Community structure and ecological responses to hydrological changes in benthic algal assemblages in a regulated river: Application of algal metrics and multivariate techniques in river management

Ehsan Atazadeh[*1, 2], **Peter Gell**[3], **Keely Mills**[4], **Andrew Barton**[5] and **Peter Newall**[3]

[1]Department of Plant Sciences, Faculty of Natural Sciences, University of Tabriz, 29 Bahman Blvd, 51666-14779 Tabriz, Iran

[2]Institute of Environment, University of Tabriz, 29 Bahman Blvd, 51666-14779 Tabriz, Iran

[3]School of Sciences, Psychology and Sport, Federation University, Ballarat, VIC 3353, Australia

[4]British Geological Survey, Keyworth, Nottingham NG12 5GG, United Kingdom

[5]School of Engineering, IT and Physical Sciences, Federation University, Ballarat VIC 3353, Australia

*Corresponding author: ehsan.atazadeh@gmail.com and atazadeh@tabrizu.ac.ir

Abstract

The flow regime of the Wimmera River was substantially modified due to the construction of a water supply reservoir. Samples of diatoms, soft algae and measurements of water quality were analysed at ten sampling sites for three years (between February 2012 and November 2014) along the MacKenzie River, a tributary of the Wimmera River, in different seasons and under different flow regimes, to understand the spatial and temporal variation in the relationship between algal communities, water quality and stream condition. Baseline information on algal communities and water quality was collected during base flow conditions, while experiments on the effect of water releases on algal communities were based on flow regime variations (manipulated flow regimes), specifically on the algae community structure, water quality and ecosystem function. Algal species composition changed along the river under different flow regimes and different seasons. Under base flow, Bacillariophyta (diatoms) were more abundant upstream and filamentous green algae were more abundant downstream. The results showed that the algal composition shifted downstream after water release events. Chlorophyta (Green algae), Cyanophyta (Blue-green algae) and Chrysophyta gradually increased from upstream to downstream under base flow conditions, and before water releases, whereas diatoms were greater upstream and increased downstream after water releases. The results suggest that by tailoring the discharge and duration of the river flows, through the amalgamation of consumptive and environmental flows would improve the condition of the stream, and supplementing the positive effects of the flows dedicated to improving environmental outcomes.

Keywords: River management; Ecological assessment; Algae; Flow regime; Aquatic ecology

Introduction

The main challenge for river scientists and water managers is to keep rivers healthy whilst sustaining productive industries and communities. To achieve this, the in-stream flow recommendations used by water management agencies, and their acceptance by regional communities, is related to an understanding of the interdependencies of management actions and ecosystem health (Ryder et al. 2010, Bunn 2016, Atazadeh 2017, Atazadeh et al. 2020). Many terms such as environmental water allocations (EWAs), environmental flows (E-flows), ecological and environmental water requirements (EEWRs), ecological water demands, in-stream flow and environmental water consumption are widely used by aquatic ecologists to refer to the flows that maintain and preserve ecological and biophysical characteristics of rivers (Acreman and Dunbar 2004, Arthington 2012, Atazadeh et al. 2012, Atazadeh et al. 2014a, Zeiringer et al. 2018). The concept of the environmental flow regime has been accompanied by an expectation, and prediction, that ecologists can provide environmental flow prescriptions that sustain and improve the condition of riverine ecosystems (Arthington et al. 2006b, Arthington 2012). The environmental flow regime relates not only to the volume of flow through a river system, but also the pattern of those flows (e.g. water frequency, water speed and depth of water) (Arthington 2012, Atazadeh 2017).

There is the potential for a range of environmental benefits to be obtained during large and small pulsed flows. Pulsed flows are water releases from structures, such as dams, reservoir and weirs, to affect water transfers between storages to meet certain demands and water supply requirements (Watts et al. 2009a, Palmer et al. 2014, Palmer and Ruhi 2019). The general form of consumptive water transfers is via a pulse flow (Richter et al. 1996, Watts et al. 2009b, Powell et al. 2013, Nichols et al. 2017). Flow regime has a significant effect on physical form, streamside zone, water quality and aquatic biota of a river (Ladson et al. 1999, Bunn and Arthington 2002, Gordon et al. 2004, Poff et al. 2010). The regulation of flow from reservoirs and dams, coupled with water abstraction, leads to severe stress on many river ecosystems. The deviation from the natural flow regime must be considered when trying to understand water quality and the allocation of water for environmental benefits (Poff et al. 1997, Norris and Thoms 1999, Arthington et al. 2006a, Poff et al. 2010). Initially, the use of environmental flows was focused on the minimum required flow in a river and according to this concept, a river's health could be evaluated by flow characteristics alone. It has since been recognised that other factors for evaluating river health must be considered. This includes (but is not limited to) water quality, water levels and inundation frequencies, floods, human impacts, irrigation, public water supply and industry needs (Acreman and Dunbar 2004, Arthington 2012, Arthington et al. 2018).

Understanding river health through the measurement and response of aquatic flora and fauna is also useful because many of these organisms are sensitive to changes in the broader aquatic ecosystem (Norris and Thoms 1999, Bond et al. 2012, Bunn 2016, Wang et al. 2019, Atazadeh et al. 2020). Contemporary water quality monitoring programmes regularly focus on both water chemistry and biological communities as indicators of aquatic ecosystem health. Over the last few decades, biological monitoring has risen to the forefront of environmental impact assessment and river biomonitoring programs (Chessman et al. 1999, Atazadeh et al. 2007, Chessman et al. 2007, Mangadze et al. 2019, Asadi Sharif et al. 2020). Biological indices can be useful tools for water resource managers in the assessment of river health and decision making with regards to water sharing amongst the consumptive users in order to improve environment benefits and river health while considering potential impacts on consumptive users. The main aim of this paper is to biomonitor the short-term and longer-term responses to water release events using periphytic algal communities to understand ecosystem response to hydrologic disturbances and their applications in river management. In the present paper, we hypothesized that: a) water release events affect structure and habitat of algal periphyton communities; b) species diversity and density would change under water release events; c) adapted taxa would tolerate the water release events and any other hydrological disturbances and anthropogenic stressors; d) DSIAR (Diatoms Species Index for Australian Rivers) represents a suitable index for assessing water quality in the river.

Study area

The MacKenzie River, which drains the northern slopes of the Grampians Ranges in western Victoria, is one of the main tributaries of the Wimmera River (Figure 1a-c). The headwaters feed into Lake Wartook in the Grampians National Park, which has a maximum capacity of 29,360 ML. The river flows approximately 50 km from Wartook Reservoir before its confluence with the Wimmera River. The catchment lies to the south of the city of Horsham and covers an area of approximately 597 km^2 (WCMA 2004). The MacKenzie River is classified as a highly modified river as a consequence of this anthropogenic modification, where consumptive flows will dominate the flow regime in some years (Figure 1d).

Annually, a total of 10,000 ML of water is released from Lake Wartook into the MacKenzie River. Of this volume, only about 4,000 ML (about one third) is released explicitly for environmental purposes. The remaining 6,000 ML (about two thirds) is released to meet consumptive demands and to transfer water to downstream reservoirs (personal communication; GWMWater). Routine water releases from Wartook Reservoir are up to 50 ML/day in summer and 15 ML/day in winter.

Ten sampling locations were established along the river, and the river was divided into three reaches: Reach 1 included sampling stations S1, S2, S3 and S4 (Lake Wartook to ‘Dad and Dave’ Weir); Reach 2 included sampling stations S5, S6, S7 and S8 (‘Dad and Dave’ Weir to Distribution Heads) and Reach 3 included sampling stations S9 and S10 (Distribution Heads to the Wimmera River) (Figure 1a-d). The upstream section (Reach 1) tends to receive water most days of the year due to the water supply requirements of the city of Horsham and is highly appreciated for its recreational and conservation values. The middle and downstream sections (Reaches 2 and 3) receive a more intermittent supply. The lower part of the river (Reach 3) has had the potential to change greatly over time, evidenced by the persistent drought conditions between 1998 and 2009 (GWMWater pers. comm.).

There are a number of channels, pipelines and waterways in the system which supplies and delivers water to various users including urban usage, irrigation, water storages, environmental and recreational needs. In the Wimmera-Glenelg supply system there are a number of water storages including Lake Wartook, Lake Lonsdale, Lake Bellfield, Lake Taylor and Lake Fyans (Wimmera system), and Rocklands and Moora Moora Reservoirs (Glenelg System). The engineered Wimmera-Glenelg system is complex because of the water supply operation itself, the different sized water storages and the varying demands from customers and the environment for water delivery (VEWH 2015). The efficiency and flexibility of the system allows waterway managers to transfer water between reservoirs. Furthermore, the facility of the system allows the off-stream storages to harvest water from channels and storages (Figure 2).

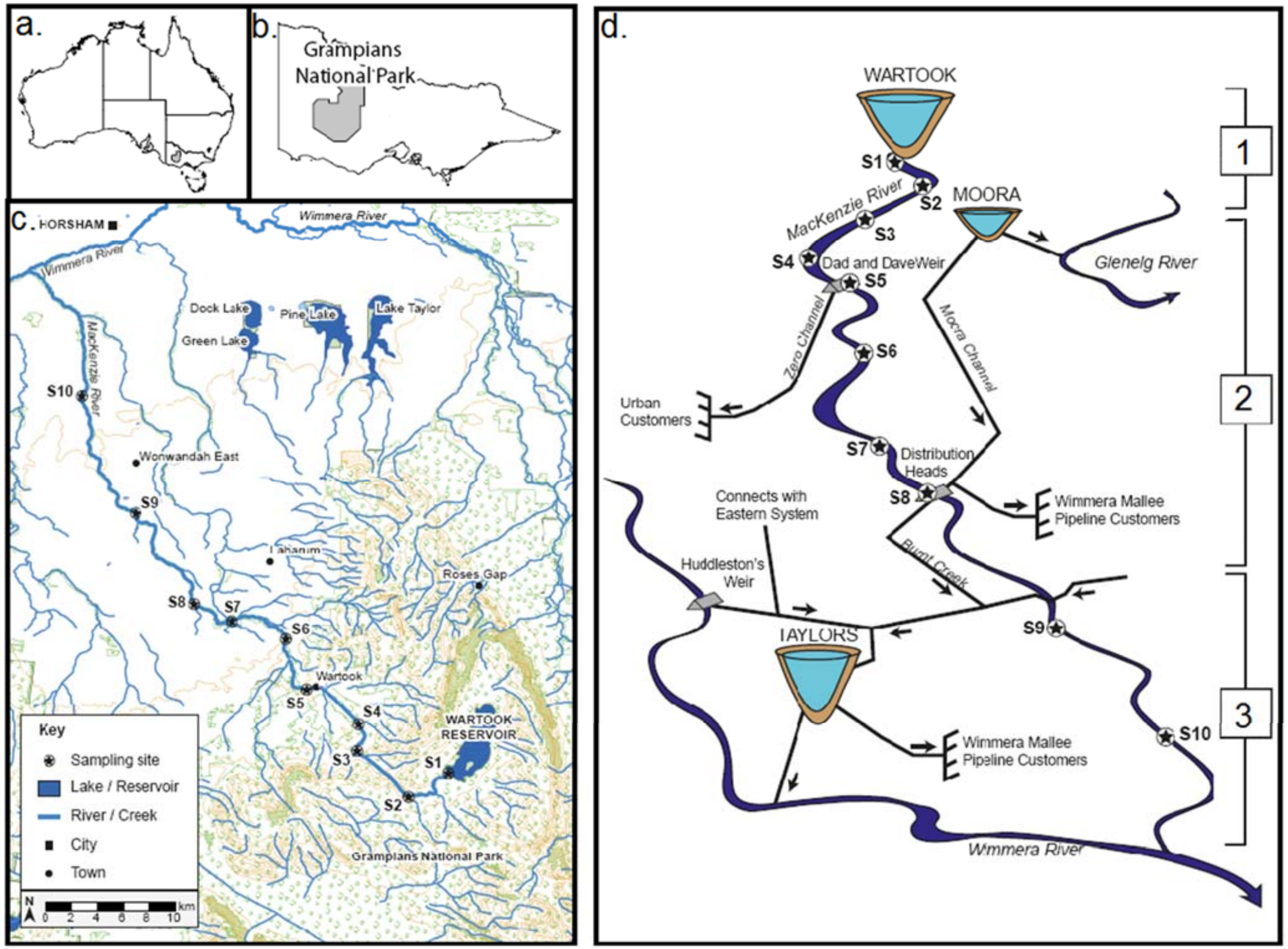


Figure 1 (a-c) Location of the ten sampling stations along the MacKenzie River system in the Wimmera catchment and **(d)** Schematic diagram showing the location of the three Reaches of the MacKenzie River within a complex water supply system (Adapted from GWMWater).

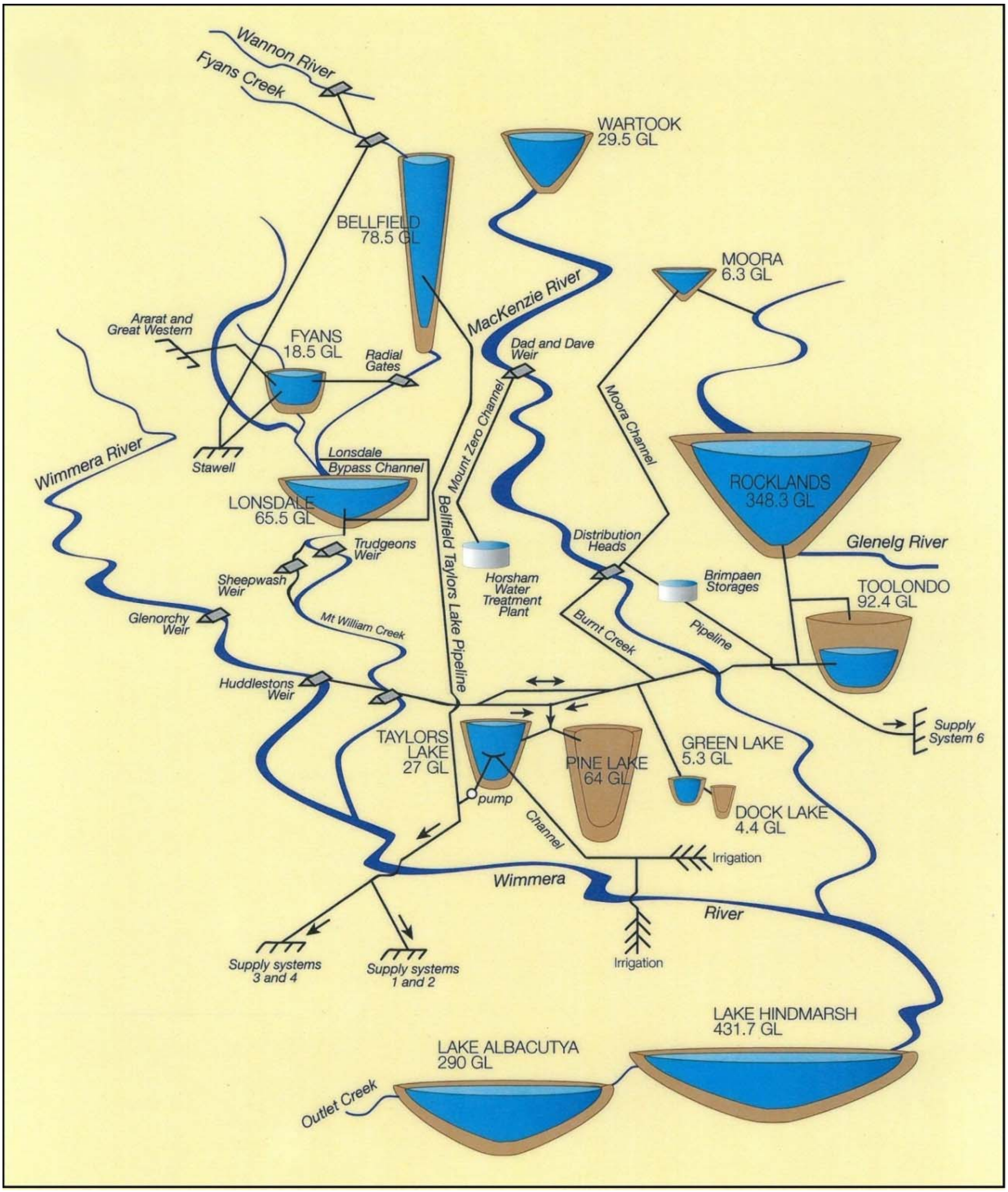


Figure 2 Schematic diagram of the complex water supply in the Wimmera-Glenelg system (Courtesy of GWMWater)

Materials and methods

Algal periphyton was scraped from an area of about 20-30 cm^2 of cobbles, pebbles or rocks with a toothbrush and rinsing the algal suspension into a collection bottle. Samples were initially taken during different seasons (28 February 2012, 17 July 2012, 9 November 2012 and 25 May 2013) to obtain baseline information of the spatial and temporal variations of the algae communities, water quality, aquatic biota and stream condition before the first water release event. After the baseline sampling, samples were taken before, during and after three water release events (event 1: 18 October 2013, 21 October 2013, 25 October 2013; event 2: 16 December 2013, 19 December 2013, 23 December 2013, 3 January 2014, 16 April 2014; event 3: 29 October 2014, 1 November 2014, 8 November 2014 and 22 November 2014). The duration of water release events (Freshes and high flows) was 3 days in the river. Data of the flow regimes from 2011-2015 were provided by GWMWater.

In situ measurements of temperature, pH, electrical conductivity, turbidity, depth, oxidation reduction potential, and dissolved oxygen were obtained using an Horiba multimeter (Water checker U-52G). Then, samples collected for water quality analyses were filtered using 0.45 µm syringe filters at each site for total suspended solids, total dissolved solids, total oxidised nitrogen, total phosphorous, total nitrogen, ammonia, silica, cations and anions were undertaken in the laboratory at Federation University Australia using a spectrophotometer and Gallery Automated Photometric Analyser and Hach DR 2800 following standard methods (APHA 2007, Atazadeh et al. 2009, Victoria EPA 2009).

Algal samples were collected from cobbles, pebbles or rocks to a collection bottle (200 mL) and then added Lugol’s solution (2 mL) for preservation. Temporary slides were prepared for soft algae to identify the species composition and to enumerate algal groups. The relative abundance of the different algal groups (green algae, Cyanobacteria, diatoms and other algae) was calculated by placing 1 mL of each sample into a Sedgwick-Rafter counting chamber. Several replications of counts of one mL were applied for accurate calculation of the relative abundance. Cells were counted using a Nikon Eclipse 80i microscope at 100-400× magnification.

For diatom species identification and enumeration, the samples were prepared following the method of Battarbee (1986). Samples were digested with 10% hydrogen peroxide in a beaker at 90°C on a hotplate for 2 hours, after which two drops of 10% hydrochloric acid were added. The beakers were filled with distilled water and left to settle overnight after which the supernatant was discarded. This process was repeated four times. Subsamples of 400 µl were air-dried on coverslips and mounted using Naphrax (Battarbee 1986). At least 300 diatom valves were identified and counted per slide using a Nikon Eclipse 80i microscope with differential interference contrast at 1000× magnification.

Separate samples were collected for dry mass, AFDM and chlorophyll-*a* measurement. Algal periphyton was scraped from an area of about 20-30 cm^2 of cobbles, pebbles, stone or rocks. Samples for the determination of dry mass (DM) were oven-dried for 24 hours at 60°C and weighed. Samples were then combusted at 525°C in a muffle furnace for four hours, and reweighed. Ash-free dry mass (AFDM) was estimated as the difference in the mass before and after combustion and expressed as $mg.cm^{-2}$ of the original substratum (Steinman et al. 1996, Biggs and Kilroy 2000, Lavoie et al. 2004).

For chlorophyll-*a* analysis, the samples were transferred into tubes containing 10 ml of 95% ethanol (Nusch 1980, Snow et al. 2000). The samples were stored overnight in a freezer and then allowed to return to room temperature. The absorbance of the supernatant at 665 nm was determined before and after adding two drops of 0.1N HCl using a Shimadzu UV 1800 spectrophotometer. Chlorophyll-*a* concentration was determined using Hilmer's equation (Hilmer 1990) that had been derived from Nusch's equation (Nusch 1980).

Ecological condition of the MacKenzie River was evaluated using the Diatom Species Index for Australian Rivers (DSIAR) as a local diatom index (Chessman et al. 2007). Sensitivity values (SV) in this index evaluate the tolerance of each species to anthropogenic stress (e.g. industry, agriculture, urban and any other manipulation in the catchment). The SV of all species are used to calculate numerical scores for each sample in the dataset, weighted by the proportional abundance of each species. High DSIAR scores signify a flora 'less impacted' by anthropogenic modification on aquatic ecosystems. In contrast low scores are interpreted as indicating a greater anthropogenic stress. Using the algae-based indices, each site can be categorised as being in bad, poor, moderate, good or excellent condition. The sensitivity values of species to anthropogenic stressors in the MacKenzie River were used to calculate algae-based index scores for each sample in the datasets.

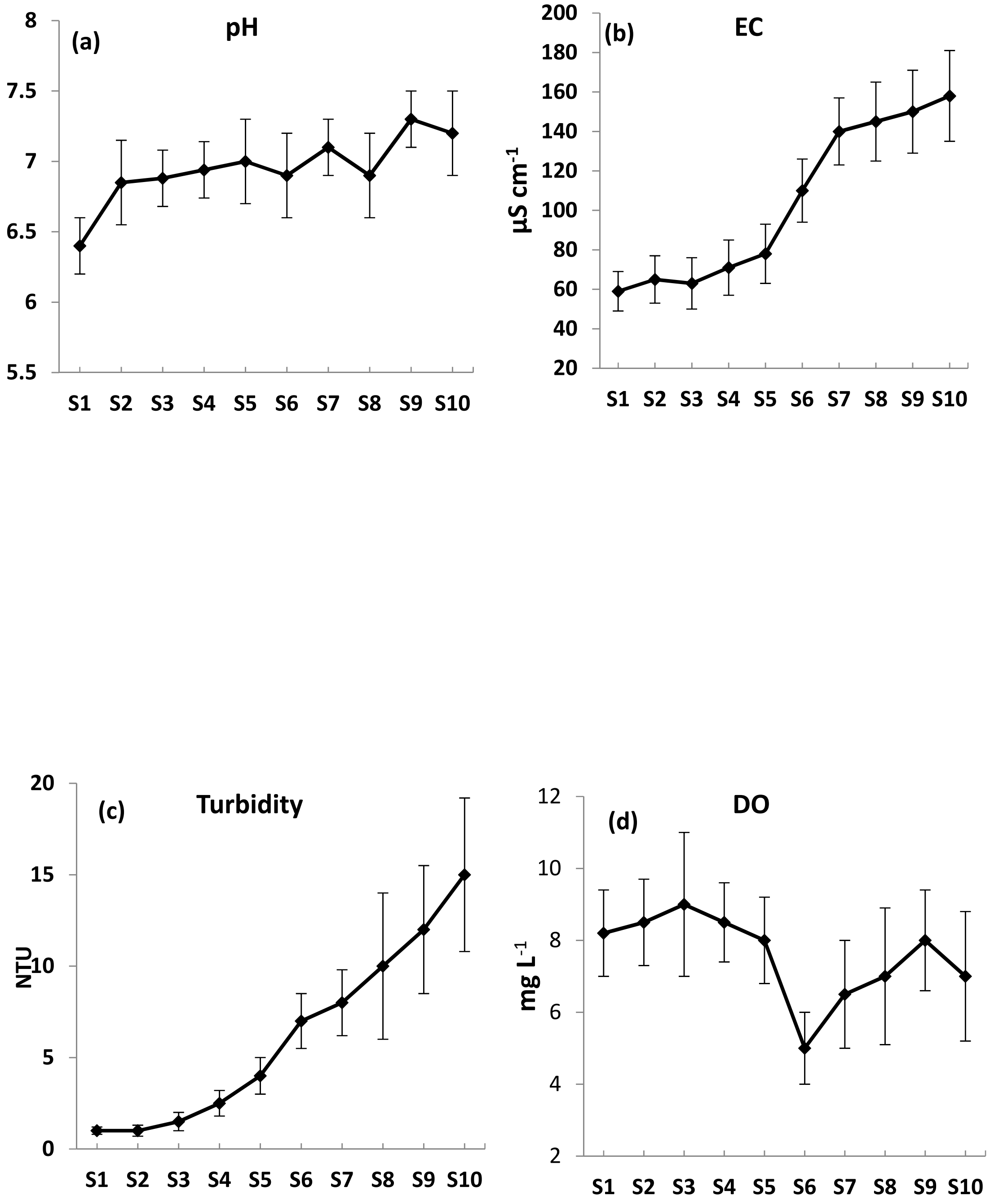
Data analysis and interpretation

The species and water quality data were transformed to reduce skewness and to, as far as possible, ensure normal distribution of the data sets. Canonical Correspondence Analysis (CCA) was used to determine the direct relationship between diatom and soft algae communities and the environmental variables. CCA is a constrained ordination which uses *a priori* hypotheses (in contrast with unconstrained tests which do not use *a priori* hypotheses). The CCA analyses were applied to determine the most important variables influencing the diatom and soft algae communities under different seasons and under different flows along the MacKenzie River. Furthermore, the CCA analyses were performed to examine how algal species respond to a range of variables under different flows.

Results

Average annual water chemistry in the MacKenzie River

There were downstream trends in most of the physical and chemical water parameters measured during the different flow regimes. Typically, the pH gradually increased (became more alkaline) downstream. The upstream sites (S1-S4) also had lower conductivity compared to those further downstream. Turbidity increased greatly downstream and the concentration of dissolved oxygen (DO) changed along the river where low concentrations were observed mid-stream due to standing water in the middle of the river. Total suspended solid (TSS) values also increased in the lower parts of the river particularly during water release events. The concentrations of nutrients (TN and TP) also increased downstream (Table 1). The concentrations of cations (Mg^{2+}, Ca^{2+}) and anions (SO_4^{2-}, Cl^-) also increased downstream consistent with an increase in total salinity and the concentration of Oxidation Reduction Potential (ORP), Total Dissolved Solid (TDS) and Total Oxidative Nitrogen (TON). In contrast, the concentration of ammonia decreased from upstream to downstream (Figure 3; Table 1).



(a) pH
8
7.5
7
6.5
6
5.5
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10
(b) EC
µS cm-1
200
180
160
140
120
100
80
60
40
20
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10
(c) Turbidity
NTU
20
15
10
5
0
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10
(d) DO
mg L-1
12
10
8
6
4
2
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10

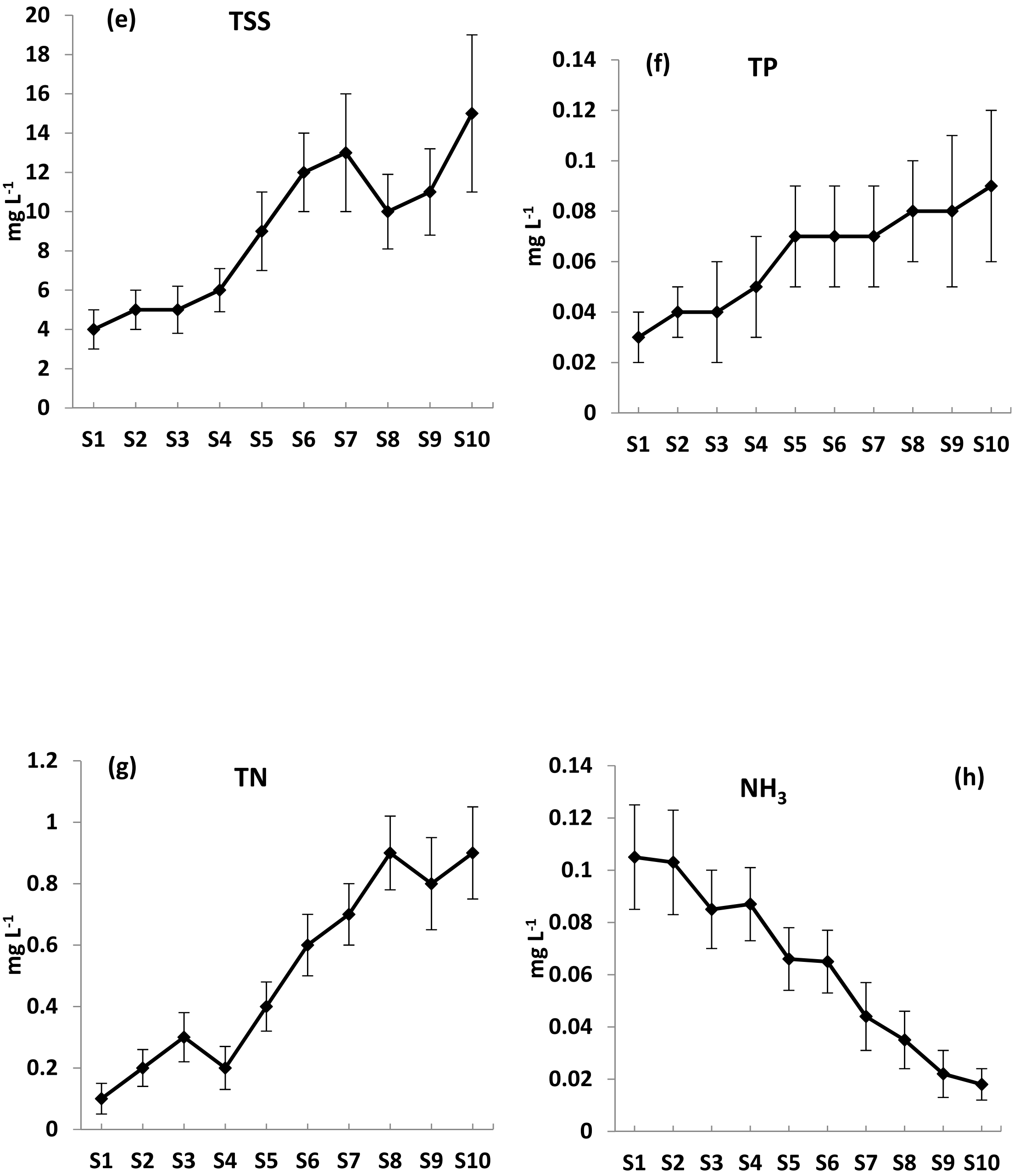


Figure 3 Physical and chemical characteristics of water at the sampling stations (S1-S10) along the MacKenzie River: **(a)** pH; **(b)** Electrical Conductivity; **(c)** Turbidity; **(d)** Dissolved Oxygen; **(e)** Total Suspended Solids; **(f)** Total Phosphorus; **(g)** Total Nitrogen; **(h)** Ammonia. Data indicate means ± SD

Table 1 Average annual physical and chemical water quality characteristics at the sampling stations on the MacKenzie River from February 2012 to Nov 2014 (Temp = temperature, ORP= Oxidation Reduction potential, TDS= Total Dissolved Solids, TON= Total Oxidative Nitrogen). Data indicate means ± SD.

	Unit	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Temp	ºC	14±7	16±6	16±7	16±8	17±6	18±4	19±8	19±6	19±7	19±6
Depth	m	0.6±0.2	0.6±0.2	0.6±0.3	0.7±0.4	0.6±0.3	1±0.5	0.8±0.4	1±0.3	0.5±0.2	0.8±0.5
ORP	mV	212±22	222±32	223±35	258±41	245±42	255±64	255±58	244±51	299±75	298±74
TDS	mg L^{-1}	22±11	35±15	41±22	68±31	71±23	86±32	91±33	98±38	106±41	111±35
Mg^{2+}	mg L^{-1}	1.1±0.5	1.8±0.8	2.2±0.9	2±0.8	3±0.5	3±0.5	3±1	4±1.2	4±1.2	4.1±1.3
$SO4^{-2}$	mg L^{-1}	0.55±0.08	0.51±0.1	0.52±0.1	0.55±0.1	0.61±0.1	0.44±0.09	0.64±0.1	0.63±0.08	0.55±0.09	0.45±0.1
Ca^{+2}	mg L^{-1}	1.5±0.5	2.1±0.6	2.5±0.5	3±0.6	3.2±0.5	3.2±0.6	3.6±0.2	3.4±0.5	3.5±0.5	3.9±0.6
SiO_2	mg L^{-1}	0.22±0.05	0.28±0.06	0.36±0.09	0.38±0.06	0.49±0.08	0.65±0.05	0.75±0.04	0.79±0.09	0.78±0.08	0.88±0.09
TON	mg L^{-1}	0.07±0.01	0.08±0.02	0.07±0.01	0.06±.02	0.08±0.02	0.07±0.03	0.07±0.01	0.08±0.04	0.1±0.05	0.1±0.05
Cl^{-1}	mg L^{-1}	19±8	22±8	23±4	28±8	29±7	30±10	30±6	29±8	33±8	40±10

Water chemistry during water release events

The changes in water quality observed during water release events were such that the water quality downstream was relatively similar to that upstream. Nevertheless, the results show this phenomenon (similarity of the water quality between upstream and downstream reaches) is only temporary in nature and antecedent conditions return within a few days of water release. Whilst the water quality does vary during different seasons, the main changes in water quality are observed during the water release events (Table 2).

Table 2 Physical and chemical water quality characteristics during water release events at the sampling stations on the MacKenzie River.

	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
pH	-	6.7	6.7	6.7	6.8	6.8	6.8	6.7	6.5	6.6	6.7
Temp.	ºC	16.2	16.5	16.3	16.2	17.4	17.2	17.5	17.2	18.1	17.9
Cond.	µS cm^{-1}	75	76	79	76	79	82	82	85	88	86
Turb.	NTU	8.5	9.3	8.2	10	8.5	12	15.2	16	14.2	14.5
Depth	m	0.8	0.8	0.7	1.2	1.3	1.5	1.6	1.7	1.2	1.3
ORP	mV	250	251	256	264	261	258	269	274	261	271
DO	mg L^{-1}	8.5	9.2	9.8	8.4	9.2	7.2	7.8	8.5	7.8	8.2
TDS	mg L^{-1}	45	46	42	55	65	64	71	75	71	85
TSS	mg L^{-1}	6	6.2	7.4	6.6	7	8.2	7.3	6.8	8.2	7.1
TN	mg L^{-1}	0.2	0.2	0.3	0.2	0.3	0.3	0.4	0.5	0.7	0.8
TP	mg L^{-1}	0.05	0.05	0.06	0.07	0.07	0.07	0.08	0.08	0.08	0.08
Mg^{2+}	mg L^{-1}	1.2	1.7	2	2.2	2.1	2.5	2.6	3.3	3.3	3.3
NH_3	mg L^{-1}	0.1	0.1	0.09	0.09	0.08	0.09	0.07	0.08	0.07	0.09
SO_4^{-2}	mg L^{-1}	0.45	0.52	0.46	0.48	0.55	0.54	0.62	0.55	0.42	0.56
Ca^{+2}	mg L^{-1}	1.6	1.8	2.2	3.3	3..2	3.3	3.1	3.2	3.4	3.6
SiO_2	mg L^{-1}	0.0.24	0.25	0.23	0.25	0.39	0.51	0.55	0.66	0.62	0.77
TON	mg L^{-1}	0.06	0.08	0.07	0.08	0.05	0.07	0.06	0.08	0.08	0.08
Cl^{-1}	mg L^{-1}	22	25	23	25	31	32	33	28	29	28

Algal response under base flow

This investigation showed that during base flow the algal flora of the MacKenzie River was composed of typical acidic taxa, especially in the upper reaches, while more alkaline taxa were recorded in lower reaches. In this study, 126 diatom species (43 genera), 44 green algae species (23 genera), 24 blue-green algae species (10 genera), and 9 other algae (6 genera) were recorded from samples collected during base flow conditions. The diatom community (species composition) was the most abundant and dominated the river samples, displaying high diversity in the upstream sites while the relative proportions of green algae and Cyanobacteria increased in the mid and downstream reaches.

The most common algal species in the upstream reaches (S1-S5) were diatoms (based on relative abundance) including: diatoms - *Brachysira brebissonii* R.Ross, *Eunotia bilunaris* (Ehrenberg) Schaarschmidt, *Frustulia rhomboides* (Ehrenberg) De Toni, *Gomphonema affine* Kützing, *Melosira arentii* (Kolbe) Nagumo & Kobayashi, *Navicula heimansioides* Lange-Bertalo, *Tabellaria flocculosa* (Roth) Kützing; green algae - *Stigeoclonium flagelliferum* Kützing, *Ulothrix flacca* (Dillwyn) Thuret; and Cyanobacteria - *Tolypothrix tenuis* Kützing ex Bornet & Flahault. In the downstream reaches (S6-S10), the most common algal species were: diatoms - *Eunotia serpentine* (Pantocsek) Hustedt, *Nitzschia capitellata* Hustedt, *Planothidium frequentissimum* (Lange-Bertalot) Lange-Bertalot, *Surirella angusta* Kützing; green algae - *Oedogonium undulatum* A.Braun ex Hirn; and Charophytes – *Chara* sp., *Nitella cristata* A.Braun and Cyanobacteria - *Schizothrix arenaria* Gomont (Table 3).

Table 3 Taxonomic composition of algae by genus and number of taxa present in each genus, in the MacKenzie River

Bacillariophyta	Taxa No.	Chlorophyta	Taxa No.	Cyanophyta	Taxa No.	Other groups	Taxa No.
Achnanthes	2	*Ankistrodesmus*	1	*Anabaena*	2	*Cryptomonas*	1
Achnanthidium	1	*Bambusina*	1	*Chroococcus*	1	*Ceratium*	2
Asterionella	1	*Bulbochaete*	1	*Lyngbya*	3	*Dinobryon*	2
Aulacosira	2	*Chara*	2	*Merismopedia*	1	*Euglena*	1
Brachysira	6	*Chlorella*	1	*Nodularia*	1	*Gymnodinium*	1
Brevisira	1	*Cladophora*	1	*Nostoc*	1	*Peridinium*	2
Caloneis	2	*Closterium*	3	*Oscillatoria*	5		
Cocconeis	1	*Cosmarium*	4	*Phormidium*	2		
Craticula	1	*Euastrum*	3	*Schizothrix*	1		
Cyclostephanos	1	*Gonium*	1	*Tolypothrix*	1		
Cyclotella	2	*Micrasterias*	1	*Nostoc*	1		
Cymbella	3	*Monoraphidium*	1	*Oscillatoria*	5		
Cymbopleura	4	*Nitella*	2				
Diatoma	3	*Oedogonium*	2				
Diplonies	1	*Oocystis*	2				
Discostella	1	*Pediastrum*	2				
Encyonema	2	*Rhizoclonium*	1				
Epithemia	1	*Scenedesmus*	6				
Eunotia	16	*Spirogyra*	1				
Envekadea	1	*Staurodesmus*	1				
Fragilaria	4	*Staurastrum*	5				
Frustulia	5	*Stigeoclonium*	1				
Gomphonema	7	*Ulothrix*	1				
Gyrosigma	2						
Hantzschia	1						
Luticola	1						
Melosira	1						
Navicula	8						
Neidium	4						
Nitzschia	5						
Pinnularia	9						
Planothidium	1						
Psammothidium	2						
Pseudostaurosira	1						
Rhopalodia	1						
Sellaphora	1						
Stauroforma	1						
Stauroneis	7						
Staurosira	1						
Stenopterobia	3						
Surirella	3						
Synedra	3						
Tabellaria	3						
Total	**126**		**44**		**24**		**9**

Diatom variations under base flow

Diatom species composition varied from upstream to downstream and between seasons. The summer (February 2012) samples presented in Figure 4a showed, *Frustulia rhomboides* *Gomphonema affine*, *Navicula radiosa* Kützing, *Tabellaria flocculosa* to be common in the upstream reaches, however, the relative abundance of those diatoms decreased downstream. In contrast, those most strongly associated with downstream reaches were *Eunotia serpentina*, *Psammothidium abundans* (Manguin) Bukhtiyarova & Round, *Rhopalodia brebissonii* Krammer and *Surirella elegans* Ehrenberg. In contrast, the winter (July 2012) samples showed the upstream sites supported *Frustulia rhomboides*, *Gomphonema affine*, *Gomphonema gracile* Ehrenberg, *Navicula heimansioides* Lange-Bertalot, *Navicula. radiosa* and *Tabellaria flocculosa* while the downstream sites supported assemblages including *Nitzschia capitellata*, *Nitzschia clausii* Hantzsch, *Meridion circulare* (Greville) C.Agardh and *Stenopterobia curvula* (W.Smith) Krammer (Figure 4b). The results of the spring survey (November 2012) showed the algal community to be similar to those in summer. The most common diatom taxa collected in the upstream (S1-S5) samples were *T. flocculosa*, *G. affine*, *N. radiosa and M. arentii* while in the downstream reaches the most common species were *Eunotia serpentina, P. abundans*, *Psammothidium confusum* (Manguin) van de Vijver, *N. capitellata* and *S. angusta* (Figure 4c). The results of the diatom comunity structure in the following winter, in June 2013, showed the most common diatom species in upstream sites (S1-S5) are *T. flocculosa*, *G. affine*, *N. radiosa*, while in the downstream section (S6-S10) the most common species were *Achnanthidium minutissimum* (Kützing) Czarnecki, *N. clausii* and *P. confusum* (Figure 4d).

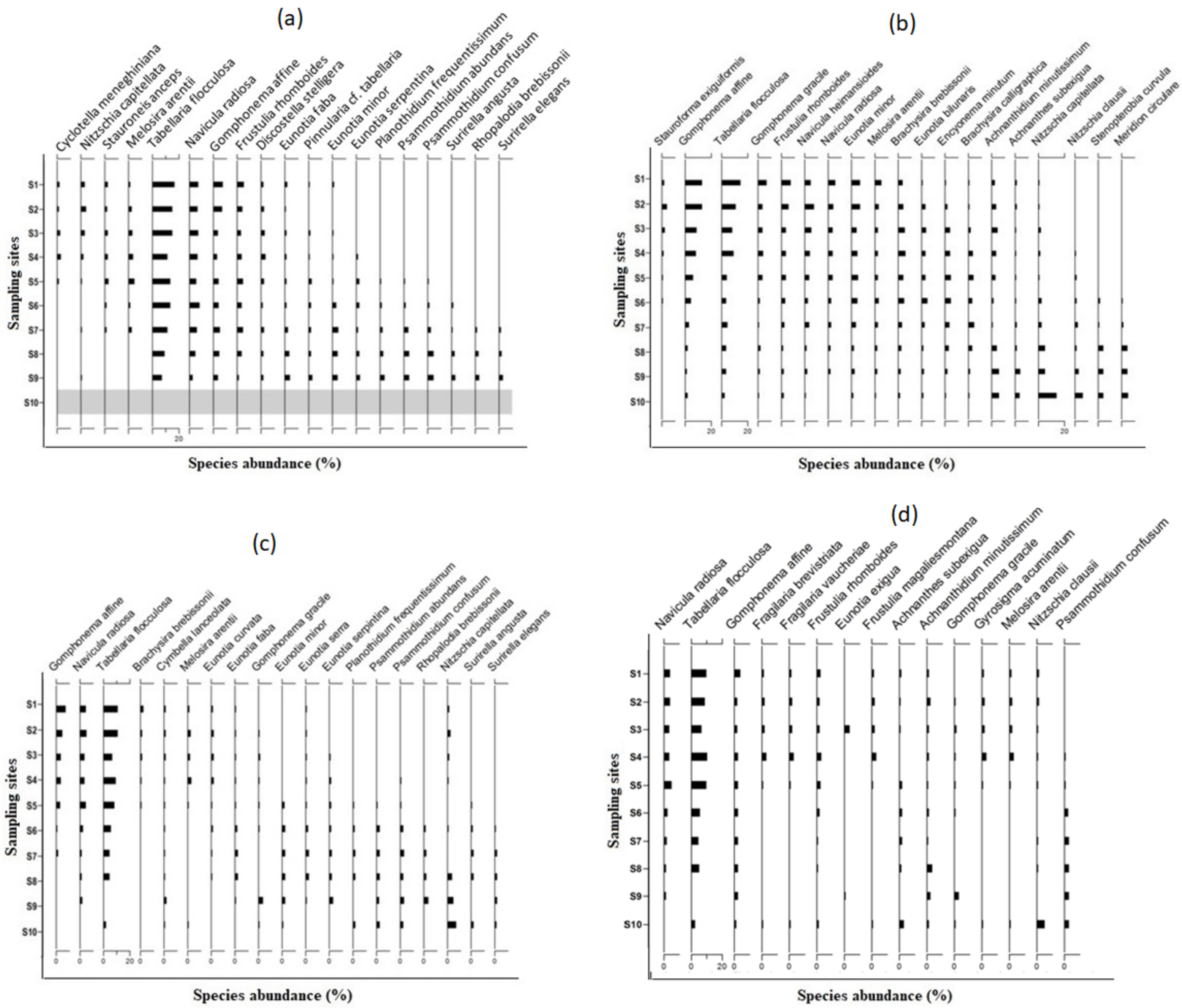


Figure 4 Results of diatom analysis along the MacKenzie River sampling stations; **(a)** Feburary 2012, Station 10 was dry at the time of sampling; **(b)** July 2012; **(c)** November 2012; **(d)** June 2013. Data indicate >4% in any one sample, sorted by weighted-averaging [ascending].

Soft algae variations under base flow

The soft algal species composition differed along the MacKenzie River and between seasons. The soft algae were classified into three different groups comprising Chlorophyta (green algae), Cynobacteria (blue-green algae) and other algae (Chrysophyta, Charophyta and Euglenophyta). The results showed that the algal asssemblages differed between sites, and from upstream to downstream. The unicelluar species were mostly found in the upstream sites while the downstream sites (S6-S10) supported both unicellular and filamentous algae.

Soft algae species composition was different from upstream to downstream and between the seasons. The summer results (February 2012) showed *Chlorella vulgaris* Beyerinck [Beijerinck], *Closterium* kuetzingii Brébisson, *Dinobryon sertularia* Ehrenberg, *Oocytis parva* West & G.S.West, *Pediastrum angulosum* Ehrenberg ex Meneghini and *Peridinium lomnickii* Woloszynska, were the most common of the soft algae in the upstream sites whilst *C. vulgaris*, *Cosmarium sportella* Brébisson ex Kützing, *O. parva*, *P. angulosum* and *Stigeoclonium flagelliferum* Kützing were common in the midstream sections. In contrast, filamentous algae such as *Lyngbya* Agardh Ex Gomont and *Schizothrix arenaria* were more often present dowstream.

The winter results (July 2012) showed upstream sites of the river had more unicelluar soft algae including *Ceratium cornutum* (Ehrenberg) Claparède & J.Lachmann, *C. vulgaris*, *Closterium* sp., *D. sertularia*, *Peridinium lomnickii*, *P. angulosum* and *O. parva* while filamentous soft algae species that were found to be more abundant in the downstream sites included *Cladophora glomerata* (Linnaeus) Kützing, *Lyngbya* sp., *Oedogonium undulatum*, *Oedogonium* sp. and *S. arenaria*.

Relative abundance of the algal groups under base flow

Base flow sampling results showed that relative abundances of the algal groups varied by stream reach and also by season. Relative abundance of diatoms was highest in the upstream sites while filamentous green algae were more abundant downstream. The taxonomic composition of the algae varied among reaches along the river. In February 2012, diatoms represented the highest proportion of algal cells (c. 48%) upstream (S1 and S2) but decreased gradually from the midstream (c. 30%) to the lower reaches (c. 20%). In contrast, the relative abundance of green algae increased from approximately 20% in upstream sites to 40% in downstream sites, while the relative abundance of Cyanobacteria increased from 15% upstream to 20% downstream. The other algae (Chrysophyta, Charophyta and Euglenophyta) varied slightly between sites (Figure 5a).

The algal group assemblages in the July 2012 samples (Figure 5b) showed that the relative abundance of diatoms, green algae, and Cyanobacteria were approximately 35%, 30% and 25% respectively in the upstream sites (S1-S3). The relative abundances of diatoms and green algae were slightly lower in the midstream sites with both approximating 25%, whereas Cyanobacteria and other algae such as Chrysophyta increased to 35% and 15% respectively. In the downstream sites the relative abundance of the diatoms slightly increased (c. 30%) while that of the Cyanobacteria decreased (c. 20%). The other algal groups also increased in relative abundances downstream, but were not dominant in the MacKenzie system.

The relative abundances of the algal groups again changed downstream seasonally, and in November 2012 (spring) (Figure 5c) diatoms were more abundant in the upstream sites while green algae and Cyanobacteria were more abundant in downstream sites. The relative abundance of the cells of diatom, green algae, and Cyanobacteria and other algae were 42%, 23%, 22% and 13% respectively in the upstream sites, changing to 25%, 30%, 25% and 20% respectively downstream. Together, the soft algal groups (especially filamentous and colonial algae) increased markedly in mid and downstream reaches in spring and summer whilst diatoms had a higher relative abundance in upstream sites in the same seasons. The results of the June 2013 sampling (Figure 5d) showed diatoms and Cyanobacteria to be the most abundant algal groups in the upstream reaches of the MacKenzie River, with diatom abundance decreasing downstream. The relative abundance of diatoms, green algae, Cyanobacteria and other algae groups was approximately 35%, 24%, 26% and 15% respectively in the upstream sites whilst downstream their relative abundances were 30%, 35%, 18% and 17% respectively.

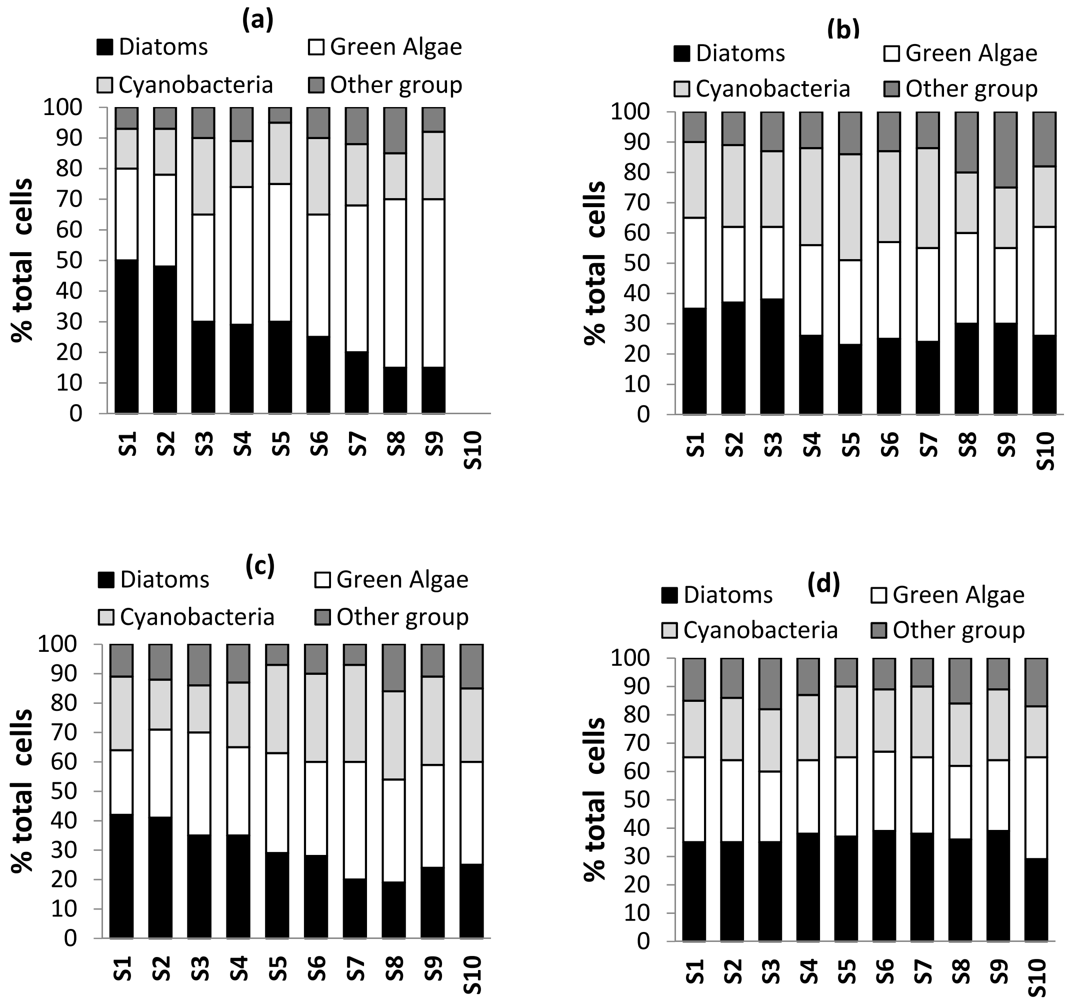


Figure 5 Percent of total cells of the algal communities in the MacKenzie River: **(a)** February 2012; **(b)** July 2012; **(c)** November 2012; **(d)** June 2013. (Station 10 was dry in February 2012).

Biological properties of algae under base flow

The results of the analyses of biomass vary significantly between sampling sites and events. The dry mass (DM) and ash-free dry mass (AFDM) showed values varied downstream in February 2012. The DM value in the upstream, midstream and downstream reaches in the February 2012 samples was $7mg.cm^{-2}$, $5mg.cm^{-2}$, and $4mg.cm^{-2}$ respectively. The river was dry in February 2012 at the most downstream site (S10) and so DM samples could not be taken for S10 in February 2012 (Figure 6a).

In July 2012, the accumulation of DM and AFDM were also the highest in the uppermost site (S1) but sharply decreased by S2. At S3 the DM and ADFM results were higher than S2, but gradually decreased further towards the mid and lower parts of the river (Figure 6b). In contrast, there was a trend of DM and ADFM results decreasing with distance downstream in November 2012 (Figure 6c). There was no clear trend for the DM and AFDM results in June 2013 (Figure 6d).

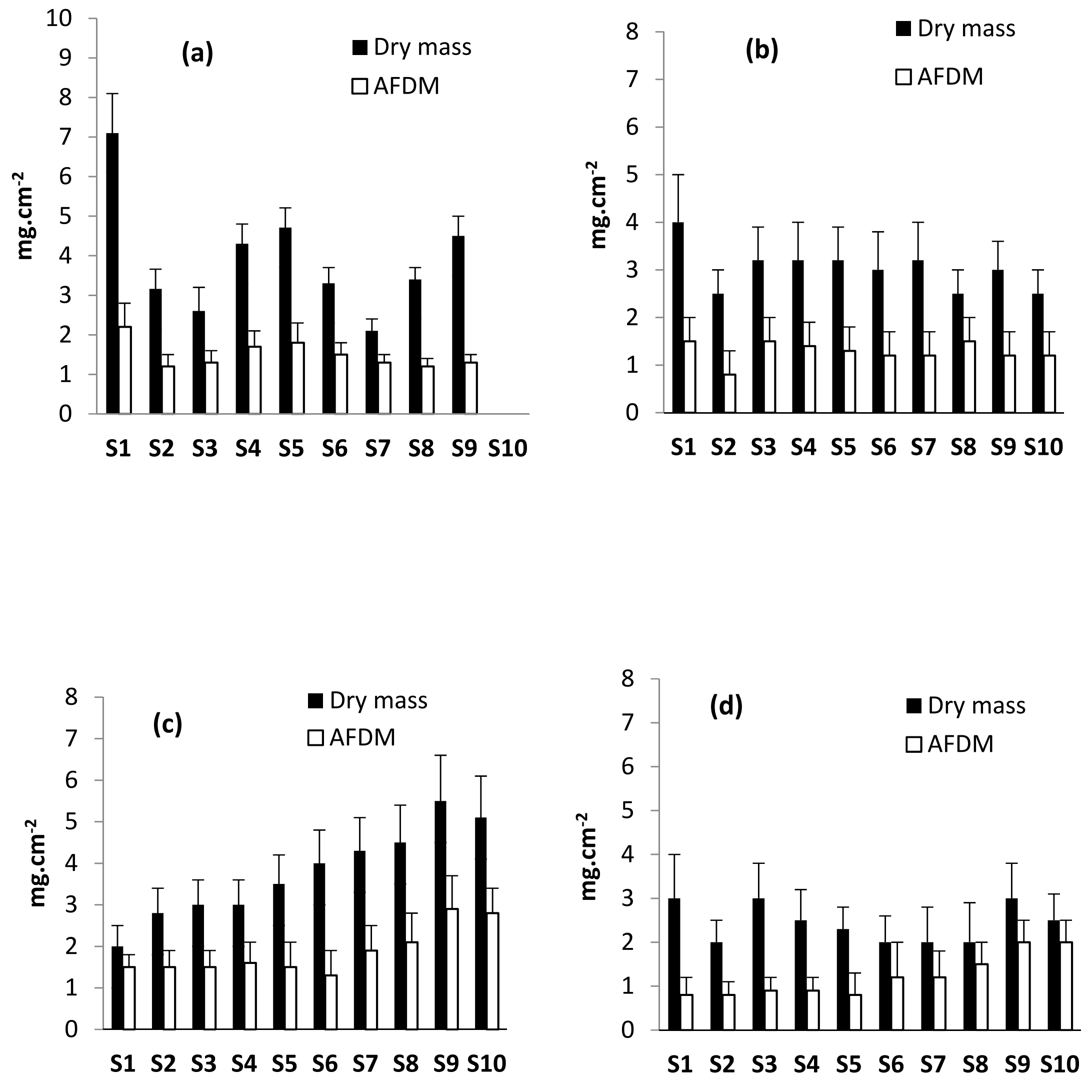


Figure 6 The accumulation of dry mass and ash-free dry mass at each of the sampling stations along the MacKenzie: **(a)** February 2012; **(b)** July 2012; **(c)** November 2012; **(d)** June 2013. Data indicate means ± SD. (Station 10 was dry in February 2012).

The upstream and downstream values for chlorophyll-*a* concentrations in February 2012 ranged from approximately 90 $mg.m^{-2}$ (highest value in S2) and 60 $mg.m^{-2}$ (mid and lower reaches of the river) with no real pattern evident (Figure 7a). The results from July 2012 showed that chlorophyll-*a* concentration gradually decreased downstream. The highest chlorophyll-*a* concentration was greatest upstream with approximately 60 $mg.m^{-2}$ recorded at S1, with the concentration gradually decreasing through mid and downstream reaches and correlating negatively with turbidity (Figure 7b). In contrast, the concentration of chlorophyll-*a* increased downstream in November 2012 (Figure 7c) ranging from approximately 35 $mg.m^{-2}$ in the upstream sites increasing to 80 $mg.m^{-2}$. Overall, it seems the algal productivity is greater in spring, especially in the lower parts of the river. The chlorophyll-*a* concentrations for June 2013 (Figure 7d) showed an unusual pattern of gradual increases (S3 to S5; S6 to S10), with substantial declines at sites (S1 to S2; S5 to S6).

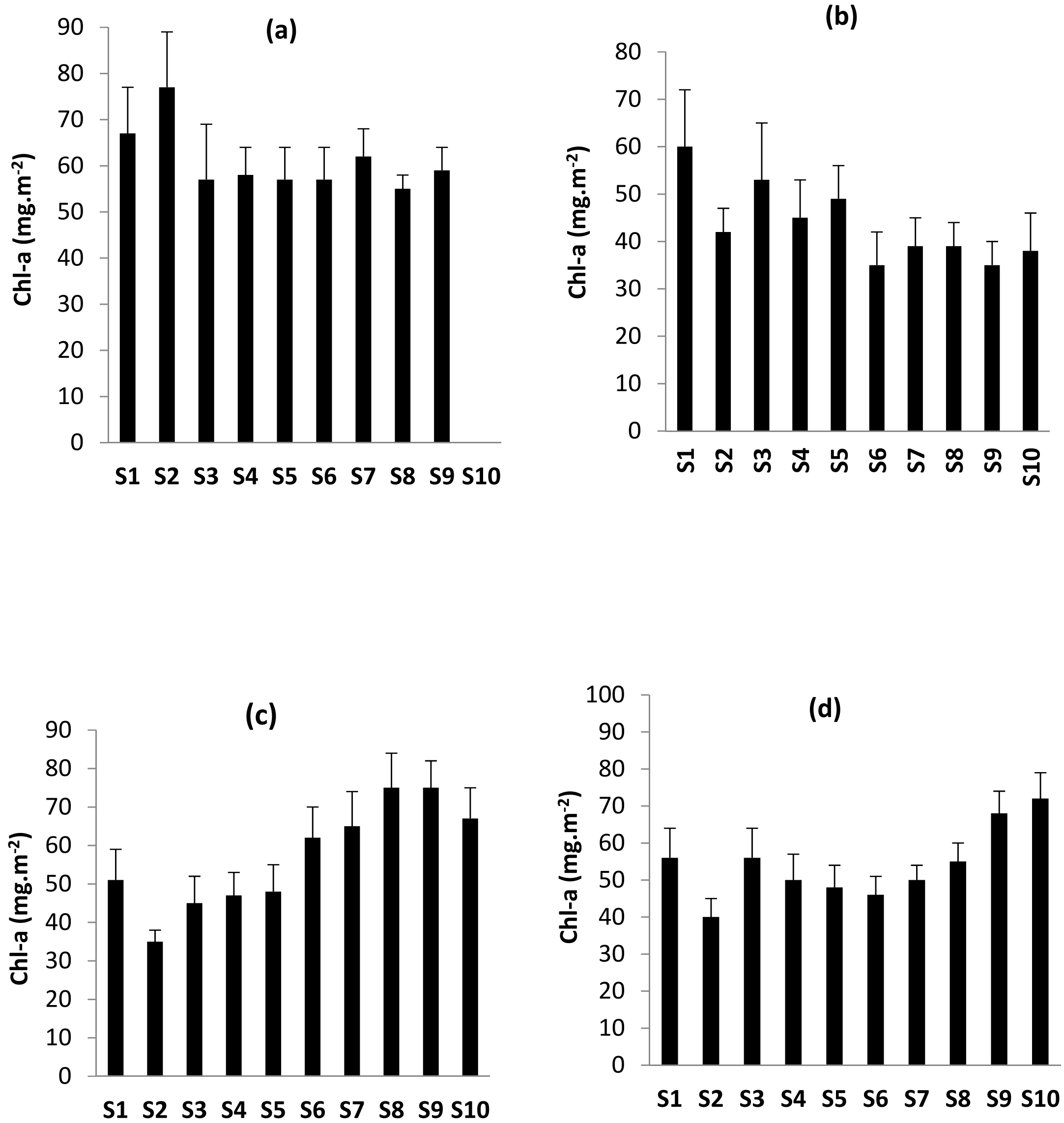


Figure 7 The concentration of chlorophyll-*a* at each of the sampling stations along the MacKenzie River; **(a)** February 2012; **(b)** July 2012; **(c)** November 2012; **(d)** June 2013. Data indicate means ± SD. (Station 10 was dry in February 2012).

Algal response under manipulated flow regimes (freshes and high flow)

Algae and water quality were monitored under different water release regimes to determine their response to river flow and so its effect on river health. Algal community structure was documented in terms of the major algal groups and then biological properties of the periphytic algal communities were measured before, during and after water release events (1 week before water release, 3 days during water release and three weeks after water release (3 times).

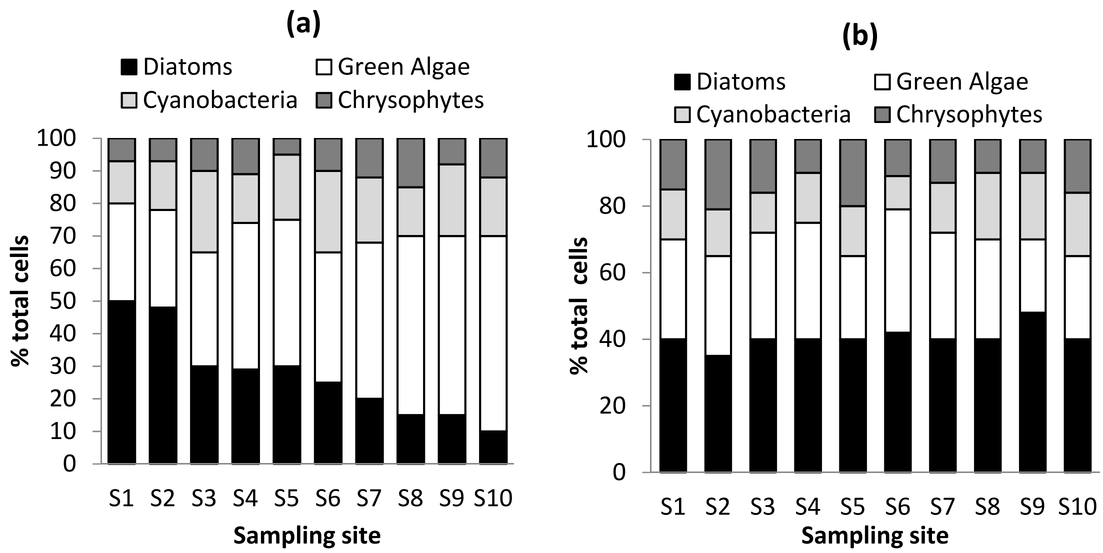
Soft algae and diatoms community structure before, during and after freshes

Algal species composition varied between sites under freshes (35-40 ML/day). The algal composition shifted downstream after water release events. Diatoms were the most abundant group (50% of cells) upstream (Site 1 and 2 in Reach 1) before the water release whilst green algae were most abundant downstream (55% of cells at Site 10 in Reach 3). The proportion of green algae and Cyanobacteria tended to be greater downstream before the water release, whereas diatoms had lower relative abundance downstream (to 10% at site S10). However, Cyanobacteria and other algae were relatively more abundant (25% and 15% respectively) in some mid-stream sites (Reach 2) (Figure 8a).

There were substantial changes in algal communities during and after water release events. The relative abundance of diatom cells (40%) increased during and after freshes, whilst green algae decreased downstream (23%); the proportion of green algae during and after freshes was lower in the downstream sites. Therefore, the algal taxonomic composition became more uniform across the reaches following a release event. For example, blooms of green algae, typical of base flow conditions in downstream reaches, were reduced by the freshes (Figure 8a-c).

The diatom species composition after freshes at upstream sites was different to those at downstream sites. The most common diatom taxa found at the upstream sites before freshes were *Melosira arentii*, *Frustulia. rhomboides*, *Gomphonema affine, Navicula radiosa*, *Neidium iridis* (Ehrenberg) Cleve, *T. flocculosa* whilst at downstream sites the common diatoms found were *Encyonema minutum*, *Eunotia bigibba*, *E. serpentina, Nitaschia capitellata* and *Stenopterobia delicatissima* (F.W.Lewis) Brébisson ex Van Heurck.

The community structure changed during and after freshes. The most abundant diatoms in the upstream reach during and after the water release were *Brachysira brebissonii*, *M. arentii*, *E. minor*, *G. affine*, *N. heimansioides*, *Brevisira* Karammer, *S. exiguiformis* and *T. flocculosa* whilst those sampled from the downstream reach were *E. serpentina*, *N. capitellata*, *N. clausii*, and *S. curvula*



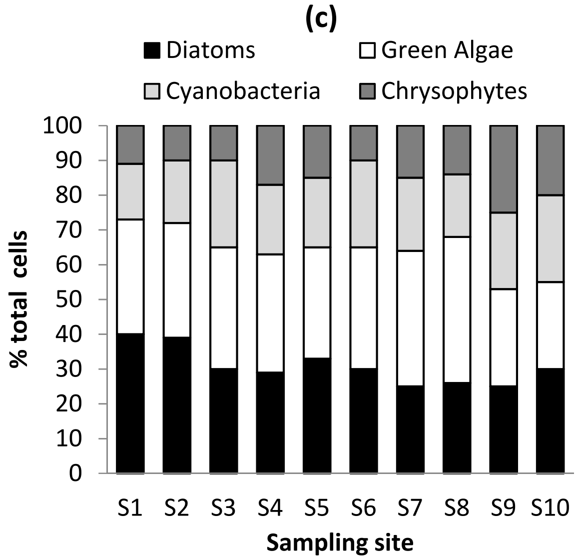


Figure 8 Relative abundance of total cells of algae in sampling sites along the MacKenzie River; (**a**) before freshes (15 ML/day); (**b**) during freshes (35-40 ML/day); (**c**) after freshes (15ML/day).

Algal community structure before, during and after high flow

Diatoms were common in upstream sites (45%), while green algae (33%), Cyanobacteria (12%) and Chrysophyta (10%) were less abundant before high flow events (Figure 9a). However, this pattern in the algae community structure changed gradually downstream. In the midstream (Reach 2), the percentage of diatoms, green algae and Cyanobacteria were similar. In contrast to the upstream sites green algae were more abundant from sites 7 to 10.

Diatoms had higher relative abundances downstream (sites 5 to 10) during high flow (c. 40%) and after the high flow event (c. 35%). In contrast, green algae and Cyanobacteria relative abundances decreased downstream (c. 30% and c. 20% respectively). The results showed that high flows had a major influence on algae communities. The abundance of Cyanobacteria and Chrysophyta increased from upstream to downstream during base flow and before high flow, whilst their composition was relatively uniform spatially during and after high flow. Overall the algal taxonomic composition became more uniform along the MacKenzie River during and after the high flow events (Figure 9b-c).

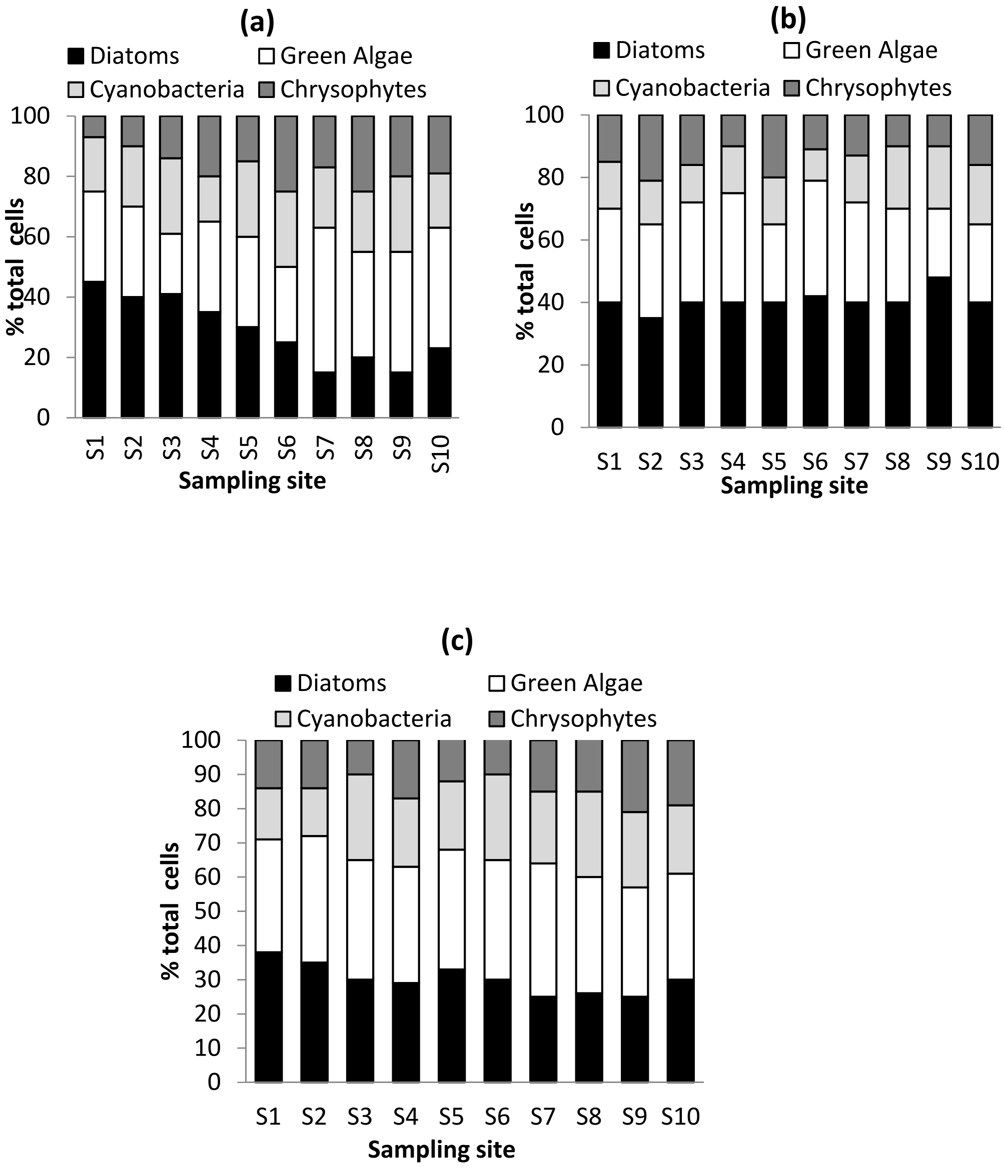


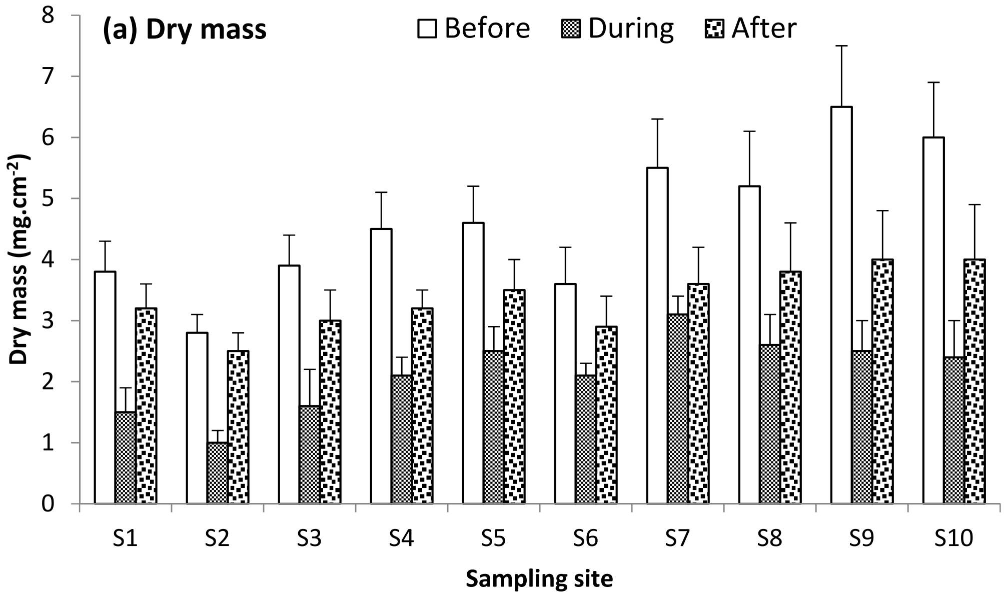
Figure 9 Relative abundance of cells of algae from sampling sites along the MacKenzie River; (**a**) before high flow (15 ML/day); (**b**) during high flow (55 ML/day); (**c**) after high flow (15ML/day)

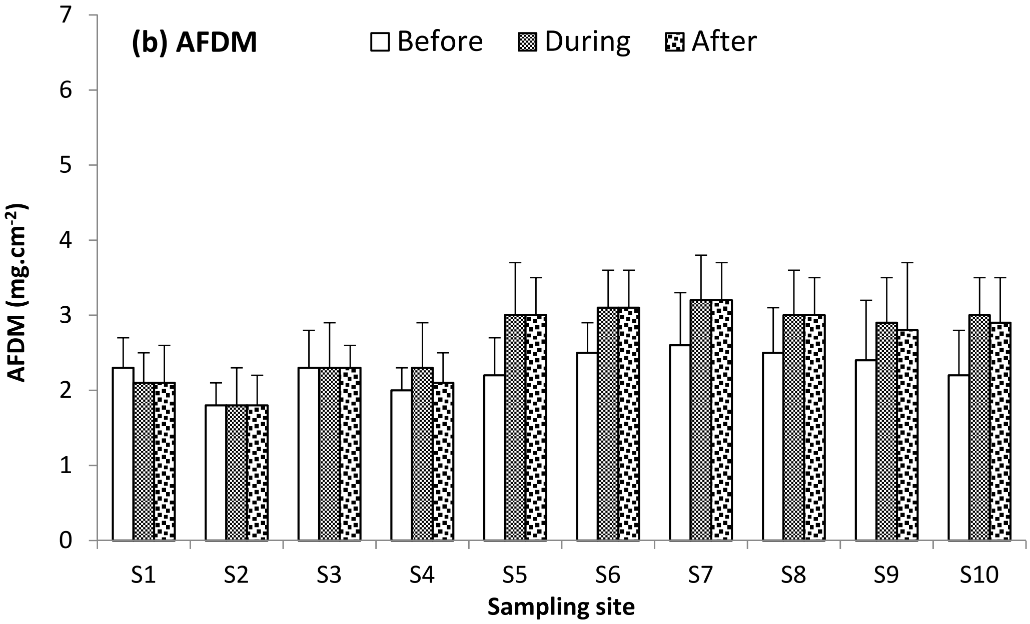
Algal biomass under high flows

Before the high flows (55ML/day) were released, dry mass generally increased from the upstream to the downstream sites with the highest value of dry mass (6.5 $mg.cm^{-2}$) found at site 9; under the same conditions however, there was more fluctuation evident at midstream and downstream sites in the values of the dry mass. Dry mass decreased dramatically during high flows and partially recovered after the high flows (Figure 10a). Overall the accumulation of dry mass decreased during high flow conditions within the system.

The accumulation of AFDM increased in upstream and midstream and subsequent decreased in downstream sites before high flows while during high flows the AFDM decreased at site 1, remained unchanged at sites 2 and 3 and increased at the other sites. After the high flows, AFDM values were almost the same as during high flows (Figure 10b).

The chlorophyll-*a* concentration fluctuated downstream (before, during and after high flows); chlorophyll-*a* concentration increased before water release (high flows) but decreased substantially during high flows and then partially increased again afterwards but still did not reach the same concentrations as before the releases (Figure 10c).


(a) Dry mass
Before
During
After
Dry mass (mg.cm-2)
0
1
2
3
4
5
6
7
8
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
Sampling site


(b) AFDM
Before
During
After
AFDM (mg.cm-2)
0
1
2
3
4
5
6
7
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
Sampling site

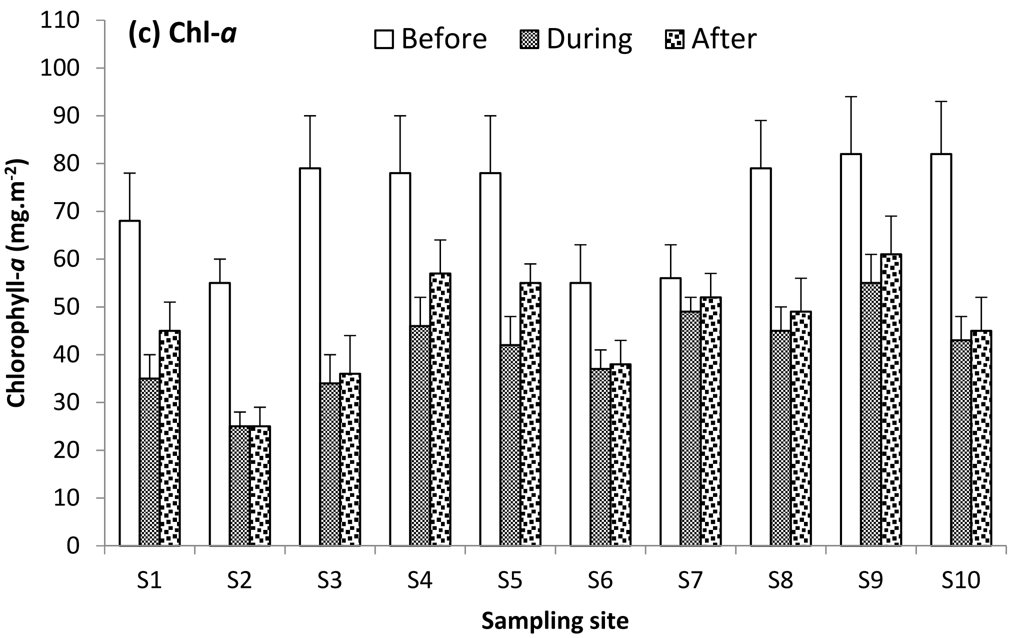


Figure 10 Accumulation of algal biomass before high flows (15 ML/day), during high flows (55ML/day) and after high flows (15ML/day) at each of the sampling stations along the MacKenzie River; **(a)** Dry mass; **(b)** AFDM; **(c)** Chlorophyll-*a*. Data indicate means ± SD.

Diatom Species Index for Australian Rivers (DSIAR)

The DSIAR was calculated to classify the condition of the waterway. The results showed sites S1 to S4 to be in 'good' condition with a DSIAR score above 60 under all flow regimes. During baseflow conditions, sites S5 to S8 were in 'moderate' condition with DSIAR scores between 41-60 and downstream sites ranged from 'moderate' to 'poor' condition (Table 4). The DSIAR scores varied more in Reaches 2 and 3 compared to those upstream (Reach 1). Overall the upstream sites had the highest scores (least impacted), with DSIAR scores decreasing downstream. The site furthest downstream (S10) typically returned the lowest, or near lowest, DSIAR score. However, during and after water release events (freshes and high flows) the DSIAR score increased downstream to scores reflective of 'good' and 'moderate' conditions, albeit temporarily (Table 4).

Table 4 The Results of modified Diatom Species Index for Australian Rivers (DSIAR) at sampling sites along the MacKenzie River in different flow regimes. The scores were used to classify the waterway as bad (0-20), poor (21-40), moderate (41-60), good (61-80) and high (81-100).

	Reach	**1**				**2**				**3**	
	Site / **Date**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Base flow (10 ML/day)	28/02/12	78	75	71	68	56	49	49	48	35	-
Base flow (15 ML/day)	17/07/12	77	72	72	66	58	48	42	48	42	38
Base flow (15 ML/day)	9/11/12	78	65	76	68	59	48	43	47	49	41
Base flow (15 ML/day)	25/05/13	75	72	75	67	55	49	45	49	47	48
During freshes (35 ML/d)	21/10/13	82	78	78	66	65	65	61	62	65	62
After freshes (15 ML/d)	25/10/13	81	75	79	69	66	65	61	63	66	65
Before freshes (15 ML/d)	16/12/13	76	74	72	71	55	42	46	48	37	38
During freshes (40 ML/d)	19/12/13	86	75	78	75	64	66	69	63	66	62
After freshes (15 ML/d)	23/12/13	78	75	72	72	57	56	55	55	59	52
After freshes (15 ML/d)	3/01/14	79	75	78	71	59	57	55	45	41	39
After freshes (15 ML/d)	16/04/14	74	71	68	62	61	49	45	41	41	39
Before high flow (15 ML/d)	29/10/14	71	72	73	74	55	42	46	48	37	38
During high flow (55 ML/d)	1/11/14	82	75	78	75	71	68	69	65	66	67
After high flow (15 ML/d)	08/11/14	78	75	72	72	67	66	65	61	59	52
After high flow (15 ML/d)	22/11/14	79	75	68	68	59	57	55	65	45	37

Canonical Correspondence Analysis (CCA)

The CCA was applied using forward-selection to determine the most influential variables, environmental drivers of flow water chemistry and biological properties for all flows. The soft algae were also evaluated under all flow conditions and their responses to environmental variables analysed. This accounted for 8.5% of the species-environment interactions on axis 1 and 3.0% on axis 2 (Figure 11). The results highlight that nutrient availability is the major driver in soft algal assemblages in the MacKenzie River. The results showed that algal community assemblages were different during high flow events compared to low flow events. The results showed that downstream species were more closely associated with turbidity, TSS and conductivity. The CCA results indicated that turbidity is a significant factor affecting both soft algae and diatoms. The statistical results of soft algae showed that that upstream species such as *Chlorella vulgaris, Dinobryon sertularia, Peridinium lomnickii, Scenedesmus acuminatus*, *Euastrum* sp. and *Scenedesmus armatus* were associated with high DO, and low TP and TDS, whilst downstream species *Anabaena flos-aquae*, *Monopraphdium subclavatum*, *Oocystis pusila* and *O. parva* were associated with high TSS, turbidity, pH, and conductivity. The CCA results showed that the diatom assemblage pattern was different during high flow compared with all the other flow scenarios. Water chemistry had a significant influence on the diatom communities along the MacKenzie River under these circumstances. Diatom assemblages were associated with TDS and turbidity, parallel with axis 1 (9.9%), and pH and TP, temperature and DO parallel with axis 2 (6.8%) (Figure 12). The statistical results of diatom showed that *G. affine*, *F. rhomboides*, *N. heimansioides*, *N. radiosa* and *T. flocculosa* were associated with high DO, low pH, and low TP while downstream species such as *E. serpentina* and *S. delicatissima* were associated with higher Si, TDS, turbidity and temperature.

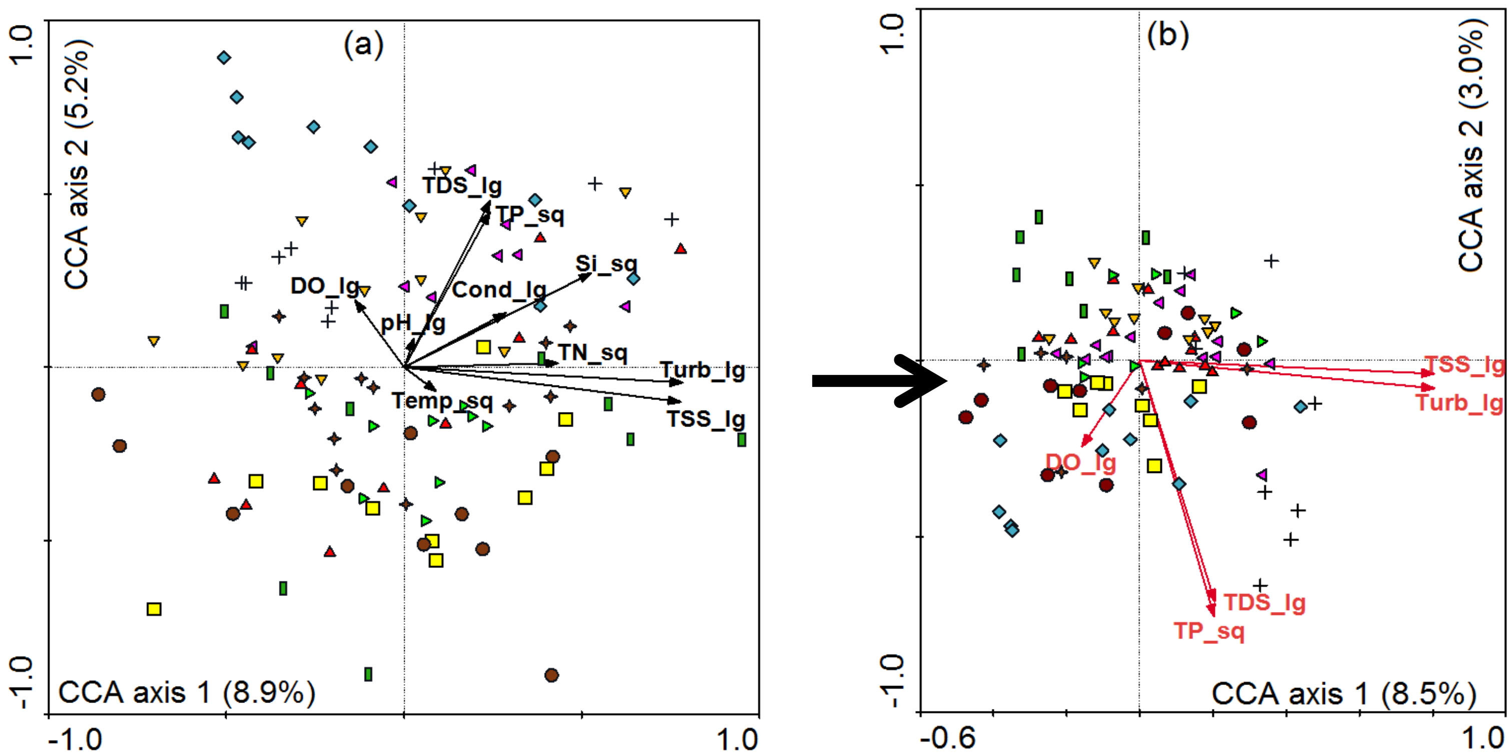


Figure 11 Cononical Correspondence Analysis (CCA) of soft algae altogether in different seasons under baseline flows and under different treatment flow regimes along the MacKenzie River: (a) with all environment variables; (b) significant ($p < 0.05$) variables after forward selection. February 2012 (brown circle), July 2012 (blue diamond), November 2012 (green box), and June 2013 (red up-triangle), before freshes (yellow square), during freshes (pink left-triangle), after freshes (right-triangle), before high flow (yellow down-triangle), during high flow (cross) and after high flow (star)

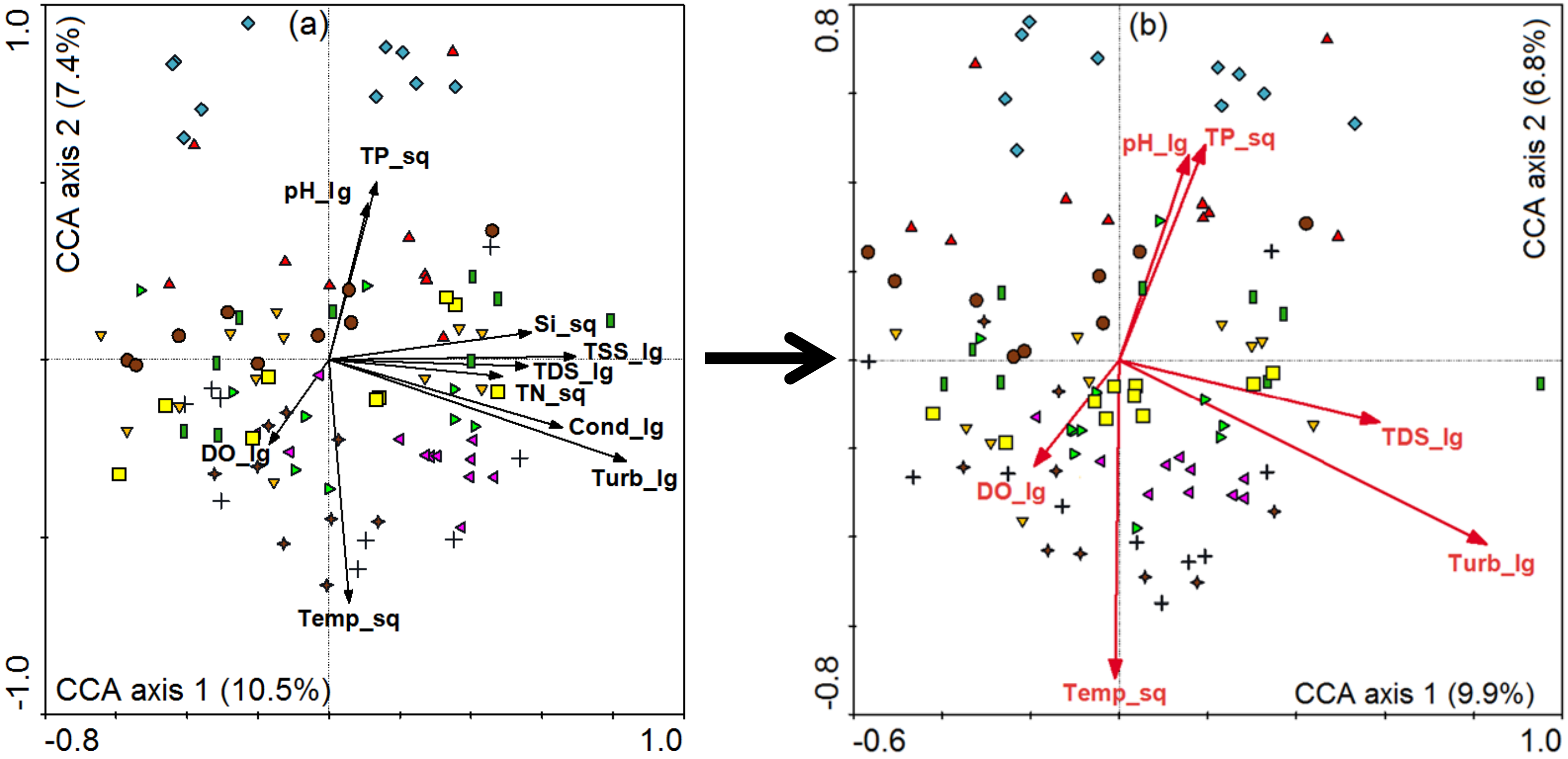


Figure 12 Cononical Correspondence Analysis (CCA) of diatoms altogether in different seasons under baseline flows and under different treatment flow regimes along the MacKenzie River: **(a)** with all environment variables; **(b)** significant ($p < 0.05$) variables after forward selection. February 2012 (brown circle), July 2012 (blue diamond), November 2012 (green box), and June 2013 (red up-triangle), before freshes (yellow square), during freshes (pink left-triangle), after freshes (right-triangle), before high flow (yellow down-triangle), during high flow (cross) and after high flow (star)

Discussion

Biological structure, ecological processes, ecosystem function and metabolism in riverine ecosystems can change due to flow patterns, water quality and climatic variability. The results presented here for the MacKenzie River show some similarities and dissimilarities to the conclusions of Boulton et al. (2014) and the River Continuum Concept (Vannote et al. 1980, Tornwall et al. 2015, Atazadeh 2017, Atazadeh et al. 2020). For example, the DO dramatically decreases in the middle reach of the river and increases slightly downstream. The water velocity is stagnant in the middle of the river whilst the River Continuum Concept suggests that average velocity increases in downstream sections of rivers. These changes can appear naturally or as a consequence of anthropogenic modification of lotic systems due to water abstractions, diversions as well as through evaporation. Turbidity, total suspended solid (TSS), cations and anions also increased with distance downstream along the MacKenzie River, particularly downstream of points of sediment input and water abstraction in the lower reaches. The range of turbidity, TSS, cations and anions were less in the MacKenzie River (Figure 3). in comparison with the Wimmera and Glenelg Rivers (Anderson and Morison 1989, Chee et al. 2009, Alluvium 2013, VEWH 2015, WCMA 2015) likely as the MacKenzie River sits higher in the catchment. The concentration of nutrients increases with distance downstream due to agricultural activities and land use which contribute to increases in the concentration of nitrogen and phosphorous in the MacKenzie River (Figure 3, Table 1). This study reveals the water quality and stream condition of the MacKenzie River are influenced by flow modifications (e.g. construction of Wartook Reservoir in 1887, human settlement in Zumsteins and lower reaches of the river, water diversion to the Mt Zero Channel, water storages and water plant treatment). In general, water quality varies in riverine ecosystems (spatially and temporally) and these changes can provide good evidence to assist in understanding the effects of human impacts and modifications (Heathwaite 2010).

The results under water release events (freshes and high flows) showed that the pH of the upstream and downstream reaches became similar (Table 3). Indeed, water release events likely bring acidic water from Wartook Reservoir to the lower parts of the MacKenzie River, reducing the alkalinity of that reach. The pH can determine solubility and availability of nutrients (e.g. N and P) in rivers and streams. The concentration of dissolved oxygen (DO) changes substantially along the river, particularly in the midstream where DO increased greatly in response to water release events. Nutrients (P, N, Si) are a main source of chemical energy for both autotrophic (e.g. cyanobacteria) and heterotrophic (bacteria) microbes in rivers and streams (Allan and Castillo 2007). Flow alteration and human activities (e.g. agriculture) profoundly influenced nutrient dynamics along the MacKenzie River. The nutrients enter the MacKenzie River as dissolved materials from the atmosphere, lithosphere and hydrosphere. The nutrients also enter the MacKenzie River in organic form via biological assimilation (nitrogen assimilation by cyanobacteria). The contribution of the dissolved inorganic and organic nutrients can be more than that of organic materials under water release events, due to greater sediment input into the water. The statistical analyses showed that total nitrogen (TN) and total phosphorus (TP) were high under water release events (Figs 11-12).

Algal colonisation and structure are known to be highly responsive to shifts in water quality and flow variation (Ryder et al. 2006, Robson et al. 2008, Atazadeh 2011, Atazadeh and Sharifi 2012, Atazadeh et al. 2014b, Chester and Robson 2014, Stevenson 2014). The results of base flow in the MacKenzie River revealed that upstream has high algal biodiversity whilst middle and downstream reaches have low algal diversity despite a high incidence of algal blooms. Watts et al. (2009b) found similar evidence in the Mitta Mitta River for increasing incidence of algal blooms downstream under constant base flows.

Under freshes and high flows, algal monitoring surveys revealed the key indicator taxa increased. Indeed, the relative abundance of diatoms increased during and after freshes and high flows, especially epiphytic diatoms such as *Tabellaria flocculosa*, *Gomphonema affine*, *Navicula radiosa*, and *Encyonema minutum* (epiphytic diatoms) Biggs and Hickey (1994) and Ryder et al. (2006) found diatoms to increase while soft algae decreased under water release events. In contrast, Davie and Mitrovic (2014) found diatom abundance to decline while filamentous green algae and cyanobacteria increased downstream with high water releases in the Severn River (NSW). The CCA results indicated that turbidity is a significant factor affecting both soft algae and diatoms (Figs 11-12). Biggs and Hickey (1994) found physiognomy of algal periphyton changed under different hydraulic gradients in the Ohau River, South Island, New Zealand.

The allocation of water for environmental purposes usually requires considerable lead-time, including that required to develop stakeholder support, a strategy for the delivery of environmental water, and a monitoring program to measure benefit. Therefore, most studies have focused on the environmental flow needs of rivers and the water volumes required for regulated systems. The necessity of environmental flows has increased significantly because of the incidence of drought, salinisation and the increased scarcity of water, especially in Australia (Bond et al. 2008). However, there is little focus in water supply systems globally on managing consumptive flows to provide ecological benefits. In fact, there are number of constraints (e.g. existing water amount limitations, physicochemical and biological conditions, social and economic restrictions and political issues) that affect the allocation of water among the consumptive users (Richter and Thomas 2007). The allocation of water between the consumptive users and the environment is dependent on the availability of water and, ultimately, the decision to release. Hence, equitable and effective sharing of the water resource between consumptive users and the environment is critical.

This paper, utilising flow releases within the MacKenzie River, provides an opportunity to measure and assess responses to inform manipulations of the nature of releases, allowing for fine-tuning, over short periods, toward an adaptive approach. These results showed that water quality, algal community structure and biological properties respond to different flow regimes.

Depending on water availability, environmental watering plans will often seek to release water along the MacKenzie River in order to improve water quality, stream condition and river health, especially for the downstream reaches. These water release events (freshes) are designed to keep the river healthy, but this research shows that the intended consequence of pulsed releases is often short-lived, with no long-term benefit to the health of the river's ecosystem. It seems the ecological impacts of the water release events are not constant in other waterways as well (e.g. Allan et at. 2009). The algal responses to different flow regimes reveal that the downstream sections of the MacKenzie River remain stressed and so require further water release events to enhance its health. The statistical results show the algal community patterns and ecosystem functions are different under different flow regimes where the water release events (freshes) play major role to improve the ecosystem processes in the MacKenzie River. The results show that the water release events (freshes) are important opportunities to improve the ecological conditions of the MacKenzie River with limited water availability, particularly in the middle and lower parts of the river. Clearly, additional work to develop the model for configuring flow regimes for ecological/environemntal benefits and setting operational rules of water management with respect to social and economic objectives are needed.

Conclusions

The algal communities responded under different flow regimes and showed the role of flows in improving stream condition. These flows can come from consumptive water transfers which is the new challenge for the river scientists and water engineers. This research provides the means by which stream condition may be enhanced from consumptive flows to complement the benefit derived from environmental flows. In addition, this research shows that benefits can accrue when management moves from a contest between volumes for allocations, to a coordinated approach to bring environments benefits without compromising consumptive needs. The results reveal that the lower parts of the river remain under stress due to flow alteration despite the allocation of environmental flows. However, good ecological condition can be achieved if consumptive flows are also released in a manner that benefits the ecology of the River. There are clear benefits that would accrue from integrating environmental flows and consumptive flow operations. This would be achieved by respective operators exchanging flow release plans and for this to be coordinated between water agencies. The agencies have this as a planning goal and so the way is paved for more effective use of all water releases. The integrated ecological response based on algal response to hydrological changes and water policy initiatives will help to provide for a healthy and resilient working river which supports the environmental values.

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