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Surface and subsurface flows of nutrients in natural and human impacted lake catchments on Broknes, Larsemann Hills, Antarctica

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Abstract: This study aimed to use nutrients in lake inflows as proxies for assessing human impact and separating this from natural transformations of material in the soil active layer. Nutrients, conductivity and δ^{18}O were monitored in surface and subsurface (using ceramic tipped piezometers) lake inflows during summer in near natural and human impacted catchments. The nutrient levels were highly variable but generally higher during the last weeks of the flow, in both subsurface waters and in human impacted catchments. Up to 2000 µgN l^{-1} subsurface dissolved inorganic nitrogen (DIN) was measured in human impacted catchments but only 315 µg N l^{-1} in natural catchments. Subsurface levels of dissolved reactive phosphorus (DRP) were up to 310 µgP l^{-1} in natural catchments and up to 108 µgP l^{-1} in human impacted catchments. The maximum levels of both DIN and DRP in surface inflows were much higher in human impacted than in natural catchments. Conductivity and δ^{18}O data showed general enrichment of snowbank meltwater presumably through evaporation from the active layer. This combined with fluctuating nutrient levels in catchment waters indicated that soil brines and decaying organic matter of natural and human origin were possible sources for nutrients and other salts. Marked salinization and substantially increased DIN levels near the research stations indicated that lake waters were receiving nutrients generated by humans.

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Key words: Antarctica, catchments, freshwater, human impact, nitrogen, phosphorus, piezometers

Introduction

Antarctic freshwater lakes are generally ultraoligotrophic with water originating from glacial ice and snowbank meltwaters that usually enter very sparsely vegetated catchments. Consequently the lakes are supplied with only very small amounts of allochtonous organic matter and nutrients. In streams and lakes typical dissolved reactive phosphorus (DRP) levels up to 10 µgP l^{-1} have been recorded and dissolved inorganic nitrogen (DIN) is usually under 100 µgN l^{-1}. Similar data has been collected in the McMurdo region (Gardner *et al.* 1984, Green *et al.* 1989, Howard-Williams & Vincent 1989, Webster *et al.* 1996) and from streams and lakes of several East Antarctic coastal areas, including Bunger Hills (Klokov *et al.* 1990, Kaup unpublished), Vestfold Hills (Heath 1988, Laybourn-Parry & Marchant 1992), Thala Hills (Kaup & Vaikmäe 1996, Kaup 1998), areas near Syowa station (Fukui *et al.* 1986) and Schirmacher Oasis (Kaup 1994, Haendel & Kaup 1995).

Higher levels of nutrients in Antarctic freshwater lakes are normally associated with:

a) enrichments from seals and birds (Hawes 1983, Ellis-Evans 1991, Pizarro *et al.* 1996),
b) monimolimnia of meromictic lakes (Green *et al.* 1989, Webster *et al.* 1996),
c) evaporation and freezing processes (Vincent & Howard-Williams 1994, Webster *et al.* 1994, Haendel & Kaup 1995), and
d) human impact (Haendel & Kaup 1995, Kaup 1998).

From December 1992–January 1994 both low and, at times, substantially higher than normal DRP levels were measured in the Larsemann Hills. Levels up to 125 µgP l^{-1} were measured in lake waters while levels up to 180 µgP l^{-1} were recorded in surface inflows and meltwater emerging from the lithosols. The DIN levels were under 100 µgN l^{-1} (Kaup & Burgess 1995, Burgess & Kaup 1997, Ellis-Evans *et al.* 1997, 1998). Enrichment from seals and birds as well as monimolimnia of meromictic lakes were clearly absent, and high levels of DRP were measured both with and without evidence of direct human impact. Coupled with conductivity and δ^{18}O data, it was concluded that snowbank meltwater was DRP enriched through leachout and evaporation in the soil active layer. Consequently enriched meltwater inflows increased substantially, albeit temporarily, DRP levels in some lakes (Kaup *et al.* 2000). Chinn (1993) reports a similar concentration of salts in the groundwater associated with permafrost in the McMurdo Dry Valleys.

It was hypothesized that in the Larsemann Hills fossil organic matter, particularly moss/cyanobacterial deposits contained in upper permafrost layers (Burgess *et al.* 1994), may contribute to nutrients in groundwater (Burgess & Kaup 1997). The aim of this study was therefore to examine

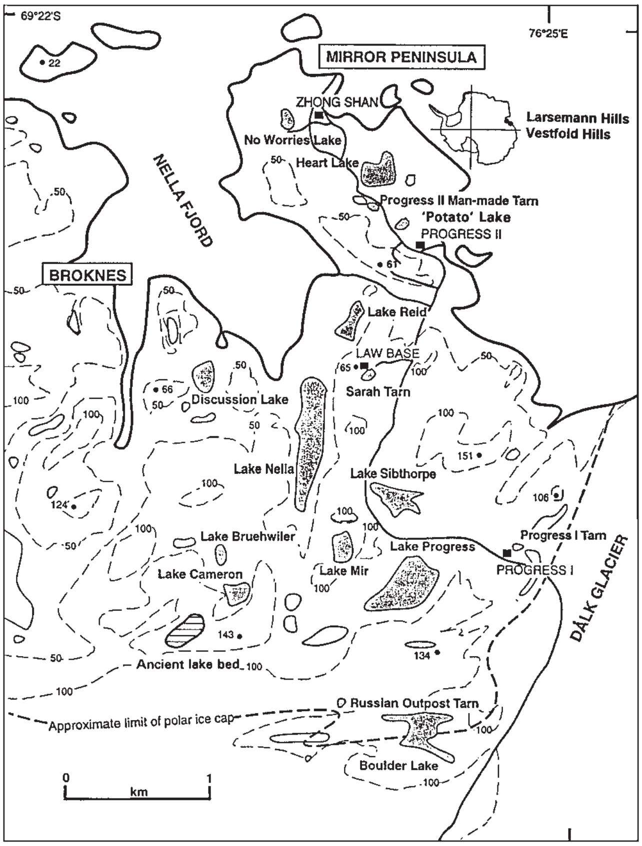

Fig. 1. Location of Larsemann Hills and lakes and stations in the east part of Broknes (modified after Gasparon *et al.* 2002). Bold line represents road through stations (with bifurcations) from north to polar ice cap.

variation in nutrient levels in lake inflows as an indication of human impact and distinguish this from natural processes of accumulation and disintegration of organic and inorganic matter in the active soil layer. To differentiate between solute enrichment from human impact and evaporation, conductivity and $\delta^{18}O$ data were collected.

Larsemann Hills environment

The Larsemann Hills (69°24'S, 76°20'E) consist of a series of rocky ice-free peninsulas and islets with a total area of *c.* 35 km^2, which are located on the Ingrid Christensen Coast between the Amery Ice Shelf and Sørsdal Glacier. Broknes (Fig. 1) at the eastern end of the Hills is a peninsula with elevations up to 143 m a.s.l. Recent evidence suggests that certain areas may not have been covered by ice during the Last Glacial Maximum (Burgess *et al.* 1994, 1997, D. Hodgson personal communication 2000). The ice-free areas include bare gneiss and granitic rocks with a thickly weathered crust, and extensive surficial gravel and sand deposits that provide sediment inputs to the lakes. Sand-sized particles dominate with less gravel and very little silt and clay. Soils less than 10 cm thick occur in association with scattered moss beds and discontinuous lichen cover. These and other soils are largely lithosols, composed of various light coloured and iron pigmented gneisses, the particles of which are frequently polished and with surface chemical coatings (Ellis-Evans 1997). The scarcity of silt and clay fractions means that soils are loose or only weakly consolidated. The permafrost lies at 20–90 cm (depending on aspect and the time of year) and provides a surface on which free water can collect and flow subsurface.

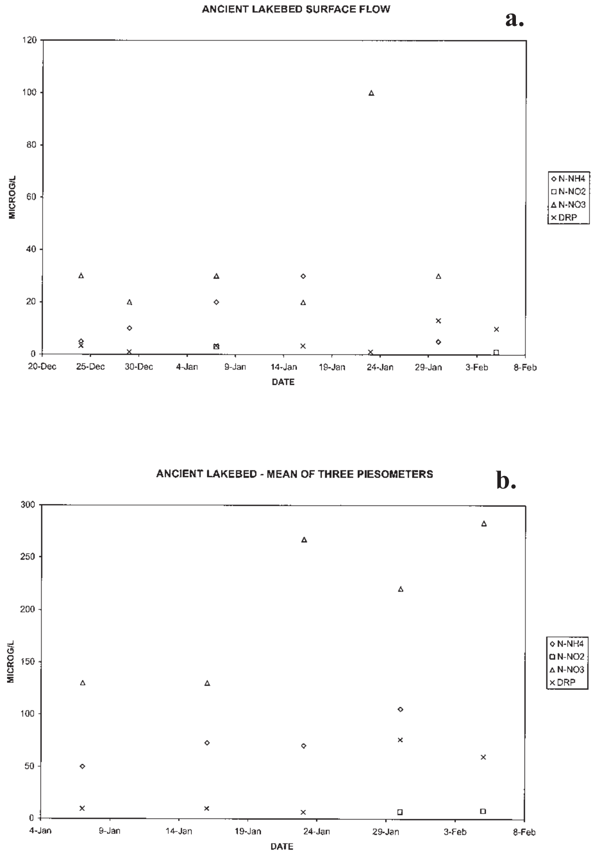

Fig. 2. Concentrations of nutrients on the ancient lake bed; **a**. surface flow, **b.** piezometers (average of three).

In early 1987, a baseline limnological survey recorded more than 70 lakes on Broknes (Gillieson *et al.* 1990). That survey indicated that the lakes are generally shallow ponds or ice-deepened basins, which thaw completely or partially between December and February. Most lakes are fed by meltwater from snowbanks and some have inflow and outflow streams that flow for up to 12 weeks in summer. Conductivity of water in 20 lakes surveyed ranged from 33 µS cm^{-1} in a small lake near the polar plateau to 3340 µS cm^{-1} in Sarah Tarn close to Law Base. The dominance of Na$^+$ and also Mg^{2+} over Ca^{2+} indicates a strong marine influence. Higher former shorelines show evaporation effects in some lakes. Lake bottoms are characterized by extensive cyanobacterial mats often up to 1 m thick with lake margin growth of filamentous green

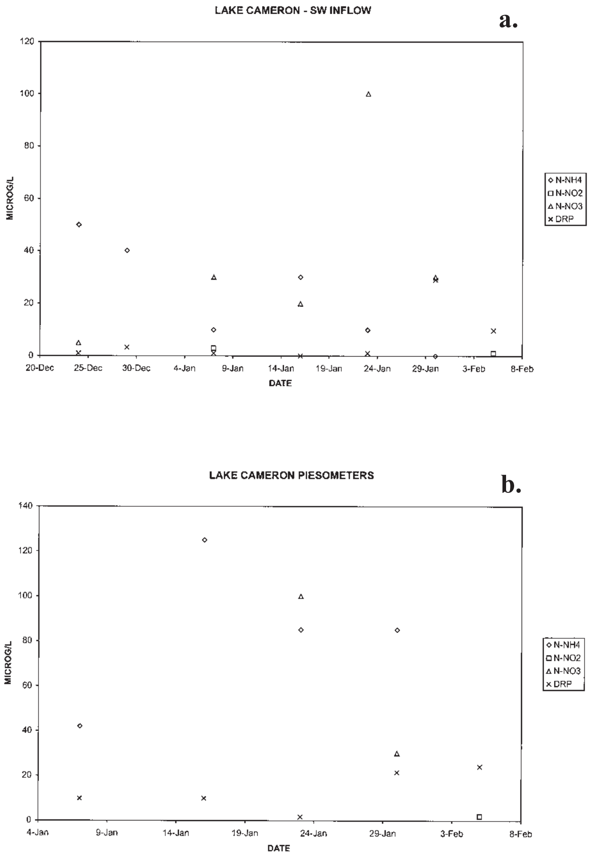

Fig. 3. Concentrations of nutrients in the south-west inflow of Lake Cameron; **a.** surface inflow, **b.** piezometers (average of two).

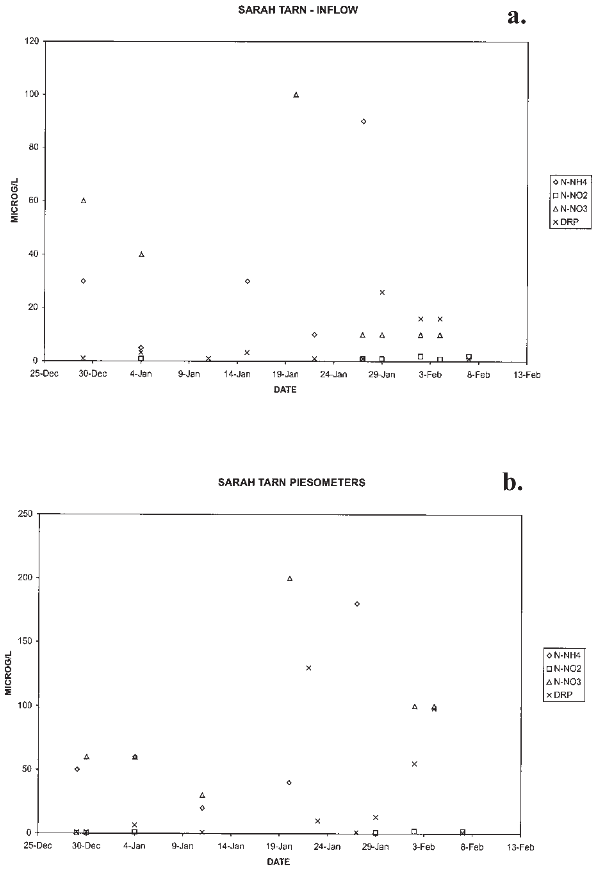

Fig. 4. Concentrations of nutrients in the north-west inflow of Sarah Tarn; **a.** surface inflow, **b.** the lower piezometer

algae and benthic mats of *Nostoc* and *Phormidium*. The deepest and largest lakes are Progress (depth 45 m, area 10 ha) and Nella (depth 18 m, area 13 ha).

Since 1986, significant human impact on lakes and catchments of Broknes has been mainly limited to the four scientific stations and to the construction of the road network used by wheeled and tracked vehicles. Unfortunately, some vehicle use has also occurred in areas that do not have roads. With the Russian airfield operating on the ice plateau 3 km south of Broknes (Fig. 1) during 1987–92 additional road traffic has occurred. Smaller impacts are generated by station staff and other expedition members and by recreational walkers on Broknes. The number of tourists visiting the area, mostly in summer as helicopter landings from ships to station areas, may reach a few hundred. Their stay in the Larsemann Hills is usually limited to areas close to the stations and as it lasts only a few hours is unlikely to cause significant impact on the catchments (Burgess *et al.* 1992, Burgess & Kaup 1997).

Material and methods

For the local precipitation background snow and firn were sampled on 30 December 1997 at depths of 10–98 cm at four locations along the 3000 m runway (not used since 1992) situated 3 km south of Broknes on the ice plateau (Fig. 1) where the snow accumulation in the winter of 1997 was 40 cm. Fresh snow upwind of Law base was sampled three times during the snowfall of 6–7 February. Nutrients, conductivity and $\delta^{18}O$ were monitored by ceramic tipped piezometers in subsurface lake inflows from the end of December to the beginning of February 1997–98 in near-natural and human impacted catchments on Broknes. The piezometers used were plastic tubes with an inner diameter of 15 mm and 5 cm long ceramic tips. They were installed in close fitting holes made in melted ground with an ice axe handle to minimize soil disturbance. Samples were taken from the piezometers with a hand pump every 2–7 days between 29 December and 5 February. Surface inflows were sampled directly into 200 ml acid-washed plastic containers beginning on 24 December.

Samples were filtered through acid-washed Whatman GF/C filters within three hours in the field laboratory at Law Base. A Hach DR/2000 spectrophotometer was used to analyse nutrients on the day of sampling. A molybdate-ascorbic acid method was used for DRP, a salicylate cyanurate method for NH_4, a 1-naphtylamine method for

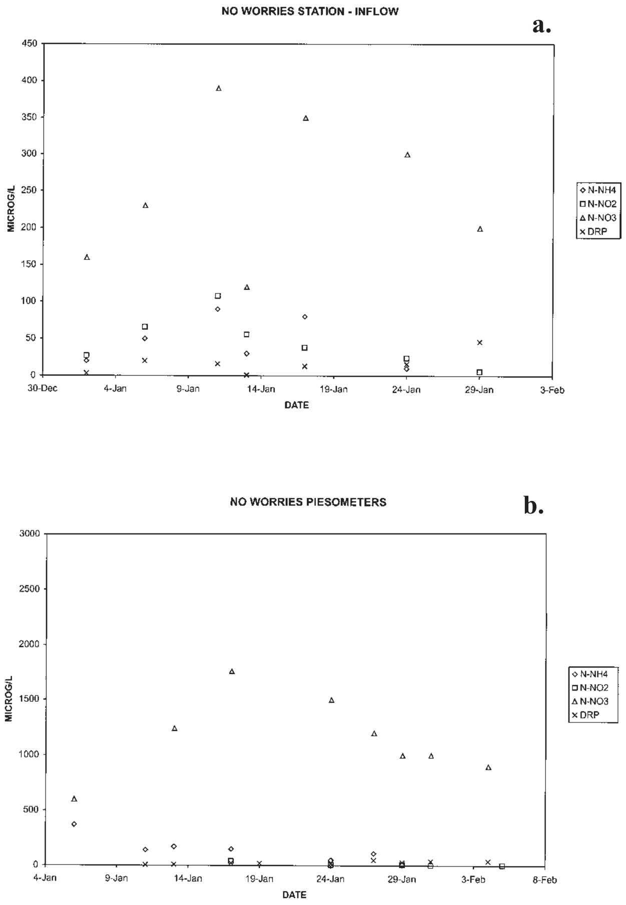

Fig. 5. Concentrations of nutrients in the east inflow of No Worries Lake; **a.** station inflow, **b.** piezometers (average of two).

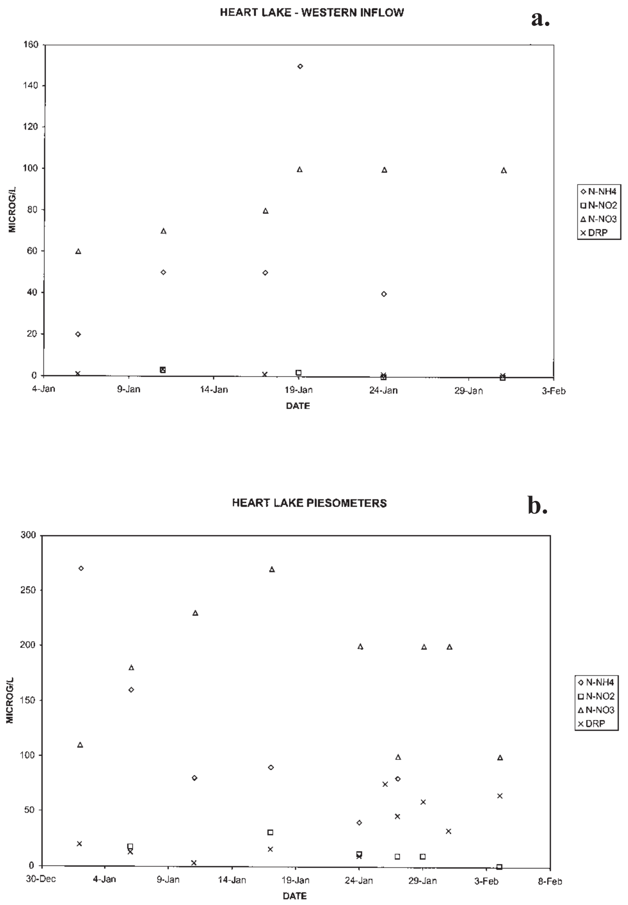

Fig. 6. Concentrations of nutrients in the south-west inflow of Heart Lake; **a.** surface inflow, **b.** piezometers (average of two)

NO_2 and a cadmium reduction method for NO_3 (Mackereth *et al.* 1978, Ellis-Evans 1992). Conductivity was measured with a Hanna probe. The samples for $\delta^{18}O$ (SMOW) were kept 4–5 months at 0–5°C in 20 ml glass vials with tin foiled caps until measurement. The measurements were carried out in the Isotope Palaeoclimatology Laboratory of the Institute of Geology in Tallinn using a Finnigan MAT Delta E mass-spectrometer.

Sampling sites

Sampling was conducted in three near-natural catchments where direct human impact has been limited to some walking and in five catchments with considerable impact from the stations and roads.

Natural catchments

a) An ancient lake bed 200 m south-west of Lake Cameron (Fig. 1)

A flat area *c.* 300 x 150 m, inclined to the south-south-west end where the former lake was probably dammed by a firnfield or ice plateau which has since retreated. The lake bed contains substantial organic material (remains of benthic cyanobacterial mats and mosses) and is fed mainly from the north by meltwater from a snowfield. The surface flow was sampled close to the south-south-west edge of the area where the lower piezometer was located some 2 m from the flow. The upper piezometer was placed near to the inflow from the snowfield and the third piezometer in the middle of the lake bed. As the active layer deepened, on 16 January, the upper piezometer was lowered from 27 to 52 cm, the middle one from 58 to 65 cm and the lower one from 28 to 61 cm.

b) Lake Cameron, south-west inflow area

A small stream fed by snowfields on the south-west slope (Fig. 1) was sampled *c.* 10 m above the lake where the lower piezometer was located 1 m from the edge of the flow. The upper piezometer was *c.* 30 m upstream, next to the flow. On 16 January the piezometers were deepened from 25 to 30 cm. Thereafter the water level was at the soil surface in the upper piezometer and 13–9 cm under the soil surface in the lower piezometer.

c) Sarah Tarn, north-west inflow area

A small area where a delta-like sediment accumulation was

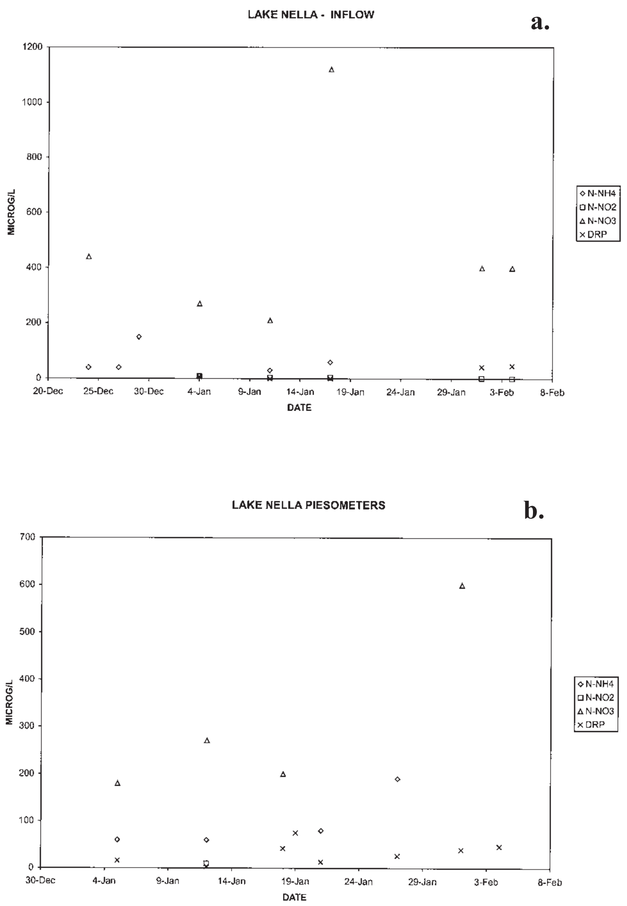

Fig. 7. Concentrations of nutrients in the north inflow of Lake Nella; **a.** the surface flow at Law Base, **b.** the piezometer north of the lake.

fed by a small stream from an upper snowfield (Fig. 1). The lower piezometer was at 57 cm depth *c.* 15 m from the lake, next to the main flow. On 8 January the depth of permafrost was 90 cm and the water level 14 cm below the soil surface. The water level then decreased to 26 cm on 27 January and to 28 cm on 4 February. The upper piezometer was at 20 cm depth *c.* 5 m downslope of the upper snowfield.

Human impacted catchments

a) 'No Worries' Lake, east inflow area

This seepage area is downslope of the Chinese Zhong Shan station buildings (Fig. 1) and receives snowmelt channelled by the station pathways, together with inorganic material resulting from snow-clearing and tracked vehicle traffic. The sediment fan formed on the lower part of the slope contains a considerable amount of silt, which is unusual on Broknes. In 1992–93, the nutrient levels in the soil water were markedly increased with considerable microbial activity resulting in subsurface anoxia. Greasy deposits on the water and soil surface were traced to leaking drums of waste food, and faeces of skuas feeding on this waste also

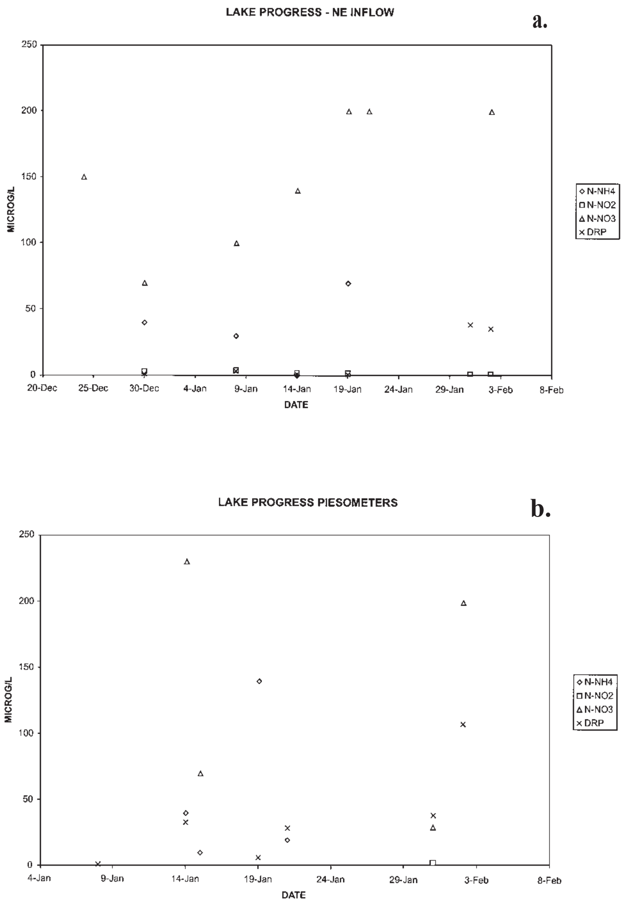

Fig. 8. Concentrations of nutrients in the north-east inflow of Lake Progress; **a.** surface inflow, **b.** piezometer.

contributed to nutrient increase (Ellis-Evans *et al.* 1997). The situation was largely unchanged between 1993–94 and 1997–98, except that the number of skuas being fed had decreased. The stream was sampled a few metres from the lake where piezometers were installed 2 m from the flow at 27 cm depth. The piezometer water level was mostly near the soil surface except on 24 and 29 January when it was 6 and 2 cm above the surface, respectively.

b) Heart Lake, south-west inflow area

The catchment includes a road system with tracked vehicle traffic that channels snow melt from the enlarged (as a result of road making) catchment which includes the northern part of Progress II station (Fig. 1). The roads run predominantly through gneiss. This gneiss breaks up into fine sand and silt as a result of vehicle action and then is very easily mobilized by meltwater. The flat delta-like inflow area also has accumulations of silt. Heart Lake is of great scientific significance, and unpublished data suggests that sediments predating the Last Glacial Maximum occur in the lake (D. Hodgson, personal communication 2000). Unfortunately, considerable vehicle traffic occurs within the lake catchment, which may be unavoidable, but further

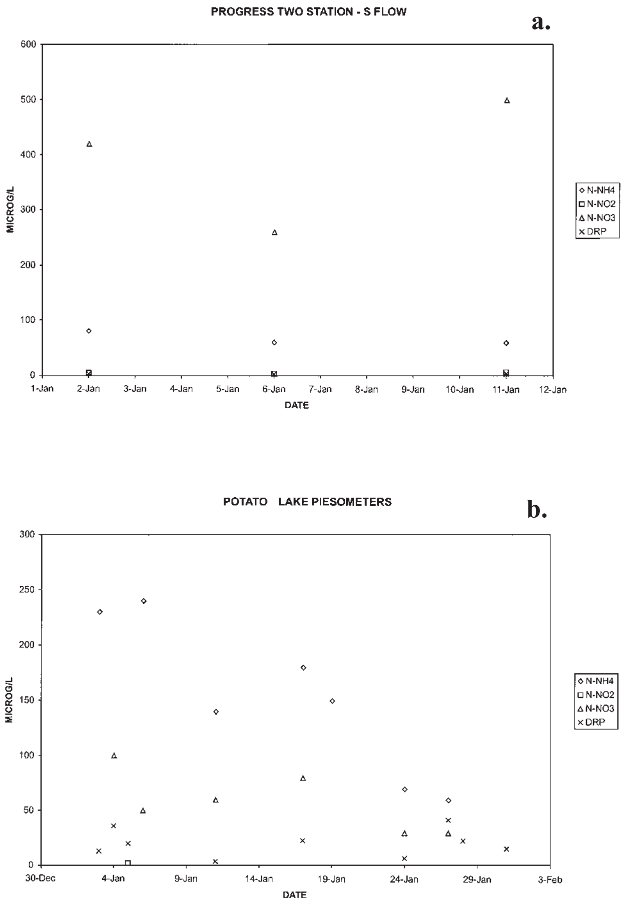

Fig. 9. Concentrations of nutrients at Progress 2 Station; **a.** the southern surface flow, **b.** the piezometer at 'Potato Lake'.

development in the lake catchment needs to be curtailed. Piezometers were established at 20 and 31 cm depth 2 m and 7 m distant from the sampling point of the main surface flow *c.* 50 m from the lake. The water level in the piezometer closest to the flow was 6 cm and 17 cm beneath the surface on 24 and 29 January, and 2 cm and 10 cm in the piezometer furthest from the flow on these dates.

c) Lake Nella, north inflow area

The *c.* 0.5 km long inflow starts downslope of the Australian Law Base (Fig. 1). The snowfield meltwaters collect various impacts from the base (grease was observed on the water surface). The flow was sampled 20 m from the base. Downhill the flow was increased by contributions from tributary snowfields. At *c.* 150 m north of the lake and 1 m from the flow, a piezometer was installed at 35 cm and lowered to 60 cm on 12 January. The piezometric level was 52 cm beneath the surface on 18 January and 33–40 cm during 27 January–4 February.

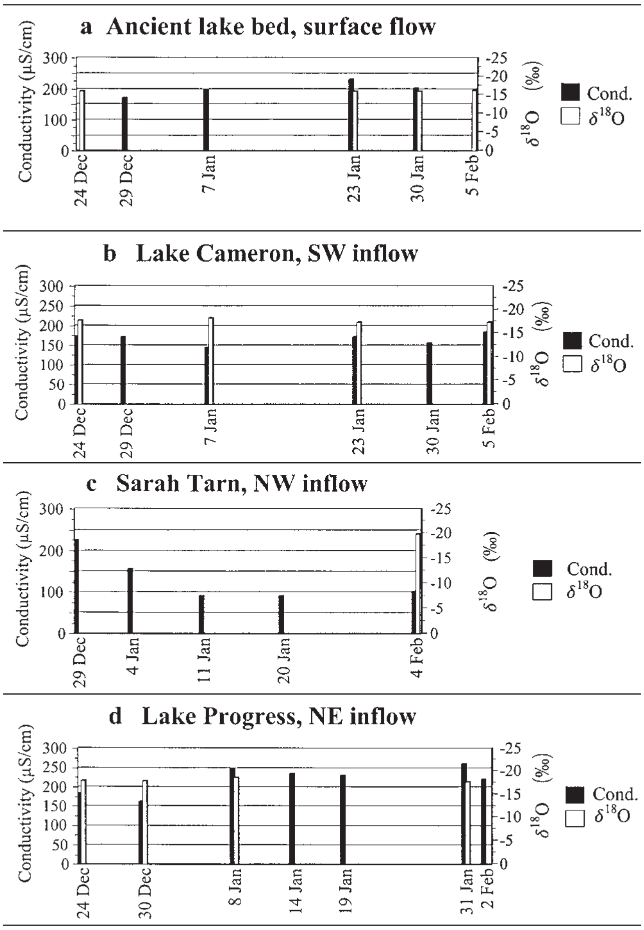

Fig. 10. Conductivity and $\delta^{18}O$ in the surface flows; **a.** ancient lakebed, **b.** south-west inflow of Lake Cameron, **c.** north-west inflow of Sarah Tarn, **d.** north-east inflow of Lake Progress.

d) Lake Progress, north-east inflow area

The catchment of the stream included the Russian Progress I station (Fig. 1), which was abandoned by 1992. However, a refuge, generators, building material and fuel remain. The area is the starting point for the Chinese ice plateau traverse with another refuge positioned there. Australia has a depot of fuel drums used for helicopter refuelling in the area. The catchment is subjected to considerable vehicle traffic, which has increased rapidly since 1999 with the building of a new Russian airport on the ice plateau and the continued use of the Chinese traverse. The stream was sampled *c.* 20 m above the lake, the piezometer was installed at 35 cm on a slope *c.* 20 m from the stream. Water level in the piezometer rose from 14 cm beneath the surface on 8 January to 2 cm

Table I. The composition of snow & firn from the ice plateau runway and of fresh precipitation at Law Base.

Locality/period	*n*	DRP µgP l^{-1}	Conductivity µS cm^{-1}	$\delta^{18}O$ ‰
Runway				
Winter	3	0–10	9–19	-23.3–25.6
Summer	5	3–10	13–89	-17.0–20.0
Fresh snow				
6–7 February	3	0–6	20–41	-13.8–17.4

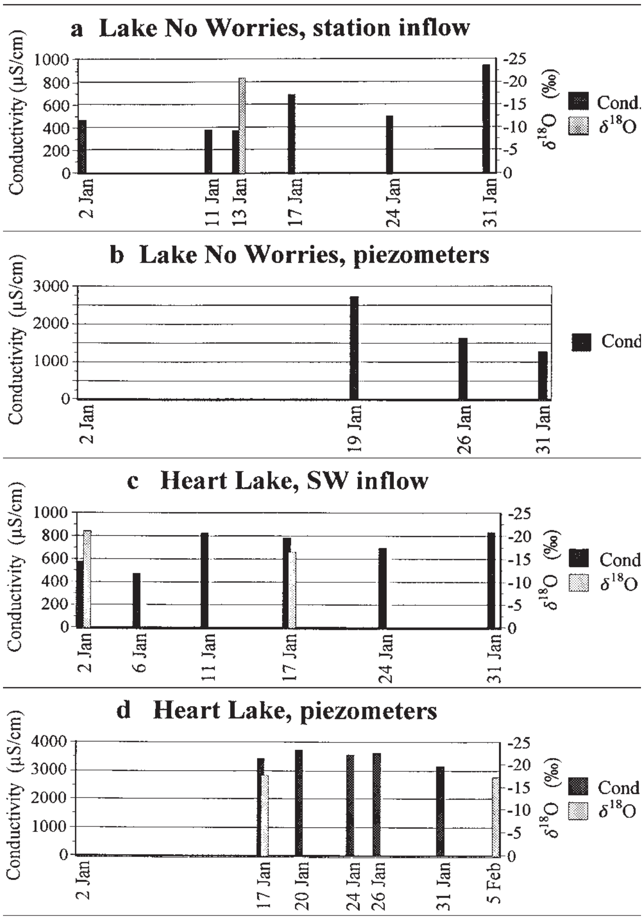

Fig. 11. Conductivity and $\delta^{18}O$ in the surface flows and in the piezometers; **a.** Lake 'No Worries' station inflow, **b.** Lake 'No Worries' piezometers (average of two), **c.** Heart Lake south-west inflow, **d.** Heart Lake piezometers (average of two).

on 31 January.

e) Progress II station area

A small stream drains the southern part of the Russian station (Fig. 1), which includes the kitchen, and, flowing partly onto the south-directed road, discharges into the ocean**.** Samples were taken *c.* 20 m before the ocean discharge. A piezometer was installed *c.* 200 m north of the latter site at 41 cm depth *c.* 10 m from the small 'Potato Lake'. Its catchment in the station includes the workshop and the road through the station. Flow down the road to the south-west of 'Heartbreak Hill' (beyond the station) was sampled before the discharge from the road to land.

Results

Precipitation

In eight snow and firn samples taken from the former runway on the ice plateau, DRP was under 10 µgP l^{-1}. Conductivity in samples of winter snow was under 19 µS cm^{-1} and in five summer samples between13–89 S cm^{-1}. The $\delta^{18}O$*,* generally increased when conductivity increased and was between -23.3 and -25.6‰ in the three winter samples and -17.0 and -20.0‰ in the five summer samples. In three samples of fresh snow at Law Base up to 6 µgP l^{-1} DRP was measured, conductivity was 20–41 µS cm^{-1} and the $\delta^{18}O$ ranged from -13.8 to -17.4‰ (Table I).

Catchment waters

DRP

In natural catchments the DRP in the surface flows generally increased during summer by up to 13–30 µgP l^{-1} close to the end of the flow period (20 December–7 February). In subsurface waters the DRP varied irregularly, with pulses of lower and higher levels, the maximum levels being between 36 and 173 µgP l^{-1} (Figs 2–4, Table II). The maximum recorded level of 310 µgP l^{-1} occurred in the upper piezometer at Sarah Tarn on 24 January.

In human impacted catchments the DRP in the surface flows also generally increased during summer by up to 39–46 µgP l^{-1} except in Heart Lake inflow, in the southerly flow from Progress II station and the roadflow from 'Heartbreak Hill' where it remained under 3 µgP l^{-1}. In subsurface waters pulses of low and high DRP levels reached 42–108 µgP l^{-1} close to the end of flow (Figs 5–9, Table II).

Table II. The ranges of nutrient concentrations (µgP or N l^{-1}) in surface (numerator) and subsurface piezometer (denominator) waters in natural and human impacted catchments from 24 December 1997 to 7 February 1998.

	Natural catchments			Human impacted catchments				
Nutrient	Ancient lakebed	Lake Cameron	Sarah Tarn	Lake No Worries	Heart Lake	Lake Nella	Lake Progress	Progress II station
DRP	0–13	0–29	0–30	0–46	0–3	0–46	0–39	0–3
	7–173	3–36	0–310	6–52	3–75	3–75	0–108	3–42
$N–NH_4$	0–30	0–50	0–30	10–90	20–150	30–150	0–70	60–80
	50–150	40–125	20–180	50–370	40–270	60–190	50–140	60–240
$N–NO_2$	1–3	1–3	0–2	6–108	0–3	1–9	1–4	4–6
	2–23	0–2	0–2	2–41	1–31	5–10	0–2	2–3
$N–NO_3$	20–100	0–100	10–100	160–390	60–90	210–1120	70–200	60–500
	130–400	25–100	30–200	600–1760	100–270	180–600	50–230	50–100

N–NH4

In natural catchments, the surface flows showed no significant trends of NH_4. The maximum levels were between 30–50 µgN l^{-1}. In subsurface waters, the maximum NH_4 levels were 125–180 µgN l^{-1} in the middle or at the end of flow (Figs 2–4).

In human impacted catchments, generally higher NH_4 levels 70–150 µgN l^{-1} in the surface flows were recorded in the middle of the flow period. In subsurface waters the maximum NH_4 levels varied between 140–370 µgN l^{-1} (Figs 5–9, Table II).

N–NO2

In natural catchments the maximum NO_2 levels were 2–3 µgN l^{-1} in surface flows and 2 µgN l^{-1} in subsurface waters (Figs 2–4). The ancient lake bed was an exception with values up to 23 µgN l^{-1} recorded by the end of flow in the lower piezometer.

In human impacted catchments the maximum NO_2 levels in surface flows ranged from 3 to 9 µgN l^{-1} but in 'No Worries Lake' inflow 108 µgN l^{-1} was recorded in the middle of flow. In subsurface waters the maximum NO_2 levels occurred at the same time and reached 10-41 µgN l^{-1}, but in the Lake Progress and 'Potato Lake' piezometers levels only reached 2 µgN l^{-1} (Figs 5–9).

N–NO3

In natural catchments the maximum levels of NO_3 were 100 µgN l^{-1} in surface flows measured on 20–23 January. In subsurface waters, the maximum NO_3 levels were between 100–400 µgN l^{-1} towards the end of flow (Figs 2–4, Table II).

In human impacted catchments the maximum NO_3 levels in the surface flows varied between 90–1120 µgN l^{-1}. In subsurface waters, the maximum NO_3 levels were 100–1760 µgN l^{-1} and mostly in the middle or at the end of flow period (Figs 5–9).

Conductivity and $\delta^{18}O$

Conductivity in the surface flows in natural catchments changed in the flow period between 92 and 231 µS cm^{-1} and $\delta^{18}O$ between -15.9 and -19.8‰ (Fig. 10a–c). In subsurface waters of the ancient lake bed a conductivity of 381 µS cm^{-1} and in those of Sarah Tarn 96 and 104 µS cm^{-1} were measured.

In human impacted catchments conductivity in the surface flows generally increased during the summer (for example in the Law Base flow the values increased from 154 to 520 µS cm^{-1}) and were mostly much higher than in natural catchments, frequently reaching *c.* 500–1000 µS cm^{-1} (Fig. 11a & c). In the southerly flow from Progress II station the values reached 2280 µS cm^{-1}. They remained < 261 µS cm^{-1} in Lake Progress north-east inflow (Fig. 10d). The $\delta^{18}O$ in the surface flows was found to change little during summer, ranging between -16.3 and -20.9‰ (Fig. 10d, Fig. 11a & c). In the subsurface waters of the station inflow to 'No Worries Lake' and of the westerly inflow to Heart Lake conductivity varied between 1274-3740 µS cm^{-1} (Fig. 11b & d). In the subsurface inflow to 'Potato Lake' up to 4370 µS cm^{-1} was measured. The $\delta^{18}O$ changed little also in the subsurface inflows during summer being -17.1 to -17.5‰ in Heart Lake piezometers (Fig. 11d).

Discussion

The results show that DRP was under 10 µgP l^{-1} in snow and firn that had accumulated both in winter and summer over the last few years and in the precipitation events in February. The winter precipitation is differentiated by lower $\delta^{18}O$ and conductivity because of increasing distance from the open sea, (Table I). Similar DRP and DIN under 60 µgN l^{-1} were measured in precipitation and lake shoreline snowbanks in the Larsemann Hills during the 1993–94 summer (Kaup *et al.* 2000). These concentrations are also close to nutrient levels and the $\delta^{18}O$ measurements made in other East Antarctic coastal areas (Haendel & Kaup 1995, Kaup 1998). For example, in nine firn and snow samples close to Thala Hills the average concentrations of total phosphorus and DIN were 3.7 µg P l^{-1} and 92 µgN l^{-1}, respectively. The $\delta^{18}O$ values were between -14.5 and -21.6‰ (Kaup & Vaikmäe 1996). These results indicate that while precipitation is a major source of nutrients for lake catchments, the frequently much higher nutrient levels in the catchment waters originate from other sources and processes.

Measurement of total phosphorus from 24 samples of weathered rock from Broknes (collected on an equally spaced grid during 1994–95) showed that the values varied considerably, with a mean of 140 mgP kg^{-1} and standard deviation of 63 mgP kg^{-1} (Burgess & Kaup 1997). These background levels of P and the extent of weathering were considered insufficient to explain variations in stream and lake concentrations. A contaminated site assessment of locations of possible impacts of Law Base in February 1996 (Australian Antarctic Division, unpublished) showed that in 12 samples of the upper 5 cm of soil horizon the total phosphorus averaged 101 mgP kg^{-1} with standard deviation of 48 mgP kg^{-1}. These data indicate that the porous soils of Broknes do not retain human originated phosphorus in their upper horizons even in areas with considerable greywater and urine loadings. This indicates a need to sample the whole profile of the active layer and the upper permafrost for contaminated site assessments.

The levels of nutrients in surface and subsurface waters of all the catchments studied varied considerably during the flow period. Generally, the higher levels occurred during the last two weeks of the flow in subsurface waters when compared to the levels in surface flows. From the comparison of conductivity and $\delta^{18}O$ data in snowbanks and catchment waters it is evident that meltwater was concentrated through evaporation in the natural soil active layer (cf. also Kaup *et al.* 2000). During the summer conductivities were found to increase in three human impacted surface flows but not in subsurface waters and δ^{18}O data did not show substantial change in evaporation in catchment waters (in Antarctic desert-like conditions meltwater is substantially enriched both in solutes and ^{18}O when undergoing evaporation, cf. Matsubaya *et al*. 1979). Therefore, the increased nutrient levels at the end of summer and in the subsurface flow probably originated from the active layer or upper permafrost rather than from evaporative processes.

In this study, rising piezometric levels were frequently recorded in the active layer by the end of flow period. Subsequent autumn freezing and evaporation of this subsurface water through porous soil may produce evaporites acting as sources of salts for subsequent summers. Chinn (1993) describes small amounts of liquid water within pores in ice in permafrost and salt brines in Antarctic soils which are not flushed by precipitation. These brines may have a patchy spatial distribution and could explain fluctuating nutrient levels in catchment waters. Surface vegetation and subsurface organic matter have also a patchy distribution and, when decaying, may contribute to the fluctuation of nutrient levels both in surface and subsurface waters. The timing and level of these fluctuations obviously depend on the extent and conditions of meltwater penetration into the active layer and subsequent emergence to the surface. These conditions vary with changing climatic conditions and, in particular, with the extent of snow cover. As the active layer grows during summer, more salt brines and decaying organic matter become available for meltwater leaching, and this, together with decreasing amounts of meltwater, could explain higher nutrient levels occurring subsurface towards the end of flow.

In human impacted catchments, the levels of nitrogen compounds were generally much higher than in natural catchments. Increased levels of NH_4 and NO_3 together with high NO_2 levels in some cases, indicate ammonification and further nitrification of organic matter both of natural (ancient lake bed) and of human origin ('No Worries' and Heart Lakes inflow areas). DRP levels in the surface flows of natural catchments were mostly lower than those of the human impacted catchments. However, a few of the highest DRP levels were found subsurface in natural catchments. This also leads to occasional higher DRP levels in natural than in human impacted lakes and has been noted earlier in Broknes (Ellis-Evans *et. al.* 1997, Kaup *et al.* 2000). These higher DRP levels are probably brought about by phosphorus delivery during the decay of surface vegetation (photoautotrophic microorganisms, lichens, mosses) and of subsurface organic matter.

The results from the ancient lake bed and earlier data on fossil organic matter in the upper permafrost on the northern shore of Lake Nella (Burgess *et al.* 1994, 1997) show a considerable spatial distribution of subsurface organic matter on Broknes. The role of subsurface organic matter as a nutrient source for lakes requires further research. However, this role is expected to increase as the active layer deepens with climate warming. Simulations based on modern climatic data and scenarios of climate change for the year 2050 indicate a 20–30% increase in active layer thickness in the Northern Hemisphere, with the largest increases concentrated in the northernmost locations (Anisimov *et al.* 1997). These scenarios of climate change predict substantial warming also in the Antarctic and, in fact, significant climate warming is currently occurring in the region of Antarctic Peninsula (Karlén 1997).

A distinct feature of surface and subsurface waters in human impacted catchments were conductivities that were up to an order of magnitude higher than those in natural catchments. These higher conductivities were not a result of increased evaporation as the δ^{18}O values were largely similar in waters of both catchment types. Winds transport sea spray onto lake catchments in Broknes, and the most human impacted catchments of lakes, 'No Worries', 'Potato' and Heart lie nearest to the sea, immediately downwind of the prevailing winds. However, these lakes did not reveal higher Mg/Ca ratios in water, which are characteristic of increased marine influence, than the ratios in other lakes in Broknes (Gillieson *et al.* 1990). This finding contradicts a marine origin for these increased conductivities. The origin of the salts is thus most likely from:

a) direct salt inputs from stations' activities (wastewater and urine, building materials, chemicals etc.), and

b) intensive rock crushing by tracked vehicles and subsequent increased weathering, indicated by the considerable silt increase in certain areas.

The data collected at all stations in Broknes show, in particular, that 'greywater' and urine seeps quickly into porous lithosols, and may then subsequently enrich surface and subsurface water downslope. In addition, considerable vehicle use has occurred off the roads in Broknes. While the situation described in this paper resulted from the activities before the Madrid Protocol came into force on 14 January 1998, it is highly unlikely that these activities were radically changed after that date in all stations in the Larsemann Hills. Clearly, the current management of greywater and urine pose problems that station managers need to address by revising waste disposal protocols. On the other hand, environmental awareness and responsible behaviour of individuals are required to limit the increasing impact of vehicles. Unless both practices are changed environmental degradation will continue.

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