Int. Revue ges. Hydrobiol.	71	1986	4	511–544

CLIVE HOWARD-WILLIAMS, CONNIE L. VINCENT, PAUL A. BROADY and WARWICK F. VINCENT

Taupo Research Laboratory, DSIR, Taupo, New Zealand, and School of Botany, University of Melbourne, Australia

Antarctic Stream Ecosystems: Variability in Environmental Properties and Algal Community Structure

key words: Antarctic streams, epilithic algae, nutrients, hydrology, glacier melt

Abstract

The variability in physical, chemical and biological properties was examined for a number of glacier melt streams in south Victoria Land, Antarctica. Streams flowed for between one and two months. Stream water temperatures (range = 0–11 °C) varied over short (hr) time scales whilst discharges varied considerably between streams (range 0.001–15 $m^3 s^{-1}$) and over diel cycles. Solar radiation and air temperature were major determinants of stream discharge. Variability in discharge was reflected in variability in nutrient chemistry and sediment load. Nitrogen and phosphorus varied considerably between streams; the meltwaters early in summer contained 10–20 times higher levels of dissolved N and P than later in the season. Within stream nutrient levels were modified by dense algal growths and penguin rookeries. Epilithic algal communities were made up predominantly of cyanophyceae which formed mats and crusts. Longitudinal and horizontal variability of species in the communities in selected streams is described. Analyses of algal cover and biomass (chlorophyll *a*) show that substrate type and flow rates are of greater importance than nutrients in influencing algal abundance and biomass. In some streams biomass values of over 20 μg Ch. *a* cm^{-2} were recorded, much of which remains viable but inactive over the antarctic winter.

Contents

1. Introduction

Stream ecosystems are a seasonal feature of Antarctica. More than 95 percent of the continent is covered by thick ice, with air temperatures rarely above freezing. Yet for a few weeks each summer small seeps, streams and rivers flow within various regions near the coast. Flowing waters are particularly abundant in the vicinity of McMurdo Sound (Fig. 1, ca. 77 °S 165 °E). More than one hundred streams flow from coastal icesheets to the sea, or inland from alpine and piedmont glaciers located in the "Dry Valleys", a 10000 km^2 area containing deep valleys largely free of snow and ice. All of the streams lie within catchments devoid of plants more advanced than mosses, and are exposed to extremes of cold (to −55 °C in winter) and aridity (annual precipitation less than 7 cm in the Dry Valleys).

Many of the streambeds are coated with thick epilithic mats and films. These are dominated by algae, with associated bacteria, fungi and microherbivores (protozoa, rotifers, nematodes, tardigrades) which must survive a highly erratic flow regime, wide variations in temperature and nutrient content, rapid freezing and thawing and a brief growing season. Allochthonous inputs to these waters from the sparse microbial communities in the catchment are probably small, although considerable material can enter from the source glacier (Downes *et al.* in press). Unlike many temperate streamwaters (e.g. Fisher and Likens 1973) the upstream origin of nutrients is a clearly defined source, and within-stream, rather than catchment processes dominate the subsequent transfer of mass and energy.

Until recently these streams have been a neglected aspect of biological studies in Antarctica (Parker 1981, Vincent and Vincent in press). A detailed sequence of hydrological measurements is available for the largest Antarctic flowing water, the Onyx River (Chinn 1974, Chinn 1981) and notes on hydrological changes in smaller streams are given in Heywood (1977), Hoehn *et al.* (1977) and Weand *et al.* (1977). Geochemical attributes of Dry Valley streams and their influence on the chemistry of inland lakes have been examined (Torii *et al.* 1971, Hoehn *et al.* 1977, Canfield and Green 1983, Weand *et al.* 1977). Published biological work has centered on the taxonomy of certain algal communities (Broady 1981, 1982, Hirano 1979, 1983, Seaburg *et al.* 1979) and photosynthetic rates of two types of epilithic community are documented in Vincent and Howard-Williams (1986).

Antarctic streams form unusual ecosystems but there have been no previous attempts to make a combined study of their communities and environmental properties. In the present study we examined the physical, chemical and biological characteristics of a diverse range of streams in southern Victoria Land in order to compare their basic ecosystem attributes with lotic systems elsewhere.

2. The Study Sites

During the summers of 1983/84 and 1984/85 we sampled 24 streams in the McMurdo Sound area of southern Victoria Land (Fig. 1). Most were situated in the Dry Valleys on the Antarctic mainland and two were on volcanic Ross Island. Five contrasting

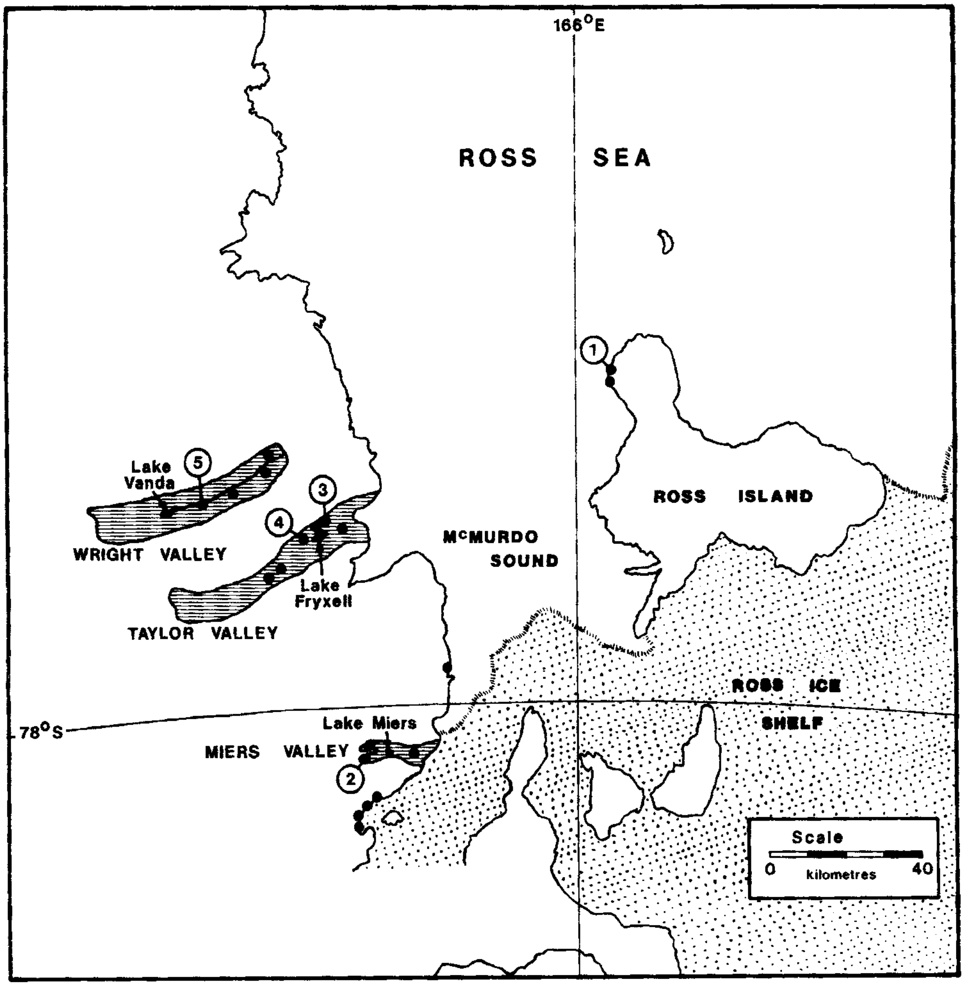

Figure 1. Map of the McMurdo Sound region of southern Victoria Land showing location of study sites. 1. Northern Rookery Stream, 2. Adams Stream, 3. Whangamata Stream, 4. Fryxell Stream, 5. Onyx River. Points with no numbers indicate streams which have been sampled but not studied in detail

streams were chosen for detailed study. These were: Northern Rookery Stream (Cape Bird); Adams Stream (Miers Valley); Whangamata Stream (Taylor Valley); Fryxell Stream (Taylor Valley); Onyx River (Wright Valley). General characteristics of these streams are given in Table 1 and Fig. 2.

Table 1. General characteristics of the principal study streams in the McMurdo Sound region of Victoria Land. See Fig. 1 for location map.

Feature	Stream					
	Northern Rookery	Adams	Whanga-mata	Fryxell	Onyx upper section	Onyx main section
Location	Cape Bird	Miers Valley	Taylor Valley	Taylor Valley	Wright Valley	Wright Valley
Reference (deg. min)	77.13 S 166.25 E	78.08 S 163.53 E	77.35 S 163.15 E	77.37 S 163.02 E	77.24 S 162.50 E	77.30 S 162.15 E
Source glacier	Mt Bird Ice Sheet	Adams	Common-wealth	Canada	Lower Wright	Lower Wright
Sink	Ross sea	Lake Miers	Lake Fryxell	Lake Fryxell	Lake Brownworth	Lake Vanda
Length (km)	1	2.7	5.6	2.0	4.8	30
Altitude (m) max	ca. 100	360	300	100	300	277
min	0	240	16	16	277	84
Mean slope ($m \cdot m^{-1}$)	~0.1	0.044	0.051	0.080	0.005	0.006
Comparative midseason flows:***						
Date	18. 1. 84	12. 1. 84	8. 1. 84	3. 1. 84	28. 12. 84	28. 12. 84
Time (h)	15.00	15.40	20.00	15.00	14.00	14.00
Stream width (m)	2.6	3.5	3.0	3.0	–	5.0*
Stream depth (cm)	9.0	10.4	7.8	5.0	–	25.0*
Discharge $m^3 s^{-1}$	0.151	0.152	0.093	0.061	0.426**	1.1 #

– =not measured
* Data from Bull pass
\# Data from Vanda Wier
** Data from L. Brownworth exit
*** Daily maximum

2.1. Northern Rookery Stream

This stream is situated near the northern end of the Cape Bird ice free area. It starts along the Mt Bird Ice Sheet (Fig. 2) and falls some 100–110 m ultimately discharging into the Ross Sea. The stream falls sharply down steep unstable moraines into a valley where it cuts through moraine and nutrient rich ornithogenic soils (Speir and Cowling 1984) created by a large (40000 nests) Adelie penguin rookery (Fig. 3). This stream, like others in the area which flow over steep unstable slopes, has a high suspended particle load giving it a grey appearance.

2.2. Adams Stream

The stream, 2.7 km long, originates along the edges of the Adams glacier 350 m above sea level and discharges into Lake Miers (Fig. 2) in the Miers Valley. The stream divides about midway down its full reach with part flowing down an extensive algal rich wash area which connects with the Miers stream; the bulk (>70 %) continues over a gravel bed in a well defined 7 m wide channel to site A3 (Fig. 4). In the final 1 km the stream descends over a series of steps with stony riffles between,

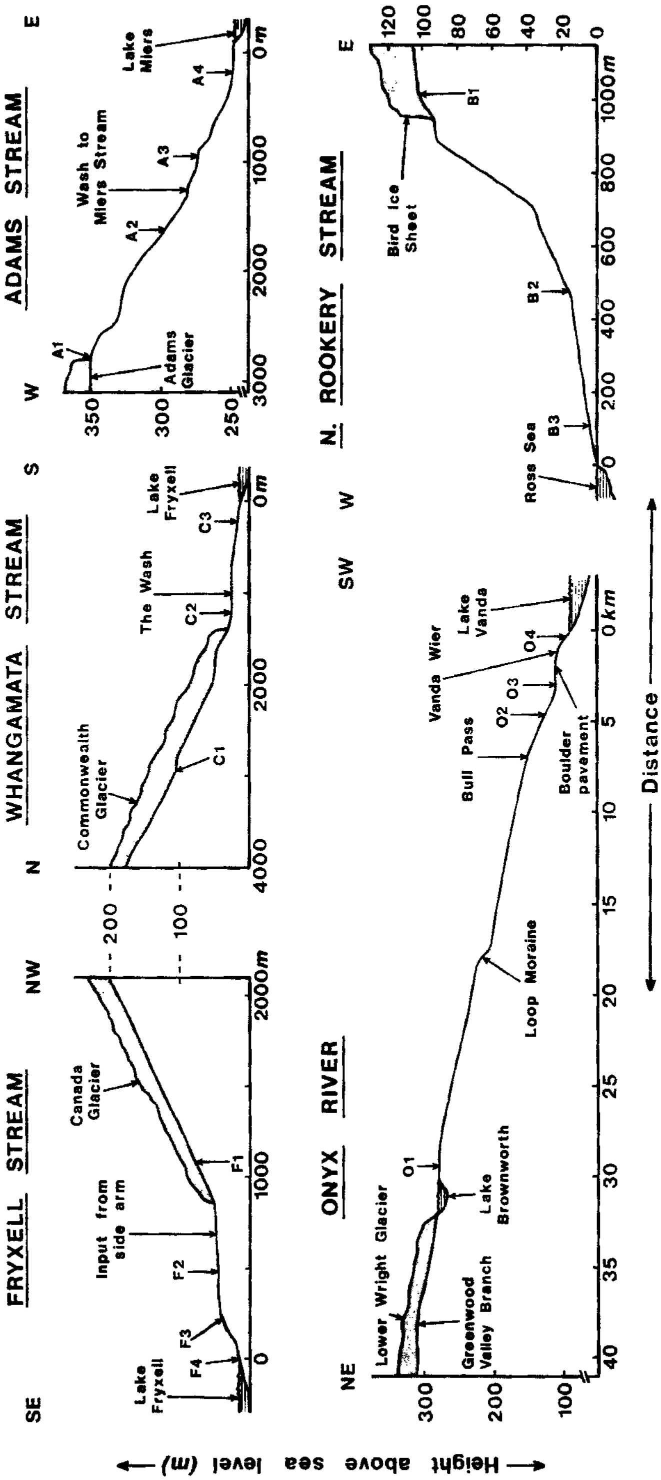

Figure 2. Profile diagrams of five contrasting streams with study sites mentioned in the text.

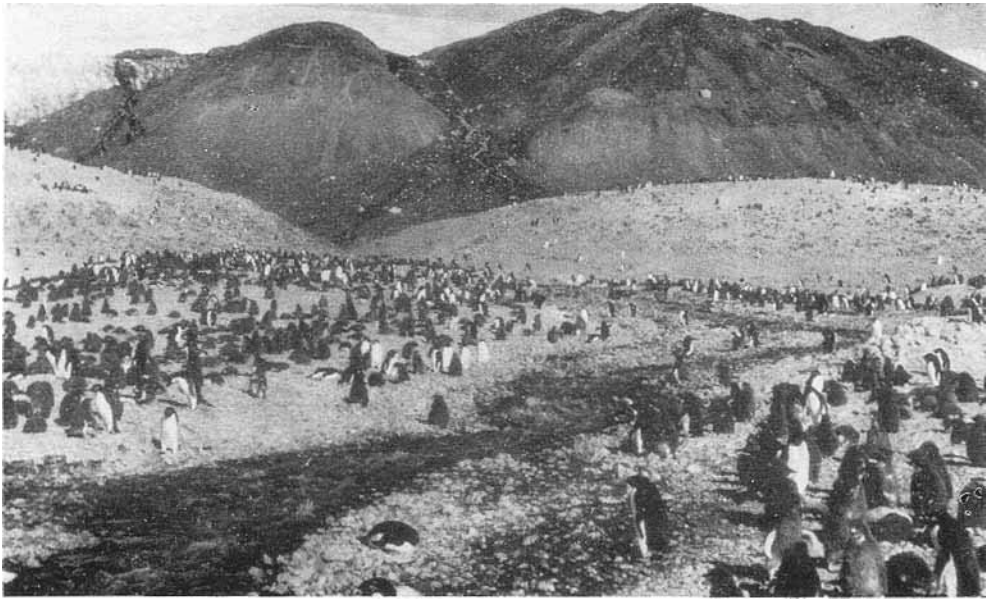

Figure 3. Northern Rookery Stream. The source is the Mt Bird Ice sheet (left rear) after which the stream falls through loose moraines before flowing through the Adelie Penguin Rookery in the foreground, and then into the Ross Sea.

Figure 4. Adams Stream, Miers Valley. The stream originates at the Adams Glacier and discharges into Lake Miers.

Figure 5. Onyx River, Wright Valley in November near site O2 before first flow. The stream bed is dry for *ca.* 10 months of the year.

Figure 6. Onyx River, Wright Valley in late December near site O2. Discharge at this time was 1.3 m^3s^{-1}.

to an alluvial fan on the edge of Lake Miers where site A4 was located. The stream bed on these steps is a firm pavement of pebbles and gravel, whilst the alluvial fan is comprised of loose gravel. The stream water remained clear throughout its length.

2.3. Whangamata Stream (unofficial name)

This stream (5.6 km long) starts about 180 m above the level of Lake Fryxell along the west side of the Commonwealth glacier. For the first 1 km of its length the gradient is steep with icefalls from the glacier which form small dams in places. The stream channel here runs along the foot of the glacier on old lacustrine sediments between large (<1 m diam.) boulders. For the next 1 km downstream the gradient is reduced slightly to a point where the stream leaves the glacier foot, cuts through loose moraine and flows across a flat sandy alluvial fan ("the wash", Fig. 2). The gradient then increases slightly, and the final 800 m of stream leads over rocks and gravel. The stream water was characterised by a turbid appearance during peak flows each day.

2.4. Fryxell Stream

The main stream (2 km long) starts along the east side of the Canada glacier some 200 m above the level of Lake Fryxell. The stream rapidly increases in size along the first km as numerous ice streams contribute from various portions of the glacier. This upper 1 km is steep and the stream flows over rocks and boulders. At site F1 (Fig. 2) the gradient decreases as the channel flows away from the glacier. Considerable algal growth was evident at this point. A small flow from a moss "flush" area and a large pond on the right bank join the stream some 500 m below site F1. From here the stream forms a 500 m stretch of gravels and stones with a dense algal cover. A steep 200 m bouldery section follows (Fig. 2) and at its lower reaches on the edge of L. Fryxell the stream spreads out across a dense *Nostoc* community growing as thick mats on a sandy substrate. We measured discharges of 0.06 m^3s^{-1} (Table 1) and the stream water was always clear.

2.5. Onyx River

This river, the largest in Antarctica can be conveniently divided into two sections, the Upper Onyx (4.8 km) and the Main Onyx (30 km). Upper Onyx: This starts at the junction of the Greenwood and Wright Valleys ca. 300 m above sea level and receives water from the Greenwood and Lower Wright Glaciers. Its flow along the foot of the Lower Wright Glacier increases steadily until it leaves the glacier face in an alluvial sandy plain leading to Lake Brownworth, 277 m above sea level (Fig. 2). Ice falls from the 30 m high glacier face have resulted in dams along the river in which the only algal mats in this stretch were seen. Flows continue around the ice moat on the northern side of Lake Brownworth to the exit from the lake where the Main Onyx begins. Chinn (1981) estimated that 86 % of the Main Onyx flow originated from the Upper Onyx.

Main Onyx: This section of the river falls 190 m over the 30 km reach from Lake Brownworth to Lake Vanda. In the upper 1.5 km stretch, the river flows over a stable stony bed (gradient 0.0037 $m \cdot m^{-1}$) with a series of shallow depressions rich in algal material. The river then increases in slope (gradient 0.0075 $m \cdot m^{-1}$) with an unstable bed as it cuts through the Trilogy Moraine complex, and receives intermittent inputs from the Clark and Denton streams. In places, sparse algal communities could be seen on rocks on the submerged sides of the river. From 6–13 km below Lake Brownworth the river meanders forming braided channels through a series of alluvial fans (gradient 0.0020 m · m^{-1}). Little algal material was visible here, but it occurred on the rocks where the stream breaches the large Loop Moraine at ca. 14 km down (Fig. 2). From here to 4 km upstream from Lake Vanda (gradient 0.0040 m · m^{-1}) the river meanders through sandy braided channels (Site O2, Figures 5, 6). At this point it enters a wide (800 m across) flat "boulder pavement" which contains abundant algal mats. The river channel in this region disappears into a network of small interconnecting flows between the flat boulders. Below this the slope steepens, and the flows coalesce into a few distinct channels which enter a large ponded area called Lake Bull. The final slope from Lake Bull to Lake Vanda is steep (gradient 0.0395 m · m^{-1}) and the streambed comprises large boulders, with crusts and films of algae. In addition to the four sites shown on Fig. 2 we also examined algal community structure at the seven sites described in SHAW and HEALY (1980) which form a useful set of reference points down the stream.

The complex river morphology on the Onyx is discussed by SHAW and HEALY (1980) and the hydrology by CHINN (1974, 1981). Flows of up to 15 m^3 s^{-1} have been recorded but the flow is highly variable from year to year.

3. Methods

3.1. Stream discharges

Discharge in the Onyx River was measured at Vanda weir by the New Zealand Ministry of Works and Development (see CHINN 1981). For other streams, discharges were estimated from stream velocities obtained with a pygmy current meter, or, in some reaches where this was not feasible, by using a neutrally buoyant float with appropriate corrections (JOHN 1978). In both cases measurements were made in straight reaches where we had previously obtained cross-sectional areas.

3.2. Water and ice samples

Water samples were collected in acid-washed polythene bottles, and ice samples in polythene beakers. The latter were melted upon return to the field camps by placing the beakers in trays of warm water. All samples were filtered within a few hours of collection (Whatman GF/C filter paper). They were kept frozen during storage and the subsequent transport to the laboratory in New Zealand.

All water analyses were carried out on a Technicon II auto-analyser system. Dissolved reactive phosphorus (DRP) was measured by the method of DOWNES (1978a). Total dissolved phosphorus (TDP) was measured as DRP after UV oxidation. Analysis of NH_4-N was determined by the CROOKE and SIMPSON (1971) method modified for auto-analysis. NO_3-N was measured by the hydrazine reduction method of DOWNES (1978b). Total dissolved nitrogen (TDN) and dissolved organic nitrogen (DON) were determined after UV oxidation to nitrate. Further details are given in HOWARD-WILLIAMS *et al.* (1983). Detection limits with these analytical procedures were as follows: 0.2 mg DRP m^{-3}, 0.4 mg NO_3-N m^{-3}, 0.5 mg NH_4-N m^{-3}, 1.0 mg TDP m^{-3}, 1.0 mg TDN m^{-3}.

Suspended sediment samples were filtered onto preweighed precombusted GF/C filters which were then oven dried at 70 °C and reweighed.

3.3. Algal samples

Algal material occurred in the form of crusts, mats and filamentous colonies. Early in the season, before first stream flows, these were still frozen and attached to the empty stream bed surfaces. Because of the problems of extreme patchiness of the algal communities and logistic limitations on the numbers of samples we adopted the following sampling protocol. In a series of selected 3 m reaches of each stream we collected six replicate samples each of 28 cm^2 area from patches where we visually estimated that the algal community had reached maximum biomass. Three samples were taken from the middle and three from the stream edge at each reach. The data we report are therefore the maximum levels of biomass found in these streams. Collections were made before first flows (i. e. overwintering biomass) and again during the middle of the flow period when the algae had developed after a few weeks of contact with flowing water. Samples were stored frozen. Analysis for chlorophyll *a* was carried out spectrophotometrically following extraction for 24 h in cold dimethyl sulphoxide (SHOAF and LIUM 1976). Algal samples for taxonomic work were preserved with 2 % glutaraldehyde solution.

3.4. *Algal community cover*

At selected reaches of each stream percent cover of algal material was analysed by the point quadrat method (GREIG-SMITH 1964). At each site points were taken at 10 cm intervals in a series of transects from bank to bank until at least 300 points were analysed. At each point algal presence or absence was noted, as was a substratum size grading in three classes: <5 mm, 5 mm–25 mm, >25 mm. Confidence limits on these cover estimates were calculated from the binomial distribution (GREIG-SMITH 1964).

4. Results

4.1. *Solar radiation and air temperatures*

Solar radiation and air temperatures are the most important features which influence water flows and thereby algal growth in these streams. During mid-late

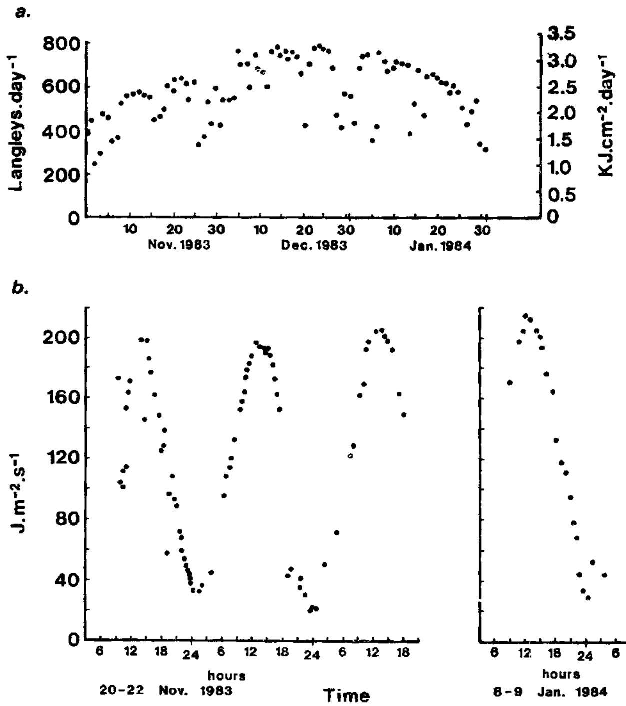

Figure 7*a*. Daily total solar radiation over the 1983–1984 summer at Lake Vanda. Values as kJ cm^{-2} day^{-1}. Data from NZ Meteorological Service.

b. Instantaneous records of photosynthetically active radiation (400–700 nm) from site C2 in the Taylor Valley over selected days.

December, the period of maximum solar radiation (Fig. 7a) values approached 3.5 kJ cm^{-2} day^{-1} (800 cal cm^{-2} day^{-1}) whereas one month on each side of this period values were only 2.0 kJ cm^{-2} day^{-1}.

Of significance for the stream plant communities in the antarctic summer environment is the continuous solar radiation over 24 h. Instantaneous records of photosynthetically active radiation in the wave band 400–700 nm from site C2 in the Taylor Valley show values ranging from 200–220 J m^{-2} s^{-1} (930–1000 μE m^{-2} s^{-1}) at ca. 14.00^h, to only one order of magnitude less at 01.00^h. Thus, in spite of high latitude, abundant solar radiation occurs for plant growth in summer.

Air temperatures (Fig. 8) over the study period of two contrasting sites in the

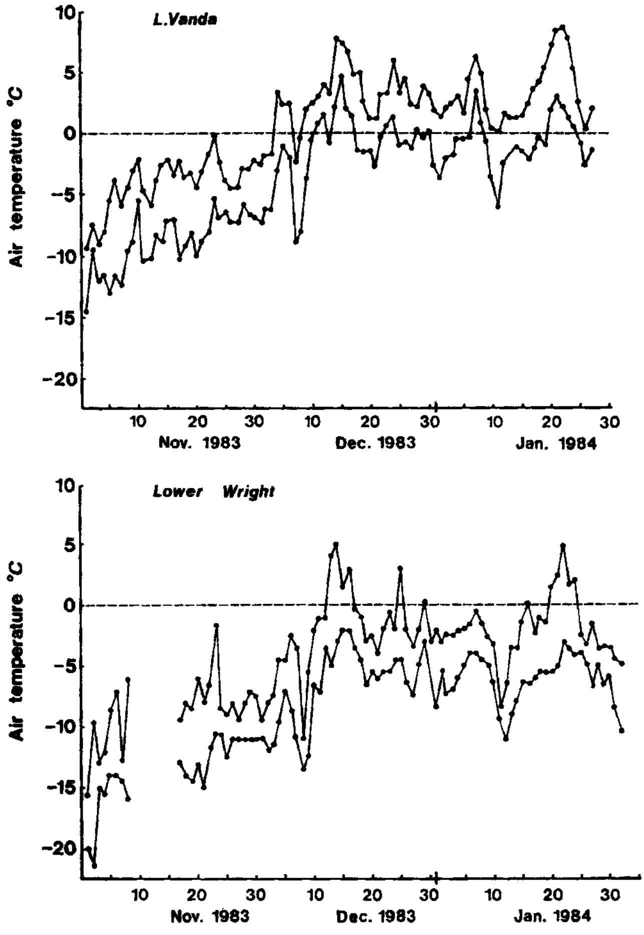

Figure 8. Daily maximum and minimum air temperatures for Lake Vanda (lower reaches of the Onyx River) and Lower Wright Glacier (upper reaches of the Onyx River) for the period Nov. 1, 1983 to Jan. 31, 1984. Data from NZ Meteorological Service.

Wright Valley (site O1 and Lake Vanda) rose rapidly through November from daily maxima of ca. −20 °C to above freezing from mid December to late January. At Vanda station, one of the warmest study locations examined, the air temperature on some days never fell below 0 °C and reached a maximum of +8 °C, while at site O1 at the top of the Onyx River some 30 km away, daily maximum temperatures rose above freezing on only 10 days. Two warm spells of several days' duration can be identified; 12–16 December 1983 and 19–24 December 1984 (Fig. 8). These had a significant effect on stream flow as will be seen in section 4.3.

4.2. *Stream temperatures*

Diel changes in stream water temperature were marked, with streams freezing to a variable extent from ca. 01.00^h to ca. 07.00^h and reaching maximum temperatures at 14.–16.00^h. The great sensitivity of stream temperature to ambient insolation can be illustrated by the Adams Stream (Fig. 9a) where a rapid drop in tempera-

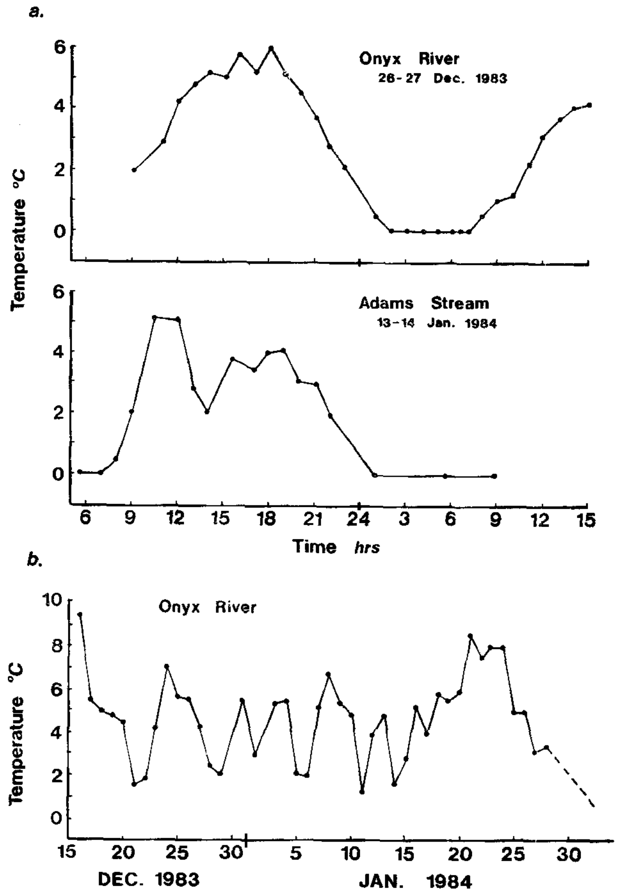

Figure 9*a*. Diel variation in stream water temperature for two antarctic streams during mid-summer: Onyx River at site O2, Adams Stream at site A3.
b. Seasonal variation in stream temperature at 1400 h each day in the Onyx River at Vanda Weir.

ture from 5.2 to 2.0 °C occurred in the space of two hours at midday when clouds appeared, and incoming total solar radiation dropped from 552 J m^{-2}s^{-1} to 177 J m^{-2}s^{-1}. At 14.00^h the sky cleared, solar radiation rose to 454 J m^{-2}s^{-1} and water temperatures rapidly rose again to 4 °C.

There was considerable variability in the maximum temperature values recorded for the streams. The warmest temperatures were recorded in Fryxell (max. 9.5 °C) and at site C2 in the Whanganata (max. 11.0 °C) streams. Even the relatively fast flowing Onyx attained 8.5 °C at the lower reaches. However, the maximum recorded in the Adams Stream was 5.2 °C and in Northern Rookery stream was 3.8 °C.

Water temperatures at 14.00^h (daily maxima) were obtained for the Onyx River at Vanda weir for the period of flow (Fig. 9b). Temperatures on the first day of flow (16 December 1983) reached 9.5° and on 21 January 1984 8.5 °C. These corresponded with the periods of warm air temperatures (Fig. 8).

4.3. Stream discharges

Most of the streams began to flow in early to mid-December 1983 and by late January 1984 were starting to freeze permanently. However, there were major differences in flows between streams (Table 2), and variations at seasonal and diel time scales within streams.

From the long-term records of CHINN (1981) we can distinguish the following "typical" pattern of flow in the Onyx River: an initial slow flow at the beginning of the season followed by an increase in flow to mid-January and then a decrease to February when flow stops. Overlying this pattern are a series of conspicuous flow events associated with warmer weather periods, and superimposed on this pattern is a marked diel change in flow. Flows in some seasons are stronger than others.

The seasonal hydrograph for the lower reaches of the Onyx River during our study (Fig. 10) show high discharges associated with the two spells of warm weather. One of these coincided with the period of first flow on the Onyx River when the largest discharges yet recorded (ca. 15 m^3 s^{-1}) occurred.

Fig. 11 shows a series of diel studies on discharge for several of the streams in mid-January and for early December for the Northern Rookery stream.

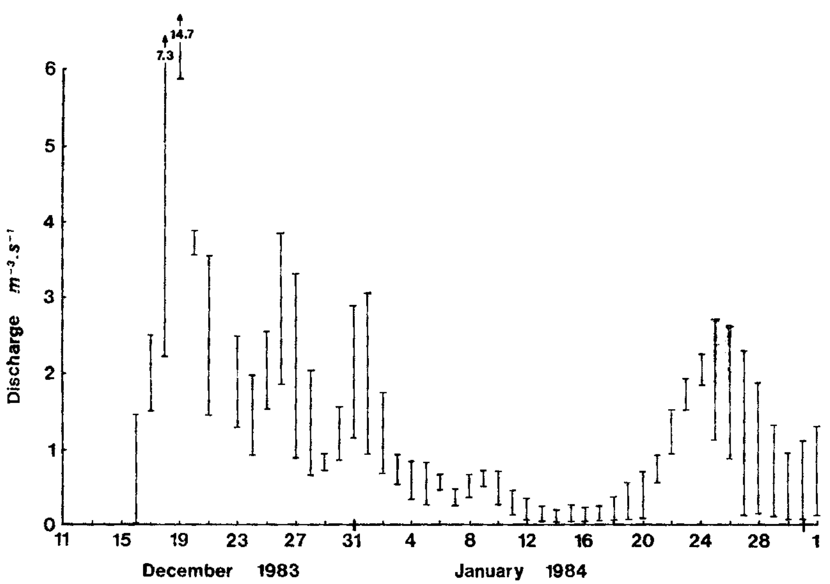

Figure 10. Maximum and minimum daily discharges for the Onyx River at Vanda Weir, just above site O4, Dec. 1983–Feb. 1984. Data from CHINN and ROBERTSON 1985.

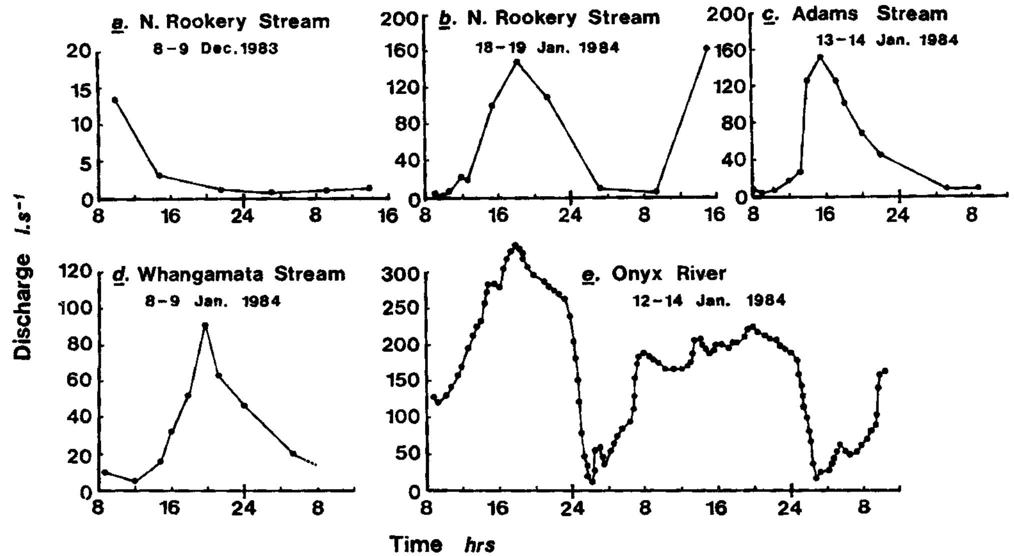

Figure 11. Diel changes in discharge in Antarctic streams. Data are from mid-January for all streams and early December as well for Northern Rookery Stream. Onyx data from CHINN and ROBERTSON 1985. Data are from sites B2, A3, C2 and Vanda Weir.

Early in the season, when flows are typically low in the small streams, no marked diel pattern was evident (Fig. 11a). During this period stream flows were greatly influenced by slight weather changes at any time. Later in the season diel periodicity dominated the flow pattern (Fig. 11b) although weather conditions sometimes altered stream temperatures (Fig. 9a).

In Northern Rookery, Adams and Onyx streams, minimum flows occurred at about 14.00^h, and maximum flows at 16.00–18.00^h, shortly after minimum and maximum water temperatures. CHINN (1981) reported on the rapid changes in flow in the Onyx between 24.00^h and 05.00^h which are probably typical for most Victoria Land streams. The stream surface iced over in the early hours of morning (e.g. Fig. 9a), and flows dropped sharply. The ice formed into small "arc terraces" which blocked the stream particularly in the boulder pavement area (Fig. 2). With the appearance of the sun from behind the ranges, the ice melted and dispersed. The release of ponded water caused a rapid rise in discharge which then settled to a steady flow.

Aspect and slope are, however, critical in determining the daily discharge pattern. If the slope is too steep, this damming effect is small and flows will gradually decline as ice becomes thicker (e.g. Adams stream). The importance of aspect can be seen by a comparison (Fig. 11) of the diel variations in the Adams stream (glacier face oriented east to north) with the Whangamata (glacier face oriented west to south). Discharge in the Adams began to rise at 12.00^h once the sun had reached its northern zenith. By 16.00^h, with the sun in the west, the flows from the glacier face began to drop and by 20.00^h the stream began to freeze. In contrast the discharge from the Whangamata began to rise only at 14.00^h when the sun was in the west and maximum discharge was reached at 20.00 with the sun southwest and shining directly on the glacier face. After this the sun moved below the tops of the Kukri Hills and flow stopped as the stream froze over.

4.4. Nutrients in glaciers and streams

4.4.1. Nutrient levels in glacier ice

Glacier ice is a complex mixture of ground-up rock material, wind-blown sand and silts, solid and dissolved salts, and frozen water. The chemistry of the ice reflects the long term changes in local snow precipitation which includes wind blown particulates, nitrates derived from atmospheric oxidative processes, marine-derived salts, and, in the region of Mt Erebus, volcanic inputs. The powdered granular rock material in the glaciers reflects the geology of the area through which they move. Sampling of glacier faces to determine the origin of meltwater for the streams poses problems as often the face is clearly made up of ice layers, each with different chemical properties. A large proportion of the runoff originates from the top surface of the glacier, where nutrients in local precipitation would constitute a considerable proportion of those in the meltwater.

Nutrient levels varied between layers of the same glacier (Table 2), and from

Table 2. Nitrogen and phosphorus analyses of frozen glacier ice, melting ice, and snow at the sources of the study streams. Data are means of 2 replicates. neg = below detection limits–see Methods. Values as mg m^{-3}.

Glacier	Site	DRP	NH_4-N	NO_3-N
Adams	Glacier face	3.7	14.5	31.3
Commonwealth	Glacier face: orange layer	22.0	24.2	30.3
	Glacier face: blue layer	3.5	10.0	12.0
Canada	Glacier face	4.0	16.0	17.8
Lower Wright	Glacier face	2.1	7.0	7.8
Bird Ice sheet	Glacier face: blue layer	10.1	25.3	6.3
	Glacier face: grey layer	44.7	25.7	13.4
Commonwealth	Icicle melt	59.5	39.7	350
Canada	Icicle melt	6.0	17.3	95.8
Lower Wright	Icicle melt	4.6	11.3	152
Adams	Adjacent snow	11.5	18.7	63.0
Commonwealth	Adjacent snow	32.9	49.5	102.0
Mt Bird Ice sheet	Adjacent snow	46.8	73.5	44.5

glacier to glacier. Of particular interest are the relatively high levels of NO_3-N and DRP in the fresh icicle melt off the glacier face early in the season. NO_3-N and DRP values in snow adjacent to the streams were also high. All these samples were collected before stream flows in November 1983, with the exception of the Mt Bird Ice Sheet which was sampled in early December when the stream flow had just begun (see Fig. 11a).

4.4.2. Nutrients in the first flows

The initial flows over the stream bed are often small and may be under an ice cover. We were able to sample first flows in the Adams stream and the upper Onyx, and the front of water (melthead) as it moved down the main Onyx river at two sites (Table 3). Values of inorganic nitrogen were higher than glacier ice in all cases and DRP in first flows was higher in the Onyx system than in the Lower Wright Glacier. These nutrient levels were substantially higher than those in stream waters following the first day of flow.

Table 3. Inorganic nitrogen and phosphorus concentrations in stream waters on the first day of flow. Data are means of 2 replicates except for #, which is a single sample. Values as mg m^{-3}.

Stream	Date	Time (h)	DRP	NH_4-N	NO_3-N
Adams	10/11/83	15.00	3.8	12.5	74.0
Upper Onyx–flow off glacier	24/11/83	12.00	4.6	5.4	147
Upper Onyx–main channel	24/11/83	12.20	6.6	15.3	156
Main Onyx–melthead at Denton Ridge #	11/12/83	16.00	15.8	40.0	99.8
Main Onyx–melthead 4 km above L. Vanda	14/12/83	16.40	4.6	17.0	764

CANFIELD and GREEN (1983) suggested that the initial pulse of nutrients (particularly nitrate) in the Onyx at Vanda weir was due to the flushing out of water from Lake Bull, 2 km upstream, where nitrification had occurred through winter. Our data would not support this contention for the 1983/84 season as high nitrate levels were recorded in the river at site O2 well above Lake Bull one day prior to the river reaching Vanda weir.

4.4.3. Nutrients from streambed soils

Nutrients leached from streambed soils on contact with the first flows were estimated from experiments on these soils conducted prior to the initial melt. Soil cores 5.0 mm deep and 5670 mm^2 in area were collected from the Adams (site A1) and Whangamata (site C1) stream beds. 500 ml of freshly melted glacier water from the adjacent glacier was added to three replicate cores from each stream. Controls were containers with water alone. Water was decanted and filtered after 12 h. Nutrients released (Table 4) were calculated from experimental minus control concentrations and expressed as mg released m^{-2} of soil surface. Higher concentrations of DIN and total N were extracted from the Adams stream soil. Total phosphorus release was largely DRP and was similar for samples from both streams.

Table 4. Nutrients released from frozen antarctic streambed soils following rewetting with glacier water for 12 h. Values as mg released m^{-2} of sediment surface. Mean for three replicates ±SE are given. Values are corrected for control (glacier water without sediment).

Nutrient	Adams		Whangamata	
	$\bar{X}$	*SE*	$\bar{X}$	*SE*
DRP	1.83	0.67	3.1	0.80
TDP	3.59	1.35	3.2	0.78
NH_4-N	3.3	0.92	0.3	0.38
NO_3-N	3.6	1.15	2.1	1.18
TDN	42.0	6.87	7.4	2.98

4.4.4. Nutrients in stream waters

Once the stream flow begins, nutrient levels are influenced by levels in the source glacier ice, characteristics of the stream bed sediments and any biological interactions which may occur within the stream. In addition, variability in nutrient levels is caused by freeze concentration when a variable proportion of the stream water turns to ice leaving the salts in solution. Thus various scales of temporal and spatial variability are inherent features of the nutrient concentrations in the streamwaters.

4.4.4.1. Variability between streams

Stream to stream variability in meltwater nutrients was evaluated from measurements taken during mid-season (early January) at the time of day of maximum discharge. Due to diel freeze-thaw cycles (Fig. 11) these values represent the minimum concentrations for the day. Reactive phosphorus and dissolved organic phosphorus ranged from low values (<2 mg m^{-3}) in the Onyx to 100 mg m^{-3} at site B3 below the penguin colony of the Northern Rookery stream. Ammonium-N and NO_3-N ranged from <0.5 mg m^{-3} to 2 mg m^{-3} respectively in the lower Fryxell stream, to a maximum of 156 and 365 mg m^{-3} at Northern Rookery stream. Even streams from adjacent glaciers could differ markedly, e.g. Fryxell stream and Whangamata stream (Fig. 1) originate on two adjacent glaciers 5 km apart in the Taylor Valley but N and P compounds analysed were 2 to 10 times higher in concentration in Whangamata than in Fryxell. This is due to differences in the nutrient content of the source glaciers (Table 2).

4.4.4.2. Longitudinal variability within streams

Three types of streams can be distinguished on the basis of upstream and downstream values of inorganic nutrients:

(1) inorganic N and P concentrations are more or less constant with distance downstream (e.g. Whangamata)
(2) inorganic N and P concentrations increase downstream (e.g. Northern Rookery stream)
(3) inorganic N and P concentrations decrease downstream (e.g. Adams, Fryxell).

Streams of type 1 were generally of high velocity (>0.5 m s^{-1}) and contained no obvious biological activity. The stream bed was unstable, and the waters turbid with shifting sediments.

In the type 2 stream the increasing nutrients were derived from allochthonous inputs from the penguin rookery and from the ornithogenic soils through which the stream flows. High levels of NO_3-N occurred in the lower reaches of this stream (Table 5) but we also recorded extremely high (for natural waters) nitrite concentrations. Values up to 80 mg NO_2-N m^{-3} were recorded from this stream on 8 December 1983.

Streams of type 3 had significant algal growths that presumably stripped nutrients from the water flowing over them. These changes in concentrations were not due to dilution as the source glacier was the only water supply to the streams except for the Onyx, which had some small side tributaries. A slight increase in discharge occurred in the Fryxell stream from 0.05–0.06 m^3 s^{-1} between the upper and lower reaches on the day of sampling, but this was small compared with the reduction in N and P compounds. Downstream decreases in nutrient concentrations in type 3 streams were therefore due to biological removal rather than dilution.

Fig. 12 demonstrates the removal of nutrients down a selected reach of a stream

Table 5. Nitrogen and phosphorus analyses of the upper (U) and lower (L) reaches of the study streams at mid-season discharges to show both stream to stream variability and within stream longitudinal variability. Data as mg m^{-3} and are means of two replicates. neg = below detection limits–see Methods. Stream type–see text. All samples collected between 1130 and 1530 h.

Stream	Reach	Date	DRP	DOP	NH_4-N	NO_3-N	DON	Type
Northern	U	18. 1. 84	32.6	35.6	12.8	21.4	56	2
Rookery	L		106	110	155.5	365	197	
Adams	U	13. 1. 84	28.0	5.6	35.5	46.5	176	3
	L		5.4	2.8	8.5	7.5	53	
Whangamata	U	8. 1. 84	36.0	3.6	13.3	75.4	89	1
	L		41.6	2.5	6.0	75.2	50	
Fryxell	U	3. 1. 84	6.5	3.1	1.5	17.6	21.7	3
	L		0.2	0.9	neg	2.0	37.1	
Onyx–main	U	2. 1. 84	0.3	2.3	2.2	12.8	28.1	1
section	*L1	2. 1. 84	2.1	0.9	5.3	19.5	43.5	3
	*L2		1.9	0.9	8.0	4.0	43.0	

* L1 – at Bull Pass, 5 km upstream Lake Vanda
* L2 – at L. Vanda weir

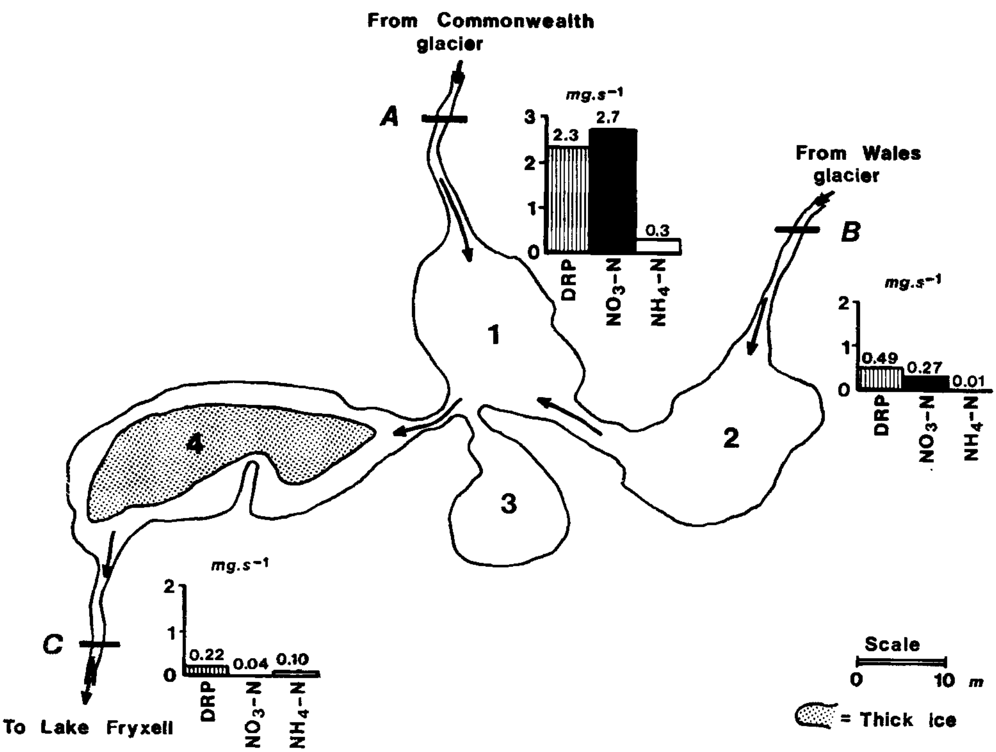

Figure 12. Biological removal of nutrients through an algal rich area at the confluence of two streams in the lower Taylor Valley. Data are presented as mass flow (mg s^{-1}) of DRP, NH_4-N and NO_3-N. Measured discharges at points A–C were: 0.023, 0.009, 0.019 $m^3 s^{-1}$, respectively.

complex in the lower Taylor Valley. Data are presented as mass flow (mg s^{-1}) to correct for changes in discharge. Ponds 2 and 3 had dense *Phormidium* mats whilst pond 4 had *Phormidium* around the edges as well as heterocystous cyanophyceans including *Anabaena* spp. and *Nodularia harveyana*. Total input flux to the system was 2.8, 3.0, 0.3 mg s^{-1} of DRP, NO_3-N and NH_4-N respectively. Output was 0.22, 0.04, 0.1 mg s^{-1} so that uptake rates were 2.6, 3.0, 0.2 mg s^{-1}. On an areal basis (area calculated between points A, B and C) the nutrient uptake rates were 6.9, 8.0, 0.5 mg m^{-2} h^{-1} of DRP, NO_3-N and NH_4-N.

A similar biological removal of inorganic nutrients from the streamwater was recorded in January 1984 on the Onyx 4 km above L. Vanda at the area known as the boulder pavement (Table 6). Samples 1–4 were ca. 400 m apart, and 4 to 5 ca. 2.8 km apart. DRP was reduced by 50 % and NO_3-N by 86 % after passage through the algal mats of the boulder pavement (0–1200 m).

Table 6. Nutrient changes in water flowing across the boulder pavement on the Onyx River 31. 1. 1984. Data as mg m^{-3} are means of two replicates

Distance m	DRP	TDP	NH_4-N	NO_3-N	TDN
0	2.7	3	4.6	47.4	82
400	2.5	3	6.9	41.9	88
800	1.1	2	4.4	12.1	32
1200	1.2	2	3.9	6.4	33
4000*	0.6	1.3	3.6	3.1	29

*Samples from Vanda weir

4.4.4.3 Temporal variability within streams

Our data showed two distinct time scales in the variability of stream nutrient levels: changes over the season and, superimposed on these, diel changes. Nutrient analyses from samples collected at Vanda weir on the Onyx throughout the summer (Fig. 13) demonstrate high levels of N and P on the first day of flow. Following this initial pulse, nutrient concentrations gradually dropped over the next 10 days to fairly low values which were maintained for most of the season. On Feb 1 1984, the river was still flowing but discharges were down to 0.12 m^3 s^{-1} with most of the channel iced over (M. McFarlane–pers. comm.), in places with 6 cm thickness of ice.

Diurnal variability in stream nutrient concentrations is related to the daily freeze-thaw cycles described earlier (section 2.3) and is illustrated by two 24-hour sampling studies on Northern Rookery stream. The first study was run early in the season (8–9 Dec 1983) at low water flows (Fig. 11a) and the second was later in the season (18–19 Jan 1984) during the more typical higher flows (Fig. 11b). In the early season, air temperatures ranged from −9 °C to −4.3 °C, stream O_2 levels were constant at around 100 % saturation and discharges fell over the period from 0.014 m^3 s^{-1} to <0.001 $m^3 s^{-1}$. Nutrient levels in the stream were inversely related to discharge (Fig. 14a) with marked increases at discharges of less than 0.003 m^3 s^{-1}.

There was a pronounced diel freeze-thaw flow regime in the late season study (Fig. 11b) as air temperatures ranged from −1.5 °C to +3.5 °C. Maximum flows occurred in the evening and minimum flows early in the morning. Minimum nutrient concentrations occurred at highest discharges (Fig. 14b) and concentrations rose rapidly at discharges of less than 0.007 m^3 s^{-1}. NH_4-N concentrations were an order of magnitude lower late in the season than they were initially although DRP and NO_3-N concentrations were similar at both times.

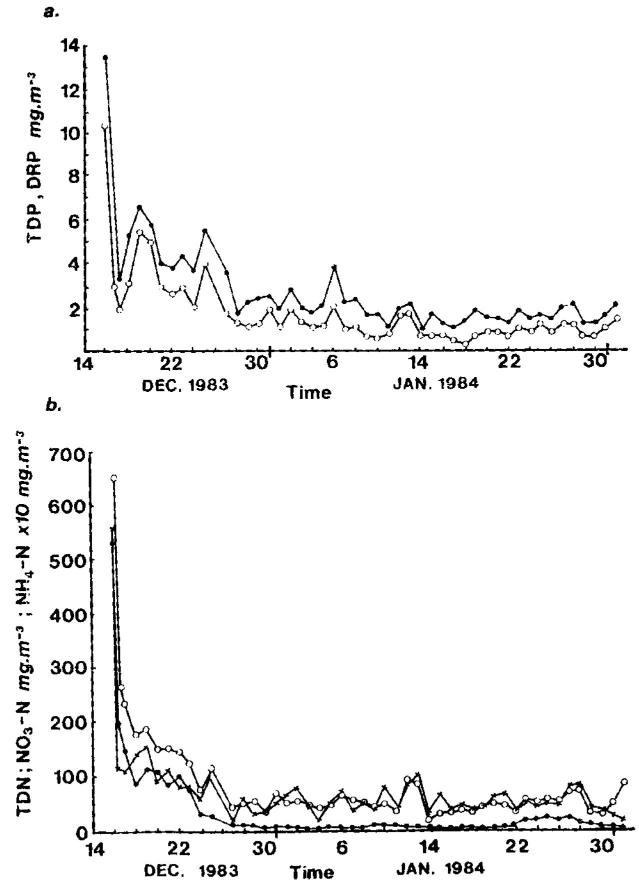

Figure 13. Seasonal changes in nutrients in the Onyx River at Vanda Weir. Replicate samples were collected daily at *ca.* 1400 h from first flow to 1 Feb. 1984. (*a*) Phosphorus: open circles–DRP; closed circles–TDP. (*b*) Nitrogen: closed circles–NO_3-N; crosses–NH_4-N; open circles–TDN.

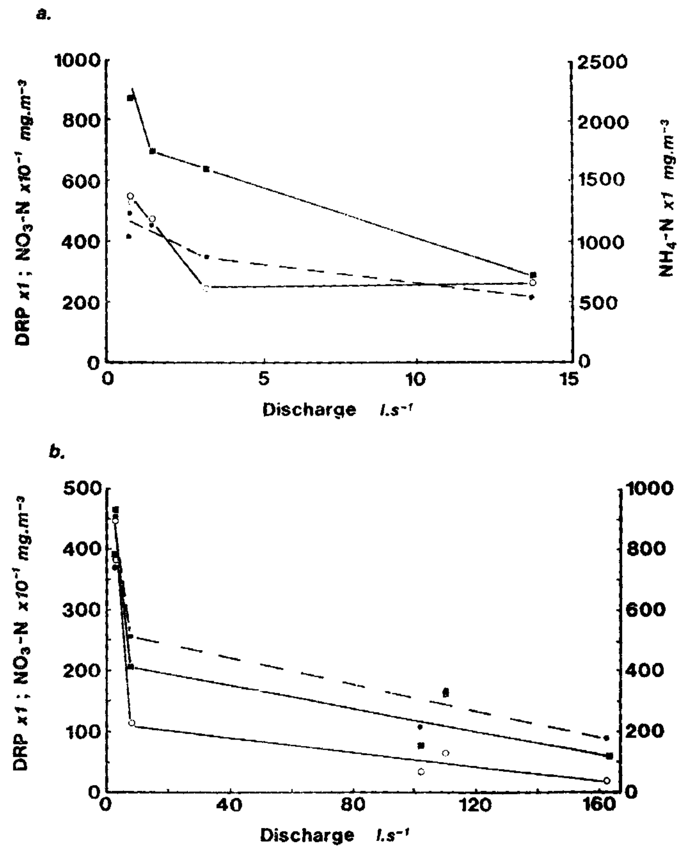

Figure 14. Relationships between nutrient concentrations and discharge at Northern Rookery Stream, Cape Bird. (*a*) early season study (*b*) late season study. Closed circles–DRP; open circles–NO_3-N; squares–NH_4-N.

4.5. *Stream sediment load*

Many of the streams of southern Victoria Land contained a high suspended sediment content that changed with discharge and distance downstream.

The streams spanned a wide range of turbidities and are separated (Table 7) into clear waters (<10 g m^{-3} of sediment) and visibly turbid waters. The latter included

Table 7. Sediment content of southern Victoria Land streams. For two or more samples, each value is the mean $\pm$2SE. Sample number in parentheses.

Stream	Date	Time (h)	Suspended sediments (g m^{-3})
Turbid streams			
Commonwealth	7. 1. 84	12.00	1016(1)
Northern Rookery	19. 1. 84	15.00	606 ± 142 (2)
La Croix (upstream)	17. 1. 85	15.00	594 ± 97 (2)
CC-2	7. 1. 84	14.00	213 (1)
Sollas	17. 1. 85	17.00	143 (1)
Onyx	17 to 21. 12. 83	15.00	131 ± 30 (12)
Whangamata	8. 1. 84	15.00	92 ± 69 (5)
Wales	7. 1. 84	14.30	34 (1)
Onyx	15 to 16. 12. 83	15.00	27 ± 4 (6)
Walcott	9. 1. 85	21.00	16 ± 1 (2)
Clear streams			
CC-6	8. 1. 84	15.00	9.3 (1)
Ward	9. 1. 85	17.00	9.0 ± 0.7 (2)
Adams	8. 1. 85	16.00	7.9 ± 1.9 (8)
Alph	9. 1. 85	24.00	6.2 ± 2.1 (2)
CC-5	7. 1. 84	16.00	5.6 (1)
Howchin	9. 1. 85	20.00	4.4 ± 2.4 (2)
Fryxell	3. 12. 84	16.00	1.7 ± 0.8 (2)
Lake Miers outflow	11. 1. 85	16.00	0.9 ± 0.6 (4)

Table 8. Change in sediment load with distance downstream. Each value is the mean for duplicates ± range. – = no data.

Site	Suspended sediment (g m^{-3})			
	Adams	Fryxell	Whangamata	CC-2
Streams off the glacier face	19.2 ± 2.7	100.8	–	–
upstream	10.7 ± 0.6	3.6 ± 0.5	185.3 ± 14.8	213.2
downstream	5.4 ± 1.1	1.8 ± 0.9	27.1 ± 1.5	12.1

the grey, extremely silt-laden Commonwealth and Northern Rookery streams. Within each stream highest concentrations were recorded in the water flowing down off the glacier (Table 8). Icicles on the glacier face also contained high sediment levels; for example 100.8 g m^{-3} in icicles on the Canada Glacier feeding into Fryxell stream. Sediment load varied from day-to-day; for example from a minimum of 23 g m^{-3} during early flow in the Onyx when discharge was less than 1 m^3 s^{-1}, to 230 g m^{-3} when discharge rose to greater than 10 m^3 s^{-1} over the subsequent week. Sediment

Table 9. Diel changes in suspended sediment and discharge in two Antarctic streams. 18/19 Jan 1984 Northern Rookery stream and 17/18 Dec 1983 Onyx river

Time of day	Northern Rookery Q ($m^3 s^{-1}$)	Northern Rookery suspended sediment ($g\ m^{-3}$)	Onyx River Q ($m^3 s^{-1}$)	Onyx River suspended sediment ($g\ m^{-3}$)
9.00	0.002	3.7	2.5	39.1 ± 1.0
15.00	0.102	749.1	2.4	23.9 ± 1.0
21.00	0.110	32.5	2.2	15.5 ± 1.2
13.00	0.008	2.2	2.1	37.0 ± 0.4
9.00	0.003	1.0	3.6	–
15.00	0.162	464.5	5.3	196.3 ± 4.0

load also varied with discharge over the diel cycle in the smaller streams. For example, in Northern Rookery stream sediment concentration rose two orders of magnitude between low and high flows (Table 9). Discharge in the Onyx on 17/18 Dec 1983 was less variable with time of day than the small streams, and similarly the suspended sediment load was relatively constant. However, turbidity rose sharply with the sudden increase in discharge on 18 December (Table 9).

4.6. *Stream algal communities*

4.6.1. Algal species composition

In many of the streams, particularly clear running waters, the rocks, gravels and sands of the streambed were covered with thick mats and films. The most common communities were black, mucilaginous mats, up to 10 mm thick, composed of *Nostoc* associated with a lesser abundance of Oscillatoriaceae (*Phormidium* spp., *Oscillatoria* spp., *Microcoleus vaginatus*) and pink, grey-green or orange cohesive layers solely of Oscillatoriaceae. Dark red to black surface films of *Gloeocapsa kuetzingiana* were common on the rocks at several stream locations and green tufts of *Tribonema elegans* and *Binuclearia tectorum* occurred in at least two streams.

The composition of algal communities commonly changed along the length of each stream. The zonation in the Adams Stream was typical (Fig. 15). In steep areas adjacent to the glacier. *Nostoc commune* and mats of Oscillatoriaceae were common. The latter consisted mostly of *P. laminosum*, *P. uncinatum* and some *Calothrix* spp. However, in stony reaches only the oscillatoriacean mats occurred between the stones. Large stones and boulders had a vertical zonation. The tops and upward-facing surfaces were covered with a reddish crust of *Gloeocapsa* spp. with associated diatoms and some *Oscillatoria* spp. Often a film of *Phormidium* spp. occurred near the base of the rocks and the low light zone under the rocks was inhabited by bright green ribbons of *Prasiola calophylla*. Long filamentous strands of *B. tectorum*, up to 5 cm in length, were common along stream margins and attached to the downstream sides of large rocks. Where the stream levelled out on alluvial sands, the algal community comprised diatoms (*Hantzschia amphioxys*, *Navicula* spp.) with some oscillatoriaceans and spherical unicellular chlorophytes.

The flora of the Fryxell stream has been described in detail by Boady (1982) who recorded a similar structure on the stones to that shown in Fig. 11. In Fryxell stream the cyanophyte *Chamaesiphon subglobosus* was also a common constituent of the dim

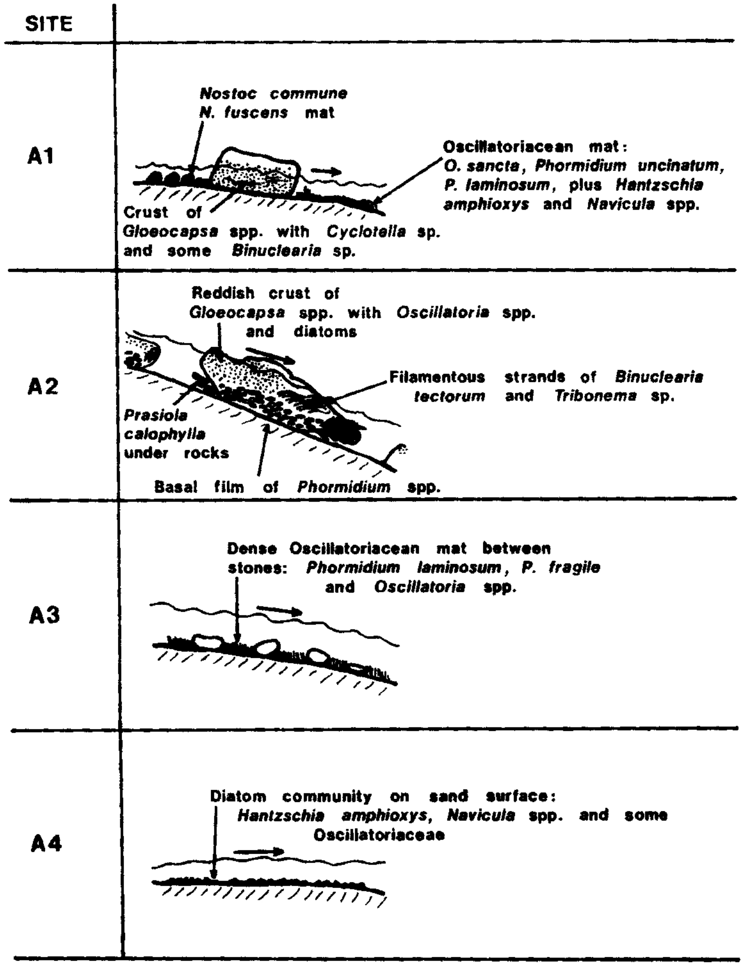

Figure 15. Profile diagrams of representative sections of the Adams Stream to show zonation of periphytic algal species both longitudinally downstream and vertically in stream section. Sites A1–A4 shown on Figure 2.

light community under stones in the upper reaches of the stream. *Prasiola calophylla* was found in the same habitat but lower down on the stream. Stones in the upper reaches of the Fryxell stream had few epilithic algae, but in the middle and lower reaches, periphyton of both mat and crust forms was abundant on rock surfaces and between rocks. Dense black *Nostoc* spp. mats occurred where the stream reached Lake Fryxell.

The streams from the Commonwealth Glacier commonly had algal mats in their lower reaches and where stream velocities slowed over gravel beds. In the Whangamata Stream, samples of algal mat were dominated by *Phormidium frigidum* and *Oscillatoria sancta*. Red coloured epilithic crusts on the rocks comprised *Gloeocapsa kuetzingiana* and the diatom *Hantzschia amphioxys*. Broady (1981) recorded a similar pattern of species from this stream, as well as an abundance of other unidentified pennate diatoms. Of particular interest was the presence of heterocystous blue-green algae (*Anabaena* spp. and *Nodularia harveyana*) which were found nearby in ponds of the confluence of the Wales Stream and stream CC-2 from the Commonwealth glacier (Fig. 12).

Taxonomic analyses were carried out on samples collected from the main section of the Onyx River at two sites–the upper reaches just below Lake Brownworth, and the boulder pavement area 4 km upstream from Lake Vanda. Rocks in the upper reaches were covered by a black crust of *Gloeocapsa kuetzingiana*. *Phormidium* cf. *corium* and *P. uncinatum*, normally mat forming species were associates. *Gloeocapsa* sp., *Navicula* cf. *fragilarioides* and a sarcinoid chlorophyte were found in the sandy substrates of the shallow depressions in this upper reach. The algal mats of the downstream boulder pavement area were dominated by *Phormidium* spp. (*P. laminosum* and *P. frigidum*, with *P. fragile* less common). Diatoms, (*Hantzschia amphioxys*, *Navicula muticopsis*, *N. cryptocephala*, *Stauroneis anceps* and *Tabellaria* sp.) were common on sandy substrata in this area, but were scarce where dense *Phormidium* mats occurred between boulders.

The Northern Rookery stream had no detectable algal growth over most of its length, but in a shallow slow-moving side-arm near the ice-sheet, there was an epilithic community mostly consisting of *Phormidium* cf. *corium*, *P. frigidum*, *Binuclearia* and *Navicula muticopsis*. *Gloeocapsa kuetzingiana* and *Stichococcus* sp. were also found in lesser abundance. BROADY (1981) also recorded thin green epilithic crusts of *Stichococcus bacillaris* in the upper parts of this stream close to the Mt Bird Ice Sheet. In adjacent slower flowing streams and seeps which received melt from the penguin colonies, luxuriant filamentous growths of *Ulothrix* sp. occurred. *Phormidium* spp., *Navicula muticopsis* and *Binuclearia tectorum* were less abundant associates.

As well as changing along the length of streams, algal communities also often changed across the width. A transect across the middle reaches of the Fryxell Stream showed the following pattern. On moist ground bordering the stream channel there were cushions of moss with *Nostoc* sp. mats on the stream edge. Within the stream different zones were recognizable due to their various colours and textures. An outer pink-purple zone near the stream edge consisted of oscillatoriacean taxa including *M. vaginatus*, and embedded within this were dark brown *Nostoc* sp. colonies. Large stones further into the main channel supported blackish epilithic crusts on their upper surfaces. These were dominated by *G. kuetzingiana* and *Schizothrix* cf. *antarctica*. Brown epilithic crusts on the same stones had *P. uncinatum* as the dominant oscillatoriacean component. Covering the sand of the deepest, central part of the channel was a yellow-brown oscillatoriacean felt dominated by *Phormidium laminosum*.

4.6.2. Algal cover and biomass

Percent cover of the algal communities differed markedly both within and between streams. In general, maximum cover was recorded in clear streams, while the highly turbid flowing waters were devoid of conspicuous growths except in quieter, shallow side-arms or washes. Fig. 16 illustrates this effect in three contrasting stream types: the Onyx, where abundant algal growth occurs only in limited stretches of the stream, the clear Adams Stream which has an abundance of algae throughout, and the highly turbid Whangamata and Northern Rookery streams where algal growth is minimal.

Algal cover was negatively correlated ($r = -0.76$, $p < 0.001$) with the proportion of fine sediment in the stream channels (Fig. 17). The effect of the presence of this unstable material was apparent in the middle reaches of the Onyx River where algae were visible only on the edges of the channels where large pebbles and stones occurred, and where this substratum was not continually shifting.

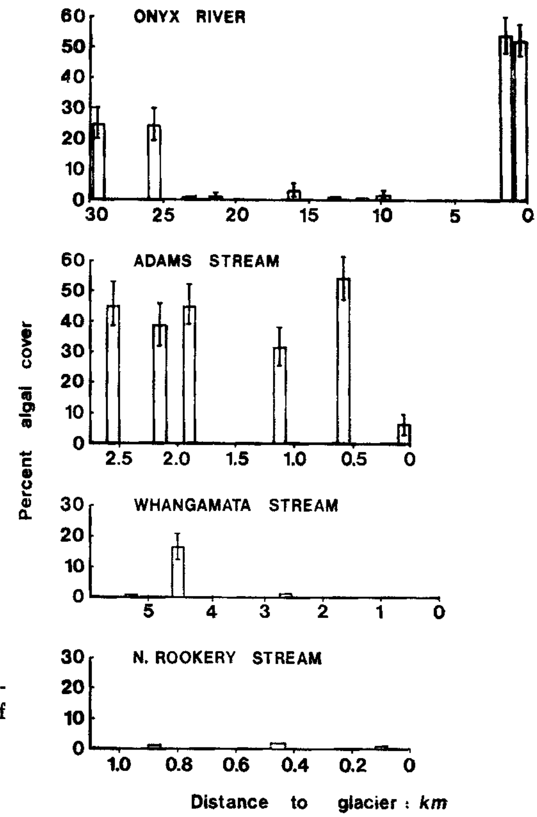

Figure 16. Algal cover (mean $\pm 95\,\%$ confidence limits) for various reaches of four of the study streams.

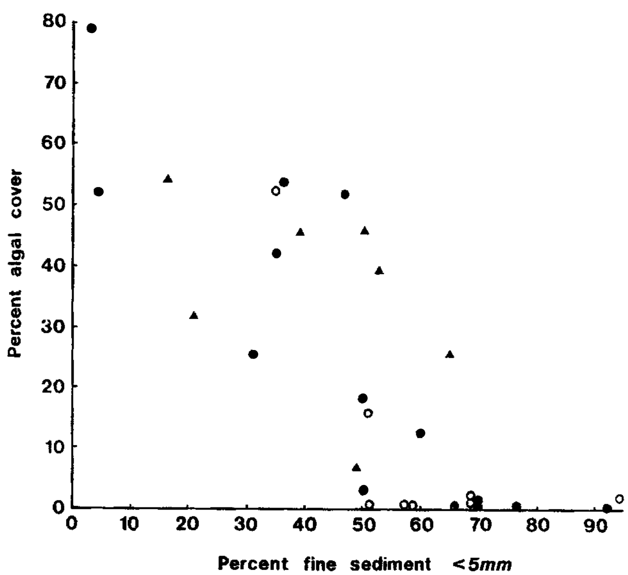

Figure 17. Relationship between % algal cover and proportion of fine sediment (as % of stream bed covered) in the channels of the study streams. Solid circles–Onyx River; triangles–Adams Stream; open circles–Whangamata Stream.

Table 10. Algal cover (% ± 95 % confidence intervals) and species composition on four habitat types recognised in the boulder pavement area of the Onyx river. Data on fine (< 5 mm diameter) sediment cover for each habitat type are also given.

Habitat Type	Sediment	Flow	% Fine Sediment <5 mm diam	% Algal Cover $\bar{X}$	95 % C.L.	Species Composition
1	sandy gravel	fast	94	2.5	2.7	Mostly diatoms: *Stauroneis anceps*, *Navicula muticopsis* etc.
2	boulders	fast	35	52.0	7.4	Mat of *Phormidium laminosum* with *P. frigidum*. Some *Oscillatoria*. Few diatoms *N. cryptocephala*, *Hantzschia amphyoxys*
3	pebbles	slow	3	79.7	6.0	Mat of *Phormidium frigidum* with *P. laminosum*. Diatoms fairly common e.g *N. muticopsis*, *Surirella angustata*
4	pebbles	very slow	14	8.0	5.8	*Phormidium laminosum* and *P. frigidum* mat. Diatoms common e.g. *N. muticopsis*, *N. cryptocephala*, *H. amphyoxys*, *Tabellaria*.

A more detailed analysis of one reach of the Onyx River showed that four distinct algal habitats could be recognised (Table 10). Habitat types 1–3 were areas which were flooded continuously over a diurnal period. The algal cover increased in inverse proportion to the presence of fine sediments as would be expected from Fig. 16. Habitat type 4, although having suitable substrata for algal growth, was inundated only for short periods each day, and as a consequence, % algal cover was reduced.

It was apparent from our analyses, that the % cover of algae present before the first flows (i.e. the overwintering algal stock) make up a considerable proportion of the mid-summer % cover. This proportion ranged from 44 % in the Whangamata stream to a high 73 % in the Fryxell stream. However, at two sites (one in the Onyx and one in the Whangamata), sediments transported by the stream during summer smothered algae which had been recorded before flows began and the mid-summer cover was less than that originally present. The apparent high overwintering stock of algae was investigated further by algal biomass measurements.

Chlorophyll *a* of the periphyton per unit stream surface area ranged from undetectable in fast flowing stream reaches with unstable sediments to a very high 57 $\mu g\ cm^{-2}$ in slow flowing areas where thick *Nostoc* mats had developed (Adams Stream, Fryxell Stream). Undetectable to very low values were recorded in the Northern Rookery stream and the Whangamata stream, with a mean (± SE) for 6 sites in each stream of 1.85 (± 0.083) and 0.02 (± 0.02) $\mu g\ cm^{-2}$ respectively.

Chlorophyll *a* values in the Onyx River varied from 12 $\mu g\ cm^{-2}$ in the upper reaches (site O1) to 0.03 $\mu g\ cm^{-2}$ in some of the mid-stream sections (Fig. 18a). The trend for biomass followed that of % cover with maximal values in the upper and lower reaches where a stable riverbed occurred. In those sections of the river with unstable sediments in the channel we found that although biomass was low it was usually higher on the more stable channel banks than in the centre.

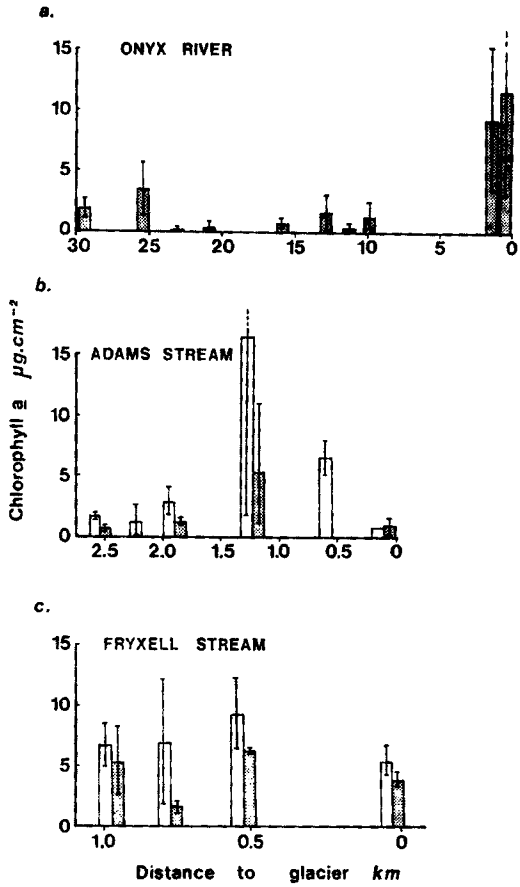

Figure 18. Mean algal biomass (chlorophyll *a* $\mu g\ cm^{-2}$) $\pm$ range from selected reaches of three of the study streams. $n = 2$ per reach. (*a*) Onyx River,–overwintering biomass. (*b*) Adams Stream,–overwintering biomass (hatched) and mid season biomass (open) (*c*) Fryxell Stream,–early season (within one week of flows) biomass (hatched) and late season biomass (open).

The highest algal biomass occurred in the Adams stream (Fig. 18b) and the Fryxell stream (Fig. 18c). The samples shown in Fig. 18b for the top site close to the glacier were collected from the main stream channel. However, the area adjacent to the glacier was a complex hydrological system of seeps and channels with very varied algal biomass accumulations. The extent of these appeared to increase with decreasing flow rates and decrease with degree of channelisation of the stream (cf. Table 11).

Data from the Adams and Fryxell streams illustrates the quantitative importance of the overwintering biomass to the final biomass which develops by mid-season. Overwintering chlorophyll *a* made up between 20 and 100 % of the values recorded later in the season (Fig. 18b, c). In the Whangamata stream and parts of the Onyx, biomass decreased through the season due to shifting stream sediments.

At some locations, very different algal communities and areal biomasses occurred above and below the stream boulders (Fig. 15). In the Adams stream, for instance, the reddish film of oscillatoriaceans on the upper surfaces of rocks (Fig. 15) had a relatively low chlorophyll content per unit area (1.5 $\mu g\ cm^{-2}$), but contained rich carotenoid pigmentation, presumably as a protection against bright light. By con-

Table 11. Variability in species composition and algal biomass (μg Chl a cm^{-2}) in a restricted area of complex hydrology near the Adams glacier.

Site Description	Species Composition	Biomass μg Chl a cm^{-2}
A. Bouldery main stream channel. Fast flow. North side of glacier	Orange brown film on downstream sides of rock, dominated by *Phormidium* cf. *corium*. *Oscillatoria sancta* and *Chlorosarcinopsis* also present.	0.64
B. Small side channel north side of glacier	Mat dominated by *Phormidium* spp.	8.62
C. Seep area at glacier snout	Mucilaginous mat of *Nostoc commune* with some *N. fuscescens*	19.89
D. Seep area on south side of glacier	Red coloured crust of *Gloeocapsa kuetzingiana*. *Binuclearia* also found	11.70
E. Bouldery channel on south side of glacier	Coarse structured mat of *Oscillatoria sancta*, *Microcoleus vaginatus*, *Phormidium frigidum*. Some diatoms e.g. *Hantzschia*, *Navicula*.	2.57

trast, the below rock vegetation was made up almost exclusively of the chlorophyte *Prasiola calophylla* which had very high chlorophyll a levels (32 μg cm^{-2}) but a much reduced carotenoid content.

5. Discussion

A useful review of high latitude stream ecology has been compiled by Harper (1981). This exclusively cites Northern Hemisphere examples and points to the lack of data from Antarctica. Harper concludes that arctic streams differ from streams elsewhere only by being subjected to extreme photoperiods and low rates of input of radiant energy. However, it is evident from our studies of the streams of southern Victoria Land that there are several other important differences which, in combination, separate them from both Northern Hemisphere high latitude streams and temperate streams.

In brief these features include:

(i) the streams are all entirely glacier-fed, rather than snow-fed which has a significant effect on their hydrology

(ii) during the short summer melt period there are marked diurnal changes in water flow

(iii) the ice in the stream channels ablates during winter due to wind erosion leaving a dry, frozen stream bed and an associated freeze-dried epilithon.

(iv) most of the streams flow through catchments with, at most, a few small patches of mosses and lichens and with a sparse soil microflora. Where significant biological activity occurs in the catchment it is associated with marine animals (birds, seals) rather than with vegetation.

Glacier-fed streams of the arctic zone show characteristics (i) and (ii) (Meier 1964, Wendler *et al.* 1972). Desert watercourses elsewhere show highly irregular flows and often flow through catchments with very little biological activity (c. f. (iv) above). Input of allochthonous material in desert streams is often negligible relative to autochthonous inputs (Naiman 1976, Dance 1981). Steffan (1972) found that glacier-fed streams in Alaska and Lappland were different to snow-fed streams of the area, being characterised by lower nutrient concentrations and lower temperatures.

The streams of Victoria Land, therefore share some physical characteristics with Northern Hemisphere glacier streams and some with desert streams elsewhere, but the combination of characters (i)–(iv) above, and the special feature (iii) which we have not seen recorded for other streams, set them aside as a very distinct group of lotic ecosystems. Perhaps the most comparable streams are those of the high Arctic polar deserts briefly referred to in BLISS *et al.* (1984) but for which we have as yet seen no descriptions. They appear to be snow-fed and flow for 7–14 days each year. The annual freezing and ablation of ice to the streambed imposes a particularly harsh set of environmental conditions on the lotic flora and microfauna of Antarctic streams which must sustain several months at temperatures to –55 °C.

In STEFFAN'S (1972) consideration of N. Hemisphere glacier-fed streams, he pointed to their low nutrient status as a special characteristic. Whilst this may be true for some Antarctic streams, none appear to be ultra-oligotrophic, and high nutrient levels are found in two sets of conditions. First, when streams flow through penguin rookeries they are enriched with nutrients. Secondly, high nutrient levels are associated with first flows (Table 3, and see WEAND *et al.* 1977, CANFIELD and GREEN 1983). This is a transient phenomenon. VINCENT and HOWARD-WILLIAMS (1986) suggest that this initial high nutrient pulse may be advantageous to the stream flora which, like terrestrial desert flora (EICKMEYER 1979, 1982) rapidly resumes metabolic activity on rehydration.

The source of these early flow nutrients has not been clearly established. There are however, three possibilities:

1. Glacier surfaces. Although glacier ice is by no means pure water (Table 2) inorganic N and P concentrations in the ice are generally low. (Organic N and P are discussed elsewhere–DOWNES *et al.* in press.). However, water samples from the initial melting surfaces of the glaciers, collected from dripping icicles, had relatively high N and P contents (Table 2). We do not as yet fully understand the reasons for this but salts may be concentrated on glacier surfaces by continuous freeze-thaw cycles, and they may be deposited as wind-blown particulates from the adjacent land surfaces and from the sea. All the glacier sites studied were within 20 km of the sea, and with the strong winds which blow in the region we may expect considerable marine aerosol development, movement and precipitation. Such aerosols will coat the surfaces of the glaciers and accumulate in winter to be released with first flows. Visually conspicuous quantities of soil and sediments from adjacent land surfaces accumulate on the glaciers and salts from this material may be largely released or leached during first flows each year. A further source of atmospherically derived high nitrate on these glaciers has been postulated and is believed to originate by atmospheric oxidation of N_2 gas, possibly by auroral activity (ZELLER and PARKER 1981).

2. Snowdrifts. Snow in drifts in stream channels and on adjacent slopes has higher nutrient levels than glacier ice, and would contribute to the first melt.

3. Streambed sediments. These can potentially supply nutrients (Table 4 and see HOEHN *et al.* 1977), particularly to the first flows by three processes: nutrients may be frozen out and deposited from the previous year's stream, the ice of which has ablated; nutrients can be generated from soil weathering processes on the dry streambeds over winter; nutrients may be generated from the oxidation or weathering of algal material from the previous season's growth. However, streambed sediments are not likely to be as important to the early nutrient pulse as glaciers and snow.

Whilst in another study (DOWNES *et al.* in press) it has been demonstrated that organic N and P may be derived in some quantity from streambed sources, this is unlikely to be the case with inorganic nutrients. For instance, if we multiply the area of streambed which is covered with water on the first day of flow by the quantities of nutrients released per unit area (Table 4) we can estimate the total released amount by the streambed. Dividing this by the total discharge over the first 24 h gives an approximation of the likely rise in concentration of the nutrient due to streambed processes. The values calculated for the Onyx River, for instance, are 1 mg m^{-3} DRP and 0.6 mg m^{-3} of NO_3-N, negligible amounts compared with the actual concentrations (Table 3, Fig. 13).

Very high nutrient levels in the lower reaches of the Northern Rookery Stream are obviously derived from the penguin rookeries, but the high proportion of the oxidised form of inorganic N is of interest. Here, we recorded up to 80 mg m^{-3} of nitrite-N and up to 4 g m^{-3} of nitrate-N. The soil nitrogen originates from penguin guano, and is mostly in the form of uric acid which decomposes rapidly to ammonium (SPIER and COWLING 1984) resulting in soil concentrations of 40 mg NH_4-N g^{-1}. These ornithogenic soils are therefore very different from most soils elsewhere where organic matter is largely derived from plants. SPEIR and COWLING (1984) speculated that in addition to natural weathering, some of this ammonium could be converted to nitrate by nitrifying bacteria. Our data on the high NO_2-N and NO_3-N concentrations in the streamwaters flowing through these soils would suggest that nitrification is an important process in the summer period here. Nitrification has been recorded from penguin rookery soils at subantarctic Marion Island (LINDEBOOM 1984). At the mean soil temperature of 6°, low rates were found, but in one experiment the process oxidised as much as 100 mg N m^{-2} day^{-1} when the incubation temperature was raised to 20 °C, a soil temperature he sometimes recorded in the field. Clearly, at the Northern Rookery, substrates are not limiting and soil temperatures can rise to 10 °C making these alkaline soils ideal sites for nitrification for at least one or two months each year resulting in high levels of oxidised nitrogen in the stream water. However, it is noteworthy that this stream, with its high nutrient concentrations, supported no significant algal growth. In contrast, the Adams stream had fairly low nutrient levels and was biologically very rich. The physical regime of the streams seems to be of greater importance than nutrients in determining biological activity. Streambed stability and the amount of suspended sediments which scour the periphyton are apparently the major physical factors affecting algal growth. This conclusion is supported by a correspondence between water clarity and algal cover: turbid streams were largely devoid of algae while all clear waters had abundant growth. In a series of artificial substratum growth experiments in these streams there was an inverse correlation between algal biomass accumulation and maximum suspended sediment load (VINCENT and HOWARD-WILLIAMS 1986). The standing crop which survives from one summer to the next usually lies close to the maximum sustainable crop for the whole season. High biomass can apparently only develop by small increments over many years on a stable substratum which lasts from year to year.

Sediment load was a highly variable component of the Dry Valley streams (Table 7, and see HOEHN *et al.* 1977). High sediment loads are a characteristic of Alaskan and Alpine glacier streams (MEIER 1964, COLLINS 1983) and are a conspicuous feature of the south temperate New Zealand glacial streams. Diurnal variability in suspended load concentrations has been noted for Alaskan glacial streams (SLATT 1972) and is apparently a function of diel variation in stream flow conditions. The decrease in sediment load with distance downstream (Table 8) is also a feature of Alaskan glacial streams (MEIER 1964). However, many of the streams we examined had flow rates too low to move considerable quantities of sediment (Table 7) and it was these which supported maximum algal growth.

The algal communities of Victoria Land streams were dominated by the Cyanophyceae (Tables 10, 11, Fig. 15). BROADY (1982) noted that this group comprised

63 % of the total algal taxa in all antarctic streams studied up to that time. Cyanophyceans are known to be highly resistant to freezing stresses (DUBOIS and KAPUTSKA 1983) which could confer an advantage over other groups of algae. The diatom flora of the streams is certainly impoverished relative to that in the benthos of the adjacent dry valley lakes where freezing would not occur, perhaps, because this group is not as physiologically resistant to freezing as the Cyanophyceae. A further advantage which may be conferred on the heterocystous N_2-fixing Cyanophyceans is the low N/P ratio of the Victoria Land streamwaters. Inorganic N/P ratios of only 2–3 occurred in all streams except the Onyx (see data in Table 5). The *Nostoc commune* colonies we examined had abundant heterocysts, and N-fixing species of *Anabaena* and *Nodularia* were recorded from ponded portions of streams in the Taylor Valley (Fig. 12). ALLNUTT *et al.* (1981) detected acetylene reduction (although rates were low) in algal mats containing heterocystous Cyanophyceae in shallow waters on the edges of the lakes of this region. Nitrogen fixation remains an unquantified component of the southern Victoria Land flowing water environments.

Despite low temperatures and a brief season of streamflow, antarctic streams can support an abundant algal epilithon. They contain chlorophyll *a* levels comparable to the highest values reported from streams of the temperate zone (cf. LOCK 1981), and maintain a viable overwintering biomass that comprises a large percentage of the late season streambed cover. These communities live in a structured, linear ecosystem that has a well-defined point source of water and dissolved materials (the glacier), longitudinal gradients of sediment load and nutrients, but minimal exchanges of mass and energy with the surrounding catchment through which it flows.

6. Summary

Running waters originating from glacial melt are a seasonal feature of Antarctica and are especially prevalent in the vicinity of McMurdo Sound. We have sampled 24 of these waters and have conducted detailed studies on five contrasting streams.

Streamwater temperatures showed a marked diel variability (freezing to 11 °C) which was sensitive to ambient air temperatures and insolation. Discharges ranged from 0.01 $m^3 s^{-1}$ in small streams to 15 $m^3 s^{-1}$ in the Onyx River and varied at diel and weekly time scales although annual flow periods were short (ca. 6 weeks). We found that aspect and slope were major determinants in the flow regimes of these streams; the time of day of maximum discharge depended on the orientation of the source glacier relative to the sun.

Nutrients (dissolved nitrogen and phosphorus compounds) were analysed in glaciers, and streamwaters on a diel and seasonal basis. Early meltwaters had 10–20 times higher levels of dissolved N and P than those later in the season. There was considerable variability in nutrient concentrations between streams at maximum discharge (e.g. dissolved reactive phosphorus ranged from <1 mg m^{-3} in Fryxell Stream to >100 mg m^{-3} in Northern Rookery Stream) within streams on a diel basis and within streams with distance from a glacier to the stream outflow.

Variability was due to: the presence of dense algal mats which removed nutrients, penguin rookeries which added nutrients and different concentrations in the source glaciers.

The suspended sediment content of the stream waters was shown to vary over four orders of magnitude with deep fast flowing streams exhibiting maximum sediment loads (>600 g m^{-3}). Diel changes in sediment loads were observed and these were directly related to discharge.

Algal communities were made up predominantly of blue-green algae (*Phormidium*,

Oscillatoria, Nostoc, Gloeocapsa). Other important genera including the green algae *Binuclearia* and *Prasiola* were the tribophyte *Tribonema*, and the pennate diatoms *Hantzschia* and *Navicula*. Water flow rates and substrate type influenced species composition and biomass. Biomass ranged from undetectable in shifting sands to values in excess of 25 μg chl *a* cm^{-2} in stable mat communities. Physical factors (turbidity, flow, sediment type) were of greater importance than nutrients in determining algal standing crop.

7. Acknowledgements

This study was part of the New Zealand Antarctic Research Programme. We thank the DSIR Antarctic Division and the U. S. National Science Foundation for logistic support. ERIC SAXBY, COLIN MONTEATH and GEOFF SPEARPOINT provided much needed assistance in some of the field operations. We are very grateful to MALCOLM MCFARLANE, leader of Vanda Station, who collected the series of water samples and stream temperatures which allowed us to present the seasonal data for the Onyx River. JEFF ROBERTSON helped considerably with collection of hydrological data. TREVOR CHINN of the NZ Ministry of Works and Development allowed us to use some unpublished hydrological data for the Onyx River and MIKE FRAZER and the NZ Meteorological Service provided some of the air temperature and solar radiation data. STUART PICKMERE and MALCOLM DOWNES assisted with water analysis, JOHN DAVIES with diagrams and JANET SIMMISS typed the manuscript. We thank JOHN PRISCU, TONY VINER and EDDIE WHITE for reviews of the text.

8. References

ALLNUTT, F. C. T., B. C. PARKER, K. G. SEABURG and G. M. SIMMONS, 1981: *In situ* nitrogen (C_2H_2) fixation in lakes of Southern Victoria Land, Antarctica.–Hydrobiol. Bull. **15**: 99–109.

BLISS, L. C., J. SVOBODA, and D. I. BLISS, 1984: Polar deserts, their plant cover and plant production in the Canadian High Arctic.–Holarctic Ecology **7**: 305–324.

BROADY, P. A., 1981: Non-marine algae of Cape Bird, Ross Island and Taylor Valley, Victoria Land, Antarctica.–Melbourne University Programme in Antarctic Studies **37**: 1–97.

BROADY, P. A., 1982: Taxonomy and ecology of algae in a freshwater stream in Taylor Valley, Victoria Land, Antarctica.–Arch. Hydrobiol., Supplement, **63**: 331–339.

CANFIELD, D. E., and W. J. GREEN, 1983: Aspects of nutrient behaviour in Lake Vanda. Antarctic Journal of the United States **18**: 224–226.

CHINN, T. J., 1974: Hydrological Research Report, Dry Valleys, Antarctica 1974–75.–Ministry of Works and Development, Christchurch, New Zealand.

CHINN, T. J., 1981: Hydrology and climate in the Ross Sea area.–J. Roy. Soc. New Zealand **11**: 373–386.

CHINN, T. J., and G. J. ROBERTSON, 1985: Hydrology and Glaciology, Dry Valleys, Antarctica. Annual Report for 1983–84.–Ministry of Works and Development, Christchurch, New Zealand.

COLLINS, D. N., 1983: Solute yield from a glacierised high mountain basin. *In*: B. W. WEBB (Ed.) Dissolved loads of Rivers and Surface Water Quantity/Quality Relationships.–IAHS Publication, Wallingford, U. K. **141**: 41–49.

CROOKE, W. M., and W. E. SIMPSON, 1971: Determination of ammonium of Kjeldahl digests of crops by an automated procedure.–J. Sci. Food and Agriculture **22**: 9–10.

DANCE, K. W., 1981: Seasonal aspects of transport of organic and inorganic matter in streams. *In*: LOCK, M. A., and D. D. WILLIAMS (Eds.) Pespectives in Running Water Ecology.–Plenum Press, New York, pp. 69–95.

DOWNES, M. T., 1978a: An automated determination of low reactive phosphorus concentrations in natural waters in the presence of arsenic, silicon and mercuric chloride.–Water Research **12**: 743–745.

DOWNES, M. T., 1978b: An improved hydrazine reduction method for the determination of low nitrate levels in freshwater.–Water Research **12**: 673–675.

DOWNES, M. T., C. HOWARD-WILLIAMS, and W. F. VINCENT, In press: Sources of organic nitrogen, phosphorus and carbon in Antarctic streams.–Hydrobiologia.

DUBOIS, J. D., and L. A. KAPUTSKA, 1983: Freeze-recovery physiology of nitrogenase activity in terrestrial *Nostoc* sp. colonies.–Appl. Environm. Microbiol. **46**: 773–778.

EICKMEYER, W. G., 1979: Photosynthetic recovery of the resurrection plant *Selaginella lepidophylla* after wetting.–Oecologia (Berl.) **39**: 93–106.

EICKMEYER, W. G., 1982: Protein synthesis and photosynthetic recovery in the resurrection plant, *Selaginella lepidophylla*.–Plant. Physiol. **69**: 135–138.

FISHER, S. G., and G. E. LIKENS, 1973: Energy flow in Bear Brook, New Hampshire: An integrative approach to stream ecosystem metabolism.–Ecol. Monogr. **43**: 421–439.

GREIG-SMITH, P., 1964: Quantitative Plant Ecology (2nd Ed.)–Butterworths, London, 256 pp.

HARPER, P. P., 1981: Ecology of streams at high latitudes. *In*: LOCK, M. A., and D. D. WILLIAMS, (Eds.) Perspectives in Running Water Ecology.–Plenum Press, New York, pp. 313–337.

HEYWOOD, R. B., 1977: Limnological survey of the Ablation Point area, Alexander Island, Antarctica.–Phil. Trans. Roy. Soc. London, Series B. **279**: 39–54.

HIRANO, M., 1979: Freshwater algae from Yukidori Zawa near Syowa Station, Antarctica. National Institute of Polar Research Memoirs, Tokyo. No. **11**: Special Issue. pp. 1–25.

HIRANO, M., 1983: Freshwater algae from Skarvsnes, near Syowa Station, Antarctica.–National Institute for Polar Research Memoirs, Tokyo. Series E, No. **35**: 31 pp.

HOEHN, R. C., B. C. PARKER, R. D. FORTNER, B. L. WEAND, J. A. GRAFT, L. S. LANE, R. W. STARROS, H. G. SUGG, and J. T. WHITEHURST, 1977: Nitrogen and phosphorus availability to plankton and benthic communities in Lake Bonney, Southern Victoria Land, Antarctica. *In*: LLANO, G. A. (Ed.) Adaptations within Antarctic Ecosystems.–3rd SCAR Symposium on Antarctic Biology. pp. 859–872.

HOWARD-WILLIAMS, C., S. PICKMERE and J. DAVIES, 1983: Decay rates and nitrogen dynamics of decomposing watercress (*Nasturtium officinale* R. Br.).–Hydrobiologia **99**: 207–214.

JOHN, P. H., 1978: Discharge measurement in lower order streams.–Int. Revue ges. Hydrobiol. **63**: 731–755.

LINDEBOOM, H. J., 1984: The nitrogen pathway in a penguin rookery.–Ecology **65**: 269–277.

LOCK, M. A., 1981: River epilithon–a light and organic energy transducer. *In*: LOCK, M. A., and D. D. WILLIAMS, (Eds.) Perspectives in Running Water Ecology.–Plenum Press, New York. pp. 3–40.

MEIER, M. R., 1964: Ice and glaciers. *In*: VEN TE CHOW (Ed.) Handbook of Applied Hydrology.–McGraw Hill Book Company, New York. pp. 16-1–16-32.

NAIMAN, R. J., 1976: Primary production, standing stock and export of organic matter in a Mohave Desert thermal stream.–Limnol. Oceanogr. **21**: 60–73.

PARKER, B. C., 1981: Physiological ecology of Antarctic algae.–Oral Paper presented to 13th International Botanical Congress. Sydney, Australia. August, 1981.

SEABURG, K. G., B. C. PARKER, G. W. PRESCOTT, and L. A. WHITFORD, 1979: The algae of Southern Victoria Land, Antarctica.–Bibliothecia Phycologia **46**: 169 pp.

SHAW, J., and T. R. HEALY, 1980: Morphology of the Onyx River system, McMurdo Sound region, Antarctica.–New Zealand J. Geol. and Geophys. **23**: 223–238.

SHOAF, W. T., and B. W. LIUM, 1976: Improved extraction of chlorophyll *a* and *b* from algae using dimethylsulphoxide.–Limnol. Oceanogr. **21**: 926–928.

SLATT, R. M., 1972: Geochemistry of meltwater streams from nine Alaskan glaciers.–Geol. Soc. America Bull. **83**: 1125–1132.

SPEIR, T. W., and J. C. COWLING, 1984: Ornithogenic soils of the Cape Bird Adelie Penguin rookeries, Antarctica.–Polar Biology **2**: 199–205.

STEFAN, A. W., 1972: Zur Produktionsökologie von Gletscherbächen in Alaska und Lappland.–Verh. dk. Zool. Ges. **65**: 73–78.

TORII, T., S. MURATA, and N. YAMAGATA, 1981: Geochemistry of the Dry Valley lakes.–J. Roy. Soc. New Zealand **11**: 387–399.

VINCENT, W. F., and C. HOWARD-WILLIAMS, 1986: Antarctic stream ecosystems: physiological ecology of a blue-green algal epilithon.–Freshw. Biol. In Press.

VINCENT, W. F., and C. L. VINCENT, In Press: Antarctic limnology: Lake, pond and stream ecosystems of Southern Victoria Land: *In*: HATHELTON, T. (Ed.) New Zealand Science in the Antarctic.

WEAND, B. L., R. C. HOEHN, and B. C. PARKER, 1977: Nutrient fluxes in Lake Bonney–a meromictic Antarctic lake.–Arch. Hydrobiol. **80**: 519–530.

WENDLER, G., C. TRABANT, and C. BENSON, 1972: Hydrology of a partly glacier covered arctic watershed. *In*: Proceedings of the Banff Symposia on the role of snow and ice in hydrology.— Published by UNESCO-WMO-IAMS. Paris. pp. 417–434.

ZELLER, E. J., and B. C. PARKER, 1981: Nitrate ion in Antarctic firn as a marker for solar activity.— Geophys. Res. Letters 8: 895–898.

CLIVE HOWARD-WILLIAMS
DSIR
Division of Marine and Freshwater Science
Taupo Research Laboratory
P. O. Box 415
Taupo, New Zealand

PAUL BROADY
School of Botany
University of Melbourne
Victoria 3032, Australia

Manuscript accepted: August 13th, 1985