

Office of the Commissioner for Sustainability and the Environment

Investigation into the state of Lake Burley Griffin and Catchment

Water Quality Assessment

Ian Lawrence March 2012



“Perception of lakes:

We know that inland waters do not have infinite capacities and cannot regulate themselves beyond certain limits. Like all ecosystems, they may change and are subject to ecological succession, that is, a predictable, directional change brought about by the effect of the relationship between the living and non-living parts of the ecosystem. In the case of Lake Burley Griffin, management seeks to prevent such changes beyond a certain point because they involve degradation of the perceived beneficial uses of the Lake.”

Professor Bill Williams, in *„Lake Burley Griffin: A body of still water’. Proceedings of a seminar on the rehabilitation of Lake Burley Griffin*, NCDC 1983

Professor Bill Williams was Head of the Department of Zoology, University of Adelaide 1975 to 1994, and Emeritus Professor 1994 until his death in 2002. He provided the foundation „taxonomy of Australian aquatic fauna“ guides, and developed the „ecology of Australian inland waters principles“. He was a member of the ACT Region Water Quality Study Advisory Panel 1976 – 1978, guiding the development of an ecological understanding of waterways of the Upper Murrumbidgee Basin, and an advisor in respect to the assessment of Lake Burley Griffin water quality and ecology in the early 1980s.

Acknowledgements:

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List of Contents

Executive summary

1. Background

2. ‘Condition of the Lake and its catchment’ assessment framework

3. Lake values and management objectives

4. Major potential threats & related water quality indicators

5. Condition of the Lake assessment

- 5.1 Description of the Lake
- 5.2 Lake water quality sampling locations & scope of data
- 5.3 Lake ecosystem categories
- 5.4 Assessment of broad Lake water quality & ecology conditions
- 5.5 Assessment of Lake water quality 1978 - 2011
- 5.6 Beach embayments assessment
- 5.7 Sediment assessment
- 5.8 Macrophyte assessment
- 5.9 Macro-invertebrate assessment
- 5.10 Fish ecosystem assessment
- 5.11 Condition of the Lake assessment conclusions

6. Condition of the Catchment assessment

- 6.1 Catchment assessment framework
- 6.2 Description of catchment
- 6.3 Location of water quality sample sites & scope of data
- 6.4 Condition of rural catchments
- 6.5 Condition of urban catchments
- 6.6 Condition of catchment: Sewage treatment plant sources
- 6.7 Condition of the Catchment assessment conclusions

7. Lake water quality & ecology response processes assessment

- 7.1 Assessment framework
- 7.2 Lake physical, chemical & biological response processes
- 7.3 High rural inflow & stormwater discharge condition
- 7.4 Moderate rural inflow & high to moderate stormwater discharge condition
- 7.5 Low rural inflow & moderate to high stormwater discharge condition

- 7.6 Low rural inflow & low stormwater discharge condition
- 7.7 Modifiers of water quality & algal growth processes
- 7.8 Faecal coliform response processes
- 7.9 Beach embayments water quality & ecology response processes
- 7.10 Sediment response processes
- 7.11 Role of urban stormwater discharge
- 7.12 Lake water quality & ecology response processes conclusions

8. Management intervention assessment

- 8.1 In-Lake management measures
- 8.2 Catchment management measures
- 8.3 Designation of value zones & related guidelines measures
- 8.4 Risk management
- 8.5 Lake user group partnership
- 8.6 Improved forecasting of blue-green algal bloom risks
- 8.7 Review of adequacy of water quality monitoring & reporting
- 8.8 Selection of preferred management options
- 8.9 Management intervention assessment conclusions

9. References

Appendix A: Summary of land and water resource related management guidelines

Appendix B. Schedule of Lake closures due to high blue-green algal levels

Appendix C: Figures

Appendix D: Figures - relative contribution of sources

List of Figures

Map 1.	Lake Burley Griffin: Water quality sampling sites
Map 2.	Lake Burley Griffin Catchment
Figure 1.	Water Quality Assessment Framework
Figure 2 A	Summer (high rural inflow) water balance
Figure 2 B	Summer (moderate rural inflows) water balance
Figure 3 A	Summer (Low rural inflow – high stormwater discharge) water balance
Figure 3 B	Summer (low rural & stormwater inflow) water balance
Figures 4 to 8.	Molonglo Reach: Physical, nutrients, biological values 1978-2011
Figures 9 to 14.	East Basin: Physical, nutrients, biological values 1978-2011
Figures 15 – 21	West Lake: Physical, nutrients, biological values 1978-2011
Figures 22 to 28	Yarramundi Reach: Physical, nutrients, biological values 1978-2011
Figures 29 to 31	Embayments: Physical, nutrients, biological values 1978-2011
Figure 32	Comparison of Trophic Lakes
Figure 33	Molonglo River Flow Duration Curves: Pre & post Googong Dam
Figure 34	Molonglo River daily loads
Figures 35 to 37 Griffin	Annual loads of water, nutrients & suspended solids on Lake Burley
Figures 38 to 46	Lake Burley Griffin: Relative TN, TP, BOD, suspended solids contribution of sources
Figures 47 – 50	Comparison of catchment exports

Figure 51 Lake Ginninderra: Algal response to storm event

Executive Summary

On the 27th May, the Minister for the Environment and Sustainable Development, Mr Simon Corbell MLA, directed the Commissioner for Sustainability and the Environment to undertake an Investigation into the condition of the Lake Burley Griffin water courses and catchment.

Lake Burley Griffin was conceived by Walter Burley Griffin as one of the major axes of the Canberra Plan, underpinning the symbolic role of the National area. Constructed in 1960 to 63, today, the Lake is seen by the Canberra community as a key city recreational and activity venue, providing water based and related recreational opportunities, and attractive foreshore areas for walking, cycling and picnicking.

Changes in health risk assessment has led ACT Health and the National Capital Authority (the Lake manager) to issue warnings regarding potential health risks to recreators, and occasional closure of the Lake. This has impacted on the perception of the Lake as „polluted“ and „unreliable“ as a venue for a range of national sporting events.

In view of the potential for these perceptions to adversely impact on Canberra’s social amenity and economy, the Reference Group appointed by the Commissioner of the Environment and Sustainability and the Environment, recommended that a review of water quality in the Lake be undertaken, against which changes in water quality and their causes can be assessed, and improvements for managing water quality can be determined.

This assessment has adopted an „evolving Lake water quality and ecology“ approach, as necessary to identify the key factors contributing to the recent decline in the Lake’s environmental and use values.

The flooding of impoverished soils, largely stripped of vegetation, at the time of the Lake’s filling in 1964, resulted in a body of water low in the nutrients and organic matter normally required to support biological life. As a result, catchment discharges, rich in nutrients and organic matter, initially generated plant and animal growth in the Lake. Gradually, as the Lake sediments accumulated nutrients and organic material, the Lake developed a capacity to sustain growth, albeit it at a low rate, between catchment discharge events.

Seasonal conditions have varied over the 49 years since the Lake's establishment. During major floods, the Lake in fact becomes a river (filling the old floodplain of the Molonglo River), scouring the bed of erodible silt & organic material, and re-depositing huge quantities of silt, clay and organic material. In between the major floods and droughts, the normal pattern of minor to moderate catchment discharges generate a „spike“ in the Lake's low level of biological activity, with their supply of fresh, highly bio-available organic material.

Then nature imposed an extreme climatic event –10 years of virtually zero rural catchment inflows. The Lake's biological processes switched from simply responding to inputs of energy from the catchments, to mobilizing the resources within the Lake itself. The algal growth promoted by bountiful nutrients, sunshine, warmth and long detention periods, grew abundantly. No longer were there the time constraints imposed by wash-out by rural catchment discharges. In an environment of light winds - poor mixing of the Lake, the normally benign Green algae were no match for blue-green algae, buoyed by their flotation vascules. An increase in daily maximum temperatures, and a decline in wind strengths over the drought period, further enhanced the blue-green algal dominance.

The statistical assessment of Lake water quality indicated an improvement between the 1982/83 and 1999 to 2009 drought periods in respect to lower phosphorus, as a result of an upgrade in the removal of phosphorus at the Queanbeyan Sewage Treatment Plant in the mid 1980s. However, there has been a history of strong blue-green algal growth during periods of low inflow to the Lake (1977/78, 1982/83 and the 1999 to 2009 drought periods). What has occurred has been the shift in algal composition, from dominance of the Green algae to dominance by the scum, odour- and toxin-producing blue-green algae over these drought periods.

The assessment concluded that under extended drought or „dry“ conditions, the combination of poor physical mixing, high temperature, high production of ammonia, and an extended period of retention, favours the growth of Blue-Green algae and disadvantages Green algae. The conclusion is that the change in algal composition was predominantly a reflection of the 1999 to 2009 hydrologic and climatic conditions. The assessment identified large urban stormwater discharges during periods of low River inflows, as the trigger to Blue Green algal blooms. With increased extreme occurrence in climatic conditions predicted with Climate Change, without intervention, there will be increasing incidence of these conditions into the future.

The assessment noted a decline in the area and composition of submerged aquatic macrophyte plants over the 1980s, as a result of light limitation caused by epiphytic growth on the surfaces of the macrophytes (prior to the Queanbeyan Sewage Treatment Plant reduction in phosphorus discharge), and high levels of Suspended Solids in inflows. Apart from these changes in macrophyte systems, there does not appear to be any ecosystem structural change that would

prevent substantial return to dominance by Green algae upon a return to a more normal set of hydrologic and climatic conditions.

A comparison of the trophic levels of Lake Burley Griffin with 40 European, North American and Australian lakes, for which data on phosphorus and algal biomass levels is available, indicates that Lake Burley Griffin is between the mesotrophic and eutrophic levels, having summer chlorophyll „a“ levels well below those of most of the eutrophic lakes identified in the comparison. Lake Burley Griffin has chlorophyll „a“ levels greater than Lake Ginninderra but less than Lake Tuggeranong, and well below levels in Burrinjuck Reservoir prior to remediation (phosphorus removal from Canberra sewage).

Given their shallow nature, elevated turbidity, and sheltered condition, the biological and microbial growth rates within the Lake’s swimming embayments are much more rapid than those in the open water zones. The statistical assessment of faecal levels in urban stormwater indicates that it is the major source of faecal contamination of the Lake. Internationally, the „build-up“ of faecal contaminants in the sediments of swimming embayments or enclosures is now recognized as a problem, necessitating a re-think regarding the provision of safe swimming venues for children.

As is the case with many inland lakes and reservoirs, the sediment data indicates that there has been a large mass of phosphorus accumulated in the sediments. The release of the phosphorus into the Lake’s water column (responsible for algal growth), is predominantly via the release of sediment bound phosphorus. The bulk (80% during „dry“ periods) of organic material driving this release process, is discharged in urban stormwater. In view of the continued growth of urban areas within the Lake’s catchment, organic material loading was identified as the major potential threat to Lake water quality and ecology, into the future.

There appears to be a limited range of practical means to reduce the discharge of organic material responsible for the release of phosphorus from the sediments to the Lake’s water column, and to reduce the extent to which the organic material promotes nutrient release, once in the Lake.

The Assessment has identified a range of possible management intervention measures. Each measure carries a different set of jurisdictional, political, social equity and cost ramifications that will have a large bearing on the viability of each option. Each option will also require preliminary design and assessment of environmental, social and economic benefits and costs, before a selection of the preferred options can be made.

1. Background:

On the 27th May, the Minister for the Environment and Sustainable Development, Mr Simon Corbell MLA, directed the Commissioner for Sustainability and the Environment to undertake an Investigation into the state of the water courses and catchment for Lake Burley Griffin.

At its meeting of 28th July 2010, the Reference Group appointed to assist the Commissioner for Sustainability and the Environment in undertaking the Investigation, identified the need for a Paper summarising water quality changes in the Lake, against which causes of impacts on water quality can be assessed, and recommendations on possible improvements for managing water quality can be determined.

This Assessment is in response to an Engagement by the Office of the Commissioner for Sustainability and the Environment, to produce a Paper on Lake Burley Griffin water quality, a comparative assessment of the historical and current water quality within the Lake, consideration of environmental flows, and recommendations for the short and long term amelioration of water quality impacts.

2. ‘Lake and its catchment’ water quality assessment framework:

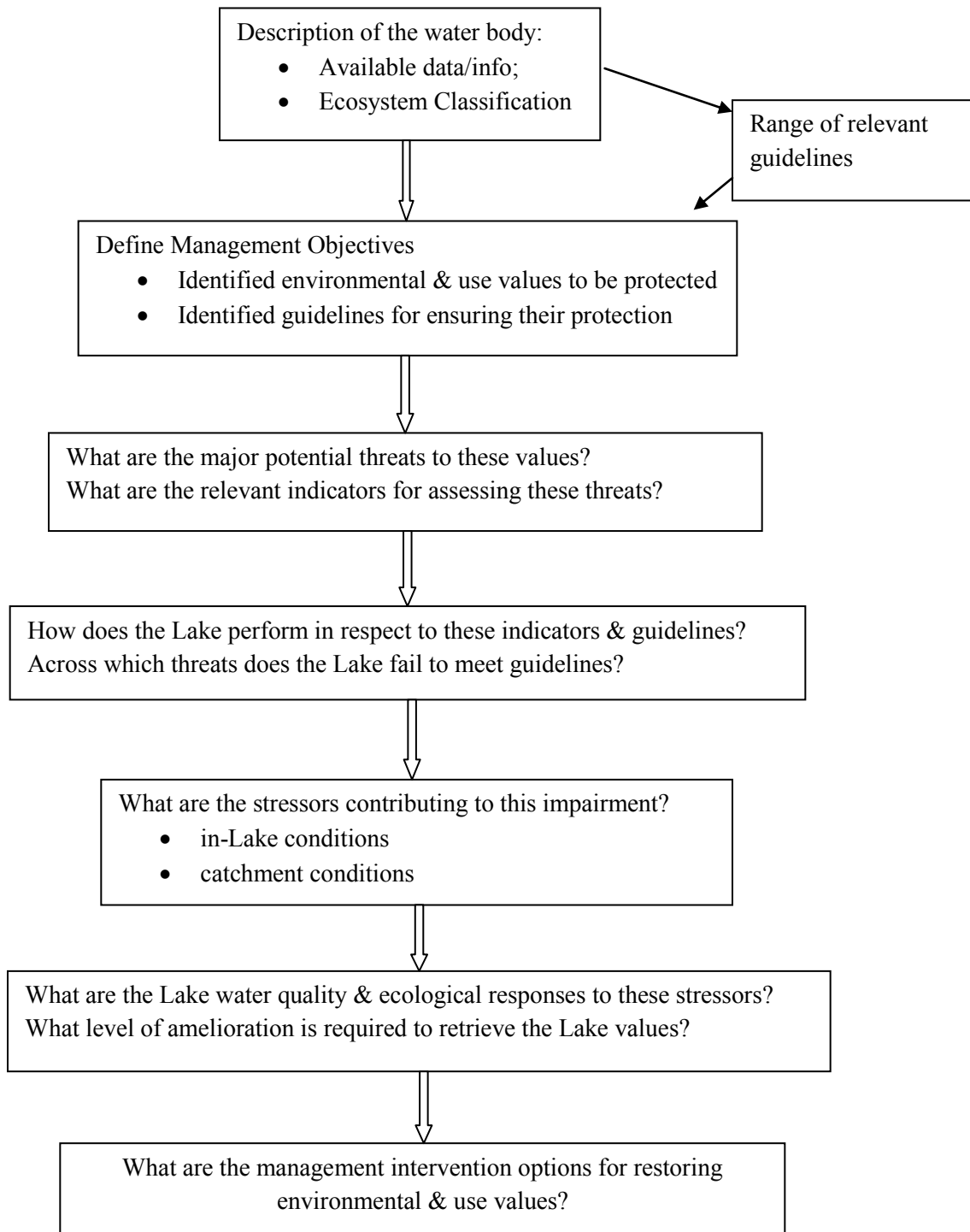
The *National Water Quality Management Strategy Implementation Guidelines 1998* provides a systematic framework for identifying waterway environmental and use values to be protected (or restored). It also outlines the catchment land and water use and management strategies to secure the protection of the environmental and use value objectives.

The *Guidelines* recognize 6 categories of water environmental and use values:

- aquatic ecosystems,
- primary industries (irrigation and general water uses, stock drinking water, aquaculture and human consumption of aquatic foods),
- recreation and aesthetics,
- drinking water,
- industrial water (no water quality guidelines are provided for this environmental value), and
- cultural and spiritual values.

The *Australian & New Zealand Water Quality Guidelines 2000* adopt a strong focus on management *issues* rather than individual indicators. Threats to ecosystems or water quality typically involve a consortium of physico-chemical stressors and modifiers.

Figure 1. Water Quality Assessment Framework



The effect of a particular stressor on biological diversity and abundance, or on water quality, depends on three major factors: the type of ecosystem, the type of stressors and their pathways (direct or indirect), and the influence of other environmental factors (modifiers). A „direct“ stressor, such as a toxicant like copper, acts directly on biota to impair growth. In the case of an „indirect“ stressor, the discharge of one contaminant, for example organic material, may cause oxygen depletion and release of phosphorus, which is bound to iron in sediments, into the water column in a bio-available form, resulting in algal growth.

The Australian & New Zealand Environment & Conservation Council (ANZECC) *Guidelines for Fresh and Marine Water Quality* „decision framework“ sets out a risk assessment protocol for assessing the health or water quality of a waterway relative to a set of „trigger guideline values“. The values cover the key indicators of the major management issues, a reference system for the waterway ecosystem category, and management level.

The risk assessment protocol requires comparison of observed indicator values with a low „adverse biological effect“ risk „trigger level“ for each issue and ecosystem. If the observed value does not exceed the „trigger level“, there is an acceptable low risk level and no further action is required. If the „trigger level“ is exceeded, then further risk assessment takes place.

Three levels of protection (and related reference systems) are prescribed in the *Guidelines*:

- i. pristine or high conservation ecosystems – „no-change“ management objective;
- ii. slightly to moderately disturbed ecosystems – maintain or enhance management objective, with median values within 90 to 95 percentile values for reference system;
- iii. highly modified ecosystems (the Lake Burley Griffin category) – selection of reference system meeting community aspirations or median values within 80 percentile of slightly modified reference ecosystem.

In summary, the effect of catchment discharges on the water quality and ecology of receiving waterways depends on three major factors:

- i. the type of ecosystem
- ii. the type of stressors or drivers in the discharge, and their physical, chemical and biological pathways (direct or indirect) within the waterway and
- iii. the influence of other environmental factors (modifiers) on the physical, chemical and biological pathways.

3. Lake values/management objectives

Section 1.2.2 of the *National Capital Plan* states that Lake Burley Griffin and Foreshores are intended to provide a range of recreational, educational and symbolic experiences of the National Capital. Section 5.2 of the *Lake Burley Griffin Management Plan* designates the Lake water uses for each of the Management Zones.

The „Zoning of uses“ adopted for the Lake, recognises the pattern of improvement in water quality associated with retention (flow distance from the inlet) through the Lake, with Primary Contact recreational uses located in the downstream Zones. The Zoning also recognizes the key role of aquatic processes in areas such as East Basin and Yarramundi Reach, and the importance of protecting the „significant aquatic habitat“ in these Zones.

Table 3.1. Designated Lake Use Values (Source: *Lake Burley Griffin Management Plan*)

Management Zones	Designated Water Uses						
	Primary Contact recreation	Secondary Contact recreation	Passive recreation - landscape	Significant aquatic habitat	Fish-ing	Discharge zone	Irrigat water supply
Molonglo Reach		Water skiing *, canoeing		Wetland & riparian habitats		Molonglo River, Woolshed Ck	
East Basin				Jerrabomberra wetland, riparian habitats		Jerrabomberra Ck, urban drains	
Central Basin		Small dinghy sailing	National setting			Urban drains	
West Basin & Tarcoola	Swimming Triathlons	Sailing				Urban drains	
Yarramundi Reach		Rowing – spectator sports		Water bird breeding area			

Notes: * The water skiing area is east of the Dairy Flat Bridge, which is outside the designated National Land area.

Appendix A. „Summary of land and water resource related management guidelines“, provides an overview of ANZECC/ARMCANZ, NHMRC, ACT & NCA water quality guidelines appropriate to lakes such as Lake Burley Griffin. Since the commissioning of this Assessment,

the NCA has made available their *Draft Lake Burley Griffin Water Quality Management Plan Sept 2011*, to the Office of the Commissioner for Sustainability and the Environment. The *Draft Report* provides a comprehensive review of the water quality of the Lake, in association with a review of water quality guidelines appropriate to management of the Lake.

To ensure consistency in reporting, this Assessment incorporates the findings and Benchmark values of the NCA *Draft Report*, except where noted in this Assessment. The focus of this Assessment is on identifying the major threats to the Lake's values, and the catchment and in-lake processes driving these changes. This understanding then provides the basis for exploring possible management intervention measures.

4. Major potential threats to values, and related water quality indicators

Six of the major potential threats identified in the *ANZECC Guidelines* are present in the case of Lake Burley Griffin.

Major potential threats to Lake environmental values:

- i. changes in micro plant structures & levels as a result of increased levels of nutrients available in the water column, and changes in nutrient composition:
 - Indicators: Chlorophyll „a“ levels, Algal composition;
 - Stressors: high nutrient & organic loading;
- ii. changes in macro-plant structures:
 - Indicators: Loss of macrophyte habitat, Chlorophyll „a“ levels, epiphytic growth, elevated SS
 - Stressors: high nutrient and organic loading, high sediment deposition;
- iii. smothering of benthic organisms, depleting benthic organism populations:
 - Indicators: Reduction in diversity/numbers of macro-invertebrates, sediment deposition rates;
 - Stressors: high suspended solids discharges and internal re-suspension of sediments as a result of loss of plant binding of the sediments;
- iv. asphyxiation of aquatic organisms:
 - Indicators: loss of respiring organisms, low bottom water DO;
 - Stressors: organic material discharged to the Lake;
- v. impairment of the diversity, populations and health of aquatic animals as a result of changes in pH:
 - Indicators: Changes in pH;
 - Stressors: changes in pH of waters discharged to the Lake, high algal production;
- vi. impacts on biota as a result of levels of heavy metals:

- Indicators: Reduction in diversity/numbers of macro-invertebrates, heavy metal levels;
- Stressors: heavy metal discharges.

Major potential threats to the Lake's use values:

- increased incidence and levels of blue-green algae and their associated toxins harmful to human health:
 - Indicators: chlorophyll *a* levels, cyanobacteria algal cell numbers, scum formation, toxin levels
 - Stressors: high nutrient & organic loading
- increased frequency of unacceptable pathogen levels (health risk):
 - Indicators: faecal bacteria (faecal coliform, *Enterococci* bacteria)
 - Stressors: increased levels of discharge of pathogens in discharges into the Lake
- impacts on aesthetic values:
 - Indicators: nuisance plant growth (scums & odours), elevated turbidity levels
 - Stressors: high nutrient and organic loading, high SS loading, erosion of banks, loss of macrophyte stabilization of shallow sediment

Based on the indicators of potential threats to the Lake, the following guideline levels have been adopted for the purpose of this Assessment.

Table 4.1. Assessment of „major threat“ indicators and „guideline“ values (*Condition of the Lake assessment*)

Threat to Lake values	Indicator	Assessment criteria	Draft Mgmt Plan * Benchmark
Change in micro-plant plant structure	Chlorophyll <i>a</i> : <ul style="list-style-type: none"> • Molonglo Reach & East Basin • West Lake & Yarramundi Reach Cyanobacteria Ratio NO ₃ /NH ₃ NH ₃	15 µg/L 10 µg/L <50000 cells/ml or 4 mm ³ /L >5 <0.2 mg/L	30 µg/L 30 µg/L <25000 cells/ml <0.1 mg/L
Biota asphyxiation	DO	>4 mg/L	
Smothering of biota	Macro-invertebrate abundance & diversity	Minor change	
Impacts on human health: Algal toxins	Cyanobacteria Frequency of exceedance of guideline Frequency of Lake closures	<50000 cells/ml <2/yr average < 1/yr average	<25000 cells/ml
Impacts on human health: Pathogens	Faecal Coliform Frequency of exceedance of guideline Frequency of Lake closures	<150 CPU/100ml <2/yr <1/yr	<150 CPU/100ml
Impacts aesthetic values: <ul style="list-style-type: none"> • Turbidity; • Scums/odours 	Turbidity Molonglo Reach; West Lake & Yarramundi Reach Chlorophyll <i>a</i> Molonglo Reach West Lake & Yarramundi Reach Cyanobacteria	40 NTU 20 NTU 15 µg/L 10 µg/L <50000 cells/ml	40 NTU 20 NTU 30 µg/L 30 µg/L <25000 cells/ml

Impacts of toxicants on biota	<i>Cd, Cr, Cu, Pb, Ni, Zn, Hg</i>	ANZECC2000 values	ANZECC2000 values
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Notes: * *Draft Lake Burley Griffin Water Quality Management Plan*. Sept 2011. NCA

Based on the potential threats to the Lake, the following major stressor water quality indicators have been adopted as the basis for the Catchment condition assessment.

Table 4.2. Assessment of „stressor indicators and guidelines values“ (Condition of the catchments assessment)

Threat to Lake values	Direct process conditions			Indirect process conditions		
	Stressors	Modifiers	Stressor Guideline	Stressors	Modifiers	Stressor Guideline
Nuisance plant growth	TP	Detention time; Light	0.06 mg/L Mol & EB 0.04 mg/L WL & Yarra	Org mat ¹ – BOD	Detention SS adsorption, light, NO ₃	20 mg/L
	NH ₃		0.2 mg/L			
Asphyxiation of biota	BOD	Mixing, re-aeration	0.2 g/m ² /d	BOD	Mixing, re-aeration	0.2 g/m ² /d
Smothering of biota	SS	TDS	<2 mm/yr sedimentat	SS	TDS	<2 mm/yr sedimentat
Impacts on human health: Pathogens; Toxins	Faecal Coliform <i>Enterococci</i>	Decay, temp. Mixing	150 CPU per 100 ml 200 CPU per 100 ml	Faecal Coliform <i>Enterococci</i>	SS adsorption	150 CPU per 100 ml 200 CPU per 100 ml
	Algal toxins		5000 cells/100 ml	Algal toxin	SS adsorption	5000 cells/100 ml
Impacts aesthetic values: Turbidity; Scums/odours	SS	TDS,	40/20 mg/L	Turbidity	TDS	40/20 mg/L
	TP	Detention time, temp, mixing, NO ₃	0.06 mg/L Molonglo & East Basin, 0.04 mg/L West Lake & Yarramundi	BOD	Detention, mixing, temp, NO ₃ ,	0.1 g/m ² /d
Impacts of toxicants on biota	NH ₃	Temp, pH	1.4 mg/L @ 20 ⁰ C & pH 7.0	NH ₃	Temp, pH	1.4 mg/L @ 20 ⁰ C & pH 7.0
	Heavy metals	SS, hardness	ANZECC Guidelines	Heavy metals	SS, hardness	ANZECC Guideline

5. Condition of the Lake assessment

5.1 Description of the Lake

Lake Burley Griffin was conceived by Walter Burley Griffin as one of the major axes of the Canberra Plan, underpinning the symbolic role of the National area. Constructed from 1960 to 63, today the Lake is seen by the Canberra community as a key city recreational and activity

venue, providing water based and related recreational opportunities, and attractive foreshore areas for walking, cycling and picnicking.

The Lake was created by the construction of Scrivener Dam, a 36 metre high concrete gravity dam across the Molonglo River, downstream of Black Mountain. The Lake is 9 km long and covers an area of 634 ha. It has a volume of 33.17 Gl, a maximum depth of 17.6 m at Scrivener Dam, and an average depth of 5.2 m. The Lake has a shoreline of 33 km, with much of it comprising natural sloping shores, beaches and inlet zones. As a part of the creation of a formal setting for the Parliamentary zone, a concrete edge wall was constructed on either side of the Central Basin area.

Major issues of design and construction at the time included the sizing of flood gates (five 32 metre x 5 metre flap gates) necessary to provide a high level of protection of the Parliament area against flooding, the management of sediment entering the Lake, and the microbial water quality in respect to use of the Lake for swimming.

5.2 Lake water quality sampling locations and scope of data

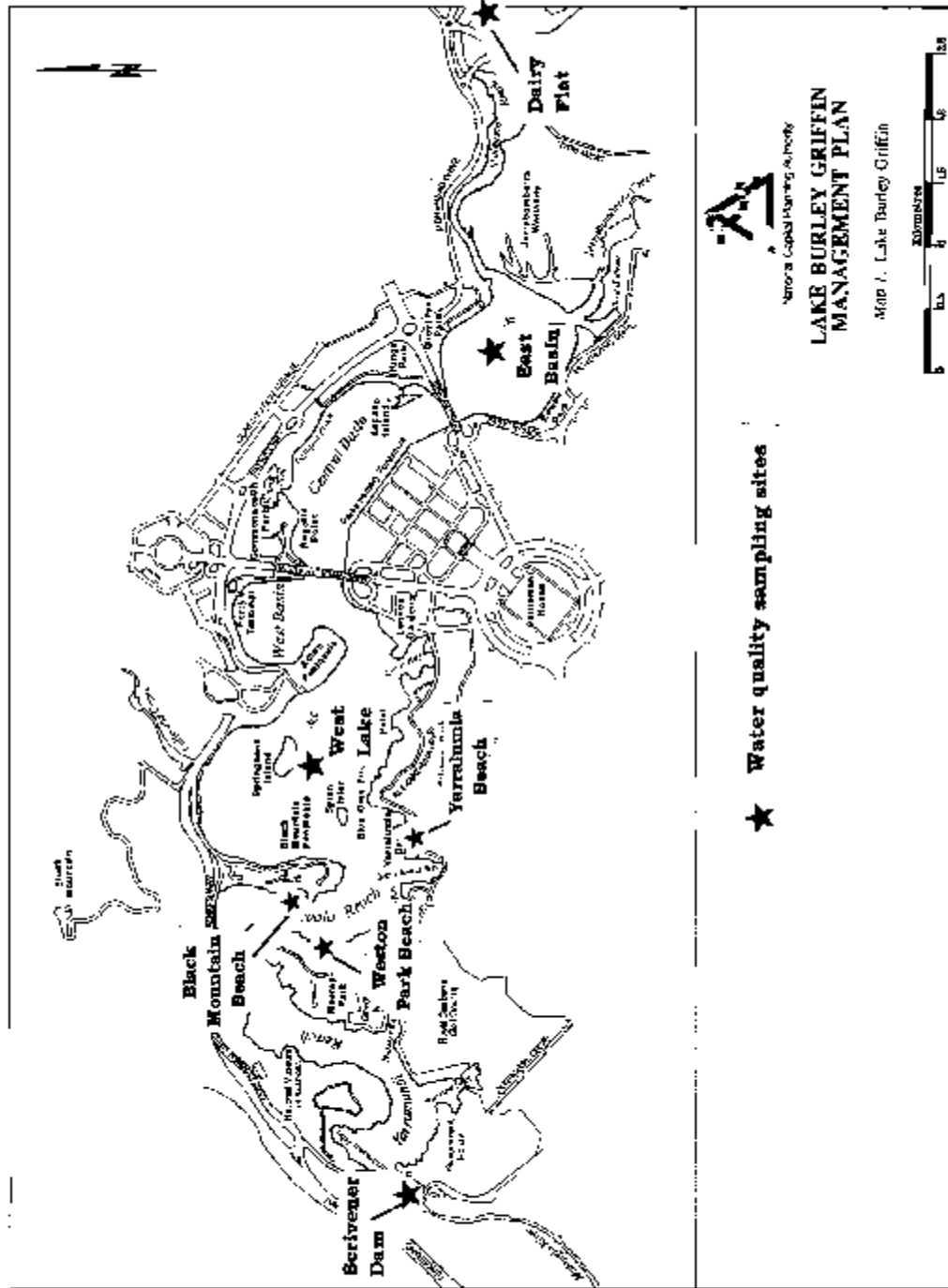
This Section draws on water quality analysis of samples collected from 4 major Lake water quality monitoring stations (Dairy Flat, East Basin, West Lake & Scrivener Dam), together with an assessment of water quality in three of the designated swimming Beach facilities. The assessment has drawn on 33 years of meteorological, streamflow, and water quality data compiled and maintained by the Bureau of Meteorology, ACTEW/ALS Global, National Capital Authority/ALS Global, ACT Health and Environment ACT (although some of the data are not continuous – see table 5.1 below). All of the laboratories engaged in the water quality sampling and analysis are National Association of Testing Authorities (NATA) registered, and have maintained full documentation of sampling and analytical procedures and standards. Analytical methods have changed in some instances, such as the enumeration of cyanobacteria in the 1990s.

Table 5.1. Scope of available data

Station	Physico-chemical	Algal/Zooplankton	Hydrology	Meteorology
Molonglo Reach	1978 - 2011	1978, 1982-2003	1978 - 2010	1978 - 2010
East Basin	1978 - 2011	1978, 1982-2011	1978 - 2010	1978 - 2010
West Lake	1978 - 2011	1978, 1982-2011	1978 - 2010	1978 - 2010
Scrivener Dam	1978 - 2011	1978, 1982-2011	1978 - 2010	1978 - 2010

Map 1. Lake Burley Griffin identifies the locations of the monitoring stations assessed in this Assessment.

Map 1 - Lake Burley Griffin



5.3 Lake water ecosystem process categories

Periods of medium to high inflow levels (wet periods) create a significantly different physical and chemical environment to that prevailing during periods of low inflow levels (dry periods). Accordingly, it is important that comparisons of Lake water quality and ecology over time are made in terms of similar physical & chemical environments. For the purposes of this Assessment, annual inflows greater than 1.5 x Lake volume (50 GL), have been designated as „wet years“, while annual inflows less than 1.5 x Lake volume (50 GL), have been designated as „dry years“.

It is necessary at this point to outline four key physico-chemical processes central to the Lake's response to discharges into the Lake. Firstly, the physical condition of mixing of water, including stratification; secondly, the microbially-mediated process of decomposition of organic material in the sediments and associated „reduction“ of nutrients and metals in the sediments; thirdly, the process of adsorption of nutrients, metals and bacteria on the surface of fine clay and silt particles, and fourthly, photosynthesis & oxidation.

With the onset of summer each year, the surface water of lakes heats more quickly than the deeper water. As the density of water decreases with rising temperature, the warming of the surface water creates „lighter“ surface water and „heavier“ deeper water, which physically separates the water column into two layers, a condition termed stratification. The interface between the warm surface water layer and the cold bottom water layer is termed the „thermocline“. Under these conditions, a barrier is created to the normal transfer of dissolved oxygen from the surface waters, to the deeper waters. Where organic particulates discharged to the lake, and dying algal cells, sink through the thermocline, into the bottom waters, de-oxygenation of the bottom waters and sediments may occur. This leads to the reduction of the sediments, and the release and accumulation of high levels of highly bio-available nutrients in the bottom waters. Lake Burley Griffin's temperature depth profiles indicate a thermocline depth range of 4 to 8 metres.

Typically, during early autumn with cooling of the surface water layer, a point is reached where the temperature of the surface and bottom water layers is equalized, and full mixing of the two layers occurs, including the dispersion of the nutrient rich bottom water throughout the lake. This may be the driver of a late „algal bloom“, depending on temperature and light (turbidity) conditions. Extensive areas of stratification occur in Lake Burley Griffin over the summer and early autumn periods, across Tarcoola and Yarramundi Reaches.

Research undertaken by the Cooperative Research Centre for Freshwater Ecology on Canberra pollution control ponds (*Lawrence et al 1998*), indicated that low wind travel (strength) over summer periods resulted in „diurnal stratification“ in shallow (<3 m depth) waters over summer,

with the potential for enhanced release of nutrients from the sediments. The same conditions would apply to shallow areas of Lake Burley Griffin. This is a key factor to understanding processes in the shallow embayments.

Except during periods of high inflow, the mixing of lake waters is primarily based on wind shear across the surface of the lakes. The surface turbulence created by the wind, enables the transfer of gases (O_2 , N_2 , CO_2) through the Lake water surface film. The wind also creates turbulence within the surface waters. This mixing energy (or diffusion) is dissipated with depth. Hence, the ability of lakes to transfer gases and nutrients is dependent on wind. Over Canberra's late spring to autumn periods, wind is typically light, with typical velocities of less than 7 km/hr. As a result, mixing conditions in the Lake are severely limited, reducing the Lake's ability to transfer oxygen to low oxygen bottom waters, and making the sediments much more vulnerable to reducing conditions.

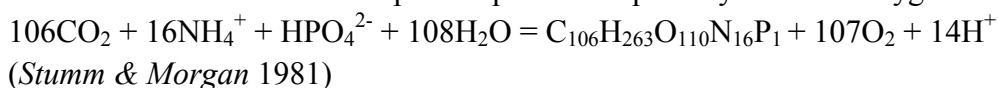
Oxidation and reduction processes are akin to the Lake's breathing. While reduction is mediated by heterotrophic and autotrophic bacteria, we describe it in chemical terms. Where there has been significant build-up of organic material in the sediments of lakes and deep pools, severe reducing conditions may occur. Reduction reactions occur when the decomposition of organic material depletes all available oxygen. The on-going decomposition of organic matter leads to the use of iron and sulfate in the sediments as electron receptors. This modifies (reduces) the speciation of these molecules (Fe^{3+} to Fe^{2+} , SO_4^{2-} to H_2S (gas)). This process continues until all the biologically available organic matter has been consumed by the bacteria, or the transfer of oxygen through the water column shifts the sediments back to oxidation conditions.

This is a key feature of lakes such as Lake Burley Griffin, where sediment data indicates significant quantities of (bound) Phosphorus and iron in the sediments. In these cases, the reduction of Fe^{3+} (solid) to Fe^{2+} (dissolved), results in the release of chemically bound phosphorus back into the water column, with the potential to promote algal growth in the Lake.

Fine particles of clay and silt have a high surface area relative to their mass (high *specific surface area*), exposing a large number of cations along their surfaces. These surfaces have a strong exchange (adsorption) capacity in respect to solutions of other cations and anions in solution, such as ortho-phosphate. The key exchangeable cations for freshwater systems include Na^+ , K^+ , Mg^{2+} , Ca^{2+} , H^+ , Fe^{3+} & Al^{3+} , and key exchangeable anions include Cl^- , HCO_3^- , NO_3^- , SO_4^{2-} & HPO_4^- . This is the keystone to indirect processes, where high levels of SS in catchment discharges result in an enormous adsorption capacity. Research on the fate of orthophosphate in a sewage effluent discharged to a stream high in SS indicated substantial removal of the orthophosphate by adsorption onto the fine suspended particles, within minutes of the discharge (Hart, McKelvie & Grace. 1998).

Soils of the Lake Burley Griffin catchment contain significant levels of illite (alumino-silicate mineral) based clays and iron. Adsorption isotherm analysis for Lake Tuggeranong suspended solids demonstrated high rates of adsorption of phosphorus capacity (*Lawrence & Baldwin 1998*). The research also demonstrated that significant reduction levels are required to break the iron binding (de-adsorb) the orthophosphate.

In the presence of light and nutrients (phosphorus & nitrogen), carbon dioxide in water is converted by plants into carbohydrates. This process is called photosynthesis. Carbohydrates form the energy base for much of the aquatic trophic system. Microscopic plants (algae) formed by this process, are either consumed by zooplankton, macro-invertebrates and fish, or ultimately die and settle to the sediments. An important product of photosynthesis is oxygen.



As noted above, the decomposition of organic material (carbohydrates) by bacteria and fungi, results in the consumption of oxygen. Hence, the natural process of photosynthesis and reduction results in a dynamic balance of oxygen, nutrient & H^+ (pH) consumption and release in natural waters. Where there is a need to compensate for minor imbalances in oxygen or CO_2 , lakes take-up or release these gases in exchange with the atmosphere. Where natural waters are enriched with discharge high in nutrients or organic material, this balance is modified, potentially leading to photosynthesis and reduction processes that exceed the capacity of water bodies to balance oxygen conditions with the atmosphere.

Stratification and mixing, photosynthesis and reduction, adsorption and de-sorption, are all key physico-chemical processes defining water quality and ecological patterns in Lake Burley Griffin!

Finally, it is important to note that there are significant differences throughout the Lake as a result of different primary drivers of algal growth and physical conditions. For example, the water quality and ecology of inlet zones such as East Basin reflects the dominance of discharges to the Lake high in SS and organic material, which deposit in the shallow inlet zone. Conversely, the water quality processes in the deeper open water zones in areas such as West Lake, reflect to a greater degree the in-Lake cycling of nutrients and organic matter. Hence it is necessary to review the water quality time series for each of the sampling stations separately.

5.4 General Lake condition – background data

The „background water quality“ table below indicates a moderate level of alkalinity in Lake water, providing an important buffer to pH change. The table indicates that sodium (Na^+) is the dominant cation. As a result, there is a low „coagulation of fine silts and clays“ capacity,

resulting in elevated turbidity during periods of elevated SS in inflows to the Lake. This is a natural feature of the Lake's catchment soils and runoff.

Table 5.2. Background water quality (Bottom water 8 samples 2007 – 2011)

Value	Dairy Flat	East Basin	West Lake	Scrivener Dam
Ca mg/L		15 - 20	13 - 20	12 - 26
Na mg/L		17 - 20	12 - 22	12 - 28
K mg/L		3.4 – 3.6	3.1 – 4.1	3.2 – 4.7
Mg mg/L		7.7 - 10	6.6 – 9.4	6.5 - 11
Mn mg/L		0.042 – 0.042	0.023 – 0.042	0.02 – 0.05
Si mg/L		5.6 – 5.9	6.8 – 8.7	7.4 – 9.5
Fe mg/L		1.2 – 1.7	1.0 – 2.2	1.7 – 2.5
Alk Tot mg/L	92 - 106	77	67 – 190	64

Source: NCA Lake water quality monitoring program

The Table highlights the significant quantities of iron through the Lake. Ferric iron is a powerful binder of ortho-phosphate phosphorus, removing the phosphorus from the water column by sedimentation. The adsorbed phosphorus is stored in the sediments, and is not available for biological uptake, except under severe reducing conditions in the sediments, when ferric iron is reduced to soluble ferrous iron. This is possibly the key process controlling algal production in the Lake.

Total dissolved salts (TDS) (equivalent to $0.70 \times \text{conductivity } \mu\text{S/cm}$), vary in inverse proportion to inflow. During „wet“ periods, the Lake TDS reflects the TDS of inflows (70 – 100 mg/L). During extended dry periods, evaporation losses from the Lake result in concentration of TDS, which can reach levels of 300 – 350 mg/L. High concentrations of TDS promote coagulation of fine colloidal particulates (SS), and their removal from the water column by sedimentation (including adsorbed nutrients, bacteria and bio-film coatings). This leads to the surface water becoming clearer and significant deepening of the euphotic (light) depth, during dry periods.

Assessment of the Lake surface water temperature indicated a 9% increase in summer average water temperature over the 1999 to 2009 low inflow period. This reflected, in part, a significant increase in air temperature over this period, and a reduction in wind strength (leading to decreased evaporative cooling). A 5 °C increase in summer temperature results in a 30% increase in biological growth rates, significantly enhancing microbial decomposition rates (through oxygen depletion in bottom waters) and algal growth rates.

Biochemical oxygen demand (BOD) values for Sullivan's Creek highlight the significance of urban stormwater as a source of organic carbon, driving the sediment redox (reduction-oxidation) conditions mentioned above. This is particularly significant in view of the 40% increase in urban areas draining to the Lake over the 1978 to 2011 period.

5.5 Assessment of Lake water quality 1978 - 2011

The Lake water quality data time series graphs (Appendix C Figs 4 to 31) indicate a significant variability in water quality in the Lake over the 1978 to 2011 period, reflecting seasonal variations in temperature and solar radiation, and climatic variability in alternating „wet“ (high runoff – high inflow) and „dry“ (low runoff – low inflow) conditions.

During periods of high inflow from the rural catchments, water quality processes in the Lake are dominated by the rural rivers physical sedimentation and re-suspension and wash-out processes. Consequently, the „in-Lake“ water quality and ecological processes are masked by the high inflow conditions. Conversely, during „dry“ periods, in-Lake water quality and ecological processes become dominant. *The extended dry periods therefore provide a window for assessment of the condition of the Lake.*

Extended dry periods are best identified by high TDS (200 – 300 mg/L) levels in the Lake. Using this approach, a number of extended dry periods were identified for comparison of in-Lake water quality over the 1978 to 2011 period. The extended dry periods were August 1982 to May 1983 and August 2007 to May 2009. Table 5.3 compares mean TDS and daily flow values for the two periods.

Table 5.3 Mean TDS & Molongo River flows for comparison „dry“ years

Dry year indicators	August 82 – May 83	August 07 – May 09
Mean TDS mg/L	240	250
Mean daily flow Ml/d	33.1	19.7

Nitrogen

Nitrogen is a key nutrient in respect to algal growth. However, it is rarely limiting, and consequently the major algal management focus is on limiting phosphorus, rather than nitrogen.

Assessment indicators and guideline values for nitrogen:

- Nitrogen/phosphorus ratio > 12 – to minimize potential for nitrogen fixing blue-green algae;
- Nitrate/Ammonia ratio > 5 – to minimize blue-green algal growth;
- Ammonia < 1.4 mg/L (for protection of aquatic ecology) & Ammonia < 0.2 mg/L (for minimizing cyanobacteria growth).

The *Lake Burley Griffin Water Quality Management Draft Plan* recommends total nitrogen (TN) limits of 1.4 mg/L for East Basin and 1.0 mg/L for West Lake. This recommendation appears to be based on current levels at these sites, rather than a specific ecological or use value

management objective. The *Draft Plan* notes that the current higher than usual nitrogen values does not have any adverse effects on ecology or human health.

The *Draft Plan* recommends an ammonia limit of 0.1 mg/L. The *ANZECC 2000* trigger value is in fact 1.43 mg/L for total ammonia at a pH of 8 (90 percentile value) or 2.3 mg/L (80 percentile value).

Early in the assessment period (1978 to 1983), the high level of phosphorus discharged in Queanbeyan Sewage Treatment Works effluent resulted in an imbalance in the nitrogen/phosphorus ratio, with outbreaks of a nitrogen fixing blue-green algae (*Anabaena*) occurring in the Molonglo Reach in mid to late summer periods. The upgrade of the Queanbeyan Sewage Treatment Works in 1983 (activated sludge facility with iron based phosphorus removal) resulted in a significant reduction in phosphorus in the Molonglo Reach (restoration of a balanced nitrogen/phosphorus ratio), with rare incidence of *Anabaena* since that time.

Nitrate (NO_3^-) is viewed as a beneficial nitrogen compound, in terms of its capacity to oxidize lake sediments previously subjected to high levels of phosphorus and organic matter loading. The direct injection of nitrate into sediments has been used as one means of offsetting the potential for reduction of sediments by ongoing organic matter. In a number of „eutrophied lake remediation projects“ involving the diversion of sewage effluent away from the lake, exacerbation of blue-green algal blooms has been observed (*Cullen & Forsberg 1988*). There is growing recognition of the value of retaining treated sewage effluent low in phosphorus and BOD, but high in nitrate, in discharges to lakes previously subject to high sewage nutrient loading, as a valuable buffer to the reduction of the sediments and associated release of sedimented phosphorus into the water column. This was the ACT experience in relation to remediation of Burrinjuck Reservoir. The commissioning of the Lower Molonglo Water Quality Control Centre (LMWQCC) de-nitrification facility in 1980 resulted in significant exacerbation of blue-green algal outbreaks. The closure of the de-nitrification facility in 1982 resulted in a major reduction in algal biomass and a return to Chlorophyta algal dominance.

Ammonia (NH_3) however, is a potential concern, both in respect to its enhancement of the growth of the blue-green algae *Microcystis*, and its potential for aquatic organism toxicity. The reduction in organic matter loading on the Lake (maintenance of well oxygenated waters), together with high nitrate levels, are the greatest defence against generation of ammonia.

Table 5.4 „Lake water quality 2007/09: TN“ summarises the mean levels of TN for the August 2007 to May 2009 period. The lack of TN monitoring up until 1994 prevented a comparison in levels between the early and late parts of the period.

Table 5.4 Lake water quality 2007/09: TN mg/L

Site	Mean 82/83	Mean 07/09
Molonglo Reach	No data	2.33
East Basin	No data	0.88
West Lake	No data	0.74
Yarramundi Reach	No data	0.58

Table 5.5 indicates a significant decrease (35%) in TN values with flow through the Lake, from the inlet end to Scrivener Dam, as a result of de-nitrification loss to the atmosphere. This level of de-nitrification suggests a healthy photosynthesis/respiration balance currently exists in the Lake. This observation conflicts with the concern regarding the decline in bottom water DO, to levels stressing bottom water dwelling respiring organisms.

Except for the early period (1978 to 1983) at Molonglo Reach, N/P ratios have met the >12 guideline value. Assessment indicates frequent spikes ($\text{NO}_3/\text{NH}_3 < 5$) in bottom water ammonia levels following stormwater discharges to the Lake. The Assessment indicates that the NO_3/NH_3 ratio is frequently less than 5 across all monitoring sites, particularly through the drought period. Failure to meet the NO_3/NH_3 guideline is less frequent at Yarramundi Reach than for the other sites.

Table 5.5 Decreases in indicator levels with flow through the Lake (August 2007 – May 2009)

Indicator	Mean values			2 tailed probability	Samples
	East Basin	Yarramundi	% reduction		
TN mg/L	0.88	0.57	35	<0.0001	10
TP mg/L	0.049	0.019	62	<0.0001	10
SS mg/L	16.1	3.8	76	<0.0001	10
Chlor a $\mu\text{g/L}$	17.6	6.3	64	<0.0001	10
T.Algae Cells/ml	53232	14897	72	= 0.0002	10
Cyano Cells/ml	28659	11363	60	=0.023	10
Faecal Coliform*	195	105	46	ND	

Notes: * means for 2000 to 2010 period ND – No data currently available

Phosphorus

Phosphorus is generally the critical nutrient in respect to limiting algal biomass growth, and the primary focus of lake eutrophication management. For Australian inland waters, TP levels vary significantly in proportion to stream flows and their SS loads (adsorbed P). A substantial proportion of this TP is removed from the water column by sedimentation of the SS particles. For „low inflow“ conditions, the in-lake TP reflects releases from the sediment into the water column, and the phosphorus contained in the algal organisms.

The Chlorophyll „a“ versus TP ratio for Burrinjuck Reservoir post LMWQCC commissioning, is 0.25 (Lawrence 2000). This Chlorophyll „a“ to TP ratio is similar to ratios observed by Harris

1986. Based on in-lake Chlorophyll "a" versus TP ratio of 0.25 value, the following values have been adopted as the guideline values for this assessment:

- 15 µg/L Chlorophyll "a" target for Molonglo Reach & East Basin translates to 0.06 mg/L TP;
- 10 µg/L Chlorophyll "a" target for East Basin & Yarramundi each translates to 0.04 mg/L TP.

The *Lake Burley Griffin Water Quality Management Draft Plan* recommends a TP guideline value of 0.1 mg/L. This Assessment adopts more stringent TP and Chlorophyll "a" values than the *Draft Plan*.

Table 5.6 „Comparison of Lake water quality 1982/83 & 2007/09: TP“ summarises the results of statistical analysis of TP values and trends over the 1978 to 2011 period. The analysis indicates an 80% decrease in TP at Molonglo Reach and a 30% decrease in TP at East Basin, but no clear indication of change for West Lake or Yarramundi Reach.

Table 5.6 Comparison of Lake water quality 1982/83 & 2007/09: TP mg/L

Site	Mean 82/83	Mean 07/09	1 way ANOVA test probability	Dispersion – F test probability	Number samples	Conclusion
Molonglo Reach	0.424	0.055	0.001	<0.0001	168	Highly significant
East Basin	0.070	0.048	0.06	0.003	25	Significant
West Lake	0.033	0.036	0.44	0.71	26	Not significant
Yarramundi Reach	0.020	0.019	1.00	0.33	22	Not significant

Table 5.6 indicates a significant decrease (60%) in TP values with flow through the Lake, from the inlet end to Scrivener Dam, as a result of sedimentation and a decrease in sediment organic loading in the lower regions of the Lake. The in-lake TP values exceed the Assessment guideline values in the Molonglo Reach. Other monitoring sites meet the guideline levels.

Assessment of the time series graphs (Appendix C: Figures 5, 10, 16 & 23) indicate frequent spikes in TP levels associated with high rural catchment discharges to the Lake. There is rapid decay in the levels following the discharge event, with the sedimentation of SS and their adsorbed TP. The algal growth spikes appear to be predominantly associated with stormwater discharges at time of low rural inflow – extended detention times in the Lake.

Suspended Solids

While SS are not directly implicated in promoting algal growth, they are an important modifier of a number of algal growth related processes, including the adsorption and removal of phosphorus from the water column, and the modification of euphotic (light) depth during wet –

high inflow periods. As discussed in Section 6 Condition of Catchments, soils of the Lake Burley Griffin catchments are typically sandy silts and sandy (moderately dispersive) clays, having a high capacity for adsorption of phosphorus. When suspended in water, these fine particulates are extremely stable in suspension. During dry periods, there is a significant increase in Total Dissolved Salt (TDS) levels in the Lake as a result of evaporation losses. The elevated TDSs coagulate the fine particulates, thereby enhancing their sedimentation rates.

While elevated turbidity – decreased light depth associated with elevated SS levels – advantages cyanobacteria algal growth over the growth of Green algae. However, sustained high turbidity throughout the water column is indicative of strong „mixing“ within the water column, promoting the growth of Green algae. Hence, there is rarely a cyanobacteria algal bloom under these conditions.

The *Lake Burley Griffin Water Quality Management Draft Plan* recommends a SS guideline value of 40 mg/L for East Basin and 20 mg/L for West Lake. These values were based on past patterns of SS at these sites. The mean levels for 2007/09 in Table 5.7 below are within the *Draft Plan* guideline values.

Table 5.7 Lake water quality 2007/09: SS mg/L

Site	Mean 82/83	Mean 07/09
Molonglo Reach	No data	12
East Basin	No data	16.8
West Lake	No data	10.1
Yarramundi Reach	No data	4.1

In the case of SS, the lack of SS monitoring up until 1994 prevents a comparison in levels between the early and late parts of the period. Table 5.7 „Lake water quality 2007/09: SS“ summarizes the mean values for SS for the 2007/09 period.

Table 5.7 indicates a significant decrease (75%) in SS values with flow through the Lake, from the inlet end to Scrivener Dam, as a result of extended detention – settling of fine SS particles. Wind is also a factor influencing SS values in the Lake. Strong NW winds along the Lake create significant waves, which re-suspend sedimented SS in the shallow East Basin area.

pH

pH is a master variable in relation to chemical equilibrium. The pH levels reflect the pH of catchment discharges, and the plant production and respiration processes in the Lake. Alkalinity of Lake water is an important buffer to pH change. The *Lake Burley Griffin Water Quality Management Draft Plan* recommends a pH range of 6.5 to 8.5.

Photosynthesis and reduction processes increase pH, while respiration and oxidation processes decrease pH levels. Table 5.8 „Comparison of Lake water quality 1982/83 & 2007/09: pH“ summarises the results of statistical analysis of pH values and trends over the 1978 to 2011 period. It appears that there is little change in this indicator over the 1982/83 to 2007/09 period.

The pH values are well within the Assessment guideline range.

Table 5.8 Comparison of Lake water quality 1982/83 & 2007/09: pH Units

Site	Mean 82/83	Mean 07/09	1 way ANOVA test probability	Dispersion – F test probability	Number samples	Conclusion
Molonglo Reach	7.81	8.03	0.15	0.054	28	Not significant
East Basin	8.24	8.28	0.61	0.007	32	Not significant
West Lake	8.24	8.12	0.38	0.003	34	Not significant
Yarramundi Reach	8.22	7.99	0.09	0.005	31	Probably significant

Dissolved Oxygen

Dissolved Oxygen (DO) is key to the health of aquatic respiring organisms. Levels of DO also influence the organic material oxidation/reduction products, as in the case of production of ammonia rather than nitrate under low DO/anoxic conditions. DO levels reflect variation in temperature (variation in DO saturation levels), and the balance of Photosynthesis oxygen production and Respiration oxygen consumption.

Where excess organic material loading occurs, a serious imbalance in photosynthesis/respiration (P/R) may occur in summer periods, resulting in severe depletion of DO levels. The time series Oxidation – Reduction indicators Figures 7, 12, 18 & 19, and 25 & 26 demonstrate DO peaks around mid-winter (low temperatures – high DO saturation concentrations & low rates of bacterial decomposition of organic matter) and troughs in mid-summer (high water temperatures – low DO saturation concentrations & high rates of microbial decomposition). The Figures also indicate elevated bottom water ammonia and TP levels, in association with low bottom water DO conditions. The *Lake Burley Griffin Water Quality Management Draft Plan* does not set a benchmark value for DO.

Table 5.9 „Comparison of Lake water quality 1982/83 & 2007/09: Bottom water DO“ summarises the results of statistical analysis of bottom water DO values and trends over the 1978 to 2011 period. The analysis indicates a 35% decrease in bottom water DO at West Lake between the 1982/83 and 2007/09 periods (significant statistically). This trend indicates a situation of increased loading of organic material on the Lake, potentially leading to increased production of ammonia and enhancement of blue-green algae.

With just one exception (following December 2010 flood), surface water DO is above the 6.0 mg/L ACT guideline values throughout the 1978 to 2010 period.

Table 5.9 Comparison of Lake water quality 1982/83 & 2007/09: DO_{bottom water} mg/L

Site	Mean 82/83	Mean 07/09	1 way ANOVA test probability	Dispersion – F test probability	Number samples	Conclusion
Molonglo Reach	7.8	No data				
East Basin	No data	No data				
West Lake	8.02	5.22	0.07	0.015	23	Significant
Yarramundi Reach	5.57	4.26	0.29	0.61	22	Not significant

Table 5.10 Frequency of DO_{btm} < 4.0 mg/L (Number/yr)

Period	West Lake	Yarramundi Reach
Aug 82 to May 83	1.0	3.0
Aug 07 to May 09	3.5	3.0

Chlorophyll ‘a’

Chlorophyll ‘a’ is a green pigment in plants responsible for their adsorption of the sun’s energy by the plants. It provides a useful measure of algal biomass. Lakes having Chlorophyll ‘a’ levels in the range of 5 - 15 µg/L are designated mesotrophic lakes, while those having Chlorophyll ‘a’ levels greater than 15 µg/L are designated as eutrophic lakes. In view of the huge range in algal sizes (2 orders for the more common freshwater algae), Chlorophyll ‘a’ does not provide a reliable guide to total algal cell numbers. Figure 32 „Trophic comparison of lakes” provides a trophic based comparison of lakes, including Lake Burley Griffin. The chart places Lake Burley Griffin on the meso – eutrophic boundary.

This Assessment proposes the adoption of 15 µg/L for Molonglo Reach and East Basin, and 10 µg/L for West Lake and Yarramundi Reach. These values are based on the level of Chlorophyll ‘a’ beyond which an unacceptable incidence of blue-green algal blooms has been observed. However, it is important to acknowledge that Chlorophyll ‘a’ is a coarse indicator of the risk of algal blooms – there are a range of complex factors that influence the algal biomass levels beyond which cyanobacteria blooms may become a problem. The *Lake Burley Griffin Water Quality Management Draft Plan* recommends a Chlorophyll ‘a’ value of 30 µg/L, based on the pattern of Lake algal levels over the last 15 years.

While Table 5.11 „Comparison of Lake water quality 1982/83 & 2007/09: Chlorophyll ‘a’” indicates reductions in Chlorophyll ‘a’ for all sites between 1982/83 and 2007/09, the scatter in the data is such that the difference between the means for the two „dry” periods is not statistically

significant.. A reduction (64% - statistically significant) in Chlorophyll „a“ levels is apparent with flow through the Lake.

Table 5.11 Comparison of Lake water quality 1982/83 & 2007/09: Chlorophyll „a“ µg/L

Site	Mean 82/83	Mean 07/09	1 way ANOVA test probability	Dispersion – F test probability	Number samples	Conclusion
Molonglo Reach	32.6	24	0.37	0.09	19	Not significant
East Basin	30.7	15.3	0.136	0.001	25	Not significant
West Lake	10.1	7.7	0.50	0.081	26	Not significant
Yarramundi Reach	6.3	5.7	0.91	0.065	22	Not significant

Mean Chlorophyll „a“ levels at Molonglo Reach exceed the Assessment criteria values for both the 1982/83 and 2007/09 periods. Mean Chlorophyll „a“ levels at East Basin exceed the Assessment guideline values for the 1982/83 period, but met the guidelines for the 2007/09 period. Both West Lake and Yarramundi mean levels are within the Assessment criteria values throughout the 1978 – 2011 period.

Total algal cells & cyanobacteria cells

The term „algae“ is used to identify a group of photosynthetic organisms not included among the mosses, liverworts or the vascular plants. It includes both eukaryotic cells (plants) and a group (cyanobacteria) of prokaryotic cells (bacteria). (*Entwistle, T.J. et al 1997*)

Lake Burley Griffin supports a diverse range of algae, with a strong seasonal succession evident from spring, through summer, into autumn periods. While a comprehensive range of algal genera have been surveyed over the 1978 to 2011 period, this Assessment has focused on the three major algal divisions – the yellow to light brown *Bacillariophyta* (diatoms), the green *Chlorophyta*, and the blue-green *Cyanophyta* divisions of algae. A number of the *Cyanophyta* genera have the potential to develop toxicity. Both *Microcystis* and *Anabaena* have the potential for development of toxins, and have been recorded in Lake Burley Griffin.

As noted above, there is a significant range in algal sizes. Chlorophyta (Green) and Bacillariophyta (Diatoms) algae typically (with a few exceptions) have a size range of 10^{-6} to 10^{-7} mm³. The cyanobacteria (blue green) algae are generally much smaller, ranging from 10^{-8} to 10^{-9} mm³. The Assessment and *Draft Plan* guideline level for cyanobacteria cells is 50,000 cells/ml.

Table 5.12 & 5.13 Comparison of Lake water quality 1982/83 & 2007/09: Total algae & cyanobacteria respectively, indicate increases in algal cell numbers between the 1982/83 to

2007/09 periods for Yarramundi Reach. The scatter of values for East Basin and West Lake do not permit any statistically valid conclusion regarding trends for these sites.

Tables 5.12 & 5.13 indicate a significant (60 to 70%) reduction in both Total algae and cyanobacteria cell numbers, with flow through the Lake. This pattern is critical in respect to the siting of primary contact recreational areas.

Table 5.12 Comparison of Lake water quality 1982/83 & 2007/09: Total Algae Cells/ml

Site	Mean 82/83	Mean 07/09	1 way ANOVA test probability	Dispersion – F test probability	Number samples	Conclusion
Molonglo Reach	51056	No data				
East Basin	37449	42368	0.37	0.355	25	Not significant
West Lake	16117	18059	0.44	0.006	26	Not significant
Yarramundi Reach	12250	13366	0.16	0.003	22	Not significant

Table 5.13. Comparison of Lake water quality 1982/83 & 2007/09: Cyanobacteria cells/ml

Site	Mean 82/83	Mean 07/09	1 way ANOVA test probability	Dispersion – F test probability	Number samples	Conclusion
Molonglo Reach	34639	No data				
East Basin	24316	14827	0.80	0.036	16	Not significant
West Lake	12250	11889	0.46	0.085	19	Not significant
Yarramundi Reach	726	9724	0.17	<0.0001	12	Not significant

Assessment of the time series graphs (Figures 8, 13, 20 & 27) indicate frequent cyanobacteria blooms during „dry“ periods, for all sites except Molonglo Reach, well in excess of the guideline value.

Table 5.15. Summary Tables for cyanobacteria & faecal coliform Guideline exceedance events, indicates highest incidence of blooms over the „dry“ years, with an average frequency of 2 bloom events/yr, in exceedance of Assessment guideline values for West Lake.

Faecal coliform

Levels of faecal coliform in the Lake reflect the levels in catchment discharges to the Lake, and in particular, the urban stormwater discharges, the faecal droppings of birds and other mammals in the Lake, and re-growth of sedimented Coliforms.

Up until 2008, faecal coliform (or *Escherichia coli*) were used as the indicator of faecal pollution of recreational waters. In view of the unreliability of faecal coliform as an indicator of faecal

pollution of freshwaters, the *NHMRC 2008* recommended the adoption of *Enterococci* for use as an indicator of faecal pollution in Australian freshwaters. The Assessment guideline for evaluation of the „Condition of the Lake“ is the previous *NHMRC* faecal coliform guideline of 150 CPU/100 ml. Because a reliable correlation between faecal coliform and *Enterococci* has not yet been developed for the Lake, faecal coliform has been used to provide the time based assessment of changes in the Lake over time.

Table 5.14 Lake water quality 2000 to 2010: Faecal Coliform (CPU/100 ml)

Site	Mean 82/83	Mean 2000 – 2010
Molonglo Reach	No data	152
East Basin	No data	195
West Lake	No data	217
Yarramundi Reach	No data	105

A comparison of 1982/83 and 2007/09 values was not possible for faecal coliform, due to missing data for the period prior to 1988. However, faecal coliform monitoring during the 1970s and early 80s identified a number of faecal contamination events, resulting from sewage spills from Queanbeyan Sewage Treatment Works and Morriset St Pump Station, and sewer capacity constraints within the Sullivan’s Ck catchment.

Average values for the period 2000 to 2010 are shown in Table 5.14. There is no pattern of decline in numbers with flow through the Lake in this case, indicating additional faecal pollution from urban stormwater discharges directly to the Lake from adjacent urban catchments..

Table 5.15 provides a list of the number of faecal coliform guideline exceedances for the period 1978 to 2010.

The records indicate an average exceedance of 0.2/yr for the period 1988 to 2010 for West Lake. A number of the faecal coliform events in Yarramundi Reach are classic „re-growth“ situations, occurring in late summer (collapse of algal biomass), with numbers from 5000 to 14,000 CPU/100 ml, and in an area remote from any stormwater discharge (source of possible contamination).

While the incidence of faecal indicator level exceedances of the Guideline value are probably similar for the early 1980s and the 1999 to 2010, the frequency during the 1980s was primarily point source related spills/overflows and non-point source sewer leakage. For the period 1999 to 2010, the frequency of exceedances reflects a number of factors, including non-point source house connection leakage, wildlife excreta, and re-growth on faecal bacteria indicators.

Table 5.15. Summary Tables for cyanobacteria & faecal coliform Guideline exceedance events

Year	Cyanobacteria cell levels				Faecal Coliform levels			
	Mol R.	East B	West L	Yarr R	Mol R.	East B	West L	Yarr R
1982	2	2	4	3				
1983	3	2	2					
1984								
1985	2		1	1				
1988								2
1989						1		1
1990						3		1
1991						3		
1992						3		1
1993								
1994			1					
1995							1	1
1996							1	
1997					2			
1998					1			
1999					1			
2000					1			
2001					1	1		
2002						3		1
2004							3	
2005					1	3		
2006					1	2		
2007		1			1	1		
2008			1	2	1			
2009		4	1		1			
2010		2	3		3			
Total	7	10	13	6	14	20	5	7

5.6 Beach embayments condition

As part of developing the recreational potential of the Lake, a series of swimming beaches were developed in the late 1960s/early 1970s. Sites were selected on the basis of:

- locations well downstream of significant discharges to the Lake (in order to maintain a high bacteriological water quality, suitable for swimming);
- locations having shallow - gently sloping beds, and some measure of separation from the open water recreational activities (for the safety of children using these facilities).

As a result, the beaches were located within the West Lake area. With the exception of the Black Mountain beach, the swimming locations comprised local embayments at Yarralumla Beach, and Weston Park East and Weston Park West beaches.

Over the last 10 years, these sites have been subject to greater incidence of elevated faecal coliform, and cyanobacteria algae levels than for the adjacent open water Lake areas. This

Section presents a review of water quality performance for these embayments. Regular monitoring of the beaches, separate from the Lake open water monitoring, has only recently been established, so the period of records for the embayments is limited.

Levels of faecal coliform in the Lake are the result of inflows to the Lake, and in particular, the urban stormwater inflows, production by water birds and other mammals in the Lake, and re-growth of sedimented coliforms under suitable temperature and organic material (macrophytes, algae, organic detritus) breakdown conditions. *Escherichia Coli* was used in the past as indicators of human faecal contamination. However, in view of its unreliability as an indicator of faecal contamination, the NHMRC has recently recommended the adoption of *Enterococci* for use as an indicator of faecal pollution in Australian freshwater.

Table 5.16 Summary of cyanobacteria, faecal coliform & *Enterococci* values for the Embayments (Sept 2007 to April 2011)

Indicator	Embayment		
	Yarralumla Beach	Black Mnt Beach	Weston Beach
Cyanobacteria (Cells/ml)	451,440	24,632	12,284
Faecal Coliform (CPU/100 ml)	69.4	90.9	92.8
<i>Enterococci</i> (CPU/100 ml)	122.9	120.4	194.5
Number of days exceedance of cyanobacteria Guideline value	8	8	8
Number of days exceedance of <i>Enterococci</i> Guideline value	5	14	17

The time series plots (Figures 29 to 31) indicate extreme levels of cyanobacteria, faecal coliforms and *Enterococci* for the 3 Beaches. While Table 5.16 indicates that the cyanobacteria mean values for the Black Mountain Beach and Weston Beach are significantly lower than for Yarralumla Beach, statistical analysis indicates a non significant difference between these means. Similarly, there is no statistical significant difference between the mean *Enterococci* values across the three beaches.

Since 2009, *Enterococci* has been used as the indicator. Monitoring has indicated 16 exceedances of the Assessment criteria value for Yarralumla Beach, 10 exceedances for Black Mountain Peninsula Beach, and 15 exceedances for the Weston Park Beach.

The Weston Beach embayment has by far the greatest level of enclosure, protecting it from high-wind blown algal scums, but as a result of poor mixing, retaining much of the faecal coliform & *Enterococci* generated in the embayment. While Yarralumla Beach has marginal levels of enclosure, it is on the windward side of the Lake in respect to prevailing NW wind, resulting in significant accumulation of wind-blown scum in the embayment. The Black Mountain Beach is the most open site, and its NW to SE orientation means that there is minimal accumulation of blue-green algal scum on the beach, and greatest dispersion rate of locally generated faecal coliform and *Enterococci*.

The comparison between the 3 Beaches, and with the adjacent „open water“ West Lake monitoring site, indicate that shallow (warm) water, poor mixing, and high wind-blown algal scum accumulation, are all major factors contributing to the severity of algal and bacteria problems in the Beach areas.

5.7 Sediment condition

As noted previously, the sediments play a key moderating role in respect to the storage, modification and release of nutrients, determining Lake water quality and ecology responses.

The Table 5.17A indicates a number of significant features:

- the large mass of phosphorus stored in sediments;
- the high mobility (variation in levels) of nitrogen;
- the high organic carbon content of the sediments and associated sediment BOD loading on the Lake; the moderate Sulfate levels, and the significant variation in levels, indicating significant levels of sediment accumulation (CaSO_4 & metal sulfide sedimentation), and sediment reduction (H_2S (g) release) during summer periods; and
- the significant range in values reflects the heterogeneity of sediments, and the mobility of oxygen, nitrogen, carbon, and iron and sulfate, as key redox (reduction-oxidation) process components.

Table 5.17A. Lake sediment values: Nutrients (8 samples 2007 – 2011)

Value	Dairy Flat	East Basin	West Lake	Scrivener Dam
TP mg/kg	500 - 1000	270 – 340	360 – 670	450 – 650
TN mg/kg	1000 - 6700	1600 - 1900	1400 - 3200	3000 - 3300
BOD mg/kg	1600 - 6360			
TOC %	1 – 7.6	0.8 – 3.1	1.4 – 3.5	3.0 – 3.1
SO_4 mg/kg	20 - 200	160 - 950	26 - 190	58 – 220

Source: NCA Lake water quality monitoring program

Table 5.17B Lake sediment values: Heavy Metals (8 samples 2007 -2011)

Value	Dairy Flat	East Basin	West Lake	Scrivener Dam
As mg/kg		3 - 4	2 - 7	6 - 9
Cd mg/kg		0.5 – 1.2	0.2 – 1.0	0.5 – 0.8
Cr mg/kg		12 - 17	13 - 43	29 – 32
Cu mg/kg		14 - 28	10 - 51	34 – 37
Hg mg/kg		<0.1 – 0.2	<0.1 – 0.2	<0.1 – 0.2
Ni mg/kg		10 - 15	11 - 29	19 – 22
Pb mg/kg		28 - 55	19 – 89	71 – 85
Zn mg/kg		420 - 790	160 - 780	470 - 580

Source: NCA Lake water quality monitoring program

With the exception of zinc and lead, the heavy metal values are within the *ANZECC 2000* Guideline values for heavy metals content of lake sediments. Prior to the stabilisation of the Captains Flat Mine Dumps, significant quantities of heavy metals were reaching Lake Burley Griffin in Molonglo River discharges.

The implied high level of iron present in Lake Burley Griffin sediments would maintain a high AVS/SEM ratio, minimizing the potential for mobilization of the heavy metals. (AVS - Acid Volatile Sulfides – iron & manganese mono-sulfides; SEM - Simultaneous Extractable Metals - cumulative mass of Cd, Cu, Ni, Pb, Zn).

Unfortunately, the sediment analysis has not included an assessment of total iron levels in respect to binding of PO₄. Values of iron in the sediments of Canberra pollution control ponds range from 10,000 to 20,000 mg/kg of sediment (Lawrence et al 1998), representing a PO₄ – phosphorus bonding capacity of the order of 5,000 to 10,000 mg/kg of sediment. Burrinjuck Reservoir sediment iron levels range from 1200 to 4140 mg/kg (*Dept of Construction 1978*).

5.8 Macrophyte ecosystem condition

Annual surveys were undertaken of the macrophyte beds across Lake Burley Griffin 1978 to 1989, by Chris Nazer, Department of Capital Territory.

Table 18. Seasonal growth of macrophytes (ha)

Year	Cover (ha)	Year	Cover (ha)	Year	Cover (ha)	Year	Cover (ha)
1966	17	1972	29	1978	11	1984	3
1967	10	1973	15	1979	33	1985	0.5
1968	17	1974	22	1980	8	1986	0.1
1969	18	1975	29	1981	23	1987	2.5
1970	8	1976	22	1982	24	1988	
1971	4	1977	52	1983	6	1989	

Source: *Cullen 1991*

Dominant submerged species have been *Vallisneria gigantea* (Ribbonweed) and *Potamogeton crispus* (Curly Pondweed). Emergent littoral zone plants include *Juncus articulatus* (Jointed Rush), *Typha domingensis* (Cumbungi), *Typha orientalis*, and *Phragmites australis* (Common Reed).

A significant ecosystem change for the Lake, not addressed by the monitoring, has been the substantial loss of submerged and emergent macrophytes across much of the East Basin area, and a large area between Springbank Island and the Acton shoreline. *Potamogeton crispus* and *Vallisneria gigantea* were the dominant submerged species in these areas.

These systems occupied some 10% of the Lake area in the early 1980s. There was little evidence of these macrophyte beds through the 1999 to 2009 drought. It is assumed that they have been inhibited by the epiphytic growth and elevated SS levels of inflow and re-suspension (in the case of East Basin) limiting light available for plant photosynthesis, or as a result of annual „cutting harvesting“ of macrophytes, to minimize conflicts with recreational activities. This is a significant ecosystem change, particularly for the East Basin area.

Littoral macrophyte systems around the edge of the Lake have been dominated by *Typha domingensis* (Cumbungi), *Phragmites australis* and *Juncus*. The littoral stands of macrophytes were severely impacted by the low Lake levels during the 1999 to 2009 drought period. The domination by a single species is the result of constant Lake level management practice.

5.9 Macro-invertebrate ecosystem condition

There is no data currently available on macro-invertebrates for the Lake.

5.10 Fish ecosystem condition

The Lake has been actively stocked with recreational fish fingerlings, as part of promoting the Lake as a recreational fishery. Consequently, in this instance, the composition and populations of fish do not provide a useful indicator of ecosystem health.

However, the population and composition of the fishery is important in respect to grazing pressures on algae and zooplankton, and the potential impact of species such as European Carp (*Cyprinus carpio*) on the sediments and macrophyte systems. It is recommended that further information is sought in respect to this component.

5.11 Lake condition assessment conclusions

During periods of high inflow from the rural catchments, water quality processes in the Lake are dominated by the Molonglo River physical sedimentation and re-suspension and wash-out processes. Consequently, the „in-Lake“ water quality and ecological processes are masked by the high inflow conditions. Conversely, during „dry“ periods, in-Lake water quality and ecological processes become dominant. *The extended dry periods therefore provide a window for assessment of the condition of the Lake.*

Two dry periods (1982/83 & 2007/09) were selected for the time based assessment of change in Lake water quality. The results of the analysis of change between these periods, is summarized in Table 5.19.

What are the in-Lake „dry“ period water quality conditions?

- high TDS, high water clarity/low turbidity, low SS;
- low TP;
- low bottom DO, elevated bottom NH₃, elevated bottom TP;
- low TN, low NO₃;
- generally low chlorophyll „a“ except at time of algal blooms;
- cyanobacteria algae becomes more prevalent, with occasional blooms;
- levels of TP, SS & Chlorophyll „a“, were generally within the assessment criteria levels over the 1999 to 2009 low inflow period, with occasional spikes (exceedances) associated with urban catchment discharges during „dry“ periods.

While the Molonglo Reach site has experienced a number of these features, there has been a much lower incidence of blue-green algal blooms at this site than for the East Basin, West Lake and Yarramundi Reach sites.

Table 5.19. Summary of changes in mean water quality levels between 1982/83 & 2007/09

Indicator	Molonglo Reach	East Basin	West Lake	Yarramundi Reach
TP mg/L	0.424 to 0.055 HS	0.070 to 0.048 S	0.033 to 0.037 NS	0.020 to 0.019 NS
TN mg/L	ND to 2.33	ND to 0.88	ND to 0.74	ND to 0.58
SS mg/L	ND to 12	ND to 17	ND to 10	ND to 4
pH Units	7.81 to 8.03 NS	8.24 to 8.28 NS	8.24 to 8.12 NS	8.22 to 7.99 PS
DO _{btm} mg/L	7.8 to ND	ND to ND	8.02 to 5.22 S	5.57 to 4.26 NS
Chlorophyll a µg/L	32.6 – 24 NS	30.7 – 15.3 NS	10.1 – 7.7 NS	6.3 – 5.7 NS
Total algal cells #/ml	51026 to ND	37449 to 42368 NS	16117 to 18059 NS	12250 to 13366 PS
Cyanobacteria cells #/ml	34639 to ND	24316 to 14827 NS	12250 to 11889 NS	726 to 9724 NS
Faecal Coliform CPU/100 ml	ND - 152*	ND - 195*	ND - 217*	ND - 105*
No BG algae exceedance/yr	2.5 to ND	2 to 1.7	3.0 to 0.7	1.5 to 0.7
No of Faecal exceedance/yr	ND to 1.0	ND to 0.3	ND to 0	ND to 0

Notes: ND – no data available for period

* Means for 2000 to 2010

NS – Not statistically significant (>0.05 single tail)

PS – Probably statistically significant (<0.05 single tail)

S – Statistically significant (<0.01 single tail)

HS – Highly statistically significant (<0.001 single tail)

What are the in-Lake „dry“ period water quality changes over time?

- An 80% reduction in TP levels in Molonglo Reach, and 30% reduction in TP levels in East Basin;

- a 35% decline in bottom water DO levels in West Lake;
- a decline in the frequency in cyanobacteria bloom exceedances of the guideline value;
- comparisons of TN & faecal coliform were not supported, because of lack of data;
- comparisons of pH, Chlorophyll „a“, Total algal cells & cyanobacteria cells were not supported statistically, due to small changes or scatter in the data.

The comparison of cyanobacteria cell numbers between the 1982/83 and the 1999/2009 periods is less clear. However, there was a decreased frequency of cyanobacteria cell numbers exceeding the guideline value (50,000 cells/ml) during 1999/2009 than for the 1982/83 period.

In addition to changes in Lake water quality as a function of time, there is a consistent pattern of reduction in mean levels (35% TN, 60% TP, 75% SS, 67% Chlorophyll „a“, 72% Total Algal Cells & 60% cyanobacteria Cells – all highly significant statistically) with flow through the Lake, from Molonglo Reach at the inlet end of the Lake, down to Scrivener Dam – the outlet end of the Lake.

Assessment of the Lake surface water temperature indicated a 25% increase in summer average water temperature over the 1999 to 2009 low inflow period. This reflected in part, a significant increase in air temperature over this period, and a reduction in wind strength (decreased evaporative cooling). A 5 °C increase in summer temperature results in a 30% increase in biological growth rates, significantly enhancing microbial decomposition rates (oxygen depletion in bottom waters) and algal growth rates.

It is concluded that the condition of the Lake during the 1999 to 2009 drought, was certainly no worse than for the comparable 1982/83 drought period. There was a substantial improvement in water quality and reduction in algal biomass in the Molonglo Reach and East Basin area, as a result of the 1985 upgrading of the Queanbeyan Sewage Treatment Plant. In the case of West Lake and Yarramundi Reach, this improvement was diminished by significant increase in the stormwater discharge of organic material associated with urban growth in the catchment.

What are the in-Lake „wet“ period water quality conditions?

- low TDS, poor water clarity/high turbidity, high SS;
- high TP (adsorbed on surfaces of SS);
- high bottom DO, (except for Yarramundi Reach over summer), low bottom NH₃, low bottom TP;
- high TN, high NO₃;
- highly variable Chlorophyll „a“, with frequent elevated (but not bloom) peaks;
- cyanobacteria blooms rare;
- levels of TP, SS & Chlorophyll „a“ frequently exceed the guideline values;

What are the in-Lake „wet“ period water quality changes over time? This question will be addressed in the assessment of Conditions of the catchments, Section 6.

There is a strong seasonal pattern of algal succession evident in the Lake - a healthy reflection of the ability of the Lake's ecology to adapt to changing seasonal conditions. It appears that the shift in algal composition to cyanobacteria dominance during „dry“ periods, is a reflection of the physical and nutrient environment associated with „dry“ periods, disadvantaging growth of the Chlorophyta algae, and promoting the growth of cyanobacteria algae.

It is apparent that the Lake has demonstrated an amazing resilience in adapting to an extreme range of climatic conditions. Unfortunately, some of these responses have resulted in symptoms (algal scums and odours, algal toxins) which conflict with the community's use (recreation, aesthetic) of the Lake.

There are some concerns regarding the ecological health of the Lake. Lake surveys indicate substantial loss of macrophyte beds in or adjacent to the inlet zones (East Basin & Sullivan's Ck inlet). The time series trend analysis of bottom water DO indicates a decline of 35% in mean bottom water DO values, down to a median value of 40% of DO_{saturation} – a level placing bottom water dwelling respiring organisms under stress. (Figures 7, 12, 18 & 19, and 25 & 26).

The background data indicated a moderate level of alkalinity in Lake water, providing an important buffer to pH change. The data also demonstrated that Sodium (Na⁺) is the dominant cation. As a result, there is a low „coagulation of fine silts and clays“ capacity, resulting in elevated turbidity during periods of elevated SS in inflows to the Lake. This is a natural feature of the Lake's catchment soils.

The data also highlighted the significant quantities of iron through the Lake. Ferric iron is a powerful binder of ortho-phosphate phosphorus, removing the phosphorus from the water column by sedimentation. The adsorbed phosphorus is stored in the sediments, and is not available for biological uptake, except under severe reducing conditions in the sediments, when Ferric iron is reduced to soluble Ferrous iron. This is possibly the single key process controlling algal production in the Lake.

The assessment indicated a significant level of exceedance frequency in respect to Chlorophyll „a“, blue-green algal cells & faecal coliform guideline values, in the swimming beach embayments. The frequency of health warnings and Lake closures in respect to either the risk of toxin or pathogens effects on human health, over the last 5 years, raises serious doubts regarding the ongoing sustainability of primary contact activities in the embayments of the Lake.

Analysis of the embayment water quality data indicated extreme levels of cyanobacteria, faecal coliforms and *Enterococci* for the 3 Beaches. However, the cyanobacteria values for the Black Mountain Beach and Weston Beach are significantly lower than for Yarralumla Beach. The faecal coliform and *Enterococci* levels for Weston Beach are significantly higher than for Yarralumla Beach and Black Mountain Beach.

The comparison between the 3 Beaches, and with the adjacent „open water“ West Lake monitoring site, indicate that shallow (warm) water, poor mixing, and high wind-blown algal scum accumulation, are all major factors contributing to the severity of algal and bacteria problems in the Beach areas.

Assessment of the sediment data indicated that with the exception of Zinc and Lead, values are within the ANZECC 2000 Guideline values for heavy metals content of lake sediments. The high level of iron present in Lake Burley Griffin sediments, maintains a high AVS/SEM ratio, minimizing the potential for mobilization of the heavy metals. The data highlights the significant levels of nitrogen, carbon, and iron and sulfate in the sediments, all key redox process components.

Finally, it is helpful to consider the condition of Lake Burley Griffin in a wider „eutrophic lake“ context. Figure 32 Comparison of Trophic Lakes, compares some 40 European, North American and Australian lakes for which data on phosphorus and algal biomass levels is available. The comparison is based on the in-lake TP and Chlorophyll „a“ levels – two key indicators of lake trophic conditions.

The Comparison indicates that Lake Burley Griffin is between the Mesotrophic and Eutrophic categories, having summer Chlorophyll „a“ levels well below those of most of the „eutrophic lakes“ identified in the Comparison. Lake Burley Griffin has Chlorophyll „a“ levels greater than Lake Ginninderra but less than Lake Tuggeranong, and well below levels in Burrinjuck Reservoir prior to remediation (phosphorus removal from Canberra sewage) of the Reservoir.

Potential rehabilitation of the Lake through reduction in point source phosphorus loading, has now largely been exploited, with the 95% reduction in Queanbeyan sewage effluent phosphorus levels. Reduction in loads of organic material discharged in urban stormwater is a much tougher assignment.

6. Catchment condition assessment

6.1 Assessment framework

Section 4 of the Assessment outlined the typical external stressors related to each of the identified potential threats to Lake environmental and use values, and the relevant indicators for assessing the presence of these stressors in catchment discharges to the Lake (Table 4.1).

Table 4.2 Assessment „stressor indicators and guidelines values“ (Condition of the catchments assessment), listed the indicators for assessing these impacts within the Lake.

Section 5 undertook an assessment of Lake water quality data in relation to these key indicators, in respect to both „dry“ and „wet“ periods. Preparatory to addressing the management options for ameliorating adverse impacts on the Lakes environmental and use values, it is necessary to review the external loads (water, nutrients, organic material, sediment, iron) on the Lake, in order to establish the „cause – effect“ links, and thereby, provide an ability to explore possible management measures to ameliorate the frequency and severity of the impacts.

In order to address the related „means of amelioration of water quality impacts“ question, there is also a need to assess changes in the major drivers of the „water quality and ecology responses“ of the Lake, and their modifiers. The following lists of points summarise the relevant water quality indicators.

Key ecological balances:

- nutrients – catchment inputs, internal cycling (adsorption & settling to sediments, sediment redox transformation/release of nutrients, algal uptake/growth, decay and return to sediments, losses to the atmosphere, wash-out losses);
- oxygen – surface re-aeration, photosynthesis, inflow – oxygen consumption by decomposition organic material, respiration of organisms, oxygen demand of sediments, losses to the atmosphere.

Key stressor modifiers:

- Levels and patterns of inflow to the Lake, determining the water „detention time“ – a major determinant of plant growth levels within the Lake, and influencing mixing conditions within the Lake;
- Particulate adsorption & removal of nutrients – sodium dominant soils – dispersive, high iron – rapid adsorption of nutrients & removal by sedimentation;
- Light limitation as a result of high suspended solids;
- Temperature/heat – growth rates and chemical reaction rates (Seasonal factors);
- Mixing/turbulence energy (flow, wind) – re-aeration, diffusion, stratification, transport of algae through euphotic zone (Seasonal factors);

- Total Dissolved Salts promoting coagulation of fine suspended particles and their settling to sediments (clarification of water column – enhanced light depth);
- Macro-plants, promoting trapping and oxidation of organic material.

6.2 Description of Catchment

Lake Burley Griffin is located on the Molonglo River, a catchment of 1,866 km² in area.

Topographically, the catchment is part of the southern tablelands, with rounded hills and elevated plains (600 m), rising to the eastern Tinderry Mountains (1600 m) in the south east. The Great Dividing Range defines the eastern boundary of the catchment.

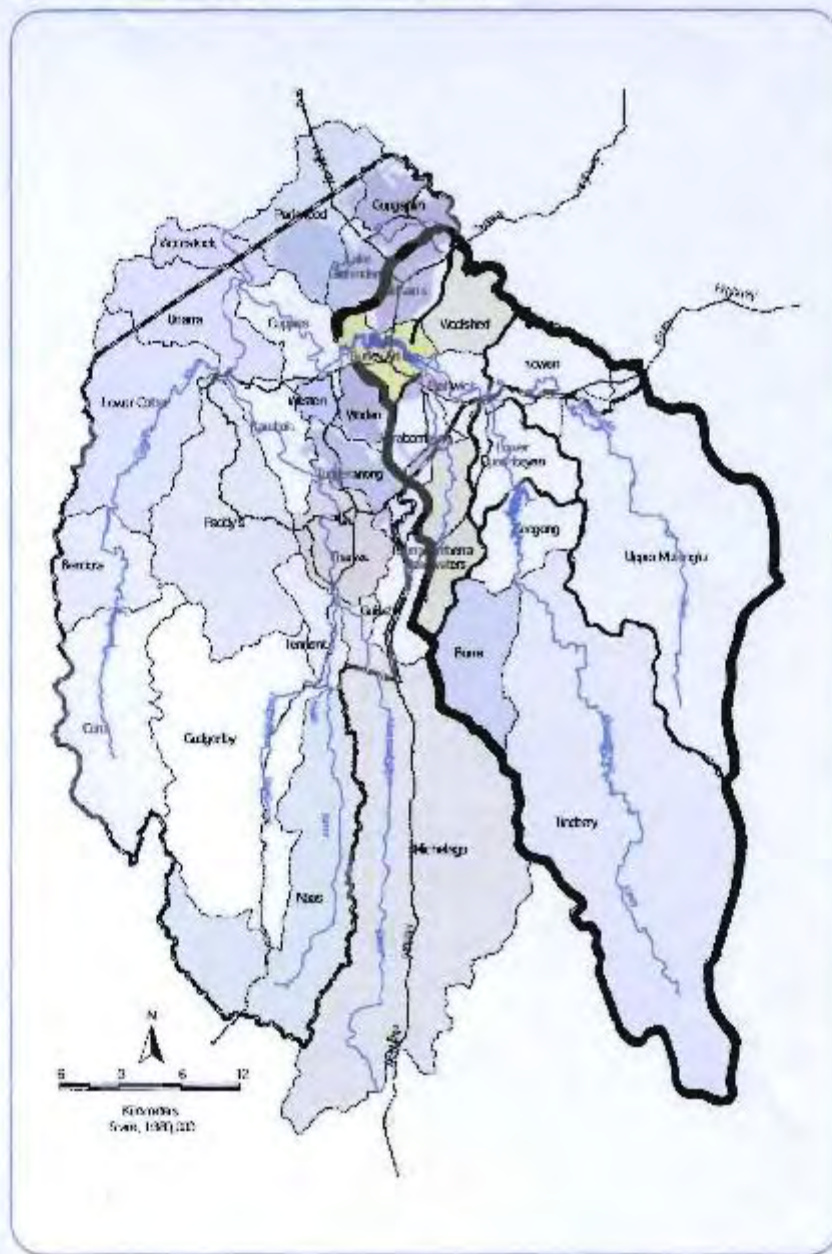
The northern catchment boundary is formed by the Ginns Gap, Greenwood, Womboin, Poppet, Amongula, Cohen, and Bald Hill Range (ACT Border). The Michelago and Tinderry Mountains form the southern catchment boundary.

The NSW Southern Tablelands has a continental climate, with hot summers and cold winters, with rainfall distributed relatively evenly throughout the year. The catchment experiences periodic severe drought conditions. It has two distinct climatic zones; the (600 – 800 mm rainfall) zone to the east, where the major rainfall influence is the tail of the coastal cyclonic depressions running down the Australian eastern coastline, reaching inland; and the low rainfall (450 – 550 mm) tablelands zone to the west, where the Brindabella & Fiery Mountain Ranges to the west cast a rain shadow over the Jerrabomberra valley and Canberra plains in respect to the continental rain depressions.

The CSIRO Climate Change forecast for the Southern Tablelands, is a shift from winter & spring dominant rainfall, to higher summer and autumn rainfalls, increased variability and extremes in the weather, and increasing temperatures. An increase in temperatures of 0.6 to 1.0 °C is forecast by 2030. Theoretically, more rainfall over summer should result in increased wash-out of algae during the critical algal growth period. Both the increased temperature and increases in atmospheric CO₂ will enhance the rates of the Lake's plant (including algae) growth.

Geology of the catchment is predominantly Ordovician sandstone and shale sediments across the hills and mountains to the east, and Silurian shale and volcanic sediments across the western plains. Isolated limestone intrusions occur in the Googong and Acton areas.

Plan 2. Lake Burley Griffin Catchment



Map 2. Lake Burley Griffin Catchment, displays the location of the major sub-catchments.

A sulfide ore intrusion in the Captains Flat area was the site for mining of gold, silver, lead, copper & iron in 1882 to 1899 and 1939-1962. The Mine became insolvent in 1962, leaving large mine tailing dumps of mine waste adjacent to Captains Flat Creek, and highly acidic and toxic mine drainage water discharging to the Creek. The potential „toxicant impacts“ has been an issue historically, and was addressed by *Joint Commonwealth and NSW Governments Mine Pollution Abatement Works* in 1975. Monitoring (DHC & BMR) undertaken post completion of the Works (1974 to 1978) determined that they had been effective, and that there were no longer detectable impacts on the Molonglo River or Lake within the ACT.

The *Environmental Impact Statement on the proposed Googong Dam* (1973) identified a concern that the reduced inflow to Lake Burley Griffin as a result of the Dam construction, could exacerbate the impacts of toxic pollutants from the Captains Flat Mine waste, on the Lake. In 1975, the Commonwealth and NSW Governments agreed on a *Project of Mine Waste Pollution Abatement*, to manage this potential impact. The Works were completed in 1977.

Given the age of the sediments (460 to 416 million years), soils of the catchment are highly weathered and low in nutrients. A large proportion of soils across the plains are Sodosols - Yellow Duplex soils, with deeper Kandosols - Red Earth soils adjacent to the Tinderry Mountains zone to the south east. These soils have high erosion susceptibility, as a result of their sandy clay A Horizon, and moderately dispersive kaolinite and illite clays in their B Horizon. The base of the B Horizons is also a zone of high iron content. As a result, the catchment yields high loads of suspended soil particles and iron during periods of high rainfall.

Clearing, over stocking and rabbit plagues late in the 19th Century, resulted in the initiation of erosion gullies across large areas of the Molonglo and Queanbeyan catchments. At the time of the design of Lake Burley Griffin, the potential level of sedimentation was seen as one of the major threats to the Lake's viability. In 1960, the Commonwealth and NSW State Governments agreed on the establishment of a joint soil conservation program across the catchment, to manage this threat.

Land uses across the catchment are predominantly rural (63.5%) and forestry and conservation (30.4%), with just 5.7% of the area urban land use. There are growing areas of rural residential development within the rural areas (3% of the rural area).

The extensive areas of natural grassland across the Canberra plains were augmented by the clearing of woodland areas across the plains and thinning of open forest on the lower slopes, beginning with European settlement across the region in the 1830s, to create areas for grazing of stock. Grazing areas comprise both native and improved pasture, and application of Super-phosphate and nitrogenous fertilizers through the 1950s and 60s.

Apart from the Turf Farm on Dairy Flat, there is little intensive horticulture across the catchment. As part of the early erosion control measures in the early 20th Century, extensive planting of pine trees was undertaken in the region, including Kowen within the Molonglo catchment. The establishment of vineyards and olive plantations are two more recent significant agricultural trends across the catchment. Their low use of water and fertilizers, means that they have minimal impact on water quality of catchment streams.

Of greater concern is the significant growth in rural residential development across the rural areas. These areas impact significantly on local runoff (farm dam retention), and have the potential for fertilizer, pesticide, and domestic waste water (septic tank effluent) discharges to local streams. Management of the rural residential development in the Burra catchment, a catchment discharging directly to the Googong Reservoir, is specifically addressed in the Commonwealth and NSW *Googong Water Acts 1978*.

Palerang Council has recently completed a survey of potential water pollution sites across the western Palerang area, including the upper Molonglo River catchment and the Googong Reservoir catchments. (Palerang Council 2011. *Draft Water Quality Snapshot for Western Palerang*). The survey adopts the Sydney Catchment Authority (SCA) „land use – pollution risk“ categories and pollution indicators (Nitrate, Phosphate, SS, pathogens) as the basis for identification of pollution sources and assessment of their water quality impact risks.

Table 6.1. Details of Catchment areas and land uses (2004)

Catchment	Sub-catchment	Land Use (km ²)			Total Area (km ²)
		Urban Area	Rural	Forest & Conservation	
Molonglo	Upper Molonglo		456.8	24.1	480.9
	Kowen		36.3*	54.5	90.80
	Woolshed		47.7	13.4	61.1
	Dairy Flat & Fyshwick	2.7	31.4		34.2
	Jerrabomberra - NSW	7.1	71.9		79.0
	Jerrabomberra - ACT	9.9	39.5		49.4
	Sullivan's	20.9	17.8	13.6	52.3
	Lake Burley Griffin local	34.1	5.6	17.5	57.2
Queanbeyan	Tinderry		353.5	353.5	707.0
	Googong Dam			73.2	73.2
	Lower Queanbeyan	32.2	24.2	24.2	80.6
	Burra		100.6*		100.6
Total Area		106.9	1185.3	574.0	1866.2
% Total Area		5.73	63.51	30.76	100

Source: ACT Govt. Think water, act water Volume 3: State of the ACT's water resources and catchments. 2004.

Notes: * Catchments undergoing significant rural residential development

The *Snapshot* concluded that On Site Sewage Management Systems (Septic Tanks) represented the most prevalent water quality risk issue, followed by waterway road crossings, and gully and

streambank erosion. The highest risk pollutant was identified as SS, followed by Nitrate, pathogens, Phosphate and other chemicals. Further details of the *Snapshot findings*, and the *Waterwatch water quality reports*, are addressed in the sub-catchment assessments below.

By far the greatest land use change and potential impact on water quality across the catchment, is urban development and related infrastructure. There has been a 35% increase in the urban area over the period 1978 to 2011, and a 34% increase in the urban population living within the catchment area.

The construction of Googong Dam (ACT & Queanbeyan water supply) on the Queanbeyan River, has the potential to reduce average annual inflow to the Lake by 45% (Dept of Construction 1978). While Googong Dam was completed just prior to 1978, diversion of Queanbeyan River flow has been limited as a result of the water supply operation practice based on the use the cheaper Cotter water in preference to the more expensive (pumping and treatment) Googong water. Analysis provided by ACTEW indicates an average annual diversion of just 7% of the average annual inflow to the Lake for the period 1978 to 2010. It is acknowledged that this diversion would have increased to an annual diversion of 50% of the average annual inflow to the Lake for the period 2003 to 2010 (consequence of the impact of the drought and the 2003 fire on Cotter water supply).

Queanbeyan sewage is treated at the Queanbeyan Sewage Treatment Plant, located just west of Oaks Estate, on the banks of the Molonglo River. Sewage discharge has increased from an Average Dry Weather Flow (ADWF) of 6 ML/d in 1978, to 9 ML/d in 2010. The facility is owned and operated by the Queanbeyan City Council. Its treatment capacity and standard has been progressively upgraded by the Council and NSW Public Works. In 1983/84, the plant was upgraded to an activated sludge facility, including an iron adsorption of phosphorus facility, resulting in significant reduction (95%) in phosphorus and in biochemical oxygen demand (BOD) (85%).

Sewage from Canberra's eastern residential and Industrial areas, is treated at the Fyshwick Sewage Treatment Plant, with treated effluent then pumped to the Molonglo Outfall Sewer Tunnel for further treatment at Lower Molonglo Water Quality Treatment Plant on the lower Molonglo River, or transferred for effluent re-use in north Canberra.

In 1995, a sewage overflow detention tank (City West Overflow Detention Facility) was installed on the Sullivan's Ck Trunk Sewer, to limit storm discharges to Sullivan's Ck to a frequency not exceeding 1 in 10 years. When overflows do occur, the facility is designed to separate and retain solids, and to disinfect the Sewage overflow to the Creek.

In view of their significant proportion of impervious areas (30 – 40%), and activities having the potential for emission of significant levels of nutrients, BOD and toxicants, urban stormwater is a key discharge of potential concern in respect to impacts on Lake Burley Griffin water quality and ecology.

6.3 Location of water quality sampling sites & scope of data

This Section draws on water quality analysis of samples collected from 4 major River water quality monitoring stations (Molonglo Reach, at Dairy Flat, Lower Queanbeyan River, at the ACT Border, Jerrabomberra Ck, at Hindmarsh Dr & Sullivan’s Ck, at Barry Dr), and Queanbeyan City Council monitoring of the Queanbeyan Sewage Treatment Works effluent discharge water quality.

In the case of the „condition of the catchment“ assessment, the analysis has drawn on 33 years of meteorological, streamflow, and water quality data compiled and maintained by the Bureau of Meteorology, ACTEW/ALS Global, National Capital Authority/ALS Global, Queanbeyan City Council, ACT Health, and Environment ACT. All of the laboratories engaged in the water quality sampling and analysis are NATA registered, and have maintained full documentation of sampling and analytical procedures and standards.

Table 6.2. Scope of available data

Catchment	Physico-chemical	Hydrol Gauge Stn	Period
Upper Molonglo River	1994 – 2011	Molonglo @ Oaks Estate	1978 - 2010
Lower Queanbeyan River	1994 – 2011	Queanbeyan @ ACT Border	1978 - 2010
Jerrabomberra Ck	1997 - 1998	Jerrabomberra @ Hindmarsh Dr	1996 - 2010
Sullivan’s Ck	1999 - 2007	Sullivan’s @ Barry Dr	1986 - 2010
Queanbeyan STWks	1991 - 2011	Queanbeyan STWks	1991 - 2011

Typically, catchments exhibit a two stage pollutant concentration versus flow relationship, comprising the base flow conditions, wherein groundwater discharge (and associated constituents) are dominant, and the elevated discharge, wherein surface wash-off and transport is dominant. viz: $C_{\text{export}} = k_{\text{base flow}} + k_{\text{elevated flow}} Q^m$.

The power fraction in the case of the elevated flow export is a feature of most catchments, with a decline in concentration per unit of discharge in pollutant concentration with increasing flow levels. This is a feature of the transport capacity constraints and non-linear wash-off processes.

While urban stormwater concentration correlation with flow follows a similar pattern, low flow (groundwater infiltration into stormwater pipes & channels) is complicated by the breakdown of

organic material and associated re-mobilised of phosphorus & nitrogen in material trapped in stormwater entry pits, traps and pond in prior stormwater discharge events.

$$\text{viz: } C_{\text{export}} = k_{\text{base flow}} \pm k_{\text{prior event}} Q^p + k_{\text{elevated flow}} Q^m$$

Because the flow versus concentration regression does not make separate provision for the a-priori event contribution, this component results in additional variation in the base flow values.

The low flow – high concentration outliers in the urban stormwater catchment, where associated with a significant storm within the 4 week period prior to the sampling date, were statistically identified and eliminated from the urban stormwater data set, providing a data set better reflecting the low (groundwater) flow and elevated flow related processes.

The generation of daily loads is based on the correlation having the highest level of significance.

$$M_{\text{load}} = (k_{\text{base flow}} + k_{\text{elevated flow}} Q^m) \times Q, \text{ or } (k_{\text{flow}} Q^b) \times Q \text{ kg/d}$$

where C is concentration in g/m^3 and Q is flow in ML/d ,

„ k “, „ m “ & „ b “ are correlation coefficients.

Note that in this application, catchment scale factors are not applied, as monitoring is based on the whole of the sub-catchment discharges and pollutant levels.

6.4 Condition of rural catchments

This assessment of conditions of the sub-catchment is based on monitored water quality over the period 1978 to 2011, together with other available land use & management assessment information. The analysis builds on the data for the Upper Molonglo catchment, a large catchment of predominantly rural and conservation land use. There is, however, a growing area of rural residential development occurring within this catchment.

The Jerrabomberra Ck catchment has also been included as predominantly rural catchment. However, this is a catchment in transition, with the development of the Hume industrial area, the commencement of Jerrabomberra extension to Queanbeyan, and the Mugga Land Disposal Facility. The Narrabundah broad acre developments drain into the Creek below the Hindmarsh Drive sampling location. While there is some urban development underway in the catchment in the 1997/1998 period, it is limited.

Regression analysis of flow versus each of the stressor indicators was undertaken for the periods 1994/96 and 2007/2010, and used as the basis for determining change in catchment conditions over that time. Each of these periods comprises a mix of „dry“ and „wet“ years, having similar overall discharge volumes. These results are summarized in Table 6.3.

The analysis indicates little change in total nitrogen (TN) export levels as a function of flow over the 1994 to 2010 period. There was a 13% reduction in total phosphorus (TP) loads as a function of flow. The Jerrabomberra TP export level was 60% higher than the Upper Molonglo catchment level. This may reflect the impact of some urbanization in this catchment, and be influenced by the extremely limited period of monitoring.

The 34% increase in BOD (organic material) loads as a function of flow for the 2007 to 2010 period, as compared to the 1994 – 1996 period, for a catchment that has still not seen significant re-establishment of stocking and agricultural production in the post drought period, is surprising. It is possible that the area of rural residential development just upstream of the Sutton Rd monitoring site may be contributing to this increase in levels of BOD.

Table 6.3 Rural catchment discharge correlations & export estimates

Site & Period	Correlation (mg/L)	No	F	Probabil	Average 95%iles	Load kg/ha/yr
Molonglo 1994/97	$C_{TN} = 0.234 + 0.022 Q^{0.503}$	23	41	<0.0001		0.60
	$C_{TN} = 0.162 Q^{0.249}$	23	65	<0.0001		
	$C_{TP} = 0.014 + 0.0013 Q^{0.613}$	23	37	<0.0001		0.08
	$C_{TP} = 0.0069 Q^{0.389}$	23	68	<0.0001		
	$C_{BOD} = 0.738 + 0.046 Q^{0.539}$	23	32	<0.0001		1.66
	$C_{BOD} = 0.494 Q^{0.235}$	23	49	<0.0001		
	$C_{SS} = 7.23 + 0.083 Q^{0.909}$	23	57	<0.0001		63.2
	$C_{SS} = 1.787 Q^{0.489}$	23	83	<0.0001		
	$C_{pH} = 7.43$ (Units)					
Molonglo 2007/2010	$C_{TN} = 0.037 + 0.331 Q^{0.204}$	16	82	<0.0001		0.67
	$C_{TN} = 0.229 Q^{0.169}$	16	176	<0.0001		(+10%)
	$C_{TP} = 0.002 + 0.030 Q^{0.169}$	16	32	<0.0001		0.07
	$C_{TP} = 0.031 Q^{0.164}$	16	69	<0.0001		(– 13%)
	$C_{BOD} = 0.600 + 0.459 Q^{0.247}$	16	137	<0.0001		
	$C_{BOD} = 0.953 Q^{0.175}$	16	269	<0.0001		2.22 (+34%)
	$C_{SS} = -9.407 + 15.23 Q^{0.151}$	16	25	<0.0001		23.9
	$C_{SS} = 7.255 Q^{0.220}$	16	52	<0.0001		(– 46%)
	$C_{pH} \text{ average} = 7.08$ (Units)					(-5%)
Jerrabomberra 1997/98	$C_{Faecal Col av} = 184$ (CPU/100 ml)					
	$Q_{flow average} = 82.5$ (ML/d)					
	$C_{TP} = 0.063 Q^{0.264}$	10	1.8	= 0.21		0.12
	$C_{TP average} = 0.215$	10			0.13 to 0.30	
	$C_{BOD} = 3.35 Q^{0.029}$	8	0.04	= 0.85		2.16
	$C_{BOD average} = 3.82$	8			2.88 to 4.80	
	$C_{SS} = 27.6 Q^{0.402}$	10	3.1	=0.115		163
	$C_{SS average} = 183$	10			99 to 267	
	$C_{pH average} = 7.8$ (Units)					
	$Q_{flow average} = 133$ (ML/d)					

The level of reduction (46%) in SS loads as a function of flow is significant. This may reflect the substantial removal of stock from the rural catchments over the 1999 to 2009 drought period.

The Jerrabomberra catchment had a SS load export as a function of flow some seven-fold higher than for the Upper Molonglo catchment. This reflects significant impacts from urban development together with more erosion sensitive soils in this catchment.

There was a 130% increase in average faecal coliform between the 1994/97 and 2007/10 periods. This may reflect the growth in rural residential development just upstream of the Molonglo River catchment monitoring site. It also supports the findings of the Palerang Council catchment snapshot survey in respect to septic tank management issues.

Based on the nutrient and organic material correlations with flow, and the availability of daily gauged flow data, daily loads of each of the key stressor indicators were generated for the 1978 to 2010 period (Table 6.4). This information is required in order to assess the implications of changing load conditions for Lake water quality and ecological responses at key points through the Lake (Section 7).

The export loads per hectare of catchment per year (Table 6.4) for the period 1978 to 2010, were used as the basis for comparison with other published catchment export data. (refer to Appendix C: Figures 47 & 48). The Figures indicate that rural export levels for the Molonglo River are at the lower level of the published TN and TP rural export values.

Table 6.4 Catchment loads per ha for 1978 to 2010 (kg/ha/yr)

Parameter	Rural (U. Molonglo)	Urban (Sullivan's Ck)
TN	0.93	2.3
TP	0.12	0.15
BOD	2.60	6.97
SS	69.8	128.7

The daily load estimates were also used as the basis for comparing the relative contribution of the various nutrient and organic material sources (rural runoff, urban stormwater, Sewage effluent discharge) to the total loading on the Lake. This analysis is presented in Pie Chart form in Appendix D: Figures 38 to 46 in Section 7. The Charts indicate that the rural catchment was a major source of TP, BOD and SS during wet periods, but only a minor source for all constituents during dry periods. The contribution of each of the catchments is summarized in Table 6.5 below.

The relatively high TP contribution to both wet and dry years from the rural catchments, reflect the power of SS as a vehicle for transport of adsorbed phosphorus. It is important to note that this phosphorus is not directly available for algal uptake. It is buried in the sediments, and requires significant reducing conditions in the Lake sediments, to release it back into the water column as ortho-phosphate.

It is also important to note the magnitude of the BOD load from the rural catchments during wet years, particularly in the light of the 60% increase in BOD loads monitored at the Sutton Rd monitoring site.

Table 6.5 Summary of contributions of catchment exports to total lake loading (percent)

Nutrient	Climate category	Rural	Urban	Sewage
TN load	Wet yr	42	39	19
	Dry yr	2	20	78
TP load	Wet yr	73	26	1
	Dry yr	20	53	28
BOD load	Wet yr	48	39	13
	Dry yr	5	28	67
	Dry – 2 mg/L Sewage BOD	13	70	17
SS load	Wet yr	87	13	0
	Dry yr	58	39	2

6.5 Condition of urban catchments

The characterization of urban catchment conditions has drawn on data for the Sullivan's Creek catchment and the Lower Queanbeyan catchment. The Sullivan's Ck catchment is currently 40% urbanized, with expansion of the urbanized area in the northern part of the catchment over the periods 1985-90 & 2000-2005. There was also significant re-development in the southern Sullivan's Creek neighbourhoods (Turner, Braddon, O'Connor, Ainslie, Lyneham) over the period 1990 to 2011. The re-development of large blocks in Ainslie, Turner and O'Connor has resulted in significant increase in urban density and impervious area. As a result of urban infill and medium density re-development, the decline in household population has been offset, with a net 34% increase in the urban population within this catchment over the period 1980 to 2011.

There was augmentation of the Sullivan's Creek Trunk Sewer in 1979, and installation of stormwater reticulation in association with the re-development of the Braddon and Ainslie areas 1985 to 1990. Sewage storm detention tanks were installed on the Sullivan's Ck Trunk Sewer late in the late 1990s in order to meet the „less than 1 in 10 yr sewage spill“ design guideline. Canberra's first Gross Pollutant Trap was installed on the Creek at Parkes Way 1981, and the installation of stormwater wetlands commenced in 2005. More recently, the development of a stormwater harvesting scheme, based on wetlands, was commenced in 2009.

As a result of the construction of Googong Dam just 5 km upstream of the Queanbeyan (9 km upstream of the ACT Border sampling site), the Lower Queanbeyan area is primarily an urban catchment. Up until 2003, water quality from this catchment was periodically modified by flood overflows from the Dam, or riparian or environmental flow releases. Dam releases over the 2003 to 2010 period has been largely limited to riparian releases (12 ML/d) from the Dam. Over the

drought, this release has been further reduced to reflect the reduced level of inflow to the Reservoir (3 ML/d).

Hence, discharges to the River for the 2007/10 period are predominantly urban stormwater based. The discharge of Queanbeyan treated sewage effluent occurs downstream of the ACT Border sampling site. Developments across Queanbeyan City East, Karabar and Greenleigh over this period represent a similar increase in the urban area draining to this sampling site.

Available water quality data for Sullivan's Creek is limited to the 1999 to 2007 period. The analysis of data for Sullivan's Creek indicates significant nutrient and organic load variation with storm events. For the September 1999 storm event, the BOD load was 230 kg/d, some 40 times the ADWF discharge of BOD from the Queanbeyan Sewage Treatment Works. The peak discharge for this storm event (60 ML/d) is a significant flow level (equivalent to the 50 percentile Molonglo River flow) – a demonstration of the significance of urban stormwater flows in terms of organic material transport and deposition capacity.

The flow based correlation values (Table 6.6) identifies „load levels as a function of flow“ significantly higher than for loads for equivalent flows in rural catchments (2 fold TN levels, +30% TP levels, and 2 fold BOD levels). Faecal coliform levels as a function of flow were 2 fold the rural rate. SS loads as a function of flow were 3 fold the rural catchment levels, reflecting the high level of land disturbance.

Based on the *ACT Integrated Urban Waterways* stormwater abstraction program, and on wetland interception rates for the ACT, it is expected that the full development of wetlands and stormwater harvesting measures in this catchment will secure a further reduction of 20% in the Sullivans Ck derived nutrient, BOD & SS loads.

As in the case of the rural catchments, daily loads of each of the key stressor indicators were generated for the 1978 to 2010 period. The export loads per hectare of catchment per year (Table 6.4) for the period 1978 to 2010, were used as the basis for comparison with other published catchment export data. (refer to Figures 49 & 50). The Figures indicate that rural export levels for the Molonglo River are at the lower level of the published TN and TP rural export values.

The daily loads were also used to compare the relative contribution of the various nutrient and organic material sources (rural runoff, urban stormwater, Sewage effluent discharge) to the total loading on the Lake. This analysis is presented in Pie Chart form in Figures 38 to 46, and in Table 6.5.

Table 6.6 Urban catchment discharge correlations & export estimates

Site & Period	Correlation (mg/L)	No	F	Probabil	Average 95%iles	Load kg/ha/yr
Lower Queanbeyan 1994/97	$C_{TN} \text{ average} = 0.439$	23			0.404 – 0.473	1.9
	$C_{TP} \text{ average} = 0.028$	23			0.022 – 0.035	0.10
	$C_{BOD} = 1.91$	23			1.72 – 2.11	8.4
	$C_{SS} \text{ average} = 10.19$	23			6.17 – 14.21	44.6
	$C_{pH} \text{ average} = 7.6 \text{ (Units)}$					
	$C_{\text{Faecal Col average}} = 299 \text{ (CPU/100 ml)}$					
	$Q_{\text{flow average}} = 36.8 \text{ (ML/d)}$					
Lower Queanbeyan 2007/10	$C_{TN} = 0.256 + 0.189 Q^{0.463}$	18	784	<0.0001		6.5 (+240%)
	$C_{TP} = 0.059 + 0.0008 Q^{0.788}$	18	291	<0.0001		0.50 (+272%)
	$C_{BOD} = 1.474 + 0.908 Q^{0.326}$	18	56	<0.0001		11.6 (+39%)
	$C_{SS} = 6.668 + 1.314 Q^{0.606}$	18	270	<0.0001		147.2 (+230%)
	$C_{pH} \text{ average} = 7.0 \text{ (Units)}$					
	$C_{\text{Faecal Col av}} = 126 \text{ (CPU/100 ml)}$					
	$Q_{\text{flow average}} = 23.6 \text{ (ML/d)}$					
Sullivan's Ck 1999 - 2007	$C_{TN} = 0.936 + 0.022 Q^{1.05}$	31	16	<0.0001		
	$C_{TN} = 0.931 Q^{0.197}$	31	25	<0.0001		1.49
	$C_{TP} \text{ average} = 0.152$	37			0.12 to 0.18	0.102
	$C_{BOD} \text{ average} = 5.37$	37			4.0 to 7.0	
	$C_{BOD} = 4.12 Q^{0.12}$	31	3.0	=0.09		4.65
	$C_{SS} = 9.78 + 0.009 Q^{2.13}$	30	5.0	=0.014		
	$C_{SS} = 9.48 Q^{0.274}$	30	14	<0.0001		71.7
	$C_{pH} \text{ average} = 7.89 \text{ (Units)}$					
	$C_{\text{Faecal Col av}} = 635 \text{ (CPU/100 ml)}$					
	$Q_{\text{flow average}} = 3.5 \text{ (ML/d)}$					

The Table 6.5 values indicate that during a wet year, the urban catchments contribute 39% of the Lake's annual TN load, 26% of the Lake's annual TP load, and 39% of the Lake's BOD load. The Table indicates that during a dry year, the relative contribution of stressor loads to the Lake is still significant, at 20% of the Lake's annual TN load, 52% of the Lake's annual TP load, and 28% of the Lake's BOD load. When the 2010/2011 reduced BOD loads from Queanbeyan Sewage Treatment Plant effluent are factored into this analysis, urban stormwater contributes 70% of the dry year BOD (Figure 46).

While the assessment indicates that urban stormwater is a significant source of TP loading on the Lake, it is important to note that this phosphorus is not directly available for algal uptake. It is buried in the sediments, and requires significant reducing conditions in the Lake sediments, to release it back into the water column as ortho-phosphate. However, in this case, the associated high loads of urban stormwater BOD make a significant contribution to the energy required for the reduction of sediments and release of phosphorus back into the water column.

Canberra prides itself as „the garden City“! The build-up of organic material and fertility of our garden soil, necessary to sustain green and productive gardens, inevitably leads to an increase in

the annual loss of plant and soil organic biomass, via drains and streams, to the Lake. And so the Lake is enhanced in respect to organic material and fertility levels, supporting increases in aquatic plant growth. Our land use and management is inextricably linked with the quality of our waterways.

There is anecdotal evidence supporting this hypothesis. Firstly, the significant quantities of rich sediment trapped in the stormwater Gross Pollutant Traps. Secondly, the significant biomass of Autumn leaves collecting in street gutters and drains, and ultimately being washed through to the Lake.

Stormwater is the major source of faecal coliform loading on the Lake. This is partly a reflection of domestic pet populations across the catchment, but primarily the leakage from household connecting sewer ties to the public sewers during wet periods. While sewer breaks or sewer pump failures can contribute significant single event discharge, in overall loading terms, this contribution is minor.

6.6 Condition of catchment: Sewage treatment plant discharges

The Queanbeyan Sewerage Treatment Plant is located just west of Oaks Estate, on the southern bank of the Molonglo River. The Centre comprises primary treatment screens & settling tanks, a secondary biological treatment system (trickling filters, followed by activated sludge – aeration process) and effluent clarifiers. The treated effluent is then passed through a series of maturation ponds. Ferric chloride is added at the discharge to the final maturation pond, for phosphorus removal. Lime is also added for pH control.

A series of by-pass systems is provided to protect process systems in the event of capacity exceedance (wet weather flows) or process breakdown. By-pass of partially treated („primary“ or „primary + secondary“) sewage is directed to a series of maturation ponds, where it is mixed with fully treated sewage, and undergoes maturation pond sedimentation and aeration. The maturation pond outlet discharges to the Molonglo River.

The Plant has undergone a series of capacity and treatment standard upgrades over the 1978 to 2011 period, resulting in significant reduction in the discharge of SS, BOD & phosphorus to the River. The two major improvements were the addition of activated sludge biological treatment in 1985, and the iron chloride dosage system for phosphorus removal.

On several occasions, the site has been inundated by extreme Molonglo River floods, or extreme rainfall over the urban catchment, resulting in the flooding or wash-out of the maturation pond. In these situations, the maturation pond normally contains fully treated sewage effluent, undergoing further polishing prior to discharge to the River. As noted in the Sections 5.3 & 5.5

above, under extreme flood conditions, the Molonglo and Queanbeyan Rivers discharge contain high numbers of faecal bacteria. Under these conditions, the faecal bacteria washed out from the Queanbeyan maturation pond is minor compared to the large loads in the Molonglo and Queanbeyan River flows. However, it does clearly constitute a human faecal contamination source, and therefore presents a potential health risk during these extreme events.

Table 6.7 Queanbeyan STWks exports & trends: 1978 to 2010

Nutrient	Period	Regression Kg/ML/d	No samples	F coef	Signific	Load	Change
TN	1994/96	14.2 Q _{STWks}	160	910	<0.0001	124 kg/d	-26%
	2007/11	15.3 Q _{STWks}	132	398	<0.0001	92 kg/d	
TP	1994/96	0.095 Q _{STWks}	171	240	<0.0001	0.83 kg/d	-4%
	2007/11	0.134 Q _{STWks}	132	482	<0.0001	0.80 kg/d	
BOD	1994/96	26.1 Q _{STWks}	171	1221	<0.0001	227 kg/d	-90%
	2007/11	3.324 Q _{STWks}	132	65	<0.0001	20 kg/d	
pH*	1994/96	8.47 – 0.069 Q _{STWks}	132	16	=0.0001	7.87 Units	Not statistic signific
	2007/11	7.68 – 0.0127 Q _{STWks}	172	0.27	=0.61	7.60 Units	

Notes: Median Q_{STWks} 1994 = 8.7 ML/d

Median Q_{STWks} 2010 = 6.0 ML/d

Shaded rows – weak correlation

* pH Regression Units/ML/d

Prior to 1980, frequent spills of sewage occurred at the Morisset St pump. A major upgrade of the pump in the early 1980s has resolved this source of sewage spills. The growth in Queanbeyan Sewage discharge reflects the City's population growth over the period 1978 to 2011.

Analysis of the Queanbeyan Sewage Treatment effluent data for the period 1978 to 2010, indicates a significant reduction in TP (70%), TN (30% reduction) and in BOD (95% reduction), as a result of major upgrades to the Treatment Plant. This reduction has been achieved, notwithstanding a 2 fold increase in population over the 1978 to the 2010 period.

The Treatment Plant appears to now have a low (0.25 mg/L) TP level, well oxidized Nitrogen, and an extremely low BOD (1 mg/L). The high NO₃ level has a positive impact on the River and Lake water quality, in respect to the significant oxygen contribution made to offsetting the BOD of decomposing organic material in the River and Lake.

Applying the daily loads, it is possible to compare the relative contribution of the various nutrient and organic material sources (rural runoff, urban stormwater, Sewage effluent discharge) to the total loading of key stressors on the Lake. Figures 38 to 40 indicate that during a wet year, the sewage source contributes 19% of the Lake's annual TN load, less than 2% of the Lake's annual TP load, and 13% of the Lake's total BOD load.

Table 6.8. Queanbeyan Sewage Treatment Plant comparison of 1978/81, 1994/96 & 2007/2010 effluent quality values (Kg/ML/d)

1978/81 Flow Correlation	1994-96 Flow Correlation	2007-2010 Flow Correlation
TN = 30 Q _{STWks}	TN = 12.9 Q _{STWks} kg/d	TN = 14.2 Q _{STWks} kg/d
TP = 4 Q _{STWks}	TP = 0.091 Q _{STWks} kg/d	TP = 0.139 Q _{STWks} kg/d
BOD = 30 Q _{STWks}	BOD = 29.9 Q _{STWks} kg/d	BOD = 2.18 Q _{STWks} kg/d
	pH = 7.6-0.004 Q _{STWks} Units	pH = 8.0+0.0004 Q _{STWks} Units

Figures 41 to 46 indicate that during a dry year, the relative contribution of sewage derived stressor loads is more significant, at 78% of the Lake's annual TN load, 28% of the Lake's annual TP load, and 67% of the Lake's BOD load. When the 2010/2011 reduced BOD loads from Queanbeyan Sewage Treatment Plant effluent are factored into this analysis, sewage sources of BOD represent just 17% of the total dry year BOD (Figure 46).

6.7 Condition of the catchments assessment conclusions

By far the greatest land use change and potential impact on water quality across the catchment, is urban development and related infrastructure. There has been a 35% increase in the urban area over the period 1978 to 2011, and a 34% increase in the urban population living within the catchment area.

The construction of Googong Dam (ACT & Queanbeyan water supply) on the Queanbeyan River, has the potential to reduce average annual inflow to the Lake by 45%. While Googong Dam was completed just prior to 1978, diversion of the Queanbeyan River flow has been limited, with an average annual diversion of just 7% of the average annual inflow to the Lake for the period 1978 to 2010. It is acknowledged that this diversion would have increased to an annual diversion of 50% of the average annual inflow to the Lake for the period 2003 to 2010 (consequence of the impact of the drought and 2003 fire on Cotter water supply).

Significant urban growth in the Lake catchment over the 1978 to 2011 period has contributed to a major increase in BOD loads. This was offset in some measure by a substantial upgrading of sewage treatment at the Queanbeyan Sewage Treatment Plant.

Change in catchment load exports 1994/96 to 2007/10:

- Upper Molonglo: TN = + 10%, TP = -13%, BOD = +34%, SS = -46%, Faecal = +130%
- L. Queanbeyan: TN = +240%, TP = +400%, BOD = +39%, SS = +230%, Faecal = +250%.
- Queanbeyan STWks TP = -95%, BOD = - 90%;
- Monitored data for Sullivan's Ck not available prior to 1999.

Table 6.9. Summary of Sub-catchment load export rates (kg/ha/yr)

Stressor	Period	Sub-catchment			
		U.Molonglo	L.Queanbeyan	Jerrabomb	Sullivan's Ck
TN	94-96	0.6	1.9		
	07-10	0.67	6.5		1.49
TP	94-96	0.08	0.1	0.12	
	07-10	0.07	0.5		0.102
BOD	94-96	1.66	8.4	2.16	
	07-10	2.22	11.6		4.65
SS	94-96	63.2	44.6	163	
	07-10	23.9	147.2		71.7
Faecal CPU/100 ml	94-96	184	299		
	07-10	428	126		635

Notes: Faecal coliform in Median CPU/100 ml

Exceedance of stressor assessment (Indirect process) criteria:

- BOD < 20 mg/L & 0.2 g/m²/d (470 tonnes/yr) deposition – guideline values exceeded in 13 of the 33 years of the assessment;
- Faecal coliform < 150 cells/100 ml – exceeded frequently by L.Queanbeyan & Sullivan's Ck (urban catchment) discharges;
- SS < 40 mg/L Molonglo Reach & East basin – 4 exceedances U.Molonglo 1994-2011;
- SS < 20 mg/L West Lake & Yarramundi – 3 exceedances Sullivan's Ck for 1999 – 2007;
- NH₃ < 1.4 mg/L - 1 exceedance in Sullivan's Ck for period 1999 – 2007.

It is concluded that the cumulative BOD and Faecal Coliform loads from the rural and urban catchments have been in excess of sustainable Lake levels.

The „relative contribution of rural, urban and Sewage catchment to total Lake loads (Table 6.5), indicate 52% of BOD contributed by the Queanbeyan Sewage Treatment Works during „dry“ years. For the „dry year“ (2006), the concentration of BOD in treated Queanbeyan sewage effluent ranged from 20 to 30 mg/L. In early 2009, an upgrade in the Plant resulted in an effluent having a 2 mg/L BOD component – a 90% reduction in BOD loads from the Plant. Adjusting the relative contributions for this decrease in Sewage BOD contribution, the dry year BOD contribution would be 14% rural, 76% urban & 10% Sewage.

Comparison of catchment nutrient loads (kg/ha/yr) with published levels for rural and urban catchments indicates that levels for the Upper Molonglo catchment and the Sullivan's Ck catchment are at the lower levels of the published values.

The major change in catchment conditions, relates to the substantial upgrading of the Queanbeyan Sewage treatment Plant, with a 95% reduction in phosphorus and a 90% reduction in BOD discharged from the Plant.

The other major change is the 40% growth in urban areas within the Lake's catchment over the 1978 to 2011 period. The Assessment identified urban stormwater as the major source (80%) of organic material discharge to the Lake during „dry“ periods.

7. Lake water quality & ecology response processes

7.1 Assessment framework

Section 5 „Condition of the Lake assessment“ of this Review examined the pattern and levels of water quality and biology of the Lake, and how it impacted on the Lake environmental and use values.

The Section identified the key potential threats to Lake ecological and use values as:

- a Lake prone to poor mixing across summer months;
- the accumulation of significant quantities of phosphorus bound to iron in the sediments;
- the frequency of DO depletion in the bottom waters;
- shifts in algal composition to Cyanobacteria (Blue Green), having a propensity for formation of blooms and toxins;
- A moderate frequency and level of Blue Green algal blooms, threatening primary and secondary recreational use values, and impairing the aesthetic values of the Lake;
- A moderate frequency and level of Faecal Coliforms in the swimming embayments, indicating unacceptable risks to the health of users of these facilities.

The „Conditions of the Lake's catchments“ assessment identified two major factors bearing on these threats:

- A potential decrease (of up to 52%) in flows through the Lake, as a result of diversion of the Queanbeyan River at Googong Dam for water supply in the future, with the potential for significant future increase in the water detention time in the Lake, thereby enhancing algal growth;
- The high loading of BOD from urban catchments during the drier periods, and the significant growth (40%) in the urban developed area within the Lake catchment.

Section 6 examined the conditions of the catchments and point sources in respect to external inputs of key stressors to the Lake. This Section draws these Sections 5 & 6 together, as a means of identifying key „cause – effect“ chains. This understanding then enables a more rigorous

exploration of a range of management intervention measures, and their effectiveness in ameliorating impacts.

In the case of Lake Burley Griffin, the key modifiers of water quality and ecological responses to discharges to the Lake, comprise fine suspended; alkalinity of waterway; wind or flow mixing and diffusion shear; temperature; sedimentation; benthic fauna; and Total Dissolved Salts levels.

7.2 Lake physical, chemical and biological response processes

As noted in Section 6, Lake water quality is first and foremost, a reflection of its catchment – the pattern, composition and levels of external water and pollutant loads on the Lake over time. Not only is the rate of inflow a key driver of Lake water quality processes, but the inflow pathway is also a critical factor in respect to deep stratified lakes.

The temperature of catchment discharges is a reflection of the season, and the level of discharge (temperature inversely proportional to rate of flow). As a result, high levels of rural or urban stormwater discharge (together with their nutrient and organic loads) will dive to the bottom water zone during periods of Lake stratification.

Temperature vs flow regressions analysis for:

- Molonglo R @ Oaks Estate: $T_{\text{summer}} = 25.4/Q^{0.03}$
- Sullivans Ck @ Parkes Way: $T_{\text{Summer}} = 23.4/Q^{0.043}$

Table 7.1 A: Surface & bottom water zone average summer temperatures
(West Lake 1985 – 2010)

Zone	Average	Minimum	Maximum
Surface water	22.65	20.8	26.9
Bottom water	20.23	19.0	21.8

Table 7.1 B: Temperature of Molonglo River discharge over summer (1978 – 1995)

Inflow ML/d	100	500	1000
Temperature °C	23.2	20.0	18.4
Lake detention time (yrs)	0.9	0.2	0.1

Table 7.1 C. Temperature of Sullivans Ck discharges over summer (1999 – 2007)

Inflow ML/d	5.0	10.0	50.0	100
Temperature °C	21.8	21.2	19.8	19.2/17.7
Lake detention time (yrs)	18 yrs	9 yrs	2 yrs	1 yr

Comparison of inflow temperatures in Table B & C with average Lake water temperatures in Table A, indicates that for Molonglo River flows > 500 ML/d & Sullivans Ck flows > 50 ML/d, the discharges entering the Lake will be to the bottom water zone.

Finally, it is necessary to separately examine the Lake water quality responses in terms of individual Lake zones:

Upstream inlet zones:

- Confined deep pools based Molonglo Reach
- Open & shallow East Basin

Mid and downstream zones:

- the open & shallow to moderate depth West Lake zone
- the deep – confined Tarcoola & Yarramundi Reach zones

Building on this understanding of the catchment discharges, and the in-Lake physical arrangement and depths, this Section explores a number of conceptual models explaining the observed behavior of the Lake over time.

7.3 ‘High rural inflow and stormwater discharge’ condition

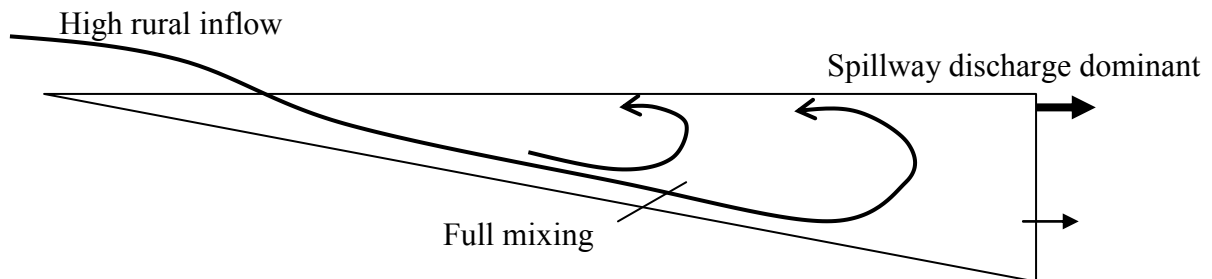
Molonglo River inflow of 1000 ML/d & Stormwater discharge > 500 ML/d:

Table 7.3 A. Summer periods of „high rural inflow & stormwater discharges“

Year	Molonglo average summer inflow ML/d	Molonglo range of summer inflows ML/d	Maximum Sullivans Ck discharge ML/d
1984	860	200 – 18,000	700
1989	1265	300 – 37,000	1600
1993	846	300 – 8,000	700

Inflow path and water balance conditions:

Figure 2 A. Summer (high rural inflow) water balance



$$Q_{\text{spillway}} = Q_{\text{Molonglo}} + Q_{\text{stmw}} - V_{\text{evap}} - V_{\text{abstraction}} = 1455 \text{ ML/d}$$

Under high rural inflow conditions, the high and sustained inflow energy results in mixing throughout the Lake, and rapid wash-out of any algae, with spillway (surface water) the dominant discharge mode.

Lake physical & chemical water quality response conditions:

- Extended flow hydrograph, with elevated flows and mixing sustained over several weeks, and SS and organic material dispersed through-out the Lake; significant levels of washout of dissolved and suspended constituents;
- Highly turbulent mixing throughout the Lake, Lake de-stratified (fully mixed);
- Discharges high in SS, together with re-suspension in shallow inlet zones; low conductivity (catchment surface runoff dominant);
- High TP inflow, but rapid SS adsorption of nutrients and removal by sedimentation;
- Deposition and burial of organic material in the sediments;
- High BOD loads, but predominantly rural refractory organic matter. Dispersed deposition & burial in sediments, dominant refractory composition, and high mixing energy maintains high oxygen levels throughout the Lake;
- Oxidation of refractory organic material, with release of N₂ gas (denitrification) & CO₂ (g), but retention of phosphorus;

Algal growth & composition response conditions:

- Light – the high inflow turbulence and low conductivity sustain fine particle suspension, limiting light availability for algal growth;
- Bio-available phosphorus - adsorption of orthophosphate on the extensive SS surfaces, and removal from the water column by sedimentation, resulting in low levels of bio-available phosphorus;
- Nitrogen level & composition – high nitrate under well mixed (oxidized) conditions during sustained inflow period;
- Residence (available growth) time & washout – short residence time & high rate of washout, limit the potential for algal growth;
- Mixing conditions – high turbulence, favouring larger algae (Bacillariophyta, Chlorophyta).

Molonglo Reach & East Basin water quality and algal responses:

In the case of high Molonglo River inflow condition, the water quality and algae (including washout from the Queanbeyan STWks maturation ponds) of the Molonglo River inflow dominates water quality and algae in the upstream inlet zones. Much of the inflow SS and organic material is washed through into the mid and downstream zones of the Lake, including some re-suspension of sediment from the Molonglo Reach deep pools and East Basin.

Observed water quality and algae

Table 7.3 B. Molonglo Reach observed summer water quality & algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1984	NA	15	134	0.08	NA	0.16	0.08	8	15	770	NA	310
1989	NA	19	150	0.06	NA	0.24	0.04	11.3	160	720	170	0
1993	NA	15	125	0.035	NA	0.19	0.04	18.5	60	170	30	30

Table 7.3 C. East Basin observed summer water quality & algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1984	140	NA	NA	0.105	NA	0.280	0.060	10.9	180	370	0	220
1989	NA	NA	NA	NA	NA	NA	NA	15	1640	1540	1640	1240
1993	124	NA	144	0.062	NA	0.046	0.044	25.6	680	1080	350	690

The observed water quality and algal levels and composition data are consistent with the responses predicted by this conceptual model.

West Lake & Yarramundi Reach water quality and algal responses:

Water quality in West Lake and Yarramundi Reach reflects the wash-out of SS, nutrients and algae from East Basin, and the decomposition of organic material deposited by the rural discharge. The potential for algal growth under these inflow conditions is limited. Expect low chlorophyll „a“ levels, and dominance of the larger algae (Bacillariophyta & Chlorophyta).

Observed water quality and algae

Table 7.3 D. West Lake observed summer water quality and algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1984	NA	30	122	0.07	NA	NA	0.07	6	350	2464	Nil	80
1989	NA	45	140	0.08	NA	NA	0.03	6	800	500	880	0
1993	NA	NA	180	0.05	NA	NA	0.05	13	600	550	600	0

Table 7.3 E. Yarramundi Reach observed summer water quality and algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1984	NA	25	130	0.07	NA	0.23	0.05	4.7	170	420	0	150
1989	NA	NA	150	0.09	NA	NA	0.05	5.0	270	680	260	170
1993	NA	NA	150	0.05	NA	NA	0.04	5.1	370	530	370	50

The observed water quality and algal levels and composition data are consistent with the responses predicted by this conceptual model.

7.4 ‘Moderate rural inflow and high to moderate stormwater discharge’ condition

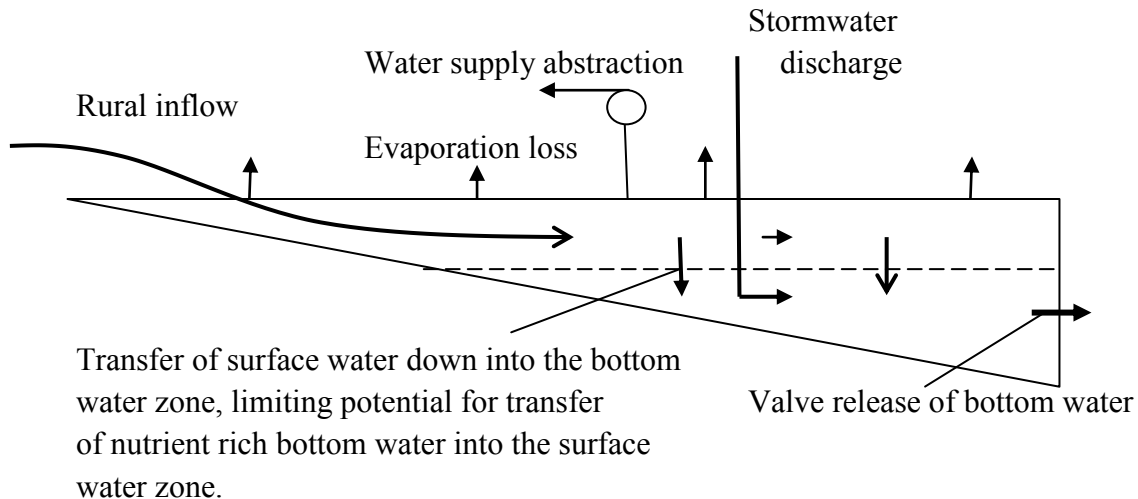
Molonglo River inflow < 500 ML/d & Stormwater discharge 500 ML/d:

Table 7.4 A. Summer periods of ‘high rural inflow & stormwater discharges’

Year	Molonglo average summer inflow ML/d	Molonglo range of summer inflows ML/d	Maximum Sullivans Ck discharge ML/d
1979	220	200 – 1200	100
1986	205	200 – 300	100
1992	203	100 – 400	700
2000	140	20 – 400	120
2001	70	20 – 200	480
2002	60	10 - 600	800

Inflow path and water balance conditions:

Figure 2 B. Summer (moderate rural inflows) water balance



$$V_{\text{transfer}} = Q_{\text{Molonglo}} - V_{\text{evap}} - V_{\text{abstraction}} = 455 \text{ ML/d (surface water to bottom water zone)}$$

$$Q_{\text{valve}} = Q_{\text{stmw}} + V_{\text{transfer}} = 955 \text{ ML/d}$$

Under moderate rural inflow conditions, the Molonglo River discharge will be to the surface water zone, sustaining mixing in the zone. Lake water releases will be via the valves (bottom water zone) for this level of Lake inflow (no wash-out of algae). The moderate level of inflow into the surface water zone will provide marginal enhancement of the wind mixing of the surface water zone. Importantly, the level of inflow into the surface water zone, and release via the bottom water zone valve, will result in water transfer of water from the surface water zone downwards into the bottom water zone.

Lake physical & chemical water quality response conditions:

- Inflow levels and mixing sustained over several weeks, and low conductivity results in sustained suspension of fine SS;
- Well mixed surface water zone, and later commencement of stratification of Lake;
- High TP inflow, but rapid SS adsorption of nutrients and removal by sedimentation;
- Deposition and burial of organic material in the inlet deposition zones (pools of the Molonglo Reach, East Basin);
- High BOD loads, but predominantly rural refractory organic matter in upstream inlet zones – mix of refractory and labile organic material in mid and downstream Lake zones. Well mixed/aerated across the shallow areas of the Lake, but on-set of stratification isolates deeper water from re-oxygenation.;
- Decomposition of organic material in the deeper zones resulting in depletion of oxygen levels, and a mix of N_2 (g) and NH_3 production; oxidation of labile organic material with release of N_2 gas (denitrification) & CO_2 (g), but limited release of phosphorus.
- The a sharp flow peak in the urban stormwater discharge, with flow lasting only 2 to 4 hrs, results in a discharge plume well into the bottom water zone, with deposition of labile organic material into the poorly mixed bottom water zone, rather than the inlet depositional zone, further exacerbating depletion of oxygen and release of bio-available P from the sediments into the bottom water zone;
- The high inflow energy associated with the high velocity urban stormwater discharge, has the potential for enhanced mixing across the boundary between the surface and bottom water zones. However, this effect is offset by the downward transfer of the surface water zone into the bottom water zone. The release of water from the bottom water zone valve, rather than the surface water zone spillway, enhances this downward water movement.

Algal growth & composition response conditions:

- Light – moderate light availability under moderate SS levels;
- Inflowing phosphorus adsorption on the SS surfaces and removal by settling of the SS to the Lake sediments. Potential for transfer of bottom water phosphorus limited by downward transfer resulting from rural inflow to surface water zone;
- Nitrogen level & composition – generally well nitrified surface water zone, under moderate mixing conditions and settling of organic material (BOD) to bottom water zone;
- Increased water detention time, and cessation of washout, providing the potential for increased algal growth;
- Mixing conditions – moderate levels of mixing, sustaining growth of Chlorophyta algae.

Molonglo Reach & East Basin water quality and algal responses:

In the case of moderate Molonglo River inflow condition, the water quality and algae (including washout from the Queanbeyan STWks maturation ponds) of the Molonglo River inflow will continue to dominate water quality and algae in the Molonglo Reach.

For the moderate inflow condition, there is a significant reduction in the Molonglo River flow velocity on entering East Basin. As a result, the bulk of the organic matter flushed-out by these events is deposited in East Basin. This is reflected in the severe reducing conditions observed in the data in East Basin, following urban catchment discharge events, not-with-standing the shallow nature of the Basin.

Water quality in the Basin reflects wash-out from the deep Molonglo River pools, the decomposition of organic material deposited in East Basin by significant storm (Stormwater) events or flood (Molonglo and Jerrabomberra catchments Rural discharge) events, and wind events. However, the level of sustained through-flow will limit time available for algal growth in the Basin, and maintain good mixing conditions and re-aeration, limiting algal biomass, and promoting Chlorophyta growth rather than Cyanobacteria.

Observed water quality and algae

Table 7.4 B. Molonglo Reach observed summer water quality & algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	TN	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1986	NA	4	200	0.125	NA	0.53	0.04	19.3	620	1070	700	810
1992	NA	19	NA	0.050	NA	0.40	0.09	12.7	50	420	55	1
2000	3.7	4.4	220	0.032	0.55	0.05	0.06	3.9	250	1370	1	0
2001	8	9	240	0.034	0.67	0.35	0.03	5.4	260	920	70	0
2002	19	21	290	0.057	1.60	1.00	0.09	5.7	250	450	0	0

Table 7.4 C. East Basin observed summer water quality & algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1986	17.0	NA	178	0.140	NA	0.195	0.021	13.3	300	590	300	80
1992	14.4	11	NA	0.034	NA	0.267	0.025	11	250	950	160	210
2000	11	13	221	0.043	0.002	0.110	0.009	4.9	495	2450	1	140
2001	16.7	18	239	0.057	0.005	0.068	0.042	20	630	3510	1	540
2002	17	21	270	0.060	0.006	0.350	0.020	23	150	12870	3	720

The observed water quality and algal levels and composition data are consistent with the responses predicted by this conceptual model.

West Lake & Yarramundi Reach water quality and algal responses:

As the Lake will stratify over summer for this inflow condition, the moderate Molonglo River inflow is now into the surface water zone, with net water balance transfer through the thermocline from the surface water zone, downwards into the bottom water zone, minimising the potential for transfer of nutrient rich bottom waters into the surface water zone.

With the oxidation of organic material across the shallow areas of West Lake, some phosphorus will be released into the shallow water zone, sustaining algal growth. For the extended retention period, the moderate “light” conditions and the moderate „mixing“ conditions, it is expected that there will be moderate levels of algal growth, with Chlorophyta the dominant algae, and excepting in situations of a major urban stormwater discharge, low levels of Cyanobacteria.

In the case of Yarramundi Reach, the deeper – more confined nature of this Reach means that limited phosphorus is available from its sediments to support algal growth. Nutrient supply is predominantly via the pre-stratification levels of phosphorus, together with wash-through from West Lake upstream.

Observed water quality and algae

Table 7.4 D. West Lake observed summer water quality and algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1979	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1986	NA	32	150	0.11	NA	0.25	0.03	7	300	600	250	0
1992	NA	NA	180	0.05	NA	NA	0.04	3	20	300	20	700
2000	6	12	220	0.037	0.003	0.24	0.02	5	250	550	0	400
2001	5	8	220	0.033	0.006	0.06	0.03	9	170	1100	0	250
2002	10	10	270	0.030	0.005	0.08	0.03	14	200	1300	0	220

Table 7.4 E. Yarramundi Reach observed summer water quality and algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1979	NA	18	164	NA	NA	NA	NA	NA	NA	NA	NA	NA
1986	NA	NA	160	0.07	NA	0.20	0.041	6.4	180	300	180	15
1992	5	6	NA	0.034	NA	0.10	0.030	2	60	120	60	1
2000	4.8	8	220	0.030	0.006	0.15	0.023	1.9	80	500	0	150
2001	4.9	4.3	220	0.026	0.003	0.022	0.016	7	120	1295	1	20
2002	5.9	5.6	280	0.021	0.003	0.083	0.024	6.5	160	850	3	1

The observed water quality and algal levels and composition data are consistent with the responses predicted by this conceptual model.

7.5 ‘Low rural inflow and high to moderate stormwater discharge’ condition

Molonglo inflow of 20 ML/d and Stormwater inflow of 300 ML/d:

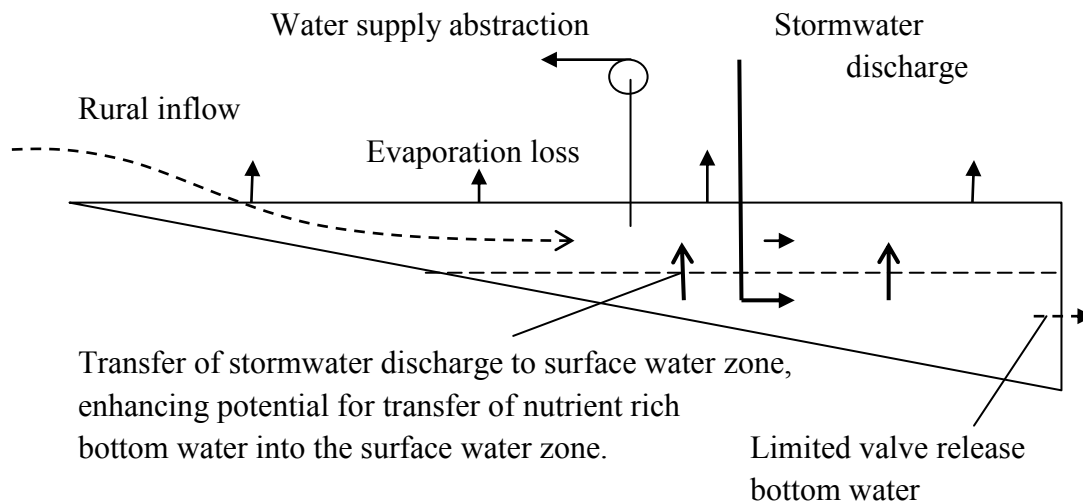
Table 7.5 A. Summer periods of „high rural inflow & stormwater discharges”

Year	Molonglo average summer inflow ML/d	Molonglo range of summer inflows ML/d	Maximum Sullivans Ck discharge ML/d
1982	30	10 – 40	320
1983	33	3 – 40	310
2007	20	1 – 40	150
2008	35	6 – 50	140
2009	22	1 – 40	300
2010*	??	10 - 100	350

Notes: * values up until 13/2/2010

Inflow pathway & Lake water balance conditions:

Figure 3 A. Summer (Low rural inflow – high stormwater discharge) water balance



Daily water balance for Surface water Zone = $Q_{\text{rural}} + Q_{\text{STWks}} - Q_{\text{evap}} + Q_{\text{abstract}} + Q_{\text{transfer}}$

Daily water balance for Bottom water Zone = $Q_{\text{urb stmw}} - Q_{\text{valve}} - Q_{\text{transfer}}$

where: $Q_{\text{STWks summer}} = 8 \text{ ML/d}$ (surface water zone top-up)

$Q_{\text{evap summer}} = 30 \text{ ML/d}$ (surface water zone loss)

$Q_{\text{abstract summer}} = 15 \text{ ML/d}$ (surface water zone loss)

Consequently, for conditions of low rural inflow, there is a daily deficit of 37 ML/d.

Under low rural inflow conditions, the contribution of the Molonglo River to surface water inflow is minor, with little contribution to mixing in the zone, and zero „wash-out” of algal growth. The discharge of significant stormwater volumes to the bottom water zone results in significant transfer of nutrient rich bottom waters into the surface water zone, enhancing both the

potential for algal growth and the physical and nutrient conditions favouring dominance by cyanobacteria.

Lake physical & chemical water quality response conditions:

- Low Molonglo River inflows (predominantly groundwater based – low in SS, high in TDS) are into the surface water zones, but contribute little mixing energy;
- Poorly mixed surface water zone, and stratification of Lake over the late spring to early autumn period;
- Low TP inflow, but potential for low levels of bio-available Phosphorus, in view of the low level of SS adsorption of nutrients, and „direct“ availability processes (particularly for upstream Lake zones);
- Ongoing decomposition of organic material in sediments previously deposited by elevated flows, under conditions of poor mixing in shallow surface waters, and cessation of re-aeration in the deeper stratified zones of the Lake;
- Decomposition of organic material in the deeper zones resulting in depletion of oxygen levels, and greater production of NH_3 under the more severe reducing conditions, with the potential for reduction of ferric iron and release of orthophosphate in some areas;
- The sharp flow peak in the urban stormwater discharge, with flow lasting only 2 to 4 hrs, results in a discharge plume well into the bottom water zone, with deposition of labile organic material into the poorly mixed bottom water zone, rather than the inlet depositional zone, further exacerbating depletion of oxygen and release of bio-available P from the sediments into the bottom water zone;
- The high inflow energy associated with the high velocity urban stormwater discharge, has the potential for enhanced mixing across the boundary between the surface and bottom water zones;
- Some recycling of nutrients in shallow waters associated with death and deposition of algae, but depletion of nutrients in surface water zones for both the deep (stratified) areas and the shallow (weakly mixed) areas of the Lake, unless replenished by transfer of nutrient rich bottom water into surface water zone.

Algal growth & composition response conditions:

- Light – excellent penetration of light deep into the surface water zone;
- Significant transfer of bio-available phosphorus into the base of the surface water zone, in association with stormwater discharges to the bottom water zone, and mixing of the interface by the high inflow energy of the stormwater discharges;
- Bio-available phosphorus – significant levels of phosphorus transferred from bottom water zone to surface water zone;
- Nitrogen level & composition – potential for increased ammonia levels associated with transfer from ammonia rich bottom waters, and poor mixing/aeration in surface water zone;

- Residence (available growth) time & washout – long residence time & cessation of washout – no longer a limiting factor;
- Mixing conditions – poor mixing of the surface water zone, favouring growth of the cyanobacteria with their buoyancy vacuole facility.

Molonglo Reach & East Basin water quality and algal responses:

In the case of the low Molonglo River inflow condition, there is a shift to a dual „direct“ and „indirect“ algal uptake of phosphorus, with phosphorus discharged in Queanbeyan STWks effluent directly available to algae under the low SS condition, and ongoing decomposition of organic material deposited by previous discharge events, with release of ammonia under the severe reducing conditions in the deeper pools, and reduction of ferric iron and release of previously bound orthophosphate into the water column. Under conditions of low flow – extended detention time, and poor mixing, there is a potential for high algal biomass growth and domination by Cyanobacteria.

Significant water stratification and associated reducing conditions in sediments of the Molonglo Reach pools are evident in the physical and oxidation–reduction graphs, with periods of anoxic bottom waters following large discharge events, and low pH (indicating $P/R < 1$). While the upgraded phosphorus removal at the Queanbeyan Sewage Treatment Works has significantly reduced TP levels in the Molonglo Reach area, it appears that algal biomass in this zone is more a function of available growth (water detention) time than limits to available phosphorus.

The severe reducing conditions – low DO and extreme algal levels in the Molonglo Reach pools, point to the significant role of these features in mobilizing nutrients in a highly bio-available form, and in generating significant organic loads, which are periodically washed into East Basin during storm events.

For the Queanbeyan STWks effluent $TP = 0.1 \text{ mg/L}$ since 2009, full utilization of the bio-available phosphorus would yield a Cyanobacteria levels of the order of 50,000 cells/ml. A TP discharge close to 0.1 mg/L is about the limit of the technology for a sewage treatment plant the size of the Queanbeyan STWks. It is recommended that a surface water zone mixer be installed in the Molonglo Reach, as the means of limiting Cyanobacteria growth.

In the case of East Basin, under the low Molonglo River inflow conditions, there is ongoing decomposition of organic material deposited by previous discharge events, with release of ammonia under the severe reducing conditions in this inlet depositional zone, and reduction of ferric iron and release of previously bound orthophosphate into the water column. Under conditions of low flow – extended detention time, and poor mixing, there is a potential for high algal biomass growth and domination by Cyanobacteria. Wind is an important modifier of

conditions in East Basin, as a result of its open shallow nature, and location at the eastern end of the Lake (prevailing westerly winds). While enhancing mixing over the duration of the wind condition, the waves generated by the wind also re-suspend the fine clays in the sediments, limiting light, and thereby enhancing the competitive advantage of Cyanobacteria.

Observed water quality and algae

Table 7.5 B. Molonglo Reach observed summer water quality & algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	TN	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1982	NA	16	320	NA	NA	NA	0.01	NA	NA	NA	NA	NA
1983	NA	8.5	400	0.590	NA	0.01	0.02	49	1720	9430	0	51450
2007	10	8	400	0.048	1.08	0.32	0.02	11	NA	NA	NA	NA
2008	16	10	370	0.085	0.85	0.01	0.01	32	NA	NA	NA	NA

Table 7.5 C. East Basin observed summer water quality & algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1982	27.4	NA	NA	0.055	NA	0.008	0.010	30	0	1320	0	171630
1983	37	NA	NA	0.078	NA	0.005	0.046	15	490	7970	0	5140
2007	27	23	420	0.076	0.002	0.002	0.007	28	3280	6960	1000	39160
2008	11.7	9.3	320	0.044	0.003	0.003	0.001	17.3	2830	4170	230	8620
2009	16.7	15.7	350	0.054	0.003	0.003	0.003	33	22450	20790	1330	69800
2010	42	39.3	310	0.082	0.003	0.231	0.060	25	6680	4640	280	99990

The observed water quality and algal levels and composition data are consistent with the responses predicted by this conceptual model.

West Lake & Yarramundi Reach water quality and algal responses:

Under the low Molonglo River inflow condition, the SS levels are low, with excellent light availability, high levels of transfer of bio-available phosphorus and ammonia associated with the transfer of nutrient rich bottom waters into the surface water zone, long detention times and poor mixing conditions. As a result, there is a significant potential for high levels of algal biomass, and dominance by Cyanobacteria.

As noted above, the high inflow energy associated with the high velocity urban stormwater discharge, has the potential for enhanced mixing across the boundary between the surface and bottom water zones, significantly increasing the transfer of bottom water zone nutrients into the surface water zone.

The CRC for Freshwater Ecology Research on Canberra's water pollution control ponds (*Lawrence & Baldwin 1998*) indicated that under summer high solar radiation conditions and

light winds, even waters as shallow as 2 m are subject to stratification during the day, with re-mixing over night with cooling of the surface water layer.

Under the poor mixing conditions, Chlorophyta are seriously disadvantaged in respect to lack of turbulence to cycle the cells through the surface euphotic zone. Algae having buoyancy vacuoles such as the Cyanobacteria *microcystis*, on the other hand, is better able to maintain their position in the euphotic zone under the thermal current conditions during the day, while sinking to the bottom water zone overnight (opportunity to access nutrients), and to re-float to the surface over the day, to photosynthesize.

In the case of Yarramundi Reach, the deeper – more confined nature of this Reach means that limited phosphorus is available from its sediments to support algal growth. As in the case of West Lake above, the nutrient supply is predominantly via the pre-stratification levels of phosphorus, together with the transfer of nutrient rich bottom waters into the surface water zone, as a result of the discharge of stormwater into the bottom water zone. Under the poor mixing conditions, Cyanobacteria again becomes the dominant algae under this condition.

The deep waters through the Tarcoola and Yarramundi Reaches develop a strong temperature gradient with depth over the summer periods, resulting in the isolation of the bottom water zone (hypolimnion) from the re-aerated surface water zone (epilimnion). Consequently, with continued deposition of organic matter, including the dead algal cells, to the bottom sediments, bottom waters become anoxic. As a result, nitrogen in the sediments is transformed into ammonia (rather than nitrogen gas and nitrate for well aerated sediments), and iron is transformed from an insoluble to a dissolved form, releasing phosphorus from the sediments as ortho-phosphate.

With daily variation in temperature over the summer, and variable wind conditions, the actual depth of the layer separating the surface and bottom water zones varies. As a result, a portion of the nutrient rich bottom water, will be transferred into the surface waters.

Observed water quality and algae

Table 7.5 D. West Lake observed summer water quality and algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1982	NA	14	280	0.04	NA	0.03	0.03	24	100	1160	0	135800
1983	NA	12	350	0.026	NA	0.03	0.04	5.1	100	1065	0	2500
2007	13	7	410	0.04	0.009	0.002	0.02	9.0	1200	2130	760	6300
2008	5	8	320	0.03	0.002	0.003	0.01	12	2400	1100	5	26600
2009	8	8	350	0.03	0.005	0.01	0.03	9	2000	1560	160	31200
2010	9	6	400	0.03	0.002	0.02	0.01	10	800	6000	0	63750

Table 7.5 D. Yarramundi Reach observed summer water quality and algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
1982	NA	6	280	0.028	NA	0.09	0.03	10.1	16	360	0	61300
1983	NA	6.5	350	0.026	NA	0.03	0.04	5.1	100	1065	0	2500
2007	6	3.6	400	0.025	0.002	0.003	0.004	6.0	2160	3820	980	670
2008	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2009	4	4.5	350	0.030	0.003	0.003	0.003	10	1350	1500	100	27710
2010	6	3.5	390	0.030	0.001	0.006	0.030	31	8130	4450	0	35730

The observed water quality and algal levels and composition data are consistent with the responses predicted by this conceptual model.

Regression analysis has confirmed that for low rural inflow & moderate to high stormwater discharges conditions, the stormwater discharges were the major trigger of Cyanobacteria blooms and Faecal Coliform (regrowth) blooms in West Lake and Yarramundi Reach, over the period 1999 to 2010.

West lake (2000 – 2010):

$$\text{Cyanobacteria} = 17800 - 197.2Q + 0.60Q^2; F = 20.4, p = 0.0003, n = 13$$

(Statistically Highly Significant)

Yarramundi Reach (2000 – 2010):

$$\text{Cyanobacteria} = 6950 - 48.1Q + 0.175Q^2; F = 9.4, p = 0.003, n = 16$$

(Statistically Significant)

For rural discharges of 500 ML/d or higher, the algal levels appear to be substantially moderated.

The effects of the urban stormwater discharge into the bottom water zone comprise:

- Transfer of nutrient rich bottom water into the surface water zone;
- Further contribute to the loads of nutrients and organic material accumulated within the bottom water zone;
- Provide some turbulence (physical disturbance) adjacent to the thermocline, enhancing the transfer of nutrients across this zone.

It is probable that it is this last dot point that is primarily responsible for the rapid response of Cyanobacteria following stormwater discharges to the Lake (1 to 2 weeks).

Analysis of the daily summer transfer of hypolimnion P to the epilimnion as a result of net evaporation and water abstraction losses from the epilimnion yields a 3 kg/d transfer of phosphorus from the bottom water zone into the surface water zone. This translates to 1.8 µg/L

Chlorophyll „a“ in the surface water zone, or 11000 cells/ml of cyanobacteria (assuming 100% cyanobacteria algal composition).

It is concluded that the cyanobacteria cell density explained by the net evaporation and water abstraction related transfer of nutrients from the hypolimnion, is well below the observed levels of 70,000 to 140,000 cells/ml following stormwater discharges.

There appears a strong case for mixing across the thermocline caused by the energy of the stormwater discharge, as the principal driver of cyanobacteria blooms. Because of their hydraulic efficiency, urban stormwater discharges occur over a period of 1 to 2 hrs, as compared to several days for rural discharges. In addition, the hydraulic efficiency of large concrete open channels results in discharge velocities of 3 to 7 m/s. As a result, the mixing energy of a 500 ML/d stormwater discharge is equivalent to some 30 to 50 times an equivalent Molonglo River flow.

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7.6 ‘Low rural inflow and low stormwater discharge’ condition

For Molonglo inflow of 10 ML/d and Stormwater discharges of 5 ML/d

Table 7.6 A. Summer periods of „high rural inflow & stormwater discharges“

Year	Molonglo average summer inflow ML/d	Molonglo range of summer inflows ML/d	Range Sullivans Ck discharges ML/d
2003	5	0 – 10	0 – 50*
2004	15	2 – 20	0 - 40
2005	15	1 – 50	0 – 10#
2006	24	7 - 30	1 - 20

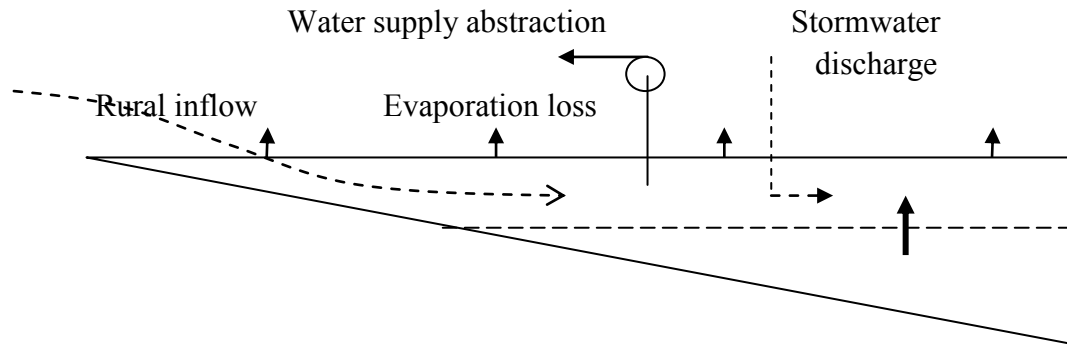
Notes: * One exception – 300 ML/d on 21/2/2003

Two exceptions – 155 ML/d on 4/1/2005; 226 ML/d on 20/1/2005

Inflow pathway & Lake water balance conditions:

Low rural inflow and stormwater discharges result in full transfer of surface water deficit ($V_{\text{evap}} + V_{\text{water abstraction}} - Q_{\text{inflow}}$) from nutrient rich bottom water zone. Cessation of valve release of bottom water, under condition of Lake water deficit.

Figure 3 B. Summer (low rural & stormwater inflow) water balance



$V_{\text{transfer}} = V_{\text{evap}} + V_{\text{abstraction}} - Q_{\text{Molonglo}} - Q_{\text{stormwater}} = 0 \text{ to } 20 \text{ ML/d}$ (bottom water to surface water zone), depending on the volume of the stormwater discharges

Lake physical & chemical water quality response conditions:

- Low Molonglo River inflows (predominantly groundwater based – low in SS, high in TDS) are into the surface water zones, but contribute little mixing energy;
- Poorly mixed surface water zone, and stratification of Lake over the late spring to early autumn period;
- Low TP inflow, but potential for low levels of bio-available Phosphorus, in view of the low level of SS adsorption of nutrients, and „direct“ availability processes (particularly for upstream Lake zones);
- Ongoing decomposition of organic material in sediments previously deposited by elevated flows, under conditions of poor mixing in shallow surface waters, and cessation of re-aeration in the deeper stratified zones of the Lake;
- Decomposition of organic material in the deeper zones resulting in depletion of oxygen levels, and greater production of NH_3 under the more severe reducing conditions, with the potential for reduction of ferric iron and release of orthophosphate in some areas;
- The more moderate stormwater discharges in this case inflow to the surface water zone, and as a result, significantly decrease the level of transfer of nutrient rich bottom water into the surface water zone;
- Some recycling of nutrients in shallow waters associated with death and deposition of algae, but depletion of nutrients in surface water zones for both the deep (stratified) areas and the shallow (weakly mixed) areas of the Lake, unless replenished by transfer of nutrient rich bottom water into surface water zone.

Algal growth & composition response conditions:

- Light – excellent penetration of light deep into the surface water zone;

- A reduced level of bio-available phosphorus transfer into the base of the surface water zone, as a result of the stormwater discharges inflowing to the surface, rather than the bottom water zone;
- Nitrogen level & composition – a reduced level of ammonia transfer into the base of the surface water zone, as a result of the stormwater discharges inflowing into the surface, rather than the bottom water;
- Residence (available growth) time & washout – long residence time & cessation of washout – no longer a limiting factor;
- Mixing conditions – poor mixing of the surface water zone, but moderated as a result of some stormwater inflow to the surface water zone.

Molonglo Reach & East basin water quality and algal responses:

As for Section 7.5 above.

Conditions in the Molonglo Reach continue to reflect the dual „indirect“ and „direct“ phosphorus supply processes.

Observed water quality and algae

Table 7.6 B. Molonglo Reach observed summer water quality & algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	TN	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
2003	5.4	5.9	500	0.028	0.72	0.01	0.02	18	240	2100	0	0
2004	8.9	8.6	380	0.046	0.73	0.01	0.01	20	NA	NA	NA	NA
2005	5.0	2.6	460	0.032	0.52	0.01	0.02	13	NA	NA	NA	NA
2006	6.0	6.5	360	0.039	0.75	0.13	0.01	11	NA	NA	NA	NA

Table 7.6 C. East Basin observed summer water quality & algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
2003	19.7	19.3	330	0.053	0.004	0.002	0.008	11	200	1780	3	6490
2004	13	11	360	0.044	0.004	0.002	0.005	13	340	5750	7	3410
2005	13.7	10.8	390	0.041	0.005	0.011	0.022	6.6	470	1210	0	1040
2006	12	13	350	0.057	0.004	0.035	0.006	13.3	1500	7330	31	2250

The observed water quality and algal levels and composition data are consistent with the responses predicted by this conceptual model.

West Lake & Yarramundi Reach water quality and algal responses:

Under the low Molonglo River inflow condition, the SS levels are low, with excellent light availability, but in this inflow condition, limited levels of transfer of bio-available phosphorus

and ammonia from the nutrient rich bottom water zone. While there is a high potential for algal growth under these inflow conditions in respect to available light and detention time, nutrients necessary to support growth are generally limiting.

The poor mixing conditions continue to favour Cyanobacteria growth. However, the excellent light condition, and the absence of a „high nutrient“ layer at the base of the surface water zone (cessation of transfers from the bottom water zone), appear to disadvantage the Cyanobacteria.

Observed water quality and algae

Table 7.6 D. West Lake observed summer water quality and algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
2003	7	7	330	0.03	0.008	0.004	0.012	7	70	1900	0	1300
2004	9	7	370	0.037	0.003	0.003	0.005	11	570	4300	0	860
2005	6	4.6	400	0.027	0.003	0.01	0.007	5.4	1140	1390	0	1930
2006	8	6.4	340	0.04	0.003	0.05	0.007	8.1	1670	5400	0	1232

Table 7.6 E. Yarramundi Reach observed summer water quality and algae levels & composition

Year	Light			Nutrients				Algae				
	SS	Turb	Cond	TP	PO ₄	NO ₃	NH ₃	Chlor	Bacil	Chloro	Chrys	Cyano
2003	2.7	2.8	320	0.018	0.004	0.003	0.012	4.3	40	740	0	320
2004	6.2	4.9	370	0.020	0.003	0.009	0.015	5.3	1175	2800	0	3150
2005	3.5	2.0	400	0.017	0.002	0.003	0.003	4.9	2070	1740	0	990
2006	5.5	3.1	340	0.022	0.002	0.060	0.006	5.0	1200	4150	7	2100

The observed water quality and algal levels and composition data are consistent with the responses predicted by this conceptual model.

Management ramifications

The management ramifications of this analysis is that it is the „volume“ and „rate of discharge“ of urban stormwater during extended dry periods that are the major triggers of Cyanobacteria blooms. Actions to reduce (attenuate) this discharge, such as abstraction of stormwater prior to discharge to the Lake for sportsground irrigation, will be highly beneficial.

The rate of the surface water zone - water loss is another key management area. The Sewage Treatment Plant Effluent discharge into the surface water zone, significantly reduces the bottom water transfer over summer periods. Conversely, the abstraction of water from the surface water zone for watering of the Golf Course, parks, the Botanic Garden, and the Turf Farm, significantly exacerbates the rates of bottom water transfer to the surface water zone.

There is a management option here to require abstraction from the bottom water zone, and to review the balance between the economic benefits of use of Lake water for irrigation, and the environmental impacts on the Lake.

The significant (and growing) contribution of urban stormwater to labile organic matter in the bottom water zones of the Lake, is the key underlying driver of bio-available nutrients sustaining algal growth in the Lake. The pattern of stormwater events modify the timing and quantity of nutrient transfer from the bottom water to the surface water zone.

7.7 Modifiers of the water quality and algal growth processes

Role of iron binding of phosphorus

Throughout the 1978 to 2011 period, phosphorus appears to be the limiting nutrient in respect to algal biomass in the lake. Mention has been made through this Assessment regarding the key role of iron in binding of phosphorus as FePO_4^+ , and its removal from the water column. How does this process bear on the responses of cyanobacteria?

In natural waters, Ferric Phosphate occurs primarily as part of a metastable chelate, comprising a mix of FeHPO_4^+ & $\text{Fe}(\text{OH})_2^+$ in varying proportions, depending on pH:

- at pH values less than 7.0, FePO_4 will precipitate as solid $\text{FePO}_4(\text{s})$.
- at neutral to slightly alkaline pH range, the precipitate is a metastable ferric compound containing both PO_4^{3-} and OH^- in varying proportions, depending on pH.
- as pH increases above pH 7.0, the attachment of hydroxyl ions OH^- will begin to increase, and the attachment of PO_4^{3-} ions will decrease. viz: the non-chelated phosphorus will become more biologically available.

Hence, both pH and redox levels, play an important role in determining the level of adsorption of ortho-phosphate in iron chelates. Cyanobacteria also modifies these systems, by photo-reduction of $\text{Fe}(\text{III})$ to $\text{Fe}(\text{II})$, and the production of siderophores (a chelating organic compound), holding FeHPO_4^+ in a soluble form available to the prokaryotes (cyanobacteria), but not to the eukaryotes (Greens, Diatoms). Typically, there are moderate levels of „chelated – low solubility $\text{Fe}(\text{III})$ “ in the well oxidized surface waters, and high levels of „chelated - high solubility $\text{Fe}(\text{II})$ “ in the low oxygen bottom waters.

The pH of surface waters is typically alkaline, as a result of the consumption H^+ ions in the photosynthesis process. Conversely, the pH of bottom waters is typically less than the surface waters (by up to 1 unit), as a result of the production of H^+ ions by the reduction process.

Cyanobacteria are typically found in low O_2 environments, in which nitrogen will be predominantly in NH_4^+ form. The presence of NH_4^+ suppresses the synthesis of nitrate reductase, blocking the transport of NO_3^- across the algal cell membrane. Cyanobacteria have to reduce NO_3^- to NO_2^- and NO_2^- to NH_4^+ , in order to assimilate nitrogen in the photosynthesis process. Hence, direct uptake of NH_4^+ is a much more efficient pathway for the organism's growth.

Role of Nitrate in ameliorating cyanobacteria levels

Many lakes and reservoirs downstream of large urban areas, have accumulated a large organic biomass in their sediments, resulting in „high reduction“ stress in bottom waters and sediments – conditions conducive to low oxygen, high production of NH_4^+ , and cyanobacteria blooms.

Nitrate (NO_3^-) is viewed as a beneficial nitrogen compound, in terms of its capacity to oxidize lake sediments previously subjected to high levels of phosphorus and organic matter loading. The direct injection of nitrate into sediments has been used as one means of offsetting the potential for reduction of sediments by ongoing organic matter (*Ripl 1994*). In a number of „eutrophied lake remediation projects“ involving the diversion of sewage effluent away from the lake, exacerbation of blue-green algal blooms has been observed (*Cullen & Forsberg 1988*).

There is recognition of the value of retaining treated sewage effluent low in phosphorus and BOD, but high in nitrate, in discharges to lakes, as a valuable buffer to the reduction of the sediments and associated release of sedimented phosphorus into the water column. This was the ACT experience in relation to remediation of Burrinjuck Reservoir. The commissioning of the Lower Molonglo Water Quality Control Centre (LMWQCC) de-nitrification facility in 1980 resulted in significant exacerbation of blue-green algal outbreaks. The closure of the de-nitrification facility in 1982 resulted in a major reduction in algal biomass and a return to Chlorophyta algal dominance.

Nitrate acts as a significant oxidant in respect to the decomposition of organic matter. NO_3^- is reduced to NO_2^- and subsequently to NH_4^+ (ammonification). Some NH_4^+ will then react with NO_2^- to produce $N_2(g)$ (de-nitrification), diminishing the mass of NH_4^+ in the bottom water. De-nitrification rates for these waters are typically of the order of 30%. viz: high NO_3^- waters are able to „oxidise“ significant quantities of organic matter, without significantly increasing bottom water NH_4^+ levels, taking some of the demand off the O_2 system. It provides a significant buffering of the sediment reduction process – a decrease in the formation of NH_4^+ and release of phosphorus.

High nitrate may also limit the ability of cyanobacteria to block (production of siderophores) the growth of the Greens & Diatoms, enabling strong growth of Green and Diatom algae, or the high NO_3^-/NH_4^+ ratio simply promotes the Green algae, which will outcompete the cyanobacteria in

respect to rate of uptake of phosphorus. However, the mechanism for limiting the cyanobacteria production of siderophores is not clear.

Stability of fine suspended solids

Irrespective of catchment discharges, the turbidity levels in the Lake are primarily determined by wave (wind driven) re-suspension of SS in East Basin and erosion of the eastern shoreline, and the rate of coagulation and deposition of re-suspended material (function of Lake TDS levels). Hence, the turbidity levels reflect in large part the dominant ions for soils of the catchment (sodium), and are unlikely to change into the future.

The SS loading results in mixed outcomes. The high rate of loading on East Basin results in burial of sediment fauna in the Basin. Conversely, the blanket of SS, high in iron, provides a significant adsorption capacity in respect to binding of phosphorus in the sediments, thereby limiting the mass of available phosphorus for algal growth in the Lake water.

The frequency and severity of algal scums and odours appears to be the principal threat to aesthetic values.

Role of wind

Table 7.7 Impact of 10th December 2009 wind event, Yarramundi Reach

Date	Surface water		Bottom water		Cyanobacteria Cells/ml
	Temp °C	DO mg/L	Temp °C	DO mg/L	
18/11/2009	23.4	9.3	13	3	818
18/12/2009	21.4	7.7	21.2	7.4	7262
14/1/2010	25.5	7.8	14.6	0.3	20190
15/2/2010	23.2	6.8	21.3	0.1	39578

Typically, in early to mid-Autumn, the surface waters have cooled to the point where surface and bottom waters are in equilibrium in terms of temperature, and full mixing of the two water zones – an event termed „turnover“ occurs. However, the timing of „turnover“ can be modified by a strong wind event (60 km/hr wind in December 2009 resulting in an algal bloom in February 2009), or a significant discharge to the Lake, such as the December 2010 flood. Apart from the years 1993, 1994, and 2009, there is little indication of algal blooms associated with this „turnover“ event.

7.8 Faecal coliform response processes

Levels of faecal coliform in the lake reflect levels in inflows to the Lake, and in particular, the urban stormwater inflows, production by water birds and other mammals in the Lake, and re-

growth of sedimented Coliforms under suitable temperature and organic material (macrophytes, algae, organic detritus) breakdown conditions.

Escherichia Coli was used in the past as an indicator of human faecal contamination. However, in view of its unreliability as an indicator of faecal contamination, the NHMRC has recently recommended the adoption of *Enterococci* for use as an indicator of faecal pollution in Australian freshwater. As the monitoring for faecal pollution in Lake Burley Griffin has been based on *E. Coli* up until 2009, this Review is based on the results of *E.coli* monitoring.

Free bacteria are exposed to losses as a result of salinity & predation (mortality), by solar irradiation, and by adsorption onto particulate material and its removal by sedimentation. Adsorbed bacteria are masked from the effects of salinity, predation & irradiation (e.g. impact of turbidity on chlorine & UV disinfection), but are removed from the water column by sedimentation.

While upgrades to sewage infrastructure in Queanbeyan (Sewage Treatment Works & Morriset St Pump Stn) have significantly reduced the frequency of point source (sewage) spills, the continued frequency of sewage pond flooding or failure, or other storm event related spills, has resulted in a significant number of Lake closures.

While upgrades to sewage infrastructure in the Sullivan's Creek within the ACT have significantly reduced the frequency of point source (sewage) spills, the house-connecting sewer ties (non-point source) continue to be a significant source of faecal contamination to urban stormwater. The „condition of the Catchments“ assessment indicated that there was a significant increase in the discharge of faecal coliform from urban catchments. This trend, together with the increase in urban areas within the catchment, is resulting in significant increase in the level of faecal material discharged to the Lake.

The faecal pollution indicator (*Escherichia coli*) used over the period 1978 to 2009, is able to re-grow under conditions of elevated temperature and high nutrients, frequently present in summer in association with decomposing plant material (macrophytes or algae). In 2008, NHMRC adopted the use of *Enterococci* in place of *E. coli*, as a more reliable indicator of freshwater faecal pollution. Within the Lake Burley Griffin monitored data, there are several instances where faecal coliforms appear to be re-growth, rather than fresh faecal contamination based.

While the *NHMRC Recreational Waters Guidelines 2008* recommend the adoption of *Enterococci* bacteria in place of *Faecal coliform*, as more robust as an indicator of faecal pathogens, the *Guidelines* are silent on the issue of the potential for regrowth of this indicator, or of the health risks associated with regrowth.

The *World Health Organisation* acknowledges that viruses and parasites are unable to reproduce without a warm blooded host. viz: they are not viable in „regrowth“ situations.

However, *WHO* notes that there are a few (opportunistic) pathogens that have been observed to grow under regrowth conditions. Typically, their growth is associated with sediment or biofilm substrata.

Testing indicates that the regrowth pathogens comprise different strains of the pathogens to those implicated in gastro-intestinal diseases. (Fricker, C.R. (2003). *The presence of bacteria in water after regrowth*. In J. Bartram (Ed) 2003. *Heterotrophic Plate Counts and Drinking Water Safety*. WHO)

The research undertaken by Dr David Gordon, for the National Capital Authority 2007, on regrowth related *Faecal coliform* in Lake Burley Griffin, similarly indicated that the regrowth coliform was a different strain to that present in sewage.

The inference is that the risk to health in situations of regrowth is low. However, further epidemiological studies are required before dismissing the potential for health risks associated with regrowth of faecal contamination indicators.

Where elevated *Enterococci bacteria* are monitored, the NHMRC Guidelines require the implementation of a „sanitary survey“. Where a sewage spill or discharge is identified, then the assessment of risk can be based on the discharge of a specific source and quantity of discharge.)

The management response in respect to assessment of health risk associated with faecal contamination, comprises a six fold set of actions:

- Undertake a review of the adequacy of Queanbeyan STWks infrastructure in respect to unacceptable frequency of flooding or failure or storm related spills of partially treated sewage from the Works;
- Overview of the performance of *Enterococci bacteria* in place of *Faecal Coliform*, in respect to confoundment by animal excreta;
- monitor the performance of *Enterococci bacteria* in respect to the „re-growth“ conditions in embayment sediments, including review of ongoing epidemiological research findings in respect to health risks associated with „regrowth strains“ of pathogens;
- establish a rigorous and comprehensive procedure for rapid „sanitary surveys“ in the event of elevated indicator levels;
- investigate sources of faecal contamination entering the urban stormwater systems, the significance of this source, and long term strategies for reducing this loading;
- investigate the composition of faecal contamination in the embayments, including bather shedding, birds and animal sources, and sediment re-growth of bacteria, as part of an ongoing assessment of health risks;

- introduction of pump based circulation of embayment and deep open waters.

7.9 Embayments response processes

As noted in the „Condition of the Lake“ assessment, the embayments have experienced frequent moderate Cyanobacteria cells number events, and Faecal Coliform & *Enterococci* exceeding Health guidelines, over the period of available data (October 2007 – 2011) period.

The shallow nature of the embayments and their semi- enclosed locations, results in poor mixing and high temperatures over the summer months. Wind-blown algal scums from the open waters, collect in the embayments, contributing to build-up of high organic loads within the sediments. Elevated turbidity within these shallow zones may also contribute to dominance by Cyanobacteria algae.

The Weston Beach embayment has the greatest level of enclosure, protecting it from high wind blown algal scums, but as a result of poor mixing, retaining much of the Faecal Coliform & *Enterococci* generated in the embayment. While Yarralumla Beach has marginal levels of enclosure, it is on the windward side of the Lake in respect to prevailing NW wind, resulting in significant accumulation of wind-blown scum in the embayment. The Black Mountain Beach is the most open site, and its NW to SE orientation means that there is minimal accumulation of Blue Green algal scum on the beach, and greatest dispersion rate of locally generated Faecal Coliform and *Enterococci*.

Research under the „Californian Clean Beaches Initiative“, have identified the regrowth of Faecal bacteria in sediments of shallow embayments, as a major source of Faecal bacteria within the water column. Management responses include the cleaning and periodic replacement of sediment material. (*Largier & Taggart 2006*).

The comparison between the 3 Beaches, and with the adjacent „open water“ West Lake monitoring site, indicate that shallow (warm) water, poor mixing, and high wind-blown algal scum accumulation, are all major factors contributing to the severity of algal and bacteria problems in the Beach areas.

7.10 Sediment response processes

The monitoring of sediment quality indicates significant variation in sediment P & N over each season. In part, this is a reflection of the heterogeneity of sediments, but it also reflects the seasonal uptake and sedimentation of organic material and particulates and their adsorbed P.

Four key conclusions with respect to Lake processes:

- The sediments have accumulated a significant mass of nutrients and organic matter and iron, since the initial filling of the Lake (1964);
- The sediments are the principal source of bio-available nutrients for plant growth in the Lake, and play a significant mediating role in respect to availability of and storage (cycling) of the Lake nutrients;
- The high summer temperatures and light wind conditions result in weak mixing energy in the water column, limiting the transfer of oxygen from surface to bottom waters, and thereby exposing the sediments to severe reducing conditions;
- As the sediments accumulate and/or are subjected to increased loads of organic material, so their rate of reduction of iron and release of P into the water column will increase.

Table 7.8. Lake sediment values (Source: NCA Lake water quality monitoring program)

Value	Dairy Flat	East Basin	West Lake	Scrivener Dam
TP mg/kg	500 - 1000	350 – 420	340 – 690	470 – 630
SO ₄ mg/kg	20 - 200	260 - 950	30 - 300	58 – 180
BOD mg/kg	1600 - 6360			
TOC %	1 – 7.6			
TKN mg/kg	10 - 400			
TN mg/kg	1000 - 6700			

A key sediment process is the oxidation and reduction of nutrients and metals stored in the sediments, changing their speciation and solubility properties. The sedimentation of organic matter leads to growth in sediment heterotrophic bacteria (decomposition of the organic matter), resulting in firstly, the depletion of Dissolved Oxygen, then secondly, the reduction of NO₃⁻ to N₂ (g) or NH₄⁺. This phase is then followed by the reduction of Fe³⁺ (solid) to Fe²⁺ (aqueous), with the release of PO₄⁻ into the water column.

It is important to note the role of NO₃⁻ in the reduction process, as a significant buffer against reduction of Fe³⁺. Hence, a well nitrified Sewage effluent is a positive factor in respect to moderating the Fe³⁺ reduction & PO₄³⁻ release process. When the de-nitrification plant was commissioned at Lower Molonglo Water Quality Control Centre in 1980, there was a sudden deterioration in water quality in Burrinjuck Reservoir, with the development of high levels of Blue Green algae. On the closure of the de-nitrification plant and restoration of an effluent high in NO₃⁻, the pattern of high levels of Blue Green algae ceased. Retention of a well nitrified effluent at LMWQCC has been maintained since that time.

7.11 Role of urban stormwater

As part of the CRCFE urban water research program, sediments from a Canberra Pond were sampled, and placed in a series of long flasks (mesocosms) in a „dark“ room (algae excluded) in the Laboratory. The cylinders were then filled with Pond water, and water quality samples were

taken from each cylinder, in order to establish the starting conditions. Varying levels of ground-up macrophyte material (*Typha*) was then added to the cylinders, and the cylinders were then sealed for a period of 20 days. All cylinders became anaerobic, with release of a significant mass of P. ($\Delta M_{P \text{ release}} = 0.051 \text{ g/m}^2$ per 1 g/m^2 of $\Delta M_{BOD \text{ load}}$, $n = 6$, $F = 36$, $p = 0.0019$). (*Lawrence et al 1998*).

Research was also undertaken on the BOD characteristics of a range of riparian plant material, to assess the variation in BOD decomposition rates. Native plants such as Eucalypts, are high in lignin (refractory) material, and decay slowly (low BOD rate), as compared to grasses and deciduous plants high in cellulose (labile) material, which decay rapidly. Grass had a BOD rate 6 times that of Eucalypt leaves, Willow leaves 2 times, and Macrophytes 1 to 2 times (Moles O_2 /Mole Carbon/day). (*Esslemont et al 2007*). These results highlight the greater BOD/gm of organic material demand rate of decomposing organic matter in urban stormwater discharges, as compared to rural discharges.

But perhaps the most significant impact of urban stormwater loading is the sustained discharge from impervious urban areas during „dry“ periods, as compared to the cessation of runoff from the rural areas over these „dry“ periods.

There is another factor having a major bearing on the potential impact of summer discharges to the Lake on algal growth – the temperature of the discharge water. Cold discharges relative to the thermocline temperature, will dive into the bottom water zone, with little impact on summer algal growth patterns. Warm discharges relative to the thermocline temperature, on the other hand, will discharge into the surface water layer, replenishing the available P mass, and thereby potentially promoting strong algal growth post the stormwater discharge.

Urban catchments have huge effective drainage coverage, which facilitate organic matter transport via gutter systems, to stormwater. The loading typically dwarfs that of riparian inputs and alters the benthic quality of receiving waters. As a result, receiving waters experience high dissolved oxygen demands. (*Belt et al 2007*).

There are two other features of urban stormwater having significant implications for the Lake water quality and algal growth response processes:

- the sustained discharge from impervious urban areas during „dry“ periods, when the algal growth limiting „mixing“ and „washout“ effects of rural discharge are absent;
- the high energy of stormwater discharges, having the velocity and mass to penetrate deep into the Lake, and to create turbulence adjacent to the thermocline, significantly enhancing the transfer of nutrient rich bottom waters to nutrient limited surface waters.

The Burrinjuck Reservoir algal succession research (*Lawrence et al, 2000*) established that the temperature of River discharges were a function of the season, and the level of River discharge (inversely proportional to temperature). This pattern is even stronger with urban stormwater discharges, as a result of the large area of impervious (heat adsorbing) surfaces. Hence, it is the smaller – more frequent stormwater discharge events that are critical with respect to promotion of algal growth – change in algal composition, over extended „dry“ or drought periods.

7.12 Lake water quality & ecological response processes conclusions

The impacts on Lake environmental and use values are primarily related to the increased incidence and levels of nuisance algal growth and faecal pollution.

With the exception of the Molonglo Reach, the growth of algae in the Lake occurs via an indirect process. Phosphorus discharged to the Lake in runoff from its catchments or from the Queanbeyan treated sewage effluent, is adsorbed onto the surfaces of fine silt and clay particulates in the discharge. On entering the Lake, the reduced flow velocities result in the settling of these particulates (and their adsorbed P) to the sediments. Given the high levels of iron in the sediments, P is bound onto the iron, and remains buried in the sediments.

High levels (loads) of organic matter, discharged to the Lake from its catchments, settle to the sediments. Following the sedimentation of organic material, the sediment heterotrophic bacteria grow, consuming oxygen as they decompose the organic material. Continued growth of the bacteria (assuming continued availability of organic material) following depletion of oxygen, leads to the reduction of the bottom water Nitrate, followed by the reduction of Ferric iron (solid) to Ferrous iron (aqueous) and the release of phosphate into the water column. Thus the availability of the stressor (P) for algal uptake is via an indirect pathway.

Algal growth occurs in response to the release of sedimented P and N. Only early in the 1978 to 1980 period, when Queanbeyan sewage effluent discharge contained 8 mg/L of P, was there any indication of occasional N limiting conditions (occurrence of N fixing algae), and then, only in the Molonglo Reach. Hence, phosphorus is the limiting nutrient in respect to Lake Burley Griffin.

The assessment of the „Lake water quality & ecological response“ to catchment discharges, demonstrated that the Lake is highly susceptible to reducing conditions in its sediments, as a result of high summer temperatures, and weak inland wind (major source of energy driving mixing with the water column) conditions over the summer period.

During extended „dry“ or low inflow periods, such as the 1999 to 2009 drought, while discharges from the urban catchments continue to stimulate algal growth cycles in the Lake, the in-Lake

cycling (direct) processes maintain a base level of „bottom water organic matter decomposition – mixing of nutrients through the water column – uptake by algae – algal photosynthesis & decay – deposition of dead algal cells (organic matter) to the bottom waters“ nutrient and algal growth cycle.

The ultimate algal biomass level depends on ongoing availability of nutrients (N, P, C) and light, and the available growth time (days between „wash-out“ or „nutrient re-adsorption“ catchment discharge events). During normal to „wet“ periods in respect to catchment discharges, available P, light (highly turbid waters) and growth time are the limiting factors. During extended „dry“ periods, available P and light (shading from algal cells) will be the key constraints.

The Assessment identified major stormwater discharges during periods of low Molonglo River inflows, as a the key trigger of Cyanobacteria blooms in the mid to lower Lake zones. The colder temperature associated with large stormwater discharges results in the discharge diving to the bottom water zone. This causes the transfer of nutrient rich bottom waters into the nutrient limiting surface water zone, resulting in rapid growth of Cyanobacteria. The high energy associated with the high velocity stormwater discharge appears to also create turbulence and mixing adjacent to the boundary between the surface and bottom water zones, further enhancing the transfer of nutrient rich bottom waters to the surface water zone. In the extended dry period condition – moderate to low stormwater discharges, the assessment indicated that grazing of the algae by zooplankton may also be a constraint on ultimate algal biomass.

As noted above, the algal impacts on Lake environmental and use values are primarily related to the type of algae present, and in particular, to Cyanobacteria (Blue Green) algae. Of special importance is the shift in algal composition, from Chlorophyta dominance to Cyanobacteria dominance, over the period 1999 to 2009.

The major precursors to Cyanobacteria dominance comprise:

- the level of organic material loading on the Lake;
- the high summer temperatures and weak wind – poor mixing conditions in the Lake water;
- conditions of large stormwater discharges to the Lake, in association with low Molonglo River inflow.

Collectively, these conditions overwhelmingly advantage the Blue Green algae as compared to the Green algae. The conclusion therefore is that the change in algal composition was predominantly a reflection of the 1999 to 2009 hydrologic and climatic conditions, in association with the level of organic material within and discharged to the Lake.

There does not appear to be any ecosystem structural change (the macrophyte ecosystem had already largely eroded prior to the drought) that would prevent substantial return to dominance by Green algae upon a return to more normal set of hydrologic and climatic conditions. The scale of the December 2010 flood and its implications for Lake physical, chemical and biological processes, will mask in some measure, this recovery process.

The primary implication of this phenomena for our understanding of Lake response processes, is that the level of organic material build-up in the sediment is sufficient to trigger a shift in algal composition, to Cyanobacteria dominance, during low inflow – „direct“ in-lake based processes. With increased extreme occurrence in climatic conditions predicted with Climate Change, there will be increasing incidence of these conditions into the future.

As noted above, the impacts on Lake environmental and use values are also related to the increasing incidence and level of faecal pollution.

Levels of Faecal Coliform in the lake reflect levels in inflows to the Lake, and in particular, the urban stormwater inflows, production by water birds and other mammals in the Lake, and re-growth of sedimented Faecal Coliforms under suitable temperature and organic material (macrophytes, algae, organic detritus) breakdown conditions.

Escherichia Coli was used in the past as indicators of human faecal contamination. However, in view of its unreliability as an indicator of faecal contamination, the NHMRC has recently recommended the adoption of *Enterococci* for use as an indicator of faecal pollution in Australian freshwater. As the monitoring for faecal pollution in Lake Burley Griffin has been based on *E.Coli* up until 2009, this Review is based on the results of *E.coli* monitoring.

As noted in the „Condition of the Lake“ assessment, the embayments are characterized by high temperatures and high accumulation of organic material – conditions conducive to the growth of high microbial biomass. The *E. coli* based monitoring of these sites may have been compromised by faecal coliform re-growth.

Research under the „Californian Clean Beaches Initiative“, have identified the regrowth of Faecal bacteria in sediments of shallow embayments, as a major source of Faecal bacteria within the water column. Management responses include the cleaning and periodic replacement of sediment material. (Largier & Taggart 2006).

8. Management intervention assessment

The following management option suggestions are put forward, as a means of conveying an understanding of the scope of measures that are possible, and the scale of development required to restore health to the Lake.

The range of available management measure categories comprise:

- in-Lake management measures;
- Catchment management;
- Designation & zoning of use values;
- An improved „algal bloom“ risk forecasting capability;
- Level of values/objective maintenance management;
- User education/awareness/risk management measures;
- A monitoring program providing the scope of information supporting appropriate management and risk assessment decisions, both on the part of the management authority and user groups.

8.1 In-Lake management measures

Restoration of macrophyte systems

Section 5.8 „Macrophyte ecosystem condition“ noted the significant loss in areas of emergent and submerged macrophytes across the Lake, as a result of levels of epiphytic algal growth (as a result of increased levels of available nutrient) on the macro-plant leaves, and levels of SS in inflows and re-suspension (in the case of East Basin), limiting light available to the plants.

Levels of phosphorus discharge from Queanbeyan Sewage Treatment Works have now been substantially reduced, and the in-lake water quality assessment has indicated a significant reduction in phosphorus levels in Lake water since the time of loss of the macrophyte zones. This opens the possibility of re-establishing the macrophyte habitats.

A preferred Lake arrangement is one of areas of emergent and submerged macrophytes/wetlands across the inlet deposition zones, and across shallow zones and embayments around the lakes edge, in preference to the current condition of uncontrolled algal blooms.

This management option would involve the re-establishment of emergent and submerged macro-plants:

- across East Basin, maintaining a clear channel for boat movement between the Boat Harbour and Kings Avenue Bridge, and into the Molonglo River;

- between Springbank Island and the Acton shoreline (would involve a re-arrangement of the Sailing Course);
- creation of a wetland on the Yarralumla Drain on the Yarralumla Bay Oval area; and
- rehabilitation of macrophyte beds at Weston Park East Beach, Orana Bay, Lotus Bay east.

In the case of East Basin, some amelioration of SS levels may be required as a pre-condition to successful rehabilitation of macrophytes in this area. There is a strong case for stabilisation of erosion on the eastern bank of East Basin, using geo-fabric and rock stabilisation techniques. This would have the added benefit of a significant reduction in Lake turbidity levels during „dry“ periods, and diminish the cyanobacteria advantage through improved euphotic depth.

The „Condition of the Lake“ and „Condition of the catchments“ assessments identified Sullivan’s Ck as a major source of organic material and faecal coliform, impacting on the West Lake area.

There are three options for management of this source:

- The creation of a 50 ha inlet wetland within the existing Lake, by constructing a 400 m low flume wall (comprising I beams & panels) in an arc, from a point 120 m off the shoreline 80 m to the west of Sullivan’s Ck inlet, in an arc to a point 50 m west of the NW corner of Springbank Island (diverting Sullivan’s Ck flow to the east across the Springbank Island – Acton foreshore macrophyte zone); or
- extensive wetland development within the Sullivan’s Ck catchment floodplain & tributary drains (difficult to achieve this area given established urban area constraints), together with improved stormwater management across the catchment, or
- combination of in-lake and catchment based wetlands and stormwater management measures.

Under extreme flood conditions, flow would occur over the low diversion berm, thereby limiting the risk of flooding upstream. While this situation would involve short-circuiting of the wetland, the sustained discharge under these conditions, would disperse sedimentation of organic material over a wide area of the Lake, rather than the immediate inlet deposition zone.

It is noted that the re-establishment of macrophyte habitats in lakes and reservoirs has had a mixed success rate. In a number of cases, this is the result of elevated SS post the loss of macrophytes, limiting light necessary for their re-establishment. Hence it appears appropriate to approach a „macrophyte restoration“ program on a phased basis, to assess this risk.

Installation of mixer and/or re-aeration systems

The „Condition of the Lake“ and „Lake water quality and ecology response processes“ assessments highlighted the role of the sediments in mediating algal growth across the Lake, via a process of reduction of iron by decomposition of sedimented organic material, and the release of phosphorus into the Lake’s water column. The limited mixing of Lake waters over the summer period, and in particular, stratification in the deep waters of the Molonglo Reach and the Yarramundi Reach, was identified as a feature of the Lake which significantly exacerbated the sediment reduction – phosphorus release process.

A wide range of mixing and aeration techniques have been developed in attempts to ameliorate the impacts of stratification, including:

- Diffusion of oxygen or air into deep waters, using perforated pipes laid on the bed of the lake, to create the oxygen or air diffusion curtain;
- Mixing and/or aeration of the hypolimnion zone, significantly reducing the energy required to work against the temperature - density differential through the water column;
- Mixing of the surface water – epilimnion zone, to promote cycling and growth of the Green (Chlorophyta) group of algae in preference to the blue-green (cyanobacteria) algae.

The level of success in the use of mechanical mixers to de-stratify deep lakes is limited, necessitating high energy requirements. Lakes having long, narrow and deep bathymetry, such as the Yarramundi & Tarcoola Reaches, are particularly difficult to de-stratify

The option of mixing/aeration within the hypolimnion is an approach that significantly reduces the energy requirements compared to raising the heavier hypolimnion water to the surface, but it foregoes building on the „wind re-aeration of surface water“ contribution to the re-aeration of the bottom water. This approach does not directly manage the summer surface water algal growth. It will, however, ameliorate the risk of algal blooms following autumn mixing of the bottom and surface waters, and the amount of phosphorus available at the commencement of the next growing season.

Mixing within the surface water or epilimnion zone, is primarily focused on providing the turbulence necessary to cycle the Green algal cells through the light (euphotic) zone, promoting their growth in preference to blue-green algal growth. However, in view of the research finding regarding diurnal stratification of shallow water in ACT lakes, this approach will also provide an „oxidation of sediments“ benefit, reducing the release of sediment phosphorus in shallow waters. As with all „mixer“ options, there are also risks with this arrangement – turning on a mixer post de-oxygenation of the sediments, may result in the mixing of bottom phosphorus throughout the epilimnion, thereby enhancing algal growth.

The current NCA mixer trials will hopefully provide information enabling a more rigorous assessment of this option. In particular, the Trial at Yarralumla Beach will provide a valuable guide on the potential for application of this management intervention measure to re-dress problems in the embayments.

Section 7 of this Assessment recommended the installation of a surface water zone mixer in the Molonglo Reach, as the means of limiting summer Cyanobacteria growth during low inflow periods.

Application of ultrasonic devices for control of algae

Over the last decade, there has been successful development of underwater sound systems, which emit ultrasonic sound waves that rupture the cell walls and gas vacuoles of target algae. The ultrasonic sound waves do not impact on fish, insects, macro-plants or humans.

The development of units appears to be well supported by scientific assessment, and there is a growing list of successful applications. Coverage area of units is 2 to 4 ha/unit. They have a low power requirement, which can be easily met by solar units. Cost ranges from \$3500 to \$4500/unit.

This management technology appears ideal for application in the swimming embayment areas.

While the research papers supporting the application of the devices conclude that the system does not harm insects, fish or humans, if applied widely across the Lake, the devices would seriously impact on the plankton of the Lake – the base of the food web for the Lake. Wide application across the Lake of this device is therefore not supported.

Modification of phosphorus adsorption capacity – phosphorus precipitation options

The „Condition of the Lake“ and „Lake water quality and ecology response processes“ assessments highlighted the role of fine silts and clay particulates in catchment discharge, in adsorbing phosphorus and iron onto their surfaces, and settling to the sediments together with their adsorbed phosphorus. Research has established that significant reduction energy is required to break the particulate – iron-phosphorus adsorption bond, and release phosphorus into the water column. Over time, the adsorption sites on the particulates become saturated, limiting the capacity of the sediments to lock-up the phosphorus.

It is expected that the recent December 2010 flood, with its massive loads of sediment, will have replenished particulate adsorption availability, with a reduction in available phosphorus in the Lake water in the short term.

A wide range of phosphorus precipitation compounds have been used as part of eutrophic lake amelioration programs. These include aluminium and iron compounds, the use of „alum“ (aluminium sulphate) to precipitate phosphorus during a bloom, and iron chloride.

Perhaps the most significant difference between the use of alum and the iron phosphorus adsorption compounds, is the ability of alum to trap algal cells into the aluminium floc, whereas the iron phosphorus adsorption compounds can absorb only inorganic phosphorus forms. The use of alum has been limited, in view of its potential toxic effect. Similarly, the use of copper sulphate is now rarely used as a precipitation agent in lakes.

Products such as Phoslock (a modified bentonite clay which reacts with phosphorus to form Rhabdophane), are promoted as a means of removing phosphorus from the water column. The process is identical to adsorption of phosphorus and iron on clay particulates. While the electron level at which Rhabdophane is reduced is not identified in the literature, it is probably more resistant to reduction than Fe^{3+} . As in the case of iron, the adsorption sites become saturated over time, and the dosing with Phoslock needs to be repeated. In the case of local clay – iron based minerals, the supply occurs naturally (sustainable), whereas with products such as Phoslock, this material has to be imported to the region and periodically applied.

Given the natural process of supply of clay & iron minerals in catchment discharge, the benefits of application of a product such as Phoslock on a Lake wide basis will be reduced. However, there could be a place for this product as a short term response in reduction of algal problems at hot spots such as the inlet depositional zones or beach embayments.

Sediment treatment

The „Condition of the Lake“ and „Lake water quality and ecology response processes“ assessments highlighted the role of the sediments in mediating algal growth across the Lake, via a process of reduction of iron by decomposition of sedimented organic material, and the release of phosphorus into the Lake’s water column. There are a range of sediment treatment options in respect to oxidizing organic material in the sediments, thereby decreasing their rate of phosphorus release and formation of ammonium.

Nitrate is viewed as a beneficial nitrogen compound, in terms of its capacity to oxidize lake sediments previously subjected to high levels of phosphorus and organic matter loading. The direct injection of nitrate into sediments has been used as one means of offsetting the potential for reduction of sediments by ongoing organic matter. In a number of „eutrophied lake remediation projects“ involving the diversion of sewage effluent away from the lake, exacerbation of blue-green algal blooms has been observed.

There is growing recognition (Cullen & Forsberg 1988) of the value of retaining treated sewage effluent low in phosphorus and BOD, but high in nitrate, in discharges to lakes, as a valuable buffer to the reduction of the sediments and associated release of sedimented phosphorus into the water column. This was the ACT experience in relation to remediation of Burrinjuck Reservoir. The commissioning of the Lower Molonglo Water Quality Control Centre (LMWQCC) de-nitrification facility in 1980 resulted in significant exacerbation of blue-green algal outbreaks. The closure of the de-nitrification facility in 1982 resulted in a major reduction in algal biomass and a return to Chlorophyta algal dominance.

Rosich, R (*Role of Sediments*. 1983) promoted the option of oxidation of the sediments by nitrate oxidation, as the only viable measure for amelioration of Lake Burley Griffin algal levels. Ripl, W (1994) provides a detailed Paper on the injection of iron chloride directly into the sediments of Lake Lillesjon, Lake Hambutten and Lake Gross-Glienicker in Sweden in 1975. Injection of lime is also required to offset the acidification effect of the chloride. The treatment has provided a significant and sustained reduction in algal levels within the treated lakes. This option would be applied to the inlet deposition zone „organic loading of sediments“ hot spots.

The treatment technique (now termed RIPLOX) was identified as an effective measure in a recent publication on in-lake treatment. (Drabkover, M & Marsalek, B. 2007)

Water balance management

During periods of low summer inflow, the management of the Lake's water balance between the surface water zone and the bottom water zone becomes critical, in respect to minimizing the risk of triggering Cyanobacteria blooms. During these periods, abstraction from the surface water zone should be minimized, either by prohibiting water abstraction for irrigation, or by requiring abstraction from the bottom water zone.

The current Lake operation policy in respect to the use of the bottom water zone outlet valves for regulating Lake level during these periods, is positive and should be maintained.

8.2 Catchment management measures

Soil conservation programs

As noted in the „Condition of the catchments“ assessment, the Commonwealth and NSW Governments established in 1961 a joint soil conservation program across the catchment, to manage the threat of sediment on the proposed Lake. The *Captains Flat (Abatement of Pollution)*

Agreement Act 1975 was another example of a catchment management related response to protection of the Lake.

The stabilization of soils across the catchment remains an important goal of the Upper Murrumbidgee Catchment Management Committee.

Environmental flow management

Lake inflow is the major driver of in-lake physical, chemical and biological processes. It determines the external SS, nutrients and organic matter loadings on the Lake, the ionic concentration (TDS) determining turbidity levels, the in-lake mixing turbulence, the washout of nutrients and algae, and the detention (growth) time available for algae. In undertaking analysis of Lake water quality response processes, it is therefore the basic starting point for analysis.

Figure 33 „Molonglo River Flow @ Scrivener Dam pre & post Googong“ provides the flow duration curves, pre and post Googong Dam diversion. The Figure indicates a reduction from a median inflow of 150 ML/d pre-Googong to 40 ML/d post-Googong. Actew advises that little water was drawn from Googong up until 2003 – the post Cotter catchment fire period. (Googong is a high cost water compared to the gravity and limited treatment based Cotter supply).

The role of flow in generating mixing of Lake water is generally constrained, as a result of the large cross-sectional area of the Lake. While there is a potential to draw an environmental release from Googong Reservoir through the multi-level outlet tower (warmer surface waters), the water will never-the-less be colder than Lake Burley Griffin surface waters over the summer period. Hence, a release of water from Googong Reservoir will probably „plunge“ to the bottom cold water of Lake Burley Griffin (stratified over summer), having limited benefit to mixing turbulence within the warmer epilimnion surface layer, and potentially exacerbating summer algal growth as a result of the upwelling of nutrient rich bottom water into the surface water zone. viz: the application of environmental flow releases to limit water retention time in the Lake, and/or to promote physical mixing of water, does not appear practical.

The open waters of West Lake and Yarramundi Reach are stratified over the summer, with P at very low levels over summer months in the surface water over dry periods, limiting algal growth. It appears to be the rate of transfer of phosphorus from the hypolimnion (a function of the daily variations in the thermocline depth, due to variation in daily wind strengths, and the transfer of hypolimnion water to the epilimnion to offset evaporation and water supply abstraction losses from the epilimnion) which:

- determines P available for algal growth in the epilimnion;
- enhances the dominance of *Microcystis* (ability to access transferred P adjacent to the thermocline) as compared to other non-motile algae.

Regression analysis has confirmed that moderate to high stormwater discharges (Sullivans Ck) to the Lake during the low rural inflow (extended dry) period, were the major trigger of Cyanobacteria blooms and Faecal Coliform (regrowth) blooms in West Lake and Yarramundi Reach, over the period 1999 to 2010. For rural discharges of 500 ML/d or higher, the algal levels appear to be substantially moderated.

There is a daily transfer of 37 ML/d during low inflow – extended dry periods, of nutrient rich bottom water, into the base of the surface water zone, maintaining an environment conducive to Cyanobacteria growth in the surface water zone.

While this preliminary assessment suggests that the provision of an „environmental flow“ to enhance physical mixing of Lake water over summer periods is not practical, there remains the question of „topping-up“ water required to limit the transfer of „nutrient rich bottom water“ into the surface water zone – the primary source of nutrients driving Cyanobacteria growth over dry periods.

„Topping-up“ water requirement during critical „dry year“ summer periods (including the current 10 ML/d environmental flow):

- 15 ML/d, excluding water supply abstraction during critical dry periods;
- 23 ML/d excluding the 8 ML/d Queanbeyan Sewage Effluent contribution;
- 30 ML/d including the 15 ML/d water supply abstraction over summer;
- 38 ML/d including the 15 ML/d water supply abstraction but excluding the 8 ML/d Queanbeyan Sewage Effluent contribution

Should it be determined that there is some „reduction in Cyanobacteria incidence and levels“ as a result of environmental flows, there are two possible sources of water for augmentation of flow through the Lake:

- releases from Googong Reservoir;
- pump treated sewage effluent from LMWQCC to the Lake.

Table. Summary of Environmental flow requirements and costs[^]

Daily top-up req ^m * ML/d	Daily environ flow release ML/d#	Probability Molonglo Riv flow ≥ Env flow	Av summer flows for probability level#	Daily environ flow release ML/d	Annual operating cost (\$million)	Annual total cost (including Restriction Cost) (\$million)
15	15	27%	7.2	7.8	Within current 10 ML/d release	Within current 10 ML/d release
23	23	37%	10.3	12.7	\$0.03	\$0.24
30	30	44%	12.8	17.2	\$0.08	\$0.64
38	38	49%	15.0	23	\$0.10	\$1.20

Notes: [^] Costs based on REALM model estimated costs provided by ACTEW x 120/365 days adjustment

* including the current 10 ML/d environmental flow release

long term average flow for the Molonglo River for the probabilities of inflows less than these environmental flow levels

The preliminary cost analysis indicates that there is little difference between the cost of the two options. The summer temperature of the water sources relative to the Lake's surface water zone temperature will probably be the ultimate determinant of the preferred option.

Sewage management

The „Condition of the catchments“ assessment made note of the substantial upgrading of the Queanbeyan Sewage Treatment Plant over the 1978 to 2011 period. The „Condition of the Lake“ assessment noted that the high algal levels in the Molonglo reach over the 1999 to 2009 period, were largely a reflection of the level of phosphorus and BOD discharged from the Plant at that time. Since that time, there has been a significant upgrade in respect to BOD concentrations in the discharged effluent. A review of the appropriate phosphorus discharge level is required.

The TP in Queanbeyan Sewage Treatment Works effluent has ranged from 0.07 mg/L to 0.30 mg/L over the last 2 years. During „dry“ periods, levels above 0.1 mg/L are significant, particularly in respect to the Molonglo Reach and East Basin algal levels. There is a case for a more consistent TP effluent discharge level at around 0.1 mg/L.

Two features of the Queanbeyan Sewage Treatment Plant seen as beneficial, are firstly, its contribution to inflows to the Lake, particularly in extended dry periods, and secondly, its discharge of an effluent high in oxidized nitrate. The case for maintenance of an effluent discharge, high in nitrate, has been outlined under „Sediment treatment“ above.

One aspect of concern in respect to the Queanbeyan Sewage treatment Plant has been the impact of flooding or failure or storm related spills of partially treated sewage from the Plant, on the frequency of Lake closures due to faecal contamination. It is recommended that a review be undertaken of the adequacy of the Plant infrastructure in respect to protecting the Lake recreational amenity.

Mention has been made through the Assessment of the contribution of house sewer connecting ties leaking faecal material into the urban stormwater drains. Over time, with redevelopment, the old Vitrified Clay pipe sewer ties are being replaced with modern – less leak prone materials.

Urban stormwater management

Residents as key „catchment management stakeholders“

Urban residents living within the Lake Burley Griffin catchment are key stakeholders in respect to non-point source pollutant management across the urban areas. There is a strong case for raising awareness regarding the impact of disposing leaves shed by deciduous trees in Autumn, grass or other garden waste in street kerbs, on the Lake. Just as the leaves or grass, when composted, provide carbon and nutrient rich compost to our gardens, promoting verdant growth, so they do when washed into the Lake. Given the high leaf loading each Autumn on sub-catchments such as Sullivan’s Creek, this is a significant source of organic loading on the Lake.

There is also a case for a Government partnership with residents within these „high impact“ residential areas, in providing a green waste collection service, or provision of neighbourhood compost facilities.

Water Sensitive Urban Design

The assessment noted the ongoing growth in urban areas within the Lake’s catchment, and that urban stormwater now represents the major source of BOD loading on the Lake (68% of loading during dry years) – the key driver of algal growth in the West Lake area, and becoming more significant in East Basin with growth of Queanbeyan within the Jerrabomberra catchment, Kingston re-development, and the proposed East Lake development.

In addition, the Assessment of the West Lake and Yarramundi Reach Cyanobacteria blooms concluded that it was the volume and high flow rates of urban stormwater discharges during periods of low Molonglo River inflow, which triggered these blooms. There is a need to address means of reducing both the volume and rate of stormwater discharges to the Lake.

While nationally, there have been substantial improvements in stormwater design (WSUD) there has been a limited take-up of these practices in the Lake Burley Griffin catchment related urban areas. This is a key area for change, particularly in view of the continued strong urban growth across the catchment, and in view of ACT Government, NSW State & Local Government policy commitment to the application of WSUD measures.

In addition, there is a case for improving the performance of two stormwater pollution control measures in the ACT – the Gross Pollutant Traps and the Water Pollution Control Ponds.

Gross Pollutant Traps (GPT's)

The GPT's have been highly effective in trapping significant volumes of sediment, organic material and trash, so successful that they have introduced a significant cleaning cost, in a utility that traditionally has had very low maintenance costs. The technology is now applied world-wide, in the management of stormwater discharges.

A serious disbenefit of the Traps has been the phosphorus and ammonia leached from the trapped sediment and organic material pending their periodic removal, potentially impacting on downstream waters, and in this case, Lake Burley Griffin. The discharge of leachates high in ammonia is of particular concern in respect to its promotion of blue-green algae.

The Traps were located adjacent to sewers, so that this leachate could be discharged to the sewer at the time of de-watering of the Trap for clean-out of sediment. Previously, the ACT Sewerage Authorities (Commonwealth Dept of Construction, ACT Water Supply & Sewerage Authority) have refused to accept discharge of the leachate into the sewer system. This refusal has been based on their view that the leachates would also involve significant discharge of sediments, placing the sewers at risk. This option should be again taken-up with Actew-AGL.

While there are a number of „dry“ GPTs in use, these systems trap the trash discharged by stormwater only, not the sediment and fine organic material. Any dry options in respect to trapping the sediment and fine organic material, entrain serious problems in respect to associated risks of odour, mosquito and visual impacts.

The simplest means for upgrading these systems comprises the use of the existing low-flow bypass system, to take the Traps „off-line“ for low stormwater flow conditions, thus reducing the period of discharge of leachates to downstream receiving waters. It would then be possible to install a small pit based filter and aerator system, to draw leachate water from the Trap's holding basin, remove phosphorus (using iron or Phoslock multi-medium filter), aerate the leachate to oxidize the ammonia, and recirculate the treated water back into the basin. These systems would require a relatively minor pump rate of 5 kL/d for the larger traps.

Water Pollution Control Ponds (WPCDs)

In view of the undulating terrain of much of the Canberra – Queanbeyan urban areas, it has not been possible to utilize shallow – macrophyte dominant wetlands as the basis for intercepting and treating stormwater discharges. Instead, a series of ponds, typically having an average depth of 2 to 3 m, have been applied, as a means of intercepting and detaining stormwater discharge for sufficient time to enable 70 to 80% of discharged SS and adsorbed phosphorus to settle to the sediments. The WPCDs have been very successful in achieving this objective.

However, in many cases, the constraints on available area for incorporation of Ponds has resulted in the under-sizing of these ponds relative to the urban catchment they are commanding. As a result, the high rates of organic material deposition are resulting in significant levels of sediment reduction, with the production of high levels of NH_3 and some leakage of intercepted phosphorus as ortho-phosphate. This assessment has noted the significant impact of ammonia in respect to the shift from Green algae to blue-green algae.

Research undertaken by the CRC for Freshwater Ecology, in association with the CSIRO, on mixing conditions within these Ponds, indicated that diurnal stratification was occurring under high summer solar radiation and low wind strength conditions, and often elevated turbidity. As in the case of this assessment of processes within Lake Burley Griffin, the poor mixing exacerbates the reducing conditions within the sediments of these Ponds.

There is a strong case for installation of small mixers within these shallow Ponds, to maintain them as fully oxidized systems.

Green waste collection service

Another stormwater catchment management option is the introduction of a „green waste“ collection program in North & South Canberra (areas of high density of deciduous street trees), to collect the large leaf biomass associated with Autumn leaf fall in these areas, thereby reducing their significant BOD loading on the Lake.

Urban catchments have huge effective drainage coverage, which facilitate organic matter transport via gutter systems, to stormwater. The loading typically dwarfs riparian inputs and alters benthic input quality. As a result, receiving waters experience high dissolved oxygen demands. (Belt, K.T. et al 2007).

By changing riparian plants from Eucalypts to exotic deciduous trees, urban development alters the type of organic matter discharged to streams. Carbon bio-availability and mineralisation rates for exotic deciduous trees are significantly higher than for Eucalypts, with implications for DO demand rates. (Esslemont et al 2007). Calculation of BOD loads for North Canberra estimates Deciduous street tree derived BOD reaching the Lake at 84 T/annum, and Eucalypt street tree derived BOD reaching the Lake at 19 T/annum.

8.3 Designation and zoning of values & related guidelines

The *Lake Management Plan* recognizes the natural pattern of water quality and ecological process change through the Lake, with identification of East Basin as primarily a water quality

process and ecological zone, West Lake as primarily a water use (primary and secondary recreation) zone, and in view of the high water quality and „natural qualities“ of Yarramundi Reach, its primary identification as a conservation zone.

While the *Lake Management Plan* continues to reflect this strategy, the designation of East Basin as a wind surfing area, for example, with its high primary contact nature, appears inappropriate.

Also the view that given the boating designation of this area, it should be kept free of emergent macrophytes, conflicts with the natural ecological response of this area to the inflowing water quality characteristics. The eastern arm of Lake Ginninderra provides an excellent example of an effective environmental zone (extensive wetland) intercepting SS, nutrients, organic material and bacteria, in maintaining a high water quality in the downstream open waters.

The designation of swimming areas in the embayments of West Lake was based on sites well downstream of potential discharges of pathogens to the Lake. It appears that as a result of the growth in urban areas within Sullivan’s Creek, and increased populations within the City West area, that these stormwater discharges are now impinging on the embayment locations.

Should Weston Park East facility be transferred to the Weston Park West beach location, and the Yarralumla site be transferred to the southern bar on Black Mountain Peninsula? While the Weston Park West Beach is located adjacent to the less impacted Yarramundi & Tarcoola Reaches, it has a westerly aspect and so is prone to accumulation of algal scums blown by the prevailing W & NW winds. The bar on the southern tip of Black Mountain Peninsula, on the other hand, is well mixed and is less prone to trapping of algal scums. This relocation option is worthy of further investigation.

By removing the „primary contact recreation“ designation for West Lake, the Lake closure thresholds would be significantly eased. However, the loss of these swimming facilities would be a serious loss in the recreational amenity of the Lake, particularly for families.

8.4 Risk management

Following the recent revision of the *NHMRC Managing Risks in Recreational Waters 2008*, the setting of recreational use related health criteria is perhaps the most extensively developed area of guideline development and application.

There has been ongoing dialogue between Health, the Lake manager and user groups, regarding the appropriate application of the *Algal Warning and Lake Closure protocols*. This ongoing dialogue between stakeholders in this area is commended and supported.

8.5 Lake user groups partnership

Both the *NHMRC Drinking Water Guidelines* and the *NHMRC Managing Risks in Recreational Waters Guidelines* place major focus on management of risk, with the application of both „a duty of care“ on the part of the agencies, and on the part of the consumers or users of services. This requires a much stronger focus on provision of the information and knowledge necessary for users to take decisions appropriate to their well being and enjoyment of recreational activities.

The Rowing Australian Capital Territory submission to the Investigation, in particular, made a strong case for „partnership“ in health risk management.

8.6 Improved forecasting of blue-green algal bloom events

The major concern raised by Lake users in their Submissions to the Review, was the uncertainty regarding the potential for scheduled sporting events having to be cancelled close to the time of the activity.

Based on the „cause – effect“ relationships identified in this Assessment, it would be possible to develop a „risk of blue-green algal bloom“ forecast capacity. For example, regression analysis for West Lake and Yarramundi Reach indicate that the probability of cyanobacteria levels > 5000 cells/ml is a function of low inflow levels (<80 ML/d), high Conductivity levels (> 300 µS/cm), and high urban stormwater TP loads (> 0.7 kg/d). For „wet“ periods, for example, the probability of a blue-green algal bloom is extremely low. In this case, a forecast for the coming summer season could be provided. In the case of a „dry“ period, the probability of a blue-green algal bloom becomes much higher. In this case, the forecasting updates would need to be provided on a monthly basis. This is an approach which would best be developed in association with the Lake users.

8.7 Review of adequacy of water quality monitoring & reporting

Several Submissions to the Review raised concerns regarding the adequacy of the current monitoring program. This Assessment has identified a number of limitations in the current scope, in respect to the ability to evaluate in-Lake and catchment discharge conditions.

In particular, the lack of monitored data in respect to the following areas is of concern:

- for the Jerrabomberra catchment post 1999 – perhaps the most vulnerable catchment in terms of its erodible soils and land use change pressures, and immediately adjacent to the Jerrabomberra wetlands and the significant investments in Kingston Foreshore and the proposed East Lake developments;
- for the Ramsar registered Jerrabomberra Wetlands (no recorded water quality data);

- for the Sullivan's Ck post 2007 – an urban catchment undergoing further development and the most important source of organic material discharges in respect to the West Lake and Yarramundi Reach water quality;
- for the sediments, given their key role in moderating Lake water quality and incidence of blue-green algal blooms.

In the case of urban stormwater, the flow response to rainfall is extremely rapid, with significant changes in water physical and chemical constituents over the duration of the storm hydrograph. For this reason, auto-samplers are required in this case, capable of automatically triggering sampling in response to increase in flow, and capable of taking and storing multiple samples. In view of the key role of stormwater as a driver of changes in Lake water quality, improved quality of data is paramount to progressing our assessment and management of the Lake.

There is also a strong case for differentiating between routine management related monitoring, and the longer term assessment of changes in Lake water quality and ecology programs. This would yield a substantial savings, while enhancing the provision of information relevant to each of these tasks.

The difficulty experienced in accessing data in a readily accessible form, suggests that monitoring has not been linked to management decision making.

While not identified as sources of pollution in this assessment, there are four significant enterprises immediately adjacent to the Molonglo River/eastern end of the Lake, deserving of ongoing surveillance. Each of these enterprises has a series of control measures in place, to minimize the risk of impacts on the Lake. Never-the-less, their scale and proximity to the River and Lake, requires ongoing monitoring, as a necessary part to their water quality protection management strategies.

These enterprises comprise:

- Canberra Airport, involving the use of a range of chemicals potentially hazardous to the Lake's ecology;
- Dairy Flat Turf Farm, involving the application of fertilizers in the production of turf;
- Fyshwick Sewage Treatment Plant, with the potential for groundwater seepage into the underlying Dairy Flat aquifer;
- Fyshwick light industry and trade area, discharging to Jerrabomberra Ck.

8.8 Selection of preferred management options

The final selection of preferred management options will be guided by social benefit, economic cost, and risk based assessments. The overall management approach will most probably encompass a range of measures.

8.9 Management intervention assessment conclusions

The „Condition of the Lake“ assessment concluded that there has been significant loss of Lake environmental and use values, as a result of physical and nutrient conditions prevailing during the 1999 to 2009 drought.

In view of the increased incidence of extended dry periods into the future as a result of Climate Change, and the continued strong growth in urban development within the catchment, there is a need for action to reduce the levels of urban stormwater organic matter discharge to the Lake, and/or the adoption of in-Lake measures to ameliorate the potential impacts of increased discharge of organic matter to the Lake over time.

Building on the „Lake water quality & ecological response processes“ assessment, a range of appropriate intervention measures directed towards remediation of Lake environmental and use values have been identified. They comprise a wide range of approaches, including in-Lake management measures; catchment management based measures; changes in the designation & zoning of use values; refinement of the level of values/objective maintenance, and user education/awareness/risk management based measures.

The final selection of preferred management options will be guided by social benefit, economic cost, and risk based assessments. The overall management approach will most probably encompass a range of measures.

In view of the range of jurisdictions potentially impacted by the selection and implementation of management measures, and the range of implications for Lake users, it will be necessary to put in place a consultative process to determine the most appropriate suite of management measures, with respect to their technical, environmental, economic and social benefits and dis-benefits.

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Appendix A. Outline of Guidelines forming the basis of the Assessment Framework

As a constructed urban lake, Lake Burley Griffin is categorized as a moderately to highly modified ecosystem. The *ANZECC Guidelines for Fresh and Marine Water Quality 2000* Trigger levels appropriate to assessment of the Lake water quality are summarized in the following Table.

Table A1. ANZECC Trigger level median default values (Moderately to highly modified waterways)

Ecosystem	Region	Chlor	TP	FRP	TN	Total amm	Low DO	High DO	Low pH	High pH
Unit		µg/L	µg/L	µg/L	µg/L	µg/L	% Sr	% Sr	Units	Units
Lakes	SE Aust	5 – 5.5	10 - 11	5 – 5.4	350 - 380	900 - 970	90 - 75	110 - 130	6.5 – 6.4	8.0 – 8.2

Source: *ANZECC Guidelines for Fresh and Marine Water Quality 2000*

Table A2. ANZECC Toxicant (heavy metals) stressor guideline levels.

Metal	Water column		Sediments
	90%ile protection level	80%ile protection level	
Cadmium	0.4 µg/L	0.8 µg/L	10 mg/kg dry wt
Chromium	6 µg/L	40 µg/L	80 mg/kg dry wt
Copper	1.8 µg/L	2.5 µg/L	65 mg/kg dry wt
Lead	5.6 µg/L	9.4 µg/L	50 mg/kg dry wt
Nickel	13 µg/L	17 µg/L	21 mg/kg dry wt
Zinc	15 µg/L	31 µg/L	200 mg/kg dry wt
Mercury	1.9 µg/L	5.4 µg/L	0.15 mg/kg dry wt

The NHMRC *Guidelines for Managing Risks in Recreational Waters* 2008 adopts a preventative risk management approach to protection of public health, using a „classification of recreation waters“ based risk assessment framework. The major potential risks to public health include microbial viruses, parasites, and bacteria; and cyanobacteria related toxins.

The assessment of microbial risks is based on the Intestinal *enterococci* bacteria, as an indicator of faecal pollution, replacing the previous use of the *Escherichia coli* as the indicator of risk of presence of faecal pathogens. The NHMRC *Guidelines* propose the rating of recreational waters based on Table A3.

The prescribed microbial risk indicator covering the bulk of the period of the Lake Burley Griffin water quality assessment (1978 to 2011) was *Escherichia coli*, with a public health protection criteria limit of 200 CPU/100 ml. Not with-standing the occasional incidence of faecal coliform re-growth in the Lake, this criterion has been applied as the basis for assessment of Lake pathogen risk.

Table A3. Classification of recreation waters (Table 5.13 NHMRC *Guidelines 2008*)

Susceptibility to faecal inflows	Microbial water quality assessment (CFU/100 mL)			
	<40	41 to 200	201 to 500	>500
Very low	Very good	Very good	Follow-up req'd	Follow-up req'd
Low	Very good	Good	Follow-up req'd	Follow-up req'd
Moderate	Good	Good	Poor	Follow-up req'd
High	Good	Follow-up req'd	Follow-up req'd	Very poor
Very high	Follow-up req'd	Follow-up req'd	Follow-up req'd	Very poor

The NHMRC *Guidelines 2008* identify cyanobacteria which produce toxins that have harmful effects on tissues, cells or organisms, as representing a significant potential hazard to human health as a result of use for potable water, recreation or agriculture.

In line with its „management“ focus, the NHMRC *Guidelines* recommend the rating of recreational waters on the basis of Table A4 below.

Table A4. Classification of recreation waters (Table 6.4. NHMRC *Guidelines 2008*)

Susceptibility classification	History of blooms	Water temperature °C	Nutrients TP ug/L	Stratification
Very low	None	<15	<10	Never
Low	Yes	15 - 20	<10	Infrequent
Moderate	Yes	20 - 25	10 – 25	Occasional
High	Yes	>25	25 – 100	Frequent & persistent
Very high	Yes	>25	>100	Frequent & persistent - strong

In situations where high inflows are characterized by high SS and adsorbed TP (indirect water quality response processes), such as Lake Burley Griffin, the TP criteria in Table A4 are not relevant, and consequently, have not been used in the „risk of algal toxins“ assessment.

In response to growing concerns regarding the increasing incidence of blue-green algal blooms and high levels of faecal coliform, monitored in Canberra's lakes, ACT Health, in consultation with lake managers, issued the *ACT Guidelines for Recreational Water Quality 2010*.

The ACT *Guidelines* provide more detailed guidance on the agreed actions in event of exceedance of health guideline values.

Table A5. Suitability of waters for recreation (Table 6.5 *NHMRC Guidelines 2008*)

Suceptibility to Cyanobacteria contamination	Cyanobacteria history			
	A. < 500 cells/mL	B. 500 -<5000 cells/mL <i>M.aeruginosa</i> , or >0.04 to 0.4 mm ³ /L combined Cyanobacteria	C. 5000->50,000 cells/mL <i>M.aeruginosa</i> , or >0.4 to 4 mm ³ /L combined Cyanobacteria	D. >50,000 cells/mL <i>M.aeruginosa</i> , or >4 mm ³ /L combined Cyanobacteria
Very low	Very good	Good	Fair	Further assessment req'd
Low	Good	Fair	Further assessment req'd	Further assessment req'd
Moderate	Fair	Further assessment req'd	Poor	Very poor
High	Further assess req'd	Poor	Very poor	Very poor
Very high		Poor	Very poor	Very poor

Table A6. Blue Green Algae Action Plan (Table 2.7 *ACT Guidelines for Recreational Water Quality 2010*)

Alert Level	Indicative <i>M.aeruginosa</i> cells/mL	Bio-volume equivalent mm ³ /L	Action
Low	<5000	<0.4	Routine monitoring
Medium	5000 to 50,000	0.4 to 4	Twice weekly monitoring Visual inspection, sample as req'd
High	50,000 to 125,000	4 to 10	Twice weekly monitoring Visual inspection, sample as req'd Advice to public that waters closed to primary contact recreation. Warning signs
Extreme	>125,000 or scums consistently present	>10	Twice weekly monitoring Visual inspection, sample as req'd Advice to public that waters closed to secondary contact recreation. Warning signs

Table A7. Microbial Pathogens Guidelines (Table 3.5 *ACT Guidelines for Recreational Water Quality 2010*)

Alert level	Intestinal <i>Enterococci</i> numbers CFU/100 mL	Action
Open	<200	Weekly sampling
Closed	>200	Repeat sampling. Advise public regarding health risk. Warning signs. Undertake sanitary survey and identify source of contamination.

ACT Environmental Protection Regulations 2005 sets out a range of water quality objectives related to the protection of each designated environmental value, as per Table 8 below.

Table A8. Lake water quality management objectives (*ACT Environmental Protection Regulations 2005*)

Water quality indicator	Lake water quality management objectives					
	Primary contact recreat	Secondary contact recreation	Passive recreation (landscape)	Significant aquatic habitat	Fishing	Irrigation water supply
pH Units	6.5 – 8.5			6 – 9		4.5 - 9
Total Dissolved Salts mg/L						500 - 3500
Suspended Solids mg/L				25		
Turbidity NTU				<30		
Colour						
Clarity Secchi Depth (m)	>1.2					
Odour						
DO mg/L				>4		
TP mg/L	0.1	0.1	0.1	0.1		
NH ₃ mg/L *				1.49		
Nitrite mg/L				0.06		
N/P ratio	>12	>12	>12	>12		
Cyanobacteria cells/mL	<5000	<5000	<5000	<5000		
Chlorophyll „a“ µg/L	<10			<10		
Faecal coliform CFU/100 mL	<150	<1000				<1000
<i>Enterococci</i>						
Aluminium µg/L				5		5
Antimony µg/L				30		
Arsenic µg/L				50		0.1
Beryllium µg/L				4		0.1
Boron µg/L				0.2		6.0
Cadmium µg/L				0.2		0.01
Chloride µg/L						700
Chlorine µg/L				2		
Chromium µg/L				2		0.1
Copper µg/L				2		1.0
Cyanide µg/L				5		1.0
Fluoride µg/L						1.0
Iron mg/L				0.3		1.0
Lead µg/L				1		0.2
Lithium µg/L						2.5
Manganese µg/L						0.2
Mercury µg/L				0.1		0.002
Molybdenum µg/L						0.01
Nickel µg/L				25		0.2
Sodium Adsorption Ratio						<10
Selenium µg/L				1		0.02
Silver µg/L				0.1		
Sodium µg/L						115-460
Vanadium µg/L						0.1
Uranium µg/L						0.01
Zinc µg/L				5		1.0

Notes: * Ammonia value for pH 7.0 & temperature 20° C

A set of Secondary water quality criteria is also identified in the *Regulations*:

- Annual BOD load on the Lake < 51200 kg/yr
- Annual TP load on the Lake < 8600 kg/yr

In July 2011, NCA released their revised *Draft Lake Burley Griffin Water Quality Management Plan*, containing recommended water quality guides in respect to protection of Lake ecosystems, aesthetic values, recreational waters, and irrigation water supply.

Instead of defining water quality objectives based on 80th percentile values, the NCA *Guidelines 2011* proposes the adoption of water quality benchmark values. Many of these benchmark values are close to the 80th percentile values for each data set. The benchmark values as used in the NCA *Guideline 2011* are based on a combination of statistical analysis and scientific judgement. The benchmark values in this updated WQMP also take into consideration the values of the *Guidelines for Managing Risks in Recreational Water* (Australian Government, 2008).

The appropriateness of several of these benchmark values is questioned. In waters such as Lake Burley Griffin, where inflows are predominantly high in SS and adsorbed TP (non-bio-available), the setting of a <0.06 mg/L TP benchmark appears inappropriate. Indeed, in view of the „indirect“ release of bio-available phosphorus, it is not practical to set any meaningful TP criteria. The setting of TN values of <1.4 & <1.0 mg/L for East Basin & West Lake respectively, are based on observed values for these zones, without apparent adverse effect on Lake ecology. These values should not be seen as an upper limit on a well nitrified effluent from the Queanbeyan Sewage Treatment Works into the future.

Even in the „direct“ process situation, the relevance of PO_4^{3-} & NO_x^{2-} or NH_4^+ is questioned. If PO_4^{3-} & NO_x^{2-} or NH_4^+ is present, surely this is simply telling us that for some reason, algae have not utilized this available nutrient, or that there is a potential for more growth, rather than acting as an indicator of safe nutrient levels in respect to limiting algal growth!

Table A9. Summary of NCA *Draft Lake Burley Griffin Water Quality Management Plan 2011* benchmark values

Environmental or use value	Indicator	Lake general	East Basin	West Lake
Ornamental	Turbidity (NTU)		<40	<20
Freshwater ecosystems	Turbidity (NTU)		<40	<20
	SS (mg/L)		<40	<20
	TP (mg/L)	<0.06		
	TN (mg/L)		<1.4	<1.0
	NH ₃ (mg/L)	<0.1		
	Cyanobacteria (cells/ml)	<5000		
	Chlorophyll-a (µg/L)	<30		
	Conductivity (mS/cm)	<400		
	pH (Units)	<6.5 – 8.5		

	Heavy metals	ANZECC (2000)		
	pH (Units)	6.5 – 8.5		
Primary & secondary recreation	General	NHMRC (2008)		
	<i>Enterococci</i> (CPU/100 ml)	<200		
	Cyanobacteria			
	• toxin (µg/L) • Cells (No/mL)	<5 <25000		
	pH (Units)	6.5 – 8.5		
Irrigation water supply	General	NHMRC (2008)		
	<i>Enterococci</i> (CPU/100 mL)	ACT (2010)		

Table A10. Proposed guidelines for assessment (Condition of Lake assessment)

Threat to Lake values	Indicator	Assessment criteria	Draft Mgmt Plan * Benchmark
Change in micro-plant plant structure	Chlorophyll ^a <ul style="list-style-type: none"> Molonglo Reach & East Basin West Lake & Yarramundi Reach Cyanobacteria Ratio NO ₃ /NH ₃ NH ₃	15 µg/L 10 µg/L <50000 cells/ml Or 4 mm ³ /L >0.5 NonSpring >5 <0.2 mg/L	30 µg/L 30 µg/L <25000 cells/ml <0.1 mg/L
Asphyxiation of biota	DO	>4 mg/L	
Smothering of biota	Macro-invertebrate abundance & diversity	Minor change	
Impacts on human health: Algal toxins	Cyanobacteria Frequency of exceedance of guideline Frequency of Lake closures	<50000 cells/ml <2/yr average < 1/yr average	<25000 cells/ml
Impacts on human health: Pathogens	Faecal Coliform Cyanobacteria Frequency of exceedance of guideline Frequency of Lake closures	<150 CPU/100ml <25000 cells/ml <2/yr <1/yr	<150 CPU/100ml
Impacts aesthetic values: <ul style="list-style-type: none"> Turbidity; Scums/odours 	Turbidity: <ul style="list-style-type: none"> Molonglo Reach West Lake & Yarramundi Reach Chlorophyll ^a <ul style="list-style-type: none"> Molonglo Reach West Lake & Yarramundi Reach Cyanobacteria	40 NTU 20 NTU 15 µg/L 10 µg/L <50000 cells/ml	40 NTU 20 NTU 30 µg/L 30 µg/L <25000 cells/ml
Impacts of toxicants on biota	Cd, Cr, Cu, Pb, Ni, Zn, Hg	ANZECC2000 values	ANZECC2000 values

Notes: * Draft Lake Burley Griffin Water Quality Management Plan. Sept 2011. NCA

The setting of the 30 µg/L Chlorophyll-a level is remarkable. Previously, a limit of 10 µg/L Chlorophyll-a has been applied, on the basis that there are rarely algal scums or blue-green algal toxins associated with these algal biomass levels. It is proposed that the <15 µg/L Chlorophyll-a

90%ile value for Molonglo Reach & East Basin, and <10 µg/L Chlorophyll "a", 90%ile value for West Lake & Yarramundi Reach, should be used as objectives in respect to this Assessment.

Table A11. Proposed guidelines for this assessment (Condition of catchments assessment)

Threat to Lake values	Direct process conditions			Indirect process conditions		
	Stressors	Modifiers	Stressor Guideline	Stressors	Modifiers	Stressor Guideline
Nuisance plant growth	TP	Detention time; Light	0.05 mg/L	Org mat ¹ – BOD	Detention SS adsorption, light, NO ₃	20 mg/L
Asphyxiation of biota	BOD	Mixing, re-aeration	0.2 g/m ² /d	BOD	Mixing, re-aeration	0.2 g/m ² /d
Smothering of biota	SS	TDS	<2 mm/yr sedimentat	SS	TDS	<2 mm/yr sedimentat
Impacts on human health: Pathogens; Toxins	Faecal Coliform <i>Enterococci</i>	Decay, temp. Mixing	150 CPU per 100 ml 200 CPU per 100 ml	Faecal Coliform <i>Enterococci</i>	SS adsorpt	150 CPU per 100 ml 200 CPU per 100 ml
	Algal toxins		5000 cells/100 ml	Algal toxin	SS adsorpt	5000 cells/100 ml
Impacts aesthetic values: Turbidity; Scums/odours	SS	TDS, Detention time, temp, mixing, NO ₃	40/20 mg/L	Turbidity	TDS	40/20 mg/L
	TP		0.05 mg/L	BOD	Detention, mixing, temp, NO ₃ ,	0.1 g/m ² /d
Impacts of toxicants on biota	NH ₃	Temp, pH	1.4 mg/L @ 20°C & pH 7.0	NH ₃	Temp, pH	1.4 mg/L @ 20°C & pH 7.0
	Heavy metals	SS, hardness	ANZECC Guidelines	Heavy metals	SS, hardness	ANZECC Guideline

Notes:

- The asphyxiation sustainable BOD load limit is based on not exceeding oxygen re-aeration & diffusion for a wind velocity of 2 m/s & Lake depth of 4 m = 0.1 g/m²/d of DO and an initial Lake DO of 4 mg/L.
- The nuisance plant growth BOD load limit is based on oxidation of organic material yielding 0.2 g P/g BOD oxidized & 0.5 g Chlorophyll "a" per gm of phosphorus photosynthesized = 10 µg/L of Chlorophyll "a".

Appendix B. Schedule of Lake Closures due to High levels of blue-green algae

Table B1. Closures of Lakes swimming areas due to „High“ blue-green algal levels

Year	Date	Water body			
		Lake Ginninderra	Lake Tuggeranong	Lake Burley Griffin	Molonglo Reach
2002	4 Apr 2 Aug	Yes	Yes		
2003	21 Oct	Yes	Yes	Yes	Yes
2004	22 Jan 2 Feb 2 Mar	Yes Yes	Yes Yes	Yes Yes	Yes Yes Yes
2005	24 Jan		Yes		
2006	24 Jan 20 Feb 4 May		Yes		Yes Yes
Total closures		4	6	3	6

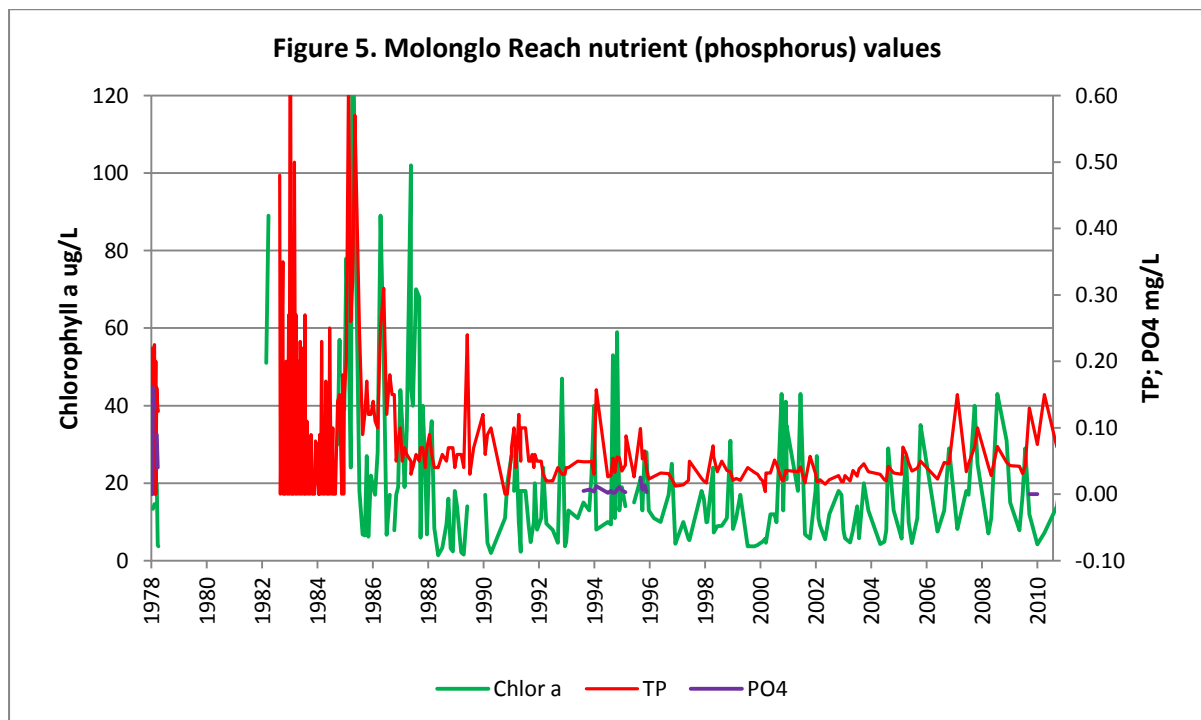
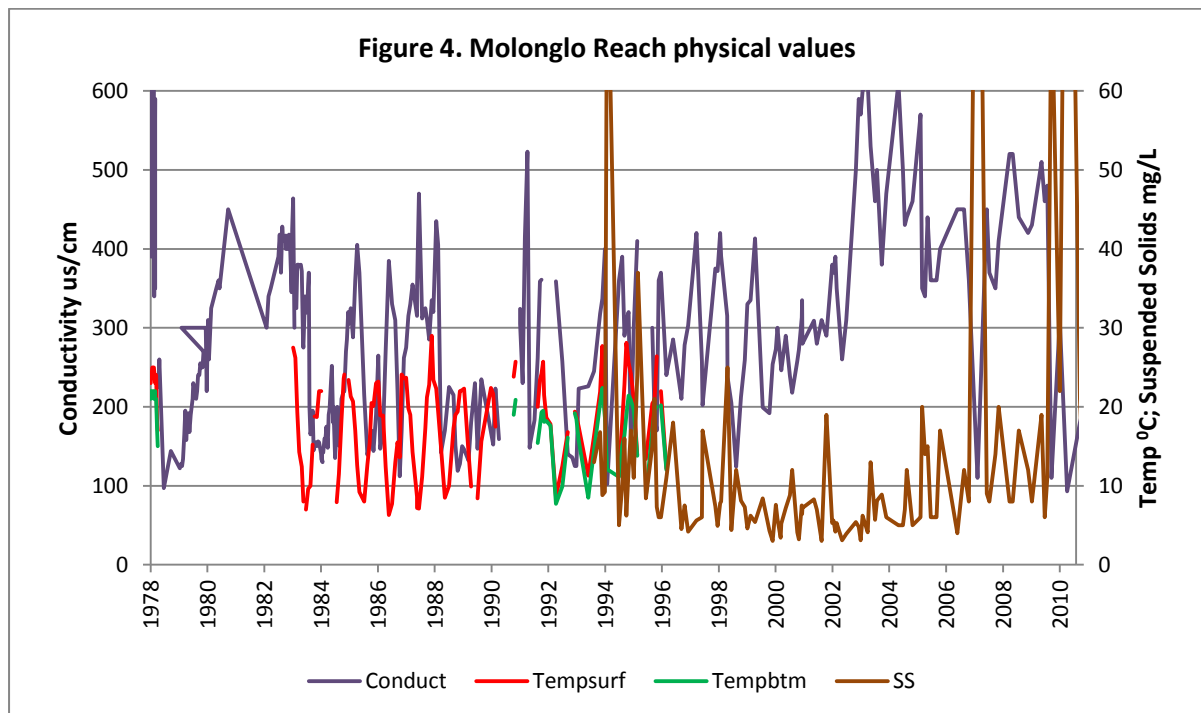
Source: ACT Health

Table B2. Closures of (Primary Contact) Canberra's lakes/swimming areas due to „High“ to „Extreme“ blue-green Algae levels.

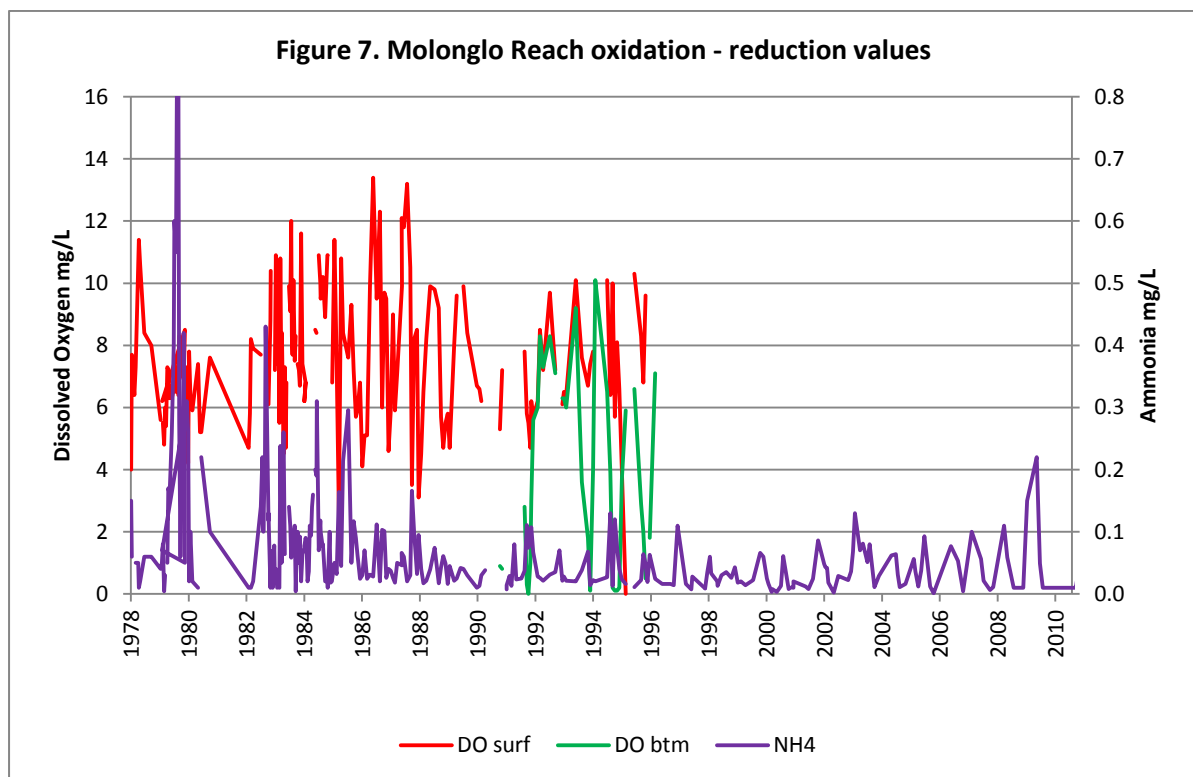
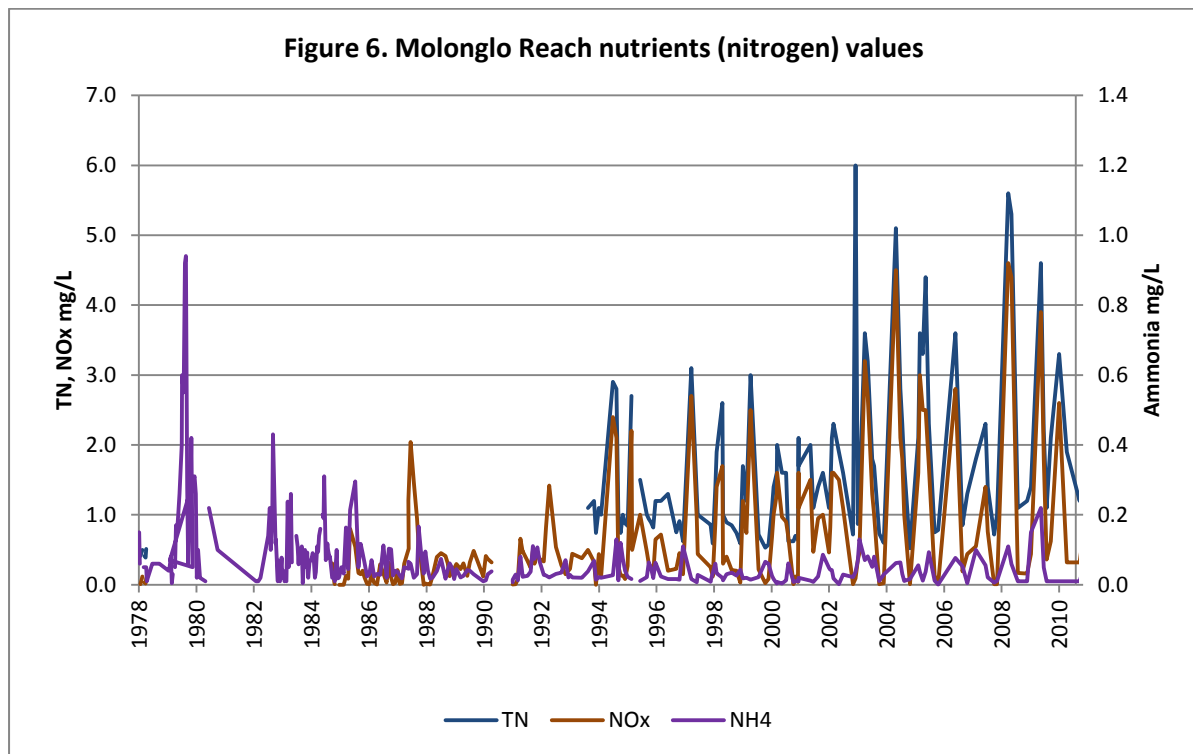
Year	Date	Water body		
		Lake Ginninderra	Lake Tuggeranong	Molonglo Reach
2007	Nov 27		Closed	
2008	Jan 10 Mar 12 Apr 4		Open Closed Open	
2009	Feb 5 Feb 11 May 18 Jun 18	Closed Open	Closed Open	Closed Open
2010	Jan 21 Jan 28 Feb 25 Apr 15		Closed Open	Closed Open
2011	Feb 10 Jun 16		Closed Open	
Total closures		1	5	2

Source: ACT Health

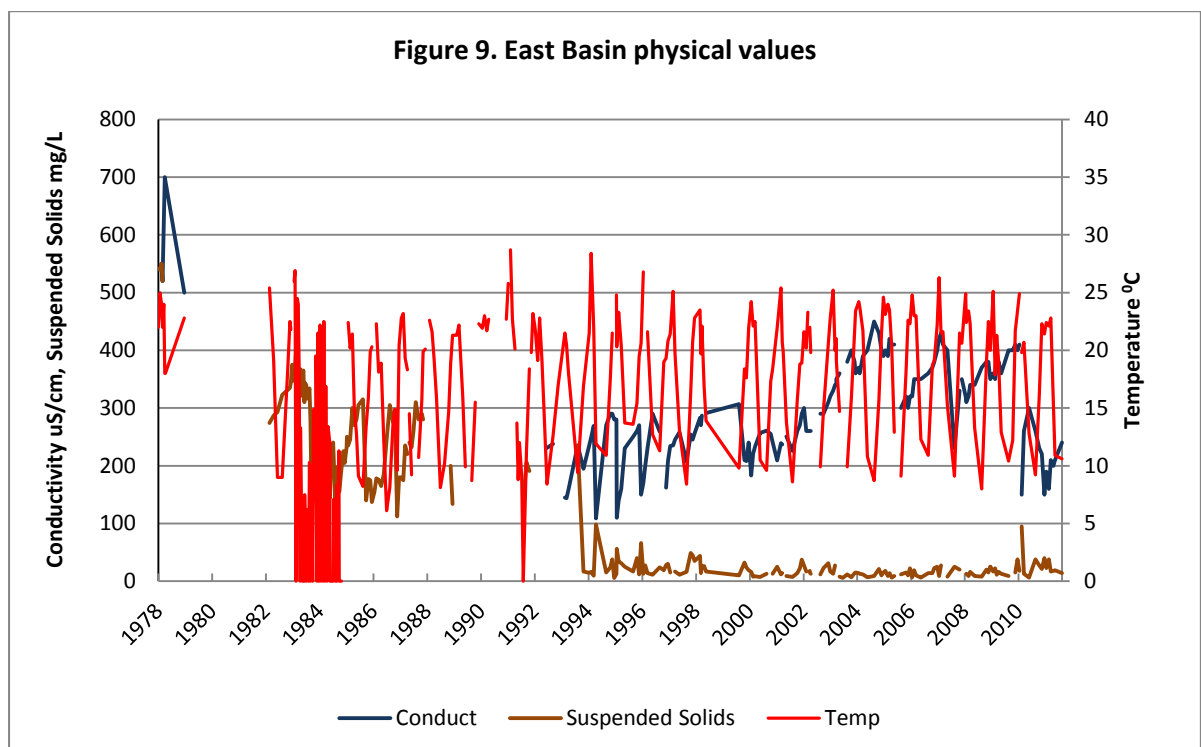
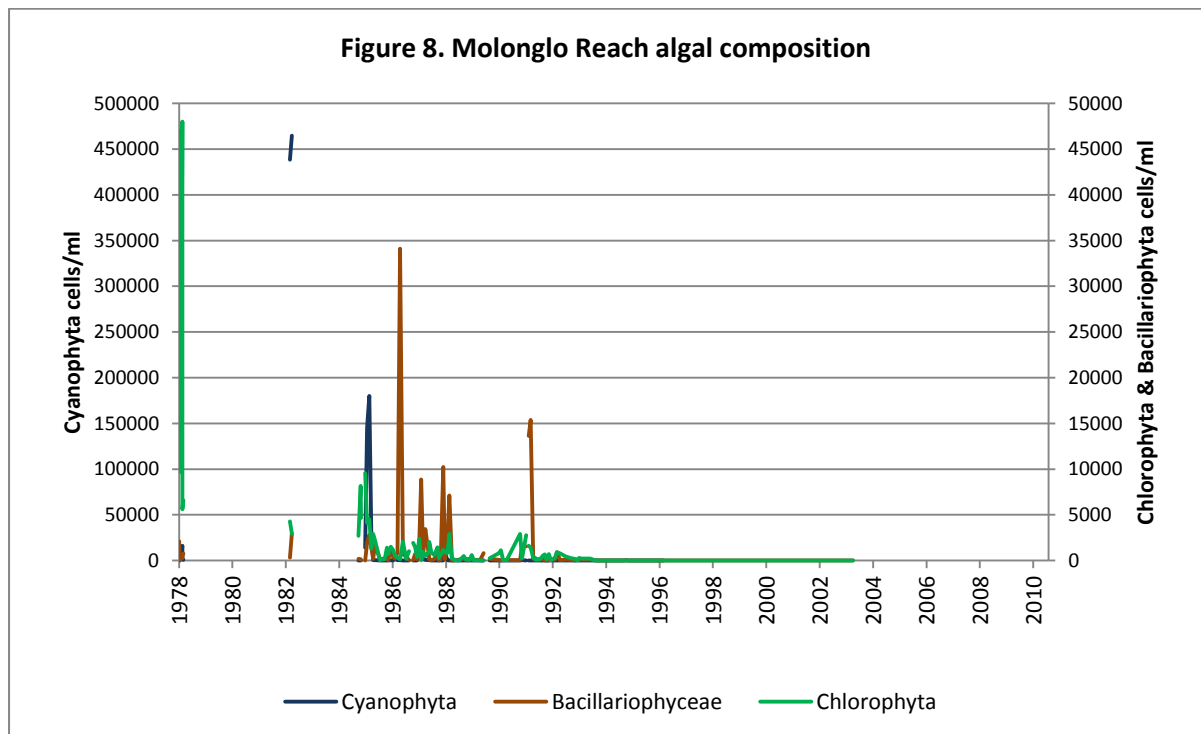
Appendix C. Water Quality Assessment Figures



Appendix C. Water Quality Assessment Figures



Appendix C. Water Quality Assessment Figures



Appendix C. Water Quality Assessment Figures

Figure 10. East Basin nutrient (Phosphorus) values

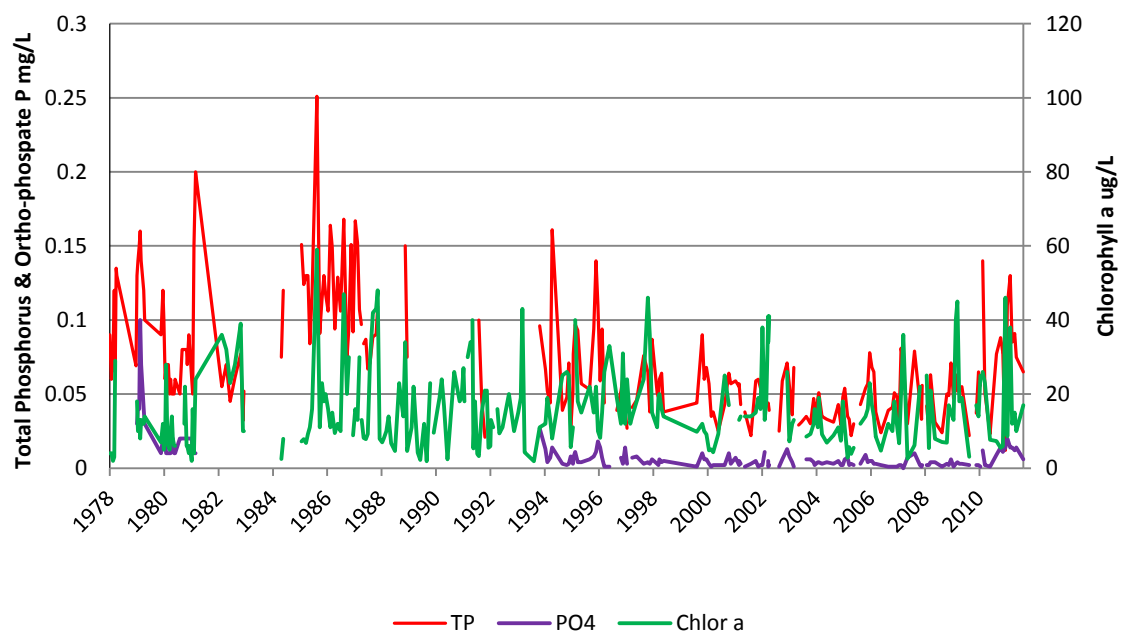
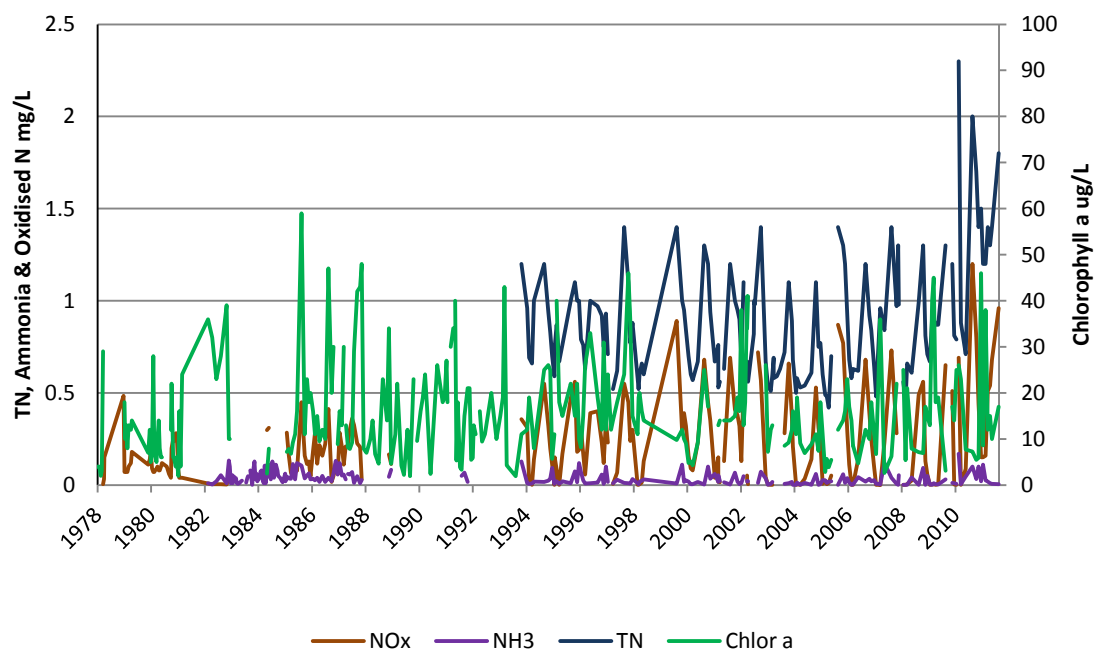
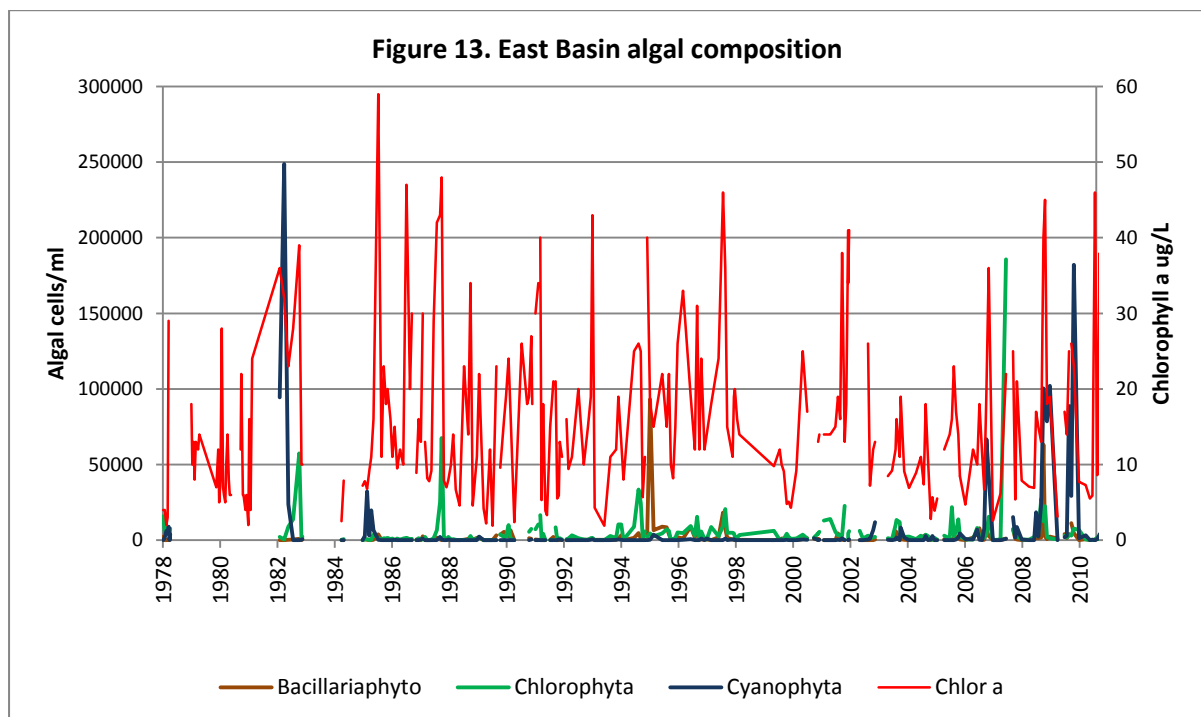
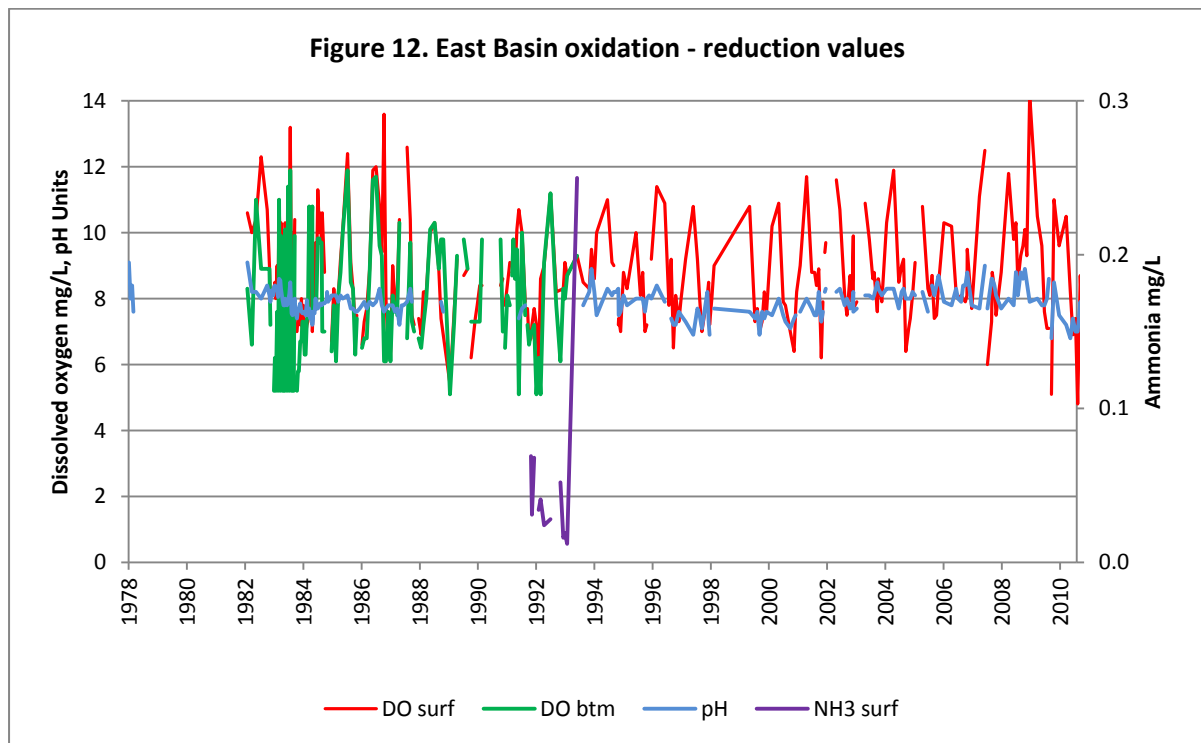


Figure 11. East Basin nutrient (Nitrogen) values



Appendix C. Water Quality Assessment Figures



Appendix C. Water Quality Assessment Figures

Figure 14. East Basin Confirmed Faecal Coliform

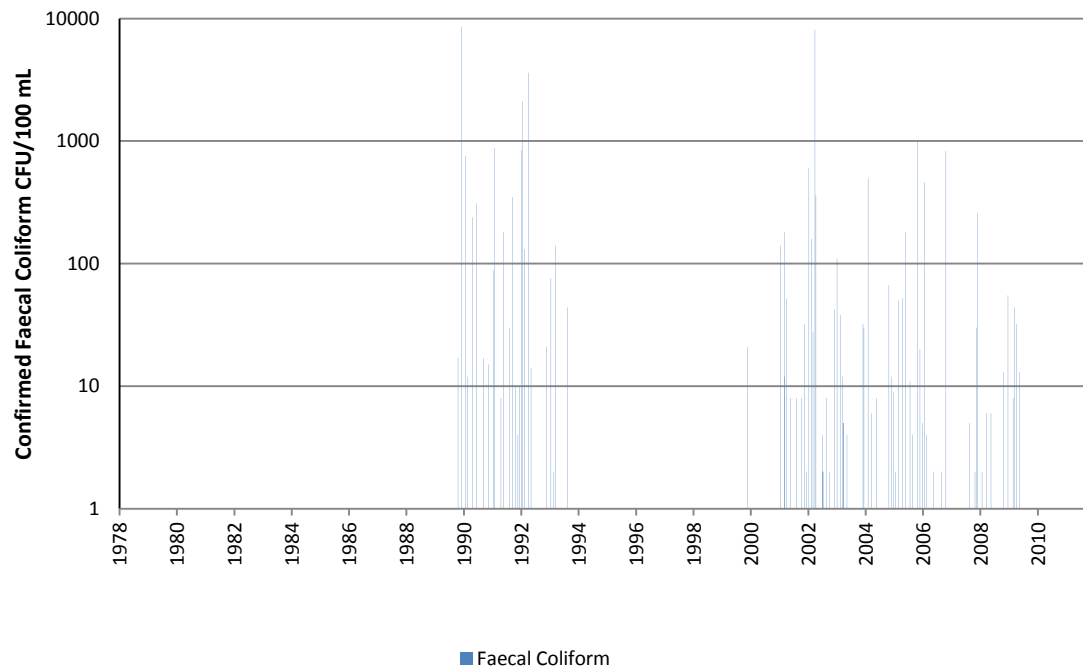
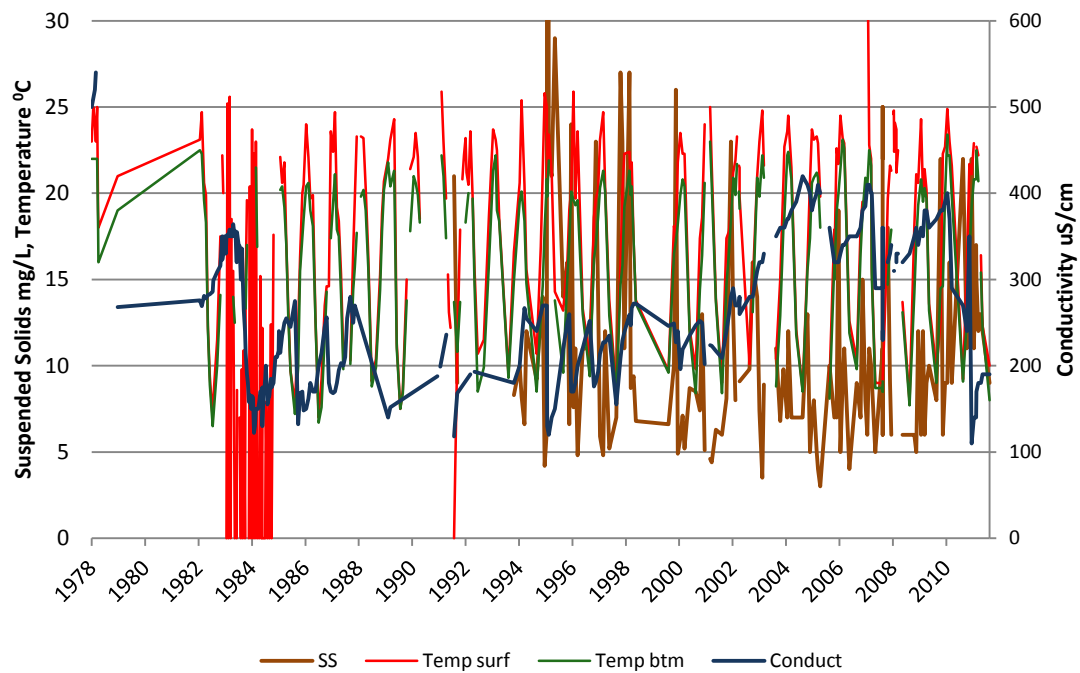
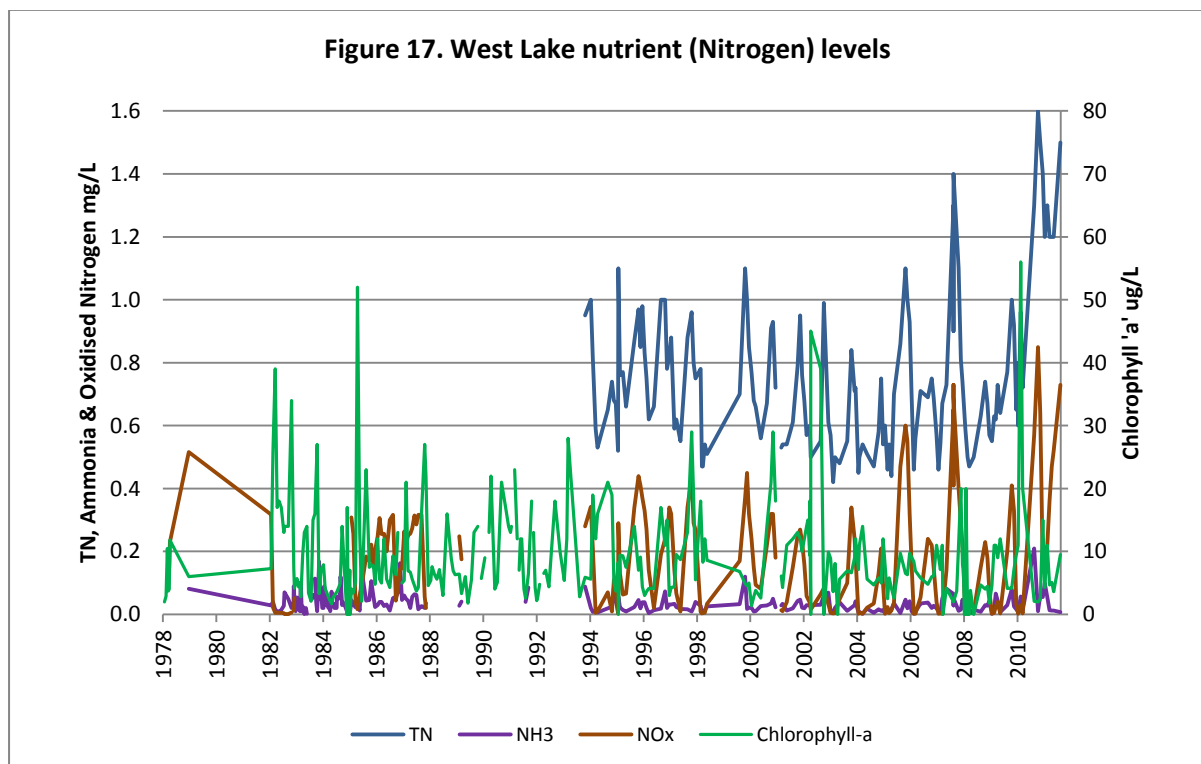
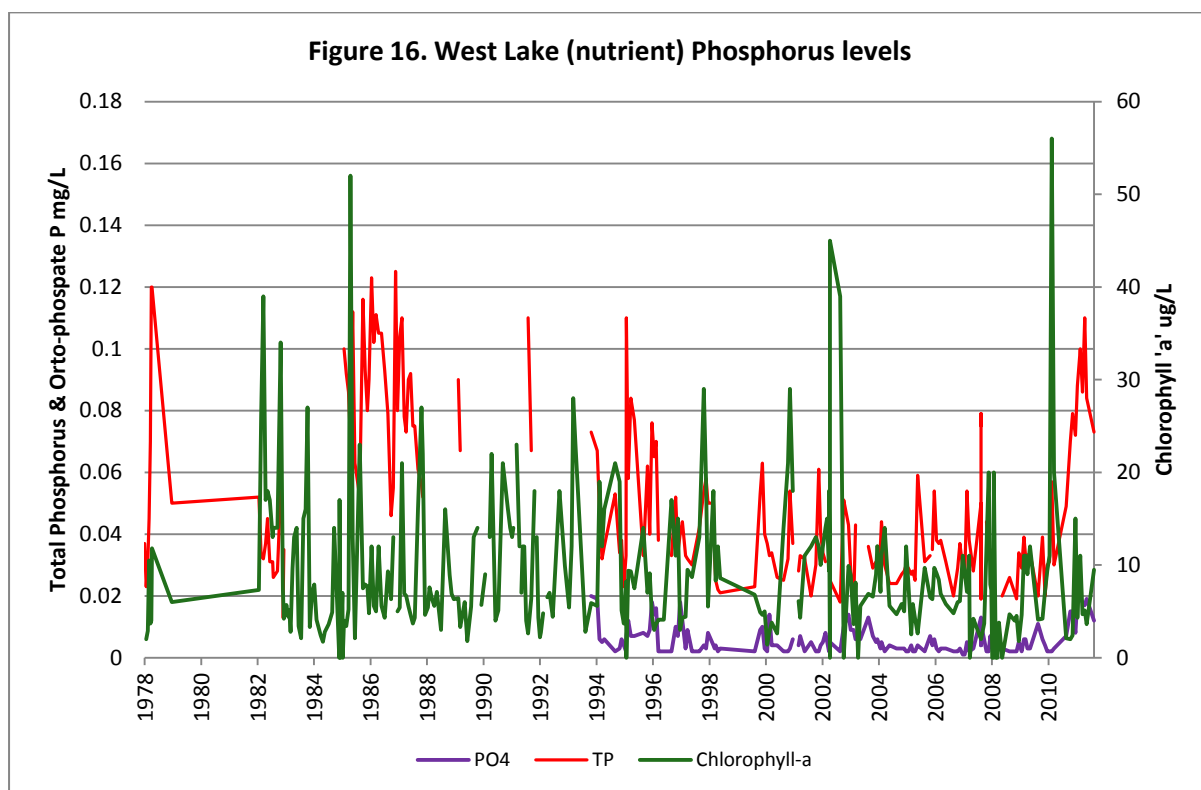


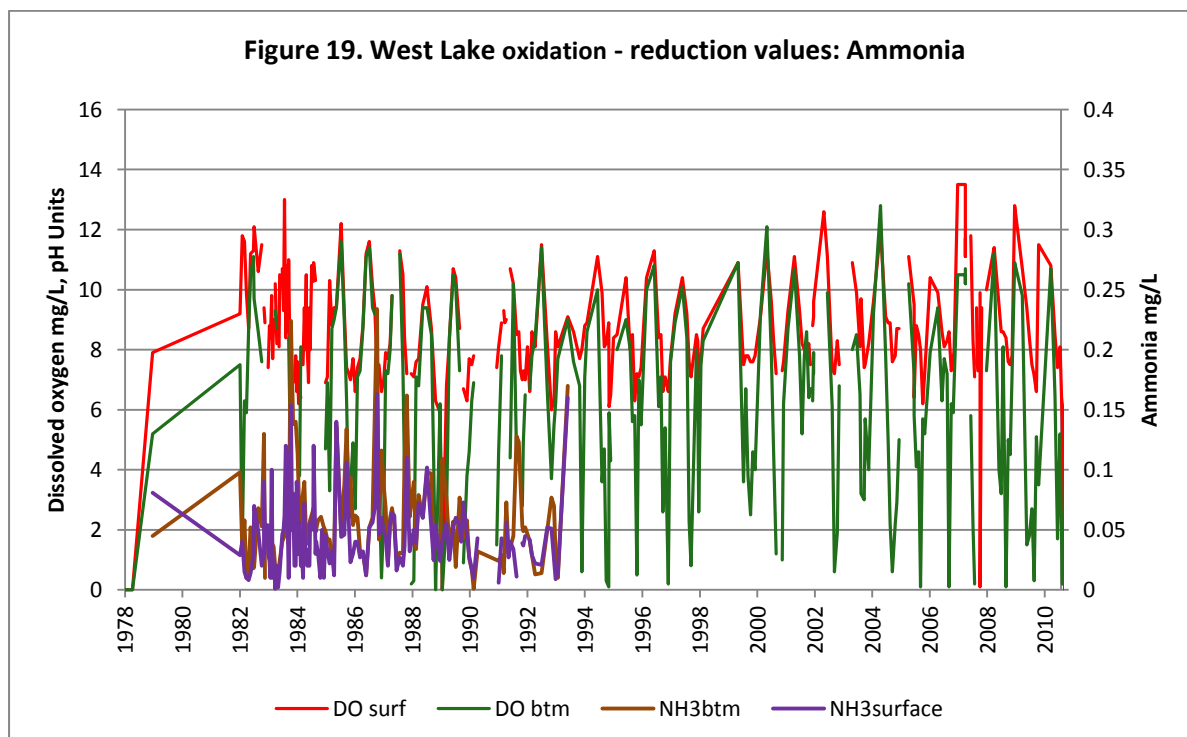
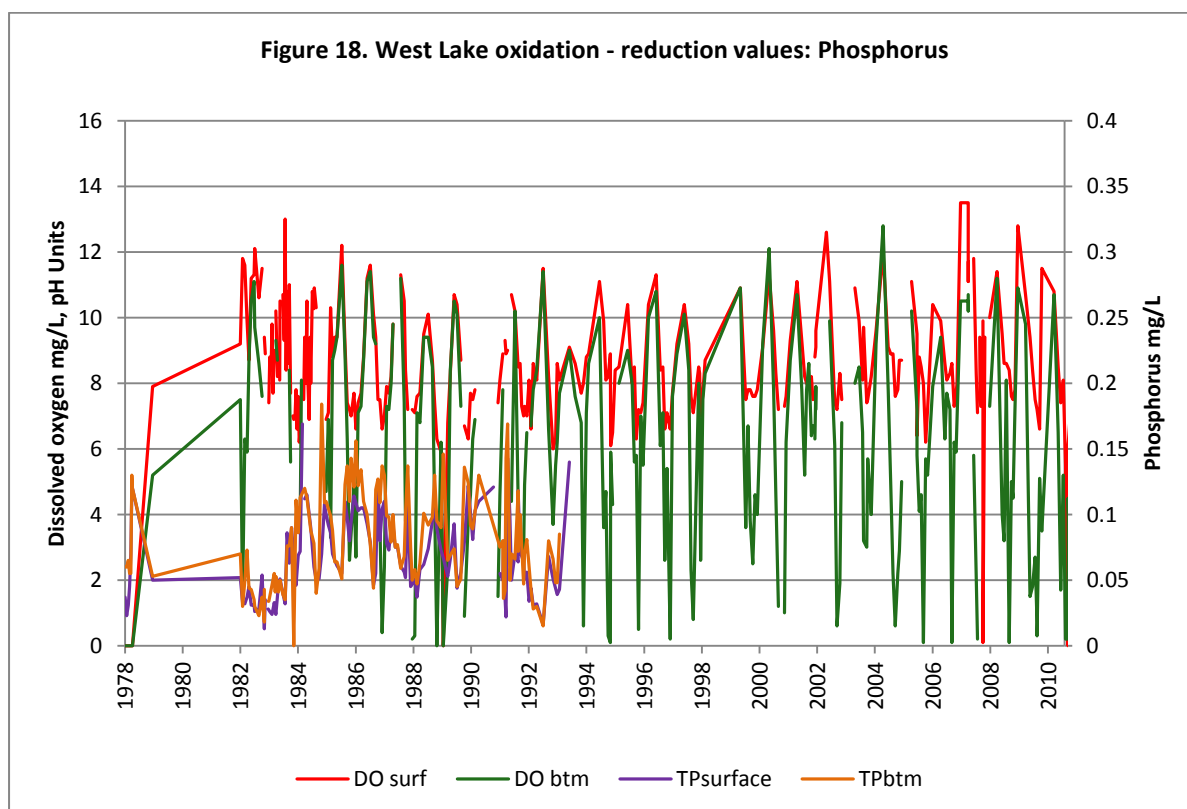
Figure 15. West Lake physical values



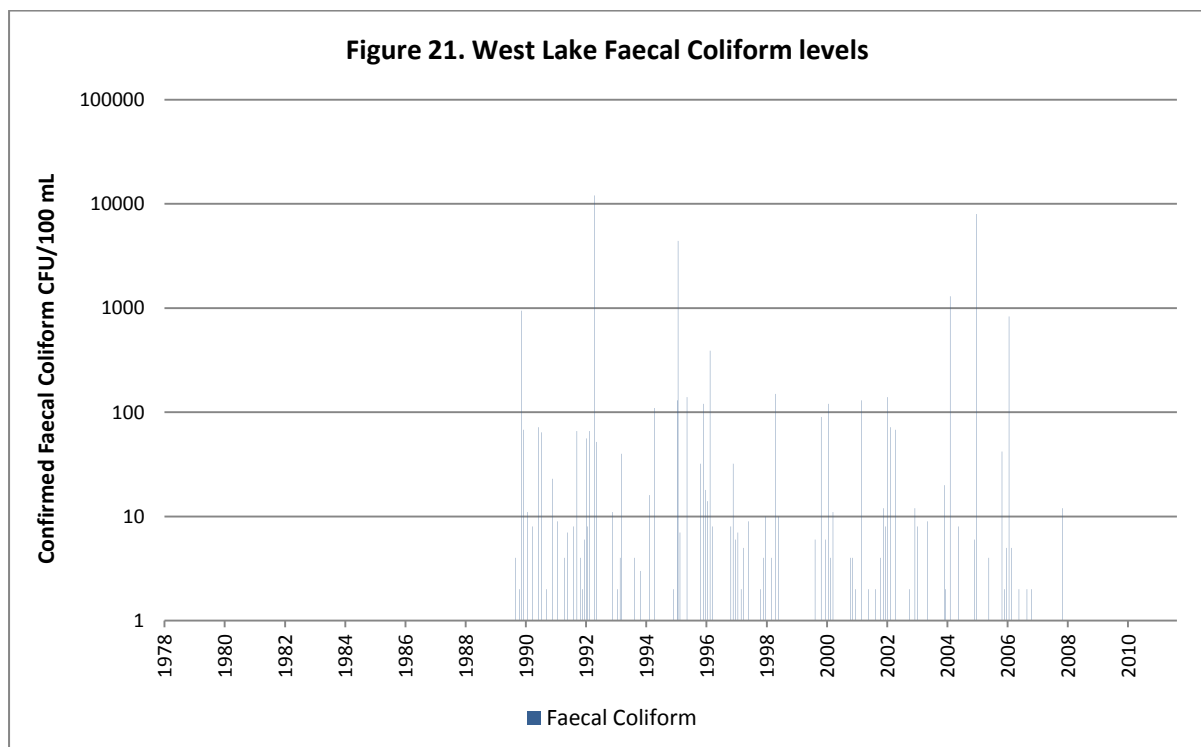
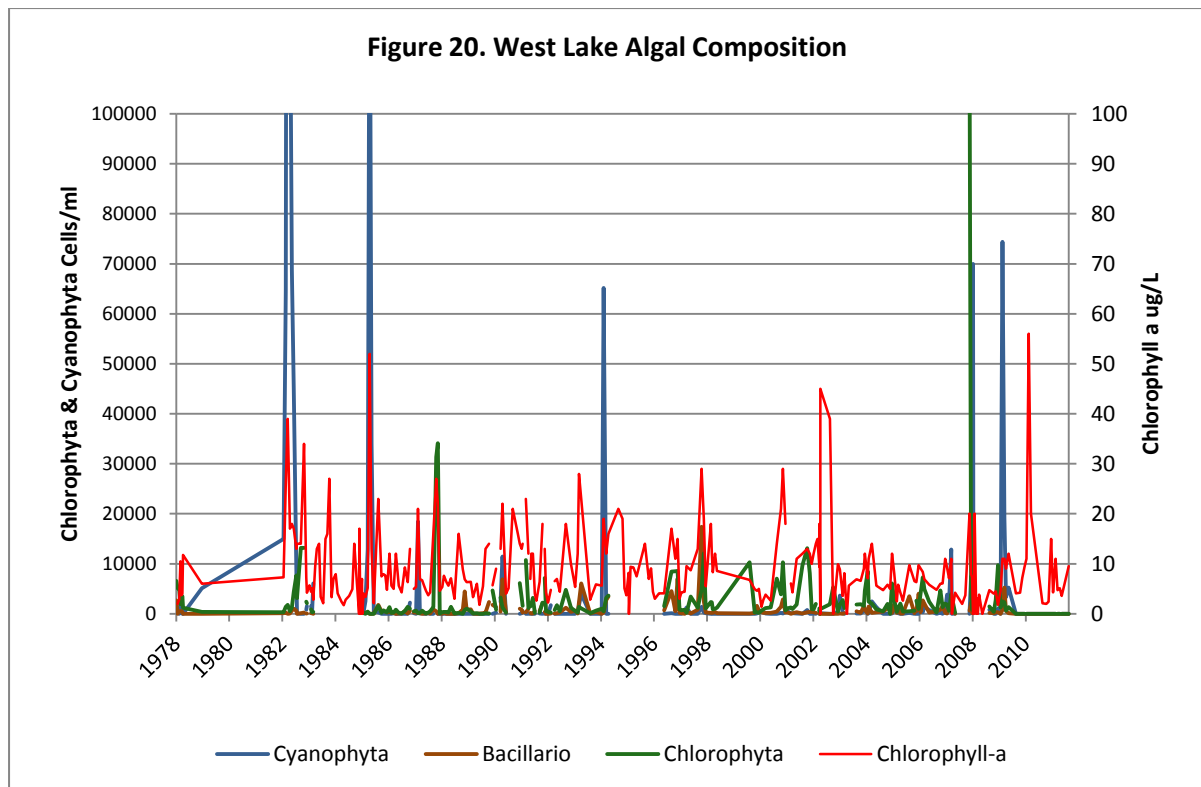
Appendix C. Water Quality Assessment Figures



Appendix C. Water Quality Assessment Figures



Appendix C. Water Quality Assessment Figures



Appendix C. Water Quality Assessment Figures

Figure 22. Yaramundi Reach physical values

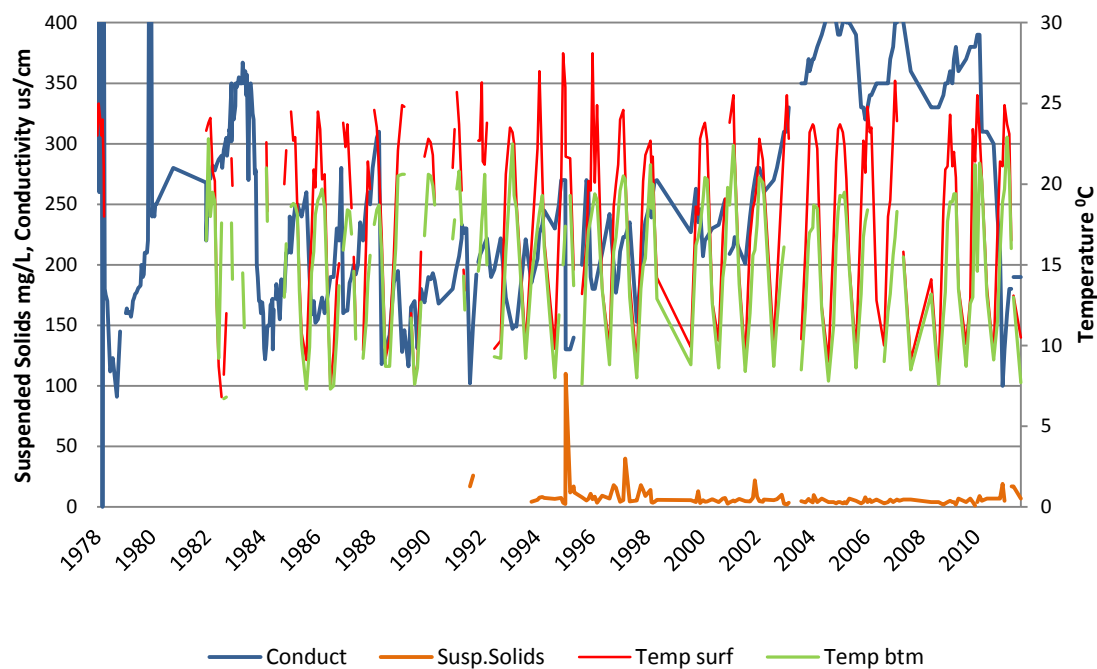
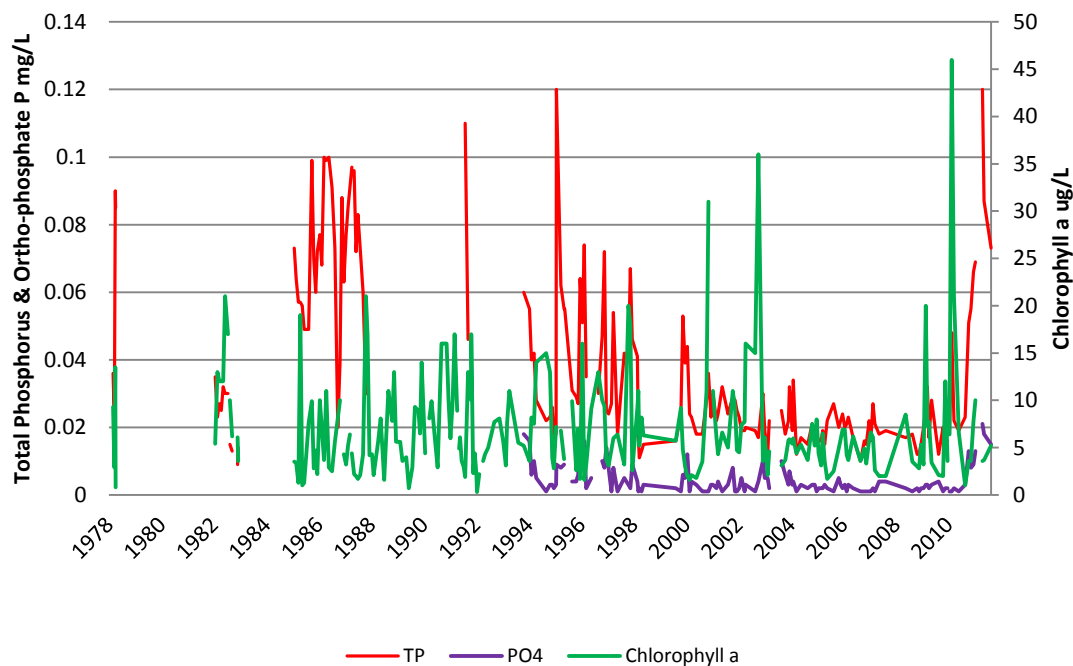


Figure 23. Yaramundi Reach nutrient (phosphorus) values



Appendix C. Water Quality Assessment Figures

Figure 24. Yarramundi Reach nutrients (Nitrogen) values

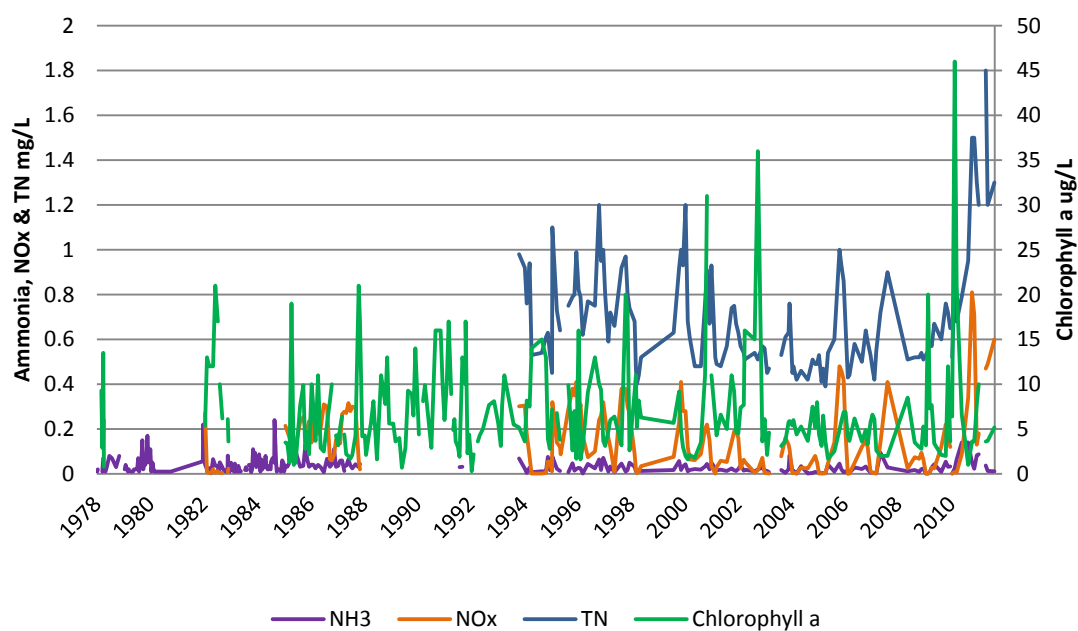
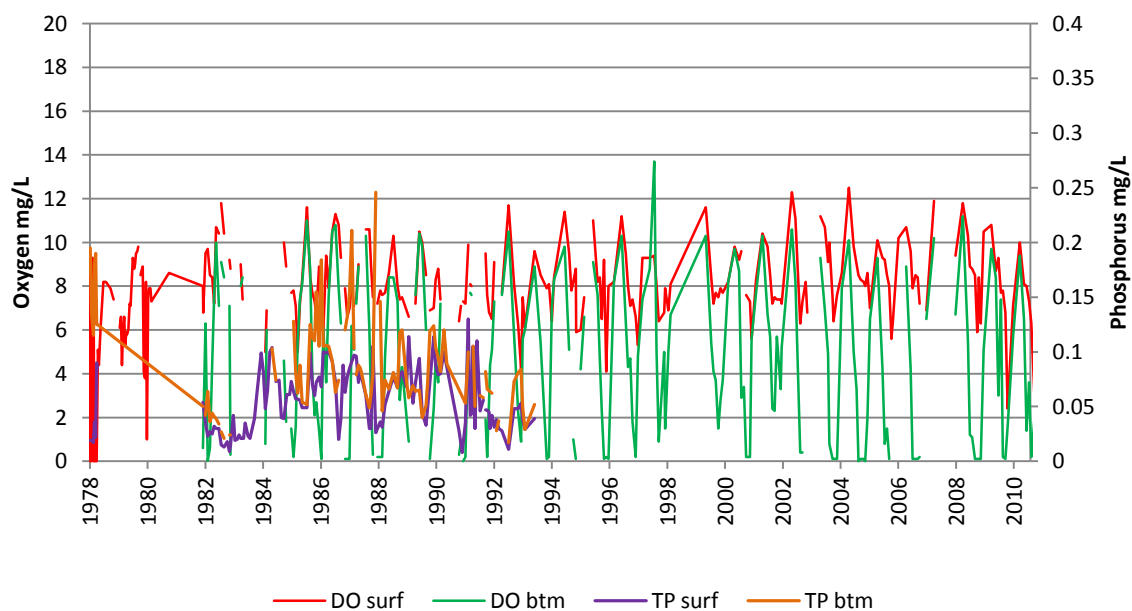


Figure 25. Yarramundi Reach oxidation - reduction (phosphorus)



Appendix C. Water Quality Assessment Figures

Figure 26. Yarramundi Reach oxidation - reduction (ammonia)

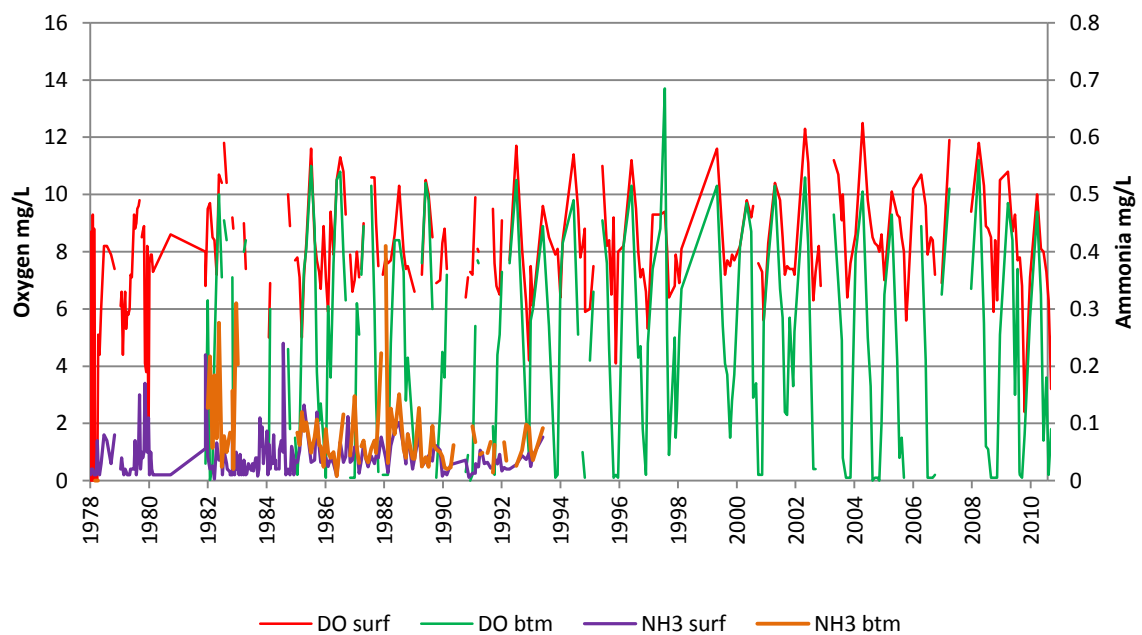
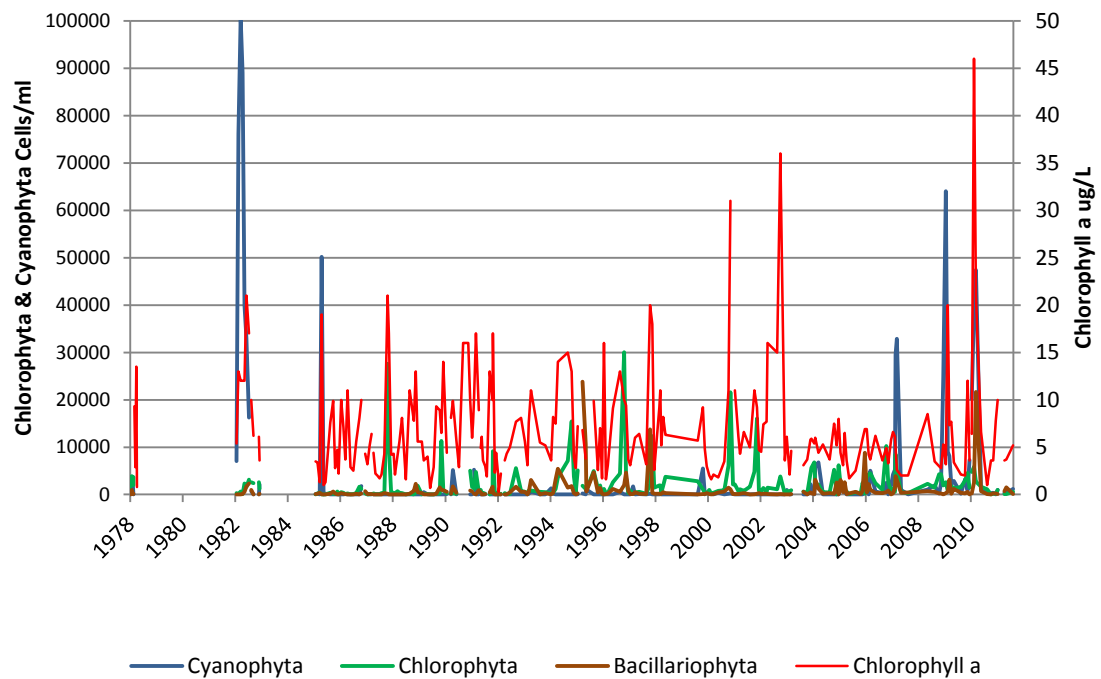
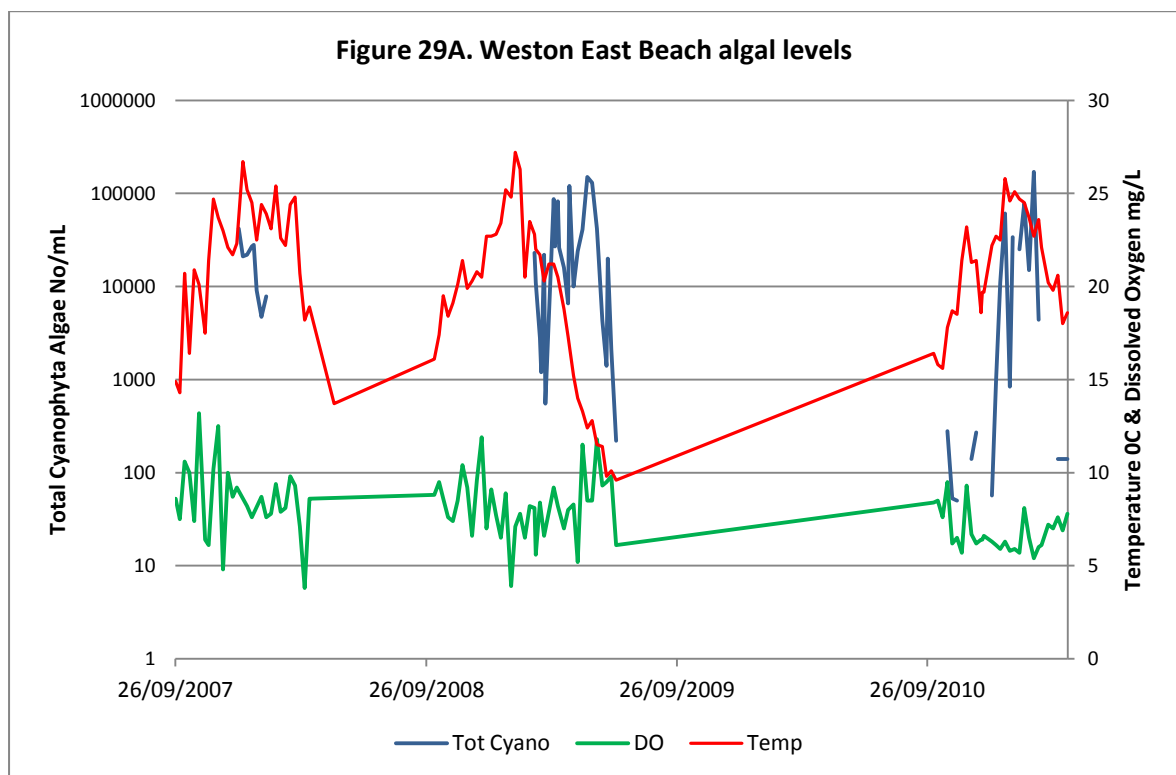
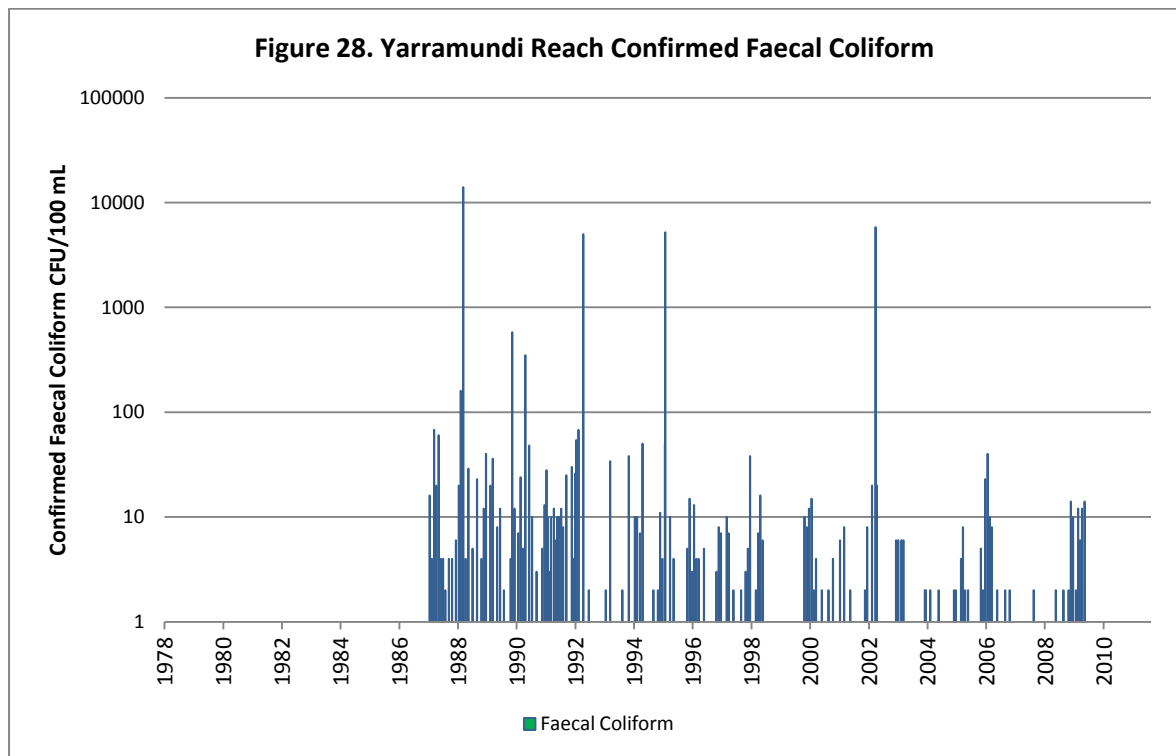


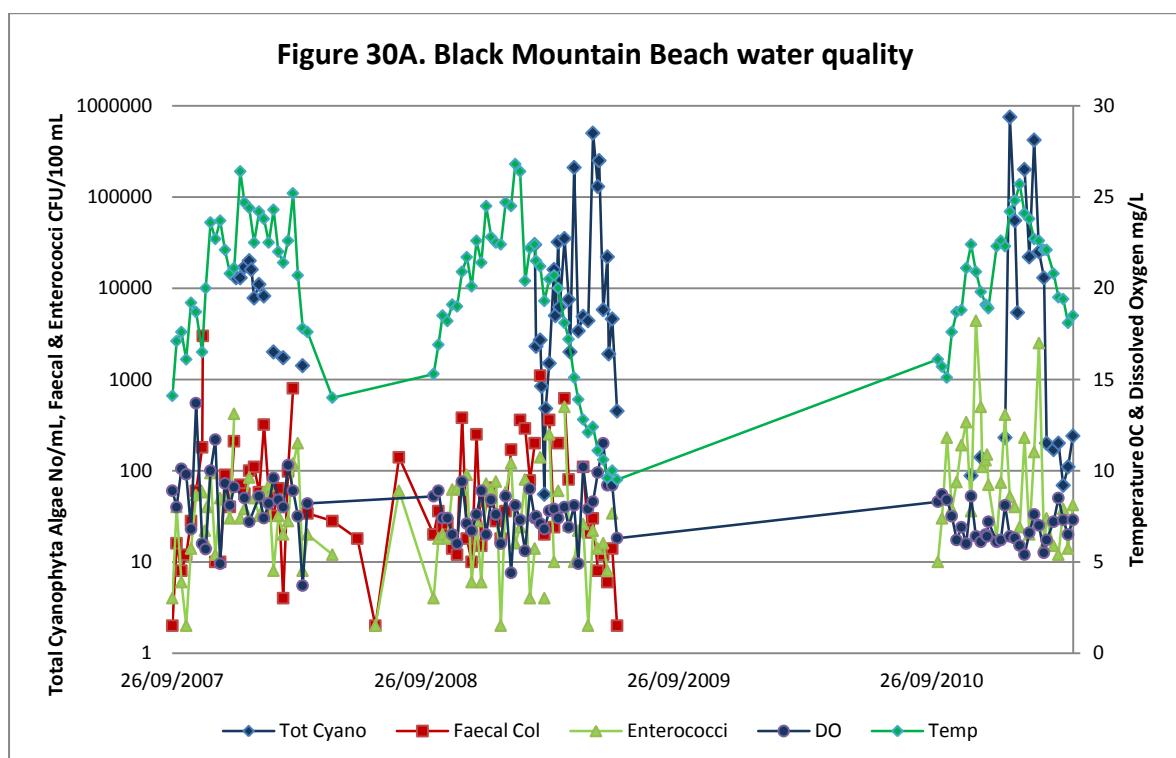
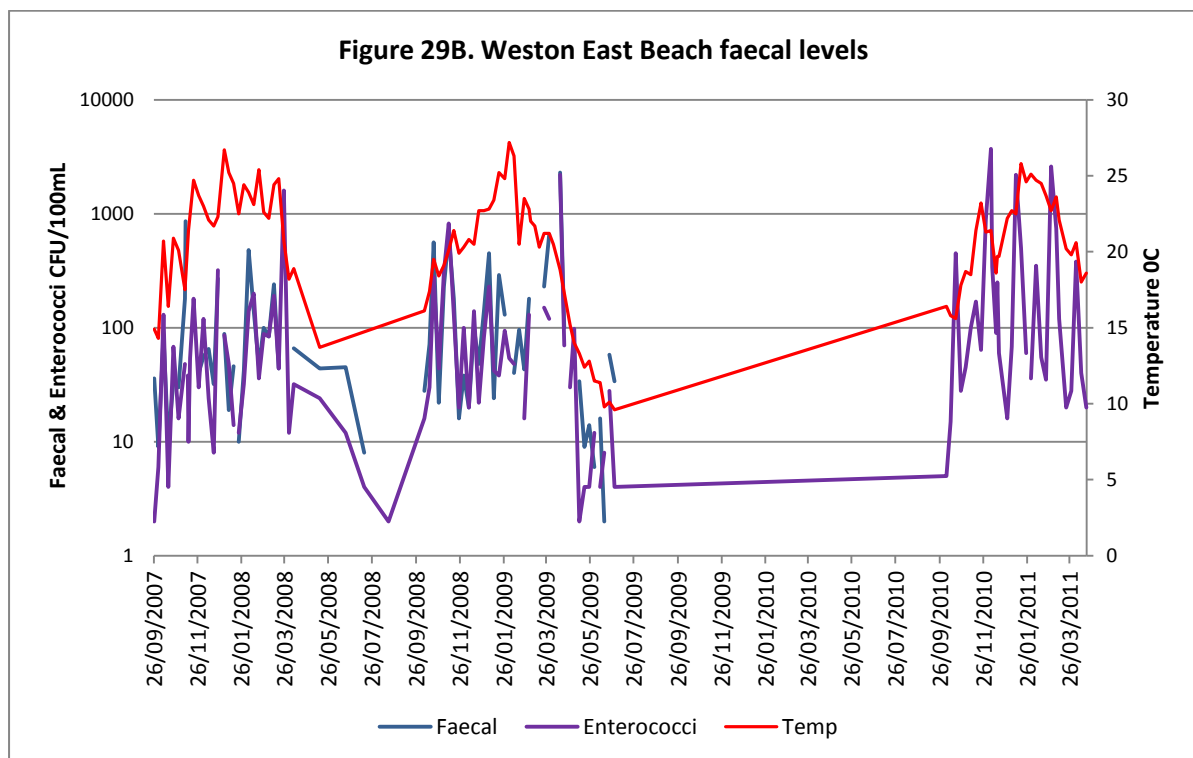
Figure 27. Yarramundi Reach Algal Composition



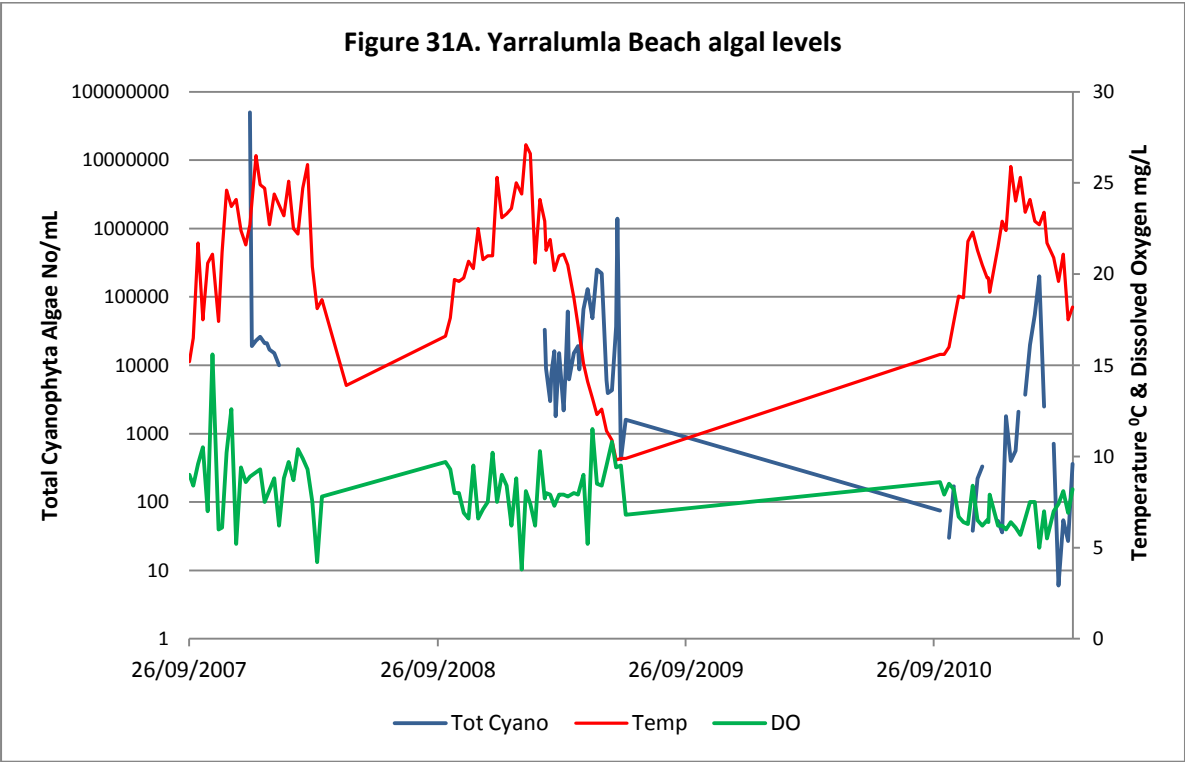
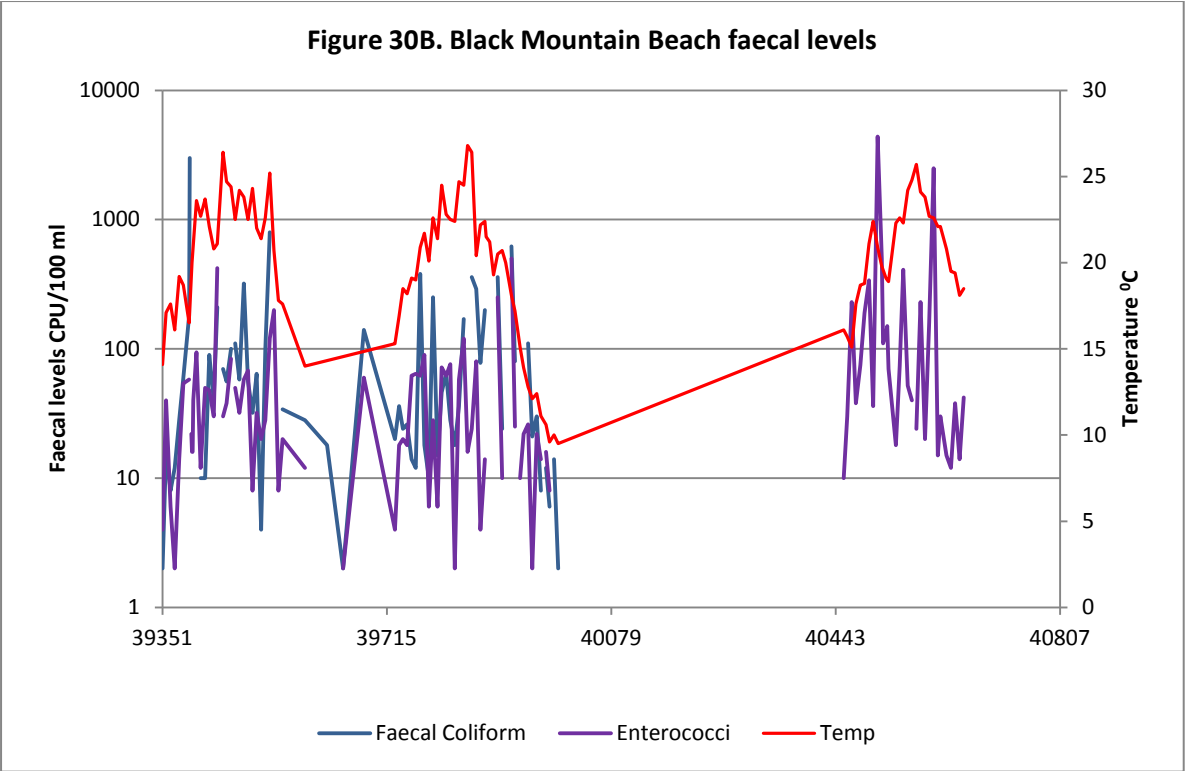
Appendix C. Water Quality Assessment Figures



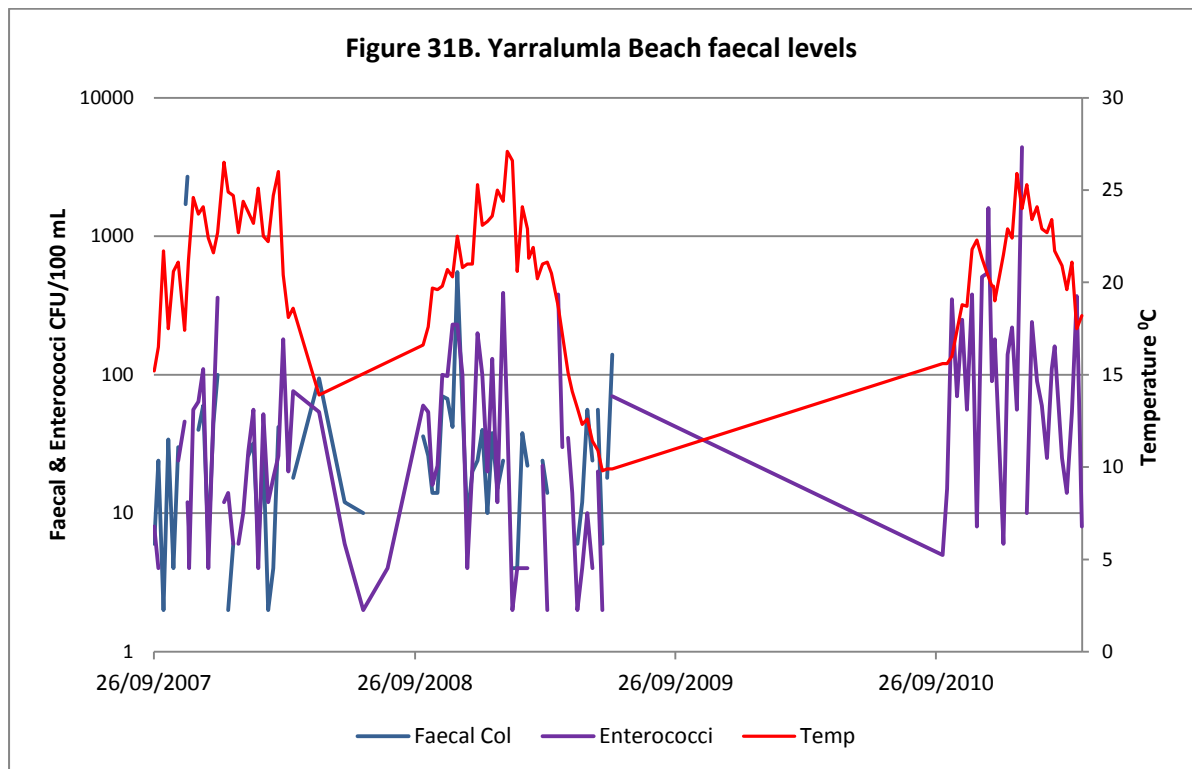
Appendix C. Water Quality Assessment Figures



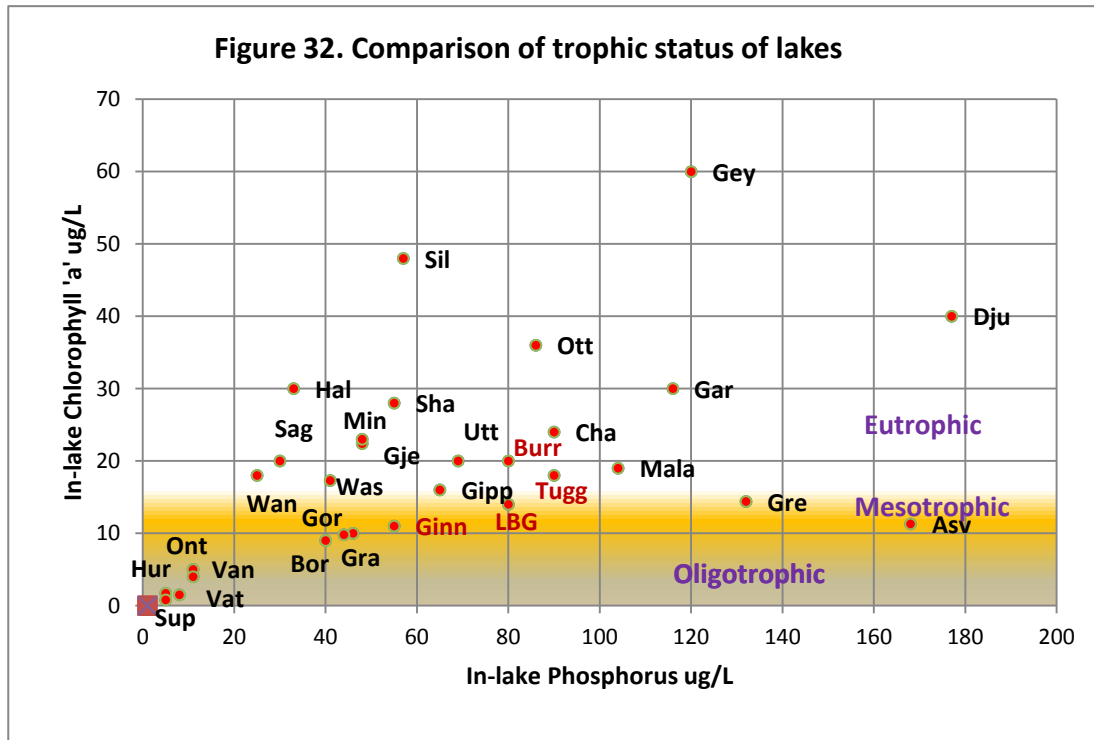
Appendix C. Water Quality Assessment Figures



Appendix C. Water Quality Assessment Figures



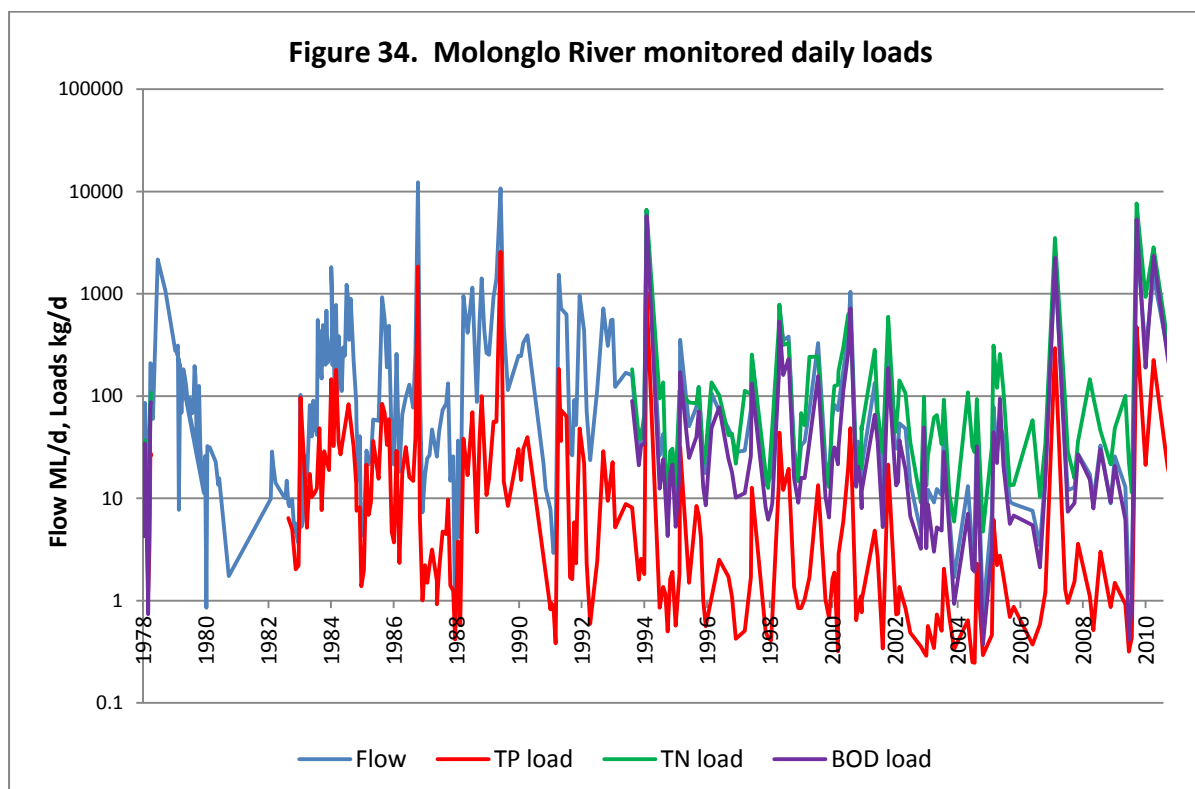
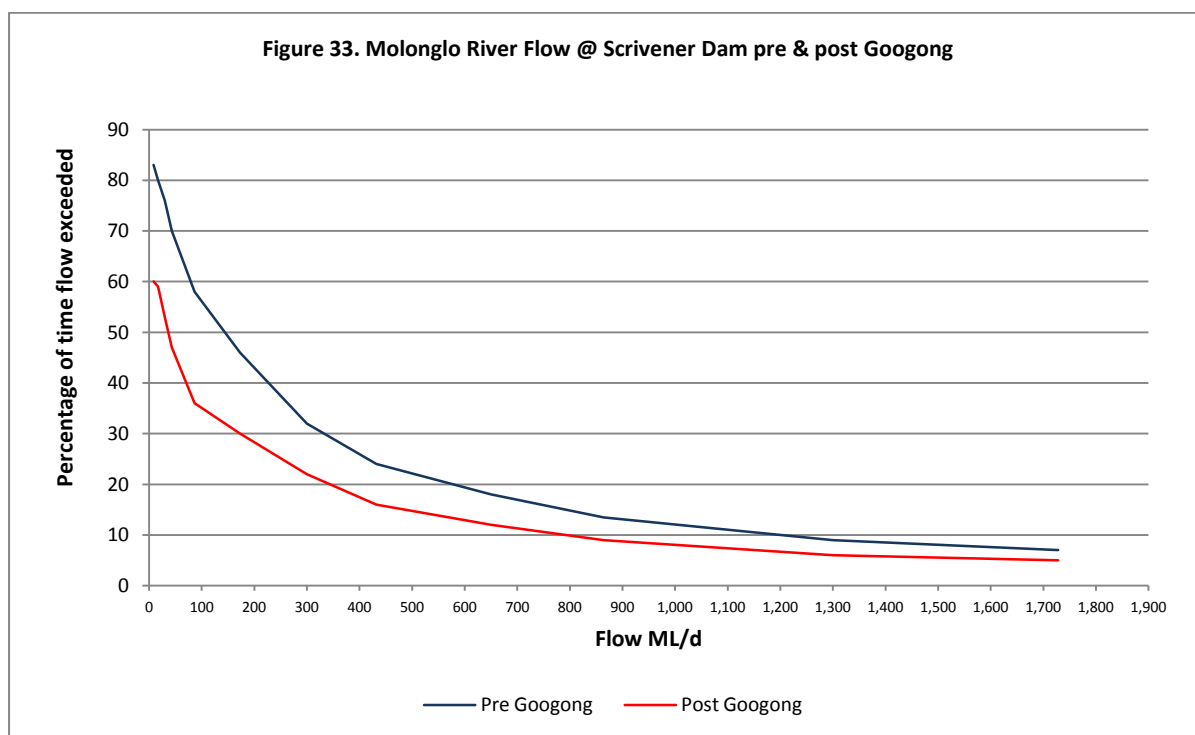
Appendix C. Water Quality Assessment Figures



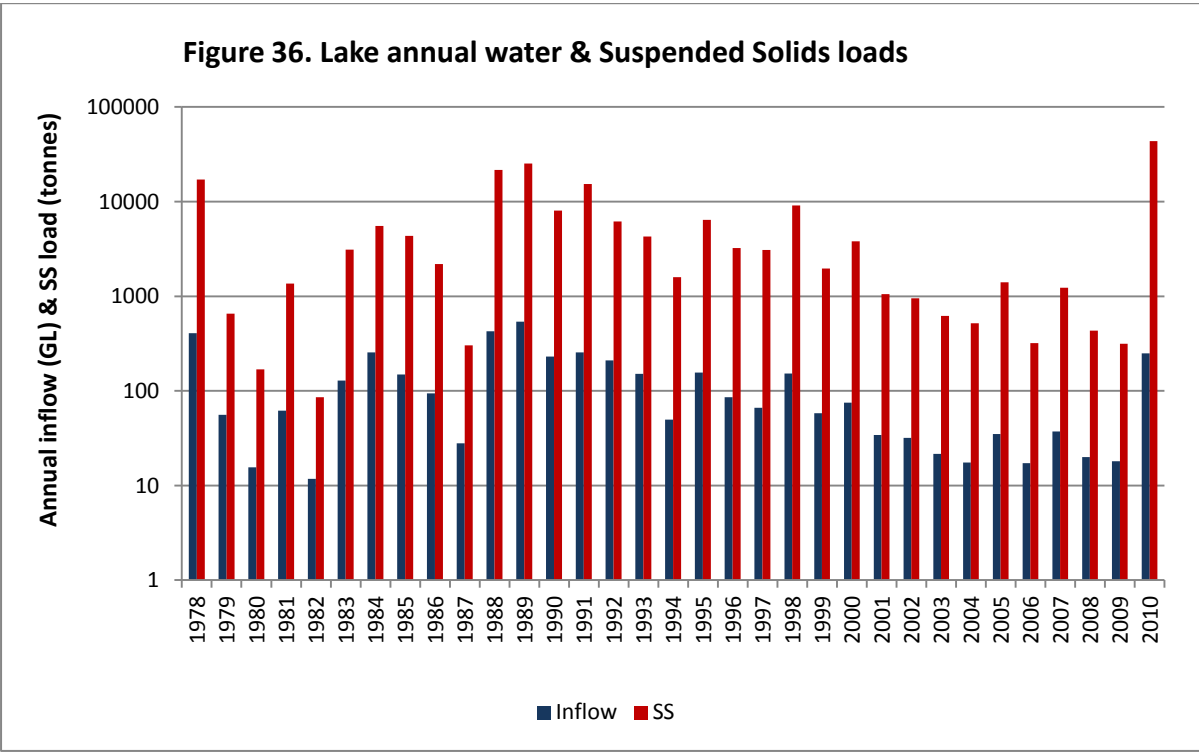
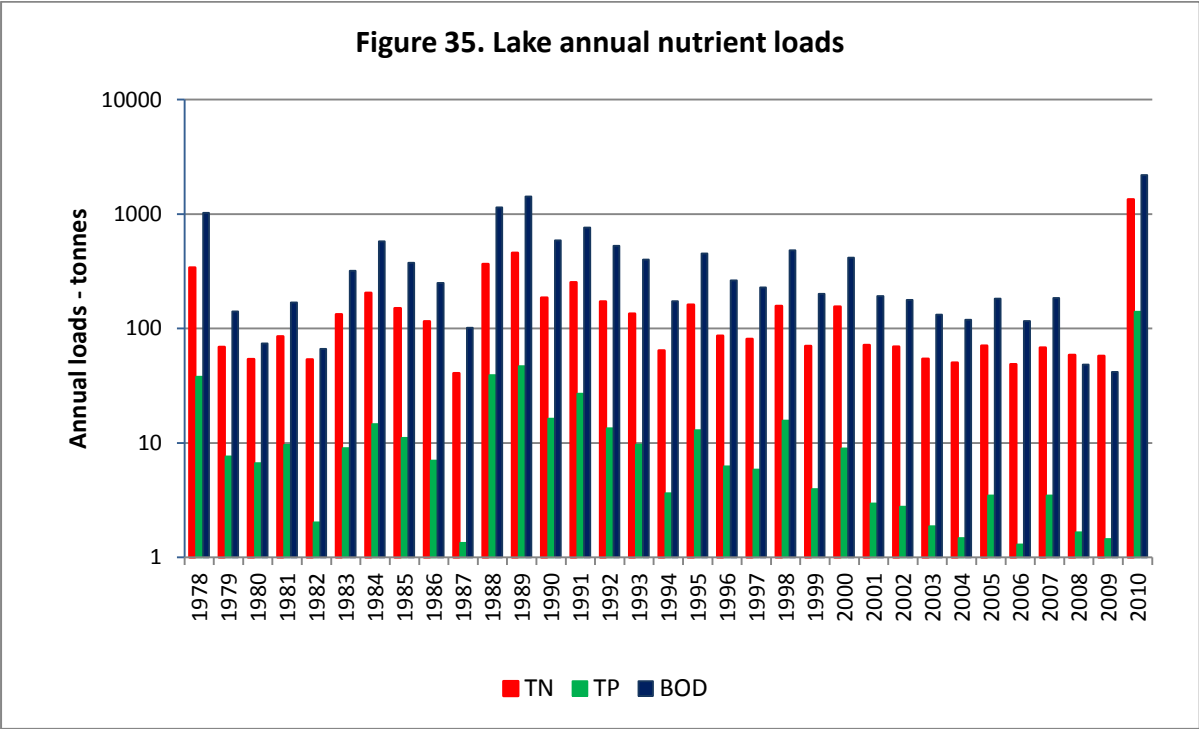
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Bor	Boren	Ott	Otter	Van	Vanern
Con	Conesus	Mala	Malaren Ekoln B	Vat	Vattern
Dju	Djulosjon	Malm	n	Wan	Wanbach Reserv
Gar	Garan	Min	Minnetonka	Was	Washington
Gey	Geysjon	Nor	n	LBG	Lake Burley Griffin
Gje	Gjersjoen	Ont	Ontario	Burr	Burrinjuck Reserv
Gla	Glaningen	Ram	Ramsjon	Cha	Chaffey Reservoir
Gor	Gorvaln Bay	Rin	Ringsjon	Ginn	Ginninderra
Gra	Gravenhurst Bay	Rys	Ryssbysjon	Gips	Gippsland Lakes
Gre	Greifensee	Sag	Saginaw	Mok	Mokoan
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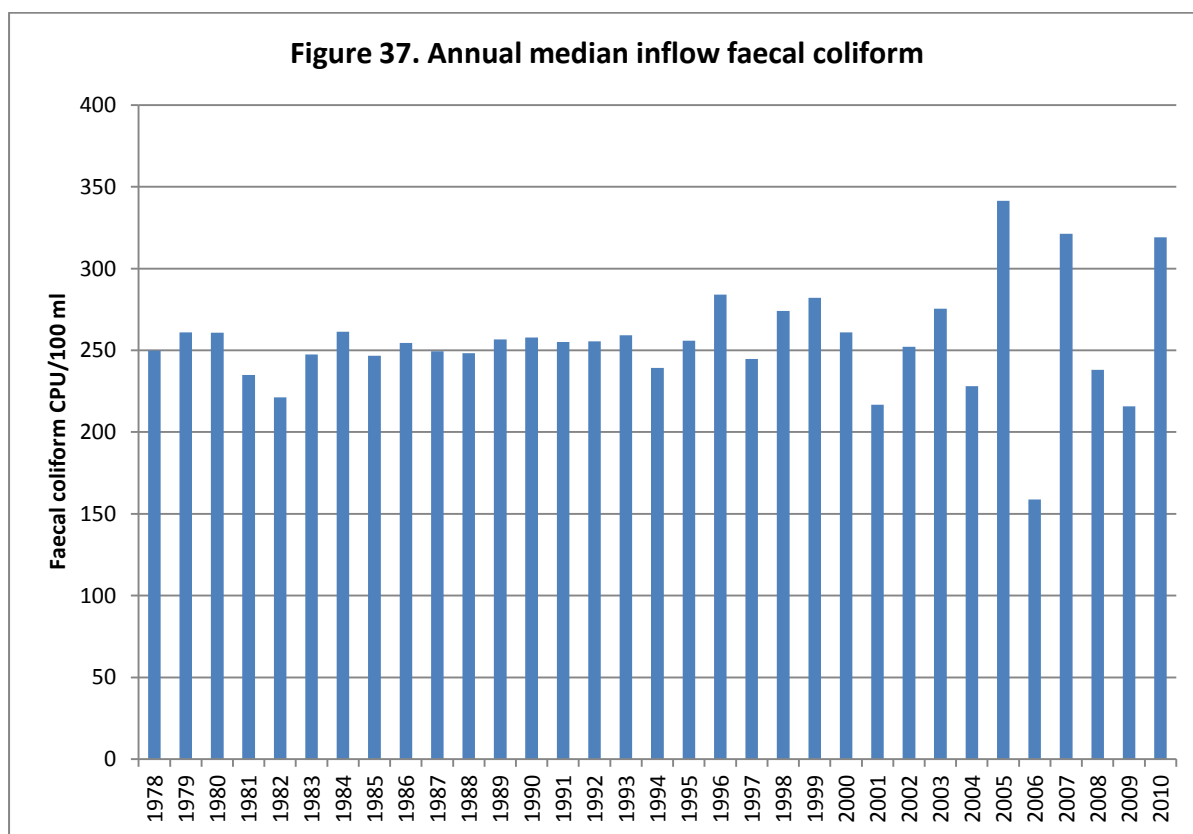
Appendix C. Water Quality Assessment Figures



Appendix D. Water Quality Assessment Figures



Appendix D. Water Quality Assessment Figures



Appendix D. Water Quality Assessment Figures

Figure 38. Lake Burley Griffin TN loads: Relative contribution of sources (Wet Year 1998)

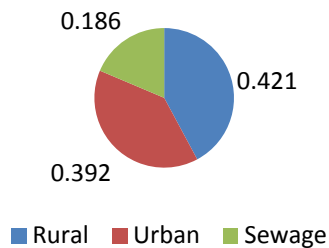


Figure 41. Lake Burley Griffin TN loads: Relative contribution of sources (Dry Year 2006)

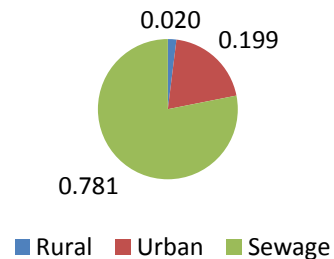


Figure 39. Lake Burley Griffin TP loads: Relative contribution of sources (Wet Year 1998)

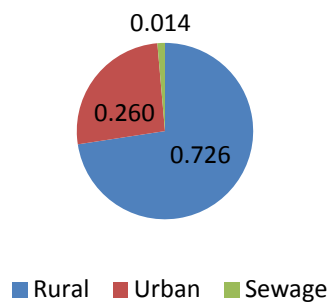


Figure 42. Lake Burley Griffin TP loads: Relative contribution of sources (Dry Year 2006)

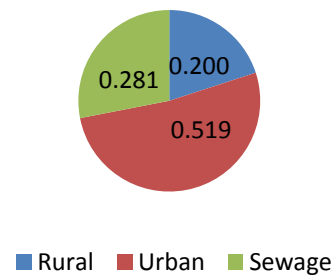


Figure 40. Lake Burley Griffin BOD loads: Relative contribution of sources (Wet Year 1998)

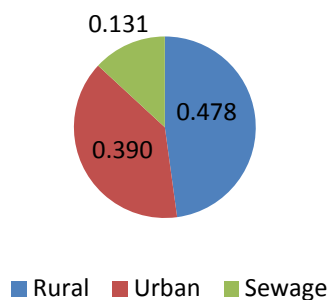
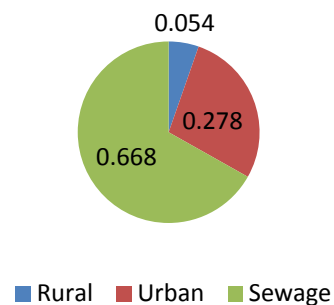


Figure 43. Lake Burley Griffin BOD loads: Relative contribution of sources (Dry Year 2006)



Appendix D. Water Quality Assessment Figures

Figure 44. Lake Burley Griffin SS loads: Relative contribution of sources (Wet Year 1998)

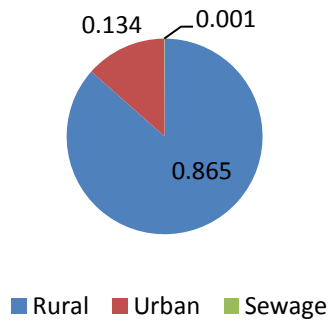


Figure 46. Lake Burley Griffin BOD: Relative contribution of sources. Dry Year (2006) with 2010 levels of Qbn STWks BOD discharge rates

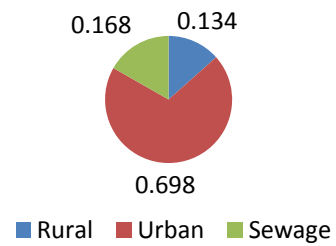
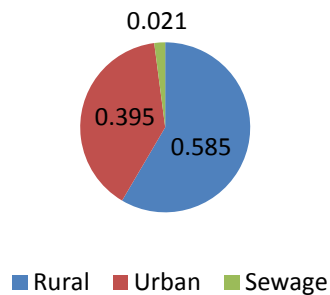
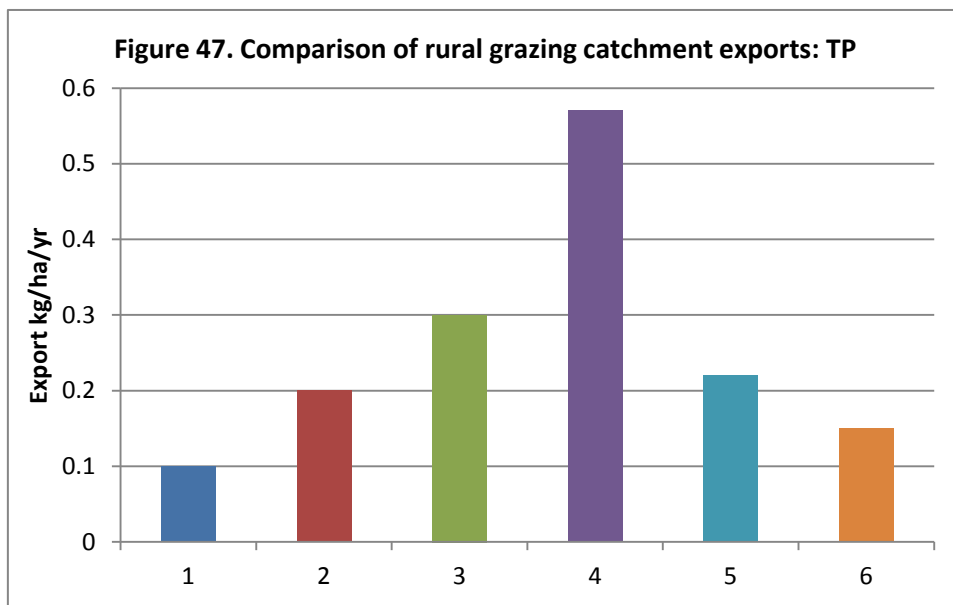


Figure 45. Lake Burley Griffin SS Loads: Relative contribution of sources (Dry Year 2006)

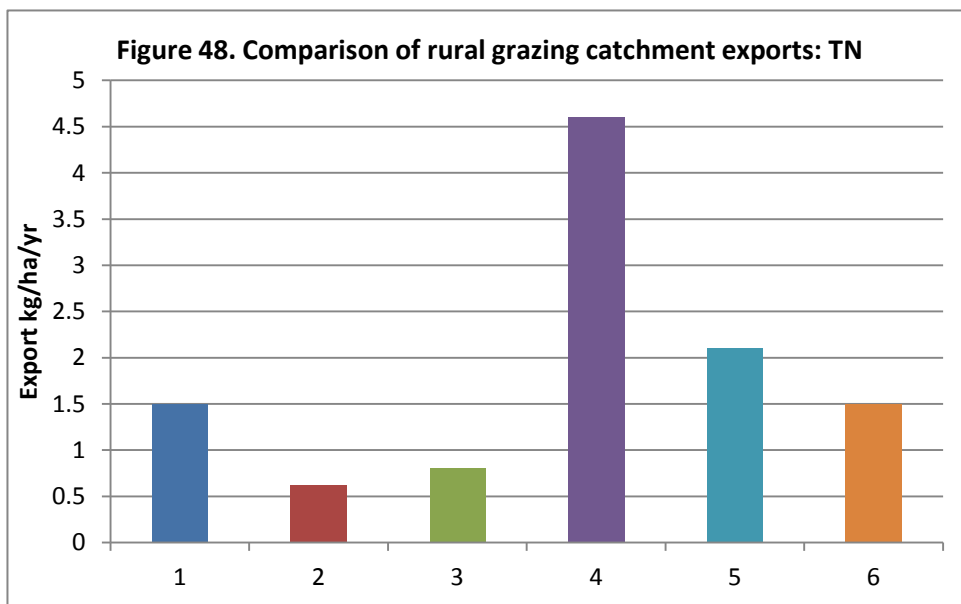


Appendix D. Water Quality Assessment Figures



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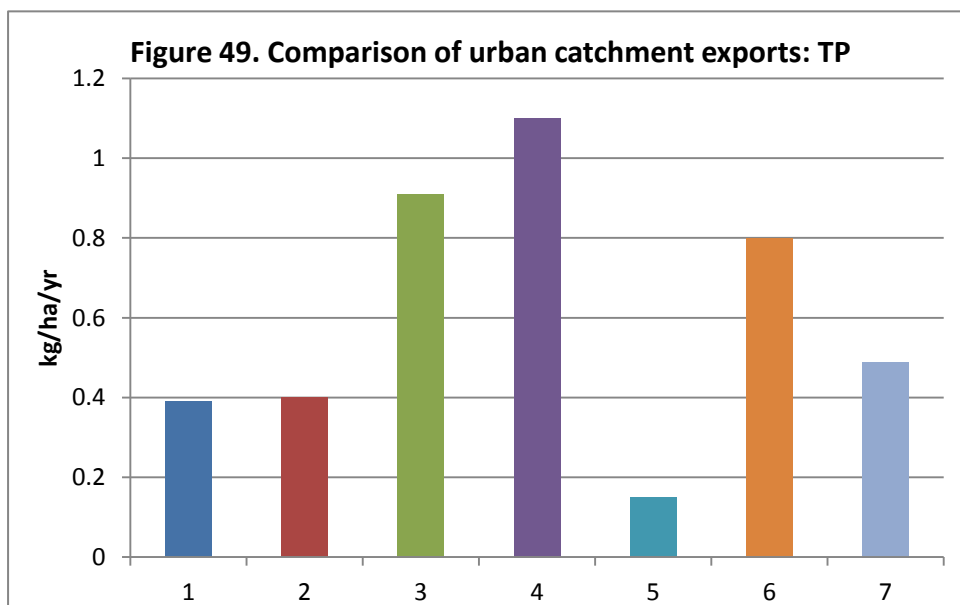
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- 5 Duncan 1999 - international
- Molonglo
- 6 catchment



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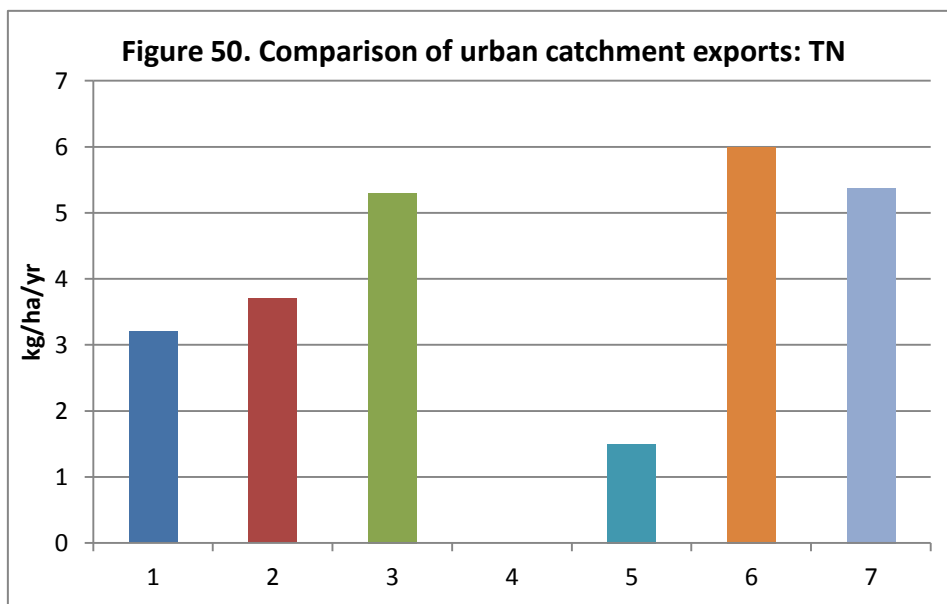
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- 5 Duncan 1999 - international
- Molonglo
- 6 catchment

Appendix D. Water Quality Assessment Figures



Source:

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- 5 to 6 Duncan 1999 - international
- Molonglo
- 7 catchment



Source:

- 1 to 4 Marston et al 1995 - SE Australia
- 5 to 6 Duncan 1999 - international
- Molonglo
- 7 catchment

Appendix D. Water Quality Assessment Figures

