Arrow Irrigation

Arrow River Periphyton Assessment

December 2019

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Prepared for Arrow Irrigation

by

Dean Olsen, PhD.

Ryder Environmental Limited
195 Rattray Street
PO Box 1023
DUNEDIN, 9054
New Zealand
Phone: 03 477 2119

Cover page: Autumn colours surround the Arrow River at Arrow Gorge Track

Executive summary

Arrow Irrigation Limited (AIL) takes water from the Arrow River upstream of Arrowtown to supply to a number of water users in the broader Queenstown Basin. This report presents the available information on the composition and environmental drivers of the periphyton community in the Arrow River to inform upcoming resource consent applications and minimum flow-setting processes.

Photographs were taken at four locations (upstream of Bush Creek, Tobins Track, Cornwall Street and Arrow Junction) on nine occasions in February and March 2019.

Hydrological data available for the Arrow catchment was analysed to assess the frequency of flushing flows in the Arrow River (flows of more than three times the median flow, or approximately 9,200 l/s). Over the period considered (30 December 2010 – 26 August 2019) there was an average of five flushing events per year, corresponding to an average period of 74 days between events of this magnitude.

Other factors known to affect periphyton cover and biomass include water quality (nutrient availability, water clarity), physical factors (substrate type, presence of fine sediments) and biological factors (e.g. invertebrate grazing, presence of trout).

The level of allocation from the Arrow catchment is not expected to affect the frequency of high-flow events that are large enough to substantially reduce periphyton biomass. Given that water abstraction is not expected to affect the frequency of disturbance events, the response of periphyton communities is expected to be driven by the rate of accrual, the physical preferences of individual periphyton types and processes governing autogenic sloughing.

Habitat modelling predicts an optimum flow of 1,600 l/s for diatoms and 600 l/s for short filamentous algae, while habitat quality for long filamentous algae is expected to peak when flow ceases. Neither cyanobacteria or Didymo are predicted to show a marked response to flows in excess of 500 l/s. The predictions of instream habitat modelling are expected to represent the periphyton composition that <u>may</u> develop over periods of low flows. However, a range of factors may influence how the composition of the periphyton community develops.

Nutrient concentrations in the Arrow River are low and this is expected to reduce the general risk of periphyton proliferation.

Available periphyton monitoring data suggests that the Arrow River supports a low-biomass periphyton community dominated by thin films and medium mats of diatoms under the existing flow regime and water quality. This is expected to continue under a flow regime with a similar or reduced level of allocation and environmental flows (minimum or residual flows).

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1. Introduction

Arrow Irrigation Limited (AIL) takes water from the Arrow River upstream of Arrowtown to supply to a number of water users in the broader Queenstown Basin. This water is currently taken under a deemed permit (WR1440AR), which authorizes a maximum take of 1,389 l/s from the Arrow river. This deemed permit expires in October 2021 and AIL will be applying for resource consent to continue to take water from the Arrow River.

In June 2017, the Otago Regional Council (ORC) embarked on a plan change process to manage water in the Arrow catchment and Wakatipu Basin aquifers, undertaking community consultation in June and December 2017. This process includes setting minimum flows and allocation limits for the Arrow catchment.

The purpose of this report is to present available information on the composition and environmental drivers of the periphyton community in the Arrow River to inform upcoming resource consent applications and minimum flow-setting processes.

2. Methods

Longitudinal photography

Photographs were taken at four locations along the Arrow River (Figure 1) between 1 February 2019 and 29 March 2019. These photographs were provided by Matt Hickey (Water Resource Management).

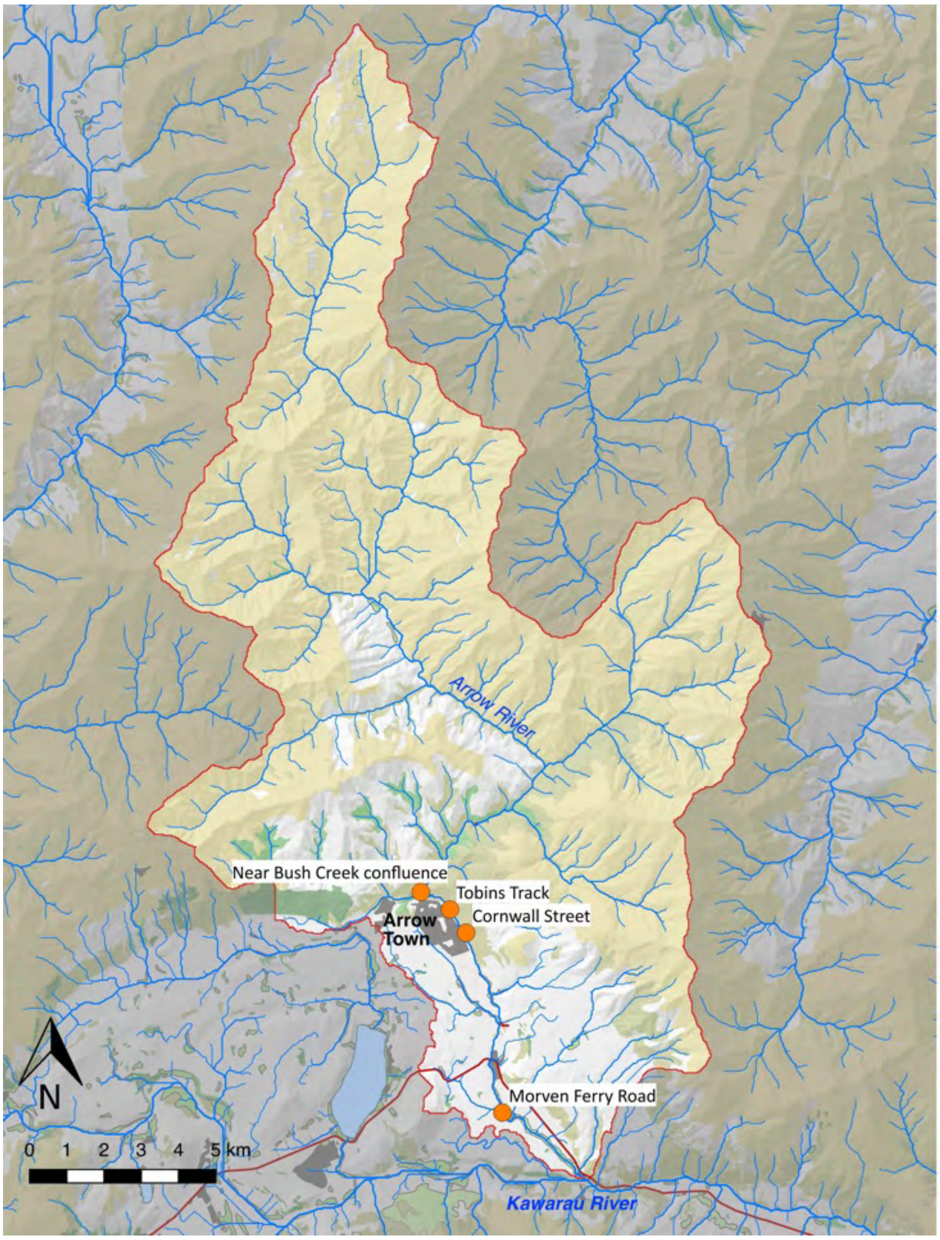

Figure 1 Location of the photo monitoring sites in the Arrow catchment

Hydrological analysis

Observed hydrological data for the Arrow at Cornwall Street d/s hydrological site was available for the period 30 December 2010 – 26 August 2019. In addition, a naturalised flow time-series has been developed for the period 3 December 1976 – 13 May 2019. Comparison of the observed and naturalised flow data for the period 30 December 2010 – 26 August 2019 indicates that the naturalised flow time series substantially underestimated the magnitude of high-flow events, most likely because the synthetic (naturalised) dataset was optimized to accurately estimate low-flows (<3,000 l/s), rather than high flows. For this reason, the naturalised flow time series was not used further in the analyses presented in this report.

The frequency of events of more than 3 times the median flow was calculated using the mean daily flow record using a filter period of 5 days (i.e. multiple FRE3 events that occurred within 5 days of each other were counted as a single event).

Periphyton Monitoring Data

Ryder Environmental has been undertaking monthly monitoring of periphyton cover and biomass (chlorophyll *a*) at two sites in the Arrow River as part of ORC's State of the Environment monitoring: Arrow at Morven Ferry Road and Arrow at Arrow Gorge Track (Figure 2). Sampling began at the Morven Ferry Road site in February 2019 and in March 2019 at the Arrow Gorge Track site. Permission was granted by ORC for this data to be used in this analysis.

Periphyton cover

Periphyton was surveyed at each site following Rapid Assessment Method 2 (RAM-2) of Biggs & Kilroy (2000) using an underwater viewer (bathyscope), which includes assessment of the percentage cover of different classes of periphyton. These periphyton classes were separated on the basis of growth form (mat, filamentous), colour (green, light brown, black/dark brown, brown/reddish) and thickness for mats (thin, medium, thick) or length for filaments (short, long). The cover of thick mats of the invasive diatom Didymo (*Didymosphenia geminata*) was also noted, where present.

Periphyton biomass

Periphyton biomass was assessed by scraping a fixed area (0.00195 m^2 – a circle with a diameter of 50 mm) from the surfaces of 10-20 stones at each site (0.0195 – 0.039 m^2). This method was based on method QM-1b of Biggs & Kilroy (2000).

Periphyton biomass analyses (chlorophyll-*a*) were undertaken using the method described in the NIWA Periphyton Monitoring Manual (for chlorophyll-a).

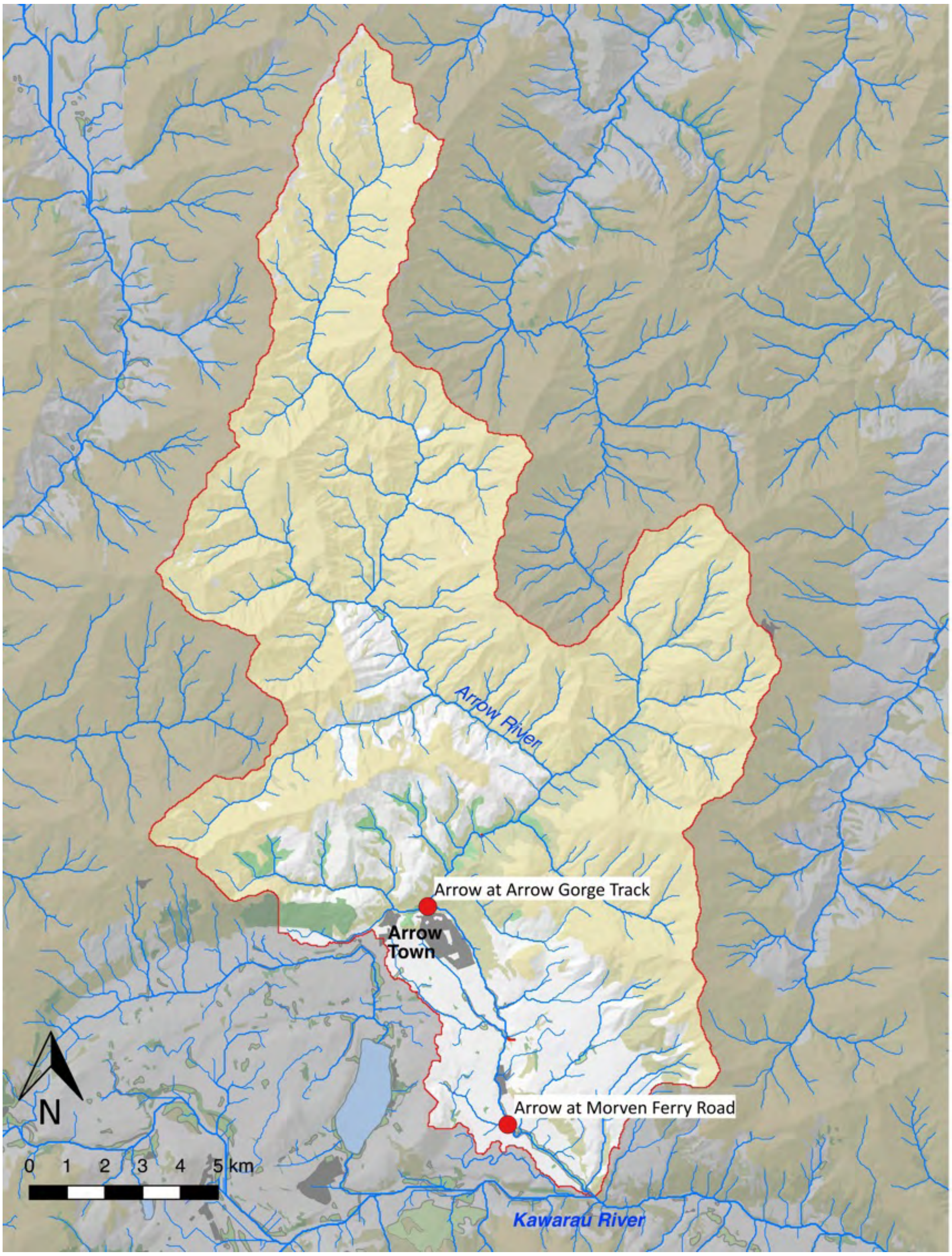

Figure 2 Location of the biomonitoring sites in the Arrow catchment

3. Water Quality Standards

Water quality

Regional Plan: Water - Schedule 15

Schedule 15 of the RPW describes the characteristics of good water quality in lakes and rivers along with numerical water quality limits and targets for waterbodies across Otago. ***Table 1*** below sets out the numerical water quality limits/targets for receiving water group 2, which includes the Arrow River.

These limits/targets apply as 5-year, 80^{th} percentiles when flows are below median flows at the relevant flow reference site. That is, 80% of values collected when flows are at or below the median flow at the appropriate flow reference site over a 5-year period should be below the Schedule 15 limit.

Table 1 ***Numerical limits and targets for good water quality in lakes and rivers in the Queenstown Lakes District from Schedule 15 of the Otago Regional Plan: Water.***

Nitrate-nitrite nitrogen **mg/L**	**Dissolved reactive phosphorus** **mg/L**	**Ammoniacal nitrogen** **mg/L**	***E. coli*** **cfu[1]/100 mL**	**Turbidity** **NTU**
0.075	0.01	0.1	260	5

National Policy Statement for Freshwater Management

The National Policy Statement for Freshwater Management (2014, amended 2017)(NPSFM) includes chlorophyll-*a* (Table 2), nitrate (toxicity) (Table 3) and ammonia (toxicity) (Table 4) as attributes in the National Objective Framework, while the draft NPSFM (2019) also includes dissolved inorganic nitrogen (Table 5) and dissolved reactive phosphorus (Table 6) as attributes intended to manage eutrophication (nutrient-enrichment).

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[1] Colony forming units. When culturing microbes, it is uncertain if a colony arose from one cell or a group of cells and expressing results as colony-forming units reflects this uncertainty.

Table 2 ***Chlorophyll*-a *attribute in the National Objective Framework of the National Policy Statement for Freshwater Management (2017) and draft National Policy Statement for Freshwater Management.***

Value	Ecosystem Health (Aquatic Life)	
Freshwater Body Type	Rivers	
Attribute Unit	mg chl-*a*/m^2 (milligrams chlorophyll-a per square metre	
Attribute band and description	Numeric Attribute State (Default Class)	Numeric Attribute State (Productive Class)[1]
	Exceeded no more than 8% of samples[2]	Exceeded no more than 17% of samples[2]
A Rare blooms reflecting negligible nutrient enrichment and/or alteration of the natural flow regime or habitat.	≤50	≤50
B Occasional blooms reflecting low nutrient enrichment and/or alteration of the natural flow regime or habitat.	>50 and ≤120	>50 and ≤120
C Periodic short-duration nuisance blooms reflecting moderate nutrient enrichment and/or alteration of the natural flow regime or habitat.	>120 and ≤200	>120 and ≤200
National Bottom Line	200	200
D Regular and/or extended-duration nuisance blooms reflecting high nutrient enrichment and/or significant alteration of the natural flow regime or habitat.	>200	>200

Table 3 ***Nitrate (toxicity) attribute in the National Objective Framework of the National Policy Statement for Freshwater Management (2017) and draft National Policy Statement for Freshwater Managment.***

Value	Ecosystem health		
Freshwater Body Type	Rivers		
Attribute	Nitrate (Toxicity)		
Attribute Unit	mg NO_3-N/L (milligrams nitrate-nitrogen per litre)		
Attribute State	**Numeric Attribute State**		**Narrative Attribute State**
	Annual Median	**Annual 95th Percentile**	
A	≤1.0	≤1.5	High conservation value system. Unlikely to be effects even on sensitive species.
B	>1.0 and ≤2.4	>1.5 and ≤3.5	Some growth effect on up to 5% of species.
C	>2.4 and ≤6.9	>3.5 and ≤9.8	Growth effects on up to 20% of species (mainly sensitive species such as fish). No acute effects.
National Bottom Line	6.9	9.8	
D	>6.9	>9.8	Impacts on growth of multiple species, and starts approaching acute impact level (ie risk of death) for sensitive species at higher concentrations (>20 mg/L).

Note: This attribute measures the toxic effects of nitrate, not the trophic state. Where other attributes measure trophic state, for example periphyton, freshwater objectives, limits and/or methods for those attributes will be more stringent.

Table 4 ***Ammonia (toxicity) attribute in the National Objective Framework of the National Policy Statement for Freshwater Management (2017) and draft National Policy Statement for Freshwater Managment.***

Value	Ecosystem health		
Freshwater Body Type	Lakes and rivers		
Attribute	**Ammonia (Toxicity)**		
Attribute Unit	mg NH_4-N/L (milligrams ammoniacal-nitrogen per litre)		
Attribute State	**Numeric Attribute State**		**Narrative Attribute State**
	Annual Median*	**Annual Maximum***	
A	≤0.03	≤0.05	99% species protection level: No observed effect on any species tested
B	>0.03 and ≤0.24	>0.05 and ≤0.40	95% species protection level: Starts impacting occasionally on the 5% most sensitive species
C	>0.24 and ≤1.30	>0.40 and ≤2.20	80% species protection level: Starts impacting regularly on the 20% most sensitive species (reduced survival of most sensitive species)
National Bottom Line	**1.30**	**2.20**	
D	>1.30	>2.20	Starts approaching acute impact level (ie risk of death) for sensitive species

* Based on pH 8 and temperature of 20°C.

Compliance with the numeric attribute states should be undertaken after pH adjustment.

Table 5 ***Dissolved inorganic nitrogen attribute in the National Objective Framework of the draft National Policy Statement – Freshwater Management (2019).***

Value (and component)	Ecosystem health (water quality)	
Freshwater Body Type	Rivers	
Attribute Unit	DIN mg/L (milligrams per litre)	
Attribute band and description	**Numeric Attribute State**	
	Median	95th percentile
A Ecological communities and ecosystem processes are similar to those of natural reference conditions. No adverse effects attributable to DIN enrichment are expected.	≤ 0.24	≤ 0.56
B Ecological communities are slightly impacted by minor DIN elevation above natural reference conditions. If other conditions also favour eutrophication, sensitive ecosystems may experience additional algal and plant growth, loss of sensitive macroinvertebrate taxa, and higher respiration and decay rates.	> 0.24 and ≤0.50	> 0.56 and ≤01.10
C Ecological communities are impacted by moderate DIN elevation above natural reference conditions, but sensitive species are not experiencing nitrate toxicity. If other conditions also favour eutrophication, DIN enrichment may cause increased algal and plant growth, loss of sensitive macroinvertebrate & fish taxa, and high rates of respiration and decay.	> 0.5 and ≤ 1.0	> 1.10 and ≤ 2.05
National Bottom Line	**1.0**	**2.05**
D Ecological communities impacted by substantial DIN elevation above natural reference conditions. In combination with other conditions favouring eutrophication, DIN enrichment drives excessive primary production and significant changes in macroinvertebrate and fish communities, as taxa sensitive to hypoxia and nitrate toxicity are lost.	>1.0	>2.05
Groundwater concentrations also need to be managed to ensure resurgence via springs and seepage does not degrade rivers through DIN enrichment. Numeric attribute state must be derived from the rolling median of monthly monitoring over five years.		

Table 6 ***Dissolved reactive phosphorus attribute in the National Objective Framework of the draft National Policy Statement – Freshwater Management (2019).***

Value (and component)	Ecosystem health (water quality)	
Freshwater Body Type	Rivers	
Attribute Unit	DRP mg/L (milligrams per litre)	
Attribute band and description	**Numeric Attribute State**	
	Median	95th percentile
A Ecological communities and ecosystem processes are similar to those of natural reference conditions. No adverse effects attributable to DRP enrichment are expected.	≤ 0.006	≤ 0.021
B Ecological communities are slightly impacted by minor DRP elevation above natural reference conditions. If other conditions also favour eutrophication, sensitive ecosystems may experience additional algal and plant growth, loss of sensitive macroinvertebrate taxa, and higher respiration and decay rates.	> 0.006 and ≤0.010	> 0.021 and ≤0.030
C Ecological communities are impacted by moderate DRP elevation above natural reference conditions. If other conditions also favour eutrophication, DRP enrichment may cause increased algal and plant growth, loss of sensitive macro-invertebrate & fish taxa, and high rates of respiration and decay.	> 0.010 and ≤ 0.018	> 0.030 and ≤ 0.054
National Bottom Line	**0.018**	**0.054**
D Ecological communities impacted by substantial DRP elevation above natural reference conditions. In combination with other conditions favouring eutrophication, DRP enrichment drives excessive primary production and significant changes in macroinvertebrate and fish communities, as taxa sensitive to hypoxia are lost.	>0.018	>0.054
Numeric attribute state must be derived from the rolling median of monthly monitoring over five years		

4. Results

Longitudinal photographs

Photographs taken at the four photo points on the mainstem of the Arrow River: near the confluence of Bush Creek (Figure 3, Figure 4), Tobins Track (Figure 5), Cornwall Street (Figure 6) and near Arrow Junction (Figure 7, Figure 8, Figure 9). Full-sized photographs are presented in Appendix A.

Figure 3 ***Photographs of the Arrow River looking upstream near the Bush Creek confluence.***

Figure 4 ***Photographs of the Arrow River looking downstream near the Bush Creek confluence.***

Figure 5 ***Photographs of the Arrow River looking downstream at Tobins Track.***

Figure 6 ***Photographs of the Arrow River looking upstream at Cornwall Street.***

Figure 7 ***Photographs of the Arrow River looking upstream at the site near Arrow Junction.***

Figure 8 ***Photographs of the Arrow River looking downstream at the Junction.***

Figure 9 ***Photographs of a riffle in the Arrow River at the site near Arrow Junction.***

Hydrology

Hydrological data is available for the Arrow at Cornwall Street d/s hydrological site for the period 30 December 2010 – 26 August 2019 (Figure 10). The median flow over the period for which a flow record was available was 3,161 l/s.

The frequency of events of more than 3 times the median flow (>9,192 l/s) was calculated using the mean daily flow record using a filter period of 5 days (i.e. multiple FRE3 events that occurred within 5 days of each other were counted as a single event).

There were 45 FRE3 events over the flow record analysed (8.65 years), with the average accrual period (period between FRE3 events) being 72 days, although accrual periods ranged from 6 to 305 days, with 7 accrual periods of more than 120 days (19%). The median accrual period over this period was 48 days.

The 305 day accrual period occurred in the 2015/16 hydrological year, which was a particularly dry year, with a 7-d low flow of 702 l/s. For comparison, at the nearby Lindis River, flows in the 2015/16 hydrological year were the second lowest in the 41 year-long record (1976-2017). Therefore, it is likely that the 2015/16 season and 305 d accrual period represent an unusual event in the Arrow River.

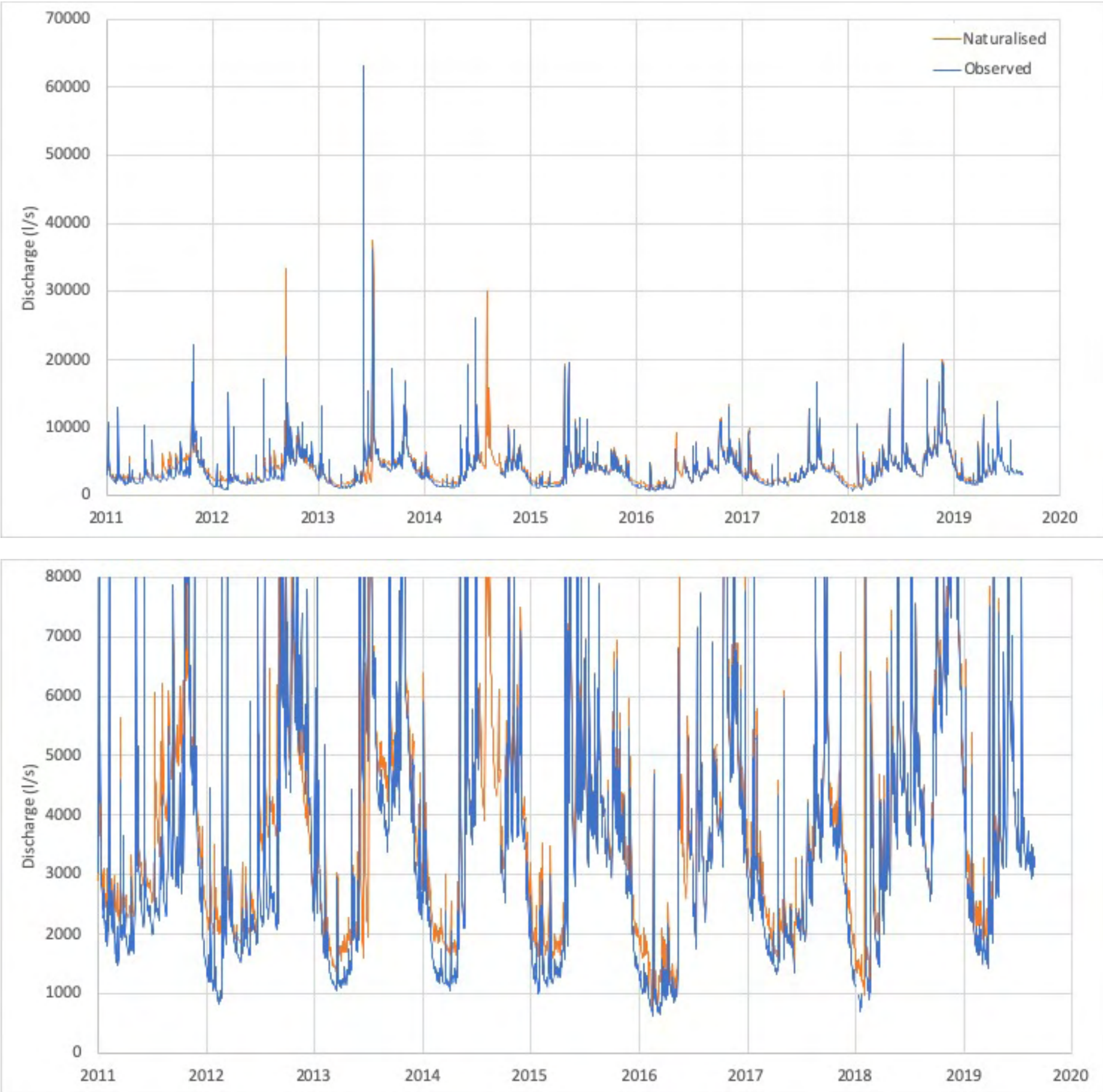

Figure 10 ***Hydrographs of naturalised (orange line) and observed flows (blue line) (top – full flow range, bottom – low flow range) at the Arrow at Cornwall Street d/s hydrological monitoring site over the period 1 January 2011 – 26 August 2019.***

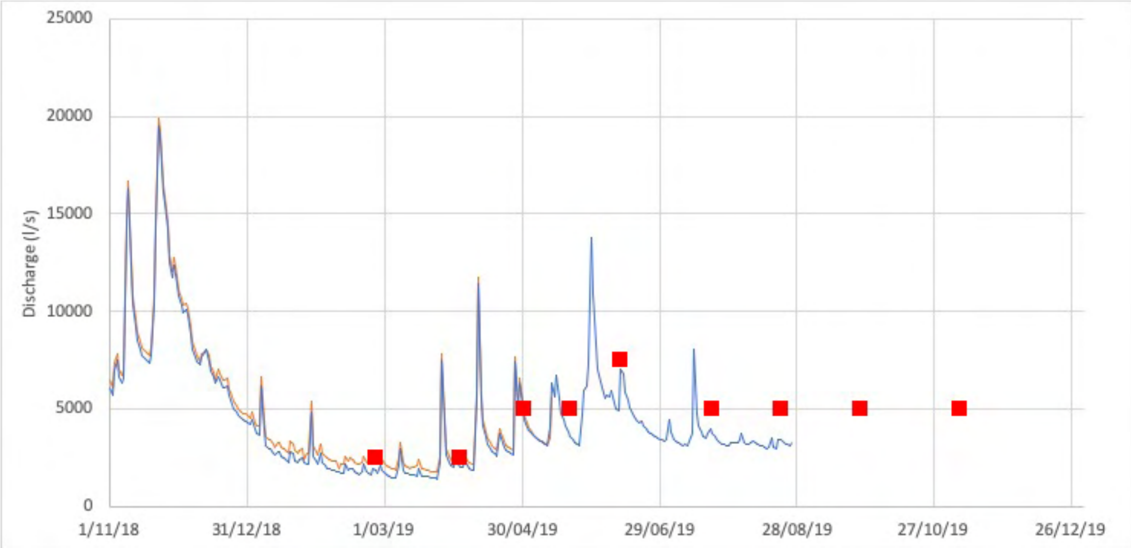

Figure 11 ***Hydrograph of naturalised (orange line) and observed flows (blue line) at the Arrow at Cornwall Street d/s hydrological monitoring site over the period of periphyton surveys (red squares) in the Arrow River (1 November 2018 – 31 December 2019).***

Water quality

Water quality samples have been collected from one site in the Arrow catchment (Arrow at Morven Ferry Road) on several occasions between 1998 and 2014, although this monitoring has not been continuous over this period (Figure 12).

Comparison to Schedule 15 of the Regional Plan: Water

Concentrations of ammoniacal nitrogen and dissolved reactive phosphorus have typically been well within the Schedule 15 limits, while NNN exceeded this limit (Figure 12).

Figure 12 ***Nutrient concentrations in the Arrow River at Morven Ferry Road (12 August 1998 – 13 June 2014). Data courtesy of Otago Regional Council. Grey line = test detection limit, red line = 5-year rolling 80th percentile, orange line = Schedule 15 limit.***

Comparison to the National Policy Statement for Freshwater Management

The 2019 proposed National Objectives Framework (NOF) attribute tables for dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP) include median and 95th percentile values based on 5-years of monthly monitoring. The most recent water quality data available (24 August 2010 – 13 June 2014) were used to make these calculations. Given that the available water quality data is over 5 years old and was not collected monthly, any comparison with NOF attribute bands is tentative.

The median (0.089 mg/l cf. ≤ 0.24 mg/l) and 95th percentile (0.146 mg/l cf. ≤ 0.56 mg/l) concentrations of DIN were well within the A-band of the national objectives framework (NOF). Similarly, the median (0.002 mg/l cf. ≤ 0.006 mg/l) and 95th percentile (0.008 mg/l cf. ≤ 0.021 mg/l) concentrations of DRP were well within the A-band of the national objectives framework (NOF).

Periphyton

Community composition

Periphyton cover at both sites was dominated by diatoms on all sampling occasions, with thin films and medium mats dominated on a similar number of occasions at the Arrow Gorge Track site (Table 7), while thin films dominated at the Morven Ferry Road site on most sampling occasions (Table 8). The invasive diatom *Didymosphenia geminata* has been recorded at both sites (Table 7, Table 8).

Other periphyton groups observed at the Morven Ferry Road site included medium black-brown mats (benthic cyanobacteria), short green filamentous algae and long green filamentous algae, although the cover of these groups has typically been low (Table 7, Table 8).

Table 7 ***Periphyton cover (%) at the Arrow at Arrow Gorge Track biomonitoring site between February and November 2019.***

Category	Thickness	25/02/19	3/04/19	1/05/19	21/05/19	12/06/19	22/07/19	21/08/19	12/09/19	7/11/19
Thin green film	<0.5mm	-	-	-	-	-	-	-	-	2.5
Thin light brown film	<0.5mm	-	46.5	2.3	18.8	2.5	13.8	11.3	17.0	-
Medium light brown mat	0.5-3mm	-	3.5	-	3.5	21.3	26.9	41.0	14.3	18.5
Medium black/dark brown mat	0.5-3mm	-	0.5	0.3	-	-	-	-	-	0.3
Thick green/light brown mat	>3mm	-	-	-	-	3.5	-	-	-	-
Thick black/dark brown mat	>3mm	-	0.1	-	-	-	-	-	-	-
Short green filaments	<2cm	-	-	-	-	-	-	0.3	0.3	-
Long green filaments	>2cm	-	-	-	-	-	-	-	0.3	-
Didymo	>3mm	-	-	-	-	-	11.1	11.2	31.3	7.0
Total algal % cover (incl. Didymo)		**-**	**50.6**	**2.5**	**22.3**	**27.3**	**51.7**	**63.8**	**63.1**	**28.3**

Table 8 ***Periphyton cover (%) at the Arrow at Morven Ferry Road biomonitoring site between February and November 2019.***

Category	Thickness	25/02/19	3/04/19	1/05/19	21/05/19	12/06/19	22/07/19	21/08/19	25/09/19	7/11/19
Thin green film	<0.5mm	-	-	-	-	-	-	-	-	1.5
Thin light brown film	<0.5mm	4.5	4.4	-	4.8	-	10.0	32.5	42.5	5.0
Medium light brown mat	0.5-3mm	12.5	1.0	-	2.3	-	0.5	2.5	9.5	4.8
Medium black/dark brown mat	0.5-3mm	1.7	-	-	-	-	-	2.3	0.8	-
Thick green/light brown mat	>3mm	4.3	-	-	-	-	-	-	-	-
Thick black/dark brown mat	>3mm	-	-	-	-	-	-	-	-	-
Short green filaments	<2cm	-	-	-	-	-	-	-	0.8	-
Long green filaments	>2cm	0.0	-	-	-	-	-	-	0.9	-
Didymo	>3mm	-	0.3	-	-	-	-	-	3.6	3.5
Total algal % cover (incl. Didymo)		**22.9**	**5.7**	**-**	**7.0**	**0.0**	**10.5**	**37.3**	**58.0**	**14.8**

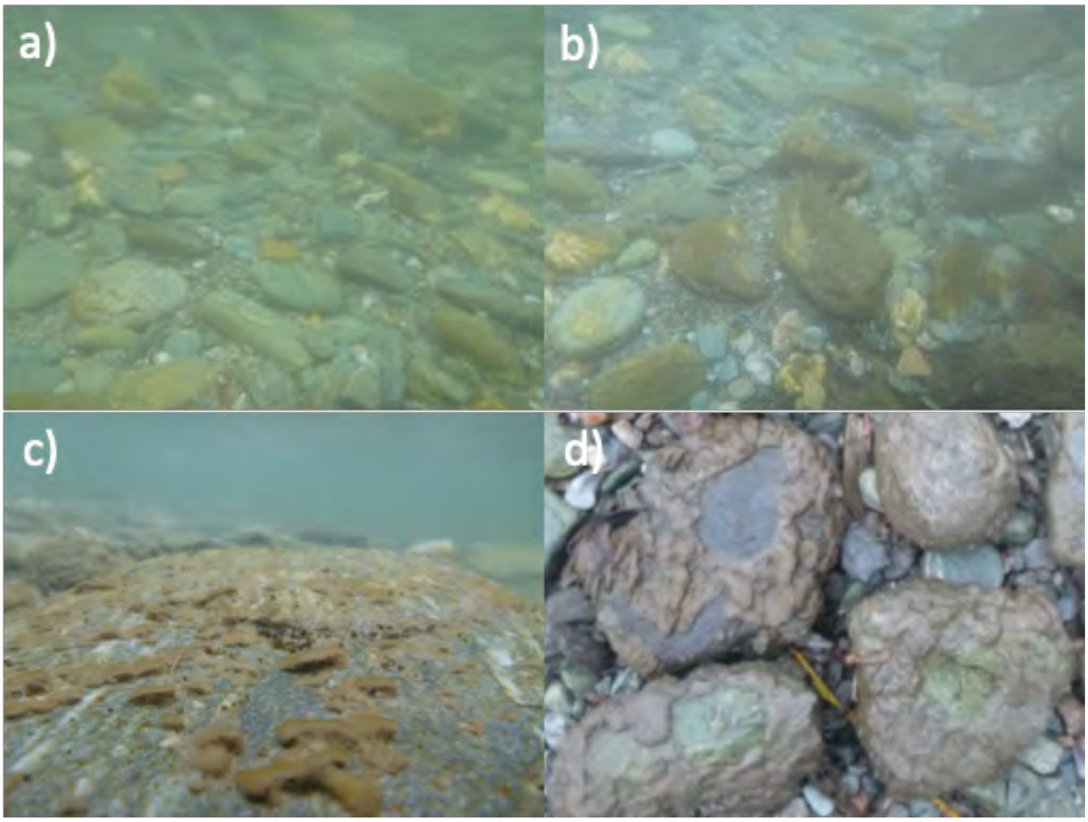

Figure 13 ***Underwater photographs showing different periphyton communities observed in the Arrow River. a) bare gravels with limited thin diatom films at the Morven Ferry Road monitoring site (November 2019), b) thin diatom films at the Morven Ferry Road monitoring site (November 2019), c) medium to thick diatom mats (likely Didymo) along with the colonial cyanobacterium*** **Nostoc** ***at the Arrow Gorge Track monitoring site (November 2019), and d) thick Didymo mats on stones from the Arrow Gorge Track monitoring site (September 2019).***

Biomass

Chlorophyll *a* biomass was low at both sites on all occasions surveyed, with the biomass on all occasions being less than 50 mg/m^2 (Figure 14). The chlorophyll *a* biomass at both sites on all sampling occasions was within the 50 mg/m^2 guideline value for the protection of benthic biodiversity of Biggs (2000) and would place both Arrow River sites in the A-band of the NOF (Table 2).

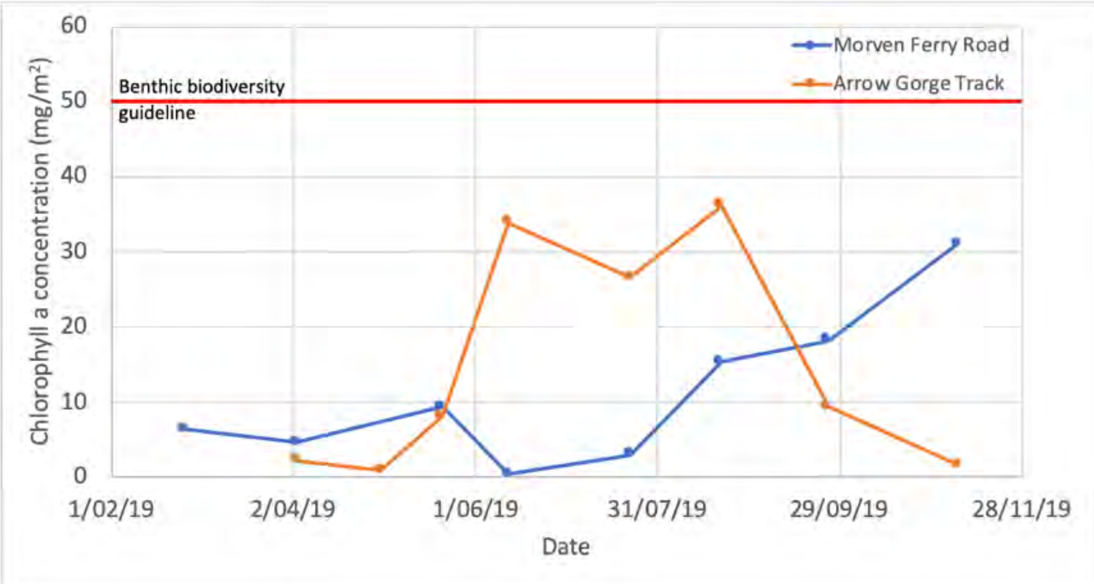

Figure 14 ***Chlorophyll*** **a** ***biomass in the Arrow at the Arrow Gorge Track and Morven Ferry Road biomonitoring sites between February and November 2019. Solid red line indicates the guideline value for the protection of benthic biodiversity and the bottom of the A-band of the NOF (50 mg/m²).***

Instream habitat modelling

Instream habitat modelling for the lower Arrow River provides predictions of how habitat suitability for different periphyton taxa is affected by flow (Figure 15). The optimum habitat suitability for each taxon reflects the tolerances and habitat requirements of that taxon. For example, the predicted decrease for long filamentous algae as flows increase is likely to reflect greater drag on filaments and higher rates of biomass loss resulting from higher water velocities. The taxa ranked according to their optimum flows (from lowest to highest) are: long filamentous algae (0 l/s), short filamentous (500-700 l/s), Didymo (800-1200 l/s), diatoms (1,500-1,700 l/s) (Figure 15). Predicted habitat for cyanobacteria does not show a clear optimum flow and shows little variation between 200 l/s and 1,700 l/s (Figure 15).

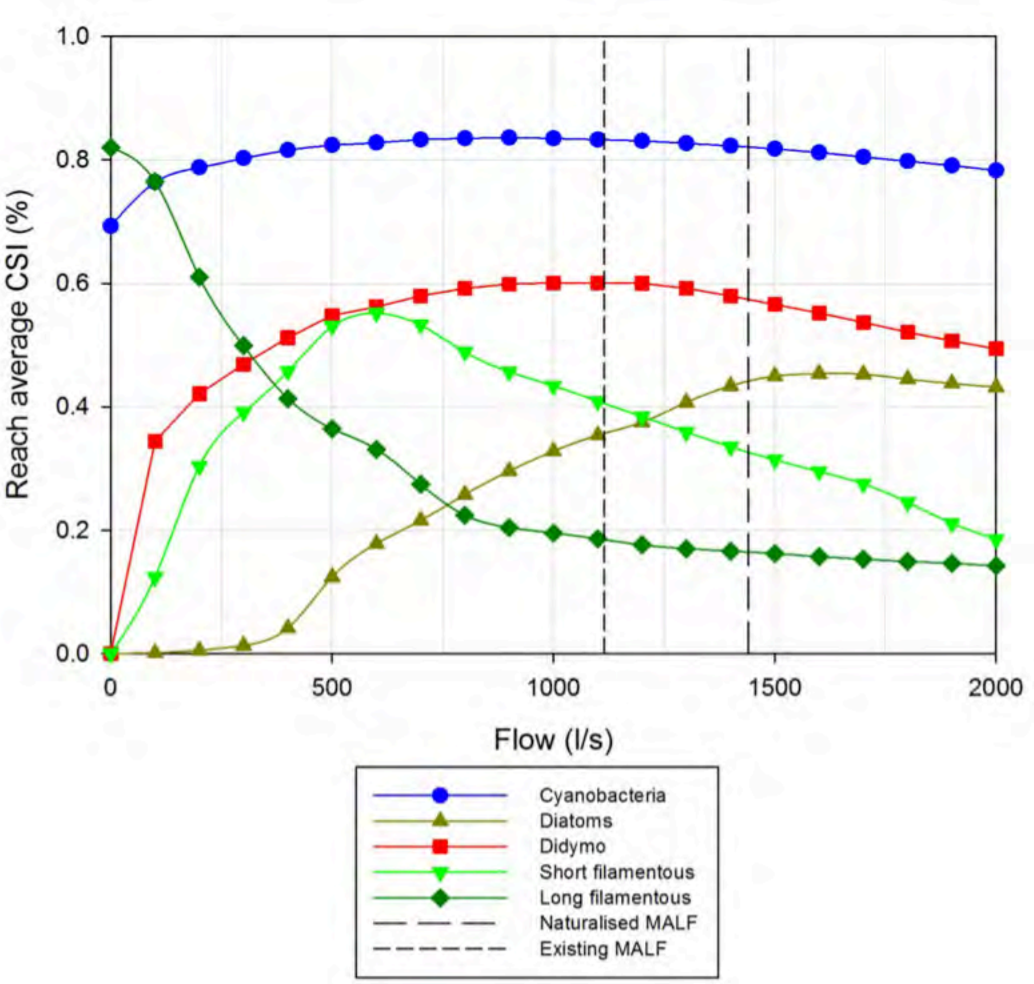

Figure 15 ***Variation in instream habitat quality for periphyton classes relative to flow in the lower Arrow River. (From Olsen*** et al. ***2017).***

5. Discussion

Periphyton forms the slimy coating on the surface of stones and other substrates in freshwaters. It is made up of a number of different types of algae, diatoms, cyanobacteria, bacteria and fungi. Periphyton is an integral part of most stream food webs; it captures energy from the sun and converts it, via photosynthesis, to energy sources available to macroinvertebrates, which feed on it. These, in turn, are fed on by other invertebrates, fish and birds, forming a food-web.

However, periphyton can form nuisance blooms that can detrimentally affect other instream values, such as aesthetics, biodiversity, recreation (swimming and angling), water takes (irrigation, stock/drinking water and industrial) and water quality. For example, some cyanobacteria, including *Phormidium* and *Oscillatoria*, may produce toxins that pose a health risk to humans and animals (MfE & MoH 2009). These include toxins that affect the nervous system (neurotoxins), liver (hepatotoxins) and dermatotoxins that can cause severe irritation of the skin (MfE & MoH 2009). The presence of potentially toxic cyanobacteria can affect the suitability of a waterway for drinking, recreation (swimming), dogs, stock drinking water and food gathering (by affecting palatability or through accumulation of toxins in organs such as the liver) (MfE & MoH 2009).

Controls on periphyton

Hydrological controls

Periphyton biomass at any point in time reflects the balance of two opposing processes: biomass accrual and biomass loss (Biggs 2000). The rate of cell division controls the rate of biomass accrual and is controlled by factors such as the availability of nutrients, light and water temperature (Biggs 2000). Meanwhile, the rate of biomass loss is governed by physical disturbance (substrate instability, water velocity and suspended solids) and grazing (by invertebrates) (Biggs 2000).

Flow variability plays a major role in determining periphyton cover and biomass, as higher flows can lead to a loss of periphyton biomass as a result of high water velocities (shear stresses), scouring by sand particles, and/or bed movement (Biggs 2000).

Flows of three (sometimes less) to seven times the median flow are able to reduce periphyton biomass and diversity, while in a study of many New Zealand rivers, the frequency of flows of more than 3 times the median flow (FRE3) was the flow statistic that was most closely correlated with periphyton data (Clausen & Biggs 1997). This would correspond to flows of approximately 9,200 l/s in the Arrow

River. National hydrological modelling estimates that the FRE3 of the Arrow River at 7.4 events per annum, corresponding to an average period of 49 days between events of at least three times the median flow (Booker & Whitehead 2017). The FRE3 frequency calculated using available hydrological data (30 December 2010-26 August 2019) results in an estimate of 5 FRE3 events per year, corresponding to an average period of 74 days between events of this magnitude.

The effect of high flows on periphyton biomass depends in part on the composition of the periphyton community and the characteristics of the various constituent taxa. During sampling in 2019, the periphyton community in the Arrow River was dominated by diatoms, predominantly as thin films and medium mats. Such low-growing forms of diatoms often dominate the periphyton in steep, swift rivers with low water temperatures and low nutrient availability, all of which are characteristics of the Arrow River.

Rules-of-thumbs to estimate the magnitude of flushing flows required to reduce periphyton biomass (such as three-times the median flow), are useful as general guides to understanding the effects of high flows on periphyton dynamics. However, the magnitude of flows required to reduce periphyton biomass will depend on a range of site- and catchment-specific factors, such as the gradient of the river channel, the size of the substrate, the degree of bed armouring, and the size and quantity of fine sediments.

Fine sediments remove periphyton by scouring or abrasion (sand-blasting) as they are transported downstream by entrainment (suspended in the water column) or saltation (bouncing along the bed). There is a substantial quantity of fine sediment in the Arrow River, which may mean that flows of less than 3 times the median flow are required to reduce periphyton biomass.

Following disturbance events (e.g. flood), periphyton goes through an accrual phase, starting when it colonises the substrate, followed by exponential growth until resource limitation begins and peak biomass is reached (Figure 16). After peak biomass is reached, a period of biomass loss is expected as a result of autogenic sloughing, i.e. the detachment of the mat from the substrate resulting from internal processes. These processes include senescence of cells deep within the mat, their heterotrophic degradation and production of respiratory gas bubbles within the mat, leading to detachment and floatation of the mat (Boulêtreau *et al*. 2006).

The average accrual period over the 8.65 years of hydrological record for the Arrow River was 72 days and the mean annual maximum accrual period was 161 days. Many of these accrual periods span the irrigation season (October-April).

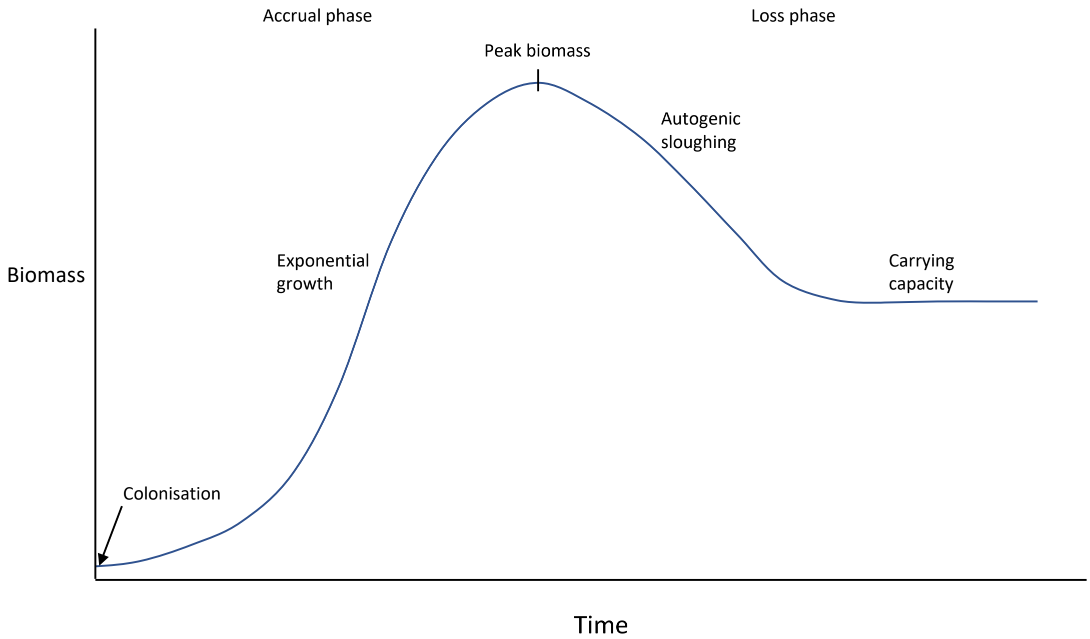

Figure 16 ***Idealised accrual/loss cycle following disturbance. Based on Biggs (1996)***

Other factors affecting periphyton

Other factors known to affect periphyton cover and biomass include water quality (nutrient availability, water clarity), physical factors (substrate type, presence of fine sediments) and biological factors (e.g. invertebrate grazing, presence of trout).

Studies in Otago streams have shown that the presence of trout can affect periphyton biomass by reducing the density of grazing invertebrates, reducing grazing pressure on periphyton communities, thereby increasing the standing crop (biomass) of periphyton in comparison to streams dominated by galaxiids (Biggs *et al.* 2000). It is expected that the difference in grazing pressure from invertebrate grazers will affect the growth form of periphyton, with taxa with erect or filamentous growth forms more prone to grazing than prostrate taxa. Therefore, the presence of trout in a stream system has the potential to affect the biomass, cover and composition of the periphyton community.

Effects of water management

Water allocation

The level of allocation from the Arrow catchment (~1,580 l/s; Olsen *et al.* 2017) is not expected to affect the frequency of high-flow events that are large enough to substantially reduce periphyton biomass. This is particularly the case when considering that the actual take from the Arrow River is typically less than 35% of the consented rate (e.g. Figures 3.5 & 3.6 of Olsen *et al.* 2017) and high flow events are usually associated with rainfall events that will reduce irrigation requirements.

Given that water abstraction is not expected to affect the frequency of disturbance events, the response of periphyton communities is expected to be driven by the rate of accrual, the physical preferences of individual periphyton types and processes governing autogenic sloughing. These factors are considered in the Minimum Flow Section below. However, the level of allocation affects the rate of recession from high flows, which may then affect the duration of low flows.

Minimum flow/residual flow

Instream habitat modelling provides a basis for assessing the potential effects of minimum flows in the Arrow River on periphyton communities. This analysis suggests that a minimum flow in excess of 800 l/s, flow is likely to have little effect on periphyton composition, with little change in habitat quality for cyanobacteria, Didymo and long filamentous algae. However, habitat quality for diatoms is predicted to decline, and habitat quality for short filamentous algae is predicted to increase as flows decline below 800 l/s.

The accrual rate of long filamentous algae is typically favoured by stable low flows, as increasing water velocities result in greater drag on filaments and higher rates of biomass loss as a result of filaments snapping or detaching. This is consistent with the results of instream habitat modelling that habitat quality for long filamentous algae was predicted to increase as flows decline below 800 l/s, with habitat quality for long filamentous algae predicted to peak at zero flow.

In comparison, the optimal flow for diatom communities is higher, reflecting greater tolerance to high water velocities, with diatoms predicted to reduce at flows below 800 l/s. Short filamentous algae and Didymo are expected to decrease as flows reduce below 500 l/s.

The predictions of instream habitat modelling are expected to represent the periphyton composition that may develop over periods of low flows. However, a range of factors may influence how the composition of the periphyton community develops.

Monitoring of periphyton cover and biomass over the summer months in 2019 suggests that the existing (status quo) flows result in a low-biomass periphyton community dominated by thin films and medium mats of diatoms. The accrual period in this monitoring period reached 126 days, yet chlorophyll *a* biomass at both monitoring sites remained very low (<10 mg/m^2) and periphyton cover remained low. The lowest mean daily flow recorded over this period was 1,422 l/s.

Water quality

Nutrient concentrations in the Arrow River are low based on available water quality data, with ammoniacal nitrogen and dissolved reactive phosphorus well within the limits in the RPW (Schedule 15) and NPSFM. The limited water quality data available suggests that concentrations of nitrate-nitrite nitrogen exceed the RPW limit (0.075 mg/l), but that dissolved inorganic nitrogen (DIN) concentrations are within the A-band of the NPSFM.

The low concentrations of nutrients in the Arrow River are likely to reduce the accrual rate of some taxa and are likely to reduce the general risk of proliferation of filamentous algae, although filamentous taxa may be abundant in areas receiving inputs of nutrient-enriched groundwater.

Some periphyton taxa (e.g. the cyanobacterium *Phormidium* and Didymo) are adapted to low-nutrient environments. For instance, Didymo prefers low-phosphorus environments (<2 ppb, or <0.002 mg/L; Bothwell *et al.* 2014), while *Phormidium* mats capture fine sediments from the water column and release phosphorus from them (Wood *et al.* 2014), which may give this taxon a competitive advantage in low nutrient environments. Therefore, while the low nutrient concentrations in the Arrow River will reduce the rate of accrual of periphyton, not all taxa will be limited.

Available periphyton monitoring data suggests that the Arrow River supports a low-biomass periphyton community dominated by thin films and medium mats of diatoms under the existing flow regime and water quality. This is expected to continue under a flow regime with a similar or reduced level of allocation and environmental flows (minimum or residual flows).

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Appendix A. Longitudinal photographs

Arrow Junction - upstream


15/2/19


22/2/19


22/3/19

Arrow Junction - riffle


22/3/19

Arrow Junction - downstream


15/2/19


15/3/19

Tobins Track - downstream


22/3/19


29/3/19

Cornwall Street - upstream


15/2/19


22/2/19


15/3/19


22/3/19

Bush Creek confluence - upstream


15/2/19


22/2/19


15/3/19


29/3/19

Bush Creek confluence - downstream


15/2/19


22/2/19


22/3/19


29/3/19