Review of the River Murray Phytoplankton Monitoring Program

A Report to the Murray-Darling Basin Authority

by

Roger Croome
InfoRail Pty Ltd

and

Rod Oliver
CSIRO Land and Water Flagship

26 June 2015

Accessibility

The Murray–Darling Basin Authority makes its documents and information available in accessible formats. On some occasions the highly technical nature of the document means that we cannot make some sections fully accessible. If you encounter accessibility problems or the document is in a format that you cannot access, please contact us.

SUMMARY

Key observations and Recommendations

The Phytoplankton Monitoring Program (PMP) is a key part of the MDBA's integrated physicochemical and biological water quality monitoring of the Murray, as defined within the National Water Quality Management Strategy, allowing it to meet its obligations under the Murray Darling Basin Agreement and Murray Darling Basin Plan.

A significant period of data collection is required in order to characterise the variability of phytoplankton communities and the PMP is only just reaching this level of detail, with statistical analyses of the data indicating that it provides a reliable basis for identifying changes within and between sites. The PMP has provided valuable information about the health of the river, yet is capable of much more.

It is the only program effectively assessing both the algae and cyanobacteria of the Murray system, and it does this in parallel with physicochemical and discharge measurements. Other monitoring, conducted by State agencies, is almost solely for nuisance cyanobacteria, and is largely operational in nature rather than for environmental purposes.

We recommend the PMP be maintained largely as is with respect to sample sites and sampling frequency, but consider the Darling and Murrumbidgee sites to be non-viable under the current sampling regime (although we see the Authority as being responsible for adequate sampling of tributaries as they enter the Murray). The Goolwa barrage site is also questionable, because it is not well connected to the remainder of the sampling sequence. (We are unable to be more specific here with respect to the Darling, Murrumbidgee and Goolwa sites without examination of the actual data, which was outside our remit.)

Equivalence of phytoplankton results assessed by different laboratories can best be assured by ongoing inter-laboratory discussions of techniques, taxonomy and data recording, and these should be fostered.

The PMP data set is currently under-utilised, in large part due to collation and storage issues, and these should be remedied. Wider use of the data should then be promoted, and it should be made more freely available.

Chlorophyll and Phaeophytin, indicators of phytoplankton biomass and health, are currently assessed in parallel with the samples for phytoplankton. To our knowledge, the Chlorophyll/Phaeophytin data are yet to be assessed, and it is suggested this be done to determine their value.

Recent work on a subset of the data (2011) identified key drivers of phytoplankton abundance within the river, and promoted modelling to link variations in algae and cyanobacteria with individual environmental variables. This work would be particularly relevant in building a model with predictive ability, and should be advanced.

Aim of this review

The objective of this review is "to assess the effectiveness, utility and efficiency of the Phytoplankton Monitoring Program (PMP) of the Murray Darling Basin Authority, and develop recommendations for any cost effective changes that enable statutory obligations for monitoring to be met".

Environmental monitoring

Environmental monitoring provides the information required to identify changes in natural and managed systems, highlighting the need for management actions to halt or reverse detrimental shifts in condition. The aim of environmental monitoring is to systematically sample and record characteristics of an environment in such a way as to provide a long term reliable record suitable for detecting and interpreting trends in changing conditions and identifying their causes. This provides the information to improve management planning and to assess the results of management actions.

The monitoring of water quality in the Murray and key tributaries was initiated in 1978 as physicochemical sampling at 32 sites. This was supplemented in 1980 by the addition of aquatic macro-invertebrate monitoring at 14 sites, and weekly phytoplankton sampling at 15 sites. Initially focussed on assessing water quality to ensure safety of supply, the program has more recently also served to identify water requirements for sustaining the ecological integrity of the system, especially in the context of the water sharing processes envisaged in the Murray Darling Basin Plan.

Phytoplankton

Phytoplankton comprises the microalgae and cyanobacteria that grow within the water column of aquatic systems. Phytoplankton abundances and community composition change rapidly in response to a range of environmental conditions including meteorological, hydrological and physicochemical characteristics. This makes them a useful indicator of short-term changes in environmental conditions. Cumulative changes in abundance and community composition in response to sustained shifts in environmental conditions also make them useful indicators of annual and longer-term changes in conditions. Long-term data sets of appropriate short-term resolution are required to interpret these connections and to underpin the development of models for management purposes.

Context and requirement of water quality monitoring

The three components of the Authority's monitoring (water quality, macro-invertebrates, phytoplankton) acquire data on cause and effect variables, and thus address the statutory criterion of an "effective" monitoring program. Effectiveness has been considered here to be the degree of compliance with the Australian Guidelines for Water Quality Monitoring and Reporting within the National Water Quality Management Strategy (NWQMS). Those guidelines promote the use of integrated assessments, which merge biological (effects) and chemical (causes) to give an integrated assessment of ecosystem health. Because of the role of phytoplankton in carbon fixation and food web dynamics, it remains a key driver of the instream ecosystem and water quality condition, and an integral component of any water quality monitoring program.

History of the Phytoplankton Monitoring Program

The PMP began in 1980 with 15 sites, from Jingellic to Tailem Bend. Two sites above Lake Hume and a site at Lock 5 were dropped early on, leaving the program as weekly sampling at 9 sites along the Murray, and at 3 tributary sites (Barr Ck., Murrumbidgee R., Darling R.) until 2013.

A further reduction in water quality monitoring sites in December 2013 led to Barr Ck. being dropped, and sampling of the Darling and Murrumbidgee Rivers being reduced to monthly. A site at Goolwa was added at this time, with weekly sampling.

A large data set has thus accumulated, last consolidated with water quality and discharge data as part of a report on the PMP in June 2011.

Current Phytoplankton Monitoring Program

12 sites are currently monitored by the MDBA for phytoplankton: 10 'mainstream sites' from Heywoods Bridge (just below Lake Hume) to the barrage at Goolwa are sampled weekly; and 2 'tributary sites' (in the Murrumbidgee and Darling) are sampled monthly. The value of monthly sampling, and thus the viability of the tributary sites, is questioned (although we see the Authority as being responsible for adequate sampling of tributaries as they enter the Murray). Likewise, the value of the site at Goolwa in describing the influence of Murray River inflows on the phytoplankton of Lake Alexandrina is questioned.

Phytoplankton counts are conducted by ALS Global in Melbourne and the Australian Water Quality Centre in Adelaide, and forwarded to the MDBA for collation. Equivalence of phytoplankton results assessed by different laboratories can best be assured by ongoing inter-laboratory discussions of techniques, taxonomy and data recording, and these should be fostered.

We regard the PMP data set to be currently under-utilised, in large part due to collation and storage issues, and recommend these be remedied. Wider use of the data should then be promoted, and it should be made more freely available.

The current aim of the PMP was re-stated in 2005 as the provision of long term data on the algal populations of the River Murray, in order that changes in the species abundance and composition may be identified and related to changes in the river environment. Samples to determine such changes in species abundance and composition are collected in the knowledge that typical doubling times of natural phytoplankton populations are around three days, but can be less than one day.

Past findings, reports and publications

There have been four substantial reports reviewing the PMP and its data, and several reports by the MDBA and its predecessor MDBC on water quality have contained phytoplankton material. Numerous other papers/reports have depended heavily on the PMP data, and there have been many papers/reports on the Murray system which have included information on phytoplankton/cyanobacteria collected in part for the Authority or generated separately by other research groups. The four reviews of the PMP are discussed in the text, and reviews, reports and papers are listed in Appendix A.

The reports and reviews have built significant understanding of the patterns of phytoplankton growth along the river and over time. The most recent review of the PMP (2011), included statistical work on a subset of the data which identified key drivers of phytoplankton abundance, and promoted modelling to link variations in algae and cyanobacteria with individual environmental variables. This work would be particularly relevant in building a model with predictive ability, and should be advanced.

Chlorophyll and Phaeophytin

Chlorophyll and Phaeophytin, indicators of phytoplankton biomass and health, are currently assessed in parallel with the samples for phytoplankton, as recommended by Lawrence and Paterson (2005). To our knowledge, the Chlorophyll/Phaeophytin data are yet to be assessed, and it is suggested this be done to determine their value.

Satisfaction of statutory requirements

The PMP has a crucial role in enabling the Murray-Darling Basin Authority to fulfil the statutory responsibilities of Clauses 44-46 of the Murray-Darling Basin Agreement, Schedule 1 of the Water Act 2007 and requirements of the Basin Plan 2012. Variations in phytoplankton populations and community composition reflect both on aspects of water quality and specific environmental objectives. Because of the rapid changes in phytoplankton populations in response to changing environmental conditions, a significant period of data collection is required in order to characterise the phytoplankton communities. With weekly sampling estimates of the data requirement are in the order of 15 years. The PMP has reached this extent with sufficiently reliable data to enable detailed analyses. However, because of the fluctuations in the influencing variables such as flow and meteorology and because the system is not stationary but varying in time due to changing pressures including from climate shifts, continued monitoring is necessary to assess these changing conditions.

State sampling for phytoplankton

"Phytoplankton" sampling occurs at 50-60 other sites along the Murray, conducted by State agencies. However, this sampling is targeted almost solely at problem cyanobacteria, and is thus "operational sampling" for purposes of water supply and recreation, rather than "environmental assessment" to determine longer term changes across all phytoplankton groups in response to modified catchment management and riverine conditions.

We were struck by the number of sites being monitored in this way, but also by the occasional comment that it would be beneficial if States shared phytoplankton monitoring data a little more freely where needs overlapped.

There are no other programs along the Murray system which monitor the broader phytoplankton community. Indeed, the only sites identified at which anything other that cyanobacteria are assessed are 4 sites in or just below Lake Hume (sampled by North East Water - fortnightly to monthly from November to March) which, along with cyanobacteria counts, classify “other phytoplankton” simply as abundant, common, frequent, occasional or rare. There are 20 sites from the outlet of Lake Victoria to Murray Bridge (assessed weekly by the SA Water) which, along with problem cyanobacteria, include counts of 1 or 2 of the dominant taxa present, which may also be cyanobacteria. All other phytoplankton assessment by State agencies along the Murray is for cyanobacteria only, much of it on an ‘as required’ basis.

Table of Contents

INTRODUCTION

1.1 Background and objectives of this review

There has been considerable budget pressure on the MDBA's joint-funded statutory water quality monitoring program in recent years, with substantial reductions to the physico-chemical component (50%) and the macro-invertebrate component (30%). The need for and size of the phytoplankton monitoring component is now under scrutiny by the jointly contributing governments. In approving the MDBA's joint funding for 2014-15, the Ministerial Council included provision for a review of the Phytoplankton Monitoring Program to be undertaken, in response to continuing budget pressure on available funds. It is expected that this review will inform their future decisions on funding for the Program.

The objective of this review is "to assess the effectiveness, utility and efficiency of the Phytoplankton Monitoring Program and develop recommendations for any cost effective changes that enable the statutory obligations for monitoring to be met."

1.2 Environmental monitoring

Environmental monitoring is a key component of environmental management. It provides the information required to identify changes in natural and managed systems, highlighting the need for management actions to halt or reverse detrimental shifts in condition. The aim of environmental monitoring is to systematically sample and record characteristics of an environment in such a way as to provide a long-term reliable record suitable for detecting and interpreting changes in conditions and their causes, to determine trends, to improve management planning, and to assess the results of management actions.

The importance of such monitoring has long been recognised for the Murray River and beyond, with the River Murray Commission, the Murray-Darling Basin Commission and now the Murray-Darling Basin Authority having relevant statutory responsibilities. A physico-chemical water quality monitoring program was initiated in 1978 at 32 sites along the system and was supplemented in 1980 by the addition of aquatic macro-invertebrate monitoring at 14 sites, and weekly phytoplankton monitoring at 15 sites. Initially the focus was on assessing water quality to ensure the safety of domestic, industrial and agricultural water supplies and of aquatic recreational activities. More recently the need to identify water requirements for sustaining the ecological integrity of the aquatic ecosystem has gained impetus, especially in the context of the water sharing processes envisaged in the Murray Darling Basin Plan. The monitoring required for this purpose puts an increased emphasis in particular on assessing changes in the biological components of the system.

1.3 Phytoplankton

Phytoplankton are generally considered a critical element of water quality monitoring programs worldwide because of their multi-faceted role in aquatic ecosystems. Phytoplankton comprises the microalgae and cyanobacteria that grow within the water column. These are microscopic, photosynthetic plants and bacteria that contribute significantly to the food resources at the base of aquatic food webs, culminating in food resources for higher organisms including fish. In some waterways attached organisms including microalgae, bacteria and aquatic macrophytes, also contribute to the food resources of food webs, but in many situations phytoplankton production predominates, and this is the case in the Murray River (Oliver and Merrick 2006; Oliver and Lorenz 2010). As a consequence, monitoring of the abundance of phytoplankton and their community composition is important in identifying the food resources available for food webs. In addition, phytoplankton have other attributes that make them important in water quality monitoring. Paramount of these is that increased concentrations of phytoplankton often result in significant water quality issues. Elevated concentrations of phytoplankton can interfere with water treatment plants by blocking filters, upsetting coagulation and settling processes, and introducing a large amount of organic matter that may induce taste and odour problems, or be converted to undesirable by-products during the water treatment process. In addition certain phytoplankton groups, especially members of the cyanobacteria, directly produce taste and odour compounds and also irritants and toxins that are potentially harmful to animals and to humans. Concerns with cyanobacteria are also relevant to the recreational use of waterways where contact with and swallowing of contaminated water may be a health risk.

Increased concentrations of phytoplankton also affect aquatic ecosystems when their metabolic activity results in large fluctuations in oxygen concentrations, which may be sufficient overnight to reduce concentrations to levels lethal to aquatic animals, sometimes resulting in fish kills. This extreme situation is less common in rivers where oxygen exchange at the water surface is distributed by mixing and buffers the oxygen depletion. However in poorly mixed standing waters, such as weir pools, de-oxygenation is more likely.

The sedimentation of phytoplankton provides an important source of organic material to benthic organisms, and influences sediment biogeochemical cycles. The release of nutrients, metals and other compounds from the sediments is significantly influenced by this supply of organic material. Increased releases of nutrients from the sediments lead to increases in phytoplankton blooms, often dominated by cyanobacteria.

Phytoplankton abundances and community composition change rapidly in response to a range of environmental conditions including meteorological, hydrological and physico-chemical characteristics. This makes them a useful indicator of short-term changes in environmental conditions. Cumulative changes in abundance and community composition in response to sustained shifts in environmental conditions also make them useful indicators of annual and longer-term changes in conditions. Long term data sets of appropriate short-term resolution are required to interpret these connections and to underpin the development of models for management purposes. This is analogous to the sampling requirements needed to reliably monitor and model hydrological change.

1.4 Context and requirement of the Murray River monitoring

The Phytoplankton Monitoring Program is one of three components of the River Murray Water Quality Monitoring Program (RMWQMP). The other two are a physicochemical component and a macro-invertebrate component. These three components were established to acquire data on both cause and effect variables, so as to address the statutory criterion of an “effective” monitoring program. Effectiveness has been considered here to be the degree of compliance with the Australian Guidelines for Water Quality Monitoring and Reporting within the National Water Quality Management

Strategy (NWQMS). Those guidelines promote the use of integrated assessments, which merge biological responses (effects) and chemical and hydrological changes (causes) to give an integrated assessment of ecosystem health, hence the establishment of the three components of the RMWQMP.

The current requirements for the measurement of water quantity and quality are set out in the Murray Darling Basin Agreement (Water Act 2007), Appendix A, Schedule 1, Part VII, "Investigation, Measurement and Monitoring". In essence this Schedule states that the MDBA must establish, maintain and operate an effective and uniform system for making and recording continuous measurements of hydrological characteristics of the River Murray and its tributaries, and for measuring and monitoring the quality of River Murray water, stored water and water in tributaries of the River Murray at or near the confluence with the River Murray as considered necessary after consultation with the appropriate States (clause 45). The Authority can establish monitoring systems in the upper River Murray and the River Murray in South Australia, but in general not within the territories of any State without consent (clause 46). Clause 47 addresses this limitation by enabling the Authority to adopt the monitoring results of any of the cooperating States, or to request that States carry out monitoring in a manner that the Authority considers necessary. An important requirement of the Basin water quality monitoring is to enable the assessment of any major proposal that would significantly influence the hydrological and water quality characteristics of the upper River Murray and the River Murray in South Australia. The statutory obligation is that the States inform the Authority of any such proposal in a timely manner and provide the necessary information and data to assess the anticipated effect on the hydrology and water quality. In this context water quality includes influences on phytoplankton and prediction of effects will require the availability of reliable models.

The water quality objectives are further expanded in the Murray Darling Basin Plan (Chapter 13 Part 2 Section 13.03) that states the responsibility for leading the monitoring and evaluation of the Plan lies with the Authority. The overarching objectives in relation to environmental outcomes are to protect and restore water dependent ecosystems and their ecosystem functions to ensure that they are resilient to threats and risks including climate change (Chapter 5, Section 5.03). The monitoring required to achieve this is to be done efficiently using existing monitoring capabilities and eliminating duplication and fragmentation of monitoring where possible. Data is to be shared and information collated using the best available knowledge, evidence and analysis to ensure credibility, transparency and usefulness of the monitoring and evaluation findings.

The overall environmental objectives for water dependent ecosystems (Chapter 8 Part 2 Section 8.04) are: (a) to protect and restore water-dependent ecosystems of the MDB; (b) to protect and restore the ecosystem functions of water dependent ecosystems; (c) to ensure that water water-dependent ecosystems are resilient to climate change and other risks and threats. Particular objectives relating to specific components of these general objectives are set out in the remaining Chapter 8 and many are relevant to the PMP, but one of importance is the objective in Section 8.06 (7), "to protect and restore ecological community structure, species interactions and food webs that sustain water-dependent ecosystems, including by protecting and restoring energy, carbon and nutrient dynamics, primary production and respiration".

The objectives in relation to water quality and salinity are to maintain appropriate water quality so that water resources remain fit for purpose for the environmental, social, cultural and economic activity in the Basin (Chapter 5, Section 5.04.). This includes minimizing the risk that raw water taken for treatment for human consumption results in adverse health effects, and to maintain the palatability rating of treated water at good, as set out in the Australian Drinking Water Guidelines (ADWG 2011). The water quality targets for recreational activities are limited to the occurrence of cyanobacteria as set out in the Australian Guidelines for Water Quality Monitoring and Reporting within the National Water Quality Management Strategy (NWQMS). Due to concerns about the occurrence and dramatic impact of cyanobacteria on water quality, extensive but *ad hoc* operational sampling is carried out by the individual States.

2. HISTORY OF THE RIVER MURRAY PHYTOPLANKTON MONITORING PROGRAM (PMP)

In 1980, 15 sites were established with monthly sampling above Lake Hume at 2 sites, and weekly sampling below Lake Hume at 10 Murray River sites and 3 tributary sites (Table 1). The two sites above Lake Hume were dropped early on, as was a site in South Australia at Lock 5, leaving the program as weekly sampling at the remaining 12 sites until 2013.

A reduction of the Water Quality Monitoring Program in December 2013 led to one tributary site (Barr Ck) being dropped, and the sampling at the two other tributary sites (Darling R, Murrumbidgee R) being reduced to monthly as part of the States adoption of a "monthly-only" sampling frequency for all their MDBA-funded tributary sites. A site at Goolwa was added at this time.

Table 1. Historical listing of sampling sites for the Phytoplankton Monitoring Program.

Original Sites 1980/ Weekly sampling	Sites discontinued early	Sites extant 2013	Sites altered December 2013
Murray – Jingellic	X		
Mitta - Tallandoon	X		
Murray – Heywoods		X	
Murray – Yarrawonga		X	
Murray – Torrumbarry		X	
Barr Ck – Capels Flume*		X	Removed
Murray – Swan Hill		X	
Murrumbidgee – Balranald		X	Made monthly
Murray – Euston		X	
Murray – Merbein		X	
Darling – Burtundy		X	Made monthly
Murray – Lock 9		X	
Murray – Lock 5	X		
Murray – Morgan		X	
Murray – Tailem Bend		X	
New sites			
Goolwa			Added, sampled weekly

*Actually added 1983

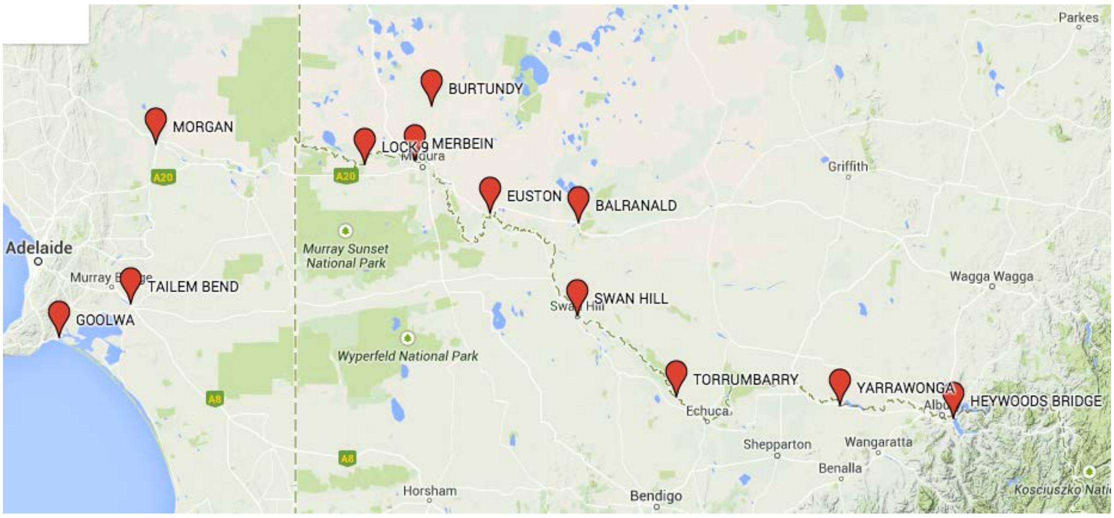
3. CURRENT ELEMENTS OF THE PMP AND THEIR ASSESSMENT

3.1 Structure

The current sampling sites of the MDBA Phytoplankton Monitoring Program are listed in Table 2, together with responsibility for sampling and counting, and shown in Map 1.

Table 2. Listing of current sites within the Phytoplankton Monitoring Program.

Station ID	Station	Sampling responsibility	Counting responsibility
409016	Murray at Heywoods Bridge	Vic	Vic
409025	Murray D/S Yarrawonga Weir	NSW	Vic
409207	Murray D/S Torrumbarry Weir	Vic	Vic
409204	Murray at Swan Hill	Vic	Vic
410130	Murrumbidgee at Balranald	NSW	Vic
414209	Murray at Euston	NSW	Vic
414206	Murray at Merbein	NSW	Vic
425007	Darling at Burtundy	NSW	Vic
4260501	Murray at Lock 9	SA	SA
4260554	Murray at Morgan	SA	SA
4260551	Murray at Tailem Bend	SA	SA
4261034	Goolwa U/S Barrage	SA	SA



Map 1. Location of the 10 mainstem and 2 tributary sites of the current Phytoplankton Monitoring Program.

3.2 Frequency and type of sampling

Samples are currently taken at weekly intervals from 9 sites along the main channel of the Murray River, at Heywoods, Yarrawonga, Torrumbarry, Swan Hill, Euston, Merbein, Lock 9, Morgan, and Tailem Bend and a sample is also taken at the single site of Goolwa in Lake Alexandrina (Map 1). Additionally samples are taken at monthly intervals from near the confluences of two tributaries, the Murrumbidgee River at Balranald and the Darling River at Burtundy.

Near surface samples are collected using a dip bottle except for Morgan and Tailem Bend which are collected via sample pump. Phytoplankton in the samples are preserved by addition of Lugol's iodine. For a well mixed river, the preferred sample is one taken mid-stream at a depth of 0.5 m. For a comprehensive discussion of sampling requirements under other conditions of mixing see Hotzel & Croome (1999).

The fixed and stable samples are then sent to the relevant laboratory for phytoplankton identification and enumeration. Over the period of collection, approximately 35 years for the core sites, there have been changes in the methods. Often these have been well documented, enabling continuous periods of reliable data to be collated. Occasionally less than satisfactory identification and enumeration methods have been employed for extended periods of time, and this data has been difficult to include in analyses. From an historical context the decisions that led to the unreliable data collections were unfortunate, leaving no legacy for future re-assessment and undermining the logic of an environmental monitoring program.

Frequency of sampling:

The weekly sampling protocol is determined by the potential for phytoplankton to grow rapidly in response to changing environmental conditions. Typical doubling times of natural populations are around 3 days, but if environmental conditions improve due to changes in flow, or increase in nutrient supply, or reduction in turbidity, then the phytoplankton can respond rapidly with growth rates of a doubling per day or even more being possible. On theoretical grounds the high variability in phytoplankton abundances means that ca. 500 samplings are required to provide a reliable data set to characterise the phytoplankton community (Carstensen 2007). Even this assumes a stationary system which is unlikely in most cases due to increasing human influences and major effects such as climate change. This is no different from identifying the characteristics of highly variable hydrological data where daily monitoring is required for many decades to provide a basis for reliable modelling. Consequently, weekly monitoring is the maximum sampling period that is likely to enable reliable assessment of these interactions in a time frame that will be useful to management. Even with weekly sampling it is likely to require over 10 years of data to provide a database sufficiently representative to begin to model these interactions. The review of the Physicochemical Monitoring Program found that the interaction of nutrient concentration and flow that culminates in a nutrient load to the system could not be reliably identified if sampling was greater than weekly (Baldwin et al 2013). Phytoplankton respond to both nutrient concentration and flow, as well as to other environmental attributes that can just as quickly change, and long term monitoring is required to unravel these interactions, as it is for water quality and hydrological assessments. As an example, the most recent review of the PMP (Croome et al 2011) showed that the frequency of cyanobacterial blooms in the system as a whole had not changed markedly over the period 1980-2008, remaining within a one to four-year range, with highest frequencies at the upstream sites. However, there was an observed increase in the duration of individual cyanobacterial blooms more recently. Without weekly sampling such critical observations about the changing nature of the system would not be possible.

Sampling sites:

Whereas the sampling frequency determines the reliability with which changes at a site can be identified and associated with environmental fluctuations, the number and location of sampling sites determines the reliability with which changes along the river can be assessed. A suitable array of sampling sites should enable basic management questions to be addressed. With respect to phytoplankton these are likely to be focussed on identifying differences in community composition along the river, and determining the extent to which changes at a site are associated with the longitudinal transport of phytoplankton from upstream or to enhanced growth in river reaches that are "hot spots" for phytoplankton population changes, perhaps due to influences such as tributaries, weirs, townships and agricultural activities.

Having knowledge of such river reaches is a basic requirement for management. Weirs and reservoirs are known change points for phytoplankton communities within river systems because of their water storage function, so this should be an important consideration in selecting monitoring sites. However, there is also a need to ensure that the river itself is being sufficiently monitored to be able to interpret the changes occurring within the channel in an ecological context including implications for biodiversity, food resources and ecosystem function.

The current main stem sampling sites, 9 in the channel of the Murray River below Lake Hume and one upstream of Goolwa Barrage in Lake Alexandrina, are distributed at reasonably regular intervals along the regulated section of the system, providing reasonable coverage of the ca. 2000 km of river (Map 1). It would seem difficult to argue for fewer sites over such a river length and previous analyses have indicated that the upper, middle and lower sections of the river have different phytoplankton communities.

The placing of these sites in relation to longitudinal transport also appears appropriate with most set apart by travel times of about 10 days, so that a weekly sampling frequency can identify differences between growth and transport over sets of sites (Table 3).

The unusual site within the sequence is the recently added station upstream of Goolwa Barrage as it does not connect directly into the sequence. It is unlikely to be representative of Lake Alexandrina, the system receiving the Murray flows, as it is in a side arm of the lake and significantly influenced locally by inflows from the Mt Lofty Ranges and seawater intrusions through the barrage. Presumably this site was selected for reasons other than describing the influence of Murray River inflows on the phytoplankton of Lake Alexandrina. For that purpose a location within Lake Alexandrina would be more suitable. One contender is Milang as it has an extensive history of water quality monitoring and is more likely to be representative of the lake and so might be more relevant to the phytoplankton monitoring program. It would also help to provide a more direct link with the Goolwa site.

Previously the PMP included some major tributaries because at times these can be major sources of phytoplankton populations. The 2013 changes in the Physicochemical Water Quality monitoring saw a reduction in the frequency of monitoring from weekly to monthly at all the tributary sites, with a consequential reduction in phytoplankton sampling at Burtundy on the Darling River and Balranald on the Murrumbidgee River. Although it would seem prudent to be monitoring phytoplankton from the major tributaries, and perhaps a responsibility of the Authority, it is unlikely that phytoplankton inflows from tributaries will be reliably identified from monthly sampling. This has rendered these sites somewhat obsolete for the purposes of environmental monitoring of phytoplankton (although we see the Authority as being responsible for adequate sampling of tributaries as they enter the Murray). Even for determining long-term trends, a prolonged monitoring period would be required, and even then reliability might be suspect due to the large variability.

Table 3. Travel times in days for the reaches of the Murray River. Travel time data kindly provided by MDBA staff via BIGMOD.

Reach	**Minimum**	**Median**	**Average**
Heywoods to Yarrawonga (237km)	4	10	13
Yarrawonga to Torrumbarry (358	8	11	12
km)	5	9	10
Torrumbarry to Swan Hill (220 km)	6	11	11
Swan Hill to Euston (294 km)	5	11	12
Euston to Merbein (c. 250 km)	2	9	11
Merbein to Lock 9 (c. 100 km)	12	40	49
Lock 9 to Morgan (c. 440 km)	7	40	55
Morgan to Tailem Bend (c. 235 km)			

Despite the apparent obligation of the MDBA to oversee the monitoring of water quality in stored waters there seems to be little phytoplankton information on the major storages that supply the waterways of the southern connected system (Dartmouth, Hume, Eildon, Burrinjuck, Lake Victoria). Reservoirs are the predominant source of water to the system and are known to significantly influence phytoplankton abundances and community composition and these phytoplankton can be transported downstream with water releases, impacting large stretches of the rivers.

3.3 Phytoplankton enumeration methodology

The PMP samples are currently counted in two laboratories, ALS Global in Melbourne and the Australian Water Quality Centre in Adelaide (see Table 2).

ALS uses the Utermohl method, in which phytoplankton cells are sedimented onto a glass coverslip and viewed from beneath using an inverted microscope. A time limit is set for counting, and past experience has determined the taxonomic categories into which the cells are placed: as individual species for the dominant diatoms; at genus level for the more common green algae; in family groupings for some diatoms; and in higher groupings for less common diatoms, cryptophyte, and golden-brown algae. Algae not readily placed into the above categories are simply recorded as "Other phytoplankton". The more important cyanobacteria in each sample are counted to genus level, while the less important are lumped as "Other Cyanophyceae".

PMP samples counted by the AWQC are subjected to a "Full enumeration" i.e. microscopic identification and enumeration of all (>80%) algae and cyanobacteria, reported as cells/mL. (Other Murray samples counted by the AWQC are subjected to "Partial enumeration" i.e. microscopic identification and enumeration of the dominant and noxious species, reported again as cells/mL.)

Similar phytoplankton samples assessed by different laboratories should, of course, yield similar results. This can be assured by ongoing inter-laboratory discussion of techniques, taxonomy and data recording, and these should be fostered. To identify and assess changes in phytoplankton community composition at a scale suitable for system management it is necessary to ensure that taxonomic resolution is adequate. The approaches used by the two laboratories appear suitable to achieve this but it is not apparent whether they are coordinated. Although the pragmatic approach of ALS seems sensible, it would be helpful to have a coordinated identification protocol across the laboratories, drawing on the information from recent reviews of the data.

3.4 Collation and availability of data

One of the terms of reference for the most recent examination of the PMP (by Croome *et al.* 2011) was the collation of the data for 1980-2008 into a single data base, and its submission to the MDBA at the completion of the project.

It is understood that since that time, the phytoplankton data progressively forwarded to the Authority by ALS Global and the Australian Water Quality Centre have simply been stored as raw data in Excel files.

Ready access to a consolidated phytoplankton data base, containing weekly data from all sites, and the ability to relate this directly to the physicochemical and discharge data held by the Authority, is mandatory for any meaningful analysis of the algal and cyanobacterial populations within the system.

Once the phytoplankton data are stored in this way, their use should be promoted, and they should be made more freely available to responsible research groups.

3.5 Past findings, reports and publications

Several stand-alone reports have been commissioned by the Authority on its phytoplankton monitoring, and the program has also received substantial comment in other Authority reports and publications.

A listing of the reports, plus publications which have drawn heavily on the database generated by the Phytoplankton Monitoring Program, plus publications on the phytoplankton of the system in general, is included as Appendix A.

Here we examine the findings of four reviews of the PMP itself:

Sullivan *et al.* (1988) reviewed the first 5 years of data (July 1980-June 1985), and found the phytoplankton monitoring to be an effective and informative component of the water quality monitoring program. This reflects the important role of phytoplankton in water quality and aquatic ecology, but also the close connections identified in the data between phytoplankton population fluctuations and the manageable environmental characteristics of flow, nutrient concentrations, salinity and turbidity. The report also identified the influence of Hume Dam on the phytoplankton populations along the Murray River immediately downstream, with large numbers introduced when the lake was low, including the release and transport of bloom concentrations of cyanobacteria. It also noted differences between the Upper and Lower sections of the Murray River, largely due to changes in diatom types which was attributed to diminishing flow along the system.

The second report on the phytoplankton monitoring was undertaken with 19 years of data (AWT 1999) and confirmed the large scale patterns and environmental influences identified in the first report. However, the report noted an apparent reduction in phytoplankton condition as indicated by a change in ratios of photosynthetic pigments that were being measured at that time. There was also an increase in diatom abundance at sites in both the Upper and Lower sections, although this observation was only descriptive as the measurement period was not long enough to confirm the trend or explore possible causes. For example, the changes may have been associated with the cyclic patterns of flow seen in the 19 years of data. The report recommended that future time series trend analyses were warranted to confirm whether the system was undergoing a substantial change in condition and to assess whether this was detrimental to the river system. It was also recommended that rather than clumping the phytoplankton into large, heterogeneous groups, that ordination techniques be used to explore the contribution of individual phytoplankton to the changing assemblage, and to relate this more detailed data to alterations in environmental conditions.

A second part to the AWT (1999) report was published a few years later (Water Ecoscience 2002) and undertook more detailed time series analyses of the water quality monitoring data using Generalised Additive Modelling. However, in the case of the phytoplankton, the data complexity was not amenable to this approach and the analysis largely reverted to interpretation of time series plots. These were still informative in that robust trends were identified that indicated increasing concentrations of phytoplankton, especially diatoms in the upper reaches and diatoms and cyanobacteria in the mid reaches of the Murray. The report also contained a warning about the change in counting practices that had occurred. After February 1989, improvements were made to the methods and cyanobacteria were recorded as cells per mL rather than units per mL as had been the case previously. Also counting of all phytoplankton groups was commenced whereas previously the six most common genera only were counted. These improvements impacted the analyses as the earlier data were of poorer quality for robust statistical testing.

The most recent report on the phytoplankton monitoring program utilised the increasing computing power that has evolved exponentially over the last decade to undertake more intensive statistical analyses than were previously possible (Croome *et al.* 2011). As with the earlier studies data simplification was necessary due to the limited resources and time available for the project. The total data set from 1980-2008 was considered, but for some analyses the time period was restricted to 1994-2008 due to the uncertainty with earlier periods of enumeration and the changes in recording methods in the early 1990's. Unfortunately this resulted in a halving of the data suitable for detailed analysis, which is a significant reduction that undermines the value of the extended environmental monitoring program. Also the number of sites considered in the analyses was reduced to 7, again for simplification purposes as data records for the other sites were less complete. Despite these drawbacks the report confirmed some of the earlier propositions, in particular indicating substantial increases in phytoplankton numbers across almost all sites and taxa over the period 1994-2008. For example, the increase in total cyanobacteria at Heywoods was 500 fold, while at Euston it was over 100 fold. The increases were not restricted to the cyanobacteria, with some diatoms and green algae showing 10 to 50 fold increases at some sites. These are not minor shifts in abundance and are likely to significantly alter the composition of the phytoplankton community indicating that fundamental changes are occurring in the river ecosystems.

In addition, this 2011 study looked at the frequency of occurrences of cyanobacterial blooms as there was a belief that they were occurring more often. Interestingly the analysis indicated that the frequency of blooms overall had not changed that much for the period 1980-2008, but that the duration of the blooms had increased, particularly in the Upper section of the river. This change could be identified because the frequency of sampling was sufficient to capture the major fluctuations in the phytoplankton populations that at their fastest can occur in just a few days. As a result of the increased bloom duration the longitudinal extent of blooms is also likely to have increased, as there is more time for downstream transport so that blooms appear in longer stretches of the river. This increased occurrence due to transport is the likely cause of public concern. Perhaps the extreme case of this situation was the bloom that occurred along much of the length of the Darling River.

Relevant recommendations from the above reviews:

[Sullivan *et al.* 1988] Fortnightly or less frequent sampling is deemed to be insufficient to determine the height and duration of growth peaks, and the minimum sampling frequency necessary for allowing algal populations to be related to factors such as nutrients is assessed to be weekly.
[AWT 1999] There have been a number of laboratories, people and analytical methods involved in the reporting of algal densities over the monitoring program. We recommend the collation and review of documentation and methods used in the collection, counting and identification (of) algae to determine the impact of any changes on the integrity of the data set.
[Water Ecoscience 2002] More sophisticated models would be necessary to elucidate trends in the algal data, without waiting for a longer data sequence to accumulate. It is debatable whether enhanced analysis is justified, a better approach would be to carry out simpler trend analyses every five years.
[Croome et al. 2011] An opportunity now exists to develop a modelling framework to characterise the amount of variation explained by the individual environmental variables. The … modelling framework would be particularly pertinent if there is a desire to build a model with some predictive ability.
[Croome et al. 2011] Any detailed recommendations with regard to sampling locations, monitoring frequency and the like should await a decision with respect to the efficacy of this analysis. The Authority's Phytoplankton Monitoring Program should continue as is for the present, albeit with greater discrimination of individual cyanobacteria (in an attempt to reduce the number of determinations of 'Other Cyanophyceae' >1,000 units/mL), and without loss of the original data set from which the 26 'taxa' provided for this project were drawn.

3.6 Chlorophyll and Phaeophytin

Chlorophyll and Phaeophytin are widely accepted measures of phytoplankton biomass and health, particularly in standing waters.

Both are currently assessed in parallel with the samples for phytoplankton, at the same sites and the same frequency, as recommended by Lawrence and Paterson (2005).

To our knowledge, the Chlorophyll and Phaeophytin data are yet to be assessed, and it is suggested this be done to determine their value.

3.7 Satisfaction of statutory requirements

This section explores the execution of the current PMP against the wording of the Murray Darling Basin Agreement – Water Act 2007, the Murray Darling Basin Plan, and the Australian Guidelines for Water Quality Monitoring and Reporting within the National Water Quality Management Strategy.

In summary, the role of the MDBA includes the following functions:

- Measuring, monitoring and recording the amount and quality of Basin water resources and condition of water-dependent ecosystems
- Research to improve knowledge on Basin water resources and water-dependent ecosystems
- Collecting, utilising and sharing information about Basin water resources and water dependent ecosystems

Murray Darling Basin Agreement – Water Act 2007:

The statutory responsibilities of the MDBA with regard to environmental monitoring and water quality monitoring are set out in Schedule 1 of the Murray Darling Basin Agreement - Water Act 2007. In many respects these have been carried over from previous agreements, emphasising the continuing and ongoing need for water quality monitoring.

The overarching objectives of the Water Act 2007 are the management of the Basin's water resources in the national interest, by ensuring the return to environmentally sustainable levels of extraction for water resources that are over-allocated or overused, and to protect, restore and provide for ecological values and ecosystem services (Water Act Part 1 Preliminary Section 3 Objects).

> This suggests that environmental monitoring needs to be sufficient to characterise impacted ecosystems and to identify the requirements for restoration of their ecological values. In the case of the phytoplankton, which are a key component of aquatic ecosystems, the current monitoring program appears to have successfully provided this information for the main stem of the River Murray.

Under Schedule 1, The Murray Darling Basin Agreement, Part VII, "Investigation, measurement and monitoring", the Authority must establish, maintain and operate an effective and uniform system for measuring and monitoring the quality of River Murray water, and also tributaries at locations at or near the confluence with the River Murray as deemed necessary, and also stored water (Clause 45 Measurement of Water Quantity and Quality).

> Although the PMP has provided reliable information on the main stem of the River Murray, only two tributaries have been monitored sufficiently to provide equivalent information, and they have been recently downgraded from weekly to monthly monitoring. Monthly monitoring of phytoplankton is unlikely to provide useful data for environmental monitoring. Consequently none of the tributaries will be monitored sufficiently to provide reliable information on phytoplankton responses to environmental conditions.
> There does not seem to be reliable phytoplankton monitoring for stored waters. Although the responsibility for measuring water quality rests with States, the Authority has the responsibility to lead monitoring programs.

Associated Clauses state that the Authority may co-ordinate or carry out surveys, investigations or studies related to the sustainable use of the waters of the Basin, including the protection and improvement of the quality of river water and the conservation, protection and management of aquatic and riverine environments (Clause 43 Investigations and Studies). To do this the Authority may establish, maintain and operate effective means for monitoring the quality, extent, diversity, and representativeness of aquatic and riverine environments (Clause 44 Monitoring).

> The Phytoplankton Monitoring Program has a crucial role in enabling the Murray-Darling Basin Authority to fulfil the statutory responsibilities of Clauses 44-46 of the Murray Darling Basin Agreement and the associated Basin Plan. Variations in phytoplankton abundances and community composition reflect both responses to changes in water quality and also the attainment of specific water quality objectives, so providing a valuable multi-faceted assessment of ecological condition.

Murray Darling Basin Plan:

Obligations with respect to environmental objectives and water quality objectives are further described in the Basin Plan developed under the Water Act 2007. The purpose of the Basin Plan is also to ensure the return to environmentally sustainable levels of water extraction taking into account the impact on the watercourses, lakes, wetlands, ground water and water-dependent ecosystems and associated biodiversity. The major objectives are captured in the following selected sections.

Chapter 8, 8.05: Protection and restoration of water-dependent ecosystems including to protect and restore biodiversity, and 8.06: restoration of ecosystem functions including (3b) ecological processes dependent on longitudinal hydrologic connectivity (6) protecting and restoring ecosystem functions and (7) ecological community structure, species interactions and food webs including by protecting and restoring energy, carbon and nutrient dynamics, primary production and respiration.

> The phytoplankton monitoring program addresses many of these issues, providing a valuable insight to changing environmental conditions in the main stem of the River Murray and their influence on the ecosystem functions of primary production and energy and carbon resources for food webs. The PMP informs on longitudinal connectivity and the biodiversity of the phytoplankton community and how it changes in response to environmental conditions. There are few aquatic biota that respond so directly to these aspects of river conditions and that can be sampled and analysed as readily as the phytoplankton.

Chapter 9, 9.02: Key causes of water quality degradation include elevated cyanobacteria cell counts.

> The PMP, in providing the detailed data required for environmental monitoring, also supplements the operational monitoring that is widely undertaken in response to outbreaks of cyanobacteria. The *ad hoc* cyanobacteria and partial phytoplankton counting used for operational monitoring by State agencies along the river systems will not fulfil the requirement for measuring and monitoring the quality of River Murray, tributary and stored water or underpin the development of a reliable modelling capability.

Chapter 13, 13.03 principles of responsibility for monitoring and evaluating the effectiveness of the Basin Plan

1: The Authority is responsible for leading monitoring at the Basin scale providing open access to information collected using an adaptive approach to test and improve monitoring, with no net reduction in existing monitoring efforts.

> The PMP data set is currently under-utilised, in large part due to collation and storage issues, and these should be remedied. Wider use of the data should then be promoted, and it should be made more freely available.

13.08: The Authority must conduct a review of water quality targets every 5 years.

> This is appropriate and should be set in the context of developing an enhanced understanding of the fluctuations in phytoplankton abundances and community composition in response to environmental conditions, particularly the links with physico-chemical water quality attributes and hydrology, and also connections with food webs and higher organisms. This will entail the progressive development of conceptual, statistical and process models aimed at providing capability for improved and sustainable management of the river system. The PMP is now in a position to begin providing such information, as reliable monitoring has continued long enough to capture aspects of these interactions. A continuing stable, consistent monitoring program is required to capitalise on what has already been done.

13.17: Take all reasonable steps to publish on its website information (including data) obtained in monitoring the effectiveness of the Basin Plan.

> This is relevant to the PMP, and the data collected should be made more readily available.

4. OTHER PHYTOPLANKTON SAMPLING BY STATE AGENCIES

4.1 Comment on “Operational sampling” versus “Environmental assessment”

There is an important disjunction between the monitoring of phytoplankton populations for operational purposes, and their use in the environmental assessment of aquatic systems.

Phytoplankton populations have long been assessed as part of the routine examination of raw water for human use i.e. for operational reasons. Historical examples of the need for such assessment are the filter-blocking properties of diatoms within water treatment works, and the different tastes and odours imparted to water by discrete groups of algae and cyanobacteria.

Modern developments within municipal water treatment plants over the past 20-30 years have made these determinations less relevant. However, over the past 40 years in Australia and elsewhere, our increasing knowledge of the presence and impact of planktonic cyanobacteria within our lakes and rivers has determined the need for detailed operational monitoring of all waters used for supply.

All State authorities are aware of the potential water quality and human health problems due to the presence of cyanobacteria, and are particularly vigilant in waters known to have a problem. Such waters are monitored for what we are calling here ‘operational reasons’, with a quick turn around of samples and rapid reporting, so that follow-up samples can be made, and remedial measures set in train if required.

‘Environmental assessment’ of surface waters using phytoplankton is very different, and is much more likely to concentrate initially on the non-cyanobacterial members present, as these are the key drivers of the phytoplankton system as a whole.

Primary production and carbon cycling within aquatic systems like the Murray are driven by the phytoplankton (as opposed to aquatic plants and outside sources of organic material in some lakes and smaller fluvial systems). Regular examination of the phytoplankton from season to season and year to year as part of routine water quality assessment will reflect, for instance, changes in discrete nutrient inputs, management variation within catchments, and broadscale impacts due to climate change.

Such issues are front and centre for the MDBA, and the current phytoplankton monitoring program can only assist in appropriate ecological management of the Murray system.

4.2 State sampling for phytoplankton

Table 4 shows other sampling of phytoplankton in the Murray and closely associated waters by State Agencies. For a sequential downstream listing see Appendix B.

Table 4. Other sampling in the Murray and closely associated waters by State agencies. All samples are for cyanobacteria only, apart from those taken by North East Water (where other phytoplankton numbers are estimated), and in South Australia (where 1-2 taxa of other phytoplankton may be included).

Testing Agency	Sites examined	Type of sampling
North East Water	Tallangatta and Bellbridge (Lake Hume) Wodonga Ck (Murray anabranch) Wahgunyah	All fortnightly to monthly, November to March. Cyanobacteria counted, but other phytoplankton present classified simply as abundant, common, frequent, occasional or rare.
Goulburn Murray Water	Dartmouth Dam Yarrawonga Weir Murray U/S Torrumbarry Weir Loddon R at Kerang 37 sites Torrumbarry Irrig. Area Murray at Woorinen and Nyah	Monthly. Fortnightly January-May & December, monthly June-November. Monthly. Fortnightly, usually October to May. “ “ “ “ “ “
Goulburn Valley Water	Murray at Cobram and Barmah	Seasonal, as required for cyanobacteria.
Coliban Water	Murray at Echuca	Seasonal, as required for cyanobacteria.
Lower Murray Water	Murray at Robinvale, Redcliffs, Mildura	Weekly when cyanobacteria present.
NSW Office of Water	Murray at Albury, Corowa, D/S Yarrawonga, Mulwala Canal,	All fortnightly November-April, otherwise monthly,

	Cobram, Tocumwal, Picnic Point, Moama, Barham, Murray Downs, Tooleybuc, Lake Benanee, Euston, Mt. Dispersion, Buronga, Merbein, Curlwaa, Fort Courage, Lock 8. Gulpa Ck. at Mathoura Edward R. at Moulamein Wakool R. at Kyalite Lake Victoria Outlet	and weekly if need be.
SA Water	Lake Victoria Outlet Murray D/S Rufus R Gauging Weir Murray 8 km D/S of Lock 6 Murray at Renmark, Lock 5, Berri, Loxton, Moorook, Cobdogla, Woolpunda, Waikerie, Cadell, Lock 1, Blanchetown, Swan Reach, Swan Reach Town, Mannum, Cowirra, Mypolonga, Murray Bridge	All weekly. A "partial count" is made, which comprises problem cyanobacteria, plus one or two of the dominant taxa (which may also be cyanobacteria).

At first sight, it appears there are many other sites along the Murray at which State agencies sample for 'phytoplankton'. However, this monitoring is almost solely for nuisance cyanobacteria alone, and is thus largely 'operational sampling' for purposes of water supply and recreation, rather than 'environmental assessment' to determine longer term changes across all phytoplankton groups e.g. in response to modified catchment and riverine conditions.

We were struck by the number of sites being monitored in this way, but also by the occasional comment that it would be handy if States shared phytoplankton monitoring data a little more freely where needs overlapped.

5. KEY OBSERVATIONS/FINDINGS

The Phytoplankton Monitoring Program began in 1980, in parallel with the physicochemical and macro-invertebrate monitoring, and currently comprises 10 sites along the main stem of the Murray which are sampled weekly, and two sites on major tributaries (Murrumbidgee and Darling) which are sampled monthly. Analyses of Chlorophyll and Phaeophytin, related to phytoplankton biomass and health, have been added to the Authority's monitoring in more recent years.

The phytoplankton samples are counted by ALS Global in Melbourne and the Australian Water Quality Centre in Adelaide, and the results are forwarded to the MDBA for collation.

There have been four substantial reviews of the PMP and its data (1988, 1999, 2002, 2011), and all have confirmed its value in describing changes in phytoplankton numbers and relating them to key drivers within the system, for the dominant diatoms and nuisance cyanobacteria alike. The most recent review (2011) concluded that recent advances in statistical techniques now presented the opportunity of developing a modelling framework to characterise variations in the phytoplankton against individual environmental variables. Such a modelling framework "would be particularly pertinent if there is a desire to build a model with some predictive ability".

The PMP provides the most comprehensive historical view of biotic changes in the Murray River that is available, and is seen as a key component of the MDBA's integrated physicochemical/ biological water quality monitoring, as defined within the National Water Quality Management Strategy, allowing the Authority to meet its obligations under the Murray Darling Basin Agreement and Murray Darling Basin Plan.

There are many other sites along the Murray at which State agencies sample for 'phytoplankton'. However, this monitoring is almost solely for nuisance cyanobacteria alone, and is thus largely 'operational sampling' for purposes of water supply and recreation, rather than 'environmental assessment' to determine longer term changes across all phytoplankton groups in response to modified catchment and riverine conditions.

A significant period of data collection is required in order to characterise the variability of phytoplankton communities and the PMP is only just reaching this level of detail, with statistical analyses of the data indicating that it provides a reliable basis for identifying changes within and between sites. However, because of the fluctuations in the influencing variables such as flow and meteorology and because the system is not stationary but varying in time due to changing pressures, including from climate shifts, continued monitoring is necessary to assess these changing conditions.

Tributary sites are limited to the Murrumbidgee and Darling, with the frequency of monitoring being recently reduced at both sites from weekly to monthly. Such monthly measurements of phytoplankton are unlikely to provide reliable data for environmental monitoring purposes.

6. RECOMMENDATIONS

We recommend the Phytoplankton Monitoring Program be maintained largely as is with respect to sample sites and sampling frequency, but consider the Darling and Murrumbidgee sites to be non-viable under their current monthly sampling regime, and question the value of the Goolwa barrage site in describing the influence of Murray River inflows on the phytoplankton of Lake Alexandrina. (We are unable to be more specific here with respect to the Darling, Murrumbidgee and Goolwa sites without examination of the actual data, which was outside our remit.)

The Chlorophyll and Phaeophytin data collected in parallel with the phytoplankton data, as recommended by Lawrence and Paterson (2005), should be assessed to determine their value.

Equivalence of phytoplankton results assessed by different laboratories can best be assured by ongoing inter-laboratory discussions of techniques, taxonomy and data recording, and these should be fostered.

We see the PMP data set as being under-utilised, in large part due to collation and storage issues, and this should be remedied. Wider use of the data should then be promoted, and it should be made more freely available.

Recent work on a subset of the data (2011) identified key drivers of phytoplankton abundance within the river, and promoted modelling to link variations in algae and cyanobacteria with individual environmental variables. This type of work would be particularly relevant in building a model with predictive ability, and should be advanced.

7. REFERENCES

Aldridge K, Lorenz Z, Oliver R & Brookes J (2012). Changes in water quality and phytoplankton communities in the Lower River Murray in response to a low flow-high flow sequence. Goyder Institute for Water Research Technical Report Series No. 12/5. 43 pp.

Anttila S, Ketola M, Vakkilainen K & Kairesalo (2012) – "Assessing temporal representativeness of water quality monitoring data", Journal of Environmental Monitoring 14: 589-595.

Australian Water Technologies (1999).Water Quality Monitoring Program Review – Part I. Data Summary and Recommendations. Report prepared for the Murray-Darling Basin Commission. 112 pp.

AWDG (2011)

Baldwin DS, Wilson J, Gigney H & Boulding A (2010). Influence of extreme drawdown on water quality downstream of a large storage reservoir. River Research and Applications 26(2): 194-206.

Baldwin DS, Whitworth KL & Pengelly J (2013). Investigating the influences of changes in the River Murray Water Quality Monitoring Program on future capacity to detect trends in water quality. Final Report prepared for the Murray Darling Basin Authority by the Murray Darling Freshwater Research Centre, May 2013, 21 pp.

Biswas T & Lawrence B (2013). Revision of the River Murray Water Quality Monitoring Program. Internal MDBA report. 28 pp.

Bormans M, Maier H, Burch M & Baker P (1997). Temperature stratification in the lower River Murray, Australia: implication for cyanobacterial bloom development. Marine and Freshwater Research 48(7); 647-654.

Bowling LC, Merrick C, Swann J, Green D, Smith G & Neilan BA (2013). Effects of hydrology and river management on the distribution, abundance and persistence of cyanobacterial blooms in the Murray River, Australia. Harmful Algae, 30: 27-36.

Carstensen, J. (2007) Statistical principles for ecological status classification of Water Framework Directive monitoring data. *Marine Pollution Bulletin* 55: 3-15.

Coucouvinis J & Croome R (1980). River Murray Commission Water Quality Monitoring Programme. Australian National Committee on Irrigation and Drainage Journal 8: 20-23.

Crase L & Gillespie R (2008). The impact of water quality and water level on the recreational values of Lake Hume. Australasian Journal of Environmental Management 15(1): 21-29.

Croome R, Wheaton L, Henderson B, Oliver R, Vilizzi L, Paul W & McInerney P (2011). River Murray Water Quality Monitoring Program: Phytoplankton data trend analysis 1980-2008. Report prepared for the MDBA by the Murray-Darling Freshwater Research Centre (MDFRC Publication 06/2011). 100+ pp.

Gawne B, Merrick C, Williams DG, Rees G, Oliver R, Bowen PM, Treadwell S, Beattie G, Ellis I, Frankenberg J & Lorenz Z (2007). Patterns of primary and heterotrophic productivity in an arid lowland river. River Research and Applications 23: 1070-1087.

Hotzel G & Croome R (1994). Long-term phytoplankton monitoring of the Darling River at Burtundy, New South Wales: Incidence and significance of cyanobacterial blooms. Aust. J. Mar. Freshwater Res. 45: 747-759.

Hotzel G & Croome R (1996). River Murray Phytoplankton – The role and population dynamics of the dominant alga Melosira granulata (now Aulacoseira granulata). Research report to the Murray Darling Basin Commission. 31 pp.

Hotzel G & Croome R (1996). Population dynamics of Aulacoseira granulata (Ehr.) Simonson (Bacillariophyceae, Centrales), the dominant alga in the Murray River, Australia. Arch Hydrology 136: 191-215.

Hotzel G & Croome R (1998). River Murray Phytoplankton – The role and population dynamics of the dominant alga Melosira granulata. Proceedings of Murray Darling Basin Commission 1996 Riverine Environment Forum. pp. 39-48.

Hotzel G & Croome R (1999). A phytoplankton methods manual for Australian freshwaters. LWRRDC Occasional Paper 22/99. 58 pp.

Lawrence B & Patterson L (2005). Review of the River Murray Water Quality Monitoring Program. Murray-Darling Basin Commission June 2005. 40 pp.

Maier HR, Dandy GC & Burch MD (1998). Use of artificial neural networks for modelling cyanobacteria Anabaena spp in the River Murray, South Australia. Ecological Modelling 105(2/3): 257-272.

Mitrovic SM, Oliver RL, Rees C, Bowling LC & Buckney RT (2003). Critical flow velocities for the growth and dominance of Anabaena circinalis in some turbid freshwater rivers. Freshwater Biology 48: 164-174.

Oliver RL & Merrick C (2006). Partitioning of river metabolism identifies phytoplankton as a major contributor in the regulated Murray River (Australia). Freshwater Biology 51: 1131-1148.

Oliver R L and Lorenz Z (2010) Flow and metabolic activity in the channel of the Murray River. Pages 267-280 *in* N. Saintilan and I. Overton, editors. Ecosystem Response Modelling in the Murray-Darling Basin. CSIRO Publishing.

Percival DB, Lennox SM, Wang YG & Darnell, RE (2011). Wavelet-based multiresolution analysis of Wivenhoe Dam water temperatures. Water Resources Research, 47(5).

Rish S, Ramsay M and Preston C (1993). Analysis of long term water quality monitoring data: Demonstration of procedures with River Murray data. Australian Water Technologies report to the Waters and Catchment Branch, NSW EPA.

Sullivan C, Saunders J, & Welsh D (1988). Phytoplankton of the River Murray. Review of monitoring 1980-1985. Murray Darling Basin Commission. 61 pp.

Sullivan C (1990). Phytoplankton. In Mackay N & D Eastburn D (Eds.) The Murray. pp 252-260.

Water Ecoscience (2002). MDBC Water Quality Review Stage 2 – Data Analysis. 52 pp.

APPENDIX A

There have been numerous reports published either directly or indirectly concerning the Authority's Phytoplankton Monitoring Program.

Additionally, scientific publications have made use of the phytoplankton database it has generated, and there have also been several papers in recent years concerning the phytoplankton of the Murray and its major tributaries in general.

A listing of the former is given below, together with examples of the latter.

Authority reports

River Murray Commission Water Quality Monitoring Programme. Paper prepared by J Coucouvinis & R Croome for Australian National Committee on Irrigation and Drainage Journal Vol 8, 1980, pp 20-23.

A simple description of the water quality, aquatic macro-invertebrate and phytoplankton monitoring programs being established by the Commission.

Phytoplankton of the River Murray. Review of monitoring 1980-1985. A report prepared by C. Sullivan *et al.* at the Rural Water Commission of Victoria and published by the MDBC in 1988. 61 pp.
Principally a description of the program and the data obtained at 15 sites over its first 5 years, but included correlation and time series analyses linking the phytoplankton data to discharge and water quality.
Criticism of the program and suggested improvements:

. "On the basis of this analysis, fortnightly or less frequent sampling is deemed to be insufficient to determine the height and duration of growth peaks, and the minimum sampling frequency necessary for allowing algal populations to be related to factors such as nutrients is assessed to be weekly."

. Three sites to be discontinued.

. Special investigations recommended for the Murray/Darling confluence, voracity of Chlorophyll *a* data, the reasons for grossly different algal populations in the Murray above/below Euston, the impact of Barr Creek inputs, a register of algal related water quality issues, an algal taxonomic collection, the feasibility of computer modelling of algal populations, a review of historical algal data held in South Australia, and the dynamics of *Melosira granulata* (now *Aulacoseira granulata*) – the dominant alga within the system.

Pages 250-262 of The Murray, N Mackay & D Eastburn Eds. Phytoplankton by Cathy Sullivan, MDBC 1990.
A synopsis and enhancement of the above publication for public readership.
"Results of the Commission's monitoring of River Murray phytoplankton have shown that their numbers are influenced by complex interactions between various environmental factors – light, temperature, water flow, turbidity and nutrients." "The Commission will continue to monitor phytoplankton in the River, with a further review of the programme in 1992." "Together with other research studies on phytoplankton, such as those being undertaken at the Murray-Darling Freshwater Research Centre, these projects will help to provide a better understanding of the processes affecting phytoplankton populations in the River Murray and hopefully indicate ways in which

the river system can be managed so as to reduce the frequency and magnitude of blooms of undesirable phytoplankton."

River Murray Phytoplankton – The role and population dynamics of the dominant alga Melosira granulata (now Aulacoseira granulata). Final research project report to the Murray Darling Basin Commission by Gertraud Hotzel and Roger Croome. June 1996. 31 pp.
A study linking *Aulacoseira granulata* populations to water quality and discharge. *A. granulata* was the dominant alga from Heywoods Bridge to Lock 9, but was displaced by solitary centric diatoms and green algae in the lower Murray, reflecting a marked change in flow conditions rather than nutrient concentrations. It was concluded that population dynamics of *A. granulata* in the Murray River were most strongly determined by flow conditions and concentrations of the nutrient silica, with turbidity having a lesser impact. A clear difference was apparent between the upper and lower parts of the river, with *A. granulata* populations developing best under conditions of high physical disturbance and low nutrient stress.

River Murray Phytoplankton – The role and population dynamics of the dominant alga *Melosira granulata* by Gertraud Hotzel and Roger Croome. Proceedings of Murray Darling Basin Commission 1996 Riverine Environment Forum. Pages 39-48. Published 1998.
Presentation of major findings from report above.

Pages 63-79 of Water Quality Monitoring Program Review – Part I. Data Summary and Recommendations. A report prepared for the MDBC by Australian Water Technologies, May 1999.
A descriptive account of algal composition along the system from 1978-1997, giving yearly median counts for diatoms and cyanobacteria (with Alert Level exceedance values) at all sites, and Chlorophyll a for 3 sites.
Criticism of the program and suggested improvements:
. "There have been a number of laboratories, people and analytical methods involved in the reporting of algal densities over the monitoring program." "We recommend the collation and review of documentation and methods used in the collection, counting and identification (of) algae to determine the impact of any changes on the integrity of the data set."

Pages 33-40 of MDBC Water Quality Review Stage 2 – Data Analysis. A report prepared for the MDBC by Water Ecoscience, March 2002.
An analysis of 'temporal trends in key water quality variables and changes in the phytoplankton communities …. carried out using a Generalised Additive Model (GAM)" with data from July 1978 to July 1997.
Various water quality trends were identified in the upper, middle and lower segments of the river. However, while "robust upward trends were discerned for diatoms and other algae at the headwater sites", "the phytoplankton data was not as amenable to GAM modelling."
More sophisticated models would be necessary to elucidate trends in the algal data, without waiting for a longer data sequence to accumulate. It is debatable whether enhanced analysis is justified, a better approach would be to carry out simpler trend analyses every five years."

Page 25 of Review of the River Murray Water Quality Monitoring Program by Lawrence B & Patterson L, a Murray-Darling Basin Commission report, June 2005.
Within a report reviewing the entire WQMP, a small section of the Phytoplankton Monitoring Program restated its primary aim as provision of "long term data on the

algal populations of the River Murray, in order that changes in the species abundance and composition may be identified and related to changes in the river environment".

Recommendations were:

"In order to best meet the aim of the phytoplankton component it is recommended that:

. Chlorophyll 'a' and pheaophytin sampling be included at all 12 of the algal sites;

. Changes in the entire algal community at sites using ordination and classification techniques be described; (Recommendation 7 from Section 5.2 of the 1999 AWT Review Report)

. The influence of key environmental factors on phytoplankton communities within the system using multivariate statistical analysis be examined (Recommendation 4 from Section 5.2 of the 1999 AWT Review Report)"

<u>River Murray Water Quality Monitoring Program: Phytoplankton Data Trend Analysis 1980-2008.</u>

A report prepared for the MDBA by the Murray-Darling Freshwater Research Centre and released in March 2011 (MDFRC Publication 06/2011, 100+ pp.).

"Statistical analyses were applied to an amalgam of phytoplankton, water quality and hydrological data in an overarching assessment of the phytoplankton of the system for the period 1980-2008, relating their presence and abundance to relevant ecological drivers, and taking particular account of the presence of cyanobacteria as a management concern."

"Generalized additive models (GAMS) were used to examine trends in nine individual taxa from seven mainstream sites for the period 1994-2008, and to associate them with environmental drivers."

"Multivariate analysis was used to test hypotheses regarding relationships between the phytoplankton community composition as a whole, and environmental variables."

"Wavelet analysis was applied to the cyanobacterial data for the period 1980-2008, to answer the specific question 'Are cyanobacterial blooms becoming more frequent or more extensive?' "

Criticism of the program and suggested improvements:

. "The phytoplankton of the Murray River (and its major tributaries) is a key driver of the instream ecosystem, playing a major role in carbon fixation and foodweb dynamics….and…. is also responsible for problems with water quality and social amenity, via algal and (potentially toxic) cyanobacterial blooms."

. "..we have reached the stage of identifying some key drivers of phytoplankton abundance…" An opportunity now exists to develop "a regression modelling framework to characterise the amount of variation explained by the individual environmental variables". "The … modelling framework would be particularly pertinent if there is a desire to build a model with some predictive ability. Any detailed recommendations with regard to sampling locations, monitoring frequency and the like should await a decision with respect to the efficacy of this analysis.

. "Hence the suggestion is made that the Authority's Phytoplankton Monitoring Program should continue as is for the present, albeit with greater discrimination of individual cyanobacteria (in an attempt to reduce the number of determinations of 'Other Cyanophyceae' >1,000 units/mL), and without loss of the original data set from which the 26 'taxa' provided for this project were drawn."

Revision of the River Murray Water Quality Monitoring Program. An internal MDBA report by T Biswas & B Lawrence, 2013, 28 pp.
Documents the history and rationale of the Authority's water quality monitoring, and recommends substantial reductions within fiscal constraints.
The Authority's phytoplankton monitoring is included in the document, but very much 'in passing' rather than being reviewed/assessed. However, one of the longterm phytoplankton monitoring sites, Barr Ck at Capels Flume, is listed as one of the Authority's 8 water quality monitoring program sites to be discontinued.

Use of the Authority's PMP database in other publications

The Authority has also directly supported the use of its phytoplankton and other data in the preparation of research papers/reports. Examples are:

Hotzel G & Croome R (1994). Long-term phytoplankton monitoring of the Darling River at Burtundy, New South Wales: Incidence and significance of cyanobacterial blooms. Aust. J. Mar. Freshwater Res. 45: 747-759.
Direct use of the Authority's phytoplankton, water quality and flow data for the period 1980-1992 to document the algal and cyanobacterial populations in the Darling River, highlighting the presence and magnitude of cyanobacterial blooms.

Hotzel G & Croome R (1996). Population dynamics of *Aulacoseira granulata* (Ehr.) Simonson (Bacillariophyceae, Centrales), the dominant alga in the Murray River, Australia. Arch Hydrology 136: 191-215.
Direct use of the Authority's phytoplankton, water quality and flow data for the period 1980-1992 to document in particular the behaviour of the system's dominant alga *Aulacoseira granulata.*

Aldridge K, Lorenz Z, Oliver R & Brookes J (2012). Changes in water quality and phytoplankton communities in the Lower River Murray in response to a low flow-high flow sequence. Goyder Institute for Water Research Technical Report Series No. 12/5. 43 pp.
Historical data on river flow, water quality and phytoplankton from SA Water, MDBA and SA EPA were combined to assess changes between high and low flow periods in the lower Murray. The work demonstrated clear linkages between the three parameters, with a phytoplankton community change being a particular feature – a change from Cyanophyta dominance under low flow to diatom dominance under higher flow conditions.

Other publications on phytoplankton within the system

Other papers/reports on the Murray system have included information on phytoplankton/cyanobacteria collected in part for the authority or generated separately by other research groups e.g.:

Bormans M, Maier H, Burch M & Baker P (1997). Temperature stratification in the lower River Murray, Australia: implication for cyanobacterial bloom development. Marine and Freshwater Research 48(7): 647-654.
Both real-time and historical data (six years) were used "to determine the stratification potential of the lower River Murray and its implication for water quality and cyanobacterial bloom development". It was found that strong winds and sufficiently

high river discharges mitigated against stratification and sustained blooms of cyanobacteria at any time of the year. (The observations were made at Swan Reach, but were taken as being representative of the lower River Murray.)

Maier HR, Dandy GC & Burch MD (1998). Use of artificial neural networks for modelling cyanobacteria *Anabaena* spp in the River Murray, South Australia. Ecological Modelling 105(2/3): 257-272.
Seven years of weekly data for eight variables were used to predict the incidence and amount of Anabaena at Morgan with some success. Flow and temperature were found to be the most important variables determining cyanobacterial growth, followed by water colour, with nitrogen, phosphorus, iron and turbidity being less important.

Mitrovic SM, Oliver RL, Rees C, Bowling LC & Buckney RT (2003). Critical flow velocities for the growth and dominance of Anabaena circinalis in some turbid freshwater rivers. Freshwater Biology 48: 164-174.
A determination of flow velocities required to prevent thermal stratification and hence cyanobacterial growth in weir pools along the Darling system. A flow velocity of 0.05 metres per second or greater prevented persistent thermal stratification and the growth of *Anabaena circinalis*.

Oliver RL & Merrick C (2006). Partitioning of river metabolism identifies phytoplankton as a major contributor in the regulated Murray River (Australia). Freshwater Biology 51: 1131-1148.
A definitive study of the importance of phytoplankton within the biological processes of the Murray River. Within-stream determinations of photosynthesis showed the Murray to be moderately productive compared to rivers of similar structure. Metabolised organic carbon within the river was derived mostly from phytoplankton. The data further suggested that the carbon fixed by the phytoplankton was being fully utilised within the aquatic food-web, indicating that food-web production within the Murray was being restricted by the supply of energy (light).

Gawne B, Merrick C, Williams DG, Rees G, Oliver R, Bowen PM, Treadwell S, Beattie G, Ellis I, Frankenberg J & Lorenz Z (2007). Patterns of primary and heterotrophic productivity in an arid lowland river. River Research and Applications 23: 1070-1087.
Concerning primary production within the Murray River, how well it is described by three riverine conceptual models, and the relative importance of phytoplankton, riparian vegetation and macrophytes.

Crase L & Gillespie R (2008). The impact of water quality and water level on the recreational values of Lake Hume. Australasian Journal of Environmental Management 15(1): 21-29.
Use of the travel cost method to determine the recreational value of visitors under different water quality and lake level scenarios. A value around $3 million pa was apparent with a full lake and low algal contamination: lowering of lake level to about half reduced the value to around $2 million, as did “a single incidence of blue-green algae”.

Baldwin DS, Wilson J, Gigney H & Boulding A (2010). Influence of extreme drawdown on water quality downstream of a large storage reservoir. River Research and Applications 26(2): 194-206.
A study involving Lake Hume during an extreme drawdown event showed the lake to be a net exporter of carbon, nitrogen and phosphorus (mostly in algal biomass), and a net sink for manganese. Substantial downstream transport of algal biomass was observed.

Bowling LC, Merrick C, Swann J, Green D, Smith G & Neilan BA (2013). Effects of hydrology and river management on the distribution, abundance and persistence of cyanobacterial blooms in the Murray River, Australia. Harmful Algae, 30: 27-36.
A very detailed examination of "cyanobacterial-infested water" travelling down the Murray (from Lake Hume to the SA border) under low flow conditions in early 2010. Elevated cyanobacterial populations persisted over 500 km of the Murray below Lake Hume for 5 weeks, while the next 650 km of the river experienced a small parcel of water containing a cyanobacterial bloom passing progressively downstream. "Global climate change is likely to promote future blooms in this and other lowland rivers."

APPENDIX B

A sequential downstream listing of other sites sampled for phytoplankton by State Agencies (principally for cyanobacteria – see Section 3.7.2).

LOCATION	AGENCY
Dartmouth Dam	Goulburn Murray Water
Tallangatta (Lake Hume)	North East Water
Bellbridge (Lake Hume)	North East Water
Wodonga Creek (Murray anabranch)	North East Water
Murray at Albury	NSW Office of Water
Murray at Wahgunyah	North East Water
Murray at Corowa	NSW Office of Water
Yarrawonga Weir	Goulburn Murray Water
Murray D/S Yarrawonga	NSW Office of Water
Mulwala Canal	NSW Office of Water
Murray at Cobram	NSW Office of Water
Murray at Cobram	Goulburn Valley Water
Murray at Tocumwal	NSW Office of Water
Murray at Picnic Point	NSW Office of Water
Gulpa Ck at Mathoura	NSW Office of Water
Murray at Barmah	Goulburn Valley Water
Murray at Moama	NSW Office of Water
Murray at Echuca	Coliban Water
Murray U/S Torrumbarry Weir	Goulburn Murray Water
Murray at Barham	NSW Office of Water
Loddon R at Kerang	Goulburn Murray Water
37 sites in Torrumbarry Irrigation Area, including 2 adjacent to the Murray	Goulburn Murray Water
Murray at Murray Downs (Swan Hill)	NSW Office of Water
Murray at Woorinen	Goulburn Murray Water
Murray at Nyah	Goulburn Murray Water
Murray at Tooleybuc	NSW Office of Water
Edward R at Moulamein	NSW Office of Water
Wakool R at Kyalite	NSW Office of Water
Lake Benanee	NSW Office of Water
Murray at Robinvale	Lower Murray Water
Murray at Euston	NSW Office of Water
Murray at Mt Dispersion	NSW Office of Water
Murray at Redcliffs	Lower Murray Water
Murray at Buronga	NSW Office of Water
Murray at Mildura	Lower Murray Water
Murray at Merbein	NSW Office of Water
Murray at Curlwaa	NSW Office of Water
Murray at Fort Courage (D/S Wentworth)	NSW Office of Water
Lake Victoria outlet	NSW Office of Water
Lake Victoria Outlet	SA Water
Murray D/S Rufus R Gauging Weir	“
Murray 8km D/S of Lock 6	“

Murray at Renmark	“
Murray at Lock 5	“
Murray at Berri	“
Murray at Loxton	“
Murray at Moorook	“
Murray at Cobdogla	“
Murray at Woolpunda	“
Murray at Waikerie	“
Murray at Cadell	“
Murray at Blanchetown	“
Murray at Swan Reach	“
Murray at Swan Reach Town	“
Murray at Mannum	“
Murray at Cowirra	“
Murray at Mypolonga	“
Murray at Murray Bridge	“