

CHANGE IN N AND P CONCENTRATIONS IN ANTARCTIC STREAMS AS A RESPONSE TO CHANGE IN PENGUIN POPULATIONS

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ABSTRACT: This study presents changes in the concentrations of nitrogen and phosphorus in two streams in Western Antarctica (Admiralty Bay, King George Island, South Shetlands) that differ in trophic status. The results suggest a decline in concentrations of the determined forms of N and P between 2001 and 2005. The decrease ranged from 9.3% for reactive phosphorus to 73.2% for ammonium-nitrogen. Such inferred declines in N and P concentrations are considered to reflect reduced deposition on land of organic matter brought in from the seas by the penguins nesting in the area. The ultimate cause of this is in turn the steady decline in abundance that is being noted for these penguins.

KEY WORDS: Antarctica, fresh water, nitrogen, phosphorus, penguins population.

INTRODUCTION

The changes in trophic systems taking place in the Southern Ocean in the late 20th and early 21st centuries are being augmented currently by trophic changes in Antarctica's terrestrial ecosystem, both in their turn reflecting global warming (Everson 1977; Russell *et al.* 2006; Moline *et al.* 2004). Climatic warming has been demonstrated for the sub-Antarctic and the Antarctic Peninsula over 4 decades now

(Martianov and Rakusa-Suszczewski 1990; King 1994; Skvarca *et al.* 1998; Cook *et al.* 2005; Turner *et al.* 2005; Turner *et al.* 2007; Stammerjohn *et al.* 2008), and the consequences have included ongoing deglaciation, and hence the appearance of new ice-free areas both along the coast and inland (Birkenmajer 2002).

The terrestrial ecosystem here is strongly interconnected with the marine ecosystem, thanks to a plethora of diverse ecological linkages. The feces organic matter originating in the sea is first and foremost brought in by birds and marine mammals that come to land to either breed or rest (Rakusa-Suszczewski 2003). In this way, ongoing changes (the aforementioned deglaciation plus changes in numbers of the birds and mammals referred to) feed back further through modifications in amounts of organic matter transferred to land. In the face of an ever-larger ice-free area on the one hand, and a decline in seabird populations on the other, it is possible to anticipate the dual effects of reduced transfers of organic matter to land. This organic matter is dispersal over an ever-wider area and dispersal of the organic matter could be a reason of a lowering of its concentrations in given places. Such relative impoverishment of land areas as regards biogenic elements is likely to slow the pace at which land newly exposed from under the ice is first colonized by plants and then undergoes succession. Furthermore, those terrestrial vegetation associations that have developed fully may now start to experience, or may already be experiencing, disrupted functioning.

The work detailed here has sought to consider the influence of changes in nesting populations of penguins on the trophic statuses of two different streams. Work done in 2001 and 2005 involved the mouth sections of the oligotrophic Petrified Forest Creek and the mezotrophic Ornithologists Creek, both located on the western shore of Admiralty Bay (King George Island, South Shetlands, West Antarctica). The results presented may also apply to other land areas of Antarctica subjected to similar changes.

STUDY AREA

Admiralty Bay falls within the sub-polar climatic zone, which is characterised by strong winds, high air humidity, precipitation totals exceeding 505 mm, major weather changes over 24-hour periods and marked fluctuations in air temperature (from -32°C to $+16^{\circ}\text{C}$) (Kratke and Wielbińska 1981, Styszyńska 1990; Marsz and Styszyńska 2000).

The watercourses studied are on the western shore of Admiralty Bay (Fig. 1), and are known to differ from each other in trophic status and type of drainage basin. Petrified Forest Creek (length c. 1300m) is an oligotrophic stream whose catchment is of initial soils, with no colonies of penguins present. The birds nesting here are mainly brown skuas (*Catharacta antarctica*). In turn, Ornithologists Creek (length c. 1100 m) is a mezotrophic stream flowing along most of its length through relict

ornithogenic soils. This Creek's drainage basin includes colonies of adelic penguins (*Pygoscelis adeliae*) and gentoo penguins (*Pygoscelis papua*), as well as brown skuas (*C. antarctica*) and giant petrels (*Macronectes giganteus*).

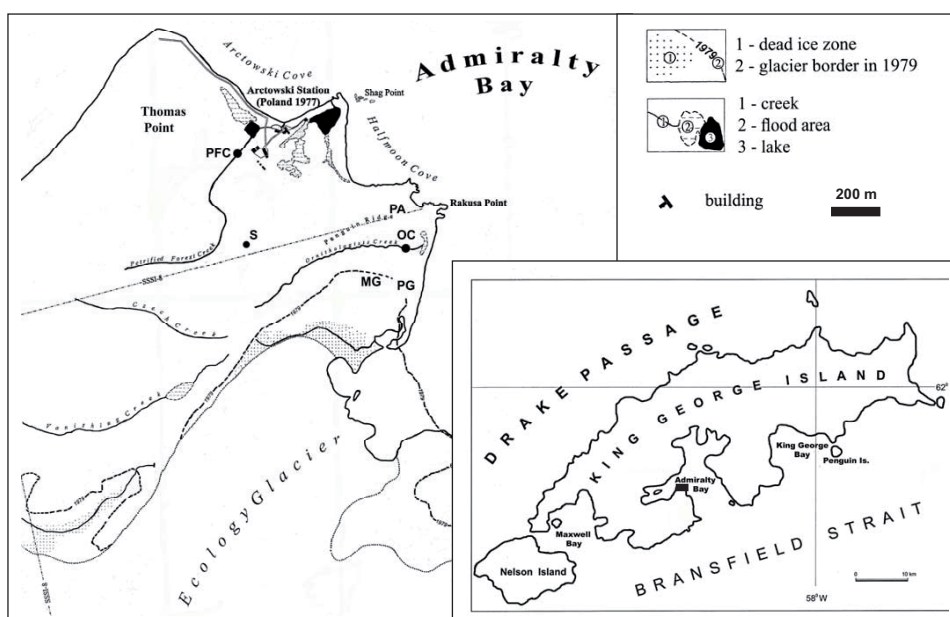


Figure 1. Locations of: water-sampling sites along Petrified Forest Creek (PFC) and Ornithologists Creek (OC), snow-sampling sites (S), and breeding colonies of: adelic penguins *P. adeliae* (PA), gentoo penguins *P. gentoo* (PG) and giant petrels *M. giganteus* (MG)

MATERIAL AND METHODS

Studies carried out in 2001 and 2005 concerned the waters of the mouth sections of Ornithologists Creek and Petrified Forest Creek (Fig. 1). Sampling in 2001 involved 9 samples taken in the January-May period and in November, while that done in 2005 comprised 4 samples taken between January and March inclusive. Then the samples were assayed for inorganic species of nitrogen (nitrite, nitrate, and ammonia nitrogen), total nitrogen (TN), reactive phosphorus (RP), and total phosphorus (TP) according to the standard colorimetric techniques recommended by APHA (1995), using a CARL ZEISS SPECOL-1100 spectrophotometer. Nitrite nitrogen was assayed with sulphanyl acid ($\lambda=543$ nm). Nitrate nitrogen was determined after reduction to nitrites on a Cu-Cd column as nitrites. Ammonium nitrogen was assayed with indophenol blue ($\lambda=630$ nm). Total nitrogen was determined, as nitrates, after mineralisation with potassium persulphate. Organic nitrogen (ON) content was calculated as the difference between total nitrogen and inorganic nitrogen (IN – sum of nitrite, nitrate, and ammonium nitrogen contents).

Reactive phosphorus was assayed using the molybdenate technique with ascorbic acid as a reducer ($\lambda=882$ nm). Total phosphorus, after mineralisation with potassium hypersulphate, was assayed as reactive phosphorus. The difference between the two phosphorus species produced organic phosphorus (OP). Total dissolved solids (TDS) was measured with a WTW LF197 conductivity meter, pH with a HANNA HI 9025 pH-meter.

The resultant data were subjected to statistical treatment involving one-way analysis of variance (ANOVA) at $p<0.05$, using the Statistica 7.1 software (StatSoft Inc. 2006).

RESULTS

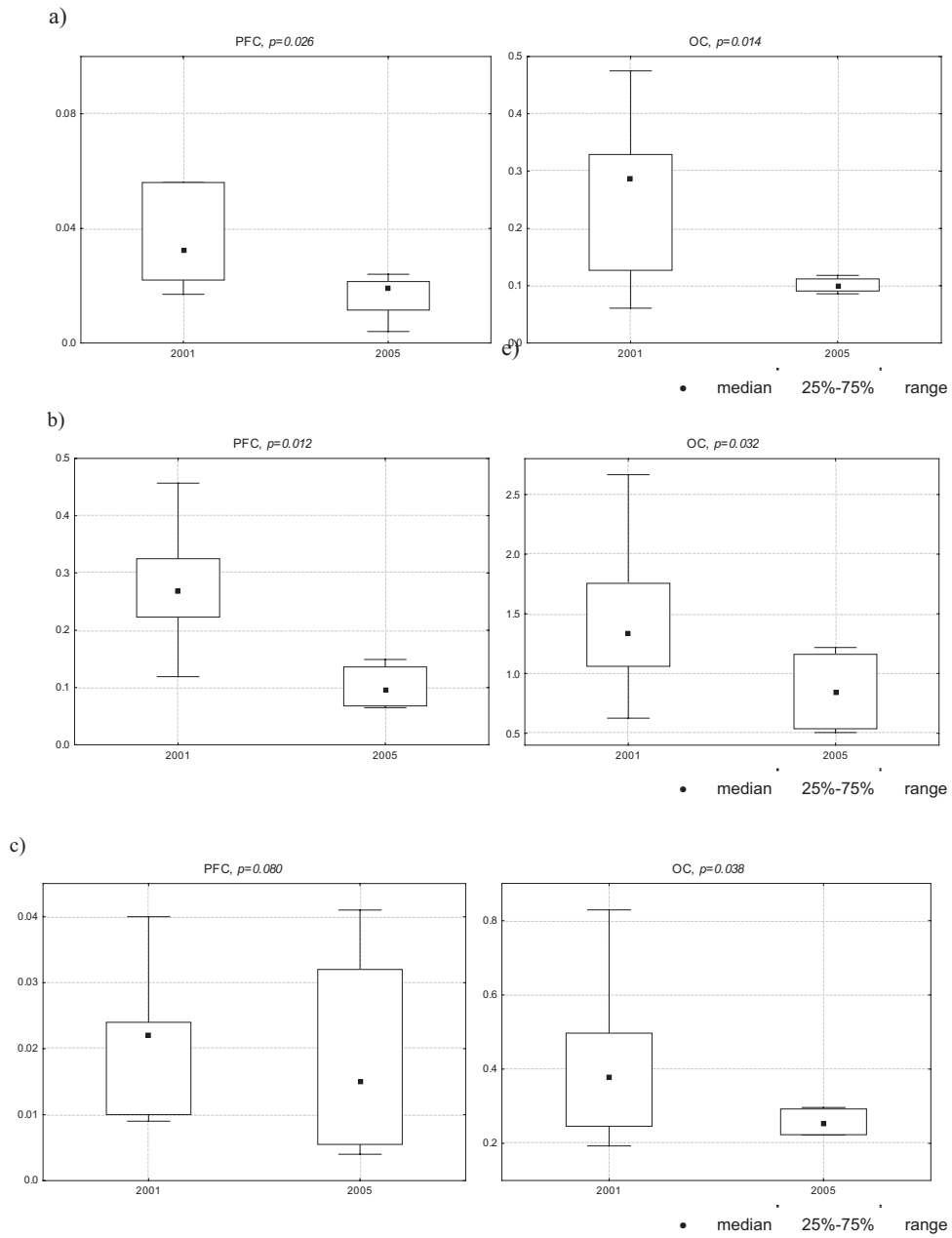
The waters of Petrified Forest Creek were characterised by a neutral or slightly basic reaction, while those of Ornithologists Creek were slightly acid (the respective mean pH values for the two periods were 7.46 and 6.42). Salinities noted were higher in Ornithologists Creek and lower in Petrified Forest Creek, respective mean TDS values for the two research periods being 207.5 and 166.0 mg dm⁻³.

The scope of changes in the determined concentrations of forms of N and P was considerable, ranging from 0.050 to 4.042 mgN dm⁻³, in the case of inorganic nitrogen, for example, as well as from 0.004 to 0.829 mgP dm⁻³ in the case of reactive phosphorus (Tab. 1). Lower concentrations of N and P were noted in the waters of Petrified Forest Creek than in those of Ornithologists Creek, which in fact had more than 10 times as much nitrogen and around 15 times as much phosphorus. The main form of inorganic nitrogen was nitrate-nitrogen, with a particular distinct prevalence of this form over ammonium-nitrogen being noted for the waters of Ornithologists Creek, where it accounted for some 90% of inorganic nitrogen. In turn, the relevant share in the waters of Petrified Forest Creek was of c. 67%. Inorganic nitrogen was the main (c. 69%) component of total nitrogen in Ornithologists Creek, while the opposite situation applied in Petrified Forest Creek, where 60% of total N was in the form of organic nitrogen. In the case of reactive phosphorus, only slight differences in the share of total P this accounted for were noted. In Petrified Forest Creek, reactive P represented 52% of total P, as compared with 60% in the case of Ornithologists Creek.

The comparison between the research periods revealed higher values for both pH and TDS in the two streams, when the 2005 samples were set against those collected and analysed back in 2001 (Tab. 2). Concentrations of nitrite- and nitrate-nitrogen were also higher in the waters of Ornithologists Creek (only) – respectively by 731.4% and 19.4%). In the cases of the remaining indicators analysed, concentrations determined for 2005 samples were lower than had been noted in 2001. That dependences were usually statistically significant (ANOVA, $p<0.05$ – Fig. 2). In Petrified Forest Creek, concentrations of all analysed forms of nitrogen were lower

Table 1. Ranges of concentrations (minima and maxima) and standard deviations (SD) for pH, TDS, determined forms of phosphorus and nitrogen in the waters of Petrified Forest Creek (PFC) and Ornithologists Creek (OC) in 2001 and 2005

Creeks		pH	TDS mg dm ⁻³	RP	mgP dm ⁻³			mgN dm ⁻³				ON	TN
					OP	TP	NO ₂ -N	NO ₃ -N	NH ₄ ⁺ -N	IN			
PFC	2001 n=9	range	6.46- 7.50	0.009- 0.040	0.005- 0.043	0.021- 0.068	0.000- 0.035	0.036- 0.521	0.017- 0.194	0.065- 0.682	0.119- 0.618	0.326- 0.905	
		SD	0.36	39.5	0.011	0.013	0.017	0.011	0.154	0.060	0.201	0.150	0.193
	2005 n=4	range	7.80- 8.01	174-205	0.004- 0.041	0.006- 0.024	0.013- 0.065	0.000- 0.010	0.030- 0.092	0.004- 0.024	0.050- 0.126	0.065- 0.149	0.135- 0.200
		SD	0.09	14.1	0.017	0.007	0.023	0.005	0.027	0.009	0.032	0.041	0.032
OC	2001 n=9	range	5.57- 6.55	0.193- 0.829	0.087- 0.982	0.282- 1.677	0.002- 0.014	0.334- 3.717	0.061- 0.475	0.639- 3.973	0.626- 2.666	1.970- 6.450	
		SD	0.39	46.4	0.215	0.324	0.519	0.004	1.067	0.149	1.060	0.707	1.530
	2005 n=4	range	6.09- 7.54	229-254	0.223- 0.297	0.044- 0.221	0.341- 0.445	0.003- 0.187	1.430- 3.921	0.086- 0.118	1.723- 4.042	0.506- 1.218	2.229- 4.260
		SD	0.67	11.9	0.040	0.075	0.048	0.089	1.040	0.014	0.883	0.363	1.309



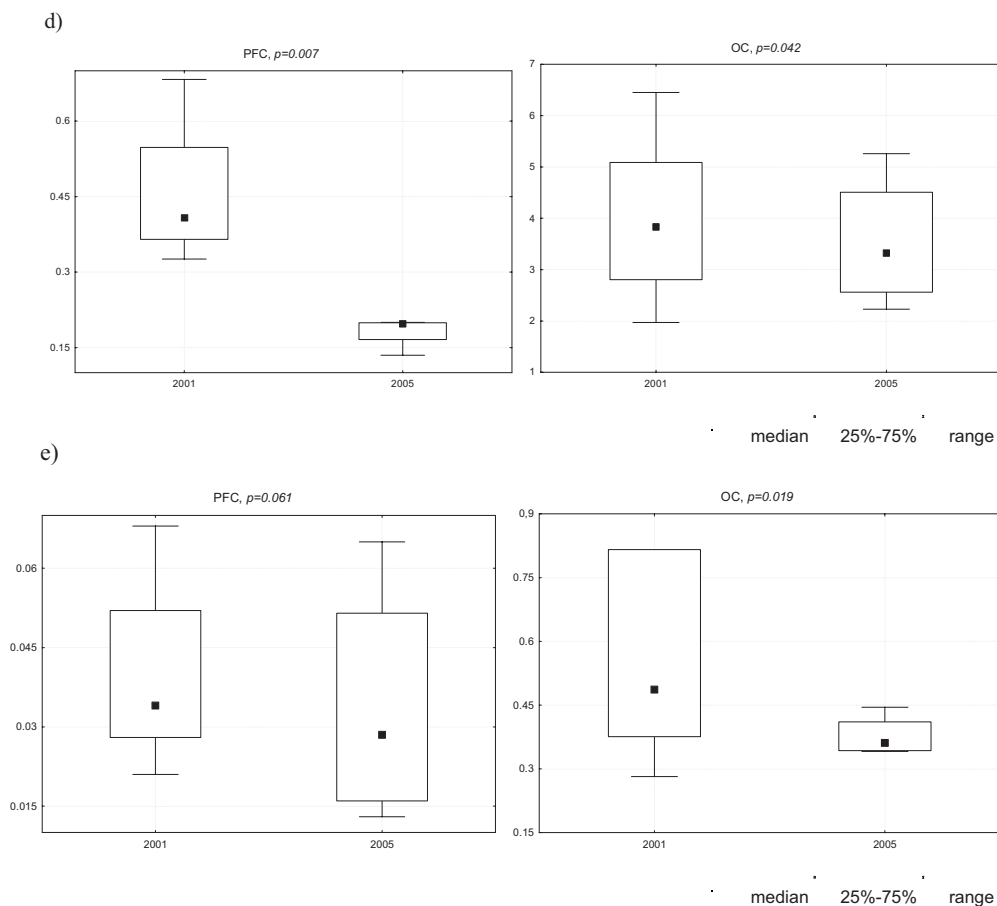


Figure 2. The differentiation of concentration: a) – ammonium-nitrogen; b) – organic nitrogen (ON); c) – reactive phosphorus (RP, mgP dm⁻³); d) – total nitrogen (TN, mgN dm⁻³); e) – total phosphorus (TP, mgP dm⁻³) at Petrified Forest Creek (PFC) and Ornithologists Creek (OC) in 2001–2005

The dependences statistically significant (ANOVA, $p < 0.05$).

– in some cases by more than 50% and *in extremis* by 73.2% (in the case of ammonium-nitrogen) (Tab. 2). In turn, the comparisons between the recent and earlier concentrations of phosphorus compounds suggested more limited change (these in no case being more than 25% lower).

In Ornithologists Creek, the concentration of total N was not more than 10% lower, while the concentration of ammonium-nitrogen was 60.5% lower. Compared with Petrified Forest Creek, Ornithologists Creek had waters in which concentrations of the determined forms of P were down by 39.2% in the case of reactive phosphorus, and 62.1% in the case of organic phosphorus (Tab. 2).

Table 2. Mean values for determined indicators in the mouth sections of Petrified Forest Creek (PFC) and Ornithologists Creek (OC) in 2001 and 2005, as well as the percentage difference (bold) noted for the comparisons between the later and earlier figures

Creeks	pH	mg dm ⁻³						mgN dm ⁻³			
		TDS	NO ₂ ⁻ -N	NO ₃ ⁻ -N	NH ₄ ⁺ -N	IN	ON	TN	RP	OP	TP
PFC	2001	140.3	0.005	0.116	0.062	0.182	0.305	0.487	0.021	0.019	0.040
	2005	191.8	0.003	0.061	0.017	0.081	0.102	0.183	0.019	0.015	0.034
	Increase	36.7									
	Decline		34.1	47.3	73.2	55.7	66.5	62.5	9.3	22.4	15.6
OC	2001	170.9	0.007	2.117	0.257	2.381	1.527	3.908	0.424	0.313	0.737
	2005	244.0	0.055	2.529	0.102	2.685	0.849	3.534	0.258	0.119	0.377
	Increase	42.8	731.4	19.4		12.8					
	Decline				60.5		44.4	9.6	39.2	62.1	48.9

DISCUSSION

The values for the analysed hydrochemical indicators reported for the two streams were typical for fresh waters in the Antarctic close to the sea. Numerous other studies have yielded similar ranges of values (e.g. Howard-Williams *et al.* 1989, Vinocur and Unrein 2000, Elster and Komarek 2003 or Toro *et al.* 2007). Like those in other climatic zones, the lotic waters of Antarctica are open ecosystems whose primary production is conditioned by the influx of allochthonous matter. At the same time, and as numerous studies have made clear, primary production is relatively low at the lotic waters of Antarctica, even where waters are very rich in biogenic elements (Peterson *et al.* 1986; Vincent and Howard-Williams 1986; Howard-Williams *et al.* 1989; Elster and Komarek 2003).

The fact that pH values in Petrified Forest Creek were higher than previously may reflect the slightly greater productivity of the stream, as demonstrated by Elster and Komarek (2003). Thanks to the relatively weak buffering capacity of Antarctic streamwaters, even quite minimal changes in levels of primary production may give rise to marked changes in reaction (Toro *et al.* 2007). As Elster and Komarek (2003) suggested, the acid reaction demonstrated for Ornithologists Creek may reflect the decay of penguin guano in its catchment, as well as the influx of acidic waters infiltrating ornithogenic soils demonstrated by Juchnowicz-Bierbasz (1999) and Juchnowicz-Bierbasz and Rakusa-Suszczewski (2002).

Streamwaters in Antarctica are fed by melting glaciers and permafrost, as well as by melting snow, this fact accounting for their low salt content. Equally, however, it is typical for marine aerosols to raise salinity levels – in the coastal zone in particular (Caulkett and Ellis-Evans 1997; Toro *et al.* 2007). As Nędzarek and Rakusa-Suszczewski (2007) showed, average conductivity of rain on the least-elevated coastal terrace (at 2 m a.s.l.) was 1613 $\mu\text{S}/\text{cm}$. The streams studied here had low salinities, the higher TDS concentration in Ornithologists Creek probably being shaped by the marine aerosol effect referred to.

The lakes and streams of Antarctica range in trophic status from the ultra-oligotrophic through to the hypertrophic, the conditioning factor here being the influx of biogenic elements from nutrients brought to land by seabirds and marine mammals (Vinocur and Unrein 2000; Rakusa-Suszczewski 2003).

The noted enriched trophic status of Ornithologists Creek is the known effect exerted by the very close proximity of seabird colonies, as well as the nature of the catchment, which has ornithogenic soils rich in nitrogen and phosphorus compounds. The waters infiltrating them are thus enriched in N and P, there being particularly high concentrations of nitrate-nitrogen as a reflection of guano mineralisation and nitrification (Juchnowicz-Bierbasz 1999; Tatur 2002; Juchnowicz-Bierbasz and Rakusa-Suszczewski 2002). This stream thus shows a prevalence of non-autotrophic biological activity (Elster and Komarek 2003).

In contrast, Petrified Forest Creek is an autotrophic stream with low concentrations of biogenic elements, since its catchment lies beyond the area of direct impact

of seabird colonies and is – therefore – built of N- and P-poor mineral soils at an early stage of development. The differences in primary production indicated by Elster and Komarek (2003) reflect the different proportions noted when it comes to the shares of different forms of inorganic and organic nitrogen comprising total N. In Petrified Forest Creek, organic nitrogen represents 60% of total nitrogen – a typical ratio for waters in which autochthonous production prevails over allochthonous influxes of matter (Elster and Komarek 2003). A prevalence of the influx of allochthonous matter was in turn observed in Ornithologists Creek, in which 69% of total N was accounted for by inorganic nitrogen.

In the case of the determined forms of phosphorus there is less sign than previously of differences in the percentage shares of total P accounted for by the mineral (reactive) form, the proportions being 52% and 60%. On account of its being able to bind permanently to alluvial material, phosphorus is a less labile element than nitrogen, and is only to a much lesser degree leached out of ornithogenic soils by percolating water. This is why P concentrations are lower than those of N even in streams that under major pressure from breeding colonies of seabirds or marine mammals (Tatur and Myrcha 1984; Juchnowicz-Bierbasz 1999).

If they represent a genuine downward trend (as seems likely), the lower concentrations of the different forms of N and P in the streams now, as opposed to before, are probably a reflection of declines in local penguin populations. Data presented by Angiel and Korczak (2008) show that the study area has probably experienced a 70+% decline in the population of penguins over the last 3 decades (Tab. 3). Recent studies have found that many penguin populations in the Antarctic Peninsula have been in decline over the past 5–20 years (Woehler *et al.* 2001, Sander *et al.* 2007). This decrease in populations has stimulated several attempts to interpret these changes in relation to such diverse factors as human disturbance, climate change, and reduced food availability (Croxall *et al.* 2002, Weimerskirch *et al.* 2003, Lescroëil and Bost 2006).

Tables 3. The number of breeding pairs of penguins on Admiralty Bay, King George Island in 1979–2006 (after Jabłoński 1984¹, Ciaputa and Sierakowski 1999², Angiel and Korczak 2008³)

Penguins	1979 ¹	1990 ²	2006 ³	Decline (%)*	
				a	b
<i>Pygoscelis papua</i>	3703	2401	3093	16.5	-
<i>Pygoscelis adeliae</i>	32918	15609	7375	77.6	52.7
<i>Pygoscelis antarctica</i>	5712	3026	1116	80.5	63.1

*Percent (%) decline describes the overall change in the number of breeding pairs between: a) 1979 and 2006; b) 1990 and 2006.

In the same period, the study area has also been subject to ongoing deglaciation, the ice-free area on King George Island having increased from 21 to 38 km² (Braun et al. 2001). In the 1970s, the mass of penguin guano deposited on land in the Admiralty Bay area was an estimated 230 t a year (Rakusa-Suszczewski 2003). The more than 70% fall in the local population of penguins already alluded to (Tab. 3) can be assumed to have resulted in a decline in guano deposition to just 70 t annually at present. This obviously suggests a major decline in the input of organic matter and biogenic elements into the ecosystem in question. It further needs to be stressed how the 70 tones of guano referred to are now the source of elements otherwise in short supply for a far larger ice-free area of land than there was previously. While the “main centres of nutrient inputs” constituted by the rookeries and their immediate surroundings (up to c. 400 m around colonies, according to the author’s own unpublished data) continue to supply a considerable load of biogenic elements, the areas inland of them are presumably obtaining ever more limited enrichment in N and P. This reflects the role of precipitation as the main agent transporting these elements inland (Nędzerek and Rakusa-Suszczewski 2007). As is made clear by presentations of determined N and P concentrations in snow sampled in 2001 and 2005 some 400 m from the centre of the breeding colony (Tab. 4), a downward trend for concentrations of biogenic elements in precipitation is to be anticipated. While the snow-sampling site is really not far from the breeding colony, concentrations of N and P are quite markedly lowered there – by as much as 80% in the case of phosphorus. One implication of this may be the observed fact that N and P concentrations in the watercourses studied (Petrified Forest Creek in particular) are now considerably lower than they were.

Table 4. Differences in N and P concentrations in snow fall sampled 400 m from the penguin colony in 2001 and 2005

Years	NO ₃ ⁻ -N	NH ₄ ⁺ -N	TN	TRP	TP
	mgN dm ⁻³			mgP dm ⁻³	
2001	0.020	0.056	0.349	0.020	0.040
2005	0.019	0.042	0.287	0.004	0.008
Decline (%)	5	25	17.8	80	80

If the inputs of N and P into the study area’s initial soils have declined as much as the figures suggest, the consequences may be negative, not only for newly ice-free areas of land – whose steady colonization by vegetation has been observable up to now, but also for areas that had become distinctly nutrient-rich previously, but may now be undergoing a nutrient impoverishment that may ultimately convert them into nutrient-poor ecosystems of the typical Antarctic tundra kind.

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