https://doi.org/10.5194/egusphere-2025-6242
Preprint. Discussion started: 19 January 2026

Diatom–environment relationships and limnological variability: an updated quantitative tool for palaeoclimatology on sub-Antarctic Macquarie Island

Caitlin A. Selfe[1], Karina Meredith[2], Liza McDonough[2], Justine Shaw[1], Stephen J. Roberts[3], Krystyna M. Saunders[2,4]

[1] Securing Antarctica's Environmental Future, Queensland University of Technology, Brisbane, 4000, Australia
[2] Securing Antarctica's Environmental Future, Environment Research and Technology Group, Australian Nuclear Science and Technology Organisation, Lucas Heights, 2234, Australia
[3] British Antarctic Survey, Cambridge, CB3 0ET, United Kingdom
[4] Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, 7004, Australia

Correspondence to: Caitlin A. Selfe (caitlin.selfe@hrd.qut.edu.au)

Keywords: Diatoms, Electrical conductivity, sub-Antarctic, Macquarie Island, Transfer function, Southern Hemisphere westerly winds, Palaeoclimate, Limnology

https://doi.org/10.5194/egusphere-2025-6242
Preprint. Discussion started: 19 January 2026

Abstract. Sub-Antarctic Macquarie Island is ideally located for reconstructing past variations in Southern Hemisphere westerly wind strength. Diatoms are a valuable palaeolimnological tool on sub-Antarctic islands, providing a means to reconstruct past climate and environmental changes. Diatom communities are sensitive to changes in lake electrical conductivity (EC) linked to westerly wind–driven sea-spray inputs on Macquarie Island, and diatom–conductivity models have previously been used to infer past westerly wind variability. Here we present new diatom data from 52 lakes to assess diatom–environment relationships and develop an updated diatom–conductivity model for Macquarie Island. Seasonal and multi-year water chemistry and isotope data were analysed to assess temporal variability in hydrochemical processes and the influence of evaporation, ensuring the resulting diatom-conductivity model reflects external climatic drivers rather than local dynamics. Statistically robust transfer functions were developed for EC (bootstrapped r^2 = 0.80, RMSEP = 0.40), while pH and temperature had weaker predictive performance. For EC, weighted averaging and maximum-likelihood approaches performed comparably, although the former showed reduced predictive power at high EC where low species turnover and nutrient collinearity affected accuracy. This quantitative-diatom model combined with understanding of hydrogeochemical processes provides an improved basis for reconstructing past Southern Hemisphere westerly wind variability, which can be applied in future palaeoclimate studies on Macquarie Island.

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1 Introduction

The Southern Ocean region exerts a strong influence on Southern Hemisphere and global climates (Jones et al., 2016; Fogt & Marshall, 2020). Sub-Antarctic islands are among the few landmasses located in the Southern Ocean, making them important sites for understanding the past and future role of the Southern Ocean on climate variability. The Southern Hemisphere westerly winds (SHW) are a major driver of Southern Hemisphere mid- to high-latitude climates, modulating ocean circulation, mid-latitude temperature and precipitation regimes, and the efficiency of the Southern Ocean carbon sink (Gillett et al., 2006; Le Quéré et al., 2009; Fletcher et al., 2021; Thomas et al., 2025). Instrumental data show that in recent decades the SHW have intensified and shifted poleward in response to warming (Marshall, 2003; Fogt & Marshall, 2020). These changes have been linked to an increase in net outgassing of carbon dioxide (CO_2) from deep-storage reservoirs in the Southern Ocean, with significant implications for future atmospheric CO_2 levels and global temperatures (Goyal et al., 2021; Nicholson et al., 2022; Mongwe et al., 2024; Olivier & Haumann, 2025). Understanding long-term SHW variability is key to assessing the impacts of SHW dynamics under future climate warming scenarios.

Diatoms are highly sensitive to environmental changes and are widely used as proxies in palaeolimnology to infer climate and environmental changes (Roberts et al., 2000; Verleyen et al., 2003; Sterken et al., 2008; Recasens et al., 2015). Previous work on sub-Antarctic Islands has demonstrated that aquatic diatom communities are significantly influenced by changes in salinity (inferred from electrical conductivity (EC)), allowing quantitative diatom-conductivity models to be developed (Gremmen et al., 2007; Saunders et al., 2009; 2015; 2018; Van Nieuwenhuyze, 2020; Menviel et al., 2023). On sub-Antarctic islands, lake water salinity changes are largely controlled by wind-driven sea spray aerosol (SSA) inputs with increased inputs occurring when winds are stronger and vice versa (Evans, 1970; Buckney & Tyler, 1974; Saunders et al., 2009, 2015). Based on this, diatom-conductivity transfer functions have been used to infer past SHW intensity on Macquarie (Saunders et al., 2018) and Marion Island (Perren et al., 2020).

Earlier studies on Macquarie Island have analysed diatom-environment relationships (McBride, 2009; Saunders et al., 2009) and their application as palaeoenvironmental and climate proxies (Keenan, 1995; Saunders et al., 2013; 2018). However, from the late 1900s to early 2000's overgrazing from increasing

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invasive rabbit populations resulted in widespread ecosystem degradation, including erosion, vegetation loss, and altered organic inputs into lakes. This affected aquatic ecosystems and diatom diversity (Marchant et al., 2011; Saunders et al., 2013). The Macquarie Island Pest Eradication Programme successfully eradicated all invasive vertebrates (principally rabbits) from the island, triggering substantial ecosystem recovery (Springer, 2018; Fitzgerald et al., 2021). Reassessing diatom–environment relationships under current post-eradication (recovery) conditions is necessary, because earlier studies were conducted during a period of disturbance related to introduced invasive vertebrates rather than when the island was in a natural state (Saunders et al., 2013). Developing new diatom models based on recovered conditions may better represent pre-invasion baseline communities, improving the accuracy and ecological relevance of palaeolimnological reconstructions. Furthermore, incorporating revised taxonomy and newly identified species will enhance the model's ecological resolution and predictive performance.

Understanding the processes that drive lake water chemistry, such as precipitation, evaporation, groundwater inputs, and nutrient cycling, and how they vary across temporal and spatial scales is essential when interpreting diatom–environmental relationships. Hydrochemical analyses of lakes across Macquarie Island show that dominant processes vary locally, and lakes can be classified as predominantly influenced by SSAs, catchment processes (i.e., with greater water-rock interaction), or precipitation (i.e., more dilute lake waters) (Meredith et al., 2022). Sea-spray-influenced lakes occur near the west coast and on the western edge on the Macquarie Island plateau, where exposure to the SHW is greatest. In contrast, catchment-influenced lakes with higher terrestrial ion concentrations are found at lower elevations, and rainfall-influenced lakes with low ion concentrations occur at higher elevations. This hydrogeochemical understanding supports the hypothesis that for lakes near the west coast, including those on the western edge of the plateau, EC-related diatom variation on Macquarie Island primarily reflects SHW-driven sea-spray inputs rather than local hydrological or geochemical controls.

While these data provide valuable insight into spatial variability, it is necessary to quantify temporal variability in hydrogeochemical processes, particularly evaporation, to assess how seasonal, interannual, and longer-term changes modify ion concentrations in lakes, including those derived from SSA. Establishing seasonal and multi-year lake water hydrogeochemical datasets will enhance confidence in proxy interpretations and form a foundation for long-term monitoring of Macquarie Island lakes. Such

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research is rare worldwide, and has not yet been undertaken on other sub-Antarctic Islands, making this study important for understanding how sub-Antarctic Island ecosystems will respond to future climate and environmental changes, which are experiencing rapid climatic and ecological shifts (le Roux & McGeoch, 2008; Lee & Chown, 2016; Nel et al., 2023).

Here, we present new data from lakes on Macquarie Island quantifying post-pest eradication relationships between surface-sediment diatom communities and environmental conditions. Using comprehensive water chemistry datasets from 2018 and 2022–23, we examine seasonal and interannual variability to develop updated diatom–environment transfer functions. This integrated approach strengthens the application of diatom-based proxies and provides a first step towards long-term monitoring of sub-Antarctic lake systems.

2 Methods and Materials

2.1 Study area: Macquarie Island

Macquarie Island (54°50'S, 158°85'E) is a small sub-Antarctic island (128 km^2) located in the Southern Ocean just north of the polar front, 1200 km south-west of New Zealand and 1300 km from the Antarctic continent (Fig. 1a). It is one of the few landmasses within the Polar Frontal Zone and modern core SHW belt (50–55°S; Fig.1), making it ideally suited to study past and current changes in temperature, the SHW, and precipitation. It has a harsh, cool, wet, oceanic climate representative of the core SHW belt, with low seasonality and high wind velocities (Selkirk et al., 1990). The SHW prevail almost exclusively from the west and north-west with a mean annual wind speed of 35km/h and gusts reaching 185km/h (between 1948-2025; BOM, 2025). The continual dominance of the SHW drive environmental and ecosystems responses on a west-to-east gradient across the island (Chau et al., 2019; Meredith et al., 2022), including the deposition and accumulation of wind-blown inputs such as sea spray and minerogenic aerosols (Buckney & Tyler, 1974; Saunders et al., 2009). Mean annual temperature ranges from 3.1–6.6°C, and the island experiences high annual rainfall of > 1000 mm with > 317 rainy days yr^{-1} (between 1948–2025; BOM 2025). Rainfall has increased in recent decades with a higher frequency of intense rainfall events, mostly occurring during winter, which are then accompanied by drier windier summers (Andersen et al., 2009; Kong et al., 2025). Persistent cloud cover over the island results in low light levels and sunshine hours per day (average 2.4 h from 1948–2022; BOM, 2025).

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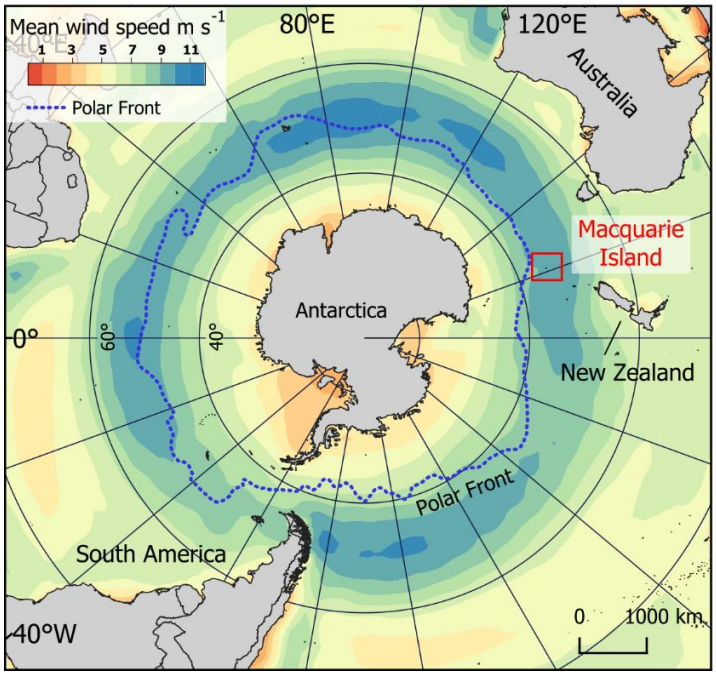

Figure 1: Location of Macquarie Island in the Southern Ocean and modern core SHW belt (50–55S°) with mean wind speed shown.

Macquarie Island is geologically unique, being the only location worldwide where an intact marine ophiolite sequence of oceanic crust and upper mantle is exposed above sea level (Davis, 1987). The island is composed mostly of pillow basalts with interspersed flows of massive basalt (Selkirk et al., 1990). Dolerite, ultrabasics and intrusives are also present but are confined to the northern third of the island (Mawson 1943). As widespread glaciation did not occur during the global Last Glacial Maximum (26–20 ka), marine, periglacial and subaerial erosional, rather than glacial processes, shaped the island as well as lake formation and ontogeny. The island is fringed by a low coastal terrace leading to steep-sided slopes (20–40°) that rise to form the island plateau sitting at ~200–400 m asl (Selkirk et al., 1990; McBride & Selkirk, 1998).

The island has numerous shallow and deep lakes and ponds across the plateau and coastal terrace (Fig. 2). High accumulation of surface water and a high water-table at or very near the surface lead to the formation of extensive mires across the island (Löffler, 1984). While lake edges can form thick ice cover during winter, complete freezing of the lakes is not typically observed (Evans, 1970; Selkirk-Bell &

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Selkirk, 2013). The island is vegetated by bryophytes, tussock grass, herbs and sedges, with no shrub or tree species present (Selkirk et al., 1990).

2.2 Data collection

Surface sediments and water samples were collected from lakes on Macquarie Island during the 2022–23 austral summer (referred to as 2022). Sites were selected to replicate those sampled in 2018 that were published by Meredith et al. (2022). Lake surface sediments were collected from 30 plateau (inland) sites for diatom analyses (lake ID = LK). Surface sediments (top 2 cm) were collected from each site using a long-handled scoop from < 1 m water depth. An additional 17 coastal and five plateau sites sampled in 2006 (lake ID = S; Saunders et al. 2009) were included in the diatom dataset to extend the EC and nutrient gradients of the updated dataset, totalling 52 samples (Fig. 2a). Two lakes were replicated in the 2006 and 2022 seasons (S9 = LK40, S18 = LK2; Fig. 2a).

Lake water general parameters were measured in-situ at each site, including temperature, EC, dissolved oxygen (DO) and pH using a YSI ProQuatro Multiparameter Meter, with calibration performed prior to every sampling trip. DO was calibrated in water-saturated air following YSI manufacturer protocols. Conductivity was calibrated using a 1413 µS cm^{-1} standard solution, and pH was calibrated using a three-point procedure with pH 4.0, 7.0, and 10.0 buffer solutions. Water samples were collected at all diatom sampling sites to measure total oxidised nitrogen (TON), phosphate (PO_4^{3-}), and silica (Si). Additional water samples were collected from 40 plateau sites for water chemistry analysis (Fig. 2b), including major ions and stable water isotopes (oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$)). Each site was sampled three times across the 2022–23 season (November, December to January, and February). All water samples were collected from ~20 cm below the water surface and were filtered in-situ with 0.45 µm polyethersulpone filters into High Density Poly-Ethylene (HDPE) bottles following the method described by Meredith et al. (2009). Water samples were refrigerated (4°C) until analysis.

Major ions, and oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) stable isotopes were analysed at the Australian Nuclear Science and Technology Organisation (ANSTO). Cations and anions were analysed using inductively coupled plasma-atomic emission spectrometry (ICP-AES). $\delta^{18}O$ and $\delta^{2}H$ stable isotopes were analysed with a Picarro L2130-i Cavity Ring-Down Spectrometer. Values were reported as per mill

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(‰) deviations relative to the international standard V-SMOW (Vienna Standard Mean Ocean Water), with a reproducible precision of ±0.2 and ± 1.0‰, respectively.

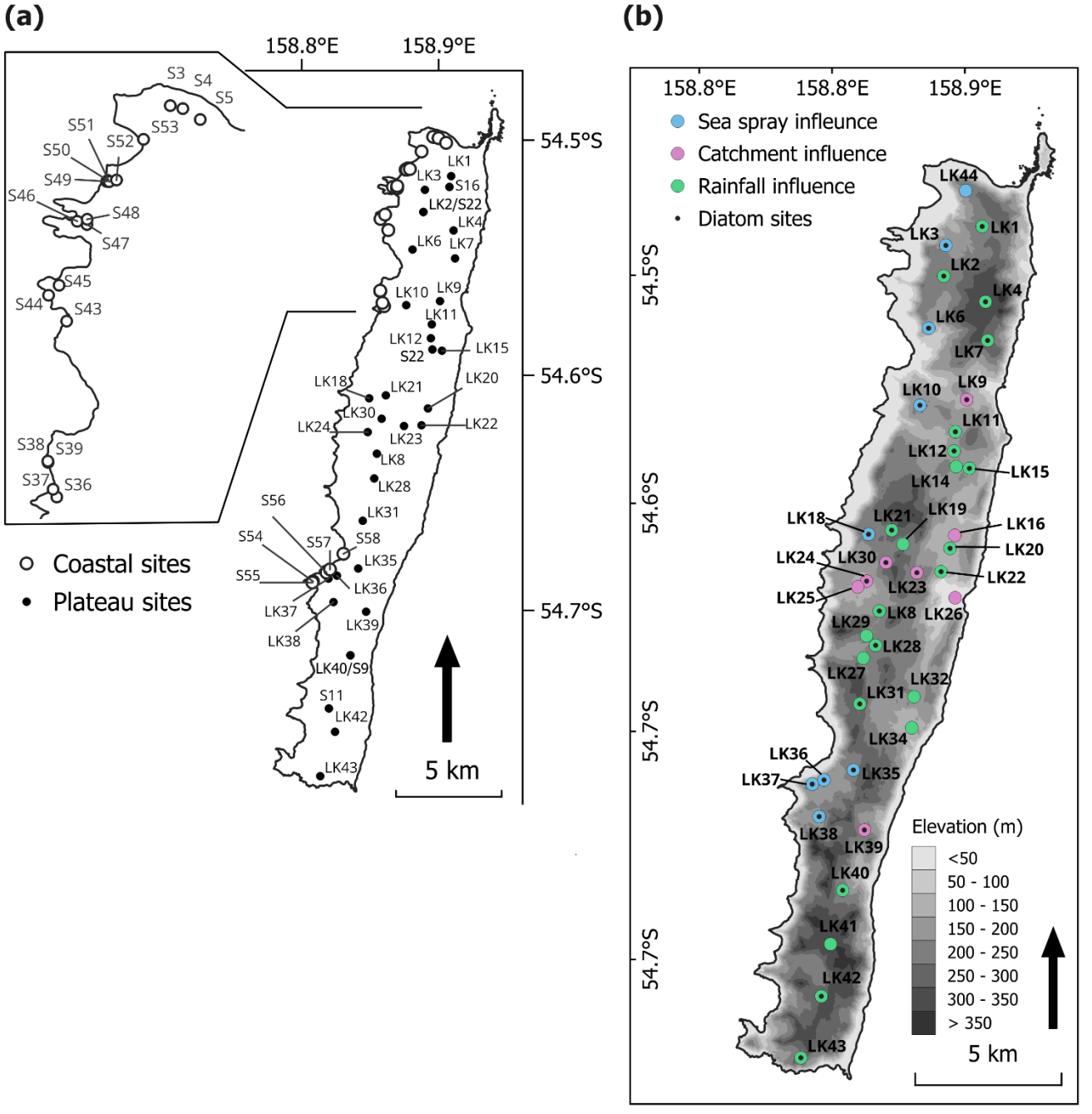

Figure 2: Maps showing lake sites across Macquarie Island, a) Diatom surface sediment sites (coastal sites were originally sampled by Saunders et al. (2009); b) Lake water chemistry sites. Colours show lake types, based on dominate hydrogeochemical processes, identified by Meredith et al., (2022). Black dots indicate that the site is included in the diatom dataset.

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Nutrient data from 2006 samples (filtered at 0.45µm) measured soluble reactive phosphate (SRP), TON (nitrate (NO_3) + nitrite (NO_2)), and silicate (Si) using an Alpkem Autoanalyser (Continuous Flow Solution Analyser), representing the operationally defined dissolved inorganic (and therefore readily bioavailable) fractions of total N, P, and Si. In contrast, the 2022 dataset measured TON, PO_4^{3-}, and Si ions using ICP-AES at ANSTO on filtered, undigested waters, with results reported as the corresponding inorganic species and concentrations consistently at or near detection limits. Despite methodological differences, the two approaches yield consistently low and broadly comparable concentrations in the two replicate lakes across sampling trips: for S9/LK40, PO_4^{3-} concentrations were 0.002 mg L^{-1} (autoanalyser) and < 0.01 mg L^{-1} (ICP-AES), and TON concentrations were 0.006 mg L^{-1} (autoanalyser) and < 0.06 mg L^{-1} (ICP-AES); for S18/LK2, PO_4^{3-} concentrations were 0.004 mg L^{-1} (autoanalyser) and < 0.01 mg L^{-1} (ICP-AES), and TON concentrations were 0.005 mg L^{-1} (autoanalyser) and < 0.06 mg L^{-1} (ICP-AES). Furthermore, if the 2022 analyses targeted the same reactive fractions measured in 2006, the results would still fall below or close to detection limits.

2.3 Diatom preparation and identification

Diatom preparation followed methods described by McBride (2009). Cleaned diatom solutions were mounted onto slides using Norland Optical Adhesive 61. At least 300–400 frustules were counted per sample, using Differential Interference Contrast (DIC) and oil immersion at 1000x magnification on a Zeiss Axioskope microscope, mounted with a TOUPTEK camera (U3CMOS). Species identification was primarily based on sub-Antarctic taxonomy described in Van de Vijer et al. (2002); Sterken et al. (2015); Sabbe et al. (2019); and Van de Vijver (2019). Species were photographed and documented (see Supplementary Material for an illustrated species catalogue).

2.4 Statistical analyses

2.4.1 Water chemistry

The lake water chemistry dataset was comprised of *in-situ* general parameters, major ion concentrations and $\delta^{18}O$ and $\delta^{2}H$ values from 2018 (Meredith et al. 2022) and 2022 (this study) to understand temporal variation across the island. Data from 2018 (January to February) are referred to as sampling event 1 (E1) and sampling from the 2022 season as E2 (November), E3 (December to January), and E4 (February). Shapiro–Wilk tests showed that isotope data were normally distributed (p >0.05), whereas

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general parameters and ion concentrations deviated significantly from normality (p <0.05). Consequently, parametric tests (ANOVA, t-test, Tukey's HSD) were applied to isotope data, and non-parametric tests (Kruskal–Wallis, pairwise Wilcoxon) to general parameters ion data. A Principal Component Analysis (PCA) with z-score standardised data was performed to explore relationships between variables and assess the consistency of lake types identified by Meredith et al., (2022; Fig. 2b).

2.4.2 Diatom model

Ordination methods were used to describe variation in the diatom dataset, explore diatom-environment relationships, and identify unique variance explained by environmental variables. Environmental variables included were EC, temperature, DO, pH, TON, PO_4^{3-}, and Si, additional major ions were not included as these data were not available for 2006 sites. Weighted Averaging (WA) was applied to dominant species to determine ecological optima and tolerance. Together WA, Weighted Averaging Partial Least Squares (WAPLS), and Maximum Likelihood (ML) models were used to develop diatom transfer functions, with cross-validation used to assess model robustness.

The relative abundance of each diatom species in each sample was calculated as the percentage of the total number of frustules counted per sample. Species occurring at ≤ 1% relative abundance were excluded from the dataset. A full species list can be found in Supplementary Material. Nutrient values that were below the limit of detection were substituted with the respective detection limit value (PO_4^{3-}, = 0.01 mg L^{-1}, Si = 0.1 mg L^{-1}, TON = 0.06 mg L^{-1}). Environmental variables were screened for skewness, with temperature, EC, PO_4^{3-}, Si, and TON log(x+1) transformed.

PCA was performed on transformed environmental data to identify the primary gradients of environmental variation across sites. Detrended Correspondence Analysis (DCA) with detrending by segments and downweighting of rare species was performed on untransformed species data to determine whether species distributions were linear or unimodal. As the DCA axis 1 gradient length (8.2 deviation units) was > 4, unimodal ordination methods were deemed appropriate (Ter Braak & Prentice, 1988). Species data were log(x+1) transformed for remaining analysis.

A series of Canonical Correspondence Analyses (CCA) were then performed with forward selection, and scaling focused on inter-species distances, biplot scaling and downweighting of rare species. Variance

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Inflation Factors (VIF) of environmental variables were used to assess collinearity. As no variables had a VIF >10, none were excluded. A full CCA, with all environmental variables included, was first performed to quantify the total amount of species–environment variation explained by the full set of variables. A series of independent and partial CCAs with variance partitioning were performed to constrain analyses, assess the relative explanatory power, and assess the unique and shared variance contributions of each variable. Individual CCAs, of each variable alone, estimate the marginal (unconstrained) explanatory power (i.e., how much variation a single variable explains when considered alone, without accounting for correlations with other variables). Partial CCAs assess the unique (conditional) contribution of each environmental variable after statistically controlling for all remaining variables. This analysis isolates the variance uniquely attributable to each predictor and identifies variables whose explanatory power is driven by covariation with others. Finally, variance partitioning was used to decompose the total explained variation into unique and shared fractions, allowing assessment of how much variation was due to individual predictors versus overlapping environmental gradients. Permutation test results (p > 0.05), CCA coefficients and lambda ratios (λ_1/λ_2) of the first constrained eigenvalue (λ_1) to the second unconstrained eigenvalue (λ_2) were used to identify the environmental variables most appropriate for quantitative inference models. As a guide, high λ_1/λ_2 ratios are necessary for a variable to have enough explanatory power to be included in quantitative inference models (Ter Braak & Prentice, 1988; Juggins, 2013). All ordination analyses were performed using the *vegan* package version 2.7-1 (Oksanen et al., 2013) in R (R Core Team, 2024).

ML and iterations of inverse ($_{INV}$) and classical ($_{CLA}$) WA models with and without tolerance downweighing, and WAPLS with up to five components were assessed to provide the best performing transfer functions. These methods were applied because they capture different aspects of species–environment relationships: WA provides a simple unimodal estimator; WAPLS allows more complex responses through latent components; and ML emphasises taxa with narrow ecological tolerances. Using multiple approaches therefore offers complementary strengths and helps identify the most reliable and robust model through cross-validation. All models were performed with bootstrapping and 100 iterations. Model r^2, bootstrapped r^2 (r^2_{boot}), root mean square error (RMSE) and root mean square error of prediction (RMSEP) values were used to assess performance. RMSEP and r^2_{boot} performance was favoured over r^2 and RMSE. RMSEP between WAPLS components was also used to assess overfitting. WA and WAPLS-1 results are often similar as WAPLS is built upon on the same weighted-averaging framework

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as WA (ter Braak & Juggins, 1993). When this was the case and WAPLS components did not improve performance, WA was favoured as it is the simplest model. Software program C2 version 1.8 (Juggins, 2003) was used to develop all transfer functions.

3 Results

3.1 Lake water chemistry

Analysis of 40 plateau lakes on Macquarie Island showed that lake water general parameters (EC, pH and DO), and nutrients, did not vary significantly across the 2022 sampling events (E2-4; Table 1). Temperature was seen to vary, being significantly lower in E2 compared to E3 and E4. Lakes are slightly acidic (pH 5.7) to slightly alkaline (pH 9.14). Mean EC ranged from 126–261 µS cm-1, with a decrease in EC from west to east across the island. Lakes are oxic (DO = 8.64–12.61 mg L-1) and oligotrophic, with PO_4^{3-} and TON concentrations under or close to detection limits (< 0.01–0.02 mg L-1 and < 0.06–0.1 mg L-1, respectively). Similarly, comparison with 2018 plateau lakes showed no significant difference across all lake water general parameters, excluding temperature, indicating generally stable conditions in plateau lakes across years. However, a comparison between plateau lakes measured in 2022 and coastal lakes in 2006 did show significant differences ($p < 0.05$). Coastal sites in 2006 were generally eutrophic with higher nutrient ranges (TON = 0.007–4.636 mg L-1, PO_4^{3-} = 0.1–9.9 mg L-1, and Si 0.07–2.71 mg L-1), and higher EC (406–1482 µS cm-1), while temperature, DO and pH were similar (Table 1; see Supplementary Table S1 and S2 for full results).

Major ion analysis of the 40 plateau lakes showed that, although dilute in concentration, Cl (1.1–3.7 mmol L-1) and Na (0.9–2.6 mmol L-1) dominate the ionic composition of all lake waters (Table 2; see Supplementary Table S3 for full cation and anion results). All lakes showed similar ionic ratios to seawater for SO_4, Cl, Mg, and Na, suggesting a marine origin. Seawater ionic ratios diverged for K, Ca and F for some lakes, while SiO_2 was higher in all lakes, suggesting additional sources for these ions. (Fig. 3).

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Table 1: Summary table of lake water general parameters and nutrient data. Temp. = temperature, DO = dissolved oxygen, EC = electrical conductivity, Si = silicate, PO_4^{-3} = phosphate, TON = total oxidised nitrogen.

	Temp. (°C)	DO (mg L^{-1})	EC (µs cm^{-1})	pH	Si (mg L^{-1})	TON (mg L^{-1})	PO_4^{3-} (mg L^{-1})
2022							
Mean	8.7	11.59	188	7.03	0.648	0.06	0.00467
Min	6.4	8.69	135	5.65	0.100	0.06	0.00326
Max	16.1	12.95	267	9.15	4.333	0.10	0.02391
E1 mean	7.6	12.47	188	7.02	0.767	0.06	0.00568
E2 mean	9.1	11.94	197	7.03	0.611	0.06	0.00414
E3 mean	9.6	10.48	177	7.05	0.515	0.06	0.00351
2018							
Mean	9.4	10.95	153	7.35	-	-	-
Min	6.8	8.56	101	5.99	-	-	-
Max	15.8	12.64	292	9.21	-	-	-
2006 (plateau)							
Mean	6.4	11.59	192	6.92	0.047	0.00564	0.0070
Min	5.5	11.35	164	6.35	0.003	0.00004	0.0013
Max	7.4	11.80	224	7.46	0.092	0.02449	0.0155
2006 (coastal)							
Mean	8.4	11.32	889	7.19	0.719	1.23331	1.124
Min	6.0	9.17	406	5.50	0.074	0.02430	0.007
Max	13.1	14.43	1482	8.13	2.706	9.89000	4.636

Table 2: Mean major ions (mmol L^{-1}) and stable water isotope (‰) results for the 40 lakes sampled in 2018 and 2022.

	Cl	SO_4	Br	Na	Ca	Mg	K	SiO_2	Fe	F-	Al	δ^2H	$\delta^{18}O$
2018													
Mean	1.965	0.103	0.003	1.350	0.085	0.325	0.032	0.013	0.001	0.001	0.002	-20.1	-2.8
Min	1.379	0.065	0.001	0.987	0.025	0.219	0.005	0.001	0.000	0.001	0.000	-34.9	-5.3
Max	3.667	0.211	0.007	2.566	0.287	0.590	0.064	0.087	0.003	0.006	0.006	-1.9	0.7
2022													
Mean	1.593	0.083	0.002	1.272	0.080	0.197	0.029	0.020	0.001	0.002	0.002	-23.4	-3.3
Min	1.191	0.055	0.001	0.931	0.025	0.133	0.009	0.003	0.000	0.000	0.000	-35.6	-5.3
Max	2.779	0.155	0.005	2.073	0.289	0.369	0.052	0.130	0.011	0.021	0.022	-14.6	-1.7
E2 Mean	1.426	0.076	0.002	1.229	0.079	0.150	0.028	0.027	0.001	0.003	0.003	-30.1	-4.6
E3 Mean	1.436	0.075	0.002	1.228	0.081	0.150	0.027	0.022	0.001	0.002	0.002	-23.4	-3.2
E4 Mean	1.448	0.073	0.002	1.223	0.075	0.146	0.026	0.018	0.001	0.002	0.002	-20.7	-2.8

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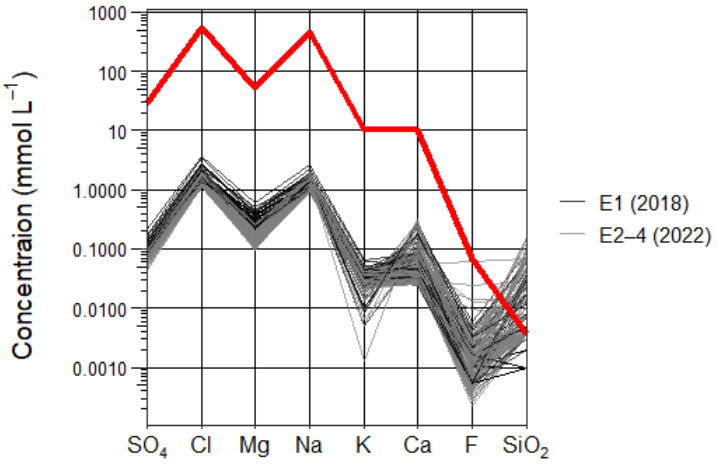

Figure 3: Scholler plot comparing the ionic composition (SO_4, Cl, Mg, Na, K, Ca, F and SiO_2) of Macquarie Island lake waters and seawater (red line), categorised into sampling years 2018 (black lines) and 2022 (grey lines).

Statistical analysis showed almost no significant differences in major ion concentrations across 2022 sampling events (E2–4), with the only significant difference occurring in Br between E2 and E4 (p = 0.023). Broader changes were detected between 2018 and 2022, with Cl, SO_4, Br, and Mg all showing higher mean concentrations in 2018 compared to all 2022 sampling events (E2–4). K and SiO_2 were greater in E1 in comparison to E4 and E2–3, respectively. Fe, Na, Ca, F, and Al did not significantly vary ($p > 0.05$) between sampling events. All ions that show significant variation ($p < 0.05$) have predominantly marine sources.

PCA showed the relationship between lake water chemistry parameters, with samples grouped by lake type and sampling year (Fig. 4). Together, PC1 and PC2 captured 53% of the total variance in the dataset. PC1 represents a salinity and sea-spray gradient with variability in EC, distance from the west coast, Na, Cl, Br, Ca, Mg, and K captured. PC2 represents an altitude and terrestrial ion gradient with variability in elevation, temperature, SiO_2, Ca, Fe, and F captured. Lakes cluster according to environmental processes (groups derived from Meredith et al., 2022), with SSA influenced lakes having positive PC1 scores, which suggests higher concentrations of marine derived ions. Three sea spray influenced outliers can be seen across PC1: LK3 in 2018 and LK37 in both 2018 and 2022. The grouping of samples influenced by catchment processes and those influenced by rainfall is driven by PC2 with catchment infleunce lakes having lower elevation and higher ion concentrations. SSA and rainfall

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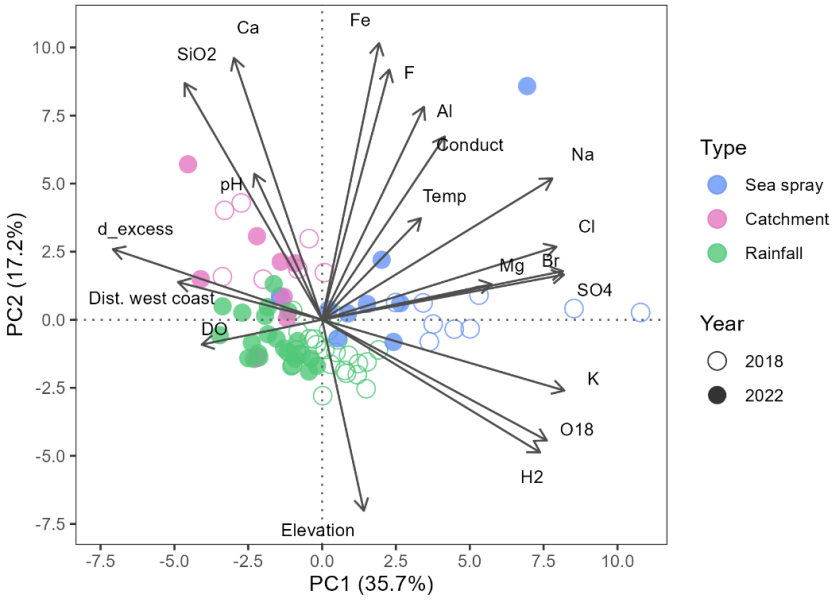
314 influenced lakes cluster based on the year that they were sampled with greater ion concentrations in
315 2018.



316

317 **Figure 4: Principal Component Analysis (PCA) of Macquarie Island lake waters, showing the relationships between major ions and**
318 **environmental parameters. Lakes are coloured by lake type, showing that lakes cluster based on the dominate geochemical**
319 **processes identified by Meredith et al., (2022). Dist. west coast = distance from the west coast (m), Conduct = electrical conductivity.**

320 **3.2 Stable water isotopes**

321 The δ^2H and $\delta^{18}O$ values were measured in the 2022 samples and ranged from -38.3 to -9.2‰ and -
322 38.3‰ to -0.67‰, respectively**.** Lake waters in 2018 and 2022 fell below the Global and Cape Grim
323 (northwest Tasmania) Meteoric Water Lines (MWLs), suggesting slight isotopic enrichment in Macquarie
324 Island's lakes (Fig. 5). In 2018 lake waters were significantly higher in δ^2H (mean -24.8 ‰) and $\delta^{18}O$
325 (mean -2.83‰) compared to 2022 (mean δ^2H = -24.8 ‰ and $\delta^{18}O$ = -3.55 ‰)**.** Significant isotopic
326 enrichment of δ^2H and $\delta^{18}O$ ($p < 0.001$) can be seen in the data at the beginning of the 2022 austral
327 summer (E2–3; Fig. 5a). SSA influenced lakes tended to have higher isotopic values, while catchment
328 influenced lakes had lower values (Fig. 5b), with a significant difference between all lake types detected
329 ($p < 0.001$). LK20 and LK21 from E2 were outliers, plotting above the MWLs with lower $\delta^{18}O$ values. Cl
330 concentrations appeared to be related to δ^2H and $\delta^{18}O$ values (Fig. 5c), however the correlation between

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the parameters was low (r^2 ≤ 0.24). This lack of relationship was consistent across lake types and sampling events.

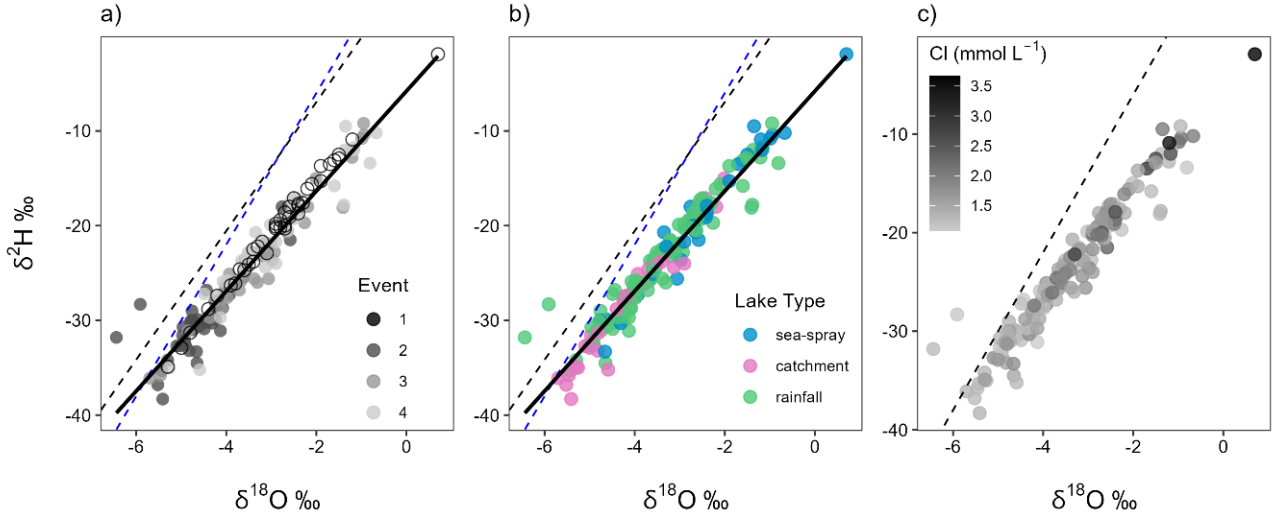

Figure 5: Stable water isotope δ^2H and $\delta^{18}O$ differences in Macquarie Island lake waters, shown across: a) sampling events; b) lake type; c) δ^2H and $\delta^{18}O$ relationship shown with Cl concentration (mmol L^{-1}). Solid black line show Macquarie Island regression, blue dashed line is the global meteoric water line (GMWL: $\delta^2H = 8\ \delta^{18}O + 10$), and black dashed line is the Cape Grim local meteoric water line (LMWL: $\delta^2H = 6.8\ \delta^{18}O + 6.65$).

3.3 Diatoms

3.3.1 Diatom communities

In total 141 diatom taxa from 45 genera were identified in the 52 plateau and coastal lakes. Ninety-six taxa from 30 genera remained in the dataset after taxa with < 1% relative abundance were excluded. The most taxon-rich genera were *Pinnularia* (16 taxa), *Psammothidium* (12 taxa), and *Planothidum* (8 taxa). The most dominant taxa being both common, occurring in > 15 lakes, and abundant, occurring > 25% relative abundance in at least one sample, were *Aulacoseira principissa* Van de Vijver, *Psammothidium abundans* (Manguin) Bukhtiyarova & Round, *Psammothidium confusum var. atomoides* (Manguin) van de Vijver, unknown species 111, *Psammothidium confusum* (Manguin) van de Vijver, *Fragilaria capucina* Desmazières, and *Navicula bergstromiana* Vyverman et al. Coastal and plateau lakes showed distinctly different assemblages, with coastal lakes exhibiting less diversity (mean number of species = 20) and dominated by taxa including *F. capucina*, unknown sp. 111, *Planothidium quadripunctatum* (D.R.Oppenheim) Sabbe, *Planothidium delicatum* (Kützing) Round & Bukhtiyarova, and *Planothidium lanceolatum* (Brébisson ex Kützing) Lange-Bertalot. Plateau lakes were more diverse (mean number of taxa = 40) and dominated by *A. principissa, P. abundans, P. confusum var. atomoides,*

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P. confusum, and *N. bergstromiana, Achnanthidium modestiformis* (Lange-Bertalot) Van de Vijver, *Cocconeis placentulata* Ehrenberg, and unknown species 21. No taxa were found in all lakes. See Figure 6 for microscopy photos of the most abundant taxa.

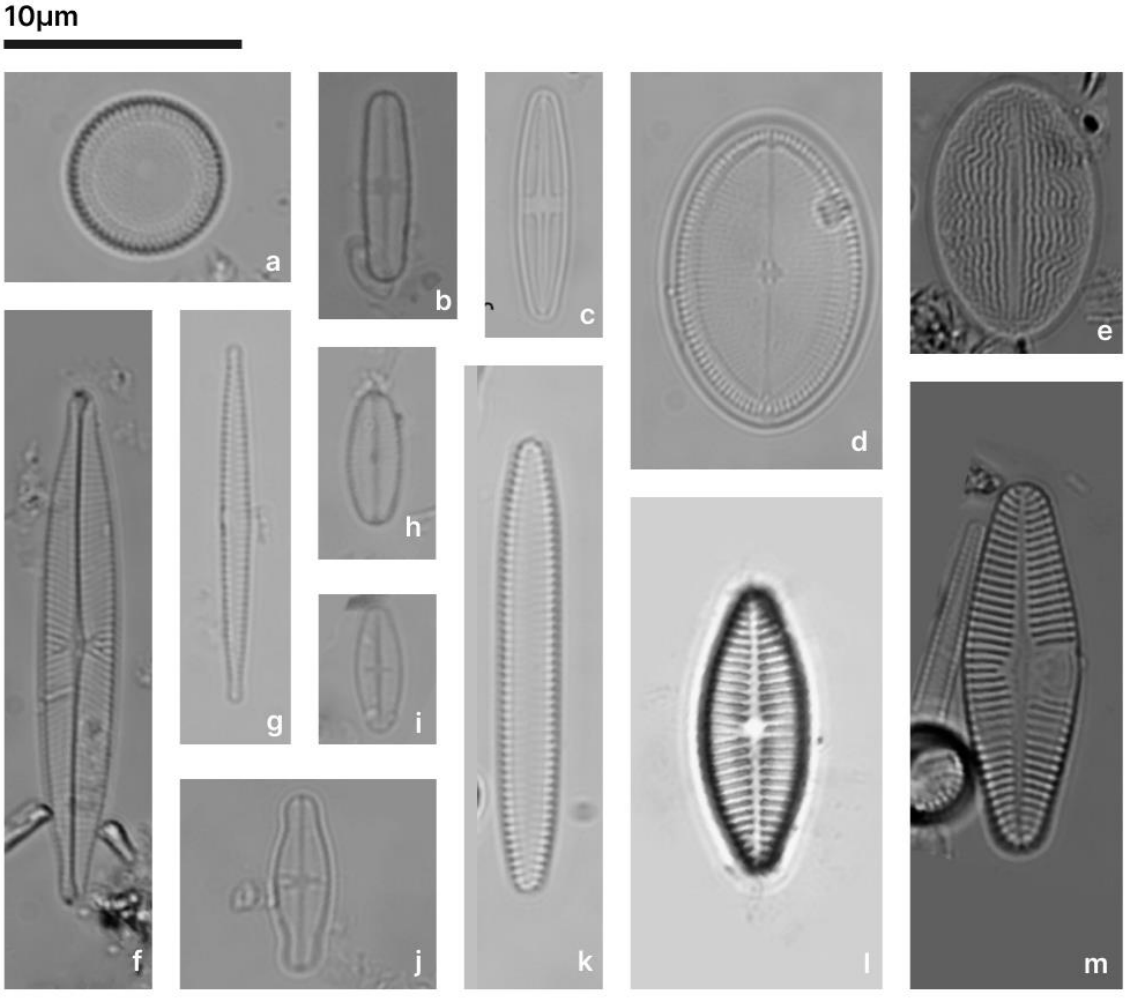

Figure 6: The most abundant diatom taxa from plateau and coastal lakes on Macquarie Island. a) *Aulacoseira principissa,* b) *Psammothidium abundans,* c) *Psammothidium confusum,* d-e) *Cocconeis placentulata,* f) *Navicula bergstromiana,* g) *Fragilaria capucina,* h) unknown species 21, i) *Psammothidium confusum var. atomoides,* j) *Achnanthidium modestiformis,* k) unknown species 111, l) *Planothidium delicatulum,* m) *Planothidium lanceolatum.*

3.3.2 Diatom-environment relationships

The full CCA model was significant (p = 0.001), with environmental variables explaining 23.9% (Table 3) of the total variance in diatom species composition (constrained inertia = 1.5). Together, the first two canonical axes explained 62.8% of the total constrained variance (Table 3; Fig. 7). Forward selection

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identified EC, pH, and temperature as the most significant predictors of diatom community composition (p = 0.001), collectively explaining 15.4 % of the total variance. This equates to 70% of the total explained variance in the full model, capturing the major environmental gradients influencing species distribution with a more parsimonious model.

Table 3: Full CCA model results

Axis	Eigenvalue	Proportion of variance explained (%)	Cumulative proportion (%)
CCA1	0.67	43.60	43.60
CCA2	0.30	19.15	62.75
CCA3	0.21	13.36	76.11
CCA4	0.15	7.61	85.60
Constrained inertia	1.5		
Constrained proportion (%)	23.97		

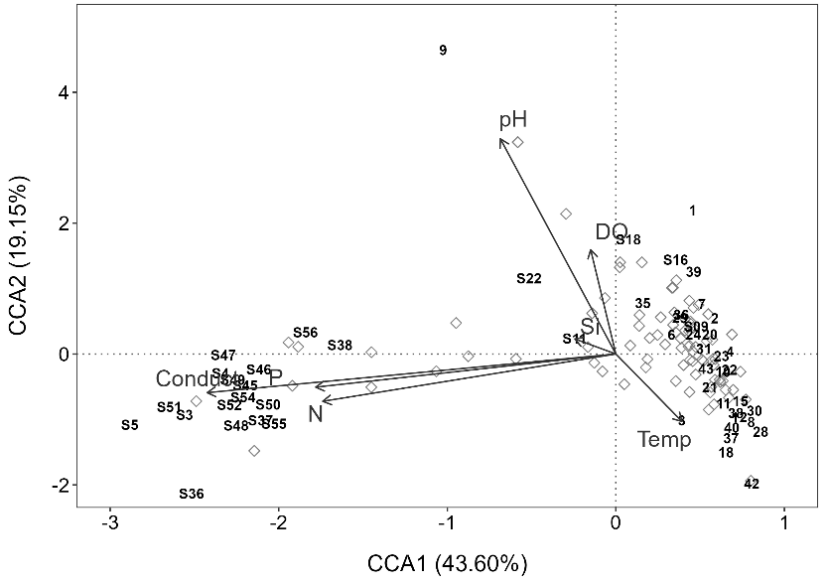

Figure 7: Full CCA ordination biplot of diatom species and environmental data, numbers indicate sites, and grey symbols indicate diatom species. Si = silicate, P = phosphate, N = total oxidised nitrogen, and conduct = electrical conductivity.

Individual CCAs were performed to assess the total explanatory power of each variable. EC and pH were shown to be the strongest, individually explaining 10.03% and 4.56% of the total variation, respectively. This corresponds to 45.83% and 20.86% of the total variance in the full CCA model. Additionally, EC was the only variable with a high λ_1/λ_2 ratio (λ_1/λ_2 = 1.31; Table 4), suggesting it is the only variable with enough explanatory power for inference modelling.

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Table 4: Individual CCA results, independent CCAs run for each variable. (* = significant *p value* < 0.05)

Variable	λ_1 / λ_2	Constrained sum	Variance explained (%)	Proportion of full model explained (%)	p-value
Electrical conductivity	1.31	0.64	10.03	45.83	0.001*
Phosphate	0.73	0.38	6.02	27.5	0.001*
Total oxidised nitrogen	0.68	0.37	5.86	26.78	0.001*
pH	0.39	0.29	4.56	20.86	0.001*
Silicate	0.26	0.20	3.2	14.61	0.023*
Temperature	0.22	0.17	2.62	11.96	0.176
Dissolved oxygen	0.12	0.10	1.51	6.9	0.879

Partial CCAs were performed with each environmental variable tested separately while controlling for covariation with all other variables, to quantify unique and shared variance contributions. EC, pH, and Si were the only variables to have significant unique contributions ($p \leq 0.01$; Partial CCATable 5). The shared and unique variance of each environmental variable is shown in Figure 8. EC explained the largest proportion of total constrained variation (46%) in diatom community composition, with a large shared component (17% unique, 28% shared), suggesting it acts along a major environmental gradient shared with TON and PO_4^{3-} (Fig. 8). Despite this, it performed well in all other CCAs and its unique contribution remained high, indicating it is an important independent driver of diatom structure across Macquarie Island lakes. Furthermore, low VIFs among all environmental variables (VIFs < 3) indicated that multicollinearity was low. EC (VIF = 2.6) showed a low correlation with other variables ($r^2 \leq 0.47$), suggesting it represents a largely independent gradient in the dataset. In contrast, pH had similar unique variance (18.4%) and lower shared variance (2.4%), implying a more independent ecological influence.

Table 5: Partial CCA results, where each variable was tested with the covariation of other variables controlled (* = significant *p value* < 0.05).

Variable	Variance explained (%)	Proportion of full model explained (%)	p-value
pH	5.02	18.35	0.002*
Electrical conductivity	4.85	17.7	0.001*
Silicate	3.85	13.93	0.013*
Temperature	3.03	10.87	0.151
Total oxidised nitrogen	2.14	7.6	0.651
Phosphate	1.8	6.37	0.774
Dissolved oxygen	1.36	4.8	0.991

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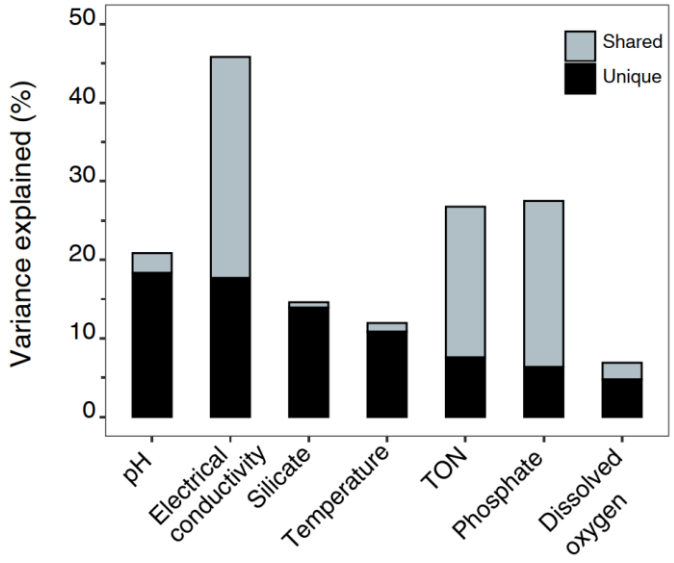

Fig. 8: Variance partitioning showing unique and shared proportions of variance explained by each environmental variable.

3.3.3 Species optima and tolerances

Species optima and tolerance across major environmental gradients EC, pH, and temperature were determined with WA. *F. capucina, P. lancelotaum*, and *P. delicatulum* were found across the EC range, however each species showed different optima (Fig. 9). Unknown sp. 111 was found to tolerate mid to high-level EC, while most other dominant species, including *A. principissa*, *C. placentulata*, *N. bergstromiana* and dominant *Psammothidium* species have highest abundance at low EC sites.

Species optima were less clear for pH, as the dominant species had tolerances across the pH gradient, ranging from slightly acidic to slightly alkaline (Fig. 10). *A. principissa*, *N. bergstormiana*, and *P. confusum* var. *atomoides* showed optima for slightly acidic sites. While *P. confusum* had higher abundances at slightly alkaline sites. *C. placentulata*, *P. lanceolatum*, *P. quadripunctatum*, and unknown sp. 21 showed preferences for neutral pH, and unknown sp. 111 for neutral to slightly acidic sites. Species optima for temperature are described in Supplementary Material Figure S1.

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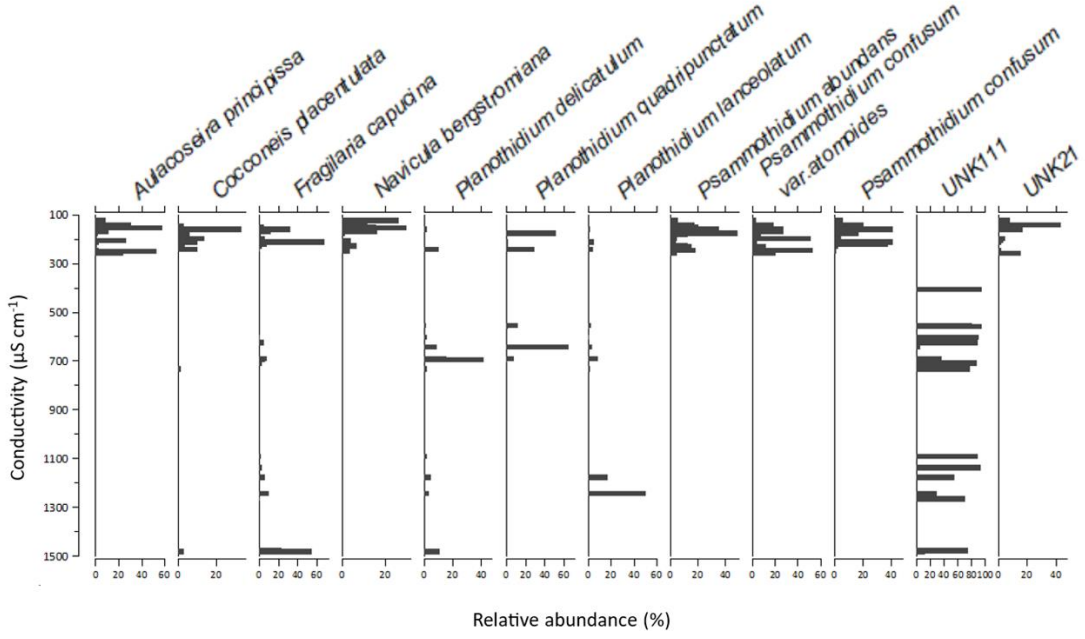

Figure 9: Relative abundance of the most dominant diatom species along the conductivity gradient (126–1482 µS/cm), UNK = unknown species.

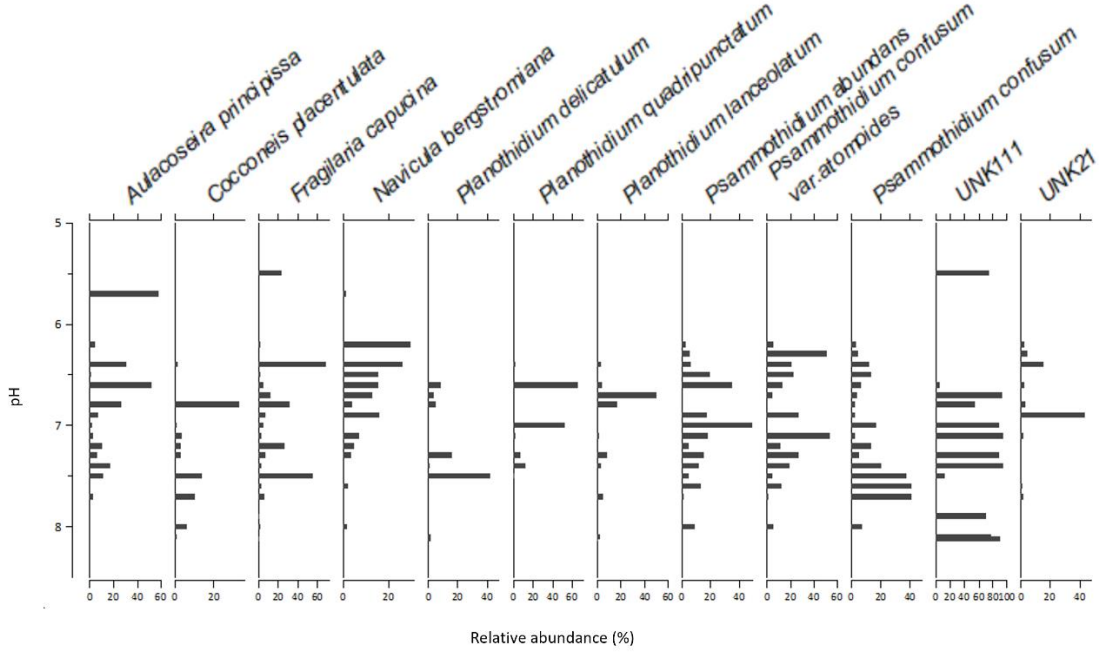

Figure 10: Relative abundance of the most dominant diatom species along the pH gradient (5.50–9.14 °C), UNK = unknown species.

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3.3.4 Diatom transfer functions

Ordination analyses showed that EC and pH explained significant and independent proportions of variance in diatom composition, with temperature contributing to a lesser extent. As such, transfer functions were developed for each. While Si was shown to independently contribute to diatom variance, reduced CCA modelling with forward selection did not indicate it to be a major environmental gradient. Transfer function results for the best performing WA, WAPLS, or ML model for each environmental variable are described in Table 6.

Table 6: Best performing WA, WAPLS or ML model results for conductivity, pH, and temperature.

Variable	Model	r^2	r^2_{boot}	RMSE	RMSEP
Electrical conductivity	WA_{inv}	0.83	0.74	0.31	0.39
	ML	0.91	0.80	0.22	0.40
pH	WAPLS-2	0.69	0.17	0.34	0.63
Temperature	WAPLS-3	0.81	0.19	0.07	0.18

For EC, WA_{INV} and WAPLS-1 produced near identical results. WA_{INV} was favoured as the simpler model ($WA_{inv,}$ r^2= 0.83, r^2_{boot}= 0.74, RMSE = 0.31, RMSEP = 0.39). Although WAPLS-2 to -5 increased r^2 and reduced RMSE, each successive component progressively increased RMSEP by 13-16%, thereby reducing performance. Given the unimodal gradient structure of the dataset, ML modelling was also assessed for EC. ML showed slightly stronger predictive performance to WA_{INV}, with higher r^2_{boot} and comparable RMSEP (ML, r^2= 0.91, r^2_{boot}= 0.80, RMSE = 0.23, RMSEP = 0.40).

Comparison of observed and predicted value scatter plots indicated that ML achieved a tighter fit, with WA_{inv} showing increased predictive error at higher EC ranges (Fig. 11). However, further inspection indicated that only ~30% of taxa displayed Gaussian (Type IV–V) response curves indicating ML may not be the most appropriate approach (see Supplementary Figure S2 and Table S4 for full Gaussian response curve results). However, overfitting from ML is not likely as RMSEP did not increase. Overall, both models show cross-validated performance and are considered robust.

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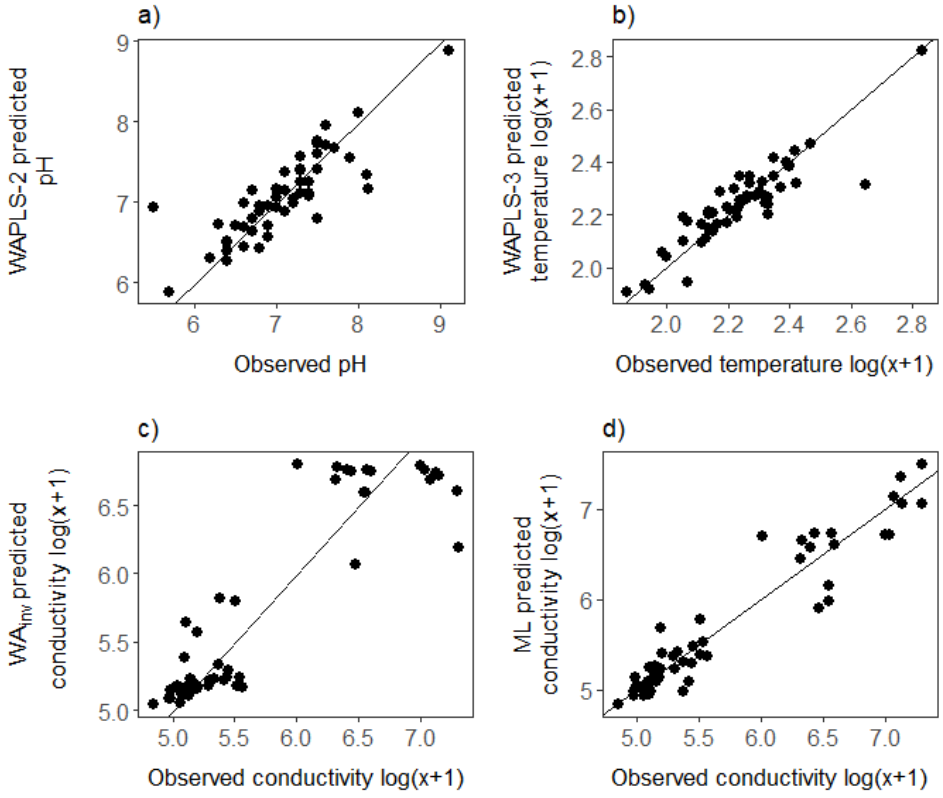

Figure 11: Comparison of observed environmental measurements with values predicted by diatom-based transfer functions: a) pH estimated using WAPLS-2; b) temperature estimated using WAPLS-3; c) conductivity estimated using WA with inverse deshrinking (WA_{INV}); and d) conductivity estimated using the modern analogue (ML) method. Black lines show the 1:1 line.

pH had poor performance across all WA and WAPLS models with high RMSEP (> 0.6) and low r^2_{boot} (≤ 0.2). WAPLS-2 was found to be the strongest model (WAPL-2, r^2= 0.69, r^2_{boot}= 0.17, RMSE = 0.34, RMSEP = 0.63). Temperature had similarly low r^2_{boot} (< 1.9) across models but low RMSEP (≤ 0.2) with WAPLS-3 showing the best performance (WAPLS-3, r^2 = 0.81, r^2_{boot} = 0.19, RMSE = 0.07, RMSEP = 0.18). ML modelling showed poor performance for pH with high RMSEP = 0.93 and temperature with low r^2_{boot} = 0.08.

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4 Discussion

4.1 Annual and seasonal lake water hydrogeochemical variation

The seasonal hydrochemistry dataset presented in this study support the 2018 baseline assessment (Meredith et al., 2022) that lake water chemistry is controlled by SSAs, terrestrial catchment processes, elevation and rainfall dilution.

The seasonal water chemistry data, which is presented for the first time in this study, shows that there is little to no significant variation in major ions across the 2022–23 austral summer. Variations in Br were observed but can be explained as being related to localised sources associated with increased organic inputs from runoff rather than SSA sources. This is indicated by Cl/Br ratios generally falling below the seawater line (Supplementary Fig. S3), suggesting Br has additional non marine sources. Br is known to be enriched in dissolved and particulate organic matter and mobilised during catchment run-off events, particularly in peat-dominated sub-Antarctic landscapes (Gerritse & George, 1988; Biester et al., 2004; Guevara et al., 2019). This interpretation is further supported by differing monthly rainfall amounts for Macquarie Island, where higher mean monthly rainfall occurred during E3 (January - 98 mm) and E4 (February -93 mm) compared to E2 (December -59 mm; BOM, 2025).

A comparison of 2018 and 2022 data shows that significant variation ($p < 0.05$), in some major ions is evident, with higher concentrations in 2018 of Br and Cl, SO_4, and Mg associated with SSAs. Although not statistically significant ($p > 0.05$), other sea-spray derived ion mean values (Na, Ca, K) were higher in 2018 (Table 2). However not all ions increased in concentration. In particular, terrestrial derived ions such as Fe, F, Si, and Al were lower in 2018. This suggests that lakes in 2022 had a stronger SSA influence.

Despite these changes, PCA of the 2018 and 2022 lake water chemistry datasets (Fig. 4) show that lakes typically cluster by the lake types identified in Meredith et al. (2022) (i.e., as SSA, catchment and rainfall influenced). This indicates that the major hydrogeochemical processes influencing Macquarie Island lakes are consistent between years, with no major environmental shifts occurring in weathering and erosion of the island's geology, suggesting these processes are stable on an annual time scale. Identifying hydrogeochemical stability is important for identifying lake sites suitable for diatom–

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conductivity inference models. It also strengthens palaeoclimate interpretations by suggesting that local lake dynamics are relatively constant, supporting the hypothesis that in sea-spray dominated lakes, proxies primarily record externally forced changes driven by the SHW rather than internal hydrological or geochemical dynamics (Saunders et al., 2018; Perren et al., 2020). This further emphasises that water chemistry characteristics are critical to consider in site-selection, to develop reliable SHW reconstructions on Macquarie Island.

Furthermore, the development of the transfer function using field parameters collected across multiple sampling events increases confidence that the model reflects representative environmental conditions (Goldenberg Vilar et al., 2018; Kennedy & Buckley, 2021). This repeated-sampling approach is rarely possible when constructing diatom transfer functions, particularly in remote regions like the sub-Antarctic and Antarctic. While this adds robustness to the diatom model developed here, the data does not include winter measurements. The transfer functions could therefore be improved with year-round lake monitoring to capture the full range of environmental variability.

4.2 Evaporation

Interpreting environmental proxies as direct indicators of climate variability can be challenging, as multiple processes may produce similar signals (Molén, 2024). When using diatom–conductivity models to infer past SHW variability, it is essential to consider how near surface evaporation has the potential to concentrate ions in surface waters and mimic the effects of other processes such as increasing lake water salinity from SSA deposition due to stronger winds. Although this study and previous studies (Evans, 1970; Buckney & Tyler, 1974; Meredith et al., 2022) have demonstrated that SHW-driven SSA inputs are a dominant control on lake water chemistry on Macquarie Island, the role of evaporation in amplifying these signals remains unclear.

To explore this, we analysed $\delta^{2}H$ and $\delta^{18}O$ values from 2018 and across the 2022–23 summer. Isotopic enrichment is evident across the 2022–23 season (Fig. 5a), unsurprisingly indicating a strengthening evaporative signal through summer. Lake stable water isotopes sampled in 2018 were significantly more enriched than the 2022 mean, as expected given that the 2018 samples were collected in late summer, when evaporative effects are strongest and cumulative due to warmer temperatures throughout summer. This is supported by lake water temperatures being significantly lower in early summer (E2) compared

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to late summer (E3 and E4; Table 1). Given Macquarie Island's persistently high cloud cover, humidity, and low sunshine hours (BOM, 2025), solar evaporation is likely limited and confined to the summer season. Evaporation can produce heavy-isotope enrichment and the residual lake water becomes progressively enriched in heaver isotopes (^{2}H and ^{18}O), moving away from the Global MWL (Gat, 1996). Comparisons between E1 (2018) and E4 (2022), which were sampled at the same time of the year in January–February provide a valuable comparison of potential interannual variability in lake water chemistry and processes (Table 2). These two sampling events show near identical mean isotopic composition ($p > 0.05$; $\delta^{2}H$ = -20.7‰ and $\delta^{18}O$ = -2.8‰ in 2022, and $\delta^{2}H$ = -20.1‰ and $\delta^{18}O$ = -2.8‰ in 2018), suggesting broadly stable summer evaporative conditions between years. Furthermore, SSA influenced lakes on the plateau are in proximity to the west coast and have the greatest exposure to the SHW (Fig. 2b). These lakes have significantly higher isotopic enrichment (Fig. 5b), providing further evidence that wind is likely the primary driver of evaporation in plateau lake waters across Macquarie Island, particularly in lakes located on the western coast, which may be most suitable for reconstructions of SHW dynamics. As both wind-enhanced evaporation and wind-driven SSA transport and deposition contributes to the concentration of SSA ions in these lakes, both ion deposition and the concentration reflect a SHW signal.

Cl^- is a robust tracer of hydrogeochemical processes and, together with $\delta^{2}H$ and $\delta^{18}O$ values, can be used to better understand evaporation (Kirchner et al., 2010). While the isotopic enrichment observed generally indicates an evaporative signal, the absence of a correlation between Cl^- and $\delta^{2}H$ or $\delta^{18}O$ suggests that isotopes are capturing short-term (summer) evaporation rather than sustained evaporative concentration sufficient to increase Cl concentration in the lake waters like those in environments driven primarily by solar evaporation (Meredith et al., 2009). On Macquarie Island, wind-driven SSA deposition and rainfall dilution therefore likely remain the primary drivers of Cl variability. Consequently, EC in lake waters of Macquarie Island remains a robust proxy for interpreting variations in SHW strength.

4.3 Diatom communities

Diatom analysis showed that typical sub-Antarctic genera (Van de Vijver, 2019; Goeyers et al., 2022), including *Psammothidum*, *Planothidium*, and *Fragilaria*, dominated lake diatom communities on Macquarie Island. Across 52 lakes, 141 taxa were identified, indicating intermediate species diversity relative to previous studies on the island which reported 102 (McBride, 2009) and 208 (Saunders et al.,

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2009) species. Consistent with these earlier studies we have demonstrated that diatoms on Macquarie Island exhibit clear and distinct ecological preferences. Combined with the pronounced environmental gradients among lakes, these species-environment relationships provide a strong basis for using diatoms as indicators of limnological conditions and environmental change.

Psammothidium species are characteristic of low EC sites (Van de Vijer et al., 2002), and while abundance and dominance of key *Psammothidium* species showed variation along the lower end of the EC gradient, they dominated low EC sites. *N. bergstromiana* is considered endemic to Macquarie Island and was commonly found with dominant *Psammothidium* species at low EC sites, typically occurring where EC was < 200 µS cm $^{-1}$, consistent with what has previously been reported (Sabbe et al., 2019). *A. principissa*, previously identified as *Aulacoseria distans* (Ehrenberg) Simonsen on Macquarie Island (McBride, 2009; Saunders et al., 2009), was also common at low EC. This taxa is commonly found on sub-Antarctic Islands and is suggested to prefer very low conductance values < 80 µS cm^{-1} (Van de Vijver, 2012), while EC was not observed < 160 µS cm^{-1} in this dataset, *A. principissa* may be an indicator of very low EC conditions.

P. lanceolatum was a dominant high EC, high nutrient taxa. While it has been found to dominate flora elsewhere, this contrasts previous studies where it has been reported to be characteristic of oligotrophic conditions (Van de Vijer et al., 2002). *F. capucina, P. delicatulum*, and unknown sp. 111 were more commonly dominant at high EC. *F. capucina* was found across the EC gradient, consistent with its cosmopolitan and ecologically tolerant nature (Van de Vijer et al., 2002).

4.4 Developing transfer functions

A key aim of this study was to update and improve existing quantitative diatom models for Macquarie Island. While the dominant taxa identified here are consistent with those reported by Saunders et al. (2009), the strength of some diatom–environment relationships differ. EC and pH remain strong explanatory variables for diatom variation, whereas PO_4^{3-} and Si showed limited influence in this study. This reduced explanatory power likely reflects the low nutrient variability across plateau lakes, where concentrations were generally below detection limits.

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Sub-Antarctic lakes are characteristically oligotrophic; high nutrient levels do occur, but they are associated with peatlands or animal colonies, as is the case with coastal lakes on Macquarie Island (Selkirk et al., 1990). The Saunders et al. (2009) dataset recorded greater nutrient variability across plateau sites at the lower end of the EC gradient, attributed to enhanced organic inputs during periods of high ecological disturbance from invasive rabbits. These differences suggest that the dataset in this study better represents post-invasive or recovered limnological conditions that more likely reflect pre-invasion or baseline states and provides an updated basis for developing robust diatom–environment models.

EC was shown to be the major independent driver of diatom assemblages, with strong performance in all CCA models, individually accounting for almost 50% of the variance in the full CCA model and strong explanatory power as indicted by λ_1/λ_2 (Table 4). Although EC reflects a high proportion of shared variance (Fig. 8), this is consistent with its role as an integrative measure of ionic strength and catchment inputs. The shared component primarily reflects its covariation with major ions and nutrient variables (TON and PO_4^{3-}), which are typically correlated with EC in these systems. Despite this overlap, EC retained a strong and highly significant independent effect (p = 0.001), confirming its dominant ecological influence on diatom distributions.

While PO_4^{3-}, TON, and Si each explained significant but moderate portions of individual variance (Table 4), they lost significance once covariation was controlled for (Table 5), meaning their explanatory power is mostly shared variance with other environmental gradients, primarily EC and each other. While pH explained a major and independent gradient in diatom variation within plateau lakes (Fig. 7), it did not capture assemblage changes across high-EC, high-nutrient sites. This was indicated by individual CCA results, which were less than half of the variance explained by EC (Table 4). This, paired with the widespread oligotrophic nature of plateau lakes on Macquarie Island lends strength to the explanatory power of EC across the whole dataset.

Furthermore, pH showed poor predictive performance as a transfer function, with the lowest r^2_{boot} = 0.17, and highest RMSEP = 0.63 from the WAPLS-2 model. While this is surprising due to the strong pH gradient across plateau sites, most diatoms were tolerant across the pH gradient with few species showing clear optima for narrowed and specific ranges. EC had the strongest performance with the WA

https://doi.org/10.5194/egusphere-2025-6242
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and ML models producing the highest r^2_{boot} (0.74 and 0.80, respectively) and comparable RMSEP. WA_{inv} and WAPLS-1 showed identical performance, with no benefit from additional WAPLS components, which progressively increased predictive error and decreased r^2_{boot}, suggesting overfitting. WA was therefore chosen over WAPLS as the simpler model.

The WA EC transfer function performed better than the previously published Macquarie Island diatom-conductivity transfer function (Saunders et al., 2009), with higher r^2_{boot}. However, some caution is warranted when predicting across the upper EC range, where greater predictive error is evident (Fig. 11). This can be attributed to lower species turnover, higher variability in PO_4^{3-}, TON, and Si, and fewer sites at the upper end of the nutrient and EC gradients. Further refinement of the EC transfer functions could be achieved with more evenly distributed sampling across the environmental gradient. The ML model, with higher r^2_{boot}, appears more capable of addressing these issues and maintains more consistent predictive power across the EC range. This is likely due to its explicit curve-fitting approach. By estimating individual species optima and tolerances, ML can better represent asymmetric or skewed response curves (Birks, 2012). The ML transfer function is therefore considered the preferred model, although both WA and ML are robust based on comparable RMSEP.

4.5 Future applications for reconstructing past climate changes

Incorporating diatom data with seasonal and multi-year hydrogeochemical data provides a unique opportunity to comprehensively understand diatom-environment responses. By quantifying temporal variability in hydrogeochemical processes, including the role of evaporation, this study strengthens confidence that EC reflects SHW-driven sea-spray inputs rather than local lake hydrogeochemical processes. This hydrological context is critical for interpreting diatom–environment relationships and ensuring the reliability of EC as a proxy for past SHW behaviour, providing a strong foundation for future palaeoclimate reconstructions. The resulting diatom–conductivity model provides a robust and ecologically grounded framework for reconstructing long-term SHW variability on Macquarie Island and establishes an important benchmark for sub-Antarctic palaeoclimate comparisons across the region.

By capturing ecological baseline and recovered conditions, the model developed in the present study offers an improved foundation for assessing long-term wind-driven variability, as it reduces ecological

https://doi.org/10.5194/egusphere-2025-6242
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noise associated with past disturbance. When applied in parallel with other proxies, such as isotopic or geochemical indicators (e.g. mercury and mercury isotopes Schneider et al., 2024), these reconstructions will contribute to a more comprehensive understanding of past SHW dynamics and their role in modulating Southern Hemisphere mid-high latitude climate, thereby providing context for understanding future changes. Furthermore, a multiproxy approach will be valuable to independently reconstruct other climatic factors such as precipitation which may also modify EC signals through dilution.

5 Conclusion

This study aimed to update and re-evaluate the reliability of diatom–conductivity models as a proxy for reconstructing SHW variability on Macquarie Island by analysing diatom–environment relationships in the context of seasonal and multi-year water chemistry and isotopic analysis. Our results demonstrate that although lake hydrogeochemical processes vary locally, they remain stable seasonally and between years. Lakes near the west coast and on the western edge consistently reflect strong SSA influence, and while short-term evaporative enrichment occurs during summer, it does not obscure the dominant signal of SHW-driven SSA inputs. Accordingly, EC reliably reflects SSA deposition rather than internal lake hydrogeochemical processes, providing a firm mechanistic basis for the use of EC as an indicator of SSA deposition in palaeoclimate studies on Macquarie Island.

Diatom–environment relationships were found to be strong and ecologically coherent, supporting the development of a robust diatom–conductivity transfer function. Importantly, this study highlights the need for careful site selection, with lakes that demonstrate stable hydrogeochemical behaviour, clear SSA influence, and limited local disturbance providing the most reliable archives for reconstructing past SHW variability. The resulting transfer function offers a reliable tool for reconstructing long-term SHW dynamics, supported by well-characterised modern hydrological controls. Together, these findings establish Macquarie Island as a well-constrained system for SHW reconstructions and provide a strong foundation for future palaeoclimate work across the sub-Antarctic region.

Supplementary material

The Diatom Catalogue and Species List can be accessed from DOI 10.5281/zenodo.18041221

https://doi.org/10.5194/egusphere-2025-6242
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Data availability

The raw data supporting the conclusion on this work is available on request.

Author contributions

Caitlin Selfe: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing - original draft; Writing - review & editing.
Karina Meredith: Supervision; Research design; Resources; Writing - review & editing
Liza McDonough: Resources; Writing - review & editing
Justine Shaw: Supervision; Writing - review & editing
Steve Roberts: Supervision; Writing - review & editing
Krystyna Saunders: Conceptualisation; Supervision; Resources; Funding acquisition; Writing - review & editing
Competing interests: The contact author has declared that none of the authors has any competing interests.

Acknowledgments

This work was supported by ARC SRIEAS Grant SR200100005 Securing Antarctica's Environmental Future. CS was supported by an AINSE Ltd. Residential Student Scholarship and acknowledges help undertaking fieldwork from Maggie Smith, Sam Beale, Jez Bird, and Adam Darragh. We thank the Tasmanian Parks and Wildlife Service and Australian Antarctic Division (AAS 4628) for field support and access to Macquarie Island. We also thank ANSTO laboratories for sample analysis, particularly Chris Vardanega and Henri Wong. This work contributes to delivering the Australian Antarctic Science Decadal Strategy, in particular the Climate System and Change key priority.

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