Catchment characteristics and chemical limnology of small lakes, tarns and mire pools in New Zealand (South Island) and Tasmania

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Abstract. Small alpine water bodies can play a large role in defining patterns of biological and landscape diversity, and may be particularly sensitive to climate change. A large limnological dataset, consisting of 65 and 6 water bodies, respectively, on South Island and Stewart Island (New Zealand) and 76 and 12 water bodies, respectively, in the Tasmanian highlands and coastal areas (Australia), was constructed to assess patterns of variation in alpine and subalpine lakes in the Australasian region. With the exception of the coastal systems, most lakes were very dilute. In general, lake water chemistry resembled world average seawater cationic ratios (WASW). In addition, some New Zealand lakes fell close to the world average freshwater cationic ratios (WAFW), due to relatively high calcium concentrations, and some were dominated by magnesium due to the presence of serpentine bedrock in the catchment area. Multivariate analyses of the joint dataset revealed that the variation in chemical limnological variables was dominated by gradients in conductivity, pH and gilvin. The concurrent relationships between pH, calcium and gilvin, which enabled the differentiation of Tasmanian water bodies into limnological provinces, were absent in New Zealand. In the latter, pH and gilvin contents were not coincident, as clear-water acidic systems occurred in New Zealand. The higher diversity of freshwater bodies in New Zealand will enable independent assessment of the effects of pH and gilvin on the distribution and diversity of biota.

Extra keywords: alpine lakes, humic substances.

Introduction

Small freshwater bodies are globally far more numerous than large lakes (Wetzel 2001) and play a disproportionately large role with respect to biodiversity, landscape and socio-economic values (Reed-Andersen \textit{et al.} 2000; Hadwen and Bunn 2004). Recent studies in Tasmania and New Zealand have highlighted the importance of small lakes and tarns as areas of high biodiversity (Tyler 1992; Vyverman \textit{et al.} 1996), and have reported high levels of endemism among diatoms and other algae (e.g. Sabbe \textit{et al.} 2001). Moreover, lentic systems in high-latitude and high-altitude regions are very sensitive to environmental change (e.g. Gregory-Eaves \textit{et al.} 2000); they may even amplify climate fluctuations (Quayle \textit{et al.} 2002) and therefore hold great potential for paleo-environmental and paleo-climatological studies (Gell \textit{et al.} 2005). However, in order to assess the use of small water bodies in Tasmania and New Zealand for environmental and climate studies, we need baseline information on their limnological and biological features. To date, most studies on lakes in New Zealand have focussed predominantly on the physical properties of larger lakes, water quality issues, fish populations, submerged macrophytes and phytoplankton dynamics (see Burns 1991 for a review; Barker \textit{et al.} 2004).

The aim of the present study is to contribute to the knowledge of the chemical limnology in small water bodies (lakes, tarns and mires) in temperate regions of Tasmania and New Zealand. We provide a newly created baseline dataset of physical and chemical variables for 71 small, lentic water bodies in South Island and Stewart Island (New Zealand). We then assess the main limnological features of these systems in conjunction with similar, freshwater systems in Tasmania, which are already relatively well characterised (Vyverman \textit{et al.} 1996). This dataset will be used in future research to study the distribution of benthic diatom communities in relation to the environmental settings. The present forms part of a broader research programme aimed at identifying the environmental, climatic and evolutionary constraints that regulate the diversity and structure of benthic diatom communities in high-latitude and high-altitude freshwater environments of the Australasian region.
Materials and methods

General descriptions of the study areas

The study sites in New Zealand (South Island and Stewart Island, Fig. 1) and Tasmania are situated at approximately the same latitude (40–46°S) (Vyverman et al. 1996).

Most of the New Zealand sites are in or near the Southern Alps, which run the length of South Island and lie on the boundary of the Indo-Australian and Pacific Ocean plates (Sturman and Spronken-Smith 2001). Catchment lithology ranges from acidic igneous rocks with low buffering capacity (e.g. granites) to highly alkaline rocks with high buffering capacities (e.g. marble; see Accessory Publication on the Marine and Freshwater Research website). Ultramafic rock intrusions (serpentine) occur in several places along the Alpine Fault. Serpentine is characterised by high iron and magnesium content and potentially also contains chromium, cobalt and nickel, and can profoundly affect species composition of catchment vegetation (Wardle 1991). Alkalinity and Acid Neutralising Capacity (ANC) of the soils are strongly associated with bedrock type (Wetzel 2001); due to the high lithological diversity in New Zealand, the ranges of these variables are large (Sturman and Spronken-Smith 2001). All sites had minimal or no apparent anthropogenic disturbances in their catchments.

New Zealand's South Island has a temperate climate with strong maritime influences in the coastal areas (Sturman and Spronken-Smith 2001). The predominant westerly to north-westerly winds cause orographic rainfall, as saturated air is pushed up the western slopes of the Southern Alps. Mean annual rainfall (MAR) at the study sites ranges from 916 mm year\(^{-1}\) (Otago) to 9967 mm year\(^{-1}\) (Fiordland, Furkert Saddle) and strongly determines soil structure (Wardle 1991; see Accessory Publication on the Marine and Freshwater Research website). Zonal soils (podzolised) are mostly found in the wettest areas, while azonal soils predominate in the drier regions (Molloy 1988; see Accessory Publication on the Marine and Freshwater Research website). The difference between summer and winter temperatures increases with altitude, and coastal areas have the smallest differences due to the buffering effect of coastal air masses (Gregory-Eaves et al. 2000). Several lakes above the winter snowline (± 1000 m) freeze over during the austral winter; duration of ice cover ranges from a few days to several months. Seasonal meltwater runoff is variable, but can account for up to 40% of the fluctuations in total spring runoff in addition to rainfall (Sturman...
and Spronken-Smith 2001). Catchment vegetation is highly diverse and characterised by a high degree of species endemism (McGlone et al. 2001). Lower altitude areas are covered by forest, dominated either by southern beech (Nothofagus spp.) or by podocarp/broadleaf forest in the West Coast ‘beech gap’ (Trewick and Wallis 2001). Above the tree line and in drier regions, grassland dominates, particularly the endemic genus Chionochloa, sometimes intermingled with species-rich sub-alpine scrub (Wardle 1991), or alpine herbaceous, or bog vegetation (Barlow 1986; see Accessory Publication on the Marine and Freshwater Research website).

Lithological, edaphic, vegetation and climatic characteristics of the Tasmanian study sites are described in detail in Vyverman et al. (1996, and references therein). The highland region of Tasmania can roughly be divided into a western and an eastern part on the basis of lithology and climate, which also results in different edaphic and vegetational characteristics. The dividing line between the western and eastern part more or less follows the Jurassic edge and the 1200 mm isohyete. West of this line, bedrock is mainly composed of acidic igneous rocks (siliceous rock types of Precambrian, Cambrian and Ordovician origin). Soils are predominantly podzols, moor peats and alpine humus. Rainfall is very high (2000–3500 mm year\(^{-1}\)). Vegetation is dominated by Nothofagus rain forest, Gymnoschoenus sedgeland or (sub-)alpine vegetation, all of which contain peat-forming Sphagnum spp. East of the dividing line, the dominant rock type is Jurassic dolerite. The dominant vegetation types are sclerophyll forest and alpine heathland on soils mainly composed of alpine humus. The eastern part receives less rainfall (800–2000 mm year\(^{-1}\)). Two major limnological provinces coincide with these eastern and western highland regions in Tasmania. The coastal systems make up a third province (Tyler 1992). The differences between the lakes from these provinces were first recognised on the basis of their optical properties. In the eastern province, lakes are mostly of the clear water green-window type. They are (ultra-)oligotrophic with low concentrations of humic substances. The western province is characterised by more acidic, red-window type lakes with high concentrations of humic substances, leaching from the catchment vegetation and soils (Tyler 1992). Humic substances and dissolved organic carbon (DOC) play an important role in high-altitude and high-latitude fresh waters by shielding biota from harmful UVB irradiation (e.g. Rae et al. 2001; Leavitt et al. 2003).

**Methods**

All limnological data on Tasmania were derived from the TASDIAT dataset (Vyverman et al. 1995) comprising 76 highland lakes (Vyverman et al. 1996) and 12 coastal lakes (taken from Bowling et al. 1993 and hereafter referred to as the TASCOST dataset). The highland lakes include systems in both the eastern and western limnological provinces (Vyverman et al. 1996). Analyses of benthic diatom and faunal communities along an east–west gradient show that the dividing line between the two limnological provinces would more appropriately be considered as a corridor of change, as intermediate types of biological communities are present on both sides of the dividing line (see Vyverman et al. 1996, and references therein). In the present study, we classify the corridor lakes with the eastern province because, from a limnological point of view, they more closely resemble the green-window type lakes. The coastal water bodies are mostly dystrophic, range from acidic to alkaline and are mostly characterised by high conductivities due to their proximity to the ocean (Table 1). Only coastal lakes with conductivities below 200 µS cm\(^{-1}\) were retained in the TASCOST dataset (Bowling et al. 1995).

Overall, the water bodies in Tasmania were selected so as to cover a wide and representative range in lake and catchment sizes, lake types, altitude, climate (temperature and rainfall), bedrock and vegetation type, all of which are known to be important factors influencing water chemistry and hence aquatic communities (e.g. Tyler 1992). Methodologies and detailed chemical data are given in the abovementioned papers or are available from the authors upon request. Climatic data for Tasmania were obtained from the Commonwealth Bureau of Meteorology website (www.bom.gov.au, verified December 2005) and were corrected by means of simple linear regression for alitudinal differences between the lake location and the location of the meteorological station (Netter et al. 1996; Table 1).

The 71 New Zealand lakes were sampled during the austral summer of 2001. As for the Tasmanian lakes, we tried to sample a set of lakes that is representative of the high diversity in lake and catchment sizes, lake types, altitude, climate (temperature and rainfall), bedrock and vegetation type present in New Zealand’s South Island. As in Tasmania, most of the sampled water bodies are fairly young, due to their recent glacial and to a lesser extent aeolian, riverine or phytogenic origin (cf. Lowe and Green 1987). Many of the systems studied are situated near or above the tree line (± 1000–1400 m). Lake typology was defined according to Wetzel (2001) and Wheeler and Proctor (2000) (see Accessory Publication on the Marine and Freshwater Research website). This classification was developed for north-west Europe and separates typical individual lake systems from more extensive wetland systems (mires). The latter are further differentiated along three gradients: an alkalinity gradient, a nutrient (N and P) availability gradient, and a water-level gradient. In the present study we define ‘lake’ as the larger individual systems, both in highland and lowland areas, whereas ‘tarn’ refers to the smaller mountain lakes or pools. Mires include both wetland systems on peat and on mineral soils; bogs are the ombrotrophic and weak minerotrophic systems, whereas fens are the base-rich mires. An additional nutrient availability qualification is applied to this classification (oligotrophic, mesotrophic and eutrophic). A lake order was assigned to each freshwater body according to Riera et al. (2000) using the Series 260 1 : 50 000 Topomaps. This is a hierarchical system, analogous to stream order, which gives a metric for landscape position of a lake.

Conductivity, ambient water temperature (T) and pH were recorded on site in the littoral zone (at 0.5–1 m depth) using a field meter (TPS Pty Ltd, Brisbane). Samples for chemical analyses were also taken in the littoral zone. Water samples were collected in acid-washed polyethylene bottles and were filtered on site or as soon as possible after collection. Samples were filtered through 0.45 µm membrane filters for gilvin, major anions and cations (Ca\(^{2+}\), Mg\(^{2+}\), Na\(^{+}\), K\(^{+}\), Cl\(^{-}\), SO\(_{4}\)\(^{2-}\)), and metal analyses (Al, Cd, Co, Cr, Fe, Mn, Ni), and through pre-ashed GF/F filters (Whatman Ltd, Maidstone, UK) for analyses of nutrients and DOC. Samples for metal analyses were fixed with concentrated HNO\(_3\). Samples for DOC analysis were collected into pre-cleaned glass vials and fixed with concentrated HCl. Gilvin (g440) was determined as absorption at 440 nm on a JASCO 7850 UV/VIS spectrophotometer (Japan Spectroscopic, Tokyo) and used as proxy for humic substances (Davies-Colley et al. 1993). Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) were determined colourimetrically on a Technicon 2 Auto-analyser (Technicon Instruments, Tarrytown, NY) after UV radiation in alkaline and acidic conditions respectively (Downes 2001). Dissolved organic carbon was determined using the high-temperature catalytic combustion technique on a Shimadzu TOC5000A (Duisberg, Germany), equipped with a high-sensitive catalyst (Wei et al. 1998). Metal analyses were done by flame atomic absorption spectrometry (APHA 1998).

Mean annual rainfall for New Zealand was derived from a rainfall surface map (normalised mean rainfall data, 1930–1980, National Institute of Water and Atmospheric Research (NIWA)) and hereafter referred to as the New Zealand Rainfall Database (Bowling et al. 1995). January and July temperatures are 30-year means (1960–1990, NIWA).

Catchment rock types were extracted from the New Zealand Land Resources Inventory (NZLRI; Newsome 1992) and from Department of Scientific and Industrial Research Geological Maps of New Zealand (1 : 250 000; New Zealand Institute of Nuclear and Geological
Table 1. Comparative table of statistics of the various datasets and subsets; New Zealand lakes are divided in South Island and Stewart Island, Tasmanian lakes in the limnological provinces described in Vyverman et al. (1996).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>New Zealand (n = 71)</th>
<th>Stewart Island (n = 6)</th>
<th>South Island (n = 65)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Md</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td>km²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;0.001</td>
<td>36.100</td>
<td>0.001</td>
<td>9.63</td>
<td>4.519</td>
</tr>
<tr>
<td><strong>Catch</strong></td>
<td>km²</td>
<td>0.100</td>
<td>380.000</td>
<td>0.500</td>
</tr>
<tr>
<td><strong>Altitude</strong></td>
<td>m</td>
<td>5</td>
<td>1520</td>
<td>854</td>
</tr>
<tr>
<td><strong>MAR</strong></td>
<td>mm year⁻¹</td>
<td>916</td>
<td>9967</td>
<td>3237</td>
</tr>
<tr>
<td><strong>January T</strong></td>
<td>°C</td>
<td>11.9</td>
<td>16.2</td>
<td>13.0</td>
</tr>
<tr>
<td><strong>July T</strong></td>
<td>°C</td>
<td>–3.5</td>
<td>7.2</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Na⁺</strong></td>
<td>mg L⁻¹</td>
<td>&lt;0.001</td>
<td>16.241</td>
<td>1.261</td>
</tr>
<tr>
<td><strong>K⁺</strong></td>
<td>mg L⁻¹</td>
<td>&lt;0.001</td>
<td>1.439</td>
<td>0.143</td>
</tr>
<tr>
<td><strong>Ca²⁺</strong></td>
<td>mg L⁻¹</td>
<td>&lt;0.001</td>
<td>23.483</td>
<td>0.469</td>
</tr>
<tr>
<td><strong>Mg²⁺</strong></td>
<td>mg L⁻¹</td>
<td>0.038</td>
<td>8.722</td>
<td>0.264</td>
</tr>
<tr>
<td><strong>Cl⁻</strong></td>
<td>mg L⁻¹</td>
<td>0.179</td>
<td>27.433</td>
<td>0.925</td>
</tr>
<tr>
<td><strong>SO₄²⁻</strong></td>
<td>mg L⁻¹</td>
<td>&lt;0.001</td>
<td>2.931</td>
<td>0.230</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td></td>
<td>4.4</td>
<td>9.4</td>
<td>5.8</td>
</tr>
<tr>
<td><strong>Cond.</strong></td>
<td>µS cm⁻¹</td>
<td>4.1</td>
<td>162.0</td>
<td>17.6</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>°C</td>
<td>6.6</td>
<td>27.9</td>
<td>16.5</td>
</tr>
<tr>
<td><strong>Gilvin</strong></td>
<td>g 440 m⁻¹</td>
<td>0.046</td>
<td>11.423</td>
<td>1.267</td>
</tr>
</tbody>
</table>

Md, median; Av, average; 1SD, unbiased standard deviation; MAR, mean annual rainfall; Cond., conductivity; T, temperature.

Tasmania (n = 76)  Western limnological province (n = 26)  Eastern province + corridor lakes (n = 50)  Coastal lakes (n = 12)
Dominant catchment vegetation type was determined on the basis of both field observations and information derived from the NZLRI, and the New Zealand vegetative cover classification (Newsome 1964). Soil types were extracted from the NZLRI. Stewart Island soil types were obtained from M. Duncan, NIWA (unpublished data). Catchment and lake surface area were obtained from Livingston et al. (1986) for some of the larger lakes, or derived from the New Zealand Department of Survey and Land Information topographical maps (Series 260 1 : 50 000). Surface areas of tarns and pools too small to feature on the maps were estimated in the field. Altitude was determined from the Series 260 topographical maps. Lake depth was extracted from current maps were estimated in the field. Altitude was determined from the New Zealand Departmen and lake surface area were obtained from Livingston et al. (1992). Soil types were extracted from the NZLRI, and the New Zealand vegetative cover classification (Newsome 1964). Dominant catchment vegetation type was determined on the basis of both field observations and information derived from the NZLRI, and the New Zealand vegetative cover classification (Newsome 1992). Soil types were extracted from the NZLRI. Stewart Island soil types were obtained from M. Duncan, NIWA (unpublished data). Catchment and lake surface area were obtained from Livingston et al. (1986) for some of the larger lakes, or derived from the New Zealand Department of Survey and Land Information topographical maps (Series 260 1 : 50 000). Surface areas of tarns and pools too small to feature on the maps were estimated in the field. Altitude was determined from the Series 260 topographical maps. Lake depth was extracted from current literature (e.g. Livingston et al. 1986; Reid 2005) for some of the larger lakes, and visually estimated for some of the smaller systems.

All available data were assessed for elementary statistical properties (e.g. distribution of data). For both regions, all variables had skewed distributions and were log\(_{(10)}(x + 1)\)-transformed before analyses, except for pH and gilvin (Zar 1984). Metals, TDP and TDN, which were only available for New Zealand lakes, were not included in the correlation and multivariate analyses. Pearson product-moment correlation coefficients were used to describe the relationships between variables. Summary statistics, ternary graphs and correlation matrices (Fig. 2, Table 1, see [Accessory Publication] in the Marine and Freshwater Research website), and statistical analyses and tests (e.g. Shapiro–Wilks normality test) were generated using the software package STATISTICA 5.5 (Statsoft Inc. 2000). Standard deviation was unbiased following the (\(n - 1\)) method. Multivariate analyses were performed using the software package CANOCO for Windows 4.5 (Ter Braak and Smilauer 2002). Principal component analysis (PCA), with centring and standardisation of the variables, was used to examine the principal patterns of variation in the environmental data in the combined dataset, and in both separate datasets. Standardisation of variables in PCA allows for vary disparate variables to be compared (Ter Braak and Smilauer 2002). In all analyses, only the ion concentrations (not proportions), conductivity, gilvin and pH were introduced as active variables. In the separate PCA analyses (per subset), cation proportions, monovalent-divalent cation ratio and physical (catchment and lake area, latitude and altitude) and climatic parameters (MAR, average January and July temperature) were introduced as supplementary (i.e. passive) variables.

**Fig. 2.** (a) Ternary diagram showing cationic proportions of New Zealand lakes. Lakes are labelled according to their locations (Table 1). World Average Sea Water (WASW) and World Average Fresh Water (WAFW) are indicated (Boulton and Brock 1999). Inset: detail of New Zealand lakes. (b) Ternary diagram showing cationic proportions in Tasmanian lakes: East + Corridor (E), West (W), Coastal (CL). Inset: detail of Tasmanian lakes.
In the following sections, the ‘New Zealand’ dataset refers to all South Island and Stewart Island sites combined. The South Island and Stewart Island subsets as such are referred to separately.

Results

Physical characteristics of New Zealand water bodies

No physical characteristics were available for the TASCOAST dataset. Except for a few larger lakes in New Zealand (see Accessory Publication on the Marine and Freshwater Research website), the remainder of water bodies in the dataset are relatively small (median areas 0.03 and 0.00115 km$^2$ respectively). The largest lakes are $\pm 24$ km$^2$ in surface area in Tasmania, whereas the largest lake in New Zealand is 36.1 km$^2$. We refer to lakes with a surface area larger than 2 km$^2$ as large lakes (see Accessory Publication on the Marine and Freshwater Research website). Log-normal size distributions of the New Zealand and Tasmanian freshwater bodies are comparable. Lake depth was only available from literature for some larger lakes or visually estimated for smaller lakes. Median altitude of the New Zealand and Tasmanian sites (excluding the coastal lakes) is 854 m and 972 m respectively. Lake order in New Zealand ranges from $-3$ to 5 and is significantly correlated with lake surface area and catchment area (see Accessory Publication on the Marine and Freshwater Research website).

Westland lakes (New Zealand) are situated on acidic igneous bedrock or alkali bedrock of alluvial origin, with both azonal and zonal soils (podzols). Sites in Fiordland and Stewart Island are predominantly situated on acidic igneous bedrock, covered with well structured soils (podzols). The Canterbury site catchments typically have greywacke bedrock, with drier azonal soils. Sites in Nelson–Marlborough are characterised by ultramafic rocks with clay soil and those in Nelson are characterised by alkaline marble bedrock and soils with a high ANC (see Accessory Publication on the Marine and Freshwater Research website).

Water chemistry

Median values for pH in the New Zealand and Tasmanian datasets are comparable. The New Zealand dataset, however, contains some truly alkaline lakes, whereas no such lakes are present in the Tasmanian dataset (Table 1). This holds important implications for the biological diversity, as such systems contain characteristic alkaliphilous biota (Wetzel 2001). Median gilvin ranges are more or less comparable between the TASIAD and New Zealand datasets, but median values are considerably higher in the TASCOAST dataset. Dissolved organic carbon measurements are only available for the New Zealand water bodies; they range from 0.24 to 35.94 ppm and overall are significantly and strongly correlated with gilvin (see Accessory Publication on the Marine and Freshwater Research website). Low values for gilvin and DOC are associated with low lake order. However, lakes of high lake order may attain increased DOC while maintaining relatively low gilvin values (e.g. NZ 21).

With the exception of the coastal systems, most of the New Zealand and Tasmanian water bodies sampled are very dilute. Median and average ion concentrations values are well below global average conductivities (Wetzel 2001). Mean values for monovalent (potassium and sodium) and bivalent (calcium and magnesium) cation concentrations in the New Zealand and TASIAD lakes fall similarly well below global average values ($\text{Ca}^{2+}$: 15.0 mg L$^{-1}$, $\text{K}^+$: 2.3 mg L$^{-1}$, $\text{Na}^+$: 6.3 mg L$^{-1}$, $\text{Mg}^{2+}$: 4.1 mg L$^{-1}$; Wetzel 2001; see Accessory Publication on the Marine and Freshwater Research website).

The median value for sodium is distinctly higher in the TASIAD than in the New Zealand dataset (Table 1). Median and mean values for sodium and magnesium are significantly higher in the TASCOAST and the Stewart Island subsets, due to a strong maritime influence. These datasets are also characterised by high chloride values, with medians and averages well above global average values ($\text{Cl}^{-}$: 7.8 mg L$^{-1}$), as was NZ 17 (a coastal dune lake). Average and median chloride values are also significantly higher in the TASIAD than in the New Zealand dataset (Table 1). In some New Zealand lakes the ratio between sodium and chloride (see Accessory Publication on the Marine and Freshwater Research website) markedly exceeds the ratio 1:1.5 (i.e. ± 0.66), which is the normal ratio when a marine source for sodium is dominant. This suggests a significant input of sodium derived from non-marine sources (Dring 1982; Pienitz et al. 1997). Sulphate concentrations are generally slightly lower in New Zealand than in the TASIAD lakes.

Apart from the mean and median values of the cation concentrations, an important limnological difference between New Zealand and Tasmania is observed regarding the respective ranges (Table 1). These are clearly much wider in New Zealand and result in a higher limnological diversity (Fig. 2). A similar phenomenon can be observed in the ratios of the major ions. On average, these are near world average seawater (WASW) proportions for both New Zealand and Tasmanian sites (Fig. 2; Wetzel 2001). However, New Zealand lakes are more widely dispersed along the entire gradient from WASW (sodium-dominated) to world average freshwater proportions (WAFW; calcium-dominated) (Wetzel 2001; Table 1, Fig. 2). A few lakes in Nelson–Marlborough on serpentine bedrock are uniquely characterised by the dominance of magnesium.

Nutrients (TDP, TDN) were only determined for a subset of 19 of the New Zealand sites. The trophic status of the lakes ranges from oligo- to mesotrophic (Wetzel 2001), but most values correspond to those typical of oligotrophic conditions (Accessory Table 1). TDP : TDP ratios range from 45:1 to 247:1. Micronutrients and potentially toxic metals were determined for the same subset of lakes (see Accessory Publication on the Marine and Freshwater Research website). Values for cadmium, cobalt and chromium are below
detection limit in all samples. Iron was detectable in 15 lakes, aluminium in 7 lakes, manganese in 5 lakes and nickel in only 2 lakes (see Accessory Publication on the Marine and Freshwater Research website).

**Multivariate analyses**

The joint PCA of the New Zealand and Tasmanian water bodies reveals that variation in the chemical limnology is dominated by gradients in conductivity and ion concentrations (Fig. 3). The first two axes account for 76.8% of the variation in the chemical variables; consecutive axes have lower eigenvalues (Table 2). The water bodies from the TASCOAST and the Stewart Island datasets, which are characterised by high concentrations of all major ions (except calcium), and hence conductivity, as well as high gilvin values, are separated along the first axis from all other lakes. An important part of the New Zealand sites (mostly from Fiordland, Canterbury and Nelson, see below) are characterised by very dilute conditions and therefore cluster to the left of the TASDIAT water bodies. The western and eastern limnological provinces in Tasmania have similar conductivities; the western lakes, however, have distinctly higher gilvin values. The second axis mainly represents a pH/calcium gradient. At the higher end of the pH and calcium range we mainly find New Zealand sites (predominantly from Westland, see below), next the slightly acidic eastern Tasmanian lakes and the remainder of New Zealand water bodies, and finally the highly acidic lakes of Tasmania’s western province. The Stewart Island and the TASCOAST datasets, which take an outlier position in the joint PCA analysis (Fig. 3), were omitted from the separate PCA analyses of New Zealand and Tasmania respectively.

In the PCA of the South Island dataset (Fig. 4), which explains 61.5% of the variation in the chemical limnological data along two axes (Table 2), conductivity remains the most important variable. However, unlike in the joint PCA and the PCA of the TASDIAT dataset (see below), the conductivity gradient, which is significantly correlated with the major cations (see Accessory Publication on the Marine and Freshwater Research website), largely coincides with the pH gradient. On the right side of the first axis, we mainly find larger, low-altitude water bodies with higher conductivity and pH/calcium concentrations, including most Westland sites, the three Otago sites and some lakes from Fiordland (NZ 38, 39, 42–44, see Accessory Publication on the Marine and Freshwater Research website). Lakes in the upper right quadrant have higher sodium concentrations, while those in the lower right quadrant have higher calcium concentrations. The Westland lakes experience significantly milder winters and

![Fig. 3. Standardised principal components analysis (PCA) biplot (axes I and II) illustrating environmental patterns of variation in ionic composition, pH, conductivity and gilvin in New Zealand and Tasmania (axes I and II cut off at −0.6 and −0.4 respectively). Full triangles (W), samples from western province (Tasmania); crosses (E), samples from eastern province (Tasmania); grey diamonds (CL), samples from coastal province (Tasmania); grey circles, samples from South Island (New Zealand); full squares, samples from Stewart Island (New Zealand).](image-url)

| Table 2. Eigenvalues for PCA axes I to IV, ratios of eigenvalues for axes I and II, and II and III, and cumulative percentage variation for the first four axes |
|---------------------------------|------|------|------|-------|-------|-------|
| PCA summaries                   | Axes |       |       |       |       |       |
| Combined datasets               | I    | II    | III   | IV    | I/II  | II/III |
| Eigenvalues                     | 0.538| 0.23  | 0.078 | 0.059 | 2.3   | 2.9    |
| Cumulative % explained          | 53.8 | 76.8  | 84.5  | 90.4  |       |       |
| South Island                    |      |       |       |       |       |       |
| Eigenvalues                     | 0.413| 0.202 | 0.166 | 0.069 | 2.0   | 1.2    |
| Cumulative % explained          | 41.3 | 61.5  | 78.1  | 85    |       |       |
| TASDIAT                         |      |       |       |       |       |       |
| Eigenvalues                     | 0.367| 0.305 | 0.116 | 0.094 | 1.2   | 2.6    |
| Cumulative % explained          | 36.7 | 67.1  | 78.8  | 88.2  |       |       |
summers, and have higher pH and potassium concentrations. The Otago sites are in a much drier area, with colder winters; they also have significantly higher potassium concentrations (see Accessory Publication on the Marine and Freshwater Research website). Most Fiordland and Canterbury water bodies, and those of Nelson, are more dilute and are therefore largely situated on the negative side of the first principal component. These water bodies are smaller. The Fiordland sites have significantly lower potassium, sodium, magnesium, gilvin and DOC concentrations than the other New Zealand lakes (see Accessory Publication on the Marine and Freshwater Research website). The second principal component mainly reflects variation in gilvin and, to a lesser degree, magnesium concentration. Interestingly, despite the higher total concentrations of the monovalent cations sodium and potassium in the Westland and large Fiordland lakes (right side of the diagram), the proportion of monovalent cations is actually higher on the left side of the diagram. The first principal component thus largely reflects a gradient from lakes dominated by the bivalent cation calcium to lakes dominated by sodium and, to a lesser degree, also potassium.

As was already shown in Vyverman et al. (1996), there is a clear separation between the two limnological provinces in Tasmania, viz. a western one and an eastern one (which also includes the corridor lakes; Fig. 5). The western lakes have lower pH and higher gilvin values, and a higher ratio between monovalent and bivalent cations. Western lakes are proportionally dominated by sodium, while eastern lakes are calcium dominated. The conductivity gradient is subordinate to the pH/gilvin gradient and separates lakes along the second axis. Western water bodies with higher conductivities are sodium dominated, while the corresponding eastern lakes have higher calcium concentrations. Lakes in the western Tasmanian province therefore clearly hold seawater proportions whereas lakes in the eastern province tend to fall in between WASW and WAFW (Fig. 2).

Discussion

The present study evaluates the chemical and physical limnological diversity of mostly small and predominantly glacial lakes, tarns and mires that litter the coastal and alpine regions of Tasmania and New Zealand’s South Island and Stewart Island. The limnology of the Tasmanian water bodies has previously been described in Tyler (1992) and Vyverman et al. (1996, and references therein). To our knowledge, the limnology of similar lentic water bodies in New Zealand’s South Island and Stewart Island has to date not been comprehensively described. As with other Australasian inland waters, the fresh waters in Tasmania and New Zealand are very dilute with low ion concentration (Boulton and Brock 1999). They are characterised by an ionic composition dominated by sodium and chloride, which therefore lies closer to world average seawater ratios (WASW) than to world average freshwater ratios (WAFW; Fig. 2). In general, this is typical
for fresh waters that lie in close proximity to oceans and receive dissolved marine salts from atmospheric precipitation (Wetzel 2001). Variation in ionic composition within the islands is controlled by the interactive effects of the climates, bedrock types, topographic differences, distances from the sea, lake morphometries (size) and soil characteristics.

In the western and coastal provinces of Tasmania, high rainfall on siliceous bedrock and peaty soils results in dilute lakes and tarns with an ionic composition close to WASW due to the marine cation deposition through rainfall. Acidic igneous rocks also contain proportionally higher sodium concentrations, and are thus an important additional source of typically ‘marine’ cations. Eastern and corridor lakes, with less rainfall on predominantly dolerite bedrock and richer soils, move towards WAFW (Fig. 2; Tyler 1992).

The cationic composition of the New Zealand sites, however, spans the whole range from WASW to WAFW, and even contains some magnesium-dominated lakes (Fig. 2). The lakes dominated by magnesium, are situated in Nelson–Marlborough and are strongly affected by the serpentine bedrock, which is rich in magnesium and iron (Wardle 1991). Lakes on Stewart Island, which lie in close proximity to the ocean, are more or less comparable to those of the Tasmanian coastal province, i.e. they have high conductivities caused by high sodium concentrations (Table 1; Fig. 3). An increased chloride : sodium ratio (>±1.5) in Stewart Island may indicate the additional presence of fossil marine deposits (Henriksen et al. 1998; Wetzel 2001).

Calcium-dominated lakes are predominantly found in Westland, which can largely be attributed to degradation processes of calcium-rich alluvial soils (Sturman and Spronken-Smith 2001). For other sites in the New Zealand dataset, the relationship between geographic region, bedrock and cationic composition is less pronounced. This again contrasts with the situation in Tasmania, where gradients in rainfall, bedrock and vegetation, which strongly influence the ionic composition of lake water, are largely congruent and result in discrete limnological provinces (Tyler 1992). In New Zealand, both calcium- and sodium-dominated water bodies can be found in Fiordland, Westland and Canterbury (Figs 2, 3). Here, cationic composition appears to be more strongly related to lake size, with the larger lakes having higher ion loads (Fig. 3). This is most probably related to lower throughputs of water and solutes in these lakes, whereas the smaller water bodies in the same regions have much lower water-residence times (especially in areas with very high rainfall, such as Fiordland) and are often situated on podzolised soils.

Climatic conditions (and precipitation) may thus not only strongly affect ion composition, but may also lead to differences in conductivity between both regions. South Island fresh waters are overall more dilute than those in Tasmania (Fig. 3; Table 1), which is most probably related to mean annual rainfall in South Island being almost twice as high as that in Tasmania. Low conductivities are especially notable in areas such as Fiordland where there is a combination of very high rainfall and catchment bedrock dominated by erosion-resistant rock types (e.g. granites). Likewise, concentrations of humic substances (gilvin) are generally lower in South Island, which may also be related to higher flushing rates of the water bodies; again most notable in Fiordland (Curtis and Schindler 1997). The Stewart Island water bodies, which have mean annual rainfall comparable to the western province of Tasmania, have higher gilvin concentrations than the South Island water bodies (Table 1). High rainfall regimes resulting in high flushing rates have an additional negative feedback effect on the production and transport of humic substances through influencing the composition of catchment vegetation, soil formation and bedrock erosion processes (e.g. Reche and Pace 2002). Very high rainfall (e.g. >8000 mm year$^{-1}$; Fiordland) results in conditions such as waterlogged soils, which are unfavourable for the release of humic substances from the catchment (e.g. Sturman and Spronken-Smith 2001). As such, humic substances and DOC are prevented from arriving and accumulating in the lake water. It is uncertain how other factors like temperature, topography and vegetation type may additionally affect concentrations of humic substances in the studied lakes (e.g. Pienitz et al. 1997; Michelutti et al. 2002).

The pH gradient in the datasets covers a wide range from acidic to alkaline systems (4.4–9.4 in New Zealand and 3.7–6.8 in Tasmania), which is much wider than is reported for many lake-water acidification datasets from Arctic and sub-Arctic regions (e.g. Gregory-Eaves et al. 2000; Michelutti et al. 2002) and from northern hemisphere alpine regions (e.g. Cameron et al. 1999; Juggins 2002). Tasmanian fresh waters are on average more acidic than the New Zealand fresh waters (Table 1). This is mainly caused by the highly acidic water bodies of the western province, which, like the coastal Tasmanian lakes, are characterised by high concentrations of humic substances. Humic substances are known to depress lake water acidity up to 2.5 units, provided the ANC is low (0–50 µeq L$^{-1}$; Wetzel 2001). This is the case in the lakes of the western province, which are situated on acidic igneous rocks with poor buffering capacity. However, there are several small fresh waters in Fiordland, which are acidic but have low gilvin values (cf. above). Lake water acidity in these systems in a region that is characterised by extremely high rainfall regimes, is probably mainly a function of rainwater acidity (pH ± 5.6; Verhoeven et al. 1987).

Like in Tasmania, most sampled fresh waters in New Zealand have low nutrient concentrations typical of oligotrophic and dystrophic conditions. Increased values for TDN and TDP in Otago, Nelson and Nelson–Marlborough, however, indicate increased nutrient conditions, possibly related to human exploitation of the catchment (see Accessory Publication on the Marine and Freshwater Research website). TDP concentrations are low in comparison to several northern hemisphere datasets (e.g. Juggins 2002;
Michelutti et al. (2002), yet are in agreement with other reports from New Zealand (Burns 1991). This probably reflects the extremely low phosphate concentrations in New Zealand catchment soils (Timperley 1987). The TDN: TDP ratios suggest that phosphate concentrations may be limiting in New Zealand alpine freshwater systems, which is in agreement with Cameron et al. (1999). Interestingly, Burns (1991) explicitly mentions N limitation for New Zealand lakes, rather than P limitation. Apparently, both types of nutrient limitation occur in New Zealand and are probably related to properties of catchment soil and bedrock.

For only seven and five lakes respectively did the total iron and manganese concentrations exceed the lower threshold of what is generally common in oxygenated surface water (0.05–0.2 mg L⁻¹, Wetzel 2001). At such low concentrations iron and manganese can also be limiting elements in oligotrophic lakes, as has already been reported from Arctic and temperate regions (Pientitz et al. 1997, and references therein). In conclusion, the small, predominantly alpine freshwater systems in New Zealand are characterised by high chemical limnological diversity, mainly governed by lithology, geomorphology and climate. In comparison with systems in Tasmania in a similar setting, fresh waters occur in both areas characterised by an ionic composition close to WASW. However, in New Zealand, the range of water chemistry expands fully towards lakes more closely resembling WAFW. In addition, some lakes were observed in New Zealand that are dominated by magnesium. Contrary to Tasmania, New Zealand fresh waters could not be grouped into discrete geographically defined limnological provinces. Although, a gradient in acidity is predominant in both regions, in Tasmania, pH is correlated with gilvin and calcium (or alkalinity), whereas in New Zealand the variation in gilvin is independent of the pH gradient, as a result of the presence of clear water acidic systems in Fiordland. The high limnological diversity in New Zealand holds promising prospects for studies on the diversity and composition of aquatic biota.

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