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Hydrochemistry of two headwater peatlands affected by deep gullies in the Maloti Mountains of Lesotho

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SUMMARY

Gully erosion in the peatlands of the Maloti Mountains has been reported since the 1980s, with recent observations indicating continued widening and deepening. Yet, how gullies alter peatlands hydrological functioning remains poorly understood, despite the importance of these systems for regulating downstream river baseflow. The study assessed the influence of gullies on peatland hydrology in two peatlands of Khalong-la-Lithunya using hydrochemistry, stable isotopes ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) and macro-ions (Ca^{2+} , Mg^{2+} , K^+ , Si^{4+} , HCO_3^- , SO_4^{2-} , Cl^- and Fe-total). Groundwater was sampled from piezometers and wells installed at different depths and positions relative to gullies during the wet summer and dry winter conditions, and compared with precipitation and stream water. Water sources and flow paths varied seasonally. During summer, depleted $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in groundwater following rainfall indicated recharge. In winter, groundwater was isotopically distinct from snow, while stream water closely resembled groundwater, indicating an important contribution of groundwater discharge to surface flow. Macro-ions concentrations varied spatially in relation to gullies. Sites farther from the gullies showed upward movement of mineral-rich groundwater, whereas sites near gullies showed infiltration of mineral poor water. Rainfall diluted macro-ion concentrations in surface water during summer, while limited infiltration and evaporation during winter produced higher ion concentrations in the shallow groundwater near deeper gullies. The results indicate that gully incision has altered groundwater movement and chemistry, reducing the capacity of these peatlands to retain water and sustain slow release to downstream systems, with associated changes in vegetation patterns and implications for local water resources and livelihoods.

KEY WORDS: Deuterium, Hydrological functioning, Macro-ions, Oxygen-18

INTRODUCTION

Globally, peatlands cover approximately 3 % (4.27 million km²) of the global land and freshwater surfaces (Lehner *et al.* 2024). Africa contributes 8 % to the global peatland coverage with the Cuvette Central in the Congo Basin (16.7 million ha) covering more than one-third of all tropical peatlands. Wetlands in Lesotho are estimated to cover 0.92 % of the country's area (FAO 2023) with peatlands only found in the highlands physiographic zone (2000–3482 m a s l) of the Maloti Mountains (Hughes & Hughes 1992). They are extensive at 2900–3300 m a s l, with smaller peatlands occurring around 2100–2900 m a s l (Schwabe 1985). There is limited literature on their areal coverage due to their remoteness and inaccessibility. Nevertheless, these peatlands are important for their regulatory services such as flood attenuation, water purification, sustaining the base-flow of rivers, biodiversity maintenance and climate mitigation (Mokuku & Taylor 2015). Their provisioning services include water supply to down-stream communities, paludiculture through harvesting *Merxmuellera* grass species (Chatanga *et al.* 2020) and livestock grazing for local herdsman (Schwabe 1985; Grundling *et al.* 2015; Grab & Knight 2018). Furthermore, the peatlands are recognised for contributing to the water supply from Lesotho to South Africa, which is a significant source of income for Lesotho (Mokorosi & Van Der Zaag 2007). Within a focus area of 49155 ha, Van Tol (2024) used digital soil mapping to record 3094 peatlands ranging from < 0.01–1335 ha (15.1 % of the focus area) in the Maloti Mountains and almost all the peatlands exhibited gully erosion.

Peatlands in Lesotho are prone to degradation caused by livestock overgrazing (Du Preez & Brown 2011), burrowing impact of ice rats (*Otomys sloggetti robertsi*) (Grab 2012) and stormwater channelled through road culverts which cut through the peatlands, causing gully erosion (Marneweck & Grundling 1999). Gully erosion causes drainage of peatlands and leads to lower groundwater tables (Price *et al.* 2003) which increases the depth of the aerated peat layer, thus its oxidation (Turunen *et al.* 2024). Its desiccation and oxidation result in peat shrinkage and mineralization (Van Diggelen *et al.* 1991), which affects the hydraulic properties of the peat. For example hydraulic conductivity and volumetric water content decreases, whereas specific yield and bulk density increase (Waddington *et al.* 2015; Elmes *et al.* 2021). Furthermore, in groundwater-fed peatlands, the influence of rainwater in the topsoil will increase at the expense of groundwater, causing it to become more acidic (Van Diggelen *et al.* 1991; 1996; Jansen *et al.* 1996). Gully erosion is a widespread phenomenon for peatlands in the Maloti Mountains. Yet, relatively little has been done to halt the spread of gully formation, or more importantly, to stop its cause(s), although some efforts have been made to rehabilitate peatlands in some catchments (ORASCOM & DWA 2018). Gully erosion is not restricted to these peatlands. It has been documented in peatlands in the United Kingdom (Bragg 2002, Allot *et al.* 2009, Howson *et al.* 2023) and in China (Li & Gao 2019), where research assessed the effect of gullies on hydrological parameters such as water tables levels, hydraulic heads and saturated hydraulic conductivity rather than on hydro-chemical properties, which are the focus of the present investigation. A hydrochemical approach was taken because the site's remoteness allowed infrequent visits, and the high susceptibility of the instrumentation to vandalism. The assumption is that hydrochemistry is indicative of hydrological processes and provides some integration of the site's hydrology over space and time.

This study examines the Motete and Matsoku peatlands, located within the Maloti Mountains of Lesotho, southern Africa, which are also prone to erosion, causing significant gully formation. The problem of erosion has been documented since the 1980s (see Schwabe 1985; Grobbelaar & Stegmann 1987; Grab & Deschamps 2004; Grab & Knight 2018; Chatanga *et al.* 2020). In Motete peatland, Grobbelaar & Stegmann (1987) recorded 0.5–1 m deep gullies, which now reach depths of up to 2 m. In the Matsoku peatland, a major gully—up to 6 m deep—transects the peatland, effectively, dividing it into two distinct sections.

In order to prevent further peatland degradation in the Maloti Mountains due to erosion, as well as to rehabilitate the peatland areas, it is necessary to gain a better understanding of the hydrological functioning of these gullied headwater peatlands (Maltby 2006), for the management of their water resources (Bresciani *et al.* 2018). The aim of this study, therefore, is to provide insight into the hydrological functioning of peatlands in the study areas, as characteristic examples of peatlands in the Lesotho highlands, by using hydrochemistry and stable isotopes. The specific objectives are 1) to determine the macro-ionic and isotopic composition of the different water sources (precipitation, groundwater, and stream water) in the peatlands; 2) use this to determine the origin of groundwater; and 3) evaluate the impact of the gullies on groundwater flow.

METHODS

Study site

The Motete and Matsoku peatlands are located in the north-eastern Lesotho in the Maloti Mountains. This region forms part of the highlands physiographic zone, which covers 59 % of Lesotho's total land area (ORASECOM 2014). The peatlands belong to the Khalong-la-Lithunya catchment and are situated along the road from Afriski Mountain Resort to Letseng Diamond Mine. They form the headwaters of the Motete and Matsoku Rivers, respectively (Fig. 1). Motete peatland is found 3201 m a s l at coordinates 28° 53' 57" S, 28° 48' 2" E while Matsoku peatland is found 3132 m a s l at coordinates 28° 54' 36" S, 28° 49' 08" E. Motete peatland has north, north-east facing aspect with slope <10° while Matsoku peatland has a south facing aspect with slope <5° (Marneweck & Grundling 1999). Their surface areas are approximately 20 and 15 ha, respectively.

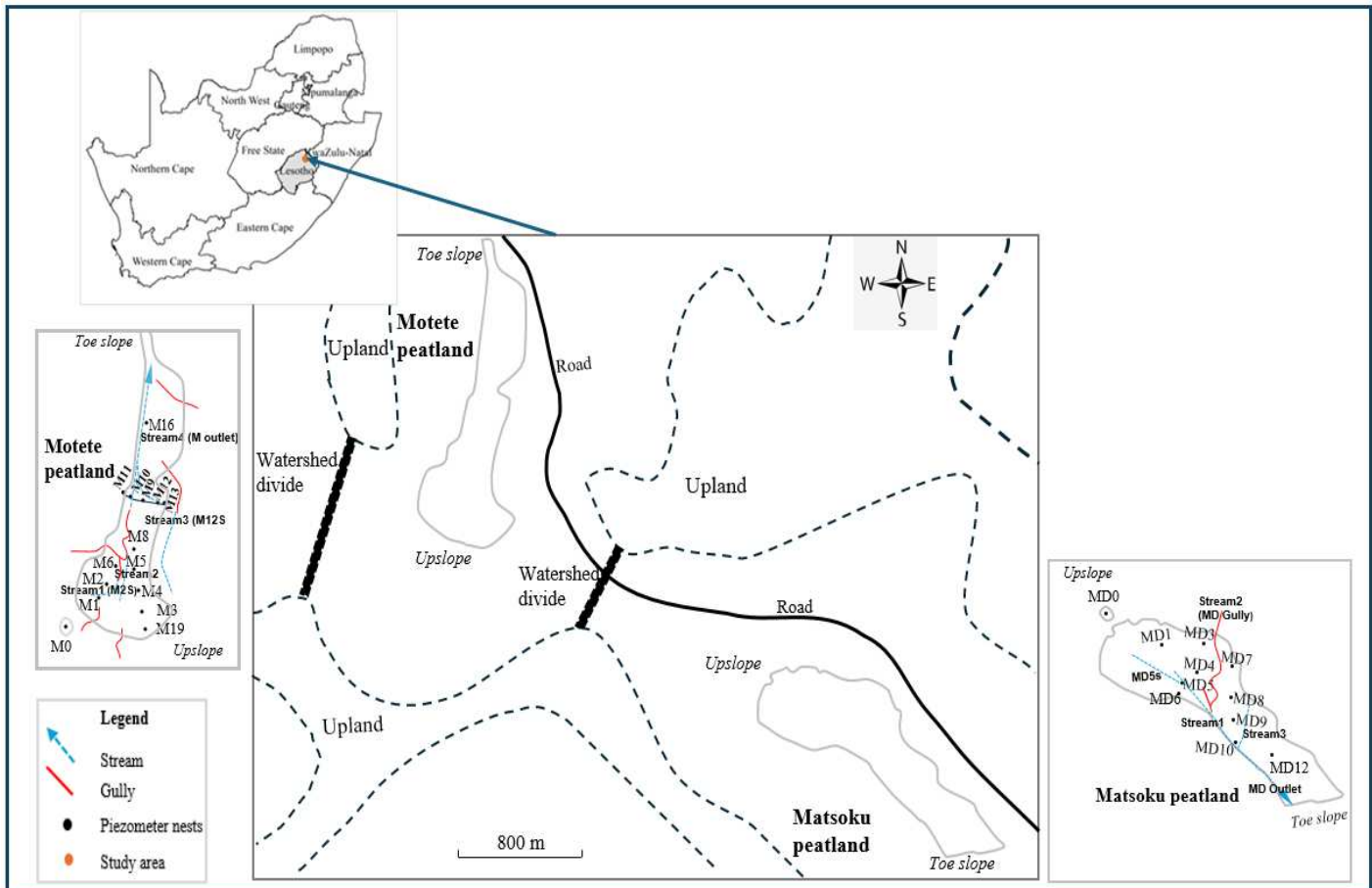


Fig. 1: Location of the study area with the two peatlands that were studied, as well as the piezometers and wells from which water samples were taken.

The mean annual rainfall from the closest weather station at Letseng Diamond Mine amounts to 767.8 mm (King & Brown 2003; Nel & Sumner 2008). Evaporation ranges between 700–1,500 mm annually (Mucina et al. 2014). Average air temperatures are 0 °C and 10 °C in winter and summer, respectively (Mills et al. 2012).

Basalt is the major geologic material surrounding the landscape that surrounds the peatlands. According to Rapopo & Sobie (2018), basalt covers approximately two-thirds of Lesotho. Bare rock, rock fragments and stony soil can be found on the upper most section of slopes surrounding these peatlands (Schmitz & Rooyani 1987), while at the foot of the slopes mineral soils of mollic epipedon occur. In the peatlands, peat is underlain by layers of clay and clayey gravel (Marker 1995). These peatlands have peat dated 8020±80 year BP and accumulating at a rate of 0.25mm/ year (Van Zinderen Bakker & Werger 1974). The peatlands have peat depth of up to 2.5 m interbedded with gravel layers (Marneweck & Grundling 1999). These peatlands have crept upslope to cover small alluvial fans extending from intermittent channels that emanate from exfiltration sites upslope.

Steep mountain slopes encompass these peatlands (Grundling et al. 2015). These slopes generate peak run-off from rain showers and snowmelt water (Grab & Deschamps 2004). Deeply incised gullies ranging from 0.5–6 m deep cut through the peatlands, as previously noted, caused mostly by road culvert placements. The peatlands are cirque-shaped and taper towards the stream valley that drain these systems. In addition to gullies, they have geomorphic features such as peat hummocks, stone outcrops, flarks (pools developing when water stagnates in small depressions (Backeus 1989), and turf exfoliation pans (closed basins developing through processes involving livestock trampling, needle ice, wind deflation and runoff (Grab 2010). A small rodent, *Otomys sloggetti robertsi*, has colonised these peatlands and created channels (0.12–0.32 m), which can widen during heavy runoff (Hinze et al. 2006).

Overgrazing has affected the vegetation diversity and standing crop of these peatlands (Du Preez & Brown 2011). The current vegetation comprises grasses (*Poa annua*), forbs (*Haplocarpha nervosa*, *Athrixia fontana*, *Sebeae marlothii*), sedges (*Cyperus marginatus*) and mosses (*Bryum alpinum*) (Marneweck & Grundling 1999). The slopes surrounding the peatlands are dominated by upland species such as *Chrysocoma cilliata* and *Helichrysum trilineatum*, though they have encroached into the peatlands, especially around the gully in Matsoku peatland.

Selection of parameters for analysis

The concentrations of the macro ions: Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , HCO_3^- and SO_4^{2-} , and furthermore of Si^{4+} and Fe-total were determined. Differences in their ratios or in their individual concentrations provide information about the extent to which the chemical composition of the water is determined by rainwater, groundwater or stream water (Van Wirdum 1991). Furthermore, their concentrations were used to determine the origin of the groundwater (Grootjans & Jansen 2012, Bootsma et al. 2019). Iron (Fe-total) indicates the oxidation-reduction processes that are triggered by water table fluctuation, which is indicative of the effect of gullies on groundwater flow.

Furthermore, water isotopes (deuterium and oxygen-18) were used to determine the age and subsequently the possible origin of groundwater (Fry 2008; Grootjans & Jansen 2012). Elevated stable isotope values may originate from slowly infiltrating water that has been exposed to evaporation and from old recharging (rain)water (Elshehawi et al. 2019).

Precipitation, ground- and stream water sampling

Piezometer nests were installed at different depths across the peatlands with one installed on the peat layer and the other on the subsequent substrates (clay or clayey gravel) to collect groundwater samples for chemical analysis of ions and stable isotopes (Table 1). Piezometer depths differed at different locations because of differences in the peat layer. A 20 cm screen covered with a geotextile membrane (to prevent siltation of the pipe) was attached at the bottom of a 50 mm diameter PVC pipe to allow groundwater (under piezometric pressure) into the pipes and was centred on the peat layer. Wells, perforated along their entire length, were used to collect water samples for further analysis of stable isotopes. Wells had similar length with piezometers installed on the subsequent substrate to peat and provided a mixed sample (deeper and superficial groundwater), whereas piezometers sampled groundwater from a specific depth (Acworth 2019). The piezometers were located at different distances from the gullies. A Russian peat auger was used to create a pilot hole to insert piezometers and wells constructed from PVC. Piezometers consisted of a 20 cm long screen, covered with a geotextile membrane (to prevent siltation of the pipe), that was attached to the bottom of an unperforated 50 mm diameter PVC pipe. Water samples were collected during two campaigns to capture seasonal variability. Sampling was conducted on the 29th–30th June 2024 (dry winter season) from piezometers, wells, stream water, and snowpack and on the 14th–15th November 2024 (wet summer season) from piezometers, wells, streamflow, and rainfall. Piezometers and wells were flushed out a day prior to sampling to allow fresh groundwater inflow. One water sample was collected from each piezometer and well, one stream water sample from each primary drainage channel, and one sample from precipitation sources (snowpack and rainfall) from each peatland at similar elevation (3132 m a s l). Snowpack was sampled at different depths and integrated into one sample. A total of 58 samples were collected in winter and 44 samples in summer for ion analysis, whereas 79 samples were collected in winter and 90 in summer for isotope analysis. The seasonal difference in the number of samples collected for ion analysis was largely attributable to vandalism of the piezometers. In addition to piezometers, wells were sampled for isotope analysis, accounting for the higher number of isotope samples collected in both seasons. A hand-held water pump was used to collect water samples into 175 ml plastic bottles for ion analysis and into 100 ml dark-brown plastic bottles for isotope analysis. Stream water samples were collected from the primary drainage channels of each peatland. Samples were stored in an iced cooler box and sent to the laboratory within two days after sampling, where they were refrigerated at temperature between 4 and 10 °C until chemical analysis.

Table 1: Monitoring points, substrates, and their depths

Motete				Matsoku			
Monitoring Point	Monitoring pipe	Substrate	Depth of screen (m)	Monitoring Point	Monitoring pipe	Substrate	Depth of screen (m)
M0	P1	Clayey gravel	1.28	MD0	P1 P2	Clayey gravel Peat	1.60 1.40
M1	P1 P2	Clay Peat	3.32 1.90	MD1	P1 P2	Clayey gravel Peat	3.00 2.50
M2	P1 P2	Peat Peat	2.71 1.66	MD3	P1 P2	Clay Peat	2.50 1.50
M3	P1 P2	Clay Peat	2.30 1.00	MD4	P1 P2	Clayey gravel Peat	1.50 1.20
M4	P1 P2	Clay Peat	1.00 1.54	MD5	P1 P2	Clayey gravel Peat	2.00 0.80
M5	P1	Peat	1.25	MD6	P1 P2	Clayey gravel Loam	1.80 1.00
M6	P1 P2	Clayey gravel Peat	1.62 1.00	MD7	P1 P2	Clayey gravel Gravelly loam	1.50 0.70
M8	P1 P2	Clayey gravel Peat	1.73 1.35	MD8	P1 P2	Clayey gravel Peat	2.70 2.00
M9	P1 P2	Clayey gravel Peat	2.30 1.55	MD9	P1 P2	Clayey gravel Peat	1.80 1.40
M10	P1 P2	Clayey gravel Peat	2.05 1.80	MD12	P1 P2	Clayey gravel Peat	1.50 0.50
M12	P1 P2	Clayey gravel Peat	1.80 1.00				
M16	P1	Peat	0.70				

Gully distances and depths

Gully distances from monitoring sites were measured using Garmin eTrex 10 GPS with a precision of 3m. Length measurements were taken from the sampling point to the edge of the gully. Gully depths were measured using a tape measure.

Laboratory analysis

Macro-ions

Samples were analysed at the Agricultural Research Council Laboratory (ARC) in Pretoria for the following ions: SO_4^{2-} , HCO_3^- , Cl^- , Si^{4+} , Fe-total ($\text{Fe}^{2+} + \text{Fe}^{3+}$), Na^+ , K^+ , Ca^{2+} , Mg^{2+} . The samples were filtered using a 0.45- μ m membrane vacuum filter to remove impurities. Cations were analysed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and anions by using Ion Chromatography. A pH meter (Hannah) was used to determine pH and Electrical conductivity (EC). The reliability of the analyses was checked by calculating the ionic balance according to Stuyfzand (1993). Analyses with a deviation in the ionic balance of more than 10% from electro neutrality were discarded.

Isotopes

Samples were analysed for stable isotopes (deuterium and oxygen-18) at the Environmental Isotope Laboratory of iThemba LABS. Samples were analysed using Los Gatos Research (LGR) Liquid Water Isotope Analyser. The analytical precision is estimated at 0.5‰ for O and 1.5‰ for H. Analytical results are presented in the common delta-notation:

$$\delta 18(\text{‰}) = \left[\frac{(180/160)_{\text{sample}}}{(180/160)_{\text{standard}}} - 1 \right] \times 1000$$

The same applies to deuterium/hydrogen isotope ratios ($^2\text{H}/^1\text{H}$). The delta values are expressed as per mil deviation relative to a known standard, in this case standard mean ocean water (SMOW) for $\delta^{18}\text{O}$ and δD .

Data analysis

Ionic data were plotted in Microsoft Excel, and in R to carry out a principal component analysis (PCA) (R core team 2024). Each component shows variation among the different ions and the correlation thereof. Arrow length and direction in principal components (PC) show the magnitude and the principal component that received the greatest contribution. Furthermore, cluster analysis was performed in R (R core team 2024) to group closely associated ions together into clusters that enable classification of the different water types (Davis 1973). The Welch Two Sample t-test was used to determine the statistical significance of the differences in means between the ions in the wet and dry seasons.

RESULTS

Stable isotopes ($\delta^2\text{H}$ and $\delta^{18}\text{O}$)

Wet season (November)

The samples from Motete peatland ranged from -1.54 to -6.40 ‰ for $\delta^{18}\text{O}$ and -2.86 to -31.23 ‰ for $\delta^2\text{H}$. In Matsoku peatland samples ranged from -2.07 to -6.11 ‰ for $\delta^{18}\text{O}$ and -6.96 to -31.31 ‰ for $\delta^2\text{H}$ (Fig. 2). Most values of the different water sources (precipitation, ground- and stream water) plot above the global meteoric water line (GMWL), with rainwater plotting furthest from the GMWL and showing enrichment in $\delta^2\text{H}$ compared to average ground- and stream water values (Fig. 2). There are no previous data from which a local meteoric water line can be estimated, therefore, the Pretoria and Cape Town meteoric water lines (MWLs), which are the closest available reference lines (Fitchett et al. 2024), were used for comparison. During the wet season, the isotope compositions of most samples were more closely aligned with the Cape Town MWL than the Pretoria MWL. The different water sources from the mineral substrate, peat layer, wells and streams in both peatlands largely form a single cluster rather than separate groups with no clear distinction among the water sources.

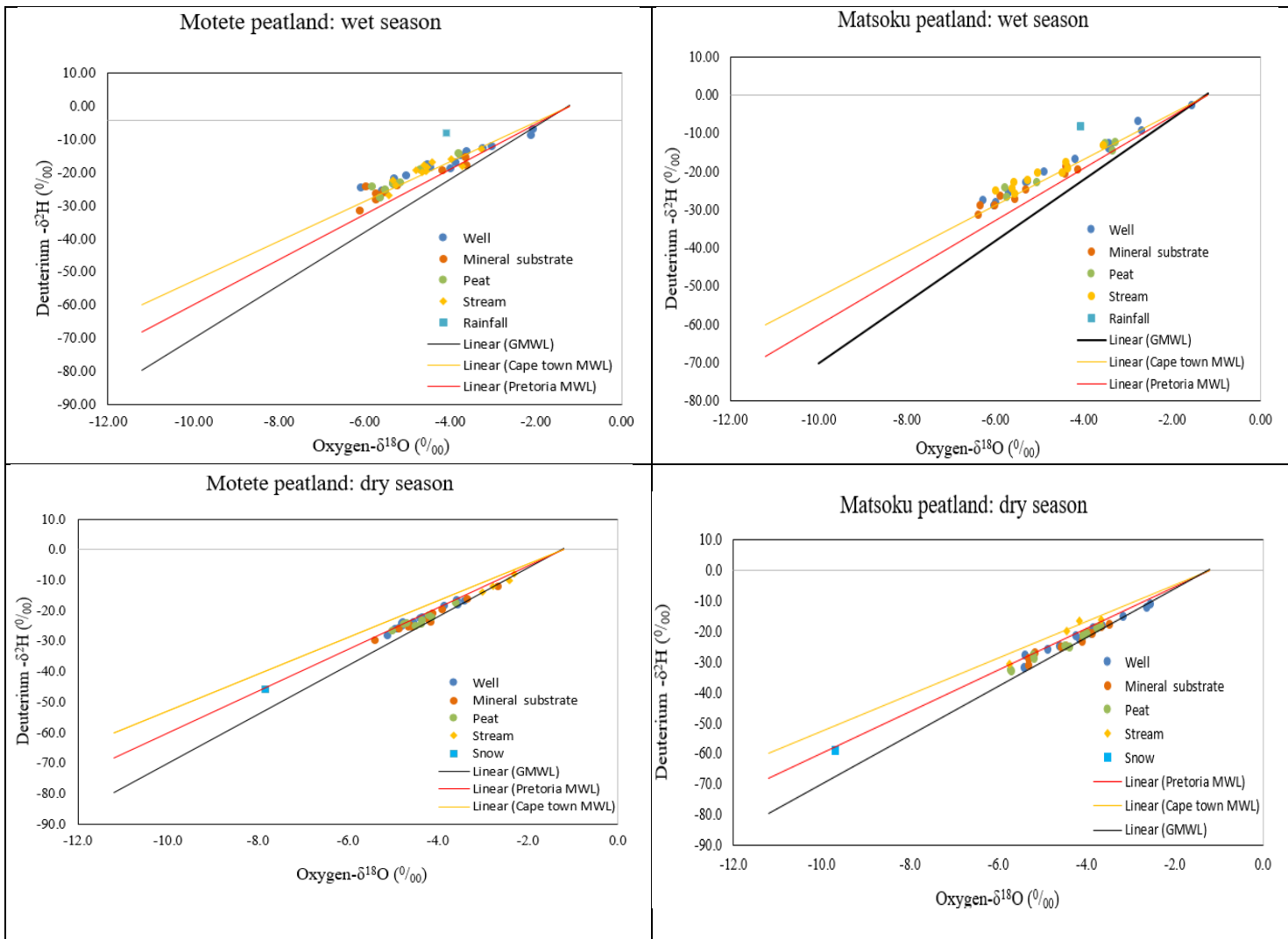


Fig. 2: Isotopic signatures ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) of waters from the Motete and Matsoku peatlands during the wet (rainfall) and dry (winter) seasons.

Dry winter season (June)

The samples from Motete peatland ranged from -2.3 to -7.8 ‰ for $\delta^{18}\text{O}$ and -8.0 to -46.1 ‰ for $\delta^2\text{H}$. In Matsoku peatland samples ranged from -2.5 to -9.7 ‰ for $\delta^{18}\text{O}$ and -11.3 to -58.8 ‰ for $\delta^2\text{H}$ (Fig. 2). Isotope ratios ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) of the various water sources (precipitation, ground- and surface water) plot at or slightly above, but almost parallel to the GMWL (Craig 1961) but below the Pretoria and Cape Town MWLs in both peatlands, indicating a greater influence of evaporative processes (Fig. 2). There is marked difference in the snow sample from other sources with a $\delta^{18}\text{O}$ value of -7.8 ‰ and $\delta^2\text{H}$ value of -46.1 ‰ in Motete peatland and $\delta^{18}\text{O}$ value of -9.7 ‰ and $\delta^2\text{H}$ value of -58.8 ‰ in Matsoku peatland. In

Motete peatland, groundwater is more depleted in $\delta^2\text{H}$ and $\delta^{18}\text{O}$ than stream water, the latter being a mixture of groundwater and precipitation.

Principal component analysis (PCA)

Groundwater

Groundwater mineral richness was assessed with PCA, and this attribute related to principal component (PC) axes 1 and 2, respectively. In Motete peatland, the principal component analysis (PCA) shows that during the wet season, 46.9 % and 23.0 % of the variation in groundwater composition is explained by axes 1 and 2, respectively (Fig. 3). In the dry season, axes 1 and 2 account for 44.6 % and 26.5 % of the variation, respectively (Fig. 3). In Matsoku peatland, in the wet season, 56.8 % and 19.9 % of the variation is explained by axes 1 and 2 and in the dry season 32.9 % and 22.6 %, respectively (Fig. 3). Overall, ion correlations with the first principal component are stronger during the wet season in both peatlands. In Motete peatland, Mg^{2+} , Ca^{2+} , Si^{4+} , Fe-total, Na^+ and HCO_3^- are positively correlated with the first axis in the wet season while K^+ and Cl^- are strongly negatively correlated with the second axis. In Matsoku peatland, the same ions show positive correlation with the first and second axis, although Na^+ shows a weaker relationship while Cl^- is positively correlated with the second axis in both seasons.

During the dry season, in the Motete peatland, almost all cations are positively correlated with the first axis, whereas SO_4^{2-} , K^+ and Cl^- have a negative correlation with the second axis (Fig. 3) consistent with the occurrence of mineral-rich and anaerobic conditions (Smolders & Roelofs 1993). Only Cl^- and SO_4^{2-} are strongly positively correlated with the second axis in Matsoku peatland during the dry season. Temporal variation of groundwater composition occurs in both peatlands (Fig. 3). During the wet season, in both peatlands, groups of ions (Ca^{2+} , Mg^{2+} and HCO_3^-) display with similar orientations on the PCA than during the dry season, thus stronger correlation between the ions.

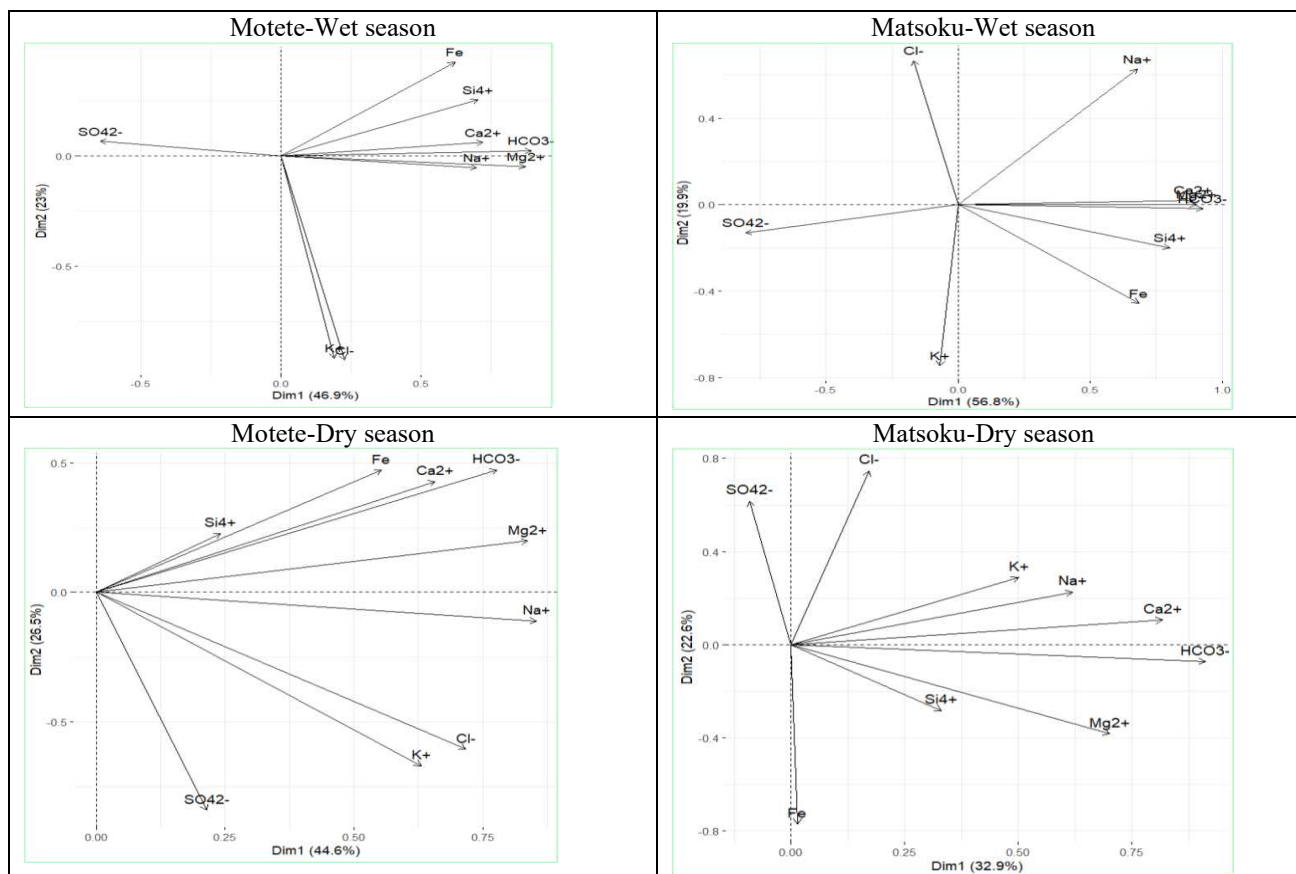


Fig. 3: Principal component analysis for the ionic composition of the groundwater samples from the Motete and Matsoku peatlands during the wet and dry seasons.

Stream water

In the wet season, 99.8 % and 97.5 % of the variation is explained by the first axis in Motete and Matsoku peatlands, respectively while in the dry season, 52.5 % and 76 % variation was accounted for by the first axis, respectively (Fig. 4). The first axis in both peatlands is dominated by HCO_3^- which is strongly negatively correlated with this axis and to a lesser extent by Ca^{2+} (Fig. 4). With the exception of sulphate (SO_4^{2-}), which has a low correlation, all other ions are negatively correlated with the first axis in Motete peatland. Furthermore, in Motete peatland, Na^+ and Cl^- are strongly positively correlated with the second axis in the wet season and in the dry season, Fe-total (Fig. 4). In both peatlands, the first axis is most strongly affected by HCO_3^- in the dry season: strongly negative in Motete and strongly positive in Matsoku peatland (Fig. 4). In Matsoku peatland, in the wet season Ca^{2+} , SO_4^{2-} , and Si^{4+} are strongly positively correlated with the second axis while Na^+ strongly negatively correlated with the same axis. In the dry season, Fe-total, Cl^- and HCO_3^- determine the second axis.

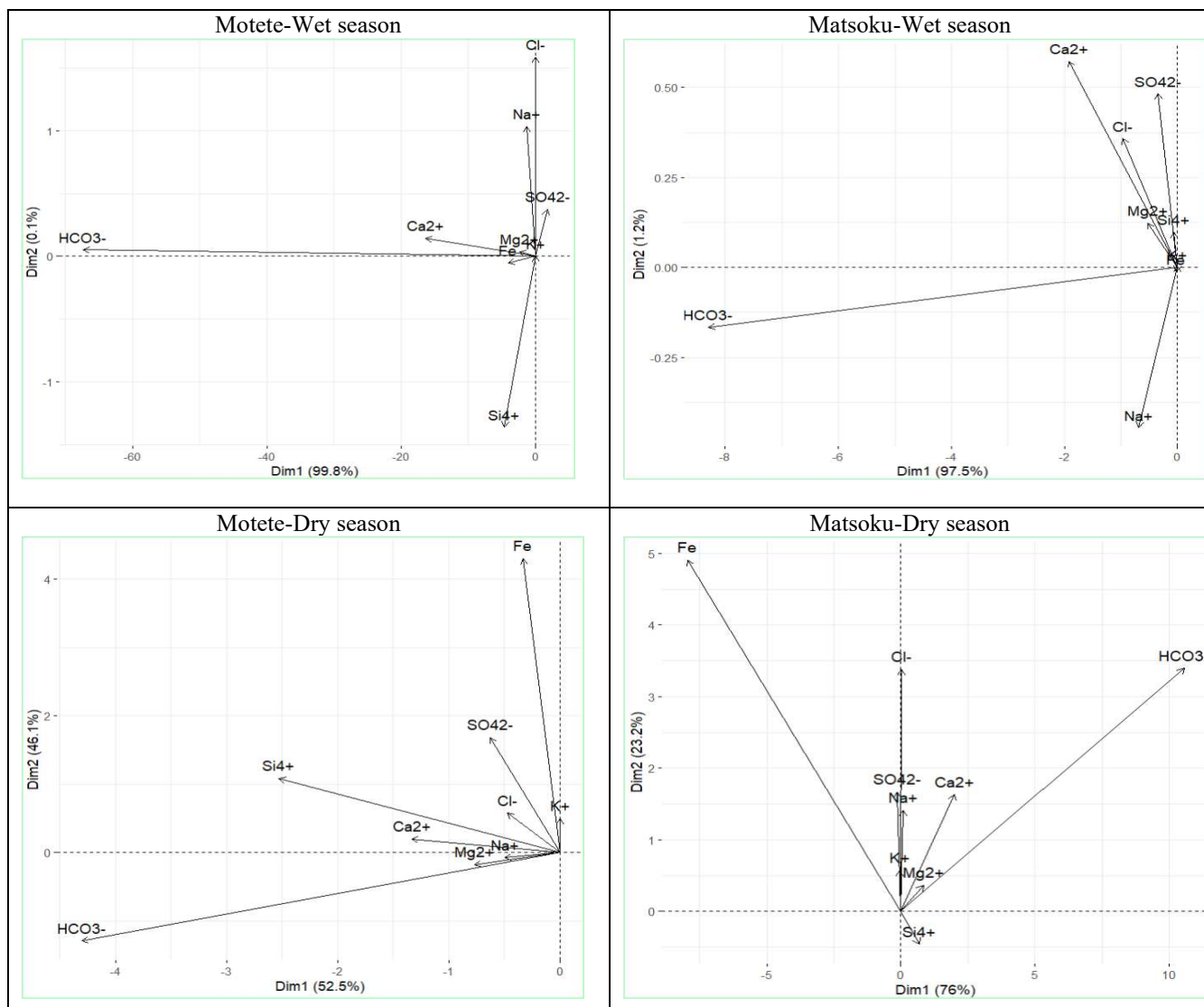


Fig. 4: Principal component analysis for the ionic composition of the stream water samples from the Motete and Matsoku peatlands during the wet and dry seasons

Ionic composition and seasonal variability

Cluster analysis grouped ground- and surface water samples according to their chemical composition (Ca^{2+} , HCO_3^- , SO_4^{2-} and Fe-total) (Fig. 5). These ions were chosen based on the results of principal component analysis, where Ca^{2+} and HCO_3^- determined principal component 1, while SO_4^{2-} explained principal component 2. Iron (Fe) was chosen for its relationship with the water table levels. The analysis produced two clusters (water types) for Motete and Matsoku peatlands in the wet and dry seasons.

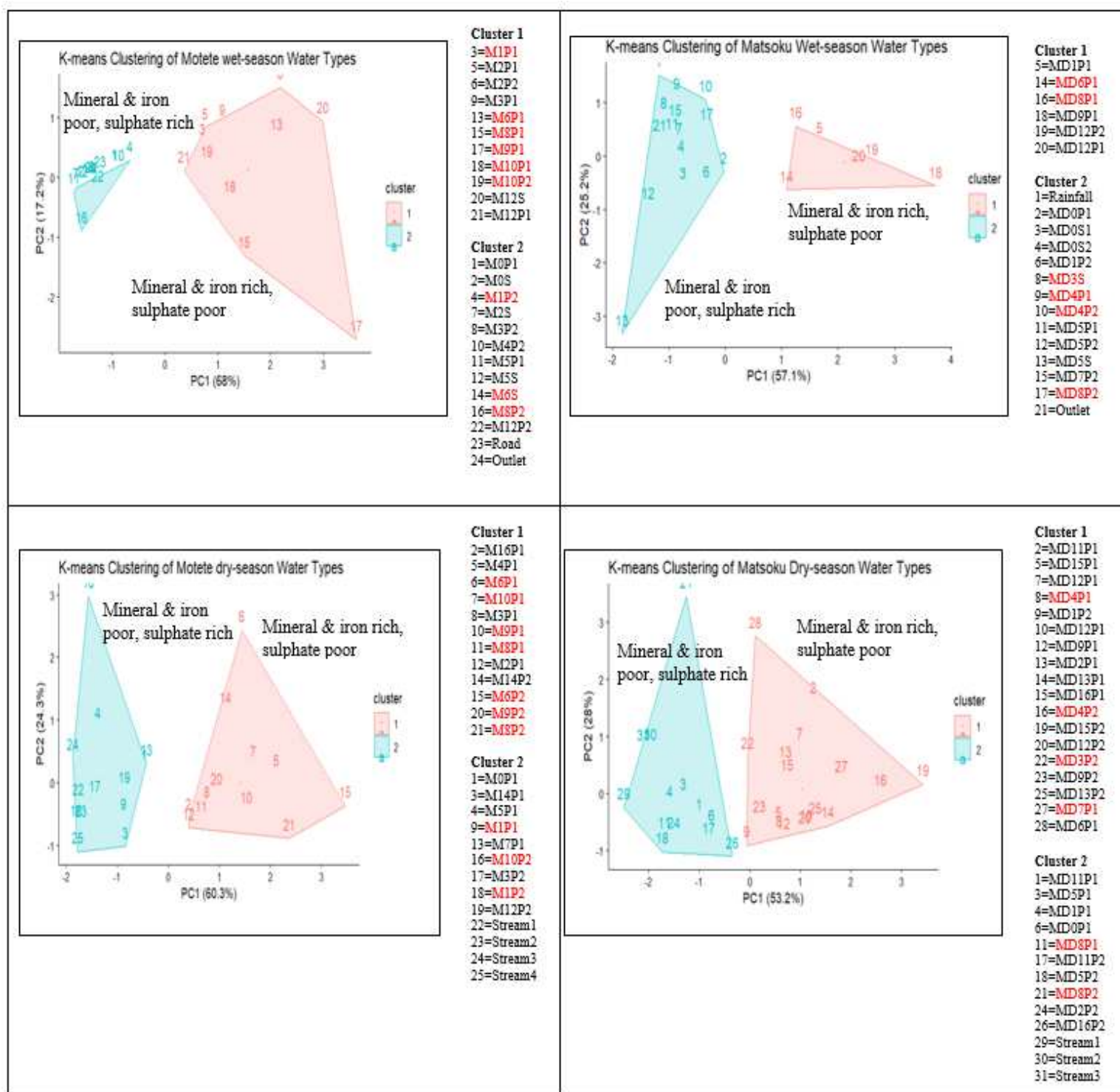


Fig. 5: Cluster diagram showing the ionic composition of ground- and stream water samples in the Motete and Matsoku peatlands during the wet and dry seasons. Note sites close to the gully labelled in red. Sample locations are listed on the right of each diagram, and correspond to locations shown in Fig. 1. The y and x-axis show the proportion of the total variation in the water chemistry explained by PC1 and PC2 with samples to the right contributing more to PC1 and samples higher on the y axis contributing more to PC2.

Type 1 comprise of mineral-rich, iron-rich and sulphate-poor (red shading) water and Type 2 mineral-poor, iron-poor and sulphate-rich water (teal shading) (Fig. 5). In the wet season, few sites in both peatlands show mineral-rich groundwater (Cluster 1), while more sites exhibit mineral poor groundwater. Stream water in both seasons, in the two peatlands, was mostly mineral poor except for site M12S which showed mineral-rich surface water during the wet season (Fig. 5). This points to the diluting effect of rainfall on ionic concentration on most sites and to intensive exfiltration of groundwater at

site M12. Most sites close to the gully in Motete peatland had mineral-rich groundwater during the wet season, compared to Matsoku peatland where more sites show mineral-poor groundwater. In the dry season, most sites close to the gully in Motete peatland show mineral-rich groundwater with the exception of sites such as M1 (P1 & P2) and M10 (P2).

The results of statistical t-test (Welch two sample t-test) performed to explain the ionic differences in the wet and dry seasons indicate that the mean ionic values in Motete peatland are not statistically different ($p > 0.05$) between the dry and wet seasons (Table 2). In contrast, Matsoku peatland has mean ionic values that are statistically different ($p < 0.05$) between the wet and dry seasons for Ca^{2+} , Mg^{2+} and HCO_3^- .

Table 2: The mean differences and p-values for the ionic composition of groundwater in Motete and Matsoku peatlands in the wet and dry seasons

				95% confidence interval of the differences			
Ions	<i>t</i>	df	p-value	lower	upper	Mean (Wet season)	Mean (Dry season)
Motete peatland							
Ca^{2+}	-1.94	46.36	0.06	-0.84	0.01	1.02	1.43
Mg^{2+}	-0.47	47.51	0.64	-0.19	0.12	0.39	0.43
Na^+	1.91	47.99	0.06	-0.00	0.06	0.16	0.13
K^+	0.61	28.15	0.54	-0.03	0.06	0.07	0.06
HCO_3^-	-1.57	47.90	0.12	-1.01	0.12	1.46	1.90
SO_4^{2-}	-0.19	46.71	0.85	-0.06	0.05	0.09	0.09
Cl^-	2.03	27.75	0.05	-0.00	0.10	0.09	0.04
Matsoku peatland							
Ca^{2+}	-3.85	43.96	0.00*	-1.33	-0.42	0.69	1.56
Mg^{2+}	-2.50	39.78	0.02*	-0.62	-0.07	0.34	0.69
Na^+	-1.84	35.23	0.07	-0.17	0.01	0.14	0.22
K^+	-1.21	33.01	0.24	-0.08	0.02	0.04	0.07
HCO_3^-	-3.57	41.18	0.00*	-2.21	-0.61	1.04	2.45
SO_4^{2-}	1.86	58.39	0.07	-0.00	0.05	0.06	0.04
Cl^-	-0.49	44.12	0.63	-0.05	0.03	0.05	0.06

*Significant at 5 % ($P < 0.05$)

The results of statistical t-test further indicate that there is no significant difference in the mean ionic composition ($p > 0.05$) of the stream water composition in the wet and dry seasons for each peatland. The mean values of SO_4^{2-} and Cl^- in Motete peatland, for example, are similar in the wet and dry seasons (Table 3).

Table 3: The mean differences and p-values for the ionic composition of stream water in Motete and Matsoku peatlands in the wet and dry seasons

				95% confidence interval of the differences			
Ions	<i>t</i>	df	p-value	lower	upper	Mean (Wet season)	Mean (Dry season)
Motete peatland							
Ca ²⁺	0.75	6.14	0.48	-0.52	0.99	0.67	0.44
Mg ²⁺	-2.29	8.01	0.05	-0.38	0.00	0.25	0.44
Na ⁺	1.37	7.49	0.21	-0.03	0.12	0.16	0.12
K ⁺	-1	3.00	0.39	-0.03	0.01	0.04	0.05
HCO ₃ ⁻	0.51	6.09	0.63	-0.81	1.23	0.96	0.74
SO ₄ ²⁻	0.05	3.99	0.96	-0.11	0.12	0.11	0.10
Cl ⁻	-0.07	8.43	0.95	-0.06	0.05	0.07	0.07
Matsoku peatland							
Ca ²⁺	-0.91	4.91	0.40	-0.26	0.12	0.41	0.48
Mg ²⁺	-2.08	4.20	0.10	-0.20	0.03	0.21	0.29
Na ⁺	-0.48	3.72	0.66	-0.11	0.08	0.12	0.13
K ⁺	-1.62	3.00	0.20	-0.04	0.01	0.04	0.06
HCO ₃ ⁻	-1.24	3.93	0.28	-0.39	0.15	0.65	0.77
SO ₄ ²⁻	-0.35	3.55	0.74	-0.06	0.05	0.09	0.20
Cl ⁻	-0.64	3.35	0.56	-0.19	0.12	0.06	0.09

Ionic concentration of ground- and stream water and gully effect

The gullies vary in depth and distance from wells and piezometers (see Appendix). Sites in Motete peatland are closer to the shallower gully than those in Matsoku peatland. To assess groundwater flow and gully influence, Ca²⁺ and HCO₃⁻ were chosen based on the strong correlation which determined principal component 1, while SO₄²⁻ was chosen because it determined principal component 2 in the PCA. Fe-total was chosen for its association with increased iron oxidation at low water tables resulting in high concentrations.

Motete peatland

There were seasonal and spatial differences in the patterns and concentrations of HCO₃⁻, Ca²⁺, SO₄²⁻ and Fe-total. For HCO₃⁻ concentrations, these were generally high throughout, except bordering the gullies, where intermediate concentrations occurred in the peat layer, at M8 in the wet season and at M10 in the dry season (Fig. 6 a, b). Surface water inflows all had low concentrations except at M12 in the wet season. Surface inflows had low concentrations in the dry season.

Patterns of Ca²⁺ concentrations were distinctly different in the wet season (generally intermediate) than the dry season (generally high) (Fig. 6 c, d). Ca²⁺ was higher in the more elevated side of the transect during the wet season, and as with HCO₃⁻ lower only at M10 during the dry season. Also similar to HCO₃⁻ concentrations, surface flow was only high at M12 in the wet season.

Patterns of SO₄²⁻ concentration were uniformly low during winter, except at M8 beside the main gully (high) (Fig. 6 e, f). It was more variable during the dry season with higher values either side of the gullies. Unlike for HCO₃⁻ and Ca²⁺, surface flow SO₄²⁻ concentration was high at M5 and M0 and low at M12, again occurring only in the wet season. Fe-total concentrations were uniformly low in the wet season (Fig. 6g) including surface flows, and highly variable in the dry season (Fig. 6h), with higher concentrations in the more elevated side of the peatland.

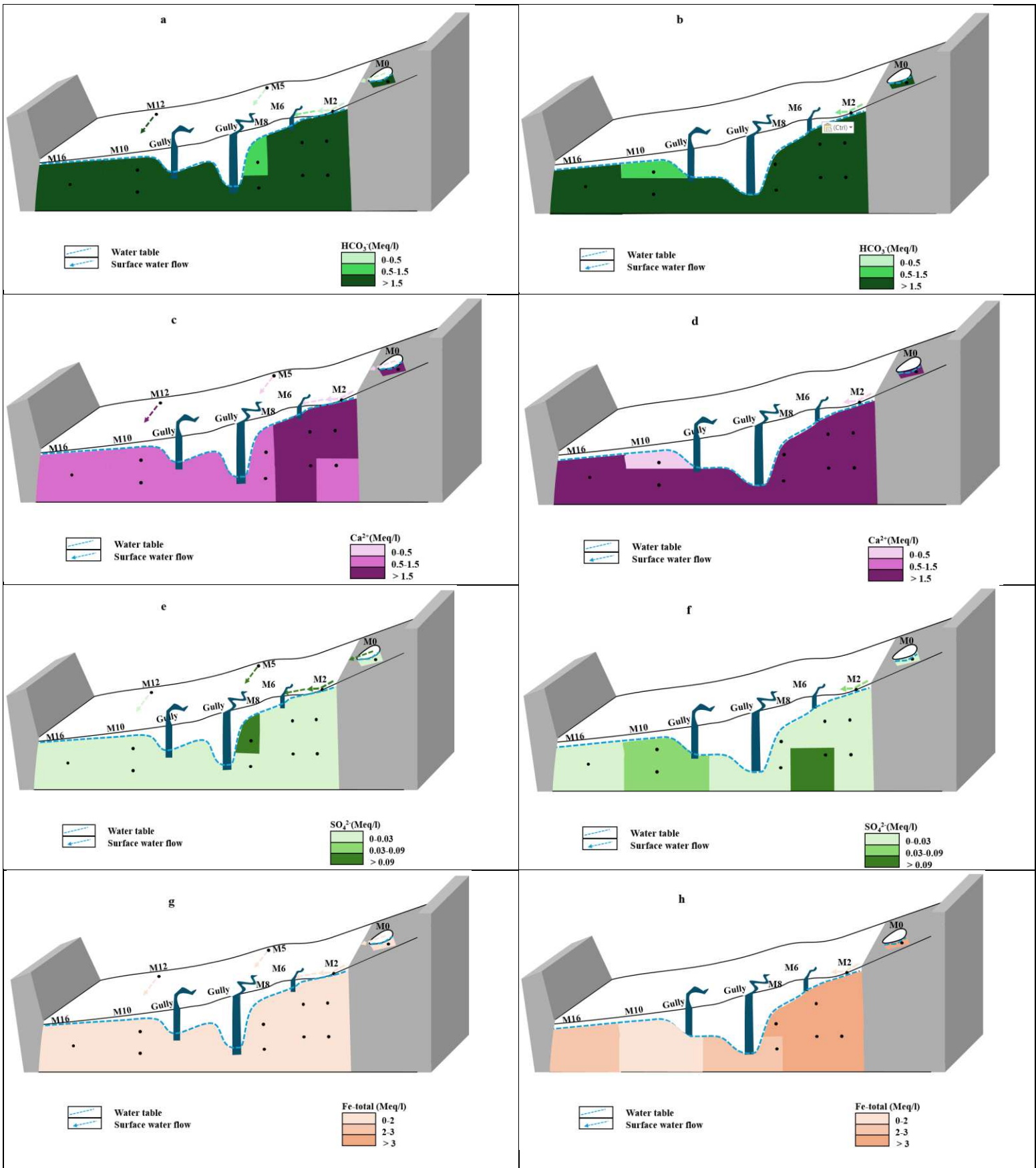


Fig. 6: Cross-section of Motete peatland showing ionic concentrations in the wet (a, c, e and g) and dry (b, d, f, and h) seasons at different sites.

Matsoku peatland

There were clear seasonal and spatial differences in the patterns and concentrations of HCO_3^- , Ca^{2+} , SO_4^{2-} and Fe in Matsoku peatland. Groundwater showed a broadly similar spatial pattern in HCO_3^- and Ca^{2+} concentrations during the wet season, although MD8, close to the deep gully, differed from the surrounding sites (Fig. 7). Here, mineral-substrate groundwater was rich in HCO_3^- but only moderately poor in Ca^{2+} . During the dry season, the spatial patterns of HCO_3^- and Ca^{2+} were more closely aligned. Concentrations of HCO_3^- and Ca^{2+} are generally higher in more elevated sections of the peatland. HCO_3^- concentrations were generally moderate in surface water during the wet season, whereas the only flowing stream observed in the dry season had low concentrations (Fig. 7).

SO_4^{2-} concentrations were generally low during both seasons (Fig. 7). However, in the wet season, moderate concentrations occurred at MD4 in the mineral substrate and at MD8 in the peat substrate near the gully. At MD8, SO_4^{2-} concentrations increased during the dry season, reaching rich levels in the peat layer and remaining moderate in the mineral substrate. Fe concentrations in groundwater were generally low during the wet season and remained low during the dry season at MD0, MD1 and the mineral substrate at MD8 (Fig. 7). In contrast, higher Fe concentrations were observed at MD4 near the gully and at MD12, farther from the gully. Overall, the concentration patterns indicate pronounced spatial and seasonal variability, particularly for SO_4^{2-} and Fe, with higher concentrations generally occurring in selected locations associated with the gully and the more elevated parts of the peatland. Surface flow concentrations of SO_4^{2-} and Fe were moderate during both seasons, though in the dry season only few sites had stream flow.

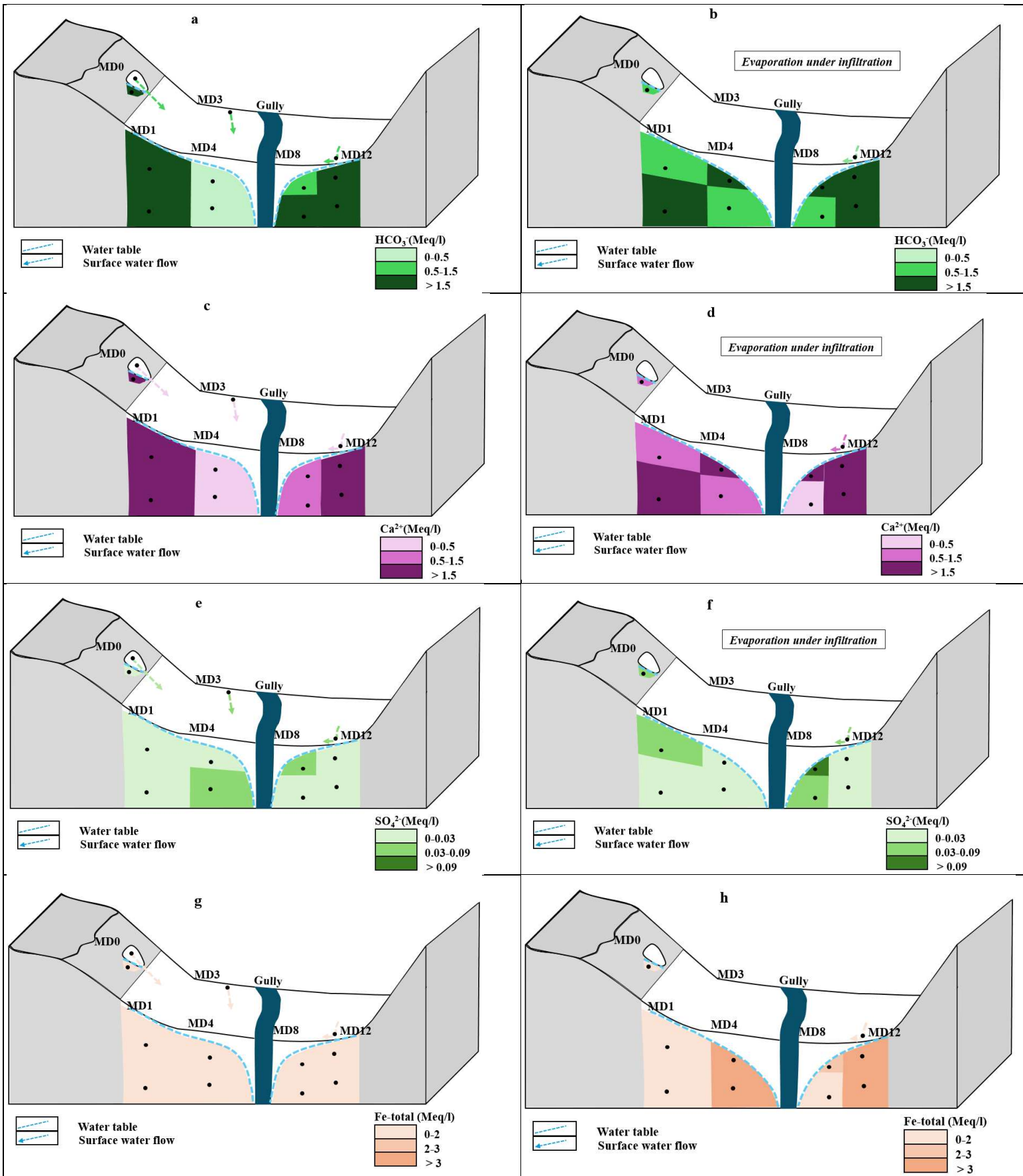


Fig. 7: Cross-section of Matsoku peatland showing ionic concentrations in the wet (a, c, e and g) and dry (b, d, f, and h) seasons at different sites.

DISCUSSION

Seasonal patterns in ionic and isotopic composition indicate that both peatlands are supplied by mineral- and Fe-rich groundwater in both wet and dry seasons (Fig. 5). This interpretation is supported by the strong depletion of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in snow relative to piezometer, well, and stream samples during the dry season, and by the enrichment of rainfall relative to ground- and stream water during the wet season (Fig. 2) and by the positive correlation of iron-total to PC1 (Fig. 3). Based on ionic composition, two water types can be distinguished in both peatlands: mineral-poor and mineral-rich (Fig. 5). Mineral-poor water type is often associated with low Fe and high SO_4^{2-} concentration in the two peatlands during the wet and dry season. This water type can be associated with precipitation. Mineral-rich water type is mostly high in Fe but poor in SO_4^{2-} (Fig. 5). In the shallow groundwater, these differences may be caused by infiltration of precipitation and/or meltwater at one location and groundwater discharge (exfiltration) at another, which hinders the infiltration of rainwater (Siegel & Glaser 1987). Moreover, the concentrations of Ca^{2+} and HCO_3^- increased with depth, especially at sites further from the gully and upslope (Fig. 6 a-d and Fig. 7 a-d), indicating that the higher ion concentrations in the streams compared to that in precipitation water are the result of exfiltration of this mineral-rich groundwater, where it is mixed with precipitation water and run-off water (Fraser et al. 2001).

After the groundwater has emerged (exfiltrated), it flows over the soil surface to the lower areas. This occurs during the rainy season at most locations and during the dry season at a fewer locations. The year-round emergence of groundwater assures the long-term preservation of the peatlands (Van Diggelen et al. 1996). However, during the wet season shallow groundwater near the gullies is mineral-poor (Fig. 6 & 7), indicating mixing with rainwater as deeper groundwater is drained by the gullies and because here, the water table is deeper and rainwater infiltrates freely. This is confirmed by the higher SO_4^{2-} content at various locations near the gullies in both peatland areas in the wet season (Fig. 6 & 7). The infiltrating precipitation water is aerobic, allowing pyrite to be oxidised and sulphates and iron oxides to form. This is an acid-forming process that increases the acidity at these locations (Madaras et al. 2012). Evaporation of the infiltrating shallow groundwater and the continued evapotranspiration of water from vegetation in the dry season, alongside pyrite oxidation and cation exchange, contributes to high mineral, iron, and sulphate content of the infiltrating shallow groundwater near the gullies (Fig. 6 & 7). This results in a unique ion distribution that differs from that at locations further away from the gullies (Dogramaci et al. 2025). Though the values of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ do not show evaporation (Fig. 2), the results of Fitchett et al. (2024) indicate that in winter, water samples from rivers, springs, snow and lakes (ponds) in the highlands of Lesotho showed evaporation. Therefore, it is likely that the water in some sites of the peatland has undergone evaporation (Andersen et al. 2008) which may result in increased ionic concentrations in some sites.

Decreased water tables in the dry season resulted in high iron (Fe-total) concentrations at sites close to the gullies relative to sites afar of (Fig. 6 & 7). Fe^{3+} is reduced to Fe^{2+} when anaerobic conditions occur as a result of permanent groundwater levels at the soil surface or due to water stagnation on the soil surface (Jansen et al. 1996; Madaras et al. 2012). In contrast to Fe^{3+} , Fe^{2+} is mobile and can be transported near the surface, leading to iron-poor shallow groundwater under reducing conditions compared to aerobic sites such as those close gullies in Motete and Matsoku peatlands (Madaras et al., 2012). Consequently, high water tables promote iron depletion, potentially increasing phosphorus concentrations in discharge and inundation zones, as phosphate binds more strongly to ferric (Fe^{3+}) than ferrous (Fe^{2+}) iron (Jansen et al. 1996). However, when reduced, phosphate-rich water is not discharged, phosphorus remains bound to Fe^{2+} , resulting in phosphorus- and nutrient-poor conditions near gullies where ferrous iron is abundant (Smolders and Roelofs 1993). This means that locations close to the gullies will be phosphorus-poor, i.e. nutrient-poor, because a large part of the phosphate will be bound to ferrous iron, which occurs there in high concentrations. This will affect the species composition of the fen system and will result in the upland plant communities encroaching into the peatland. Changes in the chemical composition of the water under the influence of drainage through the gullies has consequences for the availability of nutrients to the vegetation. Schot & Wassen (1993) concluded that high calcium concentrations can limit the availability of phosphorus for vegetation in peat areas. During field visits, spatial patterns in species composition was observed: at locations far from the channels, the vegetation consisted of herbs and sedges, while the vegetation near the channels was dominated by dwarf shrubs. Drainage through the gullies leads to lower average groundwater levels, which favours conditions for woody plants (Howson et al. 2023), which are naturally scarce in these very wet peatlands (Du Preez & Brown 2011), at the expense of sedges and herbs that are dependent on permanently wet conditions. This puts pressure on the use of the peatlands as grazing land by the local livestock headers.

Groundwater and surface water flows in the Motete and Matsoku peatlands have been conceptualised in a three-dimensional model (Fig. 8). According to this model, more groundwater emerges at ground level in the higher locations further away from the gullies than in the locations near the gullies, where the groundwater emerges in the gully soils and walls.

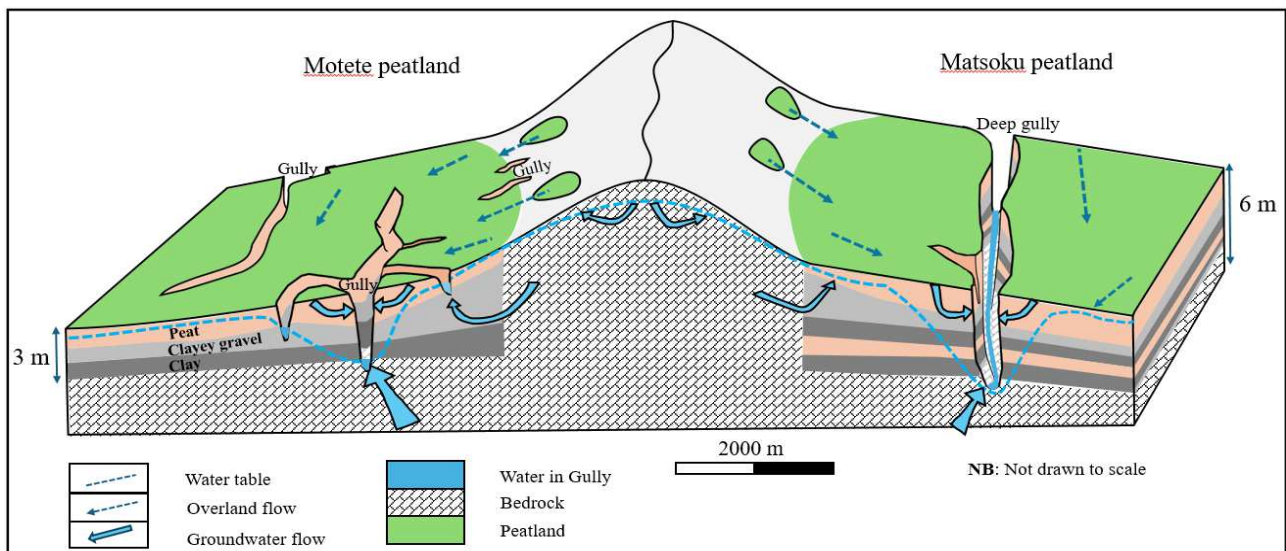


Fig. 8: Conceptual model indicating gully effect on ground- and surface water flow in Motete and Matsoku peatlands.

Locations close to the gully in the Matsoku peatland area have a weaker upward groundwater flow than those in Motete peatland. The gully in Matsoku peatland is deeper than that in Motete peatland and therefore drains the groundwater more strongly. The pronounced sensitivity to gully drainage is a consequence of the strong gradients caused by steep slopes within the watershed. Consequently, despite high groundwater fluxes, water tables adjacent to the gullies remain lowered. Groundwater in these systems is likely generated locally, from the adjacent upland bedrock, therefore, susceptible to drainage (Jansen et al. 2001; De Vries & Simmers 2002).

It can be said that the peat areas were originally fed by mineral-rich, relatively iron-poor and sulphate-poor groundwater that had infiltrated the adjacent mountain slopes as rainwater and meltwater. The groundwater then flowed through the subsoil and seeped away at low-lying locations such as M0 and MD0. Due to the local drainage caused by the gullies, larger parts of the former outflow areas near the gullies have been transformed into infiltration areas, where the infiltration of rainwater and meltwater predominates during the rainy season, resulting in base-poor shallow groundwater. If such base-poor groundwater were present throughout the year, acidification of the topsoil would be inevitable, as the soil's cation adsorption complex would eventually be depleted (Jansen et al. 1996, 2001). Until now, the soil's adsorption complex buffers this acidification during dry periods, which is reflected in the infiltration of mineral-rich shallow groundwater, which is also rich in iron and sulphate because of the oxidation of pyrite that occurs at low groundwater levels. Once the soil adsorption complex is depleted, the shallow groundwater will inevitably become acidic, eventually creating a layer of shallow acidic groundwater on top of the mineral-rich groundwater (Van Diggelen et al. 1996). This layer of base-poor shallow groundwater water on top of mineral-rich groundwater is also known as a "rainwater lens" (Stuyfzand 1993). Ultimately, the development of such a rainwater lens leads to vegetation changes, regardless of the occurrence of high groundwater levels during the wet season (Bakker et al. 1987, Jansen et al. 1996, 2001, Van Diggelen et al. 1996). The very deep channels in the Matsoku peatland area cause a greater decline in groundwater tables than in Motete peatland, as a result of which most of Matsoku peatland area will likely change from a groundwater discharge area to a groundwater recharge area (Grootjans et al. 2006).

As shown in Fig. 8, several sites of groundwater exfiltration have been observed along the mountain slopes during the wet season, providing the peatlands with mineral-rich groundwater, benefiting the characteristic peatland vegetation of grasses, forbs, sedges and mosses. In the dry season, many sites, especially those close to gullies, become infiltration zones. This, coupled with evaporation, reduces soil moisture below the level at which peat will, at a slower rate, conduct groundwater upwards through capillary forces to keep the soil surface moist (Waddington et al. 2015). This drying effect subsequently promotes further erosion in a positive feedback loop, deepening and widening gullies over time.

Gullies in the Motete and Matsoku peatlands have affected their hydrological functioning. If left unchanged, mineral-poor conditions which affect the healthy functioning of a fen system will continue. Lesotho generates revenue by transferring water to South Africa, so measures must be implemented to rehabilitate these peatlands and halt the draining effect of gullies. The cause(s) of erosion, which is responsible for the formation of gullies, must be identified and addressed before any rehabilitation efforts can be implemented. Nonetheless, Howson et al. (2023) found that gully blocking with small dams constructed from materials such as stone and timber effectively restores hydrological conditions in the peatland, enhances vegetation cover and abundance, and promotes sediment accumulation within gullies. This approach could be applied to peatlands in the Maloti Mountains.

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Data Availability

The dataset generated during this study are available from the corresponding author on reasonable request.

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose

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