Lake Molonglo water quality study

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Technical Report 2006/35
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THE UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
WATER RESEARCH LABORATORY
together with
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The work reported herein was carried out at the Water Research Laboratory, School of Civil and Environmental Engineering, together with the School of Aerospace, Civil and Mechanical Engineering, Australian Defence Force Academy, both of University of New South Wales, acting on behalf of the client.

EXECUTIVE SUMMARY

A review has been made of potential water quality issues in the planned Lake Molonglo associated with the next ACT major urban development in the Molonglo Valley. The review has been made by a combination of describing mechanisms as represented in the standard lake water literature, reviewing studies of the existing lakes in the Canberra region, supplementing those studies by additional analysis of relevant water quality data, and by simple modelling of the stratification process.

The potential issues are related to the inputs that will come from Lake Burley Griffin, other streams, the new urban development and whatever may be provided by the land to be inundated by the lake creation. By damming a river, what was once a flowing stream becomes a deeper, more quiescent body of water and hence the physics and biochemistry are unavoidably altered. The major effect is related to the stratification that occurs in warmer months when bottom and top water temperatures can differ by over 10 degrees. This stratification reduces the opportunity for mixing. With biodegradable material that will exist in, or be brought into, the lake with inflow, the decomposition that occurs in the deeper water of a stratified lake will reduce oxygen levels, possibly close to zero, and in such conditions potentially harmful products such as methane and hydrogen sulphide can be released.

A considerable quantity of water quality data exists for Canberra’s lakes and streams. A routine monitoring program samples monthly during the warmer months and once in winter. The parameters include temperature and dissolved oxygen measured at intervals through the water column. Other parameters such as nutrients (phosphorous and nitrogen), ammonia, turbidity and algae are sampled by a tube that mixes over a depth of up to 5 metres. Bacteria sampling is usually taken from surface waters. The results of these data are reported annually to convey the health of the lakes which can be compared to standards set by the relevant authorities. This report includes some additional analyses both with the data and some modelling of the stratification process to elucidate features not covered in the routine reporting.

In addition to the routine data monitoring, other targeted studies have been conducted. Notable among these are a Lake Burley Griffin Water Quality Plan by National Capital Authority and detailed studies of two of Canberra’s lakes by Peter Cullen and colleagues.

From these studies we have drawn the following conclusions:

The planned lake will stratify during the warmer months. The stratification will result in low oxygen concentration in near-bed levels which in turn will lead to release of methane and hydrogen sulphide as well as metals such as manganese and iron. These effects will be seen most clearly near the bed but from the evidence of other lakes, may not be seen in the near surface waters. The occurrence of algal blooms (caused by high nutrient levels) is not expected to be any worse than the existing lakes and may even be better as one of the major water sources (Scrivener Dam) has had the benefit of polishing during passage through Lake Burley Griffin, as evidenced by the lower phosphorous levels seen in Molonglo River at Coppins Crossing (better, that is, except for Lake Burley Griffin's final sampling site at Scrivener Dam). Nitrogen levels at Coppins Crossing are lower than all monitored lake sites.

While there is evidence for improved nutrient levels and hence expected lower incidence of algal blooms, the same cannot be said for bacteria as shown by the faecal coliform data (a pollutant indicative of possible human origin but also produced by other warm-blooded animals). While values are clearly improved in passage thought the lakes, the values at Coppins Crossing are generally higher than those in the existing lakes (except for Lake Tuggeranong). Whether these slightly higher values are due to the positioning of Lake Burley Griffin's outlet (near-bed) or due to rural sources downstream of Scrivener Dam or even urban sources from Yarralumla and Weston Creek is yet to be determined.

Given the above comments, there may be no need for any water quality control measures beyond the expected high level of stormwater quality management in the new development. If however there was seen to be need to break down or remove the stratification in warm months there are established measures that have had success in other lakes and reservoirs. Such devices typically employ a mechanical or air-driven jet of water to induce circulation designed to bring bottom waters to the surface to facilitate aeration. Our estimate of an air-curtain device is approximately $50,000 for construction and annual costs of about $25,000. Corresponding costs for a mechanical draft-tube device would be approximately $130,000 for construction and $9,000 per annum for ongoing costs. Design would need to be carried out carefully as such devices have met with mixed success in Australia.

A reasonable strategy would be to monitor any future lake carefully, leaving open the option of (and hence planning for possible location etc) installing water quality control device should the evidence indicate the necessity.

The suggestion that effluent from Lower Molonglo Water Quality Control Centre be pumped to the lake should be treated with caution. The water quality values from the effluent are close to or worse than that experienced in the existing lakes (except for faecal coliform bacteria which are considerably better). Temperatures are higher than lake values in winter and hence the effluent would not mix easily but tend to remain as a surface layer. However the effluent quality is not so poor that such an option could be completely discarded. The lake will have an assimilative capacity that could improve the wastewater before it was released to Molonglo River. There are construction and operational costs associated with this option.

Existing trees along the river bank should be cut close to ground level and removed prior to lake filling in order to reduce hazards and biodegradable material.

The lake configuration we have studied is a single lake with water level at a relatively high level. There are many other configurations incorporating a shallower lake or even multiple lakes. Many of our conclusions would apply to such alternate designs. However there would be some differences, mainly in the reduced (but not eliminated) time where the lake would be stratified. Travel times through the lake(s) however would be reduced and the efficacy of the lake in improving water quality may also be reduced.

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GLOSSARY

ACTEWAGL	ACT's joint venture water, power and gas company - acronym derives from ACT Electricity and Water/Australian Gas Light Company
ACTPLA	ACT Planning and Land Authority
ANZECC	Australia and New Zealand Environment and Conservation Council (former)
BOM	Bureau of Meteorology
cfu	Colony forming units – measure of bacteria population based on the laboratory technique
DHC	Department of Housing and Construction (former)
DO	Dissolved oxygen
LMWQCC	Lake Molonglo Water Quality Control Centre
NCA	National Capital Authority
N:P	Ratio of nitrogen to phosphorus
ntu	Nephelometric Turbidity Units, measure of water turbidity based on the instrument.
TN	Total nitrogen
TP	Total phosphorus
USEPA	United States Environmental Protection Agency

1. INTRODUCTION

The following introduction is adapted from the client brief of August 2006.

1.1 Background

The Canberra Spatial Plan, released in March 2004, presents the ACT Government's preferred direction for accommodating Canberra's future growth over the next 30 years (ACTPLA, 2006a). The Canberra Spatial Plan identifies the Molonglo Valley as a potential greenfield development area. Prior to this development occurring, extensive planning, engineering and environmental studies are required to investigate the extent and viability of suitable developable land. Preliminary plans for the Molonglo Valley development were released for public comment in 2005 (ACTPLA, 2006b). The location is given in Figure 1.

A central feature of the Molonglo Valley development area is a proposed lake[1] formed by the impoundment of the Molonglo River by a dam about 3 km downstream of Coppins Crossing. The lake would have a capacity of approximately 17 GL, a surface area of around 160 hectares and a maximum depth of approximately 24 m. This is one of several options explored on behalf of ACT Planning and Land Authority (Cardno Young, 2006a). The lake is expected to deliver significant water quality benefits downstream through the treatment of runoff from urban areas upstream. The proposed size and depth of the lake does however create the potential for unwanted biological, chemical and physical processes. These processes may include algal and bacterial growth (blooms), stratification and oxygen depletion of the water. The extent of the proposed lake is shown in Figure 2.

1.2 Project Description

The objective of the study is to undertake an investigation of the likely water quality issues associated with the proposed new lake on the Molonglo River downstream of Scrivener Dam. The investigation is to include modelling and analysis to support the investigation findings and include methods to address the water quality issues identified.

The scope of the work is to include, but not be limited to, the following activities:

- Collection of additional relevant data on the flows and water quality in the Molonglo River, the local climatic conditions and the bathymetry of the proposed lake. ACTPLA

[1] Throughout this report we will refer to "Lake Molonglo" as though it will exist. We do not mean to pre-empt the decision about whether the development, let alone the proposed lake will in fact eventuate.

will provide data it has available on flows in the Molonglo River, water quality data and, digital and hard copy plans of the proposed lake including contours.

- Review of previous studies related to similar lakes in the area including those for Lake Burley Griffin and possibly also the water supply reservoirs managed by ACTEW Corporation.
- Predictive modelling of the lake under historical flow and climatic conditions or synthesised flow and climatic conditions as appropriate. One dimensional hydrodynamic modelling would be favourably considered. This modelling would aim to predict the likelihood and degree of stratification and likely consequences of this on dissolved oxygen, nutrient and metal concentrations in the water column.
- Provide an interpretation and explanation of the results from the modelling or other predictive calculations outlining the likelihood and consequences of water quality problems occurring and what their causes are.
- A discussion of related issues, possibly including; temperature profiles, oxygen profiles, algal and bacterial blooms, densities, action of winds on the lake, conditions during calm warm weather, seasonality of water quality issues and lake design issues.
- Outline solutions to address the possible problems including those related to the use of various destratification systems, lake design and sizing. Specifically, the effectiveness and zone of influence of destratification systems is to be estimated.
- Provide an order of costs on the solutions suggested and a recommendation on a preferred option.
- Recommendations on further investigations or monitoring required to identify design constraints or opportunities.

2. POTENTIAL WATER QUALITY ISSUES

The client has supplied a good summary of the processes influencing lake water quality. Here we expand on that summary and clarify some issues based in part on our experience with other Australian lakes and reservoirs.

Water quality depends on the physical, chemical and biological processes within the water body as influenced by interactions with the boundaries – the bed, the surface and stream/drain inputs and outlets.

2.1 Stratification

In lakes there is a large difference between the horizontal and vertical physics. The reason for this is two-fold – the depth is typically much less than the horizontal extent, and there is a tendency for natural waters to stratify, especially in summer. The reason for the latter is that at the water surface there is a ready exchange of thermal energy so that the surface waters follow air temperatures relatively closely. Once a warm (less dense) layer has been created it forms a very stable structure so that energy is required to break it down, whether that be from horizontal flows, wind stirring, wave breaking (including internal wave breaking at density interfaces), convection or by artificial forcing. The classical vertical temperature structure is a top mixed layer of uniform temperature (the epilimnion) under which is a steep temperature gradient (the thermocline) that merges with a bottom layer of constant temperature (the hypolimnion). It can be shown (e.g. Miller *et al*. 2003) that the region's lakes only roughly follow this classical structure although they are usually stratified over summer.

The classic texts (e.g. Chapra, 1997, Lerman, 1978) describe the autumn breakdown of the stratification as 'overturning' although this is a misleading term for temperate lakes as it implies a rapid destruction of the thermocline. In fact, the process is more a diffusion process as the epilimnion deepens with the temperature keeping pace with the cooling surface. Over winter the thermocline barely exists and there is almost complete mixing through the water column. With spring heating the thermocline is re-established, gradually diffusing down through the water column. The difference between summer and winter thermal profiles has potential to affect water quality.

Note this discussion refers to temperature structure. The existence of stratified or fully mixed temperature profiles will be reflected to a certain extent in other parameters, however this may not always be the case. There may for example be a phase lag between temperature and other parameters so that at any time the water column could be fully mixed in temperature but still have a non-uniform dissolved oxygen (or other parameter) profile.

If the water column or lake bed has no biodegradable material, it is described as 'oligotrophic' with little biological activity and little change in dissolved oxygen with depth, no matter what the season. On the other hand, as is likely to be the case for Lake Molonglo, there is sufficient biodegradable material, it is described as 'eutrophic' and, while in winter (fully-mixed condition) the profiles of dissolved oxygen and other constituents are uniform, in summer it is a very different story. If the bed contains biodegradable material and the lake is stratified, then dissolved oxygen consumed in the decomposition process is not readily replaced as the stratification drastically inhibits vertical diffusion of any constituent including oxygen. If the oxygen concentration is low enough, the processes that then take place are anaerobic and the products include some potentially harmful substances such as methane and hydrogen sulphide.

2.2 Algal Production

If the water column or sediments contain nutrients such as phosphorus, nitrogen and silicon compounds (invariably present in humus), then phytoplankton growth is enhanced. Of the nutrients, the most studied are the phosphorus elements, as P is usually the element that controls aquatic plant growth. Excessive levels of phosphorus can result in population explosions of blue-green algae, which is an environmental hazard in several ways – algal blooms reduce light penetration, the algae are often toxic to fish and other organisms (including humans), and decaying algae adds to the biomass and hence enhances eutrophication.

2.3 Other Issues

Other environmental hazards include bacteria originating from wastewater disposal as well as urban, parkland and rural runoff, toxic substances such as heavy metals, pesticides and ammonia, release of manganese and iron from sediment, and suspended solids.

The importance of these issues depends on what use is to be made of the water. In line with existing lakes in Canberra we assume that in addition to providing a viewscape and water's edge amenity, the lake would be used for recreation (possibly including swimming, boating and fishing, i.e. contact and non-contact) and irrigation of local parkland. There is also a requirement to provide water suitable to release back to Lower Molonglo River for environmental and other downstream uses. If lake water were to be used as a supplement for water supply, we assume further treatment would be required, so we do not consider such use in this report.

3. REVIEW OF EXISTING DATA AND OTHER RELEVANT STUDIES

3.1 Introduction

There are several existing data sets that provide a basis for estimating the behaviour of the planned lake. These include routinely-collected data from existing lakes and reservoirs within the ACT as well as from the Molonglo River. Many studies have been carried out using these data sets and other project-specific data. Annual reports are provided by the authorities that summarise water quality within ACT lakes and rivers. We make use of these reports and studies and amplify by our own analysis of the data to draw conclusions regarding water quality in Lake Molonglo. Where necessary we also draw on experience from other lakes and reservoirs elsewhere in Australia.

3.2 Canberra's Artificial Lakes

The three existing major lakes in Canberra are Lake Burley Griffin, Lake Ginninderra and Lake Tuggeranong. The extent to which Lake Molonglo will exhibit water quality similar to these lakes depends on the nature of the catchment (urban, rural, natural), the characteristics of the water sources (which in turn depend on the catchment), exposure to environmental factors such as wind and air temperature, and physical dimensions. Table 1 shows the essential features of the existing lakes compared to the proposed lake. We leave the implications of these parameters until later in the report.

Table 1
Comparison Lakes (various sources, all values approximate)

Lake	Max Depth (m)	Mean Depth (m)	Volume (GL)	Surface Area (Ha)	Catchment Area (Ha)
Molonglo	24	6.8	17	160	
Burley Griffin	21	4.7	33	664	211000
Ginninderra	8	3.5	3.7	120	9800
Tuggeranong	10	2.0	2.6	60	6400

3.3 Thermal Stratification

Very few of the existing studies of Canberra's Lakes have explicitly examined temperature profile data to explore stratification. To address this issue we have been supplied profile data by Ecowise Environmental for several locations with Lake Burley Griffin, Lake Ginninderra and Lake Tuggeranong. The two main parameters monitored at several depths are water temperature and dissolved oxygen. Other parameters collected less frequently are pH and conductivity. These data are collected monthly over summer and less frequently over winter. The data span the years 1993 to 2006 (with a gap in the Tuggeranong/Ginninderra data between winter 1997 and winter 2005 when another agency was responsible for sampling – this data will be sought and incorporated if necessary). Many other parameters (bacteria, nutrients, algae etc) are measured either at the surface or averaged over a depth (tube sampling).

In Figures 3, 4 and 5 the seasonal profiles of temperature at the deepest locations in the three Canberra lakes are shown. The raw data has not been averaged to allow some distinct features to be displayed. The axis labels omitted for clarity are temperature on the x-axis (always scaled to span 15 degrees C) and depth from surface on the y-axis.

There are several features common to all three sites. The lakes are generally stratified from October to March. Conversely they are generally fully mixed from April to August. The summer profile does not always match the classic epilimnion-thermocline-hypolimnion shape as the thermocline often extends to the surface and sometimes over the whole depth. The data is not collected frequently enough to display the processes of thermocline destabilisation and the spring re-establishment of stratification, however the more comprehensive data set from Bendora Reservoir (Figure 6, from Miller *et al.* 2003) shows the thermocline starting at the surface between August and September and diffusing down through the water column over summer. Cooling starts between February and March, again diffusing down from the surface, with full water column mixing not established until June.

All of the data sets are at the deepest location in each lake. However we are also interested in how these profiles are reflected in other shallower parts of the lake. To this end we co-plot profiles from several sites within Lake Burley Griffin, choosing sample dates in summer and winter (Figure 7). The sites in order of increasing depth are LBG529 - East Basin off Bowen Park, LBG530 - Central Basin midstream, LBG504 - West Lake and LBG507 - Scrivener Dam. A plan showing the location of these sites is available in Appendix B of National Capital Authority’s Lake Burley Griffin Water Quality Management Plan (NCA, 2006).

These plots show that if the lake is stratified at Scrivener Dam, then it is stratified throughout, at least in Central Basin and West Lake. While not shown here, the very shallow (<2m) East Basin is also frequently seen to be stratified in summer, although it should be noted that sampling is carried out in daytime, and the temperature gradient may fluctuate from stratified to unstratified on a diurnal cycle. In a one-day study of the diurnal mixed layer in Lake Wellington (WA), Imberger (1985) found the mixed layer varying between 0 and 5 m and the surface temperature ranging from 22.2 to 23.9 degrees.

In winter we see that if the lake is fully mixed at Scrivener Dam, it is also fully mixed elsewhere. The feature of increasing temperature from upstream to downstream (coinciding with increasing depth) is a persistent occurrence that we have checked for the May data (10 years), whether the thermocline is present or (as here) not. We have not explored the reason for this – one possibility being related to time of day for sampling (i.e. the most common sequence for collecting samples is from upstream to downstream, S. Hure, Ecowise Environmental pers. comm.).

3.4 Dissolved Oxygen Stratification

A lake management plan published on the web site of National Capital Authority (NCA, 2006) examined seasonal averaged dissolved oxygen (DO) profiles for Lake Burley Griffin. They found values at a maximum during the late winter months and minimum in the late summer months – related to thermal stratification. They found for the two deeper sites (West Lake and Scrivener Dam) low DO levels between 0 and 10 mg/l for the near-bottom waters.

To check for detail not provided by the seasonal averages we plot the available DO profiles for the Scrivener Dam site in Lake Burley Griffin (Figure 8, matching the temperature plot in Figure 3). A comparison of these plots shows that when the lake is stratified, near-bed dissolved oxygen levels often become anoxic up to 5 or so metres above the bed. The detail in this plot shows how variable the profiles are, with at times sharp DO gradients and at other times a more uniform gradient. Although not shown here, this picture is repeated for all sites deeper than about 6 metres in the three Canberra lakes.

3.5 Nutrients

Inorganic nutrients provide the food for cell growth, including the growth of algae. Those required in large quantities, the so-called macronutrients, are carbon, oxygen, nitrogen, phosphorus, sulphur, silica and iron (Chapra, 1997). Of these, in freshwater bodies phosphorus is usually the limiting nutrient as it is the one at lowest concentration compared to the typical ratios found in the species of concern (Donnelly *et al*. 1998).

The ANZECC aquatic ecosystem default trigger concentration for phosphorus (as Total Phosphorus, TP) in south-east Australia is 10 µg/l (ANZECC, 2000, Table 3.3.2), although high turbidity can mean that much higher values are needed before algal blooms are triggered (see Australian studies quoted by Donnelly *et al*. 1998). The ACT Environment Protection Regulations set the standard for water-based recreation at 100 µg/l (Environment ACT, 2006a). Phosphorus exists in a variety of forms and not all are bioavailable. A better measure of the latter is orthophosphate which although included in the data sets for Canberra's lakes does not have a standard set in either the ACT Environment Protection Regulations or ANZECC guidelines. Although the controlling nutrient in freshwater is usually P, this is not always the case. The rough rule of thumb for whether N or P is the limiting nutrient is the N:P ratio which if less than about 7:1 indicates phosphorus limiting (Chapra, 1997), and hence high concentrations of P are more likely to lead to blue-green algal blooms. The ACT regulations for water-based recreation set a lower limit for the N:P ratio at 12:1. High values of N may seem to improve the N:P ratio, but N is still a nutrient and high values can lead to eutrophication. Indeed, the ANZECC aquatic ecosystem default trigger value for nitrogen (as total nitrogen, TN) is 350 µg/l.

3.5.1 Historical Trends

Nutrients have been studied in several report series and studies of Canberra's lakes. Annual summaries for Lake Tuggeranong and Ginninderra (and some other water bodies) covering the years 1996/7 to 2004/5 are provided on Environment ACT's web site (Environment ACT, 2006b). A summary for Lake Burley Griffin is given in the Water Quality Management Plan (NCA, 2006). More detailed analyses are provided in Lake Burley Griffin water quality management and monitoring reports a sample of which have been provided or obtained (DHC, 1984, ACTEW and Aquatech, 1994 and 1995, Ecowise, 1997 and 2002). Some of these reports conveniently provide time histories spanning several years.

In a study by Department of Housing and Construction in the mid 1980s (DHC, 1984) Lake Burley Griffin was found to be eutrophic (N < 125 µg/l all year (less than ANZECC) and P < 80 µg/l (less than ACT EPR), with N:P ratios often less than 12:1 indicating N limiting). However, N stored in the sediments was estimated at 97% compared with water column concentrations, while P release rate estimates suggest 20% from sediments, with the rest from water column. By contrast Lake Ginninderra was considered mesotrophic, with high N:P ratios; although N is similar to Lake Burley Griffin (< 60 µg/l), P is much lower (< 30 µg/l). Temperature/dissolved oxygen stratification was found to be weak and the sediments oxygenated. (Our analysis shows this not to be the case – see Section 3.3.)

A study ten years later by ACTEW and Aquatech (1994 and 1995) provided time histories of N and P (in various forms) from 1981 to mid 1995 for Lake Burley Griffin East Basin and West Lake. These data show total P was never above 250 µg/l and rarely above 150 µg/l (never for West Lake). East Basin shows significant reduction in TP after about 1987, which is more significant for filterable orthoPhosphate – attributed to improved P removal from Queanbeyan's wastewater treatment system in mid 1980's (N and P were found to be well correlated). Reduction of bio-available P was given as the reason for reduction in blue-green algae.

More recently Ecowise (2002) provided time histories since 1993 for Scrivener Dam showing a steady decline in total phosphorus (below 60 µg/l since 1999), which matches a decline in Molonglo River upstream of Lake Burley Griffin at Dairy Flat Road. Based on this data it can be concluded that the improvement is based on entering water quality. Nitrogen is seen to remain steady (consistently below 120 μg/l) and N:P ratios are consistently above 20 (compare with DHC, 1984).

A water quality management plan posted on the web site of National Capital Authority (NCA, 2006) reviewed several time histories of various parameters from 1982 to 2004 supporting above results for TP and TN in Lake Burley Griffin, viz., a gradual reduction in TP with time, values under 80 μg/l in East Basin and under 60 μg/l in West Lake in recent years. This report attributed the improvement to upgrading of the Queanbeyan Wastewater Treatment Plant in the mid 1980s and, more recently, a range of other catchment management practices. TN also reduced with time but not as markedly, with recent values usually below 160 μg/l in East Basin and below 120 μg/l in West Lake.

A series of reports posted on the web by Environment ACT (2006b) have varying degrees of details for Lake Tuggeranong and Lake Ginninderra. The 04/05 report shows TP< 110 μg/l in Lake Tuggeranong and TP < 60 μg/l in Lake Ginninderra, TN < 110 μg/l in Lake Tuggeranong, and < 60 μg/l in Lake Ginninderra. Unfortunately, N:P ratios are not given. The 03/04 showed similar results to 04/05. The 02/04 report includes long term trends since 1989. For both sites, TN has a decreasing trend, and is typically < 100 μg/l since 2001. TP also has decreasing trend, although less dramatic (< 120 μg/l for LT, < 60 μg/l for LG).

These report series are very important for describing the long term trends for water quality but they do not address short term variability as may occur during storms. Nor do they explore in detail the sources and pathways for nutrients. These issues are explored in studies by Canberra College of Advanced Education in the mid 1970s. In their study on Lake Burley Griffin (Cullen *et al*. 1978a) they found that flood events contributed 70% of the total phosphorus during the 18 months of study even though the floods occupied only about 10% of the time. Of the flood-sourced phosphorus, 90% came from agricultural and forestry lands. During normal and dry times, the effluent from Queanbeyan's sewage treatment plant was the dominant source. It should be noted that this study was carried out prior to the completion of Googong Dam and improvements to Queanbeyan's treatment methods. The Lake Ginninderra study (Cullen *et al*. 1978b) was conducted when Belconnen was in its early stage of development (17% urban). The point is made that storm events are particularly important as a source of nutrients. Ninety percent of phosphorus entering the lake did so during storms.

3.5.2 Comparison Between Lakes

While these studies provide importantly either a snapshot or time history, they do not provide a convenient summary to compare either with each other or with standards. We have therefore reworked the supplied data to give a picture of the statistical distributions. This is achieved by extracting a particular parameter for a particular site and sorting the data in increasing value. The relative rank of a particular value gives an estimate of its probability. The subsequent plot on log-linear scales gives the cumulative probability distribution in such a way that a parameter with log-normal distribution would appear as a straight line. For any parameter with a range less than a decade, the plot is given on a linear scale for clarity.

Each plot (Figures 9 to 12) shows the data for the three Canberra lakes with the sample locations given in Table 2. The x-axis is fixed to span 0.1% to 99.9% (–/+ 3 standard deviations for a log-normal or normal distribution) while the y-axis may vary depending on range of measured values.

Table 2
Sampling Locations
(sourced from data supplied by ACTEWAGL)

Code	Lake	Location Description
LBG504	L. Burley Griffin	West Lake
LBG507	L. Burley Griffin	Scrivener Dam
LBG529	L. Burley Griffin	East Basin off Bowen Park
LBG530	L. Burley Griffin	Central Basin midstream
LGN316	L. Ginninderra	off Police Jetty midstream
LGN318	L. Ginninderra	off Dam Wall midstream
LGN321	L. Ginninderra	below Naval Station midstream
LTG247	L. Tuggeranong	at weir (upstream)
LTG248	L. Tuggeranong	at Kambah Wetland
LTG249	L. Tuggeranong	in Main Channel

Unless otherwise indicated the data are taken from the tube samples representing an average over either the whole depth or the top 5 m if the depth is greater than 5 m. The distributions are given for total phosphorus (Figure 9), orthophosphate (Figure 10), total nitrogen (Figure 11), and N:P ratio (Figure 12).

The total phosphorus plots (Figure 9) show that while all lakes are consistently above the ANZECC aquatic ecosystem default trigger concentration of 10 µg/l (0.01 mg/l), they are all on average (i.e. > 50% of data), below the ACT Environmental Regulations value for water based recreation (100 µg/l or 0.1 mg/l). Lakes Burley Griffin and Ginninderra show similar levels, with consistent reduction in values from upstream to downstream. By contrast, Lake Tuggeranong values are higher by a factor of approximately five and there is no measurable improvement through the lake. It should be noted that while LTG249 and LTG248 are both upstream of LTG249 they are on different arms. The lack of a measurable improvement may be due to the relatively small size of the lake.

The orthophosphate plots (Figure 10) again show Lake Tuggeranong values consistently higher than the other lakes. The improvements through Lakes Burley Griffin and Ginninderra shown in total phosphorus is not reflected in the orthophosphate data.

Total nitrogen (Figure 11) shows a lower range at any site (and hence the linear rather than log plots) and, as for total phosphorus, values are consistently above the ANZECC trigger levels. Lake Tuggeranong levels are again higher than the other two lakes but not to the same degree. Improvements through the lake are seen in Lake Burley Griffin but not the other two lakes.

For all sites, the N:P ratios (Figure 12) are under 7 less than 2% of the time. An improvement (i.e. increase in N:P ratio) is seen from upstream to downstream for both Lake Burley Griffin and Ginninderra. By contrast, N:P in Lake Tuggeranong does not appear to vary with location and the values are also generally lower than for the other two lakes.

3.6 Algae

Chlorophyll *a* is used as a measure of algal biomass. ANZECC (2000) sets a trigger value of 5 µg/l for south-eastern Australian freshwater lakes. The ACT Environmental Protection Regulation limit for water-based recreation is 10 µg/l. A more direct measure is the total algae count, however, no guide levels are set by Australian Authorities. Of particular concern are the blue-green algae or cyanobacteria for which ACT Environmental Protection Regulations sets a limit of 5000 cells/ml for water-based recreation.

National Capital Authority (NCA, 2006) shows values for chl *a* in Lake Burley Griffin up to about 40 µg/l (maximum is 100 µg/l) in East Basin, but lower for West Lake (typically < 30 µg/l, maximum 70 µg/l). No long term trend could be seen despite reductions in P. The NCA report makes the important point that because sampling is not event-triggered, it may be underreported. (This comment could also apply to many other parameters such as turbidity.) Total algae counts are < 10^5 cells/ ml and usually < 10^4 cells/ml. The values reported here are typically slightly greater than the ANZECC guidelines and ACT regulations.

The time histories of chlorophyll *a* for Lakes Ginninderra and Tuggeranong by Environment ACT (2006b, 03-04 report) show values similar to Lake Burley Griffin with no obvious trend with time. The blue-green data are not reported. It is noted that Environmental Protection Officers undertake weekly visual monitoring for algal blooms from the shore and issue warnings depending on the assessed levels encountered (Environment ACT, 2006c). The availability or usability of this information has not been explored in this report.

To fill data gaps in the reporting and to better compare the sites, we present chlorophyll *a* and cyanophyta in the same manner as the nutrient statistics. The chlorophyll *a* data (Figure 13) shows some of the features mentioned above quite clearly (i.e. no clear difference between the lakes, but an improvement in quality through Lakes Burley Griffin and Ginninderra and possibly also Tuggeranong). Interestingly the cyanophyta data shows a somewhat different picture. Most noticeably the data do not follow a log-normal distribution, being skewed by the large numbers of zero counts. In contrast to the chlorophyll *a* data, the cyanophyta in Lake Burley Griffin do not show a reduction with distance downstream while those for the other two lakes do. The values for Lake Tuggeranong are somewhat higher than the other two lakes perhaps reflecting the higher orthophosphate and lower N:P ratios found in this lake.

3.7 Bacteria

The presence of faecal coliform bacteria may indicate pollution from wastewater systems or from animal faecal waste in stormwater or direct input from birds. It is used as an indicator organism for other possible pathogens. The ANZECC Guidelines for primary contact are that the median value should not exceed 150 cfu/100ml (colony forming units per 100 ml – standard measure related to the laboratory technique for bacteria). For secondary contact (e.g. boating) the level is 1000 cfu/100ml. The ACT Regulations do not set a value for water-based recreation although it does list the parameter as a parameter entering the waterway taken to cause environmental harm.

The National Capital Authority Water Quality Plan (NCA, 2006) found from time histories of 17 years' data that levels are sometimes above 150 cfu/100ml (particularly during late summer/early autumn) and occasionally up to 10,000 or more. There is no obvious trend in levels with time.

The time histories of faecal coliform bacteria for Lakes Ginninderra and Tuggeranong by Environment ACT (2006b, 03-04 report) show a different picture from Lake Burley Griffin. In contrast to Lake Burley Griffin these data do see an improvement with time. In the last five years values have rarely exceeded 150 cfu/100ml.

To better compare sites we plot supplied data on log-probability scales (Figure 15), where we see an improvement in values through each of the lakes. Lake Burley Griffin in particular has values at Scrivener dam much lower than the upstream sites.

3.8 Turbidity

Turbidity measures the degree of light transmission which may be diminished by suspended sediment or coloured dissolved substances. Limiting values are not given for recreational use of waters although ANZECC does discuss the issue of water clarity from a safety perspective. For aquatic ecosystems, ANZECC suggests default trigger values in slightly disturbed ecosystems in south-eastern Australian lakes and reservoirs of 1 to 20 ntu (nephelometric turbidity units).

The National Capital Authority Water Quality Plan (NCA, 2006) found that like most lakes in south-east Australia, Lake Burley Griffin is a relatively turbid lake (values generally below 30 ntu, but occasionally up to 100 ntu). They found turbidity higher in the shallower eastern parts of the lake. They also found turbidity higher just after stormwater inflow and after strong winds. The plotted time histories show no long term trends.

The time histories of turbidity for Lakes Ginninderra and Tuggeranong by Environment ACT (2006b, 03-04 report) show similar levels to Lake Burley Griffin. There is some evidence of an improvement with time for most sites. Values at Lake Tuggeranong appear a little higher than the other two lakes.

Cullen *et al*. (1978a) suggest that high turbidity (and hence low light penetration) is likely to reduce primary production, so this may be the reason that high phosphorus values have not lead to high algal growth.

Another important point to note is the role these lakes play in removing sediment. Munro and Hattersley (1969) found that Lake Burley Griffin was responsible for removing 82% of sediment in a flood of peak flow 600 m^3/s, while for smaller floods of 85 m^3/s the removal efficiency would be 96%. The silt from Molonglo River with sediment size between about 500 to 2 microns was found deposited throughout the lake, with deepest deposits near Scrivener Dam.

Our log-normal plots (Figure 16), show clearly the improvement in water clarity through Lake Burley Griffin and Lake Ginninderra but not Lake Tuggeranong. Turbidity levels near the outlet for Lake Tuggeranong (50%ile of 20 ntu) is well over that for Lake Burley Griffin (50%ile of 5 ntu) and Lake Ginninderra (50%ile of 10 ntu). As previously noted, the lack of a improvement for Lake Tuggeranong may be due to the relatively small size of the lake.

3.9 Toxic Substances

Substances that could be harmful to fish and other aquatic animals as well as water users include organochloride herbicides (and other organic chemicals), heavy metals and ammonia. The ACT Environmental Protection Regulations (Environment ACT, 2006a) list standards for a wide range of substances for both irrigation waters and aquatic waters. The standards for ammonia are temperature and pH dependant. The ANZECC Guidelines (ANZECC, 2000) include an even more comprehensive list of trigger values for the protection of ecosystems and separate guideline values for recreational waters.

The National Capital Authority Water Quality Plan (NCA, 2006) reviewed studies on trace metals which had shown relatively high concentrations in Lake Burley Griffin, due to runoff from abandoned mining, mainly at Captains Flat on the Molonglo River. Following stabilisation and drainage works in the mid 1970's the concentrations have been declining, although concentrations in the sediments are still high. This however is not reflected in levels of concern in biota. This report also examined ammonia and found values generally below 0.1 mg/l and gradually decreasing.

Cullen *et al*. (1978b), found that metals (Zn, Na and K) were lower in Lake Ginninderra than Lake Burley Griffin and were not perceived to be a problem. They also make the point that phosphorus could be used as an analogue for other materials of concern such as toxic metals, toxic organic compounds (e.g. pesticides) and oils. We would be hesitant to do this unless the similarity of pathways and mechanisms could be demonstrated.

Plots of ammonia probability distribution (Figure 17) confirm that levels are generally below 0.1 mg/l, although they are a little higher in Lake Tuggeranong than the other two lakes. Contrary to some other parameters there is no obvious improvement with passage through any of the lakes. This could suggest either the absence of nitrification processes in the water column or a compensating source such as release from sediments.

3.10 Manganese and Iron

Manganese and iron levels are generally only of concern for drinking water. ACT guidelines do not specify limits for recreational waters. However, the ANZECC guideline levels are set at 300 µg/l for iron and 100 µg/l for manganese. We have not explored data for these constituents in Canberra's three lakes but have done so for Bendora Reservoir where such data are routinely collected through the water column (Miller *et al*. 2003). In Bendora Reservoir depressed deepwater DO levels resulted in increased soluble Mn and Fe concentrations. This effect is seen most clearly near the bed where Fe levels could be as high as 2000 µg/l and Mn levels peak at 800 µg/l (except following the 2003 bushfires that destroyed much of the catchment vegetation). However, near-surface levels were much lower with Fe generally below 200 µg/l, and Mn below 50 µg/l.

3.11 Sediments

Most of the above discussion has focused on parameters within the water column. However there is the potential for exchange between bed sediments and the water column and because of this some studies have examined bed sediments.

Cullen *et al*. (1978a), compared Lake Burley Griffin sediments with those of other Australian lakes and found that levels of P were comparable, if somewhat at the lower end of the range with sediments of other lakes. The levels of P and N do not vary in response to high levels of metallic elements. N:P ratios in sediments are lower than in the water column, reflecting the overall loss of N from sediments as a result of mineralisation and nitrification. For Lake Ginninderra, Cullen *et al.* (1978b) found sediment phosphorus levels slightly lower than Lake Burley Griffin. Levels of metals (Zn, Na, and K) were significantly lower than Lake Burley Griffin. This report makes the point that the role of sediments in supplying phosphorus (and other constituents) to the water column is poorly understood. Its importance is conjectured to increase with the reduction of other external sources.

It should be noted that bed surface sediments are likely to be characterised by settling particles. These particles will sorb nutrients and metals which can be made soluble under reducing conditions that occur during prolonged stratification (Håkanson and Jansson, 1983). Deep sediments reflect historical features of the lake.

3.12 Production of Greenhouse Gases

In changing from a river to a lake environment it is almost certain that biochemical decomposition will result in increased release of some greenhouse gases. It should be noted that the Intergovernmental Panel on Climate Change has not identified artificial lakes as a contributor, indicating that other sources (fossil fuels, deforestation, and emissions from livestock, rice agriculture and landfill) are of greater concern (IPCC, 2001). Despite that, we briefly review the issue.

Both aerobic and anaerobic produce greenhouse gases. In the aerobic process, carbon content is converted into CO_2. More significance however should be placed on anaerobic processes that occur in an near the bed where the humic content will be much higher. In the anaerobic process, not only CO_2 but also CH_4 and N_2O are produced. In a study of sediments in a Finnish eutrophic lake (Liikanen *et al*. 2003) it was found that CH_4 and CO_2, were released at the highest rates in deep waters. In shallower waters another greenhouse gas, N_2O, was released at the greatest rate. However littoral sediments also released greenhouse gases (CH_4 and CO_2) and because of their aerial extent were, together with the shallow waters, seen to be of greater importance to the gas budgets for the lake.

To determine the extent to which Canberra's existing lakes and hence the likelihood of Lake Molonglo producing greenhouse gases would require a specific study similar to the Finnish study.

3.13 Seasonal Influence on Parameters

Only a few of the reports described above have commented on the seasonal variability in water quality. The NCA Lake Burley Griffin Water Quality Plan (NCA, 2006) mentions an increase in pH and bacterial counts in summer, the former attributed tentatively to greater algal decomposition. Metal levels were found to vary (with some lag) with DO levels in Bendora Reservoir (Miller *et al.* 2003).

Given the inferences related to stratification in the brief for this report it is important to explore to what extent other water quality parameters show seasonal variation. To this end we plot for the Scrivener Dam site several parameters as a function of time of year (Figure 18). The plotted parameters include the difference in temperature between 0.3 and 12 m as a measure of stratification. Apart from DO levels in bottom water, the seasonal influence on other (top 5 m or near-surface) parameters is not particularly clear. There is a tendency towards reduced water quality in the summer months but on a log scale (as is appropriate for log-normally distributed data) the difference between summer and winter is not great. It appears for this site on Lake Burley Griffin, whatever is happening in the deep waters, the top layers are relatively unaffected.

4. IMPLICATIONS FOR LAKE MOLONGLO

With the wealth of studies and data available for Canberra's existing lakes we should be able to make some reliable qualitative predictions for Lake Molonglo. The proposed lake will be subject to the same climate as the existing lakes. It has a depth similar to Lake Burley Griffin, and area similar to Lake Ginninderra and volume between Lake Burley Griffin and the other two lakes. Its sources of water (and other constituents) include the release from Lake Burley Griffin, stormwater from Yarralumla Creek and Western Creek as well as drainage from the new development. Based on the discussions in Section 3 we examine each issue below.

4.1 Stratification

From an examination of the data it is apparent that all existing Canberra lakes stratify thermally in summer every year. Therefore it is likely that Lake Molonglo will undergo similar stratification. Where there is biodegradable material in the water column or sediment, such temperature stratification will result in DO stratification with very low DO levels in bottom waters, probably even anoxic conditions. Despite efforts to reduce humic material entering the lake (such as gross pollutant traps, or ponds on the creeks) there will inevitably be a gradual accumulation of such material in the bed of the lake. Existing vegetation submerged with the lake filling will also provide an initial source. Any other parameter that is DO-dependent, such as Mn and Fe, will similarly show a gradient with depth.

4.2 Nutrients and Algal Blooms

The likelihood of algal blooms is increased with increased nutrient levels (P and N) and may also be dependent on temperature and water clarity. The more serious blue-green algae may occur if P levels are high compared to N. Although nutrient levels are often high compared to target values in Canberra's lakes, algal blooms are not especially common (at least according to the monthly data series). Of the three lakes, Lake Tuggeranong has consistently lower water quality than the other two. Of note is that water quality parameters (nutrients, chlorophyll *a*, cyanophyta) show improvement from upstream to downstream, particularly in Lake Burley Griffin.

To assess the likelihood of algal blooms occurring in Lake Molonglo we need an estimate of the input of nutrients compared to the other lakes. The studies by Cullen *et al*. (1978a, 1978b) showed that nutrient input due to storms would dominate dry-period input. This imbalance may be reduced for Lake Molonglo as Lake Burley Griffin provides a buffer for input coming from the Molonglo River, Queanbeyan River (where Googong Dam also provides a buffer), Queanbeyan Wastewater Treatment Plant and several creeks feeding directly into Lake Burley

Griffin. The stormwater study carried out for this project (Cardno Young, 2006b) showed that during large floods, inflow from Molonglo River will be about ten times that from the local creeks. During low flow periods, the environmental release from Scrivener Dam would be the main inflow. For moderate storms, the inflow from local creeks and the new development would dominate the inflow as Lake Burley Griffin would attenuate peak flow from Molonglo River.

Given that for most of the time, inflow to Lake Molonglo would be dominated by release from Lake Burley Griffin (Cardno and Young 2006a estimate average annual discharges from Lake Burley Griffin, Yarralumla Creek, Weston Creek and Molonglo east to be 215000, 9210, 4800 and 1360 ML/yr respectively), we would expect the incoming water quality to be better than any of the existing Canberra lakes. At times when local creeks dominate the inflow, the incoming water quality should be at least as good as for Lake Ginninderra and Lake Tuggeranong given the similarity in the catchments and expected best practice management of stormwater planned for Lake Molonglo (Cardno Young, 2006b).

A measure to test these assumptions is provided by water quality data from Coppins Crossing. In Figure 19 we plot the probability distributions for several years (1993-2006) of total phosphorous and total nitrogen data using similar scales as for Canberra's lakes. For total phosphorus this should be compared to Figure 9, and for total nitrogen this should be compared to Figure 11. In both cases the values are at or below those found in Canberra's existing lakes with the exception of TN for LBG530 (Scrivener Dam) which lies below Coppins Crossing.

Our conclusion is that although Lake Molonglo will stratify in summer, algal blooms are less likely to occur than in Canberra's existing lakes. Not only is the incoming water likely to be as good or better than for the existing lakes, but also the configuration of the lake (narrow, with few side arms, unlike Lake Tuggeranong) will be conducive to flushing.

The water quality being released from Lake Molonglo to the Lower Molonglo River will be cleaner than that which enters provided the released water is not taken from near the bed. This improvement is clearly demonstrated for Lake Burley Griffin and Lake Ginninderra, the two lakes nearest in configuration to the proposed lake.

4.3 Bacteria

The existing (1995-1997) faecal coliform bacteria levels at Coppins Crossing (Figure 19, compare to Figure 15) are higher than both Lake Burley Griffin and Lake Ginninderra. A possible source for these bacteria is runoff or seepage from the inflowing creeks from Woden/Weston and the largely rural local catchment. A second possibility is that the environmental release from Scrivener Dam is not taken from top water, where we have the faecal coliform data. These bacteria are known to decay in sunlight, so that levels in deeper water may be higher.

If the reason for the higher levels is local rural source, then much if not all of this activity would be replaced in the development, so that levels should drop to something like that of Lake Burley Griffin provided appropriate controls are in place to mitigate against the contamination of stormwater by wastewater. If the reason is the depth from which the environmental release is taken, then some reduction in near-surface values would occur in passing through the lake although it is unlikely to be as much as for Lake Burley Griffin.

The data to test which of the alternative sources is dominate does not exist. As discussed elsewhere, the addition by the responsible authority of a routine water quality sampling site immediately downstream of Scrivener Dam would assist.

4.4 Exposure to Wind and Seasonal Variability

A measure of exposure to wind can be found by comparing the surface area to volume ratio for Lake Molonglo with the existing lakes (Table 3). The alignment of two arms of the lake match the principle wave direction at Canberra (as measured at Canberra Airport and Canberra Forestry – BOM, 2007) but so do major arms of each of the existing lakes. However the relative surface area is less than half of any of the existing lakes, so that unless the wind regime of this valley were significantly different to elsewhere in the ACT then wind influences would be less than for the other lakes. As a consequence stratification is likely to be at least as strong as the existing lakes. This matches the conclusions of a water quality study for Bendora Reservoir (Miller *et al.* 2003) where it was found that stratification was strong, often extending to the water surface (i.e. an absence of distinct mixed layer), no correlation was found between wind and variation in water quality parameters, and modelling confirmed the limited influence of wind.

Table 3
Surface Area/Volume Aspect Ratio

Lake	Volume (GL)	Surface Area (Ha)	Aspect Ratio (Ha/GL)
Molonglo	17	160	9.4
Burley Griffin	33	664	20
Ginninderra	3.7	120	32
Tuggeranong	2.6	60	23

As mentioned above, we expect the lake to stratify in the warmer months and that stratification will result in seasonal patterns in many water quality parameters. However such seasonality will be felt most strongly in the deeper waters and, as has been found for Canberra's existing lakes, the influence on values at or near the top surface will be far less. Provided our concern is primarily for the near surface waters, then the seasonality should not be taken to be a major factor.

5. MODELLING

As a check on the chance of stratification and to get a measure of vertical diffusion rates we have modelled the planned lake with the simplest possible model – a vertical one dimensional model that assumes temperature is constant at any depth. The model used is the one-dimensional heat diffusion equation as outlined by Orlob (1982):

$$\frac{\partial H}{\partial t} = c\rho E_z a_z \frac{\partial^2 \Theta}{\partial z^2}$$

where H is the heat content per unit depth, t is time, c is specific heat, ρ is water density, E_z is vertical diffusivity, a_z is area at depth z, and Θ is temperature.

We have assumed inflow and outflow do not change the temperature structure so that the only driver is the heat exchange at the air-water interface and the only process modelled is vertical diffusion. Our simulation of the top boundary layer is based on the climate data for Bendora Reservoir, simplified to an average annual cycle. For the bottom boundary condition we have taken a constant temperature at some depth below the lake bottom. Vertical diffusivity parameters are based on a simulation carried out for Bendora Reservoir (Miller *et al.* 2003). Solution of the model equation is effected with Matlab's partial differentiation solver, *pdep*e. (Mathworks, 2007).

5.1 Model Results and Interpretation

A simulation of the temperature profiles at the deepest part of the lake is given in Figure 20. The simulation shows the evolution of profiles during the heating part (summer) and cooling part (winter) of the annual cycle. These results show behaviour similar to that found for Bendora Reservoir (Figure 6). To obtain this simulation we have taken vertical diffusivity to be 10^{-5} m^2/s, a value within the range used by USEPA (Bowie *et al.* 1985) for eddy diffusion in the vertical, thermocline and deeper regions in lakes and oceans. The fact that we can simulate the average temperature profile evolution supports the assumption that vertical processes are more important than horizontal for the behaviour of the lake. The value of diffusivity is two orders of magnitude greater than thermal conduction in water, signifying that other processes (turbulence, convection, breaking internal waves) dominate molecular heat diffusion.

To extrapolate this behaviour to other constituents we need to distinguish between conservative substances (neutrally buoyant, and bio-chemical rates much slower than diffusion) and non-conservative substances. In the case of the former, they should diffuse through the water column at rates similar to the temperature, and in the latter, other physical or bio-chemical changes will dominate diffusion.

A measure of the diffusion time is found from the depth and diffusivity:

$$t_{diff} = \frac{z^2}{2E_z}$$

An interpretation of this time is that it represents how long it takes for the width of a pollutant plume to increase by one standard deviation.

For the deeper parts of Lake Molonglo this time is of order of two years. The implications for various types of substances follows. Typical coefficient values are taken from Bowie *et al.* (1985). It should be borne in mind that rates are highly variable being very dependent on temperature amongst other factors.

- Buoyant pollutants such as oils and greases, grit or sediment, will float or settle at a rate that is independent of the stratification. The rate will depend on particle size, relative density and shape. At times of higher turbulence (high winds) the settling rate will be slower.
- Bacteria and other pathogens decay with exposure to UV at a rate that is approximately first order decay. Typical decay constants for faecal coliform bacteria are 0.01 hr^{-1}, so that a ten-fold reduction in concentration will take about 10 days. However this rate can drop to zero in dark conditions and some pathogens are known to decay at rates slower than faecal coliforms.
- Ammonia converts to nitrates and nitrites by bacterial decay with kinetic constant of order 0.1 $days^{-1}$ (equivalent to time for ten-fold conversion of 23 days).
- In the absence of any precipitating agent, phosphorous could be considered conservative, so changes will be from diffusion.
- The conversion of nitrates to nitrogen gas will occur in the deeper waters when stratified due to anaerobic denitrification. Kinetic constants for this process are of order 0.1 hr^{-1}, corresponding to ten-fold conversion in one day.

5.2 Processes that could be Modelled

The above modelling is the simplest that could be carried out to give some results to assist in predicting behaviours. By comparing the vertical diffusion rate with the rates for other processes it helps determine when stratification will be important. Where these processes are slow compared to diffusion then a single box model (i.e. ignoring stratification) such as Vollenweider's phosphorous balance model (e.g. Cullen *et al.* 1978a) could provide some predictive capability. To carry out this type of modelling we would need more detailed data on flows and constituent concentrations during storms.

We have not explored the flushing characteristics of the lake. We have noted that Lake Tuggeranong has inferior water quality to Lake Burley Griffin and Lake Ginninderra and this may be in part due to a large proportion of the lake being off to the side of the presumed main flow path. The shape of the Lake Molonglo will be more river-like and hence should have better flushing characteristics provided the main influent is at the head of the lake (see comments in following section on input from Lower Molonglo Water Quality Control Centre). If this aspect were to be explored more fully, then a horizontally averaged flow model could be used (e.g. such a model was used for Bendora Reservoir, Miller *et al*. 2003). More detailed models would be required for selective withdrawal at a spillway or detailed inflow characteristics from stormwater drains.

6. LOWER MOLONGLO WATER QUALITY CONTROL CENTRE EFFLUENT

6.1 Introduction

The major wastewater treatment facility for Canberra (LMWQCC) is about 7 km downstream of the proposed dam site. This facility processes about 100 Ml/d of wastewater to tertiary standard including nutrient removal and disinfection. If suitable or warranted this effluent or a portion of it could be pumped to Lake Molonglo to assist maintain volume. Possible advantages of this scheme would be to reduce reliance on release from Lake Burley Griffin and provide additional environmental flows in the portion of Molonglo River downstream of the proposed dam. Possible disadvantages include altering the water quality in the lake and changing the flushing characteristics. The impact on potential water uses needs to be considered.

The volume of water produced by LMWQCC greatly exceeds the dry weather flow released from Scrivener Dam (by a factor of about 170 according to 2006 flow data) so there is no doubt the water would assist maintaining the lake levels. If all LMWQCC effluent were diverted to the new lake then there would be continuous flow over a spillway and flows in the downstream river matching the discharge currently experienced in the bottom one kilometre of Molonglo River. If such discharge did not comply with environmental release policy then reduced flows could readily be supplied.

6.2 Impact on Water Quality

To assess the impact on water quality we plot (Figure 21) the probability distribution for several parameters from the effluent (2006 data). Compared to the values in existing lakes we see total P is higher (cf. Figure 9) than all cases and by up to 10 times compared to the best site in Lake Burley Griffin. Total N is also higher than lake values (cf Figure 11) and by even a higher factor (up to 50) than P. By contrast, ammonia (cf Figure 17) is similar to the existing lakes except for the higher percentiles where the effluent levels in the top 10% are above 0.1 mg/l. Faecal coliform levels are lower than lake levels by a factor of up to 10.

From this data, if LMWQCC effluent were to dominate the inflow to Lake Molonglo, then the water quality would be slightly inferior with respect to nutrient levels compared to the expected condition if this source were not used. The N:P ratio, however, would be relatively high (median value in the effluent is over 100) and not conducive to blue-green algae blooms. The values of faecal coliform would be generally low and typically below contact recreation standards.

The temperature of wastewater within the treatment works is high as a result of the biochemical processes in the treatment. The effluent is therefore at a higher temperature than would otherwise occur in the lake. Effluent temperature in winter is typically 18 degrees compared to temperatures that would get down to below 10 degrees as occurs in Lake Burley Griffin. This means that unless mixing was enhanced by a suitable diffuser, effluent would remain at the surface – i.e. not mix at such times.

6.3 Other Issues

There is a cost associated with the pipework needed and the ongoing pumping to raise the effluent from the LMQWCC outlet back to the dam. If such water were added close to the dam (the least-cost option), then much of that effluent would short circuit directly to the spillway. If, on the other hand the effluent were added at the headwaters of the lake, then passage through the lake would provide opportunities to improve the water quality prior to discharge back into the river.

7. DESTRATIFICATION

7.1 The Need for Destratification

In many lakes and reservoirs around the world artificial means are employed to reduce or remove the stratification. The reasons include: (1) controlling algal growth in the water column, (2) eliminating hypolymnetic oxygen depletion and preventing the release of nutrients and heavy metals (iron and manganese) from sediment and (3) preventing ice formation (Miyanaga *et al.* 1994). Canberra's climate mitigates against the third reason. We have argued that algal growth is less likely to occur in Lake Molonglo than for Lake Burley Griffin where it was not seen to be a major problem. However it may be desirable to eliminate the hypolymnetic oxygen depletion, particularly if release of bottom water is to be contemplated. We note that such a need has not resulted in destratification measures being adopted for any of Canberra's existing urban lakes. Within the ACT and region, the only operating system is the solar powered partial destratification device installed on Cotter Reservoir after it suffered serious water quality problems because of the destruction of the catchment vegetation in the January 2003 bushfires. An early report on the efficacy of that system (ACTEWAGL, 2006) showed some reduction in turbidity and heavy metal levels. A more comprehensive report is due for release soon although the test period has been under unusual drought conditions and final assessment may not be possible until after a more typical year. Similar, but more powerful, devices have recently been installed on Googong Reservoir. It will be some time before the results of that facility are known.

Methods for destratification by artificial mixing include mechanical mixers and, more commonly, air bubble plumes. In both cases the object is to induce a circulation that brings the near-bed waters to the surface so that natural air-water exchange processes can occur. The design and operation of such devices needs to be carried out with great care. In a review of over 50 applications of such devices in Australia, McAuliffe and Rosich (1989) found 24% could be described as successful (water quality improved to national standards or the target problem organism being eliminated) and 46% as being of limited success (improved water quality but not to the relevant Australian standard or incomplete removal of the offending organism). In 28% of cases studied, the result was judged a failure. It was found that even where the artificial mixing resulted in increased oxygen levels and subsequent reduction in heavy metal concentrations, that did not in turn always improve algal control. In fact it is possible to cause detrimental effects as reported, for example, in Bernhard (1994) who describes a case in Germany where the mixing led to a significant increase in biomass production. In an earlier review of Australian bubble plume destratification devices (Qld Dept Local Govt, 1986), only 8% of bubble-type devices were described as having completely failed although 'adequate re-oxygenation was not achieved with several other applications'.

Where destratification was prevented or could be achieved in a reasonably short time, good control of accumulation of iron and manganese was also achieved. Less success was achieved in control of phytoplankton and zooplankton.

More recent studies have likewise shown mixed results. A CSIRO study (Sherman, 2000) reported surface pump systems in Tennessee which raised release water DO from anoxic to 1.5-2 mg/l, and a draft-tube system at Little Nerang Reservoir which raised temperatures by 3°C for depths less than 16.5 m. A study by Hunter Water Australia for Tweed Shire Council (HWA, 2006) reported satisfactory results for a draft-tube system in Clarrie Hall Dam where DO and temperature profiles demonstrated relatively uniform profiles since installation in 2002. By contrast, a draft-tube mixer system installed by Hunter Water Australia to replace a bubble system at Chichester Dam (Glamore, 2004) showed the reservoir frequently falling short of required conditions with regard to thermal gradient, DO gradient, soluble Mn and soluble Fe levels. There were also operational problems due to impeller fouling.

7.2 Preliminary Costing

Should, however, it be decided to proceed with a destratification device we here provide a very preliminary estimate of the cost. Costs are provided for both an air-curtain and a draft-tube device. The air-curtain costs are derived from quotations provided by suppliers in 2007 for an air-curtain device as planned for lakes under the control of the Penrith Lakes Development Corporation. Lake Molonglo will require a greater volume of air than the lakes at Penrith, and as such the costs have been adjusted. Air usage rates for Lake Molonglo of 200 L/s have been calculated using the methods of Schladow (1993) and cross checked against many sites as summarised by Qld Dept Local Govt (1986). The estimates are given in Table 4. A more detailed design and costing should be undertaken should such a device be implemented.

Table 4
Estimated Costs for an Air-Curtain Destratification Device

Item	Estimated Cost
Device construction and installation	$25,000
Pipelines and aeration diffusers	$20,000
Installation of three-phase power	unknown
Ongoing cost (based on 60 kW unit and operating for six months)	$25,000/year

Mechanical mixers are generally costlier to install but cheaper to run. The following estimates are based on advice from Laslo Nagy for a WEARS device (Wears, 2007) and are in line with costs for a similar (unsuccessful) device operated by Hunter Water Australia at Chichester Dam.

Table 5
Estimated Costs for a Draft-Tube Destratification Device

Item	Estimated Cost
Device construction and installation	\$120,000 - \$150,000
Ongoing cost (based on 60 kW unit and operating for six months)	\$8,000-\$10,000/year

7.3 Alternate Strategies

There are many other strategies to control water quality in lakes. Stefan (1994) lists the following:

- Inflow control of water, nutrients and sediment
- Lake deepening: aimed at reducing resuspension of bottom sediments
- Sediment nutrient inactivation: intended to reduce hypolymnetic nutrients by either precipitating them during treatment and/or preventing further release of nutrients from the sediment
- Water column nutrient inactivation: in both epilimnion and hypolimnion
- Hypolimnetic oxygenation: i.e. injection of oxygen rich water without necessarily destroying the stratification
- Nutrient outflow acceleration: by selective withdrawal
- Herbicide treatment to directly reduce algal populations.

The first of these methods (inflow control) will be used in Lake Molonglo. Lake Burley Griffin will provide such a control and best practice methods are being planned for the new urban development to minimise nutrient and sediment input during and after construction (Cardno Young, 2006b).

8. CONCLUSIONS AND RECOMMENDATIONS

1. Most useful basis for exploring likely water quality issues is by comparison with existing lakes in the region.
2. We have examined published reports and re-examined sample data from the existing lakes as well as in Molonglo River in the vicinity of the proposed lake.
3. This review has been supplemented by 1D model of stratification.
4. We conclude that the lake will stratify in summer.
5. This stratification will lead to low oxygen levels in the deeper waters which will have an effect on other water quality parameters.
6. The impact of stratification on near-surface waters is likely to be much less.
7. The water quality of Lake Molonglo should be closer to Lake Burley Griffin than the other two Canberra lakes, and may be even better as the outflow from Scrivener Dam has had the benefit of polishing in the passage through Lake Burley Griffin.
8. We expect the occurrence of algal blooms to be similar to, or better than, existing lakes.
9. Faecal Coliform levels should improve compared to current values in the river. Further exploration is recommended to determine the reason for elevated coliform levels at Coppins Crossing. Part of this would be to compare the quality of water being released from Scrivener Dam with the measured near-surface values at the nearby monitoring station. There is currently no routine monitoring of the waters as released from Scrivener Dam.
10. Although we do not rule out the option, we do not see a strong case to incorporate a destratification system. While input of nutrients is kept under control, the absence of a strong seasonal signal in near-surface water quality indicates there would be little benefit from destratification in the proposed lake.
11. If however it is seen to be desirable to prevent or reduce anaerobic near-bed waters we provide an estimate for the cost of installing an air-curtain device to be about $50000 and the ongoing annual costs will be about $25000. A mechanical device would be more expensive to install but cheaper to run (or order $130000 and $10000 respectively) Design of such a device needs to avoid problems or disappointing results experienced at some Australian sites. We would recommend that a decision to install such a device await monitoring following filling of the lake.
12. The suggestion that effluent from LMWQCC be pumped to the lake should be treated with caution. The water quality values from the effluent are close to or worse than that experienced in the existing lakes (except for faecal coliform bacteria). Temperatures are elevated compared to normal lake values in winter. However the quality is not so poor

that we would rule the option out altogether and in fact the effluent satisfies contact recreational standards. There are construction and operational costs associated with this option.

13. Existing trees along the existing river bank should be cut close to ground level to remove hazards and reduce in situ biodegradable material.

14. Although we have concentrated attention on the current preferred lake configuration, this is not necessarily the final design. The question arises as to how our conclusions would vary depending on, for example, a shallower lake or even multiple lakes. The advantage of shallower lakes would be to reduced incidence of stratification (although even the smallest of Canberra's lakes exhibit this behaviour), and shorter residence times. In terms of treatment of stormwater prior to release to the lower Molonglo River, this later point could be seen as a disadvantage. The impact on changing the available area on recreational opportunity and visual amenity would need to be considered. All designs would change the characteristics of the main river channel as only the very shallowest designs would avoid drowning this part of the catchment.

15. If planning for the lake is to proceed there are some additional monitoring and studies we would recommend:

    15.1. Add a routine water quality and flow monitoring point downstream of the release from Scrivener Dam. With the existing data it is not possible to definitively isolate sources of pollutants in lower Molonglo River.

    15.2. Conduct an event-base study for water quality at Coppins Crossing. The study would be triggered by storm events in the upper Molonglo and more local catchments. Such a study would help to isolate sources and provide a basis for predicting the passage of pollutants through a future lake following storm events.

    15.3. Consider the option of variable-depth offtake for both Scrivener Dam and Molonglo Lake. The current arrangement at Scrivener Dam restricts low flow release to a depth well below the surface.

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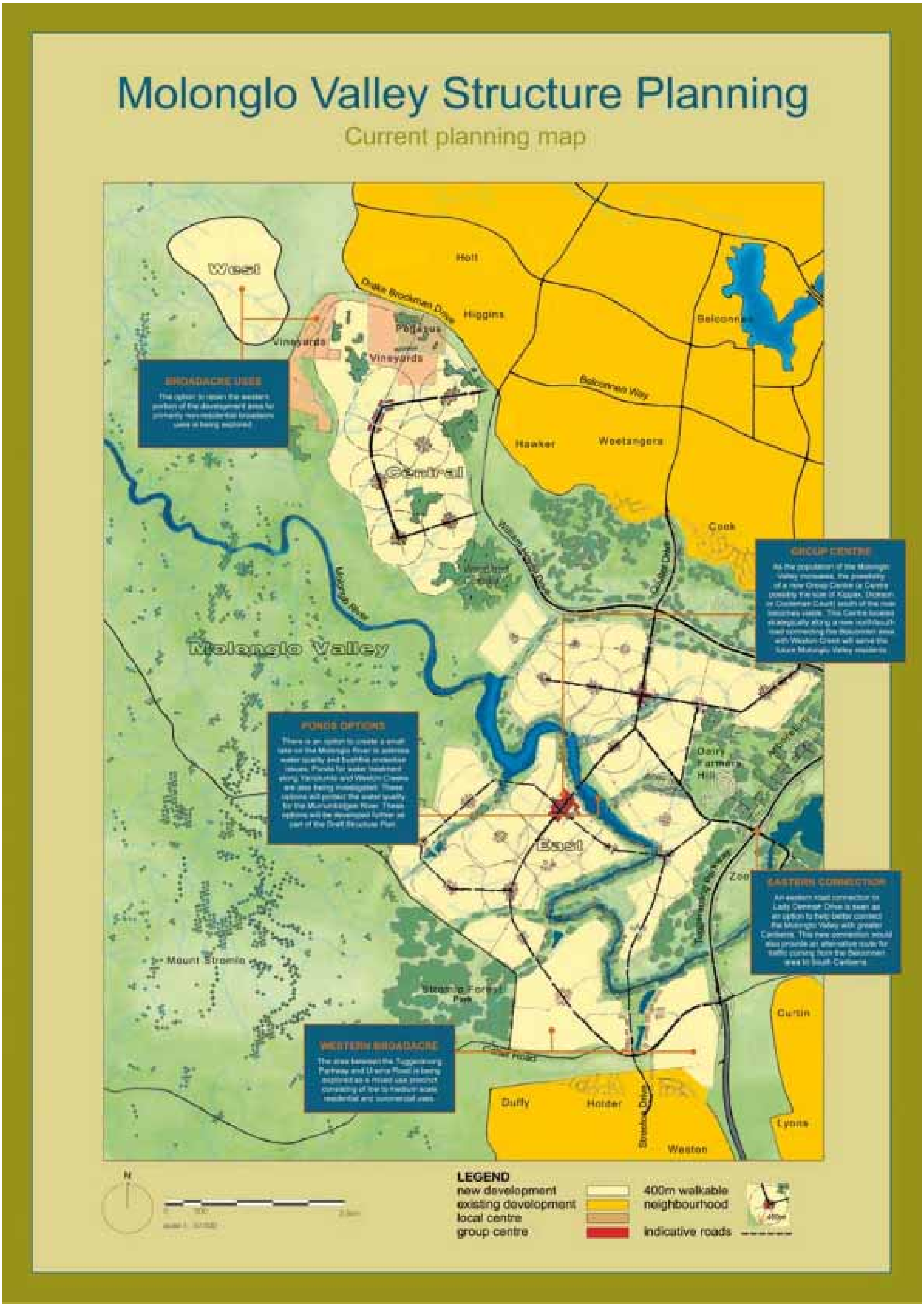
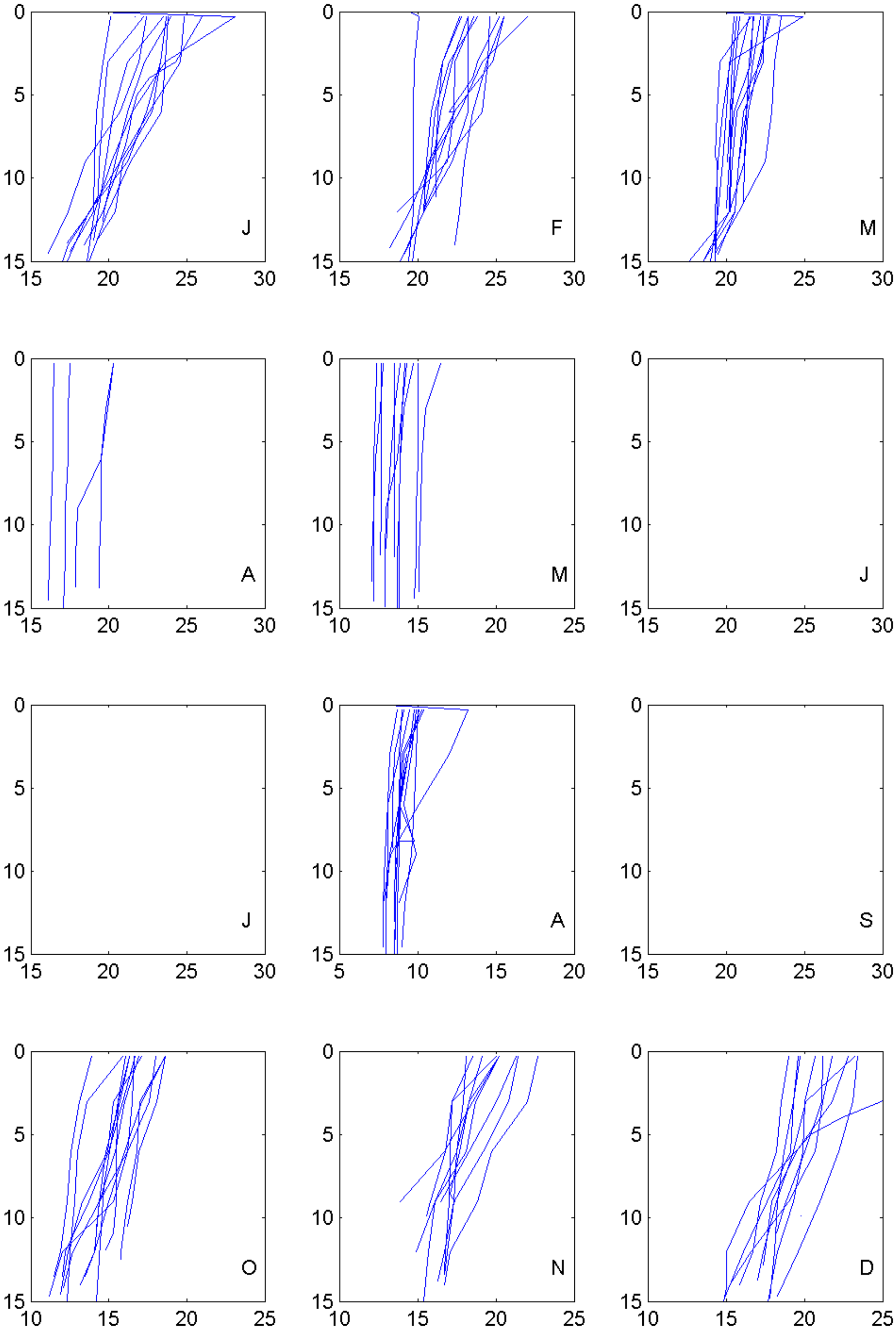


WRL Report No. 2006/35	MOLONGLO VALLEY DEVELOPMENT CURRENT PLANNING – SHOWING RELATION TO EXISTING SUBURBS (ACPLA, 2006b)	Figure 1

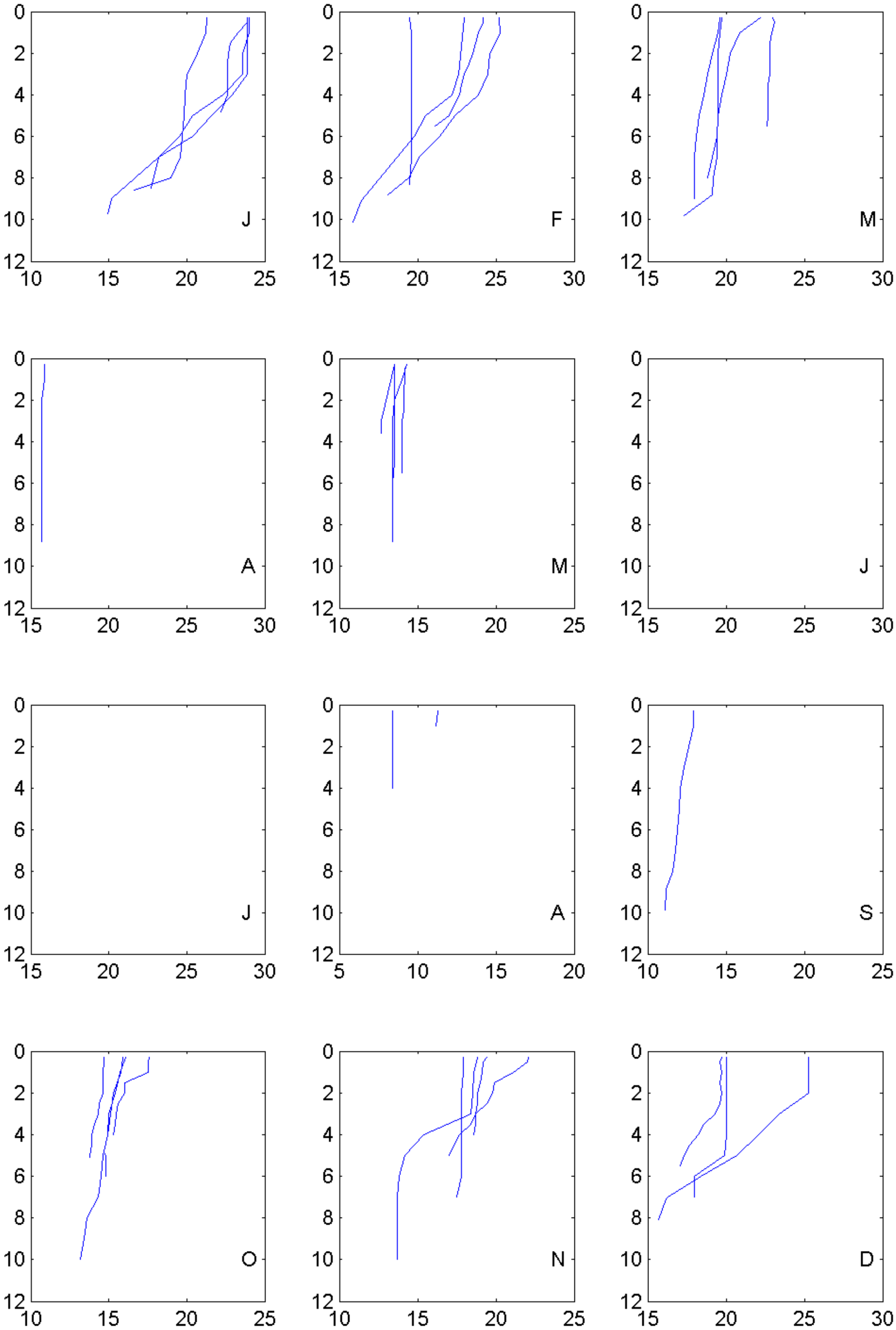
Molonglo%20Map%20with

WRL Report No. 2006/35	PLAN OF PREFERRED LAKE OPTION (FROM CLIENT BRIEF AUG 2006)	Figure 2 MolongloLake_extent.png



x-axis: water temperature (°C)
y-axis: depth from surface (m)

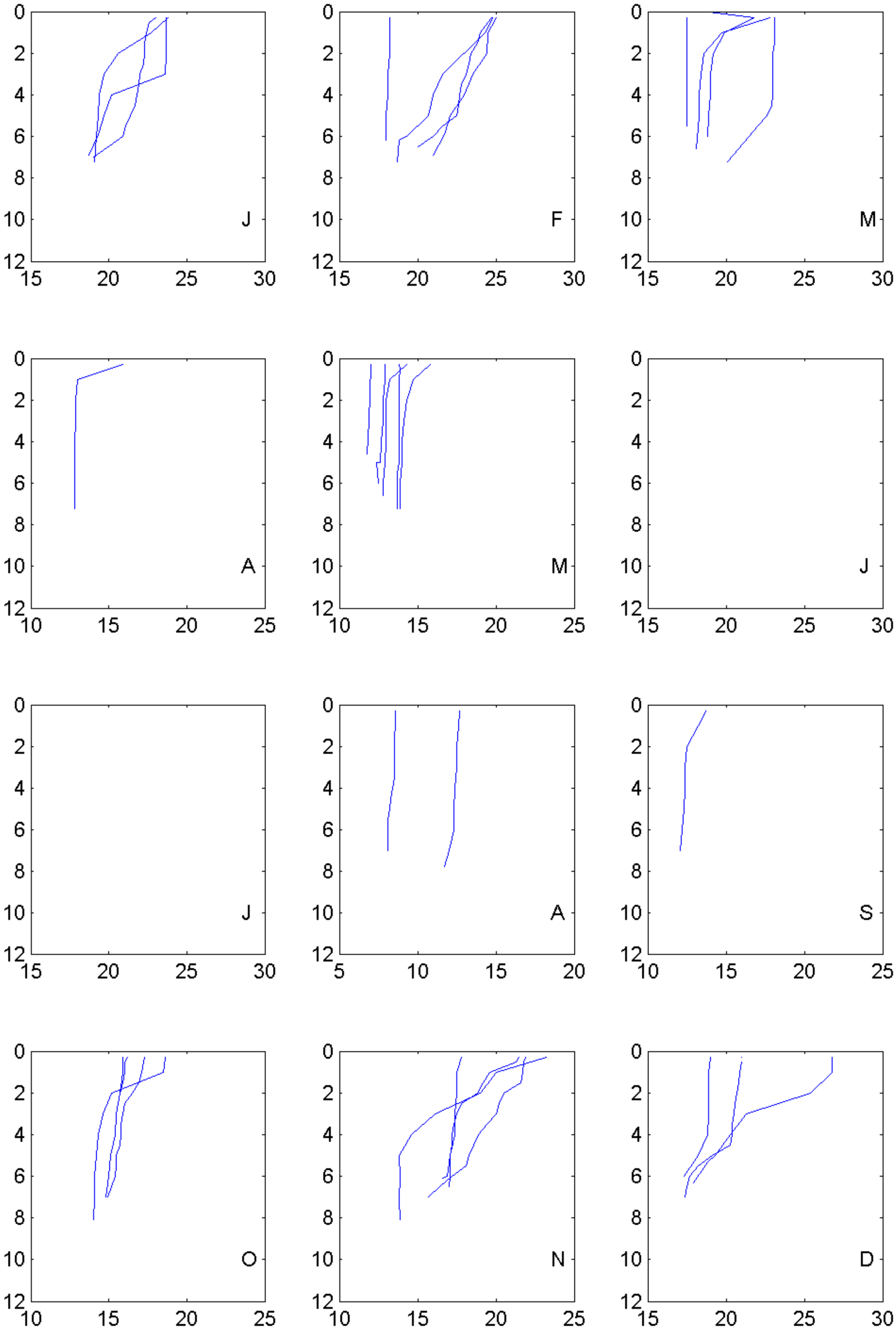
WRL Report No. 2006/35	MONTHLY TEMPERATURE PROFILES LAKE BURLEY GRIFFIN NEAR SCRIVENER DAM (SITE LBG507)	Figure 3 LBG507_by_month.png



x-axis: water temperature (°C)
y-axis: depth from surface (m)

WRL Report No. 2006/35	MONTHLY TEMPERATURE PROFILES LAKE GINNINDERRA OFF DAM WALL (LGN315)	Figure 4

LGN318_by_month.png



x-axis: water temperature (°C)
y-axis: depth from surface (m)

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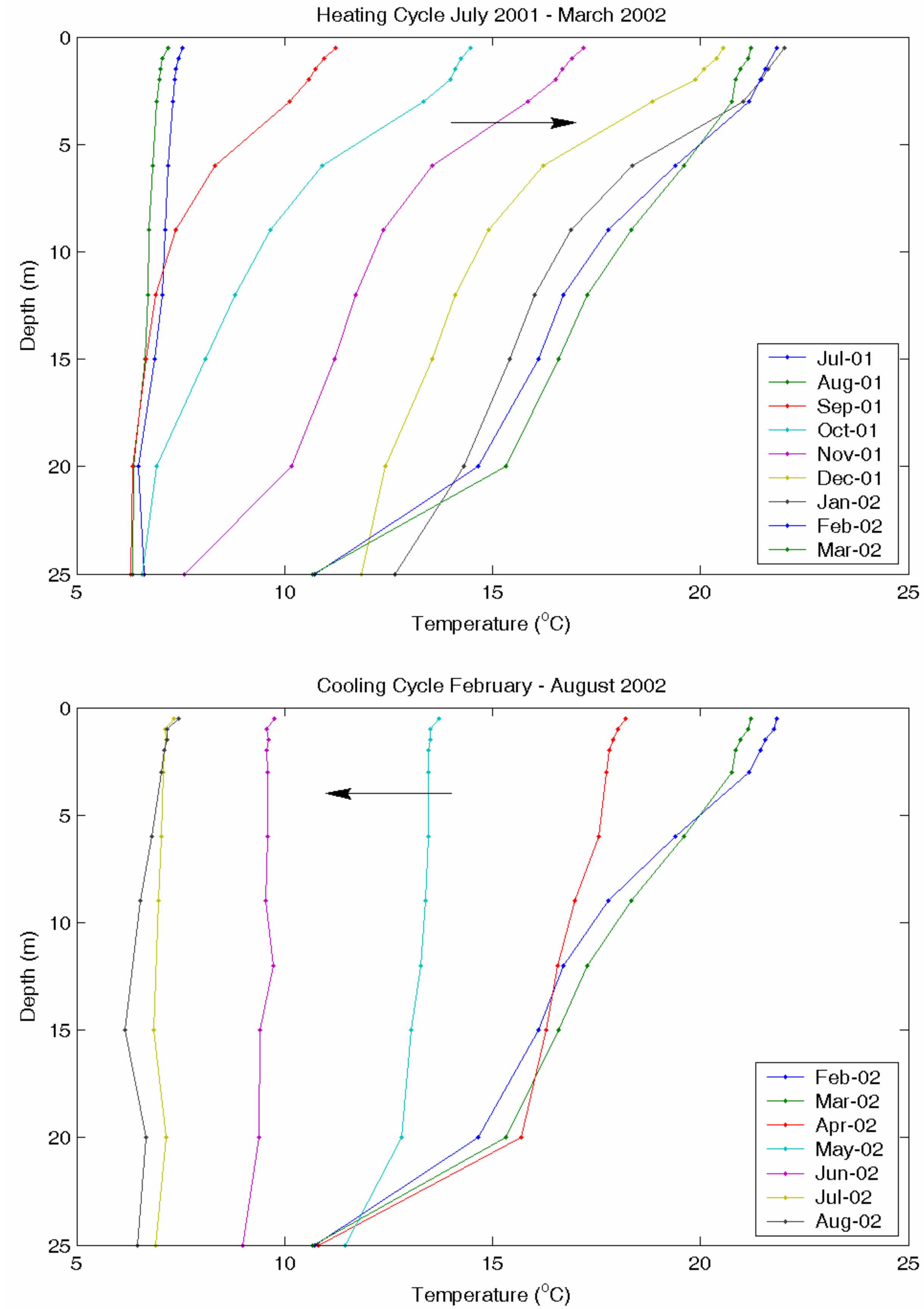
MONTHLY TEMPERATURE PROFILES
LAKE TUGGERANONG MID CHANNEL (SITE LTG249)

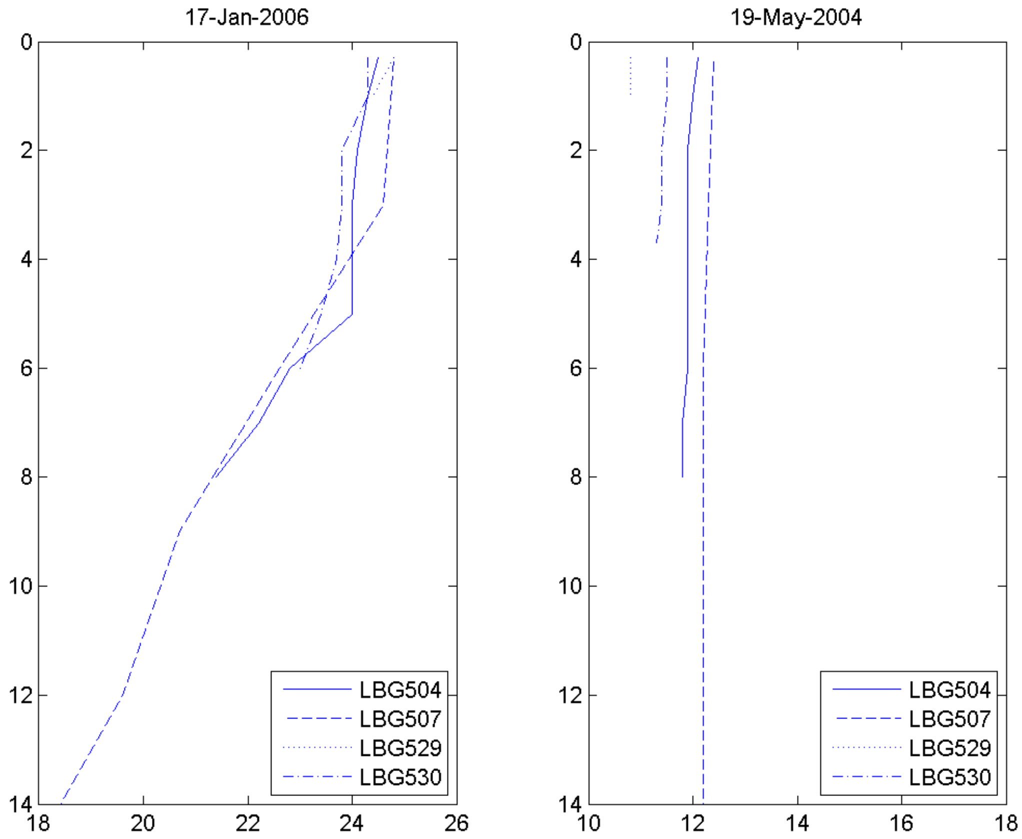
Figure
5

LTG249_by_month.png



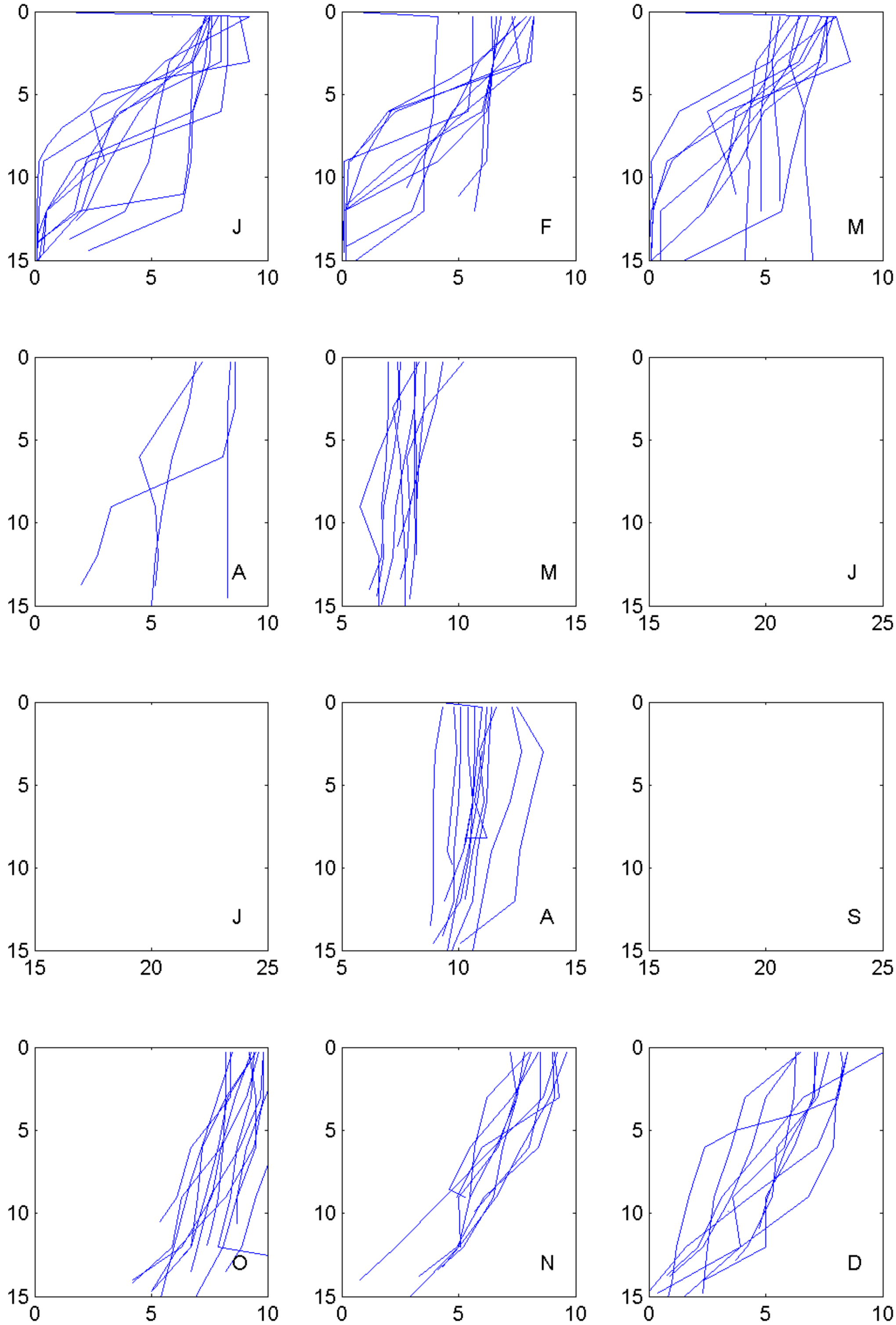
WRL Report No. 2006/35	HEATING AND COOLING CYCLES FOR BENDORA RESERVOIR (FROM MILLER *ET AL*. 2003)	Figure 6

bendoraTcycle.png



x-axis: water temperature (°C)
y-axis: depth from surface (m)

WRL Report No. 2006/35	TEMPERATURE PROFILES AT SEVERAL LOCATIONS IN LAKE BURLEY GRIFFIN	Figure 7 LBG_Temp_across_lake.pn



x-axis: dissolved oxygen concentration (mg/l)
y-axis: depth from surface (m)

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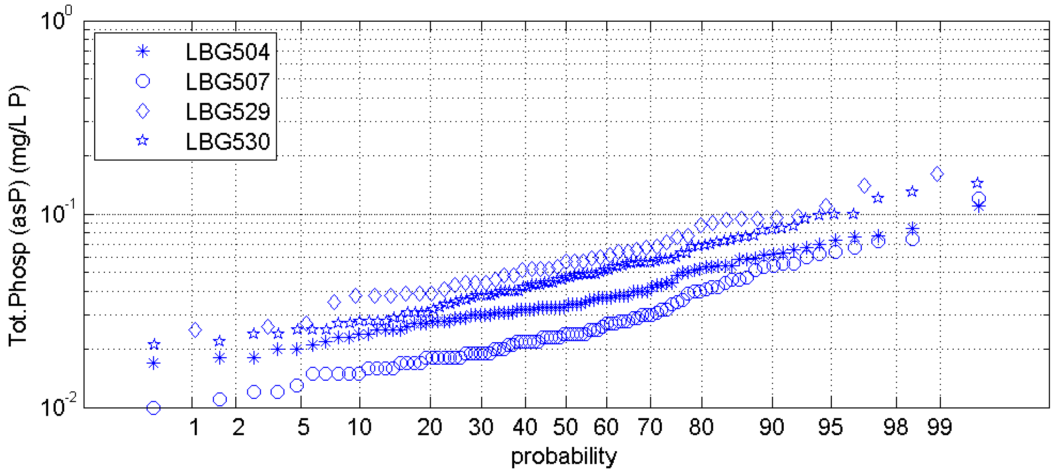
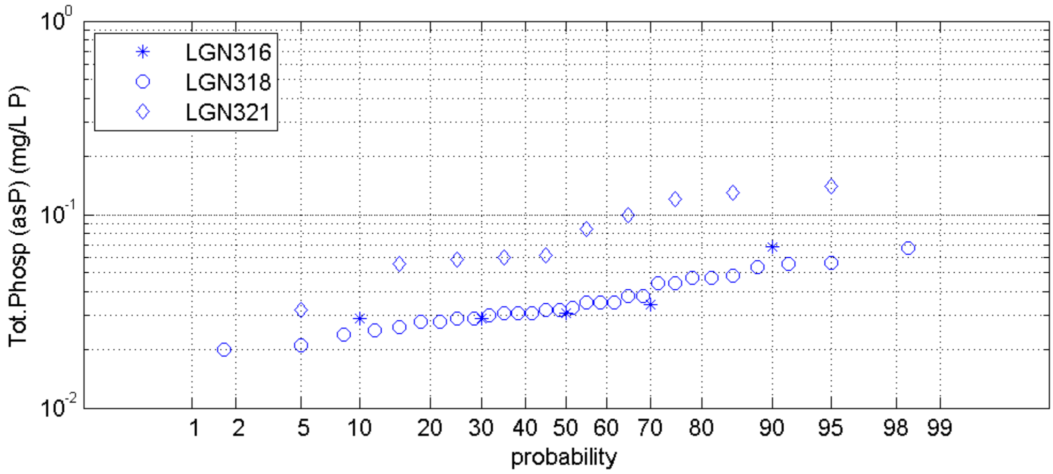
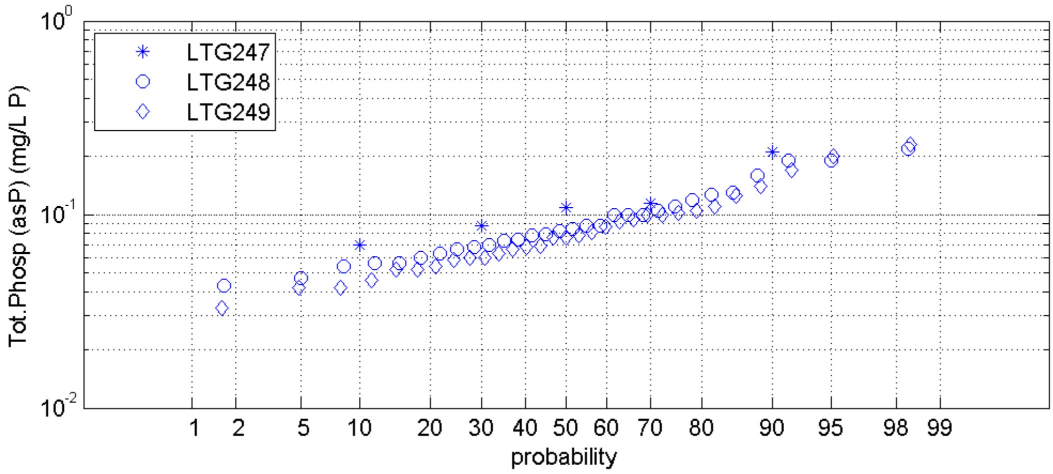
MONTHLY DISSOLVED OXYGEN PROFILES
LAKE BURLEY GRIFFIN NEAR SCRIVENER DAM (SITE 507)

Figure 8

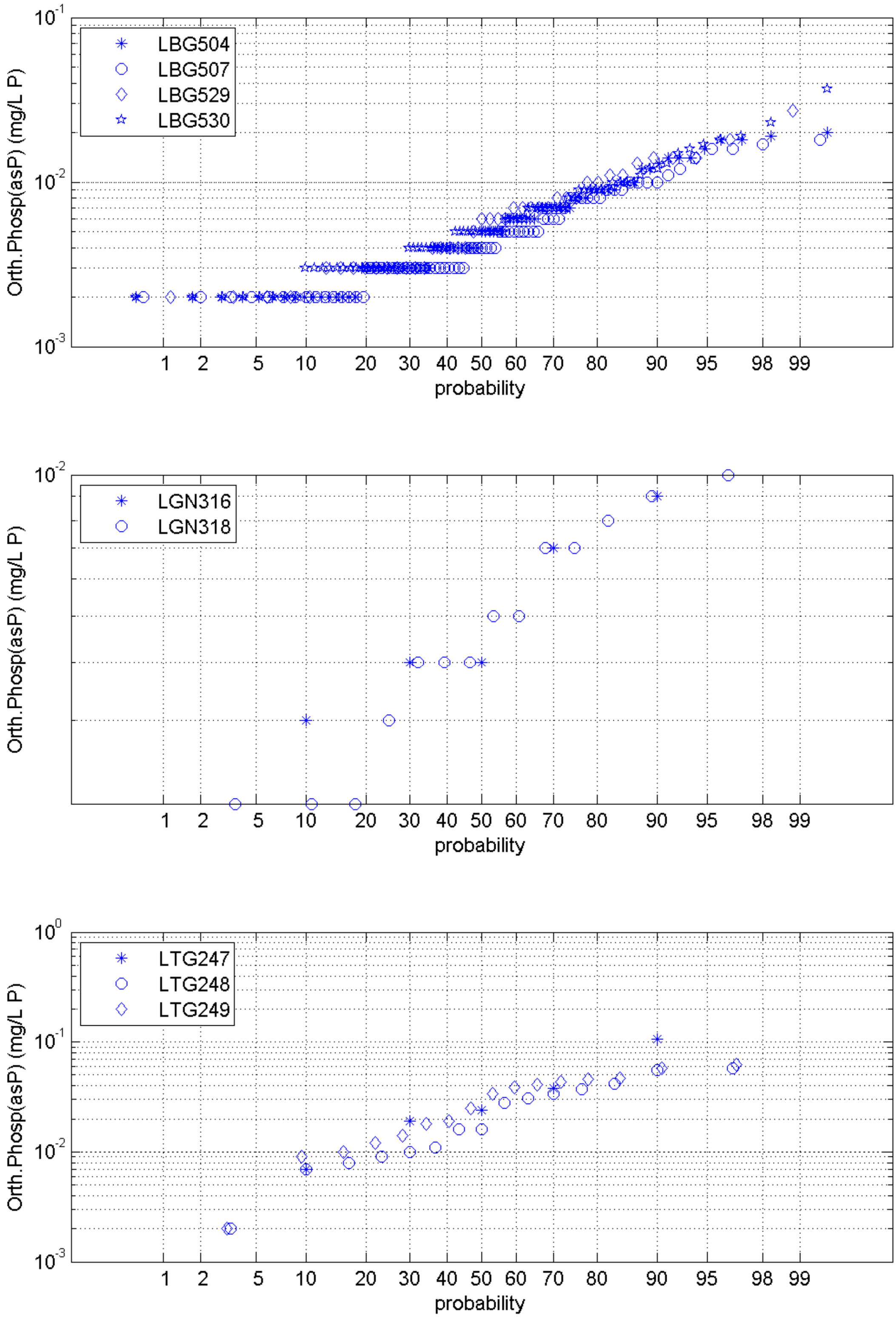
LBG507_Diss_Oxygen_by_





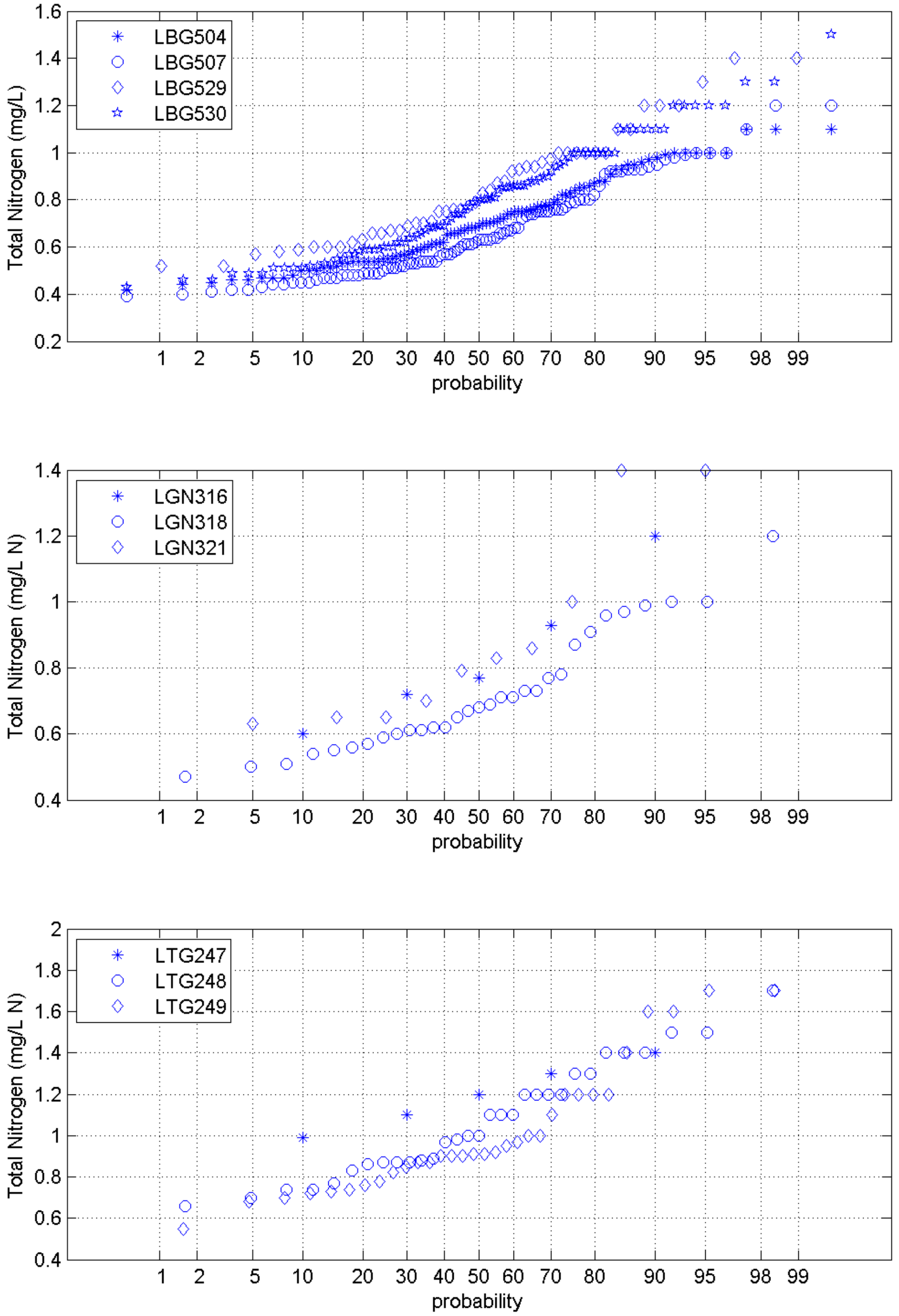


WRL Report No. 2006/35	TOTAL PHOSPHORUS PROBABILITY DISTRUBTIONS	Figure 9 CDF_Tot.P.png



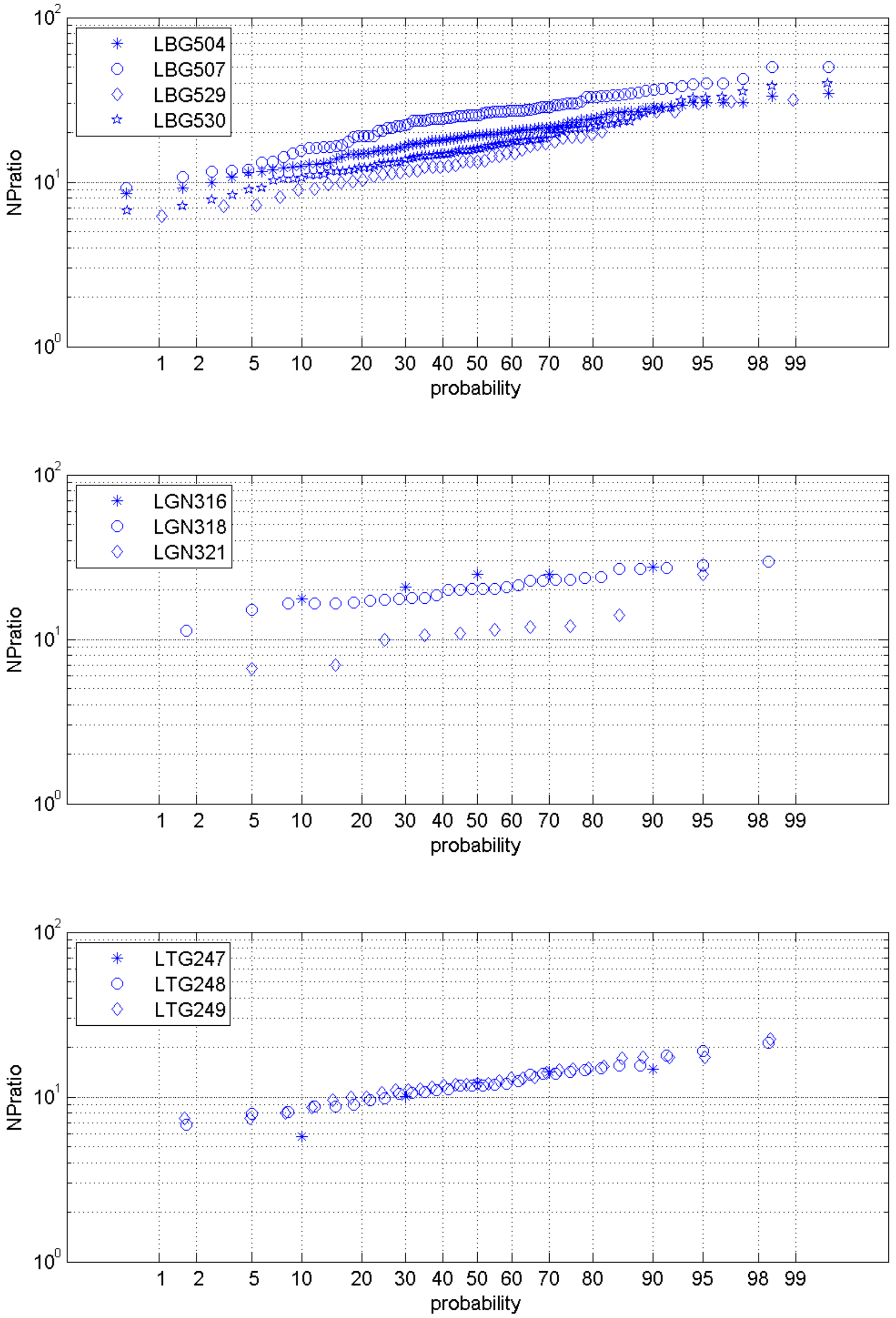
WRL Report No. 2006/35	ORTHOPHOSPHATE PROBABILITY DISTRIBUTIONS	Figure 10

CDF_Orth..png

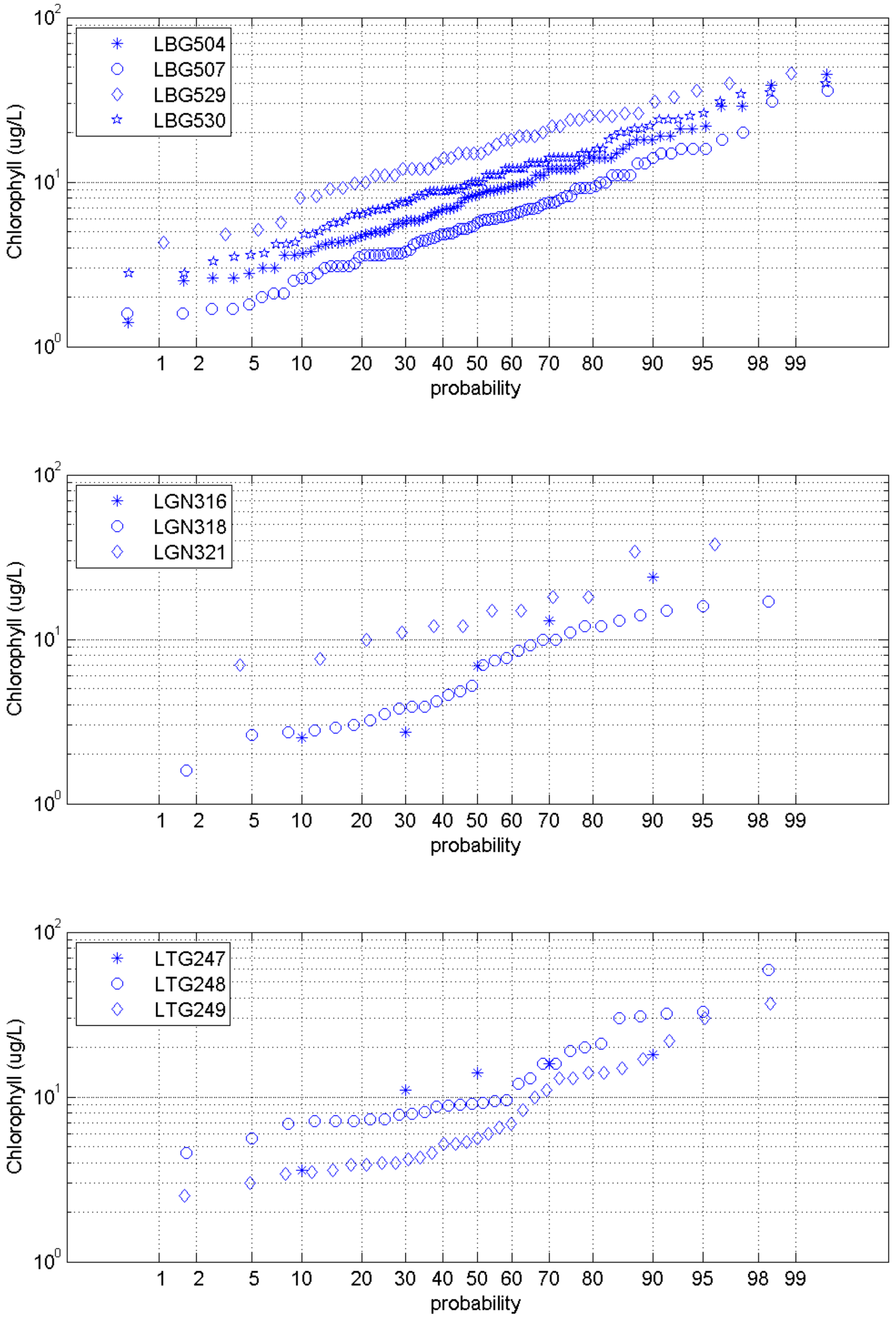


WRL Report No. 2006/35	TOTAL NITROGEN PROBABILITY DISTRIBUTIONS	Figure 11

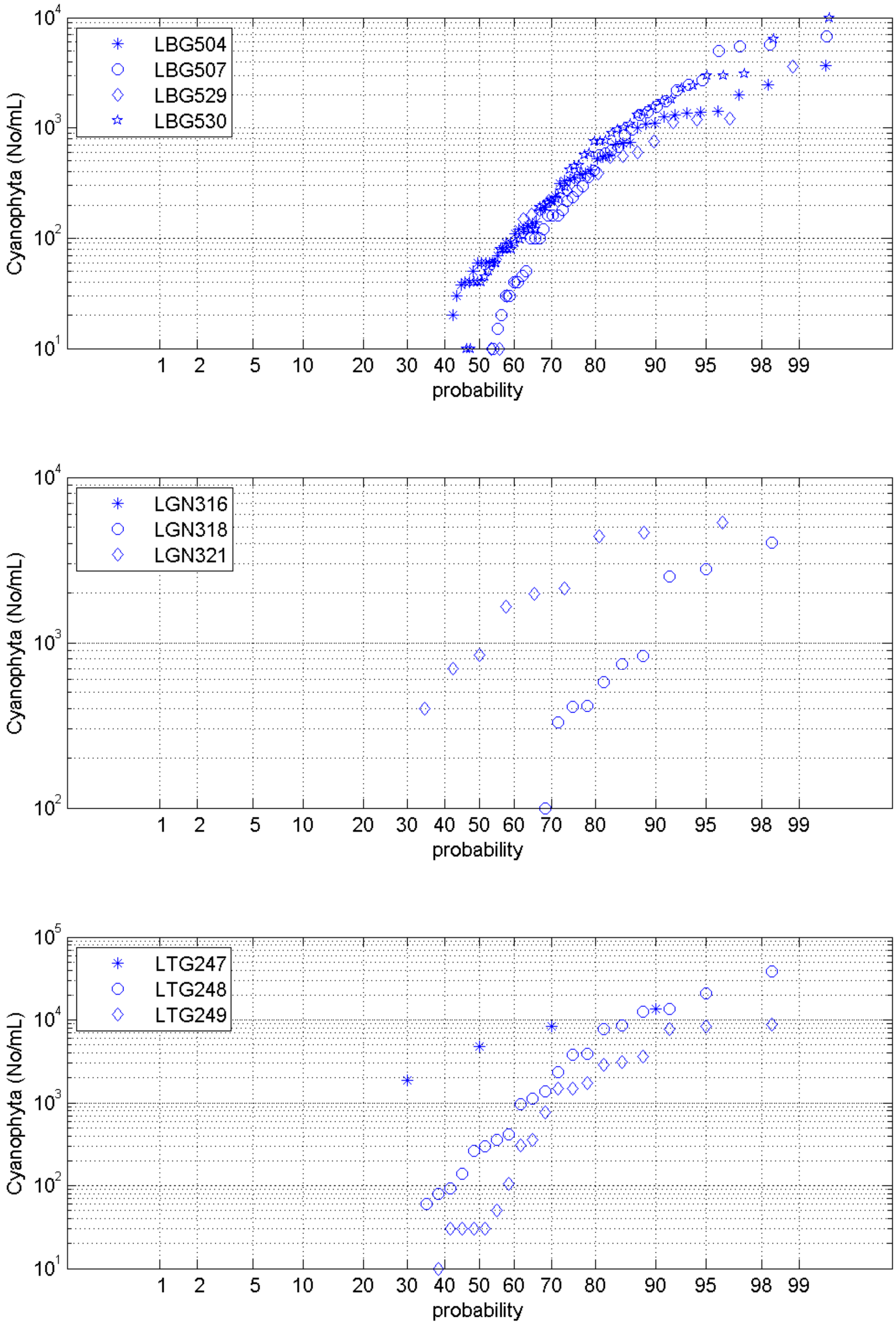
CDF_Total.png



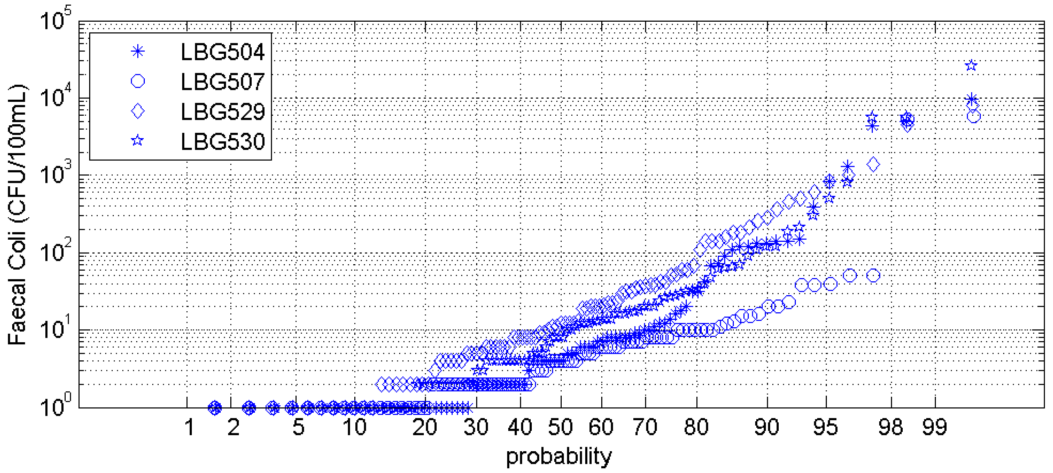
WRL Report No. 2006/35	N:P RATIO PROBABILITY DISTRIBUTIONS	Figure 12 CDF_NPrat.png

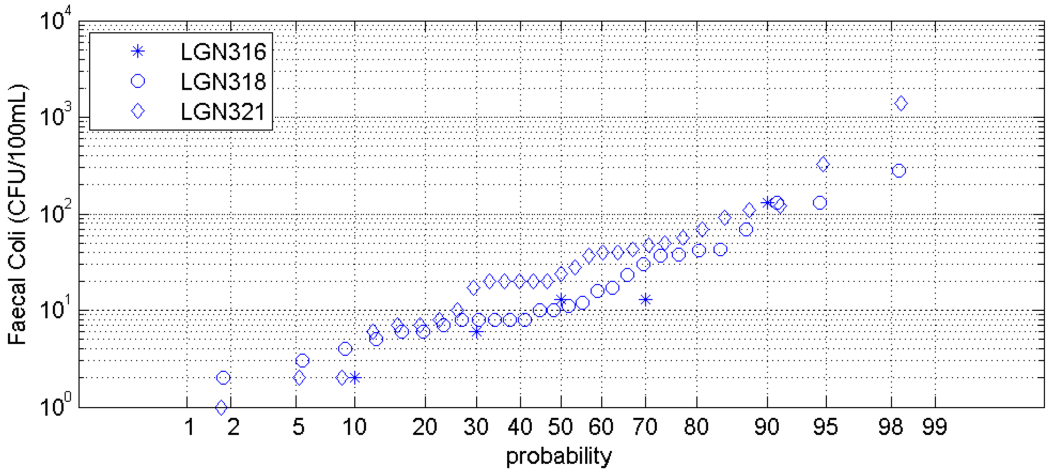


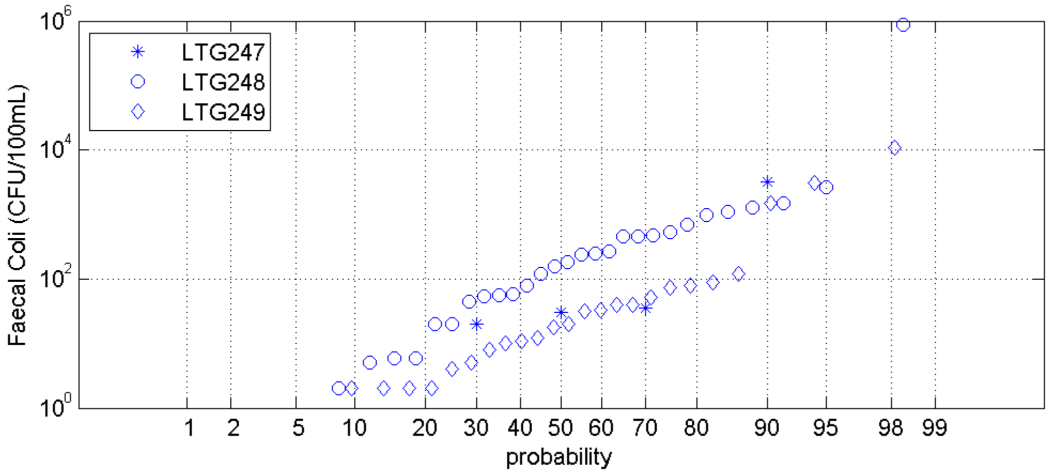
WRL Report No. 2006/35	CHLOROPHYLL *a* PROBABILITY DISTRIBUTIONS	Figure 13 CDF_Chlor.png



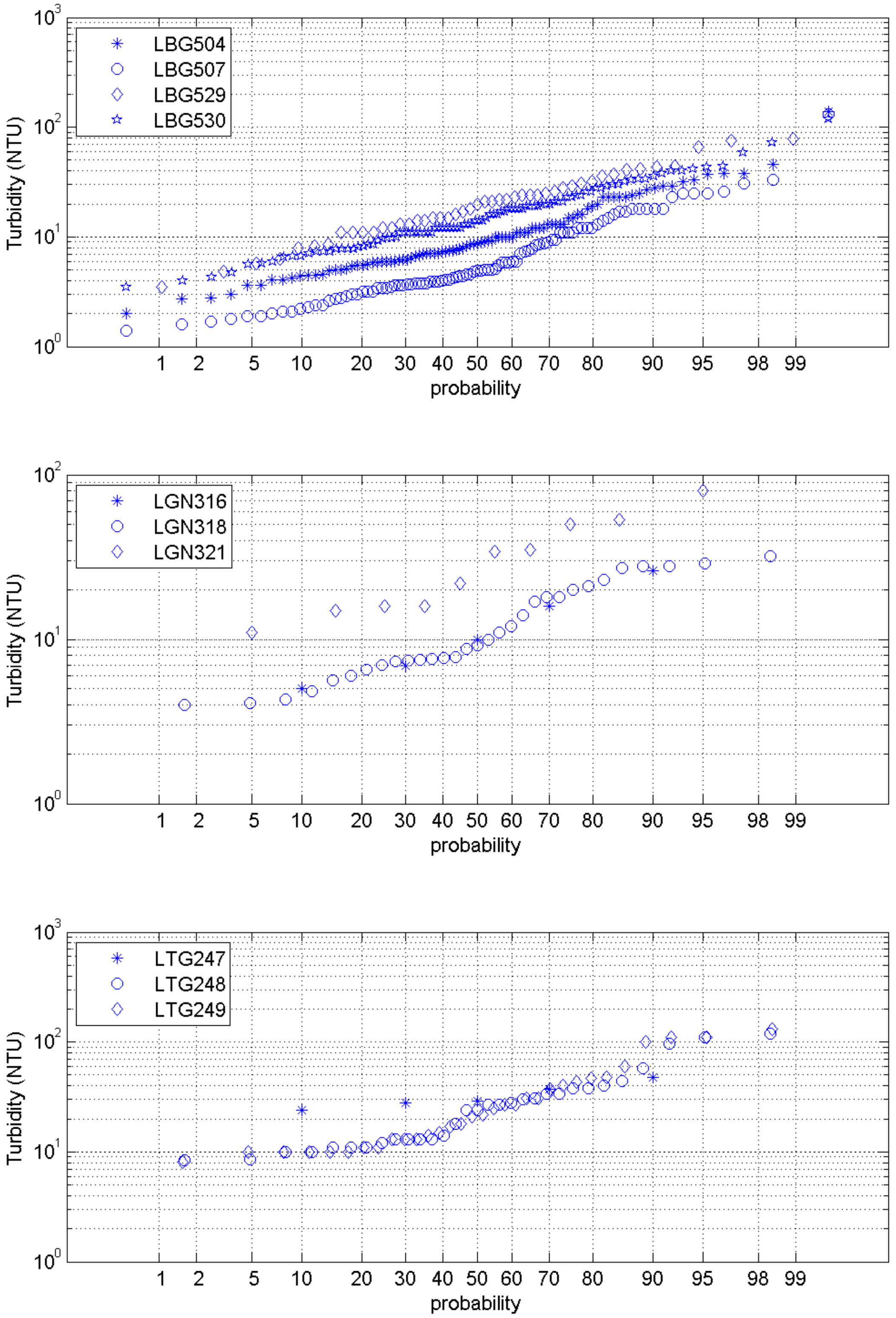
LBG504
LBG507
LBG529
LBG530
Cyanophyta (No/mL)
probability
LGN316
LGN318
LGN321
Cyanophyta (No/mL)
probability
LTG247
LTG248
LTG249
Cyanophyta (No/mL)
probability







WRL Report No. 2006/35	FAECAL COLIFORM BACTERIA PROBABILITY DISTRIBUTIONS	Figure 15 CDF_Conf_.png



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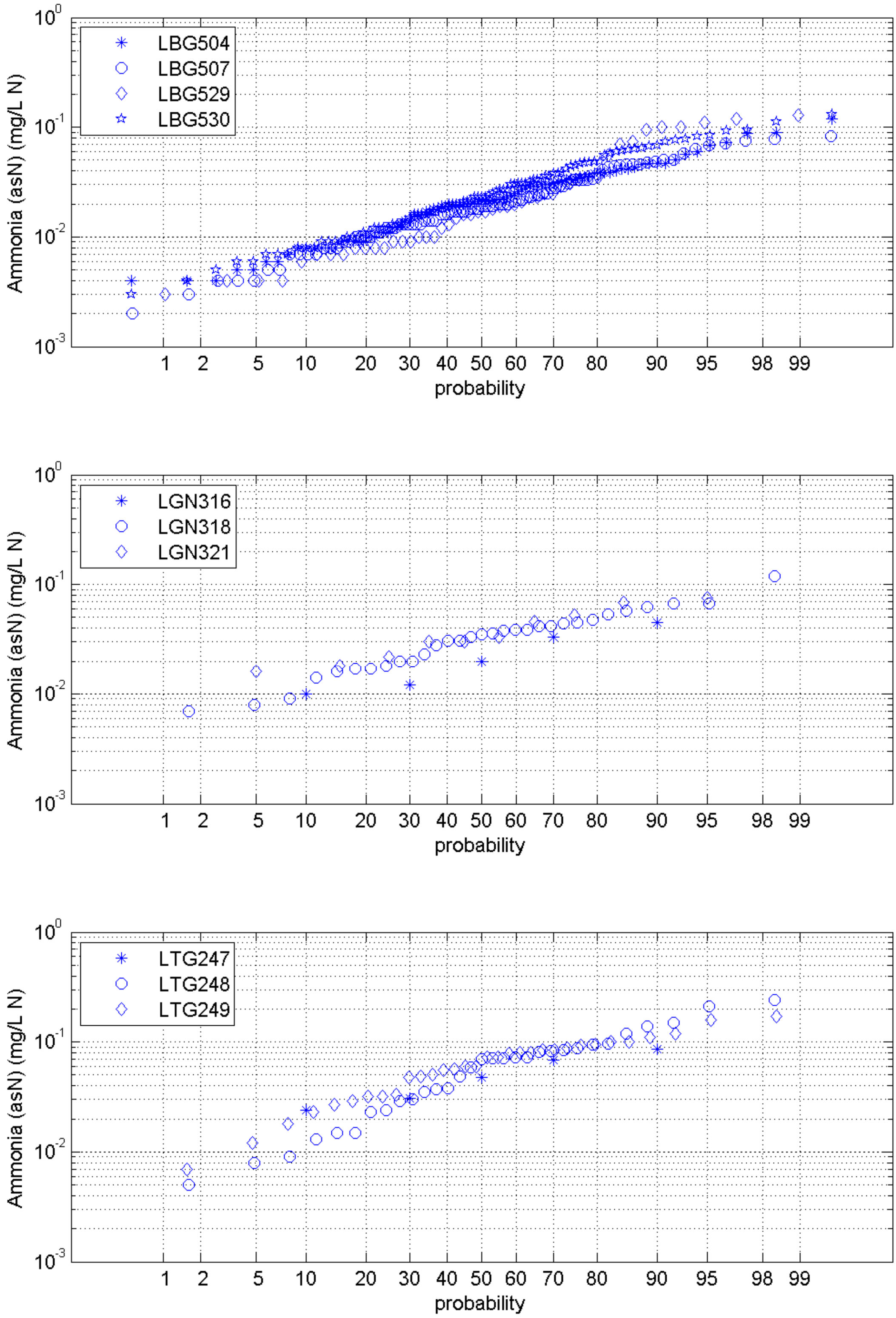
TURBIDITY PROBABILITY DISTRIBUTIONS

Figure 16

CDF_Turbi.png



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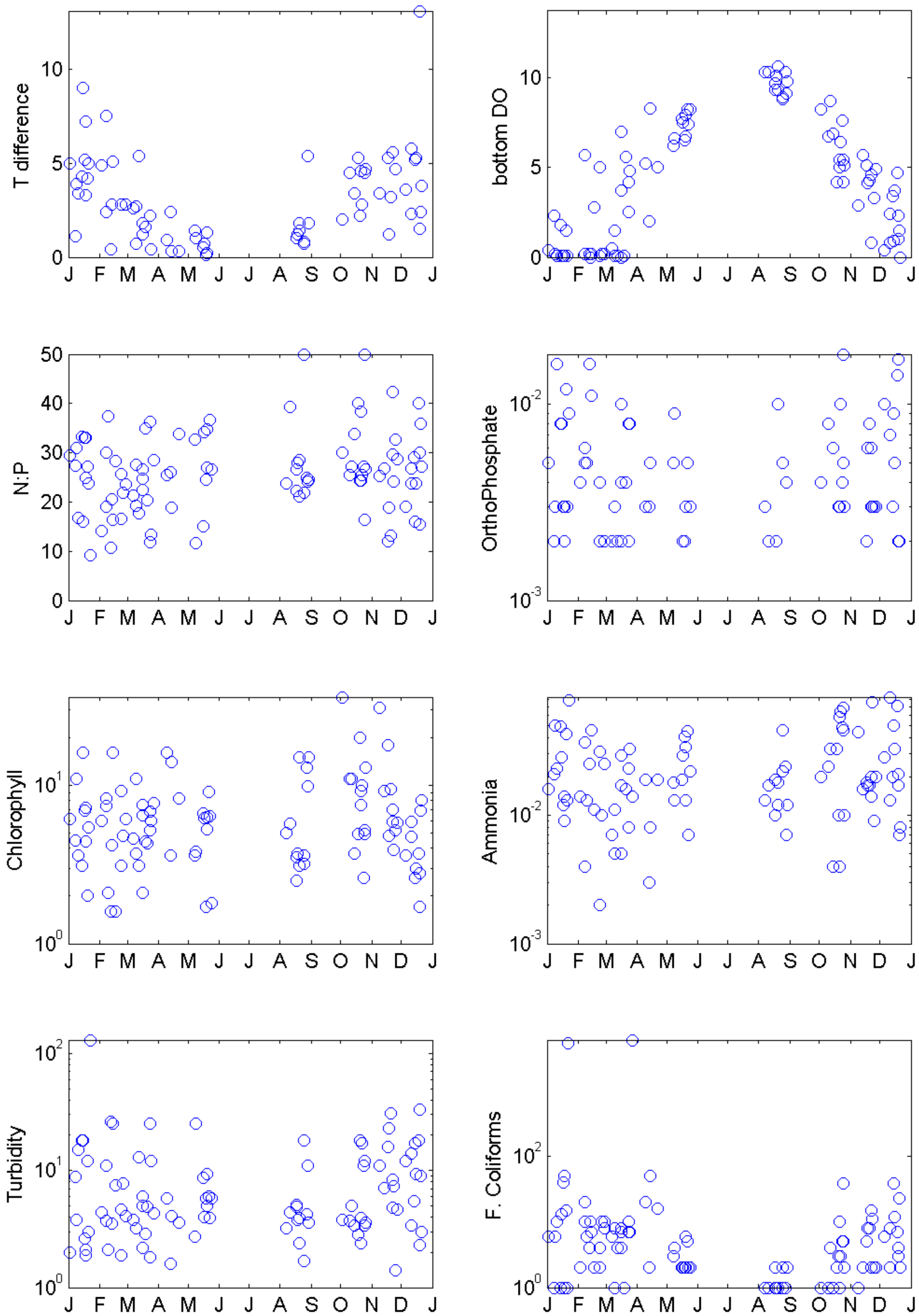
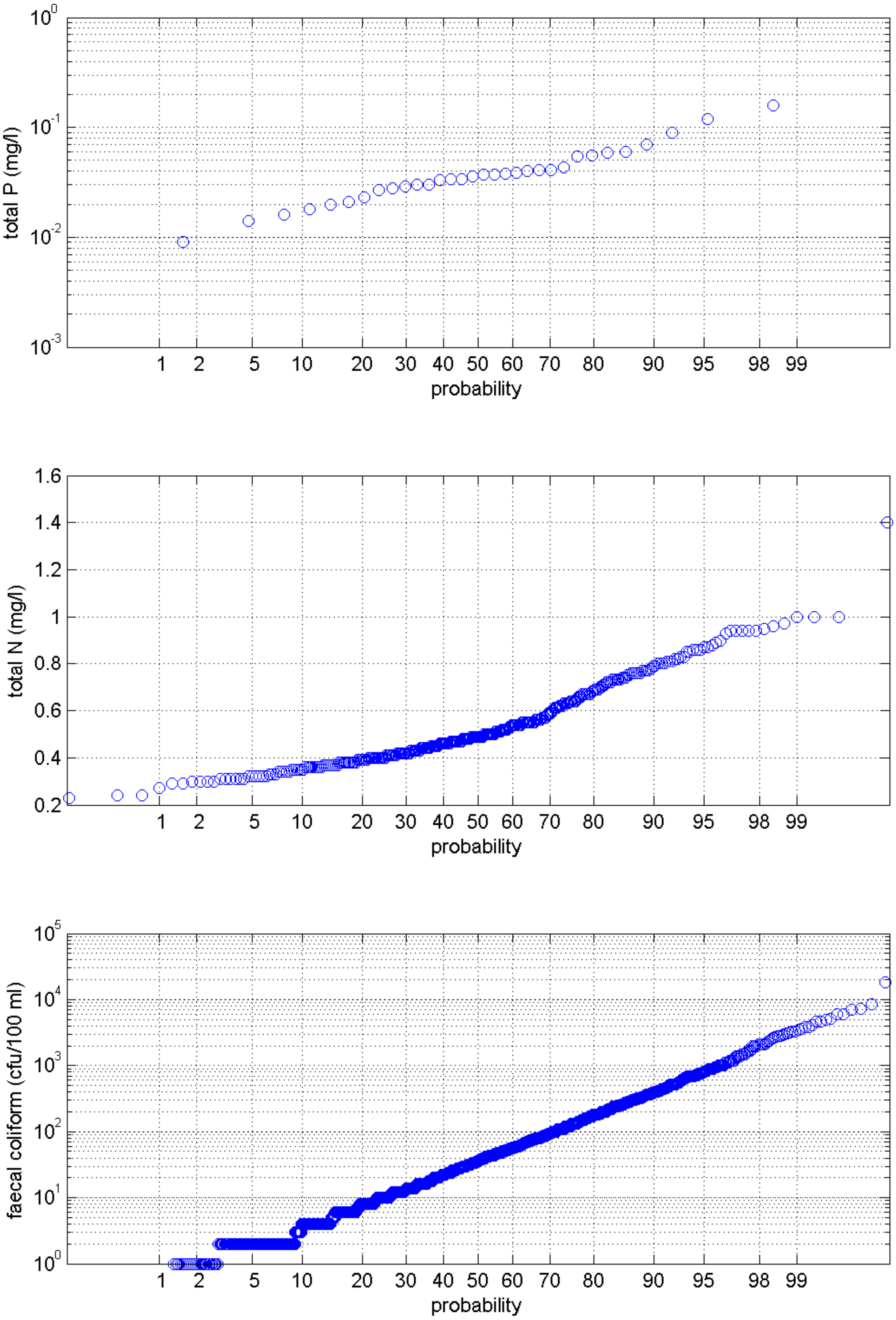
AMMONIA PROBABILITY DISTRIBUTIONS

Figure 17

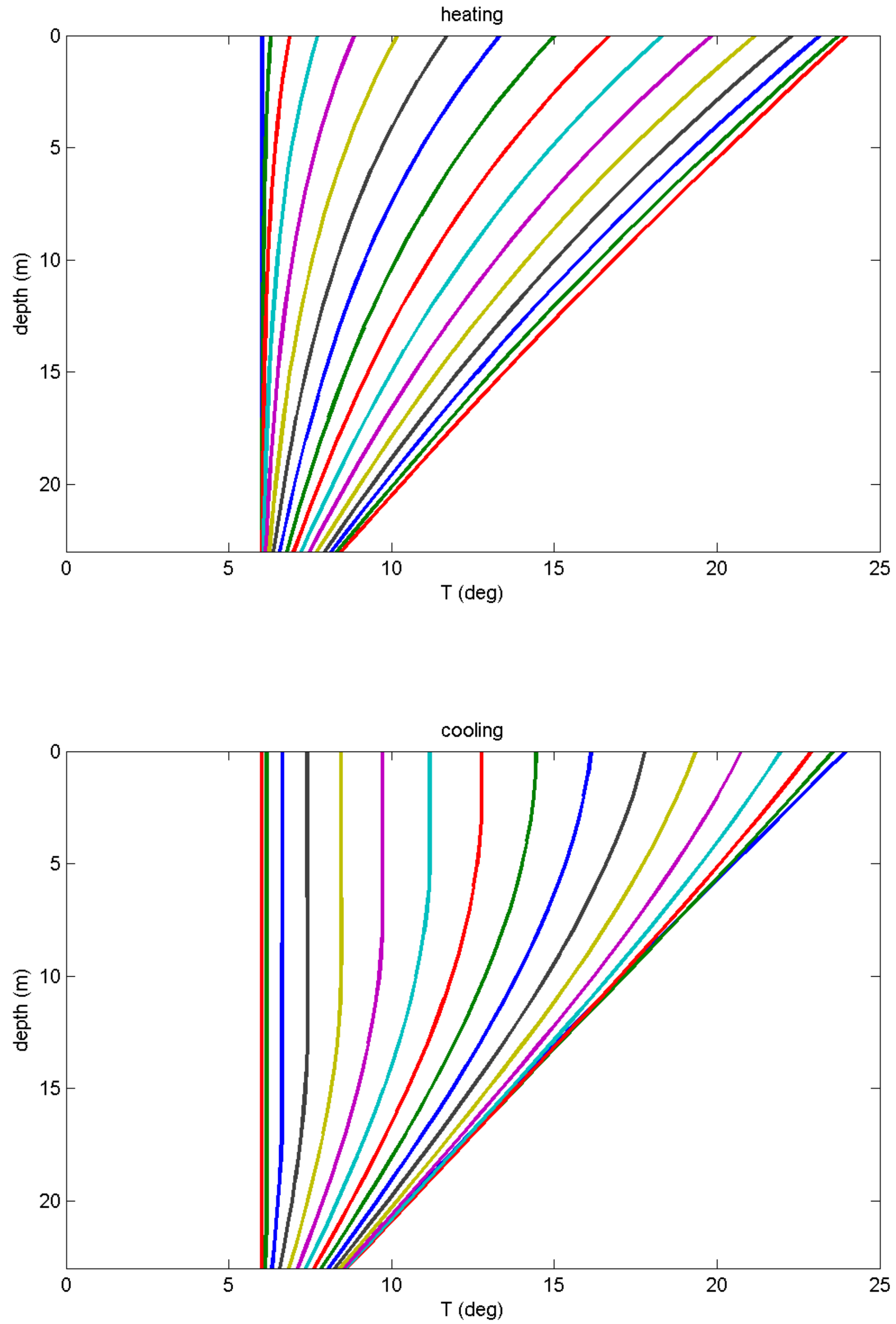
CDF_Ammon.png



WRL Report No. 2006/35	SEASONAL PLOT OF SELECTED WATER QUALITY PARAMETERS	Figure 18 seasonal_LBG507.png



WRL Report No. 2006/35	PROBABILITY DISTRIBUTIONS OF SELECTED PARAMETERS AT COPPINS CROSSING	Figure 19 CDF_Coppins.png



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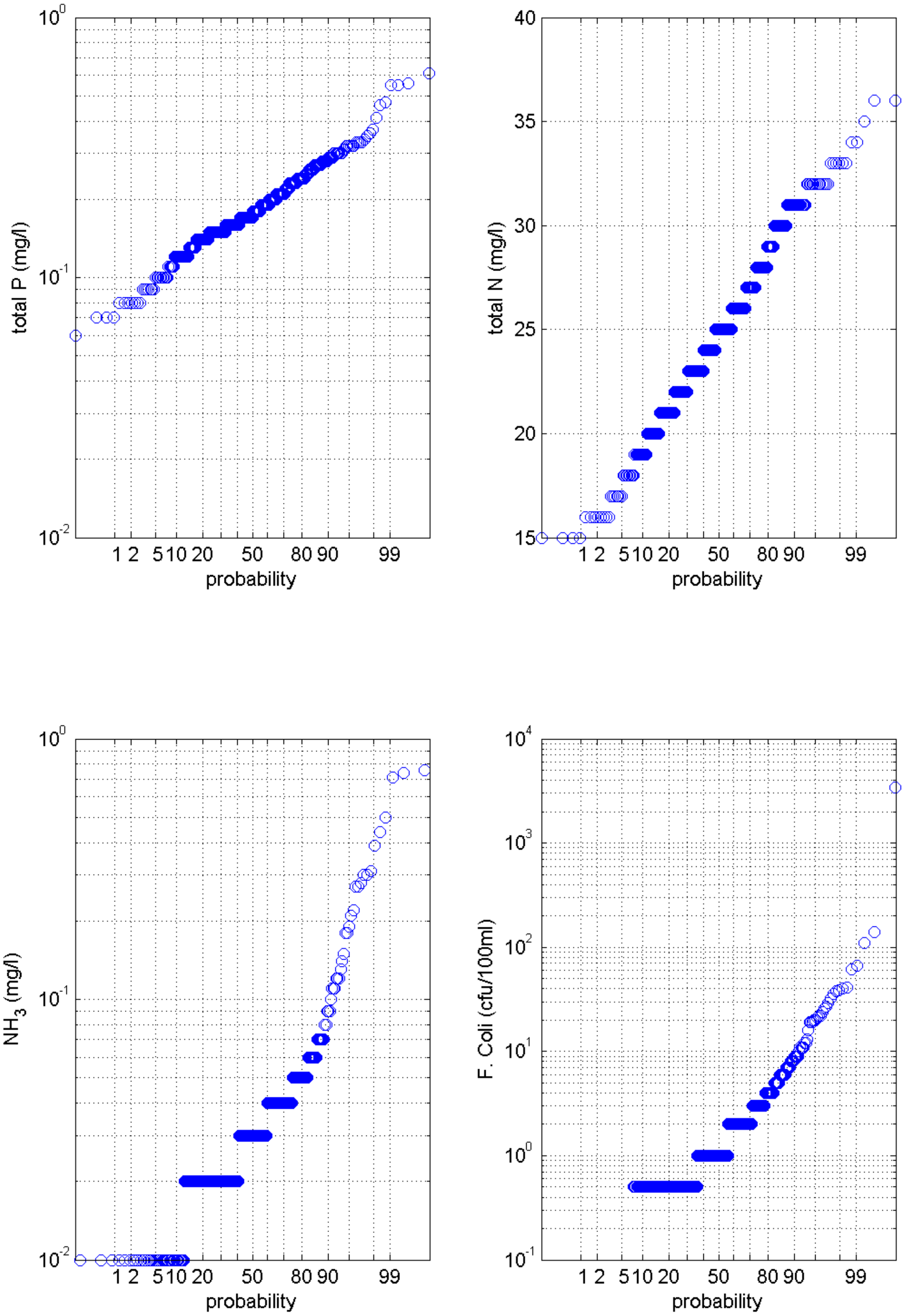
ONE-DIMENSIONAL MODEL OF SEASONAL HEATING AND COOLING

Figure 20

oneDmod.png



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PROBABILITY DISTRIBUTIONS OF SELECTED LMWQCC EFFLUENT PARAMETERS

Figure 21

lmwqc_effluent.png