



Residual contamination and environmental effects at the former site of Vanda Station, Antarctica

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TITLE: **Residual contamination and environmental effects at the former site of Vanda Station, Antarctica.**

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Executive Summary

Vanda Station was New Zealand's only base on the mainland of Antarctica from 1968 – 1993, when it was regularly occupied by a small team of people over the summer field season. The base was decommissioned and removed in 1993/94, as the level of Lake Vanda rose, threatening to inundate the site. Contaminated soil was removed from the site during the decommissioning process, but environmental assessments in 1996/97 identified minor residual contamination of soils close to buildings, helicopter pads and in "Greywater Gully", a low-lying area formerly used for the disposal of greywater waste from the base. Trace elements, hydrocarbons and nutrients were the principal contaminants identified, and their potential impact on lake water quality and microbial mat health, when soils flooded, was predicted to be minor. In the 2014/15 summer field season, 20 years after the removal of the station and with the site now mainly under water, another environmental assessment has been undertaken to test these predictions.

Lake water samples were collected from the surface, middle and base of the water column above 6 sites of former contamination near the base, as well as 2 control sites further west. Sediment pore waters were collected from these sites also. Shallow surface waters were collected from recently flooded helicopter pads, together with sediments from these sites and dry soils from the small area of the original base footprint that remains above water level. Waters, soils and sediment were analysed for a suite of chemical contaminants that could be present in this environment, and the species diversity in the microbial mats growing on contaminated sediments was determined.

This assessment revealed little evidence of elevated nutrient, trace element or organic contaminant (hydrocarbons or other synthetic organic chemicals) concentrations in the lake water that has flooded Greywater Gully and the helicopter pads. The lack of contamination emanating from previously identified contaminated Greywater Gully sites is likely to be largely due to the lack of mixing between sub-surface saline fluids and overlying lake water, together with relatively low levels of soil contamination and a high degree of dilution of any mobilised contaminants.

Healthy and luxurious microbial mats were observed within Greywater Gully, possibly responding to high nutrients availability in the more contaminated soils. Preliminary genetic sequencing of cyanobacteria indicates no variation in speciation from expected microbial mat composition in the Dry Valleys.

Exposed dry soil on the former station's footprint was moderately (though very locally) contaminated with hydrocarbons, Pb and Zn, at some of the sites sampled. There was also visible building detritus, wood and metal rubbish on the surface of the ground around the former station site and helicopter pads, and orange marker paint (Pb-based) on rocks at the helicopter pads and the survey point.

Recommendation:

The opportunity still exists to remediate the remaining contaminated soil at the former site of Vanda Station. The removal of visible rubbish from the soil and extraction of diesel-contaminated soil would reduce the risk of localised environmental effects on the lake water. This should include removing the orange-painted marker rocks, including those now residing at the Vanda Huts helicopter pad.

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1 Introduction

Human occupation of the Antarctic continent has inevitably led to contamination in the environment, and in areas of concentrated activity, such as around occupied and historic bases and stations, soils are often visibly contaminated by fuel residues and solid wastes. Although internationally agreed protocols, such as the Madrid Protocol of 1991, have led to attempts to minimise contamination (Vincent, 1996; Waterhouse, 1997), prior to their implementation there were less stringent controls on the use, storage and disposal of potential contaminants and less appreciation of the risk posed to the environment by inappropriate use and disposal of these substances. Consequently environmental contamination exists at many current and former locations of human occupation, with one example being the site of the former Vanda Station (Waterhouse, 1997).

Vanda Station, operated from 1968-1993 and was located beside Lake Vanda in the Wright Valley, Antarctica (refer Figures 1). It was New Zealand's only research station located on the Antarctic Continent and supported field parties operating throughout the McMurdo Dry Valleys. Its occupation, along with weaker environmental standards and considerations of the day, led to minor environmental contamination (Sheppard et al., 1994; Waterhouse 1997; Webster et al., 2003). "Greywater Gully", immediately south of the base site, received regular greywater disposal during the early years of occupation, receiving wastes containing detergents, food oils, cleaning water, and occasionally, lesser quantities of laboratory wastes including photographic solvents (Sheppard et al., 1993 & 1994). Fuel spills and leaks occurred in and around the station, with individual spills of up to 60L, as a result of poor practice and protocol (Sheppard et al., 1994; Waterhouse, 1997).

Lake Vanda is a closed basin lake (i.e. it has no outlet) and its level is set by the balance of inflowing water from the Onyx River and ablation from the perennial ice surface (Chinn, 1993). Hydrological monitoring since 1969 has indicated that the lake's level has been, and still is, rising (Chinn, 1993; Green & Lyons, 2009), as shown in Figure 2. A decision to decommission and dismantle the station was made in 1993, due to the risk of flooding and a change in NZ's scientific focus in the Dry Valleys. The decommissioning process was comprehensive in its attempts remove contaminants and restore the area to a natural state (Hayward et al., 1994; Waterhouse, 1997). The process included:

- The removal of all manmade structures both above and below ground
- Identification and remediation of the most contaminated sites to avoid leaching or diffusion of contaminants into Lake Vanda
- Identification of potential hazards to the lakes scientific values
- Restoration of surfaces to as natural form as possible
- Removal of 15 tonnes of heavily contaminated soil.

Following decommissioning, studies of contamination at Vanda Station identified localised areas of hydrocarbon, trace metal, and nutrient contamination (Aislabie et al., 1999; Hawes

et al., 1999; Webster et al., 2003; Webster-Brown & Webster, 2007). Although discrete, there was evidence that these pollutants would remain in the soil around the former station's footprint and helicopter pads for some time to come (Aislabie et al., 1999; Webster et al., 2003). These studies concluded that there was limited potential for contaminants to effect Lake Vanda, except through the inundation of the station site when flooded soils could release some contaminants into the water column, where they could locally affect microbial growth and speciation (Webster et al., 2003; Hawes et al., 1999). Lake Vanda is an ultra-oligotrophic lake (Canfield & Green, 1985) and any release of contaminants could adversely affect its water quality.

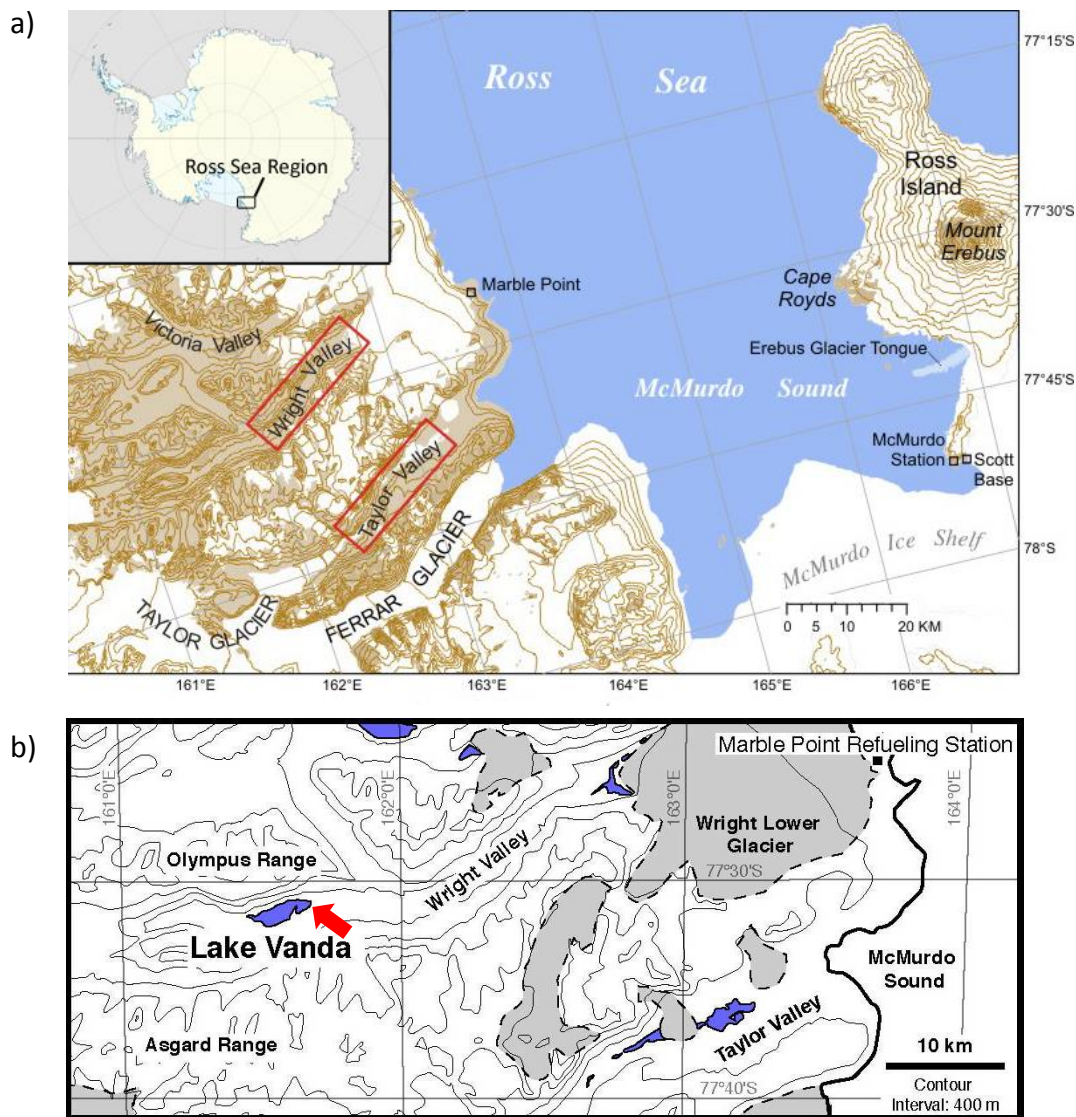


Figure 1. a) Ross Sea region and McMurdo Dry Valleys. *Inset:* Ross Sea region in relation to Antarctica (USGS, 2010), b) Wright Valley, McMurdo Dry Valleys; the former Vanda Station was located at the eastern end of Lake Vanda, as indicated by the red arrow.

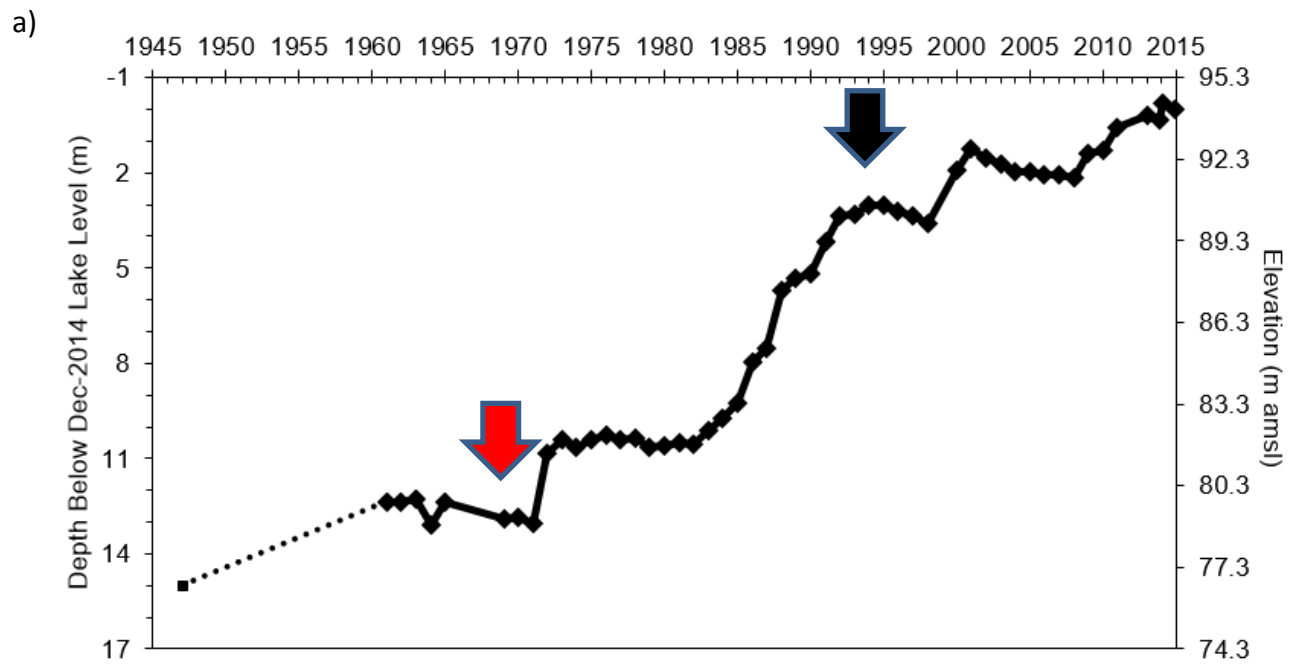


Figure 2. a) The level of Lake Vanda recorded from the “Astro A” benchmark from 1961-2014, with a value for 1947 derived from aerial imagery (modified from Castendyk et al., 2016). Red and black arrows indicate the building and decommissioning of the station. **b)** The “Astro A” benchmark in December 2014, now at water level, with Peter Taylor (L) and Ian Hawes (R).

Purpose of Research

Documenting the effects of human occupation is important. It is a requirement under the Madrid Protocol, and it provides environmental managers in Antarctica with information on the process and rate of environmental recovery of contaminated sites. Since the decommissioning of Vanda Station, lake levels have continued to rise (Figure 2a) and in summer of 2014, much of the former station site was flooded, including all of Greywater Gully (Figure 3). It is likely that the few remaining unsubmerged areas of the station site may flood within the next 5-10 years. Consequently, Antarctica NZ asked the Waterways Centre for Freshwater Management to resample the site, to determine whether the small amount of residual contamination at the site was entering and affecting the lake ecosystem, and whether further mitigation efforts would be worthwhile.

This report is a summary of a full Masters research thesis;

Taylor P.K. (2015) **Residual Contamination and Environmental Effects at the Former Vanda Station, Wright Valley, Antarctica**. Unpublished MWRM thesis, University of Canterbury.

This thesis can be accessed through the University of Canterbury Library's Research Repository.

2. Methods

Site selection, sampling and analysis followed the approach taken in the previous studies (Hawes et al., 1999; Webster et al., 2003) to allow for direct comparison of results. However, when this previous contaminant assessment was done at the Vanda Station site, the lake level was approximately 3m below present, and all sites sampled were either above the water line, or in very shallow water. When revisited in December 2014, Greywater Gully sites were under approximately 3-4m of lake water and ice (Figure 3), and the main helicopter pads were under 0.1-0.2m of water (Figure 4a & b).

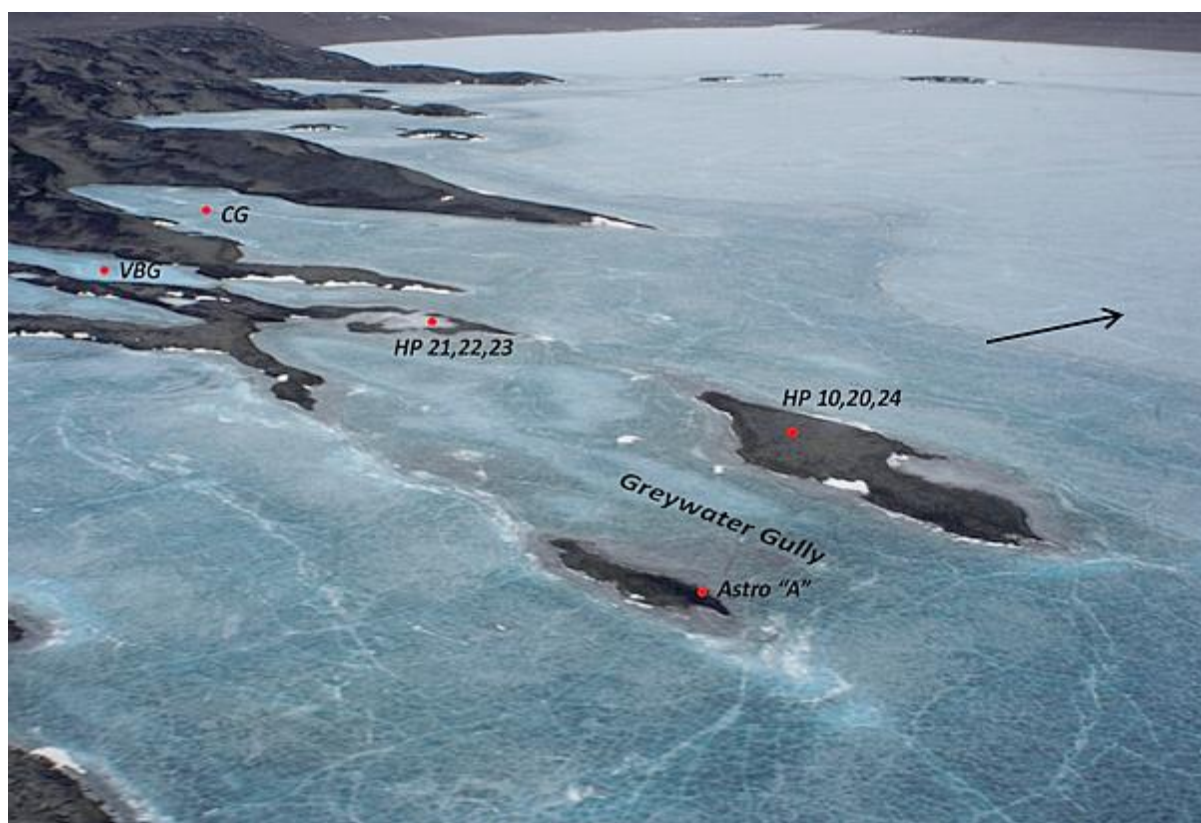


Figure 3. Aerial view of the location of the former site of Vanda Station (larger island) looking west along the lake (arrow indicates north). Sampling locations are shown approximately for perspective only. Refer Appendix 1 for an aerial image of the former station in the early 1980s.

2.1 Site selection

As far as possible sampling locations were chosen to align with those in Webster et al (2003) as shown in Figure 5. Greywater Gully (GW) sampling locations were aligned along the deepest point in the now flooded gully, as close as possible to previous GW sites. Although the exact locations of the previously monitored GW sites were uncertain, as sampling predated GPS technology, sites were located through triangulation from known features

shown on hand-drawn maps from Webster et al. (2003). Additional sites, OS and GW0, were included as sites representative of the main body of Lake Vanda, to assess contaminant dispersion into the lake.

a)



b)



Figure 4. a) View looking east across old station site, standing at the edge of the old mess building site, **b)** View looking west from old station site (standing at the edge of the old mess building site), towards the main helicopter pads (partly flooded).

Sites HP21-23 were located on the old main helicopter pad, which has experienced recent and shallow flooding. These sites were easy to locate accurately from an orange painted marker rock on the north eastern edge of the old helicopter pad. The additional site HP5 was chosen to represent the old lower helicopter pad, but the exact location of the 1996/7 HP5 site was difficult to determine, so there is uncertainty in this location.

Two control sites were chosen in flooded gullies with similar depth and surrounding bathymetry to Greywater Gully; “Control Gully” (CG) and “Vanda Back Gully” (VBG). Sites HP10 and HP20 on the Station footprint were fuel spill sites. Sites HP10 and 20 were chosen based authors’ knowledge of the previous position of the base buildings and their fuel tanks, and the faint smell of hydrocarbons coming off the soils. These soils were sampled at various depths, until it was not possible to dig further without collapsing the soil profile. Site HP24 was chosen as a representative sample from the helipad closest to the buildings of the station, and soils at CG as a control site, having soils overlying a similar geology to the station area.

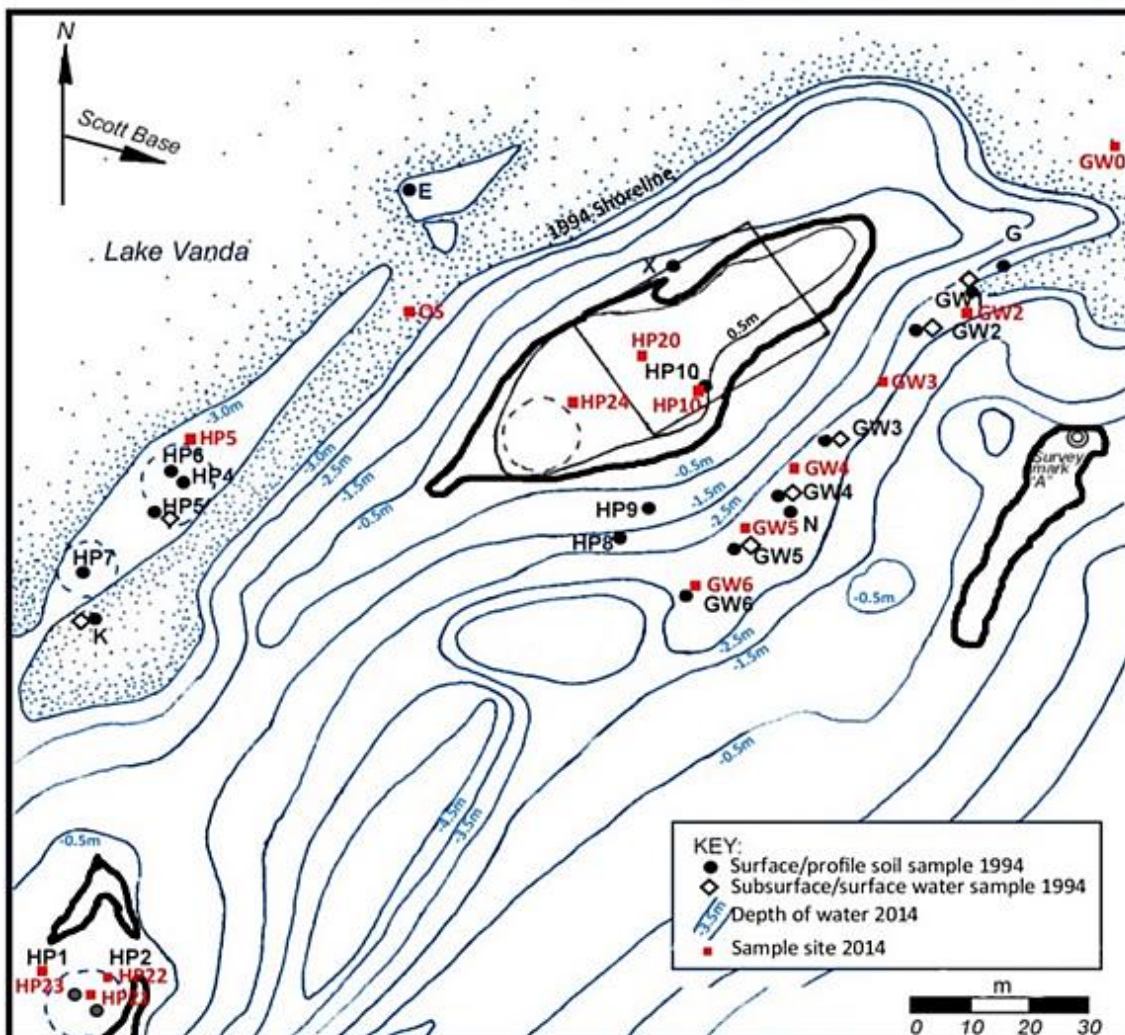


Figure 5 - Sampling locations at the former station and Greywater Gully in this study (red) and from Webster et al. (2003) (black). Control site locations can be seen in Figure 3. GPS data for these sites in in Appendix 2.

2.2 Sampling

2.2.1 Dry soils

Sampling of dry sites was conducted on the 8-9 December 2014. Control Gully (CGS) and HP24 were surface soil samples, and HP10/20 sites were sampled at varying depths through the soil profile. All samples were collected using a clean plastic hand trowel and were sieved in the field at <2mm, to ensure a high proportion of the fine fraction for later analysis. Samples collected at each site were prepared and frozen for transport back to New Zealand.

2.2.2 Flooded sites

All flooded sites, except HP21, 22, 23, were covered with ca. 2.0m of ice. Once located, the ice cap was drilled using a hand-operated Kovac auger taking care not to allow any ice to fall back in the hole (Figure 6). GPS coordinates were taken at each location, and the ice thickness and bathymetry was determined using a modified weighted measuring tape. Bathymetry measurements included both the total depth and piezometric level (depth to water level in ice hole). Using a specifically designed water and pore water sampling suction system, water samples were collected from immediately below ice cover (surface), midway, and at the base of the water column. The sampling system comprised of a rigid aluminium pole with PVC tubing running to a sealed sampling chamber at the base to allow discrete sampling at specific depths (Figure 6). Water samples were drawn through the tubing using a hand operated suction pump.

Pore water samples were collected from 10-15cm below the sediment surface, after all lake water sampling had been completed, to avoid potential cross contamination. Sediment samples were collected during pore-water sampling, as fine fraction sediments came up the sampling apparatus at the same time. The slurry recovered was allowed to settle for 12-18 hours and was decanted and filtered for a pore water sample, then the remaining fine fraction sediment was also collected for further analysis. At each sampling location, following all water and sediment sampling, the sampling holes were enlarged using a Jiffy Drill, to allow access for larger sampling equipment. Sediment cores were successfully collected from 2 sites (VBG, GW5) using an AMS 'Sludge and Sediment Corer'. However, sediment coring was unsuccessful at all other sites due to the large aggregate nature of the underlying sediment.

For the recently flooded sites; HP21, 22 and 23, sampling was easier as the sites lay under only 0.1-0.15m of water plus 0.1m ice. The ice cover was broken using an ice axe, and field measurements were made in the water beneath. Water samples were collected from the surface water, pore water samples from 0.1m below the sediment and finally sediment samples were taken.

All samples were collected into 50ml centrifuge tubes, TOC glass jars or VOC glass jars (ascorbic acid preserved) for transport back to New Zealand for analysis. Samples to be

analysed for sulphide were preserved in the field with zinc acetate. Waters for nutrient analysis and dissolved trace element were filtered through 0.45µm filters, and nutrient samples were frozen, immediately after sampling. Upon arrival in New Zealand, all samples were transferred to the Lincoln University PC1 (MAF) Water Laboratory.



Figure 6. Drilling with a Kovac ice auger in Greywater Gully (L) and sampling the water column beneath the ice using a suction system (R).

2.3 Sample Analysis

2.3.1. *In-situ* analysis

Water and pore water samples were analysed immediately in the field for pH, temperature, conductivity and dissolved oxygen using a HACH HQ40d portable multi parameter field meter. Sites GW2, GW3, GW4, GW5 and VBG were also analysed for pH and conductivity using conductivity, depth and temperature scanner (CDT scanner).

2.3.2 Trace elements

Two samples for trace element determination were collected from every sampling location. One sample was filtered at 0.45µm for determination of dissolved concentrations, and one sample was left unfiltered for determination of total concentrations. In New Zealand, these samples were acidified with ultra-pure nitric acid (HNO₃) and then left for 3 weeks to allow dissolution of elements adsorbed onto the container. Trace elements and major cations were determined via Inductively Coupled Plasma - Mass Spectroscopy (ICP-MS), with detection

limits ranging between 0.1µg/L and 1µg/L for trace elements and 0.1-100µg/L for major cations. Samples with conductivity above 5mS/cm were diluted 1:3 with 2% HNO₃ as a high salt content can create interferences in analysis.

Trace elements in soils were determined following the digestion of samples in hot nitric acid (this method does not dissolve silicate minerals, so results do not include elements bound in silicate matrices). This method was used for both dry soils and sediment cores. Samples were dried at ~45°C until no change in weight was recorded then sieved to <150µm, and this sediment digested in an accurately determined volume HNO₃ on a hot plate. Digestions were then analysed by ICP-MS. For all ICP-MS analyses, acidified deionised water blanks were included in the analyses, as well as a certified standard IV SRM 1643, and a % recovery check on a rhodium standard.

2.3.3. Organic contaminants

Total organic carbon (TOC) samples were collected into pre-prepared unpreserved amber 125ml glass jars provided by Hills Laboratories. Samples were analysed at Hill Laboratories in Christchurch. Total carbon (TC) was determined by persulphate oxidation and infrared (IR) detection, total inorganic carbon (TIC) was determined by acidification and purging, and TOC determined by difference (APHA, 2007). The detection limit for this method is 0.5 mg/L.

Volatile organic compounds (VOC) samples were collected into pre-prepared ascorbic acid preserved amber 40ml glass jars provided by Hills Laboratories. Samples were analysed at Hill Laboratories in Christchurch using purge and trap, and analysis by gas chromatography - mass spectrometry (GC-MS) (USEPA method 524.2). 64 organic compounds were analysed for with detection limits between 0.05mg/L and 0.0005mg/L. All samples were spiked with two quality control organic compounds to test % recovery. In addition, TPH was determined for the four core samples recovered; VBG, GW5, HP21 and HP22, and all soil samples taken. GW5, HP20 and CG were also screened for PAH's due to perceived (by smell) presence of hydrocarbon contamination. Analysis was done by Hill Laboratories in Hamilton using USEPA 8015B method for TPH, where the samples are analysed by Gas Chromatography - Flame Ionization Detector (GS-FID) following sonication in a dichloromethane (DCM) extract. PAH's were determined on TCLP extracts via a liquid/liquid extraction and GC-MS SIM, the detection limit for individual PAH's ranges from 0.0001-0.0005mg/L.

2.3.4 Major ions & nutrients

Major anions were determined using High Pressure Ion Chromatography (HPIC), after filtration through 0.22µm (to allow sample removal from our PCI facility). Nitrate + nitrite nitrogen (NNN) was estimated colorimetrically after cadmium-catalysed reduction to nitrite and reaction with sulphanilamide and N-naphthyl – ethylenediamine dihydrochloride to form

an azo dye (Jones, 1984). Dissolved reactive phosphorus (DRP) was analysed using the standard molybdenum blue method (APHA, 1992; method 4500-P). Dissolved inorganic carbon (DIC) was measured as free CO₂ following acidification and purging on an ADC - 225 - MK3 CO₂ analyser. Deionised water blanks, standards and duplicate samples were included for quality control.

2.4 TCLP leaching of soils

Toxicity characteristic leaching procedure (TCLP) is a method simulating leaching of contaminants from the soil. Here simulated leaching was undertaken using an acidic and neutral leachate. Experimental leaching was undertaken on samples from HP10, HP20, HP24, and CG using a modified version of the USEPA TCLP Method 1311 (USEPA, 1992), in which soils (<2mm fraction) were leached with distilled water (20ml to 1g soil) and 1N acetic acid (25ml to 1g soil). The leach tests were carried out at room temperature (~22°C), as TCLP tests on Antarctic soils previously were not affected by this temperature variance (Webster et al., 2003). Final leachates were acidified to pH<2 and prepared for analysis by ICP-MS. Leachates from CG, HP20 15cm and HP20 25cm were analysed for PAH's at Hill Laboratories using liquid/liquid extraction and GC-MS SIM.

2.5 Microbial mat analysis

Core samples recovered from sites GW5 and VBG contained fragments of microbial mat. These mat fragments were aseptically transferred to sterile tubes (2 replicates per core) and frozen for analysis of bacterial community composition. On return to NZ, samples were transferred to the molecular biology laboratory of the Cawthron Institute and analysed using a methodology that had been in other Antarctic research. OTUs represented by less than 10 reads across all samples were removed, and remaining OTUs classified to allow taxonomic annotation using the Greengenes taxonomic database (McDonald et al., 2012). Species richness (R), Shannon-Wiener diversity index (H') and Pielou evenness index (J) were calculated using the DIVERSE function in PRIMER 6. OTU frequency data were fourth root transformed and analysed using nonmetric multidimensional scaling (MDS) based on Bray-Curtis similarities with 100 random restarts and results were plotted in two-dimensions. Agglomerative, hierarchical clustering of the Bray-Curtis similarities was undertaken using the CLUSTER function of PRIMER 6 and plotted onto the two-dimensional MDS's.

3. Results & Discussion

3.1 Dry Soils

3.1.1 Context observations

During field work approximately 500g of rubbish and building debris was collected from the soils, despite the fact we were not actively seeking or collecting such debris. Debris included nails, batteries (Figure 7a), paint flecks, wood chips, and plastic. Other physical contaminants in the soils include the orange painted rocks used for both Astro A (survey point, Figure 2b) and marking out the helipads (Figure 7b). Some of the painted rocks have been repositioned from the former station site to the new Vanda Huts, to mark out the current helipad.

3.1.2 Trace element contaminants

Samples were collected as soils from HP10 (0, 15, 30, 45 cm depth), H20 (0, 15, 25 cm), HP24 (surface) and CG (surface), and as sediments (under water) from VBG and GW5. Trace element concentrations are shown in Table 1a, where those from the Vanda Station site can be compared to those from control sites VBG and CG.

The only trace elements present at significantly elevated concentrations ($>2 \times$ highest value at a control site) were the dry soils sites at HP 20 (Zn, Pb) and helicopters pads HP 21, 22 and 24 (Pb). In the depth profile at HP 20, elevated Pb and Zn contamination persisted with depth. Elevated concentrations of Pb and Zn exceeded sediment quality guidelines commonly used in more temperate climates (e.g., ANZECC, 2000) and the TPH concentrations approach the threshold recommended for Antarctic Mosses (Nydahl et al., 2015).

3.1.3. Hydrocarbon contaminants

Elevated total petroleum hydrocarbon (TPH) concentrations were recorded only at HP10 and HP20, sites which were located due to the faint smell of hydrocarbons (Table 1b) or staining of the soil (Figure 8). Because such fuel contamination tends to be localised at the site of discharge, and such sites can be hard to find if there is no surface expression, it is very likely that there are more hydrocarbon-rich sites around the old base which have gone undetected. At HP 10, elevated hydrocarbons occur principally near the surface, but at HP 20 the TPH contamination is high throughout the profile.



Figure 7a. A battery found in the soil at the former Vanda Station site, located approximately 0.15m above lake level.



Figure 7b - Painted marker rock on the edge of Lake Vanda at the site of the former main helicopter pad, near sampling site HP21.

Table 1a. Trace element concentrations in soils and sediments (mg/kg). Sb was also analysed but was below detectable levels, and for Cd there were problems with sample contamination so results are not given. Values significantly exceeding (> 2 x) control site concentrations for soil or sediment, are shown in red bold type. Control sites are shaded.

Surface soils or sediment		V	Cr	Co	Ni	Cu	Zn	As	Ag	Pb
VBG - control sed		39.2	18.8	10.7	16.2	26.8	40.7	1.1	0.6	3.7
CG - control soil		72.5	7.25	9.6	17.3	36.6	26.6	1.8	0.6	4.4
GW5 sediment		58.9	16.9	10.4	17.7	36.0	39.6	1.2	0.6	4.3
HP10 soil		54.3	15.0	10.9	20.0	39.9	43.5	1.1	0.4	7.2
HP20 soil		36.3	14.3	7.7	15.5	34.7	142	1.7	1.0	98.2
HP21 sediment		48.6	13.1	9.2	17.8	38.6	41.1	1.0	0.4	16.3
HP22 sediment		29.9	7.8	6.2	11.9	25.1	14.7	<0.1	<0.1	13.7
HP24 soil		51.7	8.8	6.7	14.8	31.2	21.0	0.5	0.5	27.7
Soil profiles										
HP 10 soil	0	54.3	15.0	10.9	20.0	39.9	43.5	1.1	0.4	7.2
(depth cm)	15	60.9	14.1	10.6	21.5	38.5	37.1	0.4	0.4	4.6
	30	28.8	12.1	8.0	15.3	33.3	26.2	0.2	0.2	6.2
	45	41.0	12.8	10.2	18.0	38.5	32.1	0.2	0.2	7.2
HP 20 soil	0	36.3	14.3	7.7	15.5	34.7	142	1.7	1.0	98.2
(depth cm)	15	40.9	12.5	7.5	13.6	30.8	158	1.0	1.0	35.5
	25	41.7	11.8	8.1	14.7	31.6	117	0.9	0.9	35.8

Table 1b. Total petroleum hydrocarbon (TPH) concentrations in soil and sediment (mg/kg), with elevated concentrations shown in red, bold type. Control sites are shaded.

Surface soils or sediment		TPH (C7-C9)	TPH (C10-C14)	TPH (C15-C36)	TPH (Total)
VBG - control sed		<14	<30	<60	<100
CG - control soil		<8	<20	<40	<70
GW5 sediment		<8	<20	<40	<70
HP10 soil		<8	<20	2,400	2,400
HP20 soil		<8	120	6,800	7,000
HP21 sediment		<8	<20	<40	<70
HP22 sediment		<8	<20	<40	<70
HP24 soil		<8	<20	<40	<70
Soil profiles					
HP 10 soil	0 cm	<8	<20	2,400	2,400
	15cm	<8	<20	1,620	1,620
	30cm	<8	<20	300	300
	45cm	<8	<20	182	182
HP 20 soil	0cm	<8	120	6,800	7,000
	15cm	9	1,090	7,200	8,300
	25cm	9	2,300	6,600	8,900



Figure 8. Hydrocarbon staining of soil in pit at site HP 10

3.1.4. Leachable contaminants

TCLP leaching test results are shown in Table 2. Distilled water leachates best emulate the neutral pH waters of Lake Vanda, whereas the acetic acid leach emulates local conditions in which slightly acidic pH conditions may develop (e.g., beneath cyanobacterial mats etc).

The water leachate extracted relatively high trace element concentrations (relative to control site soils) from surface soils at HP 10 (Zn & Pb) and HP 24 (Zn, Pb, As & Cd), and from soils at all depths of the profile at HP20 (Cu, Pb, Zn, As & Cd, with minor Cr enrichment also). Acetic acid leachates showed similar results, but with greater concentrations being leached for the mobile elements. TCLP acetic acid leachates from soils with the highest hydrocarbon content (from the HP 20 soil profile) were analysed for the 17 priority PAHs. Only naphthalene was detected, at very low levels, in HP 20 at 25cm depth. The GW 5 sediment was also submitted for TCLP (acetic acid) leach based on the faint hydrocarbon smell of sediment and its pore water. However, there were no detectable PAH's in this leachate.

Table 2. Trace element and PAH concentrations (µg/L) in TCLP leachates (water and acetic acid) mixed with soil and sediments. Concentrations >2 x control site leachate concentrations are shown in red, bold type. Concentrations of Ag and Sb were below detection in the TCLP leachates.

	V	Cr	Co	Ni	Cu	Zn	As	Cd	Pb	PAH
Water										
CG Surface	14.2	2.04	7.96	3.68	21.5	18.6	1.23	0.2	3.10	-
HP24 Surface	11.2	2.92	7.49	4.96	41.2	74.9	2.53	0.6	39.3	-
HP10 Surface	9.33	1.26	6.39	3.21	30.3	82.0	1.06	0.3	15.4	-
HP10 15cm	8.63	1.13	6.55	2.84	28.9	21.0	0.91	0.1	3.9	-
HP10 30cm	8.43	1.29	4.96	2.47	27.1	21.0	1.03	0.2	6.7	-
HP10 45cm	8.63	1.38	4.73	2.34	26.6	24.0	1.03	0.2	10.1	-
HP20 Surface	9.48	3.37	8.61	5.38	125	1480	4.77	3.7	157	-
HP20 15cm	16.9	4.25	9.50	5.85	42.6	1810	5.58	3.8	237	-
HP20 25cm	21.5	6.76	13.7	7.72	65.3	1460	5.82	3.6	237	-
Acetic acid										
CG Surface	39.9	8.7	34.1	22.0	157	57	10.7	0.1	5.9	<dl
HP24 Surface	24.9	12.8	32.0	27.7	180	240	20.2	1.0	53.0	-
HP10 Surface	23.1	7.8	27.4	20.4	130	323	8.0	1.6	19.0	-
HP10 15cm	23.5	7.5	27.3	20.5	140	95.0	8.0	0.5	6.52	-
HP10 30cm	23.4	8.3	24.7	20.4	130	90.0	8.9	0.4	10.0	-
HP10 45cm	23.8	8.7	24.2	18.4	130	119	8.5	0.3	14.0	-
HP20 Surface	30.0	15.7	33.9	27.4	250	4466	25.6	8.0	363	-
HP20 15cm	50.3	20.4	33.0	25.2	170	4813	30.6	7.2	541	<dl
HP20 25cm	58.7	28.3	38.8	27.3	190	3747	36.6	6.8	239	0.8 ²

1. The only PAH detected was naphthalene.

3.1.5 Residual soil contamination summary

Soils were sampled neither extensively nor randomly on the area of Vanda Station's footprint still above lake level. Instead likely problem areas such as helicopter pads and fuel spill sites (as identified in previous surveys) were targeted. Hydrocarbon contamination (TPH) of the soil in known problems areas was still high, with the residual contaminants being mainly the long chain, less volatile hydrocarbons which persist in this environment. Elevated concentrations were still evident at 30-50cm depth at one of the spill sites. Of the trace elements tested, only Pb and Zn were particularly elevated, and mainly in the hydrocarbon-enriched soils. Pb was also high in some of the recently flooded helicopter pad sediments, near where metal-detritus and the Pb-based red paint had been observed (Figure 7).

In order to assess how mobile these contaminants may be when the soils are flooded, TCLP leach tests were undertaken. These leachate results suggest that the flooding of old hydrocarbon contamination sites may result in locally high concentrations of Pb and Zn, and to a lesser degree, Cu, Cd, As and possibly Cr. However, the fuel residues are less mobile and are unlikely to transfer significantly to the lake waters. This is consistent with the results of Webster et al (2003).

3.2 Lake waters

At all Greywater Gully sites (Figure 5), water samples were taken from 4 depths; surface (just below the ice), mid-column, base (just above the lake floor), and pore water within the sediments. Control Gully, HP5 and VGB sites were sampled in the same way as the Greywater Gully sites, with an additional outside control (OS) sampled only at the mid-column depth. Water overlying the helipads, HP21, HP22, and HP23 was sampled after breaking through the thin ice layer. These sites were only recently flooded, and only lay under <20cm of ice and water.

Most of the water samples collected had no visible signs of contamination. Only the pore water samples collected at GW4, GW5 and GW6 sites had minor foam development, and the GW5 pore water smelled faintly of hydrocarbon.

3.2.1 General water chemistry

Field parameters; pH, conductivity, temperature and dissolved oxygen profiles were determined for all Greywater Gully sites (Table 3a & b). GW0 and GW2, which were in the main body of the lake, had lower conductivities than GW3-GW6. GW3-GW6 were trapped behind a rise in the base of the gully, and would have been isolated from the main lake during winter when freeze-concentration likely increased local conductivity. Because of this localised enrichment, a new control site was established as VBG, where gully water was similarly trapped during winter by a sill. There was little difference between controls sites and the GW sites for all of these parameters. Instead the control sites and the GW site both showed the same type of profile development, with higher pH, and lower DO, conductivity and temperature, near the surface. The conductivity stratification noted is a natural phenomenon in this lake environment, where salinity increases with depth.

Table 3a. General water quality; pH, conductivity, temperature and dissolved oxygen for lake water profiles. Depth = depth below ice surface, and therefore “surface” depth denotes ice thickness. For OS, ice thickness = 2.27m. Control sites are shown as shaded.

Site	Sample	Depth (m)	pH	Conductivity ($\mu\text{S}/\text{cm}$)	Temp ($^{\circ}\text{C}$)	DO (mg/L)
CG	Surface	2.14	8.81	179.1	3.2	6.33
	Mid	2.75	6.81	941	3.5	14.75
	Base	3.77	6.63	964	4.5	13.95
	Pore water		7.26	948	-	10.47
VBG	Surface	2.18	7.79	2016	0.8	20.39
	Mid	2.92	7.46	5010	2.1	>20
	Base	3.66	7.08	5150	3.1	>20
	Pore water		6.99	5980	-	12.54
OS	Mid	2.77	7.58	965	2.4	15.18
GW0	Surface	2.24	8.72	253	0.1	6.73
	Mid	2.92	8.31	985	2.2	15.7
	Base	3.6	8.32	981	2.5	14.82
	Pore water	-	7.25	1000	-	10.99
GW2	Surface	2.06	9.71	226	0.1	8.35
	Mid	2.49	9.14	215	2.1	9.12
	Base	2.92	8.02	960	2.5	14.59
	Pore water	-	7.28	920	-	11.19
GW3	Surface	1.93	8.76	215	0.7	8.81
	Mid	2.39	8.91	1305	3.6	>20
	Base	2.85	8.94	1310	4.7	>20
	Pore water	-	7.52	1021	-	11.04
GW4	Surface	2.08	9.04	179	0.4	10.9
	Mid	2.79	9.59	1275	4	>20
	Base	3.5	9.18	1335	4.1	>20
	Pore water	-	7.38	2260	-	10.77
GW5	Surface	2.03	10.46	187.4	-0.1	>20
	Mid	2.67	8.46	1238	1.5	21.9
	Base	3.31	9.03	1325	2.7	>20
	Pore water	-	6.93	1685	-	9.66
GW6	Surface	1.8	9.45	214	1	9.91
	Mid	2.2	9.34	1083	3.2	9.33
	Base	2.61	9.13	1315	4.9	>20
	Pore water	-	6.81	1264	-	11.1
HP5	Surface	2.25	7.07	260	0.6	7.13
	Mid	2.57	7.16	338	0.8	8.15
	Base	2.9	7.67	565	2.5	11.46

Table 3b. General water quality; pH, conductivity, temperature and dissolved oxygen for shallow flood waters on helicopter pads

Site	pH	Conductivity ($\mu\text{S}/\text{cm}$)	Temp ($^{\circ}\text{C}$)	DO (mg/L)
HP 21	8.28	501	-	9.87
HP 22	7.99	516	-	9.80
HP 23	7.5	170	2.6	11.58

3.2.2. Nutrients, TOC & sulphide

DRP was mostly at or below the limits of detection in water column samples (Table 4), both for control sites and near-surface GW site lake waters. However, within Greywater Gully detectable DRP was sometimes evident near the base of the column, or in the pore water. Note that the difficulty of sampling the pore water by suction sampling meant we may have been collecting lake water in addition to true sediment pore water.

NNN concentrations for most sites were between 17 and 30 $\mu\text{g}/\text{L}$, and we consider these to be background values. VBG stands out from the other sites, with very high NNN but this site also had very high conductivity, due to the effects of freeze-concentration after the gully was sealed off from the main lake by ice formation. It is likely that NNN-enrichment is also due to freeze-concentration at the VBG site. Within the VBG, HP and Greywater Gully sites there was, as with DRP, a tendency for NNN to increase in the deeper samples and into the pore water.

Total organic carbon was determined only for basal waters, and the concentrations observed in the GW sites falls within the range shown for the control sites. Hydrogen sulphide was not found in detectable levels ($>0.05 \text{ mg}/\text{L}$) in any of the pore waters samples taken from Greywater Gully.

Table 4. Nutrient & TOC concentrations in water samples; NNN is nitrate+nitrite-nitrogen, DRP is dissolved reactive phosphorus and TOC is total organic carbon. Control sites are shaded.

Site	Sample	NNN (µg/L)	DRP (µg/L)	TOC (mg/L)
CG	Surface	25	<2	-
	Mid	25	<2	-
	Base	27	<2	0.8
VBG	Surface	310	<2	-
	Mid	332	<2	-
	Base	581	<2	3.6
	Pore water	937	<2	-
OS	Mid	26	<2	-
GW0	Surface	24	4	-
	Mid	24	<2	-
	Base	30	5	0.8
	Pore water	77	9	-
GW2	Surface	17	<2	-
	Mid	19	3	-
	Base	23	<2	1.1
	Pore water	91	4	-
GW3	Surface	18	<2	-
	Mid	19	1	-
	Base	19	3	2.0
	Pore water	676	7	-
GW4	Surface	20	<2	-
	Mid	15	<2	-
	Base	16	3	1.3
	Pore water	447	<2	-
GW5	Surface	17	4	-
	Mid	16	<2	-
	Base	18	<2	1.9
	Pore water	15	5	-
GW6	Surface	16	<2	-
	Mid	17	<2	-
	Base	18	<2	1.5
	Pore water	28	940	-
HP5	Surface	21	<2	-
	Mid	22	<2	-
	Base	20	<2	-
HP 21	Surface	38	3	-
	Pore water	459	5	<0.5
HP 22	Pore water	60	11	-
HP 23	Surface	30	<2	-

3.2.3. Trace elements

Greywater Gully received continuous discharge of greywater throughout the operation of Vanda Station, and Webster et al (2003) identified areas of significant residual trace element contamination in this gully in 1997. The results from this study are shown in Table 5, together with the results of the subsurface suprapermafrost fluids (SPF) sampled in 1997 by Webster et al (2003), to show whether there is any change and/or release of these contaminants into Lake Vanda. The SPF was effectively the pore water of the soils, prior to flooding of the Gully.

For every trace element analysed in Greywater Gully, the concentrations were either below detection or near background (i.e., control site) concentrations at all levels in the water column. The highest concentrations were for Zn, for which higher concentrations typically occurred near the surface rather than at the base of the water column. This is a common phenomenon in ice-covered Antarctic lakes (e.g., Webster et al., 1997) and was also observed at the Control Gully site. There appeared to be no evidence that the higher concentrations of Cu, Zn and Ni observed in some of the soil pore water, or suprapermafrost layer (SPF), in 1997 have transferred to the lake water during the flooding of the Greywater Gully. The SPF has a relatively high salinity and therefore greater density than the lake water, which would help to prevent mixing.

3.2.4 Hydrocarbons (VOC)

Volatile Organic Compounds (VOCs) were analysed on pore water and basal water samples within Greywater Gully. Of the 64 individual compounds analysed as part of the VOC analysis, only three were detected in the samples; styrene, bromoform and acetone, and these were at very low concentrations (Table 6). GW pore waters and basal waters showed styrene or acetone concentrations similar to those of the controls sites (CG and VBG). However, base water from GW3-GW6 sites appeared to have slightly elevated concentrations of bromoform.

Table 5 Dissolved trace element concentrations (µg/L) for lake and pore waters, including those for the suprapermafrost fluid (SPF) for the same sites sampled in 1997 (Webster et al., 2003) shown in bold, italics. Ag, Co, As and Cd were close to or below DL (0.1 µg/L) in all water samples in this study, except in GW5 pore water where Co = 2.3 µg/L and As = 1.2 µg/L.

		Pb	Zn	Ni	Cu	Mo
<i>DL =</i>		<i>0.1</i>	<i>1.0</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>
CG	<i>1997 SPF</i>	<i>0.1</i>	<i>4.2</i>	<i><DL</i>	<i>2.9</i>	<i>-</i>
	Base	0.4	60	0.2	<DL	1.8
	Mid	0.5	88	0.3	0.1	1.7
	Surface	0.3	217	0.4	0.4	0.3
VBG	Pore water	<DL	32	1.7	1.5	17.4
	Base	0.6	51	0.8	0.7	13.0
	Mid	0.9	61	0.8	0.8	12.2
	Surface	0.8	135	0.5	0.6	4.2
GW0	Pore water	<DL	3	0.3	0.5	2.9
	Base	0.1	31	0.2	0.1	1.7
	Mid	0.7	99	0.5	0.6	1.9
	Surface	0.20	40	0.2	<DL	0.3
GW2	<i>1997 SPF</i>	<i>0.3</i>	<i>4</i>	<i><DL</i>	<i>10</i>	<i>-</i>
	Pore water	<DL	1	0.3	0.7	2.6
	Base	0.3	50	0.3	0.1	1.7
	Mid	0.4	86	0.4	0.9	0.3
	Surface	0.3	65	0.5	0.9	0.4
GW3	<i>1997 SPF</i>	<i>0.3</i>	<i>11</i>	<i>18</i>	<i>18</i>	<i>-</i>
	Pore water	<DL	1	0.3	0.4	6.9
	Base	0.7	66	0.4	0.8	2.6
	Mid	0.5	68	0.6	1.0	2.7
	Surface	0.2	46	0.2	0.3	0.3
GW4	<i>1997 SPF</i>	<i>1.4</i>	<i>17</i>	<i>29</i>	<i>23</i>	<i>-</i>
	Pore water	<DL	30	0.9	0.8	9.1
	Base	0.4	64	0.9	0.5	2.8
	Mid	0.3	112	0.5	0.5	2.7
	Surface	0.9	107	0.8	0.8	0.5
GW5	<i>1997 SPF</i>	<i>4.4</i>	<i>15</i>	<i>99</i>	<i>25</i>	<i>-</i>
	Pore water	0.1	11	3.9	0.6	14.2
	Base	0.2	34	0.3	0.4	2.8
	Mid	0.3	51	0.4	0.5	2.7
	Surface	0.3	51	0.6	0.8	0.5
GW6	Pore water	0.5	5	0.5	1.1	4.1
	Base	0.4	41	0.3	0.5	2.7
	Mid	0.5	61	0.3	0.5	2.6
	Surface	0.7	55	0.2	0.5	0.6

Table 5 cont...		Pb	Zn	Ni	Cu	Mo
HP 21	Pore water	0.5	2	0.5	2.1	3.1
	Surface	0.2	7	0.4	1.2	1.0
HP 22	Pore water	0.2	1	0.3	2.1	1.5
HP23	Surface	<DL	2	0.1	0.7	0.6
HP5	Pore water	<DL	<DL	0.2	0.5	6.7
	Base	0.1	54	0.2	<DL	1.0
	Mid	0.1	54	0.3	0.3	0.5
	Surface	<DL	132	0.3	<DL	0.4
OS	Mid	0.1	22	0.3	<DL	1.7

Table 6. VOC concentrations (µg/L) in pore water and at the base of the water column.

	Styrene		Acetone		Bromoform	
	Pore water	Base	Pore water	Base	Pore water	Base
CG	0.5	1.0	150	<50	<0.5	<0.5
VBG	0.6	1.4	<50	<50	<0.5	<0.5
GW0	0.7	1.7	140	<50	<0.5	<0.5
GW2	1.0		<50		<0.5	
GW3	1.3	1.5	70	<50	<0.5	1.8
GW4	1.1	1.9	<50	<50	<0.5	1.8
GW 5	<0.5	1.5	<50	<50	0.7	1.8
GW 6	<0.5	2.0	<50	<50	<0.5	1.6
HP 5		<0.5		<50		<0.5
HP 21		0.6		50		<0.5

3.2.5 Lake water contaminants summary

There is no evidence of significant transfer of nutrients or contaminants from the soils of Greywater Gully (or their pore waters) into the lake water column, as a result of this gully being flooded. Minor enrichments of nutrients; NNN and DRP near the base of the water column, and the presence of detectable bromoform, a volatile organic carbon compound, were observed at specific GW sites. However, overall there is little cause for concern as contaminant leaching from the soils appears minimal, and the transfer of contaminated, saline SPF fluids from the sediment to the lake water is likely to be inhibited by the density difference.

3.3 Microbial mats

3.3.1 Visual assessment

Images captured by lowering a waterproof digital camera through sampling holes GWG0 (open lake) and GW5 (contaminated gully) showed a broadly similar tan coloured mat, lifting away from the sediment in places (Figure 9). The mat appeared thicker at GW5 which may be a consequence of the higher nutrient concentrations available in the sediments and base water of the gully. It may also be affected by other factors such as light conditions. GW5 mat also had more lift-off areas, likely to reflect the higher degree of oversaturation of oxygen in the GW5 location (refer DO concentrations shown in Table 3a).

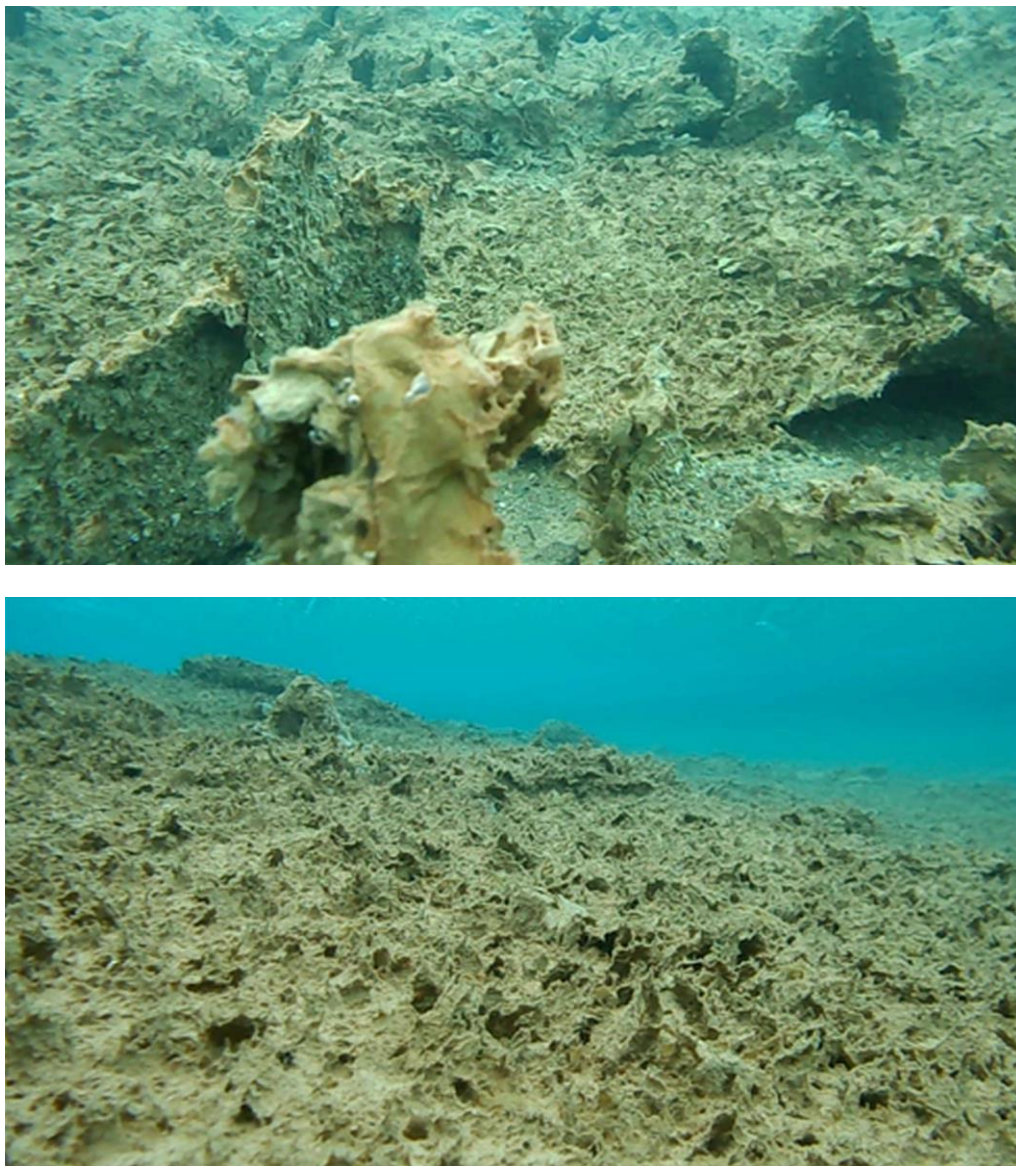


Figure 9. A visual comparison of mat development at GW 5 (top) and GW 0 (bottom).

3.3.2 Molecular analysis

Of the four subsamples from each of VBG and GW5 used in the bacterial community composition analysis, all but one of the GW5 samples amplified well and gave reliable results, resulting in seven sets of useable data (Table 7).

Table 7. Microbial mat OTU counts, Richness, Evenness and Diversity indices of three samples from VBG and four from GW5. Primers used target all bacteria.

	VBGa	VBGb	VBGd	GWa	GWb	GWc	GWd
No of OTUs	1153	1157	1215	1249	1302	1435	1227
No of reads	17737	17740	17768	17737	17731	17741	17741
Richness (S)	118	117	124	128	133	147	125
Evenness (J)	0.71	0.64	0.65	0.63	0.66	0.69	0.67
Shannon diversity (H')	4.97	4.53	4.65	4.51	4.71	5.04	4.74

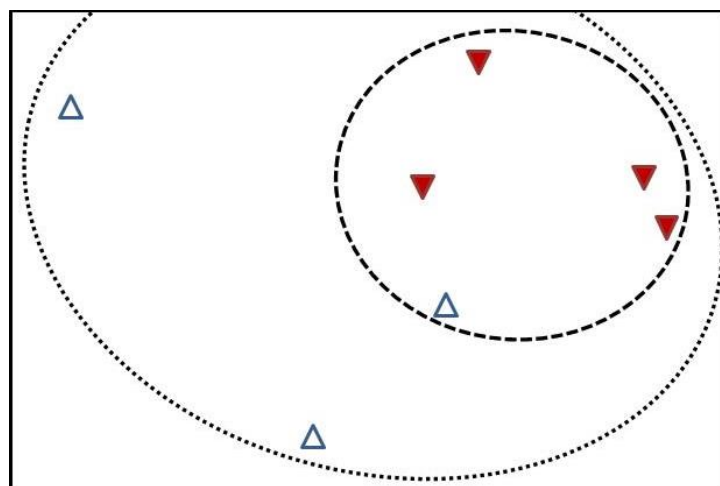


Figure 10. Multidimensional scaling plot based on fourth-root transformed OTU frequencies for all bacteria. Open triangles are VBG (control) sites, closed inverted triangles are GW5 (impacted) sites. The dashed line encloses samples that are 50% similar, the dotted line 40% similar.

Richness, evenness and diversity indices for the seven samples were similar (Table 7), and MDS based on all bacteria grouped all samples within a 40% similarity envelope, though there was a tendency for the GW5 samples to group together (Figure 10). When only the cyanobacterial data were used for MDS analysis, no grouping was observed (MDS not shown) and no consistent differences between the sites were observed (Figure 11). No taxa were unique to one site, and all of the taxa that were recognised are common across the McMurdo Dry Valleys. Species of *Leptolyngbya*, *Phormidium* and *Nostoc* are consistent mat dominants in many shallow water habitats in the Wright and Taylor Valleys.

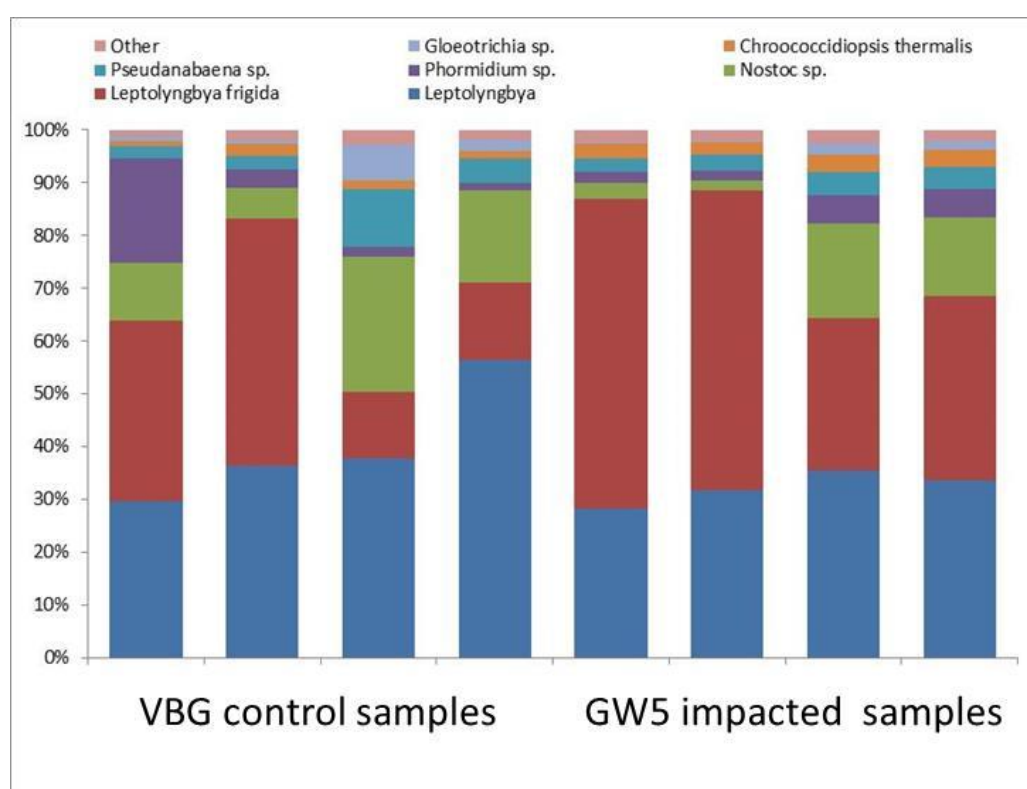


Figure 11. Relative abundance of cyanobacterial groups in the samples from VBG and from GW5.

3.3.3 Microbial mat assessment summary

There appears to be little difference in the composition of microbial mats in Greywater Gully compared to those at the control site VBG. The mats observed to be growing in Greywater Gully were thick and more voluminous compared to those outside of the Gully, possibly reflecting greater nutrient availability from contaminated sediments or possibly different light conditions.

4. Conclusions & Recommendations

4.1 Main findings

Twenty-five years of occupation at Vanda Station, coupled with relatively poor environmental protection standards, led to minor contamination of the surrounding land. During the stations decommissioning, extensive remediation removed some of the contaminated soil. Residual contamination remained at the site however and posed a risk to Lake Vanda, should the site be flooded. Now, 20 years after the removal of the station and with the site mainly under water, an assessment of local contamination in the soil and lake water has been undertaken.

This assessment revealed little evidence of elevated nutrients, trace elements or organic contaminants in the lake water that has flooded Greywater Gully or the helicopter pads. The lack of contamination emanating from previously identified contaminated soils is likely to be largely due to the lack of mixing between suprapermafrost fluids and overlying lake water, together with the relatively low levels of soil contamination and dilution of any mobilised contaminants in the large body of lake water.

Healthy and luxurious microbial mats were observed within Greywater Gully, possibly responding to high nutrients availability in the more contaminated soils, as predicted in previous studies (Hawes et al., 1999; Webster et al., 2003). Preliminary genetic sequencing of cyanobacteria indicates no variation in speciation from expected microbial mat compositions in the Dry Valleys.

Exposed soil on the former station's footprint was moderately contaminated at some of the sites sampled with elevated concentrations of hydrocarbons, Pb and Zn. There is also visible building detritus and wood/metal rubbish on the surface of the ground around the former station site and helicopter pads, and orange marker paint (Pb-based) on rocks at the helicopter pads and the survey point.

4.2 Recommendations

An opportunity still exists to remediate the remaining contaminated soil at the former Vanda Station. The removal of visible rubbish from the soil and digging out obviously contaminated soil (e.g., from HP10 and HP20) would remove any risk of these contaminants causing localised environmental effects. This would include removing the orange-painted marker rocks, including those now residing at the Vanda Huts helicopter pad.

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APPENDICES:

Appendix 1

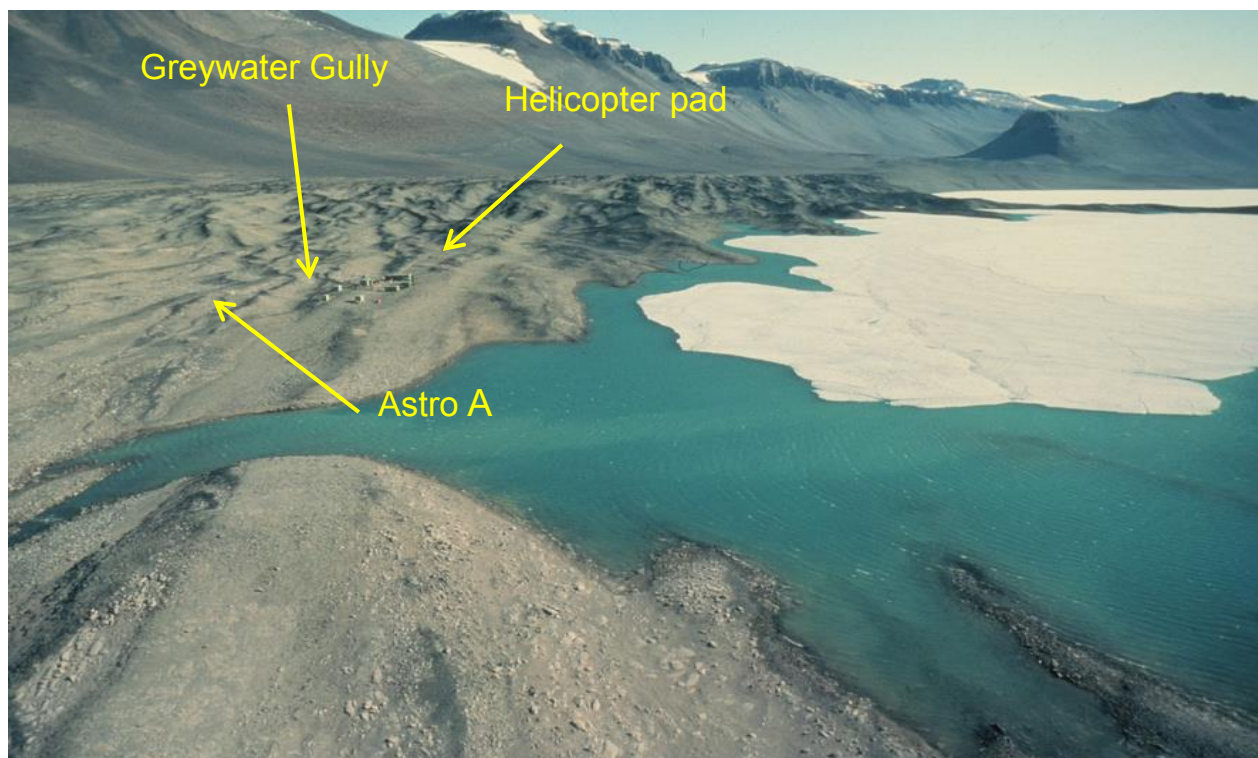


Figure A1. Aerial view of the Vanda Station site, taken during the early 1980's. Photo Kim Westerkov © Antarctica New Zealand Pictorial Collection.

Appendix 2: GPS data for sampling sites

Site	GPS	
	S	E
GWO	77' 31.602	161' 40.771
GW2	77' 31.613	161' 40.708
GW3	77' 31.614	161' 40.708
GW4	77' 31.621	161' 40.683
GW5	77' 31.627	161' 40.660
GW6	77' 31.631	161' 40.631
HP5	77' 31.620	161' 40.377
Control Gully (CG)	77' 31.822	161' 39.624
Vanda Back Gully (VBG)	77' 31.764	161' 40.157
Off Station (OS)	77' 31.607	161' 40.485
HP 21/22/23	77' 31.687	161' 40.358

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