Ecosystem Health

Utilising the analogy with human health (Rapport *et al.*, 1979) some initial comments about ecosystems can be made. Human health varies from day to day, but the variations are often small, e.g., someone is described as ‘under the weather’. When we think we are unwell a doctor tries to diagnose what the problem may be – indicators are used. Some of the indicators are easy to measure and give a general indication (e.g., blood pressure, temperature, pulse). Others require more effort and give more information (e.g., blood tests, urine tests) and others require even more sophistication but generate detailed information (e.g., X-ray, body scan). While a range of indicators has been suggested for assessing the status of estuaries, there is no simple sequence of indicators that can be used in a progressive diagnosis of the health of the system. Even deciding on what indicators to measure is a matter of debate, and the outcome will vary from system to system, e.g., indicators for a shallow intermittently closed estuary will not necessarily be equally useful in a large deep continuously open system.

A human could be in reasonably good health, even when under stress, but stress makes the likelihood of rapid decline or collapse greater. The point at which decline sets in is not easily determine in advance, but regular checks of key indicators makes this easier. For estuaries, there is an even greater concern. Changes tend to occur incrementally and are occasionally reversed. Human impacts on the system can take many different forms, some of which may be cumulative, others acting synergistically. Ecosystem response to such impacts often occurs as ‘many small steps to the edge of the cliff’. It is almost impossible to determine when the system is on the point of rapid decline, and thus planning and management activities must attempt to stop movement towards the edge.

THE STATUS OF LAKE ILLAWARRA

If we consider Lake Illawarra using the human health analogy, what can be said about the patient? Generally, the Lake would be considered middle-aged as estuaries go. It is certainly under a significant degree of stress. A middle-aged person under stress can perform well for a long time, and with care, can live happily for many years. Stress, however, makes the likelihood of rapid decline or collapse greater. In general terms, Lake Illawarra in is a somewhat similar position. The Lake shows signs of good health (see below), but indications of stress are also obvious. The range of human activities in the catchment, within and on the shores of the Lake, continues to exert stress on the system. While the system has been able to respond to these changes, there is a limit to which stress can be exerted without significant decline in health. The point at which decline sets in is not easily determine in advance, but regular checks of key indicators makes this easier. Response options when decline is near need to be determined in advance.

Causes of stress for Lake Illawarra and its catchment include:

- Population growth – the population of the Lake catchment has grown by 10 fold in s period of about 60 years and continues to expand rapidly;
- Changing land use in the catchment – vegetation changes (most of the natural vegetation in the lower catchment was removed in the 1800s - see also O'Donnell *et al.*, 2004), changes in runoff patterns with increased incidence of flooding, erosion increases with sedimentation in the lower creek areas and in the Lake itself, additions of nutrients and other chemicals in runoff (stormwater, sewage overflows);
- Changes in foreshore conditions, including the removal of vegetation and the destruction of wetlands, construction of walls and other barriers that have led to changes in local water movements;
- Changes in Lake use, including increased numbers of fishers, boats and newer activities such as jet skis and hover bikes.

INDICATORS OF LAKE HEALTH

The use of indicators is one mechanism that has become increasingly utilised in recent years to assess the sate of the environment and the status of individual ecosystems. Indicators are simplified measures to represent fundamental components of a system – providing a means of identifying and quantifying attributes contributing to ecosystem health. The use of environmental indicators is based on certain assumptions:

1. It is possible to identify particular indicators of quality and that there are threshold values of each indicator above/below which adverse effects to the ecosystem are minimised. A combination of indicators is better than trying to use just a single parameter;

2. The effective use of indicators involves repeated measures of the parameter(s) on various temporal and spatial scales (i.e., monitoring) – looking for patterns of change and/or comparison with some guideline or benchmark.

Measurement of all possible parameters is neither practical nor economic, so a set of key (core) indicators is necessary. This minimum set, if properly selected and effectively monitored, provides insight into the patterns of changes in any given ecosystem (Ward *et al.*, 1998). What indicators to use is also a subject of considerable scientific debate, particularly for estuaries, as they involve both a terrestrial and an aquatic component. In addition, the aquatic component is continually changing due to tidal movements, river inputs, seasonal variations in temperature, etc.

Several studies into the use of indicators have suggested adoption of the OECD 'State-Pressure-Response' model. In this system, different types of indicators are used: State (S) describes the current condition of the environment of the region of interest, and provides baseline information against which future trends can be compared; Pressure (P) indicators account for the various impacts on the environment resulting from human activities; Response (R) indicates the work being undertaken by government industry and the community to reduce these pressures.

For estuaries, a detailed review of possible estuarine quality indicators was prepared by Ward *et al.* (1998). ANZECC (2000) developed one set of national guidelines for assessing the quality of estuaries in future national state of the environment reporting processes in relation to estuaries and the sea. In terms of estuarine health, many of the ANZECC indicators are of the 'Pressure' type, and are of limited benefit as they are based on incomplete information and variable quality (e.g., total fish catch data). In addition, ANZECC (2000) placed emphasis on indicators for which there is data already available OR being collected for other reasons OR on indicators for which data collection is simple using current technologies. Such indicators, developed for national assessments are of very limited value for assessing changes in Lake Illawarra, with only exceedences of water quality guidelines, occurrence of algal blooms and possibly bioaccumulated pollutants being relevant.

INDICATORS FOR LAKE ILLAWARRA

A range of possible estuarine health indicators for Lake Illawarra is suggested below. These include data that has been and is being collected currently (2003).

Water Quality of the Lake and Incoming Waters

The problem with using water quality as an indicator is that it is a multi-component parameter. Numerous measurements contribute to water quality assessments (e.g., pH, dissolved oxygen, salinity/conductivity, temperature, nutrients). All of the individual components show variations, some to a much greater degree than others (e.g., see Figure 1), so determination of long-term patterns of change is difficult. Variations are usually greater for incoming waters and they are greatly influenced by rainfall events, but even for water bodies as large as Lake Illawarra (some 63 million m^3), rainfall can significantly change some parameters (Figure 1), indicating at least occasional high catchment inputs.

A review of the best available data (Pacific Power, 1996-2000, B Hodgson, personal communication) shows that water in Lake Illawarra complied with the ANZECC Water Quality Guidelines (2000) most of the time for pH, dissolved oxygen and dissolved nitrogen. Concentrations of dissolved phosphorus, total nitrogen and phosphorus, chlorophyll exceeded the ANZECC guidelines most of the time. These data clearly show than controlling nutrient inputs to the Lake should be a key management priority. The nutrient loadings have, in the past, been considered a major cause of phytoplankton and macrolagal blooms. WBM (2003) report a decrease in macroalgal blooms in recent years, but as a full explanation of bloom outbreaks has yet to be developed, this should not lead to a decline in concern about nutrients.

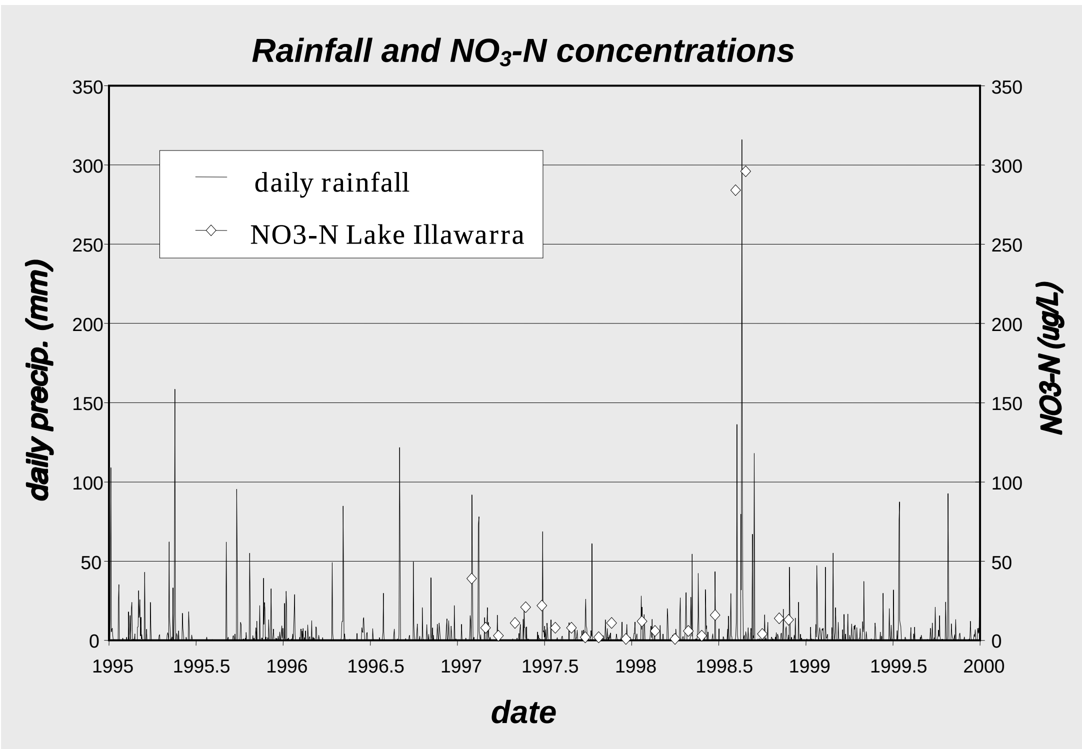
Catchment water quality has been reviewed by O'Donnell *et al.* (2004). The limited information shows that the water quality in the various Creeks is quite variable, but a number of issues are of concern. Many of the parameters fall outside the ANZECC Guidelines (2000) including low pH values (possibly due to areas of acid sulfate soils in the catchment), high conductivity values due to salinity problems, moderately high turbidity values due to construction or agricultural activities, high faecal coliform counts in both wet and dry weather, and relatively high concentrations of total and dissolved nutrients. These problems occur mainly in the lower parts of the catchment, with the less developed (upper) areas having fewer concerns.

Achieving the ANZECC (2000) guidelines should be a target for managers of the Lake and its catchment. This will not be achieved easily, but presents an opportunity for strong community and government cooperation for environmental protection.

Sedimentation Date and Depth of the Lake

As reported in Depers and Yassini (1995) and in Sloss *et al.* (2004) there was a dramatic increase in the rate of sedimentation in Lake Illawarra following European arrival in Australia. This increasing sedimentation led to significant infilling of the Lake with a consequent decrease in depth, and this has contributed to changes in the Lake's ecology. These studies have also indicated a decrease in the rate of sedimentation during the later part of the 20th century, but the depth of the Lake is now such that any significant input of sediments could lead to a dramatic change in Lake morphology,

Figure 1. Variation of Nitrate Concentrations in Lake Illawarra with Rainfall 1995-2000 (data courtesy of B. Hodgson, Pacific Power)



and a rapid decline in health. Future management strategies for the Lake and its catchment must ensure minimum sediment transport into the Lake.

Sediment Quality

Sediment quality in Lake Illawarra, particularly in terms of inorganic components, has been reported on by Chenhall *et al.* (1994), Batley and Chenhall (1995), Chenhall *et al.* (1995), Payne *et al.* (1997) and Chenhall *et al.* (2004). These studies have shown above background concentrations of certain metals (e.g., copper, zinc, lead), with these higher concentrations associated mainly with finer sediments. Most work to date has measured total metal concentrations, and there is need for further investigation of the bioavailability of the metals and the potential for toxicity. No information is currently available on organic contaminants; although no major problems are expected, low concentrations of PAHs from local industry, PCBs from old transformers, and pesticide residues from use in the catchment might be anticipated.

Fish Catches

ANZECC (2000) have suggested that total fish catches as a 'pressure' indicator for estuaries and the sea and estimated wild fish stocks as a 'condition' indicator (Table 1).

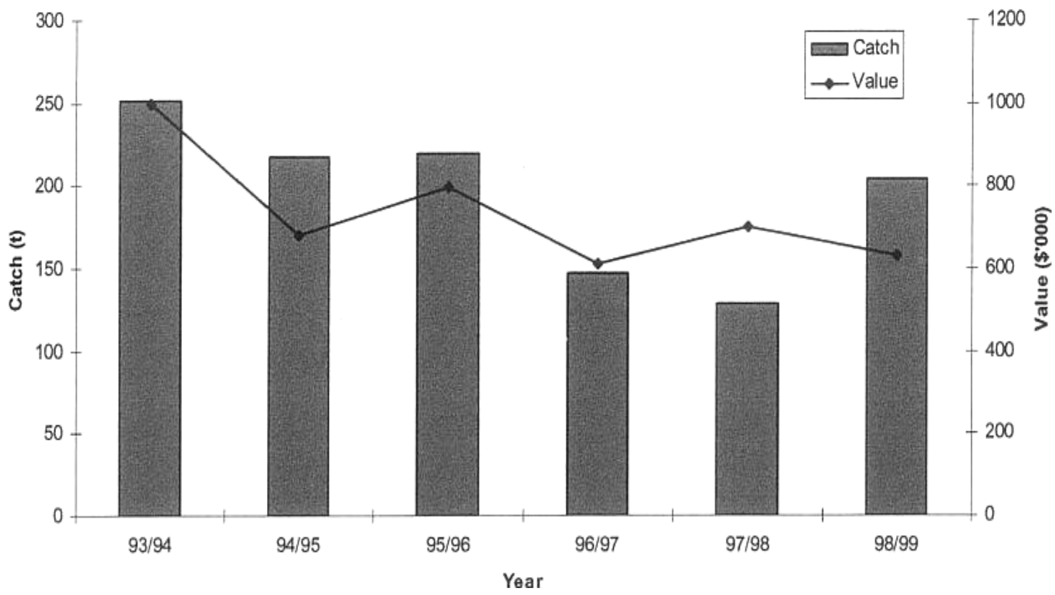
Since fish and crustaceans have been commercially harvested from Lake Illawarra for over 100 years, relatively good data are available for these catches (e.g., Figure 2). Gray (2004) has discussed some of these data in more detail, but, generally, the trends in the commercial catches for most fish species indicate few dramatic changes over the last century. For some species, recent commercial catches are almost identical to reported landings for over 50 years. While commercial catches have remained relatively steady, the numbers of commercial fishers and commercial fishing effort, in general, has decreased sine the 1980s. A major issue related to the commercial fishing in Lake Illawarra has been environmental impacts of fishing gears (see Gray, 2004)

The lack of detailed data on the recreational fishery in Lake Illawarra (and elsewhere in NSW) is of some concern, although the recent National Recreational Fishing Survey does provide some interesting, thought coarse, information (NSW Fisheries, 2002). Taken overall, existing estimates of total fish catch for Lake Illawarra are incomplete as they lack accurate figures for the recreational fish catch. As such, they are of little use as a 'pressure' indicator, as most of the increasing effort in recent years has been from the unquantified recreational sector.

While there are some sporadic data about the fish stocks in Lake Illawarra, there are no available estimates of wild fish stocks, and thus no way to establish a comparative 'condition' indicator. West and Jones (2002) have provided data on the distribution and abundance of many juvenile commercial fish species in Lake Illawarra, and demonstrated the highly variable nature of fish recruitment and the roles that lake geomorphology and climate, particularly rainfall, play.

Another important issue in relation to fishes is the diversity and occurrence of many rare or threatened species. The available data again are a useful information source for many

Figure 2. Total Fish Catches and Value for Lake Illawarra, 1993-9



management purposes, but offer little by way of an indicator of estuarine health (e.g., West and Jones, 2002; Williams *et al.*, 2004).

Biodiversity other than Fish

Limited information has been produced on the biodiversity in Lake Illawarra. Much of this data is of limited value for examining changes in the Lake and the data are often sporadic, collected using different techniques and show significant variability. For many parameters, the length of the data sets and the variability make identification of long-term patterns very difficult.

West (2004) has reviewed the information available on seagrasses. While Lake Illawarra normally has over 5 km^2 of seagrasses (including *Zostera capricorni, Ruppia megacarpa, Halophila ovalis* and *H. decipiens*), there is some evidence for long-term (decadal) permanent loss in seagrass meadows from some specific sites around the Lake, some due to management practices (e.g., dredging and reclamation). The seagrasses of Lake Illawarra are regionally significant as a fish and wildlife habitat and provide a very large proportion of the primary productivity. Other management-ecology conflicts have arisen because, in some locations, seagrasses are associated with macro-algae blooms and can be responsible for odours and public access issues. A massive dieback in seagrasses (and many other shallow water communities) occurred during the 2002-3 El Niño event, when a drop in lake water level, combined with severe westerly winds and winter dieback, were responsible for the loss of virtually all above-ground evidence of seagrasses in the Lake (West, 2004). Recovery of the seagrasses in Lake Illawarra after such a large loss will depend on the overall health of the lake, particularly in respect to key environmental factors important for seagrass growth, such as water clarity.

As noted by Rutten *et al*. (2004), macroalgal blooms are a recurring problem in Lake Illawarra. At least 35 species (16 green, 10 red and 9 brown) of macroalgae currently exist in the Lake, with the most abundant species being the opportunistic chlorophyte *Chaetomorpha linum*, which has often been cited as the most problematic species. Since 1988, macroalgal harvesting has been used as a management tool in Lake Illawarra, although the ecological impacts of this harvesting are not yet known. Ecologically sustainable management of macroalgae requires knowledge of the environmental factors determining macroalgal abundance and diversity, and the key factors limiting the growth of those species. Laboratory studies suggest that the growth of *C. linum* in Lake Illawarra is strongly nitrogen limited.

Currently there is little information available on the plankton communities anywhere along the NSW coast, including Lake Illawarra. While there are currently several studies underway, it will be some time before these can be used in an assessment of ecosystem health. This remains a significant information gap.

Chafer and Brandis (2004) report that the Lake Illawarra entrance channel is home to over 55 species of waterbird. Systematic population surveys between 1981 and 2003 found that changes in environmental conditions due to engineered habitat reduction appear to have resulted in the decrease of bird species that probe and peck for invertebrates (8 species), especially trans-equatorial migrants. This loss has been linked to losses in intertidal mudflats and saltmarsh around the margins of the entrance channel. Endemic invertebrate feeders, however, appeared to increase their local populations marginally during this study period. Populations of diving fish-eaters, especially Little Pied Cormorant and Australian Pelican, have increased markedly and both these species now breed locally.

Assessments of the biodiversity in the Lake Illawarra catchment have shown that, since European settlement, considerable areas of the Illawarra Grassy Woodlands, Swamp Forests (that feature *Eucalyptus robusta*), Swamp Oak (*Casuarina glauca*) and Lowland Dry-Subtropical Rainforest have been lost. These changes have arisen from clearing for agriculture, infilling of swamps for housing, sporting fields and shopping centres, alteration to drainage lines and patterns. The responses to these changes from the biota have not been quantitatively assessed, but changes are likely to have affected moist forest assemblages, wetland dependent fauna and fauna that are dependent on winter flowering eucalypts such as the endangered Regent Honeyeater and Swift Parrots (D. Connolly, NSW NPWS, pers. comm.)

Fish and Shellfish Quality

Limited information is available on fish and shellfish quality. Data on metals in fish and shellfish have been summarised and discussed by Brown *et al.* (2004). These data show that there are no problems associated with the concentrations of metals in Sydney rock oysters, cockles (*Anadara trapezia*), dusky flathead or luderick, and while there variations in metal concentrations over time, no specific patterns are obvious. No information on the concentrations of organic chemicals in fish is available and information on the microbiological quality of shellfish has not been published.

Problems with Indicators

A number of problems have been identified in determining possible indicators for the health of Lake Illawarra. As discussed above the length and quality of the data sets is a significant limitation, and the lack of standardisation of methods for comparison adds to the difficulty. Much of the available information on Lake Illawarra has been produced in short term or one-off data collections, frequently compiled by students, carrying out projects with defined time limits. What is needed are monitoring programs that provide data collected systematically over significant time periods to enable more reliable assessments of the status of the Lake Illawarra to be made.

Important information gaps include:

- Information on recreational fish catches;
- Processes driving phytoplankton community structure;
- Data on algal blooms - occurrence and species involved;
- Data on the ecology of rocky foreshores;
- Long-term growth dynamics of seagrass communities;
- Effects of intrusions of coastal waters into the Lake;
- Extent and effects of groundwater inputs.

Only when these information gaps are addressed, and longer data sets are collected for some other parameters, such as water quality, will we be able to develop a fully integrated picture of the behaviour and health of the Lake Illawarra system.

Based on the above information, Table 1 lists some common signs of stress, and a preliminary subjective assessment of their occurrence in Lake Illawarra (after Wells, 2003).

The data in Table 1 provide a starting point for future assessments of the health of the Lake. Management decisions should be targeted at reducing or eliminating the stresses on the system.

ENTRANCE MODIFICATIONS

This issue, often discussed under the heading 'entrance improvements' is an issue that provokes considerable controversy. While altering the entrance may improve water movement into and out of the Lake (see later comment), it is yet another example of what we are trying to change in other areas of environmental management. It is, in effect, an 'End of Pipe' solution (and not a particularly satisfactory one) when the problems need to be addressed at 'Source' (i.e., within the catchment).

It has been argued that entrance modifications will lead to greater flushing of nutrients from the Lake, and this will improve the health of the system. This argument is flawed as it has been shown in many estuaries, that up to 95% of the nutrients entering the system are retained or reprocessed with the estuary (Smith *et al.*, 2003). Any increase in flushing will only influence a small proportion of the nutrient load. Even with a 30-50 day residence time as some entrance models predict, there is still sufficient time for assimilation of nutrients in the lake processes. In addition, there has been no assessment of the impact of moving additional nutrients from the Lake into the adjacent coastal waters.

Table 1. Ecological Stress Signs and Preliminary Assessment for Lake Illawarra

Signs of Stress	Lake Illawarra	Level of Impact*
Habitat changes	Yes	++
Elevated nutrient levels	Yes	++ (at least localised)
Biological productivity changes	Yes	+ (overall) ++ (localised)
Biotic composition and characteristics	Yes**?**	++
Bioaccumulation of contaminants	Inorganic (perhaps localised) Organic	**?** Unknown
Disease prevalence	**?**	**?**
Effects of exotic species	**?**	**?**
Sedimentation rate changes	Yes	++
Changes in physical composition of sediments	Yes	+ (overall) ++ (localised)

***** ++ high + moderate **?**low

The main argument for entrance modifications is the intention to keep the system more open and allow greater movement of water into and out of the system. While increasing the efficiency of the entrance may contribute to better mixing in the areas of the Lake near the entrance, other components of the system will be affected. Given the complexity of the system and our current state of knowledge, it is impossible to confidently predict the outcomes. Potential impacts include: an increase in salinity within the Lake and tributaries, and subsequent changes in the natural aquatic communities; greater variations in depth of the Lake, with subsequent impacts on near shore communities, especially saltmarsh and seagrass communities; changes in the entrance shoreline areas used by bird communities; and, a higher energy climate, including waves and tides, around the Lake's entrance, leading to significant changes in the distribution of sand, sand bars, and the communities associated with them.

CONCLUSIONS

Lake Illawarra could be described, geomorphologically, as 'middle-aged' estuary. The health of the lake is variable, depending on climate and other features. Given the recent history of stress, the lake is in relatively good condition. The response of the Lake to the 2002 drought will give a good indication of the overall health. Further stress can only to lead to a continuing decline in the Lake's quality, but as this is likely to occur in incremental steps, a major deterioration may occur with minimal notice.

In order to maintain good health in Lake Illawarra, improvements in all aspects of Lake management are essential. Entrance modifications will not solve the problems. Continued reductions in sediment and nutrient influxes from the catchment must be a specific target.

To improve the monitoring of Lake health, better collection of ecological data is essential. Longer data sets using standard methods for comparability are required and this should be built into the Management Plan for the Lake. The Management Plan must also include a scientifically based program of research and monitoring so that the limited financial and technical resources available can generate the most value information. Strong cooperation between residents, managers and researchers is essential for continued maintenance and improvement of the health of the Lake. Until then, we will be in the position described by Pulitzer Prize winning writer, Douglas R. Hofstadter (1999) who said "Intelligence is about making decisions based upon imperfect knowledge among partially good choices".

ACKNOWLEDGEMENTS

The authors acknowledge valuable comments on an early version of this paper by Dr Joanne Wilson (NSW DIPNR).

REFERENCES

ANZECC (2000). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. National Water Quality Management Strategy, Australian and New Zealand Environment and Conservation Council, Canberra.

Batley G.E. and Chenhall, B.E. (1995). Trace element content of the Lake sediments. In: Depers, A.M and Yassini, I. (Editors) *Recent Sediments in Lake Illawarra: Implications for Management*, pp 57-77. Department of Geology, University of Wollongong, and the Illawarra Catchment Management Committee, Wollongong.

Boesch, D. and Paul, J. (2001). An overview of coastal environmental health indicators. *Human and Ecological Health Risk Assessment*, **7**, 1409-1417.

Brown, P.L., Carolan, V.J., Hafey, D.J., Iko, M., Markich, S.J. and Morrison R.J. (2004). Metals in fish and shellfish in Lake Illawarra, New South Wales, Australia. *Wetlands (Australia)*, **21,** *

Chafer, C.J. and Brandis, C. (2004). Waterbird populations in the Lake Illawarra estuary. *Wetlands*, **21,** 183-202

Chenhall, B.E., Batley G.E., Yassini, I., Depers, A.M. and Jones, B.G. (1994). Ash distribution and metal contents of Lake Illawarra sediments. *Australian Journal of Marine and Freshwater Research*, **45**, 987-992.

Chenhall, B.E., Yassini, I., Depers, A.M., Caitcheon, G., Jones, B.G., Batley, G.E. and Ohmsen, G.S. (1995). Anthropogenic marker evidence for accelerated sedimentation in lake Illawarra, New South Wales, Australia. *Environmental Geology*, **26**, 124-135.

Chenhall, B.E., Jones, B.G., Sloss, C.R., O'Donnell, M., Payne, M., Murrie, M., Garnet, D. and Waldron, H. (2004). Trace metals in sediments from Lake Illawarra, New South Wales, Australia. *Wetlands (Australia)*, **21,** 217-227

Coates, B., Jones, A.R. and Williams, R.J. 2002. Is "Ecosystem Health" a useful concept for coastal managers? *Proceedings of Australia's National Coastal Conference "Coast to Coast 2002, Source to Sea"*.

Costanza, R. (1992). Towards an operational definition of ecosystem health. In: R. Costanza, B.G. Norton and B.D. Haskell (Editors) *New Goals for Environmental Management.* Island Press, Washington, D.C. pp 239-256.

Deeley, D. and Paling, E. (1999). *Assessing the Ecological Health of Estuaries in Australia*. LWRRDC Occasional Paper 17/99, Land and Water Resources Research and Development Corporation, Canberra.

Depers, A.M and Yassini, I. (Editors) (1995) *Recent Sediments in Lake Illawarra: Implications for Management*, pp 57-77. Department of Geology, University of Wollongong and Illawarra Catchment Management Committee, Wollongong, 148 p.

Fairweather, D.J. 1999. Determining the 'health' of estuaries: Priorities for future research. *Australian Journal of Ecology*, **24**, 441-451.

Gray, C. (2004). Overview of commercial fishing in Lake Illawarra. *Wetlands (Australia),* **21,** 156-167

Haskall, B.D., Norton, B.G. and Costanza, R. (1992). What is ecosystem health and why should we worry about it? In: R. Costanza, B.G. Norton and B.D. Haskell (Editors) *New Goals for Environmental Management.* Island Press, Washington, D.C. pp 3-20.

Hofstadter, D.R. (1999). *Godel, Escher, Bach: An Eternal Golden Braid.* HarperCollins, New York, 777p.

Laegsgarrd, P. (2002). *Use of Indicators for Assessing Estuarine Health: A Guide* (draft). NSW Department of Land and Water Conservation, Bankstown

NSW Healthy Rivers Commission (2002). *Independent Inquiry into Coastal Lakes: Final Report*. Healthy Rivers Commission, Sydney, 74 p.

O'Donnell, M., Yassini, I., Taylor, E.J. and Morrison, R.J. (2004) Water quality in the Lake Illawarra catchment. *Wetlands (Australia),* **21** 253-267.

Payne, M., Chenhall, B.E., Murrie, M. and Jones, B.G. (1997). Spatial variation of sediment bound zinc, lead, copper and rubidium in Lake Illawarra, a coastal lagoon in eastern Australia. *Journal of Coastal Research,* **13,** 1181-91.

Rapport, D.J., Thorpe, C. and Reiger, H.A. 1979. Ecosystem medicine. *Bulletin of the Ecological Society of America,* **60**, 180-2.

Rapport, D.J., Costanza, R. and McMichael, A.J. 1998. Assessing ecosystem health. *TREE (Trends in Ecological Evolution),* **13**, 397-402

Rutten, K., West, R.J. and Morrison, R.J. (2004). Macroalgae in Lake Illawarra. *Wetlands (Australia),* **21,** 105-117.

Schofield, N. and Davies, P. (1996). Measuring the health of our rivers. *Water,* **23**, 39-43

Sloss, C.R., Jones, B.G., Murray-Wallace, C.V. and Chenhall, B.E. (2004). Recent sedimentation and geomorphological changes, Lake Illawarra, NSW, Australia. *Wetlands (Australia),* **21,** 74-84

Smith, S.V., Swaney, D.P., Talaue-McManus, L., Bartley, J.D., Sandhei, P.T., McLaughlin, C.J., Dupra, V.C., Crossland, C.J., Buddemeier, R.W., Maxwell, B.A. and Wulff, F. (2003).

Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. *Bioscience*, **53**, 235-245.

Ward, T., Butler, E. & Hill, B. (1998). *Environmental Indicators for National State of the Environment Reporting-Estuaries and the Sea*. Australia: State of the Environment (Environmental Indicator Reports), Department of the Environment, Canberra.

WBM. (2003). Lake Illawarra Estuary processes Study. Final Report to the Lake Illawarra Authority. WBM Oceanics Australia, Springhill, Queensland.

Wells, P. (2003). Assessing the health of the Bay of Fundy – concepts and framework. *Marine Pollution Bulletin,* **46**, 1059-1077.

West, R.J. (2004). Seagrasses in Lake Illawarra. *Wetlands (Australia),* **21,** 127-141

West R.J., Jones M.V., 2001. *Shallow Water Fish Communities of New South Wales South Coast Estuaries*. Oceans and Coastal Research Centre, FRDC Project 97/204, University of Wollongong, 135 p.

Wicklum, D. and Davies R.W. (1995). Ecosystem health and integrity? *Canadian Journal of Botany-Revue Canadienne de Botanique,* **73**, 997-1000.

Williams, R.J., Louden, B. and Jones, M.V. (2004). Recent fish sampling, Lake Illawarra. *Wetlands (Australia),* **21,** 168-182.