Changes in water quality and phytoplankton communities in the Lower River Murray in response to a low flow-high flow sequence

Kane Aldridge, Zygmunt Lorenz, Rod Oliver and Justin Brookes

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Enquires should be addressed to:
Goyder Institute for Water Research
Level 1, Torrens Building
220 Victoria Square, Adelaide, SA, 5000

tel:  08-8303 8952
e-mail:  enquiries@goyderinstitute.org

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Abstract

Flow delivers nutrients and food resources that drive the productivity of aquatic ecosystems. Droughts and floods can therefore shape river ecosystems. However, in regulated systems, such as the River Murray, droughts and floods also present several water quality risks. Between 2001 and 2010 the Murray-Darling Basin experienced a severe and extended drought, followed by a record rainfall period in 2010. This resulted in a low flow-high flow sequence in the Lower River Murray. The principal aim of this study was to investigate changes in the nutrient concentrations and phytoplankton communities in the Lower River Murray that resulted from the low flow-high flow sequence. Changes in salinity, dissolved organic carbon (DOC) and dissolved oxygen were also examined.

The study demonstrated clear linkages between flow, water quality and phytoplankton communities in the Lower River Murray. During the low flow period electrical conductivities of greater than 1500 μS/cm were observed in the river below Lock 1, which would have had adverse effects on some freshwater biota. These elevated salinities appeared to originate from Lake Alexandrina, which had elevated salinity levels during the low flow period, resulting from seawater intrusions. Whilst blooms of Cyanophyta are also of concern during low flow periods, during the low flow period of this study there were no apparent blooms, which was attributed to phosphorus limitation. It appears that the greatest risk of blooms of Cyanophyta occurs on the recession of high flows or during the onset of low flow conditions.

The high flow period resulted in the mobilisation of nutrients from the basin. A majority of these nutrients were attributed to the River Murray upstream of South Australia. However, area between Lock 9 and Lock 1 was a source of total phosphorus (TP) and total nitrogen (TN), presumably through mobilisation from the floodplain, instream productivity, groundwater inputs or resuspension of sediments. The area between Lock 9 and Lock 1 was a much larger source of TN (2782.3 tonne) than TP (296.7 tonne). Elevated nutrient concentrations during the high flow period resulted in increased primary productivity and a switch from a phytoplankton community dominated by Cyanophyta to diatoms. Whilst this has some clear benefits associated with reduced risk of blooms of Cyanophyta, the consequences for the ecosystem are less well understood. However, there is evidence to suggest that Cyanophyta are non-preferred food sources for zooplankton. Regardless, the increase in primary productivity would have trophic benefits with more carbon and nutrients available to support foodwebs.
During the high flow period heterotrophic productivity was also stimulated through mobilisation of organic carbon from the basin, largely from upstream sources. The DOC concentrations were typically below 10 mg/L until the beginning of the high flow period in late 2010, which resulted in DOC concentrations of 20 mg/L, as floodplain and terrestrially-derived organic carbon entered the river. This shifted the river from a net autotrophic system to a net heterotrophic system. Although the DOC would have been an important energy input, fuelling heterotrophic microbial productivity, it also has implications for other biota, with a resultant drawdown in dissolved oxygen concentrations. Furthermore, high DOC concentrations add to water-treatment costs as DOC must be removed for potable water supply.

Low flow and high flow periods present challenges for the management of water quality in the Lower River Murray. It is clear that during extended low flow periods adequate water needs to be supplied to the Lower River Murray if the intrusion of saline and nutrient rich water below Lock 1 is to be avoided. Whilst Lake Alexandrina appears to be a source of high elevated salinity, nutrient concentrations and phytoplankton biomass below Lock 1, consideration needs to be given to groundwater and return flows from irrigated areas. Extended low flow periods also appear to result in the accumulation of carbon on the floodplain, resulting in hypoxic conditions in the Lower River Murray upon reinundation. Reducing the interval between floodplain inundation events may reduce the risk of hypoxia. The provision of water to the floodplain needs to consider both the benefits and risks associated with return flows to the river. Return flows will carry elevated loads of organic carbon and nutrients, which will stimulate the activity and growth of heterotrophic microbes and phytoplankton. During the unregulated high flow period of this study, the increased nutrient concentrations resulted in increased primary productivity, with likely trophic benefits for the ecosystem. However, return flows from regulated water provisions to the floodplain during periods of low river discharge is likely to increase the risk of blooms of Cyanophyta. Consequently, provisions of water to the floodplain should be complemented with river flow rates that favour a phytoplankton community dominated by diatoms, particularly during periods of warm, calm conditions. These provisions would have environmental, social and economic benefits.
Introduction

Flow has been described as the *maestro* that orchestrates patterns and processes in rivers, providing habitat for aquatic biota, and ultimately governing the physiology, distribution and abundance of organisms (Walker *et al.* 1995; Poff *et al.* 1997). Flow also delivers nutrients and food resources that drive the productivity of aquatic ecosystems (Poff *et al.* 1997). These sources of energy come from autochthonous and allochthonous sources, the nature of which is essential in determining the foodweb structure of aquatic ecosystems. The relative importance of energy sources may vary longitudinally, with greater relative importance of allochthonous sources in headwaters grading to greater relative importance of autochthonous sources in lower reaches (as described by the River Continuum Concept (Vannote *et al.* 1980)). In addition, in lowland riverine systems there are lateral inputs from the floodplain resulting from the seasonal inundation of the floodplain (as described by the Flood-Pulse Concept (Junk *et al.* 1989)). During a flood, carbon and nutrient compounds are leached from organic matter and previously dry sediments on the floodplain (Baldwin 1999; Baldwin and Mitchell 2000), which are then available to be incorporated into riverine trophic pathways. Although no general model exists for southern Australian riverine ecosystems, arid systems in Australia are more reliant on autochthonous energy sources than allochthonous sources (Bunn *et al.* 2003). However, the floodplain carbon store is considerable (Robertson *et al.* 1999).

Phytoplankton are an important autochthonous energy source of riverine ecosystems, with total biomass and species composition having important implications for foodweb productivity and structure. Whilst the nutrient availability is important in determining the total biomass of phytoplankton communities (Dillon and Rigler 1974), the community composition is primarily determined by the hydrodynamics of a water-body (Reynolds *et al.* 1983; Reynolds 1984). The hydrodynamics alter the nutrient and light regimes to which the phytoplankton are exposed (Olrikk 1981; Padisák *et al.* 1988). In general, there is a shift in community composition from high to low flow conditions: under high flow conditions, immotile species dominate, with water mixing providing access to both light (euphotic zone) and nutrients (water column); and under low flow conditions, motile species dominate as they are able to actively access both light (euphotic zone) and nutrients (hypolimnion) (Reynolds 1984). Furthermore, under low flow conditions, thermal stratification may develop, limiting water mixing and favouring gas–vacuolated Cyanophyta which are able to maintain their buoyancy and position in the water column (Reynolds 1984; Sherman *et al.* 1998). If combined with available nutrients, this may result in the formation of blooms of Cyanophyta, which have significant environmental, social and economic impacts. Furthermore, these conditions can result in
oxygen depletion both in the sediments and hypolimnion (bottom waters), reducing habitat availability for aquatic organisms and stimulating nutrient release from sediments, further promoting growth of Cyanophyta.

River regulation can increase the frequency of these low flow phases, as well as decreasing the frequency of floodplain inundation (Maheshwari et al. 1995). The River Murray is highly regulated by a series of weirs and numerous other storages, operated to satisfy irrigation demand and navigation (Maheshwari et al. 1995). In the River Murray, autochthonous carbon sources, in particular phytoplankton, have been identified as more important than allochthonous sources (Oliver and Merrick 2006; Gawne et al. 2007). However, these studies were conducted during low flow periods with limited floodplain inundation, which favours autochthonous sources over allochthonous sources (Robertson et al. 1999). Since the amount of carbon and nutrients leached from the floodplain is dependent upon the flood extent, timing and frequency, it is highly probable that river regulation will have major implications for the carbon and nutrient mobilisation from the floodplain (Robertson et al. 1999). Although this poses water quality risks (such as low dissolved oxygen, nutrient enrichment), the impact of regulation in this respect is not well documented.

Suitable water quality is essential for not only the societal uses of water, but the physico-chemical and biological parameters than define water quality are also important drivers of aquatic ecosystems (ANZECC 2000; NHMRC 2004). Whilst the desired levels of various water quality parameters differ between different water uses, there are some shared water quality characteristics that are risks for both human and environmental purposes in the Lower River Murray, namely:

- Elevated salinity, which may make water unsuitable for drinking and reduce habitat for biota
- Toxic blooms of Cyanophyta, which will increase water treatment costs and reduce habitat for aquatic biota (e.g. reduced light availability for aquatic plants, oxygen depletion during the night)
- High dissolved organic carbon concentrations, which will increase water treatments costs and may lead to low dissolved oxygen levels, reducing habitat for aquatic biota.

An exception to this is high nutrient concentrations, which are a risk for water treatment (increased risk of toxic blooms of Cyanophyta), but nutrients are essential for the growth and productivity of aquatic biota.

Between 2001 and 2010, the Murray-Darling Basin experienced an extended drought period (Murphy and Timbal 2008; Leblanc et al. 2009), followed immediately by extensive flooding (see description below). This resulted in a low flow-high flow sequence in the Lower River Murray. The
principal aim of this study was to investigate changes in the nutrient concentrations and phytoplankton communities in the Lower River Murray that resulted from this low flow-high flow sequence. It was hypothesised that:

- Low flow conditions would result in limited water mixing, thus a phytoplankton community dominated by phytoplankton able to move through the water column (gas–vacuolated Cyanophyta);
- The inundation of large areas of the floodplain would result in increased mobilisation of nutrients from the basin;
- Increased nutrient inputs would be incorporated into phytoplankton biomass and so phytoplankton biomass would increase under high flow conditions; and
- High flow conditions would result in elevated rates of water mixing and thus a phytoplankton community dominated by immotile phytoplankton species, such as diatoms.

In testing these hypotheses an understanding of the river discharge required to switch the phytoplankton community from one dominated by Cyanophyta to diatoms is explored. Such a switch would have implications for domestic water supplies with reduced treatment costs, but also aquatic food-webs since Cyanophyta are considered non-preferred food sources for zooplankton (Carney and Elser 1990; De Benardi and Giussani 1990; Henning et al. 1991). Changes in dissolved organic carbon, dissolved oxygen and salinity are also examined, since these pose significant water quality risks for domestic water supplies and are important in determining habitat availability for aquatic biota. In addition, sources of the observed changes in water quality are investigated.

Methods

Study site

The Murray-Darling Basin covers an area of 1.1 million km², 14% of Australia’s land area. A majority of the basin is arid or semi-arid, with mean annual evaporation (1200 mm) generally exceeding mean annual rainfall (450 mm) (Thoms and Walker 1993). As a result, the average annual discharge is relatively low, producing only 6% of Australia’s runoff (ABoS 2009). The natural flow regime of the Lower River Murray was characterised by high interannual variability (Maheshwari et al. 1995). To overcome this variability for irrigation and navigation purposes, the flow regime is now highly
regulated. Flow is regulated by 14 weirs, five river-mouth barrages, four major water storages and numerous smaller storages, riverbank levees and off-stream wetland regulators. The Murray–Darling Basin is the major source of irrigation water in Australia and is the major source for stock and domestic water supply in South Australia. It accounted for 50% of Australia's water use in 2005-2006 and produced 39% of the total Australian value of agricultural commodities, of which one third was irrigated agricultural production (ABoS 2009).

This study is focussed on the Lower River Murray, herein defined as the area between Lock 9 and Tailem Bend (RM-1 and RM-9 in Figure 1). Within this area, there are 8 locks in addition to Lock 9. Above Lock 9, water is sourced from the River Murray and its tributaries, providing the largest and most constant flow to the study area. Water also drains to the study area from the northern basin through the Darling River. The Darling River experiences a more variable climate (Puckridge et al. 1998) and has high turbidity levels (Geddes 1984; Grace et al. 1997). The climatic differences and the degree of river regulation between the Darling River and River Murray shape the hydrograph and discharge to the Lower River Murray.

The Lower River Murray is of great importance to not only the local region, but also South Australia and Australia. It constitutes a major drinking water supply for greater than 1.2 million people; it supplies water to several large irrigated agricultural areas; and has high cultural importance, including indigenous populations (Crabb 1997). It is also an ecologically important region. The area includes two Ramsar sites (Riverland and Banrock Station Wetland Complex) and two Murray-Darling Basin Authority Icon sites (Chowilla Floodplain and Lindsay-Walpolla Islands (including Mulcra) and the River Murray Channel) (MDBA 2011). The Lower River Murray Channel can be divided into the valley and gorge sections. The valley section has a broad floodplain. The gorge section is unique to the basin, with the river is confined to a deep, narrow, limestone gorge with only a limited floodplain. Within the study area, there are also numerous permanently and intermittently connected wetlands, large areas of floodplain and a large off-channel water storage (Lake Victoria).

Many water bodies of the Murray-Darling Basin are prone to eutrophication (Walker and Hillman 1982; Geddes 1984; Baldwin et al. 2008; Aldridge et al. 2011; Mosley et al. 2012), which detrimentally impacts water quality. In 1991 a toxic bloom of Cyanophyta affected almost 1000 km of the Barwon-Darling River (Bowling and Baker 1996). The water quality of the Lower River Murray is characterised by high turbidity, nutrient and phytoplankton levels (Mosley et al. 2012), although nutrient concentrations have also been found to be relatively low at times (Baker et al. 2000). Certain parts of the river also have periodic temperature stratification and toxic blooms of Cyanophyta (Baker et al. 2000; Maier et al. 2001).
Between 2001 and 2010, the Murray-Darling Basin experienced a severe drought, with severe rainfall deficiencies (Murphy and Timbal 2008; Leblanc et al. 2009). In the southern part of the basin river flows were the lowest in over 100 years of records (Murphy and Timbal 2008; Leblanc et al. 2009), with average daily flows in the Lower River Murray in 2009 of approximately 1400 ML/day (Department for Water, unpublished). These flows were largely controlled by regulatory structures, with little or no overbank flow and minimal connectivity between the river channel and floodplain. Due to reduced inflows, water levels fell to approximately -0.9 m Australian Height Datum below Lock 1, well below normal operating levels.

However, 2010 saw the Murray-Darling Basin experience its wettest year on record, with high rainfall in the catchment continuing into 2011 (Bureau of Meteorology, unpublished). This resulted in large areas of the basin being inundated and a rapid increase in river discharge. Average daily flows in Lower River Murray in 2010-2011 were approximately 30,000 ML/day (Department for Water, unpublished), with peak flows of almost 90,000 ML/day.
Temporal and spatial changes in nutrient concentrations and phytoplankton communities

Historical data on river flow, nutrient and dissolved organic carbon (DOC) concentrations and phytoplankton were investigated to evaluate how these parameters change between low flow and high flow periods. Data were provided by SA Water, the Murray-Darling Basin Authority and the South Australian Environment Protection Authority. The databases were combined and data were plotted to identify sites and parameters where sufficient data existed for investigation. Several sites in the South Australian section of the River Murray were included and sites upstream were included in order to identify sources of nutrients and phytoplankton. Not all sites had sufficient data for all parameters, but sites investigated were:

- River Murray at Merbein – RM-1 – upstream of junction with Darling River;
- Darling River at Burtundy – DR – upstream of junction with River Murray;
- River Murray at Lock 9 – RM-2 – downstream of Murray-Darling junction;
- Rufus River outlet – RR – outlet of Lake Victoria;
- River Murray downstream of Rufus River outlet – RM-3;
- River Murray at Lock 5 – RM-4;
- River Murray at Lock 3 – RM-5;
- River Murray at Waikerie – RM-6;
- River Murray at Morgan – RM-7;
- River Murray at Murray Bridge – RM-8; and
- River Murray at Tailem Bend – RM-9 (Figure 1).

These data were obtained from surface water grab samples. Samples for dissolved nutrients and DOC were filtered through 0.45 μm membrane filters upon collection and stored frozen. Samples for TP and TKN remained unfiltered and were stored frozen before digestion. All water samples were analysed by the Australian Water Quality Centre, a National Association of Testing Authorities accredited laboratory using standard methods. Parameters measured were DOC, oxidised nitrogen (nitrate plus nitrite; NO₃), ammonia (NH₄), total Kjeldahl nitrogen (TKN), total nitrogen (TN), filterable reactive phosphorus (FRP), total phosphorus (TP), silica (Si, molybdenum reactive fraction), chlorophyll a (chl-α) and phytoplankton cell counts. On occasions when TN data were not provided concentrations were calculated as the sum of TKN and NO₃. Additional relevant water quality parameters were also investigated where appropriate data existed. These parameters included
dissolved oxygen and electrical conductivity. Phytoplankton data were not always distinguished to species or genus and so presentation of the data were limited to the available groupings.

The primary objective of this study was to examine the differences in water quality parameters and phytoplankton communities between the low flow and high flow periods. Whilst data is presented for the entire low flow and high flow sequence (2002-2011), interpretation is largely focussed on comparable low flow and high flow periods. The high flow period selected was from June 2010 to August 2011, as this represented the period where data were available and included the rise, peak and recession of the high flow period. The low flow period was chosen as June 2008 to August 2009, to allow direct comparison to the low flow period (same duration and seasons). Temporal changes in water quality parameters are also focussed on RM-7, since this site had the most comprehensive database and it is a site for water quality objectives of the Murray-Darling Basin Authority.

**Water and nutrient balance for the Lower River Murray**

To assess whether the Lower River Murray was a source or sink of resources during low flow and high flow periods, inflowing and outflowing nutrient loads were calculated following methods of Cook et al. (2010). For this, the section of the river between Lock 9 and Lock 1 was chosen due to adequate flow and nutrient concentration data. There were not adequate data available for NH$_4$ or silica load determination. Data used for Lock 9 and Lock 1 were that of RM-2 and RM-7, respectively. Whilst RM-7 is located upstream of Lock 1 (Figure 1), there were no apparent spatial differences in nutrient concentrations in this section of the river during the study period.

Monthly retention was calculated as:

$$M_{ret} = M_{in(RM)} + M_{in(LV)} + M_{atm} - M_{ext} - M_{out}$$

where $M_{ret}$ is monthly retention load; $M_{in(RM)}$ is the monthly load into the river from the River Murray upstream of Lock 9; $M_{in(LV)}$ is the monthly load into the river from Lake Victoria; $M_{atm}$ is monthly atmospheric deposition load; $M_{ext}$ is the monthly load extracted for human purposes; and $M_{out}$ is the monthly load flowing downstream of Lock 1. Transfers between the river, floodplain, sediment and groundwater were not accounted for, but retention was attributed to these.

Loads for each source and sink were calculated as the product of monthly volume and average monthly concentration. Where monthly concentration data were missing, the concentration for the missing months was taken as an average of the preceding and subsequent months. On occasions
where nutrient concentrations were below the minimum limit of detection, concentrations were
assumed to have half the concentration of the detection limit. Source data for each of the load
calculations were:

- $M_{\text{in(RM)}}$
  - Nutrient concentrations at RM-2
  - Flow data at RM-2 (provided by Murray-Darling Basin Authority)

- $M_{\text{in(LV)}}$
  - Nutrient concentrations at RR
  - Flow data at RR (provided by Murray-Darling Basin Authority)

- $M_{\text{atm}}$
  - Rainfall deposition rates of NO\textsubscript{X}, TKN and FRP from were calculated from
    concentrations in rainwater in Adelaide (Wilkinson et al. 2006; Cook et al. 2010). Rainfall volumes
    were calculated as the product of river surface area and rainfall. Average monthly rainfall
    at Lake Victoria, Renmark, Barmera and Morgan were used (provided by Australian Bureau of
    Meteorology). River surface area was the sum of the average surface area of each weir pool during
    the study period. These were calculated from average water levels during the study period and
    the relationship between river surface area and water level (provided by South Australian
    Department for Water).
  - Dry deposition rates for TKN were estimated to be 50% of wet deposition rates
    (Wilkinson et al. 2006; Cook et al. 2010). There is no information on TP deposition rates
    in the region, so total annual atmospheric deposition was estimated as 1 kg/ha/year, which is in
    the middle of the range of atmospheric deposition rates previously reported (Newman 1995; Cook
    et al. 2010). Rates of dry deposition of NO\textsubscript{X} and FRP were not included for budgeting purposes since
    these were considered to be negligible (Cook et al. 2010).

- $M_{\text{out}}$
  - Nutrient concentrations at RM-7
  - Flow data at Lock 1 (provided by Murray-Darling Basin Authority)

- $M_{\text{ext}}$
  - Nutrient concentrations were assumed to be the average of concentrations measured at RM-2
    and RM-7 for the given month
  - Water extraction volume (provided by Murray-Darling Basin Authority and Lower Murray Water)
Monthly data were summed for the two periods selected to represent the low flow and high flow periods (June 2008-August 2009 and June 2010-August 2011). Similarly, the water volumes for each of the components of the nutrient budget are also presented.

**Results**

Between June 2008 and until August 2009 river discharge at Lock 1 (downstream of RM-7) was extremely low with an average of 1460 ML/day (Figure 2). In summer 2009-2010 discharge rose following rainfall in the Darling River Catchment, with discharge remaining slightly elevated until spring 2010 when discharge rose rapidly, peaking in February 2011.

**Salinity, dissolved organic carbon and dissolved oxygen**

**Temporal changes**

Electrical conductivity was relatively low at RM-7 during the low flow and high flow periods, although there was an apparent decrease at the onset of the high flow period (Figure 2). A strong positive relationship was observed between discharge and DOC concentration, particularly during the high flow period. DO concentrations had an inverse relationship with discharge and DOC during the high flow period, falling to 3.3 mg/L in March 2011.

**Spatial differences**

Differences in electrical conductivity were observed between the Darling River and River Murray, with electrical conductivity at DR steadily increasing between flood peaks during the low flow period (Figure 3), perhaps driven by evapo-concentration and groundwater inputs. This appeared to have little effect downstream, with electrical conductivity in the River Murray between RM-1 and RM-4 reasonably constant between 2000 and 2011, rarely exceeding 700 μS/cm. At sites RM-5 to RM-9 the seasonal amplitude of electrical conductivity variation increased, along with the absolute electrical conductivity. At RM-9 there were regular excursions of electrical conductivity above 1000 μS/cm between 2004 and 2009.
The DOC in the Darling River (DR) showed two distinct increasing trends in 2003 and 2007, with peak concentrations between 30 and 35 mg/L (Figure 4). These trends corresponded with low flow and high electrical conductivity. However, the very low flows of the Darling River during these periods meant that there was little influence on DOC concentrations downstream. At sites downstream of RM-2 the DOC concentrations were typically below 10 mg/L until the high flow period in late 2010. At this time DOC concentrations of 20 mg/L were observed, with concentrations for the length of the Lower River Murray sites largely governed by upstream River Murray sites. As for RM-7, DO displayed an inverse relationship with flow and DOC at each site where adequate data existed, with minimum concentrations of less than 4 mg/L observed during the high flow peak (Figure 5). As for DOC, DO concentrations were largely governed by upstream sites.

**Nutrients**

**Temporal changes**

During the low flow period dissolved nitrogen and phosphorus concentrations (NH₄, NOₓ and FRP) were typically low; at or near detection limits (Figure 2). However, following rainfall in the Darling River Catchment and the subsequent rise in discharge at the end of 2009, dissolved nutrient concentrations began to rise. Subsequently, concentrations fell with flow, before increasing rapidly during the second flood peak. Both increases in concentrations were most likely due to mobilisation of nutrients in previously dry areas. This was the case for all dissolved nutrient forms, although NOₓ concentrations were highly variable, but generally higher than NH₄. This is not unexpected as NH₄ would be readily oxidised through nitrification in a mixed, oxygenated river system.

A similar pattern was observed for TN, TKN and TP concentrations, although the initial increase was observed prior to that for dissolved nutrients (Figure 2). This suggests an initial input of particulate nutrients, either as inorganic particles, dead organic matter or phytoplankton biomass. Whilst dissolved nutrient concentrations typically fell away after the flood recession to levels similarly to that of the low flow period, TN, TKN and TP remained elevated. This is consistent with increased productivity in the river and/or inputs from the floodplain and wetlands as the flow receded.

**Spatial differences**

There was only limited data available for NH₄ concentrations making it difficult to assess spatial differences (Figure 6). However, concentrations tended to be higher at RM-9 than RM-7 during the
low flow period. A similar observation was apparent for NO\textsubscript{x}, FRP, TKN, TN, TP and Si with sites below Lock 1 having higher concentrations than RM-7 and RM-9 having greater concentrations than RM-9 (Figure 7 - Figure 12). This suggests a local nutrient input, most likely from evapo-concentration, irrigation returns from dairies, groundwater or inputs from Lake Alexandrina.

Concentrations of nitrogen and phosphorus at RM-7 were largely governed by upstream sites, with peaks typically associated with periods of high flow at DR and RM-1 (Figure 6 - Figure 12). Consequently, nutrient concentrations at RM-7 generally followed the same pattern as RM-2. Notably, DR had very high FRP and TP concentrations which elevated concentrations downstream. Generally, nutrient concentrations had a positive relationship with river flow. However, in the Darling River this was not always the case, with TKN concentrations increasing during a period of extremely low flow (2005-2008; Figure 9), most likely associated with phytoplankton biomass.

**Phytoplankton communities**

**Temporal changes**

In spring 2010, there was a large increase in chl-a concentrations, which appeared to be a result of the elevated Si concentrations brought in by the initial rise in discharge in early 2010 (Figure 2). Following the second rise in discharge, Si concentrations again increased, resulting in increased chl-a concentrations, which continued to rise after the flood peak had passed. This rise was associated with increased abundances of diatoms (and particulate nitrogen and phosphorus). This was also the case for *Aulacoseira*, the dominant diatom genus during the study period (Figure 13). *Aulacoseira* accounted for the majority of the total biomass, with lower numbers of other centric diatoms and pennate diatoms. Whilst there was no clear relationship between flow and other centric diatoms, there was an apparent positive relationship between flow and pennate diatoms, similar to that of *Aulacoseira*. However, at flows above 40,000 ML/day, diatom abundance decreased.

Cyanophyta displayed a contrasting response to diatoms during the low flow and high flow periods, with high cell numbers during the low flow period and low numbers during the high flow period (Figure 2). At RM-7, Cyanophyta abundance tended to decrease during the study period, although a large spike was observed in late 2009. *Anabaena, Aphanizomenon* and *Cylindrospermopsis* were the dominant Cyanophyte species, with periodic increases in abundances during the low flow period (Figure 13). However, none of these accounted for the large peak in Cyanophyta abundance in late
Abundances of each of the dominant species remained low throughout the high flow period.

Chlorophyta were moderately abundant at all flows, although tended to be higher during the high flow period (Figure 2). The chlorophyte population consisted of mainly Actinastrum, Ankistrodesmus and Scenedesmus (Figure 13). Whilst Actinastrum had higher numbers towards the end of the high flow period (after the flood peak), Ankistrodesmus and Scenedesmus were largely related to seasonal changes with the former peaking in spring and the latter peaking in summer.

**Spatial differences**

Data for chl-a from upstream of the Murray-Darling junction were inadequate to assess the relative contributions of the River Murray and Darling River to downstream communities (Figure 14). However, during the latter part of the low flow period there was a gradual decline in chl-a concentrations at RM-1 despite considerable seasonal variability. At DR the seasonal variability was more pronounced with greater chl-a concentrations during summer than at RM-1. The rise in chl-a concentrations observed at RM-7 (and RM-9) were consistent with that at RM-2, although peak concentrations were higher at the downstream sites.

Numbers of diatoms were greater at RM-1 than DR during the low flow period (inadequate data during the high flow period), suggesting the River Murray is an important source for downstream sites, although during the low flow period numbers were lower downstream than at RM-1 (Figure 15). As for RM-7, Cyanophyta displayed a contrasting response to diatoms, with low numbers during the high flow period and times of high cell numbers during the low flow period (Figure 16). This was particularly evident at DR at the start of the low flow period. However, low flows in the Darling River meant there was little influence downstream. High Cyanophyta abundance at RM-1 (2007-2009), did coincide with higher abundances downstream (Figure 16). High numbers were also detected at RM-7 in early 2008, as well as brief period of very high cell numbers at RM-9 in early 2010 (Figure 16). As for RM-7, the relationship between flow and Chlorophyta was not clear, with moderately high abundances at downstream sites during both the low flow and high flow periods (Figure 17). Highest abundances were observed at RM-1 and DR during the low flow periods.
Figure 2. Changes in physico-chemical conditions and phytoplankton communities at RM-7 during the low flow (June 2008 to August 2009) and high flow period (June 2010 to August 2011). Shown are changes in discharge, electrical conductivity, dissolved organic carbon (DOC), dissolved oxygen (DO) ammonia (NH₄), oxidised nitrogen (NOₓ), total Kjeldahl nitrogen (TKN), total nitrogen (TN), filterable reactive phosphorus (FRP), total phosphorus (TP), chlorophyll a (Chl-a), silica (Si), and selected phytoplankton groups.
Figure 3. Changes in electrical conductivity in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-3, RM-4, RM-5, RM-6, RM-7, RM-8, and RM-9 (left to right). Electrical conductivity is shown by black circles. Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of electrical conductivity measurements.
Figure 4. Changes in dissolved organic carbon (DOC) concentrations in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-3, RM-4, RM-5, RM-6, RM-7, RM-8, and RM-9 (left to right). DOC concentrations are shown by black circles. Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of DOC measurements.
Figure 5. Changes in dissolved oxygen concentrations in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-6, RM-7, RM-8, and RM-9 (left to right). Dissolved oxygen concentrations are shown by black circles. Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of dissolved oxygen measurements.
Figure 6. Changes in ammonia concentrations in the Lower River Murray 2000-2011. Shown are sites RR, RM-6, RM-7, RM-8, and RM-9 (left to right). Ammonia concentrations are shown by black circles and red circles (the latter show recordings where values are below detection limit with detection limit plotted). Lines Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of ammonia measurements.
Figure 7. Changes in oxidised nitrogen concentrations in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-4, RM-5, RM-6, RM-7, RM-8, and RM-9 (left to right). Oxidised nitrogen concentrations are shown by black circles and red circles (the latter show recordings where values are below detection limit with detection limit plotted). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of oxidised nitrogen measurements.
Figure 8. Changes in filterable reactive phosphorus (FRP) concentrations in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-3, RM-4, RM-5, RM-6, RM-7, RM-8, and RM-9 (left to right). FRP concentrations are shown by black circles and red circles (the latter show recordings where values are below detection limit with detection limit plotted). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of FRP measurements.
Figure 9. Changes in total Kjeldahl nitrogen (TKN) concentrations in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-4, RM-5, RM-6, RM-7, RM-8, and RM-9 (left to right). Total Kjeldahl nitrogen concentrations are shown by black circles and red circles (the latter show recordings where values are below detection limit with detection limit plotted). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of TKN measurements.
Figure 10. Changes in total nitrogen concentrations in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-4, RM-5, RM-6, RM-7, RM-8, and RM-9 (left to right). Total nitrogen concentrations are shown by black circles and red circles (the latter show concentrations calculated as the sum of TKN and oxidised nitrogen). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of total nitrogen measurements.
Figure 11. Changes in total phosphorus concentrations in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-3, RM-4, RM-5, RM-6, RM-7, RM-8, and RM-9 (left to right). TP concentrations are shown by black circles and red circles (the latter show recordings where values are below detection limit with detection limit plotted). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of total phosphorus measurements.
Figure 12. Changes in reactive silica concentrations in the Lower River Murray 2000-2011. Shown are sites RM-2, RR, RM-4, RM-5, RM-7, RM-8, and RM-9 (left to right). Reactive silica concentrations are shown by black circles and red circles (the latter show recordings where values are below detection limit with detection limit plotted). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of dissolved oxygen measurements.
Figure 13. Changes in phytoplankton communities at RM-7 during the low flow (June 2008 to August 2009) and high flow period (June 2010 to August 2011). Shown are dominant genera and groups from diatoms (A), Cyanophyta (B) and Chlorophyta (C).
Figure 14. Changes in chlorophyll a concentrations in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RM-7, and RM-9 (left to right). Chlorophyll a concentrations are shown by black, blue (Lorenzen 1967), green (UNESCO 1966) and red circles (the latter show recordings where values are below detection limit with detection limit plotted). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of chlorophyll a measurements.
Figure 15. Changes in diatom (Bacillariophyceae) abundance in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-6, RM-7, RM-8, and RM-9 (left to right). Abundance (cells/mL) is shown by circles and red lines (abundance range). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of phytoplankton measurements.
Figure 16. Changes in Cyanophyta abundance in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-6, RM-7, RM-8, and RM-9 (left to right). Abundance (cells/mL) is shown by circles and red lines (abundance range). Where values are outside the y-axis scale range, the values are given alongside circles and red arrow. Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of phytoplankton measurements.
Figure 17. Changes in Chlorophyta abundance in the Lower River Murray 2000-2011. Shown are sites RM-1, DR, RM-2, RR, RM-6, RM-7, RM-8, and RM-9 (left to right). Abundance (cells/mL) is shown by circles and red lines (abundance range). Grey lines show the discharge at Lock 9 in River Murray and Rufus River for RR and Darling River for DR. Yellow lines for River Murray sites show the discharge at closest available site to point of phytoplankton measurements.
Water and nutrient balance

During the low flow period (June 2008-August 2009), inflows from upstream of Lock 9 and Lake Victoria contributed comparable water volumes to the Lower River Murray and were far greater than local rainfall contributions (Table 1). During this period, total inputs were greater than outputs, suggesting there was a loss of water not accounted for in the water balance. This may have been a result of evaporation and groundwater loss. This unaccounted loss was equivalent to 24% of the total outputs (accounted), suggesting this was a significant contributor to the water balance during the low flow period. During the high flow period, inputs from above Lock 9 were far greater than that of Lake Victoria and there was a net gain in water not accounted for in the balance. This suggests local inputs were greater than evaporation. This may have been a result of contributions from the floodplain via the local catchment and groundwater. Although a significant volume, this only accounted for 2% of all accounted inputs.

Table 1. Water balance for Lock 9 to Lock 1 for low flow (June 2008-August 2009) and high flow (June 2010-August 2011) periods. The balance includes total volumes from inflow from the River Murray ($V_{in(RM)}$), total volumes from inflow from Lake Victoria ($V_{in(LV)}$), total volumes from atmospheric input ($V_{atm}$), total extraction volumes ($V_{ext}$), total outflowing volumes ($V_{out}$), the total volume balance ($V_{bal}$).

<table>
<thead>
<tr>
<th>Component</th>
<th>Period</th>
<th>Volume (GL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{in(RM)}$</td>
<td>Low flow</td>
<td>543.5</td>
</tr>
<tr>
<td></td>
<td>High flow</td>
<td>14588.1</td>
</tr>
<tr>
<td>$V_{in(LV)}$</td>
<td>Low flow</td>
<td>591.6</td>
</tr>
<tr>
<td></td>
<td>High flow</td>
<td>1503.4</td>
</tr>
<tr>
<td>$V_{atm}$</td>
<td>Low flow</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>High flow</td>
<td>0.6</td>
</tr>
<tr>
<td>$V_{ext}$</td>
<td>Low flow</td>
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<tr>
<td></td>
<td>High flow</td>
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<td>$V_{out}$</td>
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<td>666.4</td>
</tr>
<tr>
<td></td>
<td>High flow</td>
<td>16114.7</td>
</tr>
<tr>
<td>$V_{bal}$</td>
<td>Low flow</td>
<td>216.5</td>
</tr>
<tr>
<td></td>
<td>High flow</td>
<td>-336.2</td>
</tr>
</tbody>
</table>
During the high flow period, the inputs of nutrients to the river between Lock 9 and Lock 1 were much greater from the River Murray upstream of Lock 9 than from Lake Victoria and the atmosphere (Table 2). However, during the low flow period, inputs from Lake Victoria were higher than that of the River Murray, except for TN, where inputs from Lake Victoria and the River Murray were similar. As would be expected, atmospheric inputs and water extractions were greater during the high flow period, owing to greater rainfall and increased water allocations, respectively. The outflowing loads were also much higher during the high flow period.

There was a greater load of FRP retained during the low flow period, with 79.3% of the inputs retained (equating to 26.6 tonnes) in comparison to only 2.2% in the high flow period (Table 2). This was also the case for TP, with higher retention during the low flow period than high flow period. However, during the high flow period, it appeared that the area between Lock 9 and Lock 1 was a source of TP, with 297.7 tonnes of phosphorus passing downstream that was not accounted for by the upstream and rainfall inputs. This suggests a significant source of phosphorus from the floodplain, groundwater inputs or sediment resuspension within the river. A very similar pattern was found for total nitrogen (TN), although there was a much larger source of TN (2782.3 tonne) compared to TP not accounted for by the upstream and rainfall inputs alone. The pattern was also similar for DOC, but despite there being a large source of DOC by mass, this was small in comparison to the inflowing loads from upstream. The area between Lock 9 and Lock 1 was a sink for NO\textsubscript{X} during both the high flow and low flow period periods. Although the mass of NO\textsubscript{X} retained was greater during the high flow period than low flow period, a lower percentage was retained during the high flow period, due to large upstream inputs and presumably reduced opportunity for retention during higher flows.
Table 2. Nutrient and dissolved organic carbon budget for Lock 9 to Lock 1 for low flow (June 2008-August 2009) and high flow periods (June 2010-August 2011). Parameters where adequate data were available include filterable reactive phosphorus (FRP), total phosphorus (TP), oxidised nitrogen (NO$_X$), total nitrogen (TN) and dissolved organic carbon (DOC). Components of the budget are total loads from inflow from the River Murray (M$_{in(RM)}$), the total loads from inflow from Lake Victoria (M$_{in(LV)}$), the total loads from atmosphere (M$_{atm}$), the total loads to extractions (M$_{ext}$), the total outflowing loads (M$_{out}$), the total load retained (M$_{ret}$, as a mass and as a percentage of all inputs).

<table>
<thead>
<tr>
<th>Component</th>
<th>Period</th>
<th>FRP (tonne)</th>
<th>TP (tonne)</th>
<th>NO$_X$ (tonne)</th>
<th>TN (tonne)</th>
<th>DOC (tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M$_{in(RM)}$</td>
<td>Low flow</td>
<td>8.3</td>
<td>37.0</td>
<td>34.9</td>
<td>497.8</td>
<td>2008.9</td>
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<td></td>
<td>High flow</td>
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<td>2907.2</td>
<td>1452.7</td>
<td>18701.4</td>
<td>172406.6</td>
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<tr>
<td>M$_{in(LV)}$</td>
<td>Low flow</td>
<td>25.8</td>
<td>99.1</td>
<td>43.6</td>
<td>458.3</td>
<td>2608.1</td>
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<tr>
<td></td>
<td>High flow</td>
<td>71.9</td>
<td>264.2</td>
<td>237.7</td>
<td>1474.1</td>
<td>10189.4</td>
</tr>
<tr>
<td>M$_{atm}$</td>
<td>Low flow</td>
<td>0.7</td>
<td>8.8</td>
<td>1.5</td>
<td>7.3</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>High flow</td>
<td>1.7</td>
<td>8.8</td>
<td>3.8</td>
<td>18.2</td>
<td>51.1</td>
</tr>
<tr>
<td>M$_{ext}$</td>
<td>Low flow</td>
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<td>15.3</td>
<td>13.0</td>
<td>210.5</td>
<td>1032.0</td>
</tr>
<tr>
<td></td>
<td>High flow</td>
<td>17.5</td>
<td>63.9</td>
<td>30.7</td>
<td>408.4</td>
<td>3654.1</td>
</tr>
<tr>
<td>M$_{out}$</td>
<td>Low flow</td>
<td>4.2</td>
<td>29.7</td>
<td>23.7</td>
<td>377.2</td>
<td>2687.3</td>
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<tr>
<td></td>
<td>High flow</td>
<td>859.7</td>
<td>3413.0</td>
<td>1373.1</td>
<td>22567.7</td>
<td>185438.0</td>
</tr>
<tr>
<td>M$_{ret}$</td>
<td>Low flow</td>
<td>27.6</td>
<td>99.9</td>
<td>43.2</td>
<td>375.8</td>
<td>918.2</td>
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<tr>
<td></td>
<td>High flow</td>
<td>19.8</td>
<td>-296.7</td>
<td>290.3</td>
<td>-2782.3</td>
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<tr>
<td>M$_{ret}$ (%)</td>
<td>Low flow</td>
<td>79.3</td>
<td>69.0</td>
<td>54.1</td>
<td>39.0</td>
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<td></td>
<td>High flow</td>
<td>2.2</td>
<td>-9.3</td>
<td>17.1</td>
<td>-13.8</td>
<td>-3.5</td>
</tr>
</tbody>
</table>

Discussion

The response to a low flow-high flow sequence

In arid and semi-arid systems, the inputs of nutrients and organic matter are less regular than those of temperate regions where the River Continuum was developed (Baldwin and Mitchell 2000; Linden et al. 2004). Such variability has important consequences for aquatic systems. This variability is typical of riverine systems in dry climates throughout the world. It is evident in Australia, which has some of the most hydraulically variable river systems in the world (Puckridge et al. 1998). This is in part determined by the El Niño-Southern Oscillation (Rasmusson and Wallace 1983; Simpson et al. 1993) and results in Australia experiencing major droughts interspersed with extensive wet periods.
The observed water quality response differed between the two main sources of water to the Lower River Murray; the Darling River and River Murray. In the Darling River, increases in DOC did not correspond with elevated discharge, which would be expected if the DOC was organic matter washed in from the floodplain or catchment. However, peak DOC concentrations coincided with periods of low flow and high salinity. There could be several explanations for this, but the most likely explanation is that the increase in salinity caused the clay particles to flocculate and settle, leading to increased DOC release by phytoplankton due to increased light penetration and productivity (Donnelly et al. 1997; Oliver et al. 2010). Indeed, high abundances of phytoplankton, particularly Cyanophyta, have been observed previously in the Darling River (Hötzel and Croome 1994). The very low flows of the Darling River during these periods meant that there was little influence on DOC concentrations in the River Murray downstream. In the Lower River Murray, DOC was mobilised from the basin during the high flow period, shifting the river from a net autotrophic system (Oliver and Merrick 2006) to a net heterotrophic system. The River Murray has previously been observed to shift between periods of autotrophy and heterotrophy (Gawne et al. 2007). The ‘blackwater’ event in early 2011 promoted microbial activity, leading to a reduction in dissolved oxygen concentrations to below 4 mg/L, which has implications for biota (Wu et al. 2003) and water treatment because DOC requires removal for potable water supply.

Similarly, there were clear differences in the nutrient concentrations and phytoplankton communities between the studied low flow and high flow periods. Whilst nutrient levels were low during the low flow period, it was clear that the high flows mobilised dissolved nutrients (NO₃, NH₄ and FRP) from the basin. This was evidenced by the mobilisation of FRP and NH₄, and perhaps oxidation of NH₄ to NO₃. The increased dissolved nutrient concentrations during the high flow period corresponded with increases in TKN, TN and TP. Whilst dissolved nutrients fell rapidly after peak flows had passed, TKN, TN and TP concentrations decreased with the recession of the high flow period but still remained elevated. This pattern is consistent with the view that dissolved nutrients were incorporated into phytoplankton biomass during the high flow period, either through instream growth or input from the floodplain and connected wetlands. Indeed, phytoplankton biomass continued to increase after the high flow peak had passed. These observations differ from those in impoundments further upstream (Walker and Hillman 1982), where nutrient concentrations showed no clear changes with flow. During a high flow event in the impoundments, increased flow resulted in increased nutrient loads, but increased turbidity appeared to limit phytoplankton productivity (Walker and Hillman 1982).

As hypothesised in this study, the mobilisation of nutrients from the basin increased phytoplankton biomass. Furthermore, the increased phytoplankton biomass during the high flow period was largely
driven by an increase in numbers of immotile diatoms, in particular Aulacoseira. This is consistent with previous studies in upstream impoundments (Walker and Hillman 1982) and the Murrumbidgee River (Sherman et al. 1998), a tributary of the River Murray upstream of this study area. Furthermore, Aulacoseira was a dominant phytoplankton of well connected floodplain wetlands of the Lower River Murray prior to European settlement (Gell et al. 2007). As with this study, Aulacoseira numbers have previously been observed to be low during peak flow periods, perhaps due to Si dilution during these periods (Hötzel and Croome 1996). Previously Aulacoseira have been observed to be in lower abundances in the slower flowing Lower River Murray than further upstream (Sullivan 1990), with other centric diatoms occurring more frequently. The dominance of Aulacoseira in this study is most likely a result of the magnitude of the discharge during the high flows period. Aulacoseira have high nutrient requirements and enter the water column during high flow through the resuspension of sediments and are maintained in suspension (Cardoso and Motta Marques 2004). At low flows, Aulacoseira tends to sediment out of the photic zone and growth cannot be sustained (Condie and Bormans 1997). When filaments sink to the sediments their protoplasmic contents often contract into a condensed resting form, remaining viable for months or years (Cardoso and Motta Marques 2004).

The buoyant Cyanophyta dominate at flows of less than 10,000 ML/day, supporting the hypothesis of Baker et al. (2000), most likely due to stratification formation (Sherman et al. 1998). Baker et al. (2000) postulated that the Cyanophyta species that exist will be controlled by nitrogen levels, with high soluble inorganic nitrogen availability favouring Microcystis and Planktothrix and low concentrations favouring nitrogen fixing genera, such as Anabaena, Aphanizomenon, Anabaenopsis and Cylindrospermopsis (Baker et al. 2000). This was indeed supported by this study, with the latter group dominating during the low flow period, with low flow and low nitrogen concentrations. Whilst large numbers of Cyanophyta might have been expected during periods of persistent stratification (Bormans et al. 1997; Baker et al. 2000; Maier et al. 2001) in the low flow period, this was not the case. It is likely that the Cyanophyta community was limited by the low phosphorus concentrations.

**Sources of nutrients and organic matter**

The low nutrient concentrations during the low flow period were a result of both low inputs from upstream but also from retention, presumably due to sedimentation of inorganic and organic material. For NO\textsubscript{X} this would have also been due to coupled nitrification-denitrification. In comparison, during the high flow period the Lower River Murray region was a source of nutrients and dissolved organic carbon, presumably through mobilisation from the floodplain (Baldwin 1999),
instream productivity, groundwater inputs or resuspension of sediments. However, groundwater inputs seem unlikely given that surface water would be expected to recharge groundwater during periods of high water levels (Lamontagne et al. 2005). Given that Cyanophyta abundance was low during this period, it is unlikely that nitrogen fixation contributed significantly to the nitrogen concentrations during this period. However, resultant nutrient and DOC concentrations and phytoplankton abundances and communities in the Lower River Murray were largely driven by upstream inputs. During the low flow period, managed releases from Lake Victoria were a major source, but during the high flow period inputs from the River Murray and Darling River were dominant. Previously, nutrient concentrations have been observed to increase downstream of the Darling River, particularly TP, FRP and Si (Shafron et al. 1990).

Whilst elevated nutrient and DOC concentrations, salinity and phytoplankton (Anabaena) abundance were observed in the Darling River during the low flow period, this appeared to have less influence on the Lower River Murray than the River Murray, owing to the low discharge of the Darling River during this time. However, during the high flow period the impact of the Darling River on downstream water quality was apparent. During the low flow period there also appeared to be a large source of nutrients to the Lower River Murray downstream of Lock 1. The sources of these nutrients may have been a combination of evapo-concentration, irrigation returns, groundwater inputs and inputs from Lake Alexandrina. During the low flow period, the Lower Lakes had elevated salinities associated with seawater intrusions (Aldridge et al. 2011), with sustained south-westerly winds pushing saline water upstream into the Lower River Murray (Robert Daly, SA Water, unpublished data), with electrical conductivities of greater than 1500 μS/cm observed on many occasions. At these levels, there would have been adverse effects on aquatic biota (Nielsen et al. 2003). The high river flows of 2010-2011 returned Lake Alexandrina electrical conductivities to <500 μS/cm (Department for Water, unpublished data) and prevented the salinity intrusions at RM-9. The Lower Lakes had higher nutrient concentrations and phytoplankton biomass than the Lower River Murray during this period (Aldridge et al. 2011), suggesting this is a plausible explanation.

Groundwater is also a likely source of elevated NOx concentrations at RM-9 during the low flow period, although inputs from irrigation returns has been attributed to the high nutrient concentrations in this region (Shafron et al. 1990; Cugley et al. 2002).
Conclusion

During the low flow and high flow periods of this study, the water quality and phytoplankton communities of the Lower River Murray appear to be largely governed by upstream inputs and to a lesser extent local inputs. During low flow periods, major water quality concerns appear to be salinity inputs from Lake Alexandrina, but also blooms of Cyanophyta. During this study, there were no apparent blooms, which may be explained by phosphorus limitation. It would appear that the greatest risk of blooms of Cyanophyta occurs on the recession of high flows or during the onset of low flow conditions. At this time, there will likely be nutrients available for growth of Cyanophyta and inputs of water from connected wetlands and floodplains, which harbour significant populations of Cyanophyta (Baker et al. 2000). During high flows, major water quality concerns appear to be hypoxia associated with elevated DOC concentrations.

This study has revealed clear linkages between flow, water quality and phytoplankton communities in the Lower River Murray. The high flow period resulted in the mobilisation of nutrients, resulting in increased primary productivity and a switch from a phytoplankton community dominated by Cyanophyta to diatoms. Whilst this has some clear benefits associated with reduced risk of blooms of Cyanophyta, the consequences for the ecosystem are less well understood. There is evidence to suggest that Cyanophyta are non-preferred food sources for zooplankton (Carney and Elser 1990; De Benardi and Giussani 1990; Henning et al. 1991). Similarly, during the high flow period heterotrophic productivity was also stimulated through mobilisation of organic carbon from the basin. The increase in riverine productivity associated with the high flow period would have trophic benefits, with greater amounts of carbon and nutrients available to support the riverine foodwebs.

Since extreme hydrological events and lower average flows are likely to become more common in the future due to climate change (CSIRO 2008), there are clearly implications for the water quality of the Lower River Murray that require consideration. In particular, the duration between high flow events is likely to alter the rates of accumulation of organic material on the floodplain, altering DOC and nutrient inputs to the Lower River Murray.
Recommendations

Low flow and high flow periods present challenges for the management of water quality in the Lower River Murray. It is clear that during extended low flow periods adequate water needs to be supplied to the Lower River Murray if the intrusion of saline and nutrient rich water below Lock 1 is to be avoided. Whilst Lake Alexandrina appears to be a source of high elevated salinity, nutrient concentrations and phytoplankton biomass below Lock 1, consideration needs to be given to groundwater and return flows from irrigated areas. Extended low flow periods also appear to result in the accumulation of carbon on the floodplain, resulting in hypoxic conditions in the Lower River Murray upon re inundation. Reducing the interval between floodplain inundation events may reduce the risk of hypoxia. The provision of water to the floodplain needs to consider both the benefits and risks associated with return flows to the river. Return flows will carry elevated loads of organic carbon and nutrients, which will stimulate the activity and growth of heterotrophic microbes and phytoplankton. During the unregulated high flow period of this study, the increased nutrient concentrations resulted in increased primary productivity, with likely trophic benefits for the ecosystem. However, return flows from regulated water provisions to the floodplain during periods of low river discharge is likely to increase the risk of blooms of Cyanophyta. Consequently, provisions of water to the floodplain should be complemented with river flow rates that favour a phytoplankton community dominated by diatoms, particularly during periods of warm, calm conditions. These provisions will have environmental, social and economic benefits.
References


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