Anthropogenic disturbances of natural ecohydrological processes in the Matlabas mountain mire, South Africa

Matlabas is a mountain mire in Marakele National Park, located within the headwaters of the Limpopo River in South Africa. This mire consists of a complex of valley-bottom and seepage wetlands with small elevated peat domes. The occurrence of one decaying peat dome, which has burnt, and desiccated wetland areas with terrestrial vegetation has raised concerns. The aim of this study was to understand the mire features and water flows in order to identify the potential drivers causing wetland degradation. Wells and piezometers were installed to monitor the hydraulic head and collect water samples for analysis of ion composition, δ¹⁸O and δ²H stable isotope content, and δ¹³C and δ¹⁴C isotope content for radiocarbon dating. Moreover, peat temperature profiles were measured and peat deposits were also dated using radiocarbon. Results indicate that the Matlabas mire developed in the lowest central-east side of the valley by paludification at the onset of the Holocene. During the Mid-Holocene, peat development was extended laterally by autogenic and allogenic processes. Three types of water flows driving peat development were identified – sheet flow, phreatic groundwater flow and deep groundwater flow – two of which are surface or near surface flows. The recent occurrence of decaying peat domes and desiccated wetland areas is possibly related to loss of exfiltrating deep groundwater flows that have resulted from drainage by the head-cut channels in the mire and interception of near surface water flow by an access road, respectively. Interventions should be undertaken to prevent further degradation of the mire.

Significance:
- This study is the first, as far as we are aware, on the ecohydrology of an inland mountainous mire in southern Africa.
- The results highlight the importance of the current wetland management (including rehabilitation) initiatives in South Africa.
- The integrative ecohydrological methods can be applied in other headwater wetlands in southern Africa.

Introduction

Peatlands play a crucial role as carbon sinks in the regulation of atmospheric CO₂ concentrations, which in turn influence climate. Peatlands also provide ecosystem services like carbon sequestration, water storage and nutrient cycling. Over the past two centuries, the health of peatlands and their ecosystem functions have been affected by direct and indirect use of these systems, e.g. use of peat for fuel, agriculture and groundwater extraction for drinking water. Hence, there is growing attention on the assessment, conservation and restoration of peatlands on a global scale. Mires are peatlands that are still actively accumulating peat, and this process is controlled by climate, hydrology and vegetation. While near-natural mires are still widespread in the northern hemisphere – such as in Canada, Russia, Siberia and Finland – they are relatively scarce in the southern hemisphere. Nevertheless, the southern hemisphere’s peatlands play an important role in the global carbon cycle.

Pristine peatlands are rare in South Africa. The best examples of pristine peatlands here are found along the eastern coast and in the central mountain areas. Two-thirds of South African peatlands occur along the northeastern seaboard of the Indian Ocean, known as Maputaland, in KwaZulu-Natal Province. Maputaland contains both the largest peatland, the Mkuzo peatland complex at 8800 ha, and the oldest mire, Mtamvuna at 48 000 years. The Matlabas mire, however, is situated in Marakele National Park in Limpopo Province, and is part of the Central Highlands Peatland Eco-Region. Matlabas is one of the largest and least impacted spring mires known to exist in South Africa. The mire falls within the reaches of the Limpopo River, which suffers events of severe drought. While the mire is largely in a good state, some signs of erosion were observed during a wetland inventory project undertaken in the park in 2008. These signs included head cuts and gully erosion. Previous land-use practices (cattle farming) and road construction (see results), which took place in the 1960s up to the early 1980s, may have affected the mire’s natural processes. However, it is not known whether this erosion is increasing or what has caused it. These head cuts and gully erosion are expected to further increase peat drainage in the future, which could result in the loss of large sections of the mire. In the present study, we aimed to determine how the Matlabas peatland developed over time in relation to the principal water flows and recent changes in land use, as this knowledge will serve as a strong basis for effective conservation and rehabilitation planning.

Study area

Figure 1 shows the location of the Matlabas mire in the Waterberg Mountains, within Marakele National Park (an area of approximately 290.5 km²). The altitude of the Matlabas mire is around 1200 m above sea level (a.m.s.l.), and it has a total surface area of 64 ha, only 14 ha of which have peat accumulation. It has been managed as a national park since 1988 but was only officially proclaimed a national park on 11 February 1994. Before 1988, the area was used for agriculture, with both farming of crops and cattle grazing.
The mire can be divided into two sides: a western side (6 ha) and an eastern side (8 ha). The western side of the mire drains from west (from 1621 m a.m.s.l.) to east along a slope of 4%, while the eastern side of the mire drains primarily to the north (from 1614 m a.m.s.l.) along a slope of 5%.16 Two seepage wetlands upslope of the mire were intersected in the late 1960s by a road that runs along the southern edge of the mire. The mire is located close to a watershed within a major east to west stretching valley.

Matlabas is underlain by sandstone bedrock of the Aasvoëlkop Formation, part of the Matlabas Subgroup in the Waterberg Supergroup (with shale and mudstone), and the Sandriviersberg Formation, part of the Kransberg Subgroup also in the Waterberg Supergroup.17 The formations developed on the parent materials range from shallow to deep sandy soils on sandstone and clayey soils on diabase dykes and mudstone.15 Wetlands in the Waterberg Mountains mainly occur in the valleys, and are arranged in a prominent kite-like pattern as a result of the diabase dykes intruding along faults striking west-northwest to east-southeast and northeast to southwest into the Waterberg Supergroup sandstones.16

Average daily ambient temperatures range between a high of 19.5 °C and a low of 5.1 °C, with the maximum daily temperature reaching 22.8 °C and minimum night temperature reaching -1.7 °C. The average annual ambient temperature was 17.6 °C during the period 2011–2013.16 Average rainfall during the same period was around 1000–1200 mm/year, with an average daily rainfall of about 5.5 mm/day during the hot and wet season, which takes place from October to April.16

Methods

Surface elevation and channel tracing

Elevations were determined with a differential GPS method, using a network of fixed, ground-based reference stations to broadcast the difference between the positions as indicated by the GPS and a known fixed position to obtain accurate contour lines at 50-cm intervals. Data for 290 points were obtained in February 2012 by F.J. Loock Surveyors Inc. from South Africa. The data were calibrated to height above sea level (a.m.s.l). Channelled surface water flows in the mire were recorded in the field by a hand-held GPS, visually plotted using aerial imagery and classified as either permanent or intermittent. Moreover, historical aerial images of the mire surface taken in 1956 and 1972, i.e. before and after road construction, were visually analysed.

Vegetation description

The different plant communities present in the area were mapped to determine their spatial spread as an indication of the inundation patterns. The Braun-Blanquet approach was followed to describe the vegetation.18 Using aerial images, the area was divided into homogeneous units, in which a total of 54 sample plots (4x4 m) were placed in a randomly stratified manner per unit.19 Plant species within the sample plots were identified and cover abundance values were assigned using the modified Braun-Blanquet scale.20 Thereafter, a modified TWINSPAN was performed to classify the different plant communities present.21 These vegetation patterns were used as environmental indicators to locate the zones of hydrological changes, and, therefore, to identify the most prominent sampling targets.

Peat thickness and dating

The thickness of the peat in the mire was recorded along four south-to-north running transects (A, B, C and D) covering the eastern side and at five points (W1 to W5) covering the western side (Figure 2). A Russian peat auger was used to sample peat cores, at 50-cm increments at a time, down to the top of the mineral soil.

A total of 14 peat samples (at a thickness of 1 cm) were collected for radiocarbon (14C) dating to estimate the age at the bottom of the peat (at five locations) and to determine accumulation rates along two vertical profiles at points B3 (3 samples, a to c), B4 (6 samples, a to f) and C (2 samples, a and b). Samples from the vertical profiles were taken at the observed boundaries of facies change, e.g. degree of peat decomposition. Also, δ13C content in the peat was measured to estimate the type of plant remnants forming the peat, i.e. C3, C4 or CAM (crassulacean acid metabolism) plants.22 Each plant type has a different photosynthesis process, which leads to different δ13C
values as a result of the isotope fractionation.21 C3 plants indicate wetter conditions with δ13C values ranging from -22 to -25‰, and C4 plants indicate dry conditions with δ13C values ranging from -11 to -14‰.22,23 The colour and texture of each peat sample were described according to the Von Post Humification Scale,24 and then the sample was sealed in a plastic bag. The samples were sent to the Centre for Isotope Research at the University of Groningen in the Netherlands for analysis.

Peat temperatures

Peat temperatures were measured to identify the direction of the groundwater flows in the peat layer.26 They were measured using a 2-m-long steel probe along the four transects on the eastern side (A, B, C and D) at 20-cm depth intervals. The measurements were carried out at each transect during a cold and dry period in June 2011, with ambient air temperatures around 12 °C.

Ions

Water samples were collected from piezometers during a wet summer season in October 2011 and a dry winter season in June 2012, with 54 samples taken for each season. Another sampling round was added in October 2017, but there were only 29 samples because many piezometer tubes had been burnt by a natural fire. All piezometers were emptied with a hand pump one day before sampling to replenish the water before sampling. The sampled water was then stored in PVC bottles in volumes of 100 mL and 50 mL for cation and anion analyses, respectively, and kept in the dark at a temperature of 4 °C.

These water samples were analysed at the Agricultural Research Council laboratory in Pretoria, South Africa. The samples were passed over a 0.45-µm membrane vacuum filter to remove sediments and impurities. Water pH was measured by titration, and ion concentration of Ca, Cl, NO3, SO4, PO4, HCO3, Mg, Na and K were measured by inductively coupled plasma mass spectrometry. In the third round of sampling, Fe and SiO2 ions were also measured. The results were checked for deviations in ionic balance, and samples with deviations higher than 20–30% were disregarded in further analyses.

18O/2H stable isotopes

In March 2014, 22 water samples were collected to measure the stable isotopes of oxygen and deuterium (δ18O and δ2H) in the water (Figure 2, Supplementary table 2). These water samples were collected in dark glass bottles of 50 mL and 30 mL and stored in the dark at a temperature of 4 °C. Later, they were analysed at the Centre for Isotope Research laboratory by dual inlet isotope ratio mass spectrometry (DI-IRMS). The sampling was repeated in October 2017 (29 samples), and these samples were analysed at the Environmental Isotope Laboratory of iThemba LABS at the University of the Witwatersrand, South Africa. The stable isotope ratios in the samples (δ18O and δ2H) were reported in ‰ w.r.t. VSMOW, i.e. the reference used was the Vienna convention material.21

Carbon isotopes

The radiocarbon content of water samples is an indication of the residence time of groundwater in the soil.26 Six water samples were taken, using 500-mL dark glass bottles, from the piezometers in the sand layer at the end of the dry season in October 2017 to measure the radiocarbon content. Five points were selected on the eastern side at transects A, B and D (A2, B4, B6, D4 and D5) and one point on the western side of the mire at W5 (Figure 2). These samples were analysed for their carbon isotope content (δ13C and δ14C) at the Centre for Isotope Research laboratory. δ13C values of the samples were analysed using DI-IRMS and reported in ‰ w.r.t. VSMOW, similarly to the stable isotopes. The ratios were then used to infer whether there had been dilution of the δ13C values as a consequence of infiltration through the peat layer, which is indicated by δ13C values lower than -16‰.32

Results

Elevation and peat thickness

The peat soils in Matlabas cover a total of 14 ha, which is only 22% of the larger wetland area of 64 ha. Peat depth varied from 30 cm at the steep slopes to almost 5 m in the central parts of the eastern side of the mire, while average peat thickness was 1.5 m. Hence, the estimated volume of the peat layer was around 150 000 m³. Most of the peat layers were fibrous, and they were interrupted by clay and sand layers at the bottom, where some layers of gravel occurred, e.g. at B4.

Six channels with concentrated surface water flow were identified (Figure 3). Two of these are permanent water flow channels on the eastern side. A third channel starting from the western side also has a permanent flow. The permanent channels are incised about 40–50 cm into the peat. Surface water drains the mire in a northerly direction.
Aerial images taken in 1956 and 1972 show the mire before and after the road was built. These images show that some channel formation was already apparent in 1956 (Figure 4a). Since the construction of the road in the late 1960s, however, channel formation in the eastern section of the mire had increased in number and volume by 1972 (Figure 4b). Furthermore, the extent of two seepage wetlands visible on the 1956 images south of the later constructed road are largely reduced in the 1972 images.

Moreover, the mire has developed a series of elevated peat domes, with heights of approximately 1 m above the surrounding landscape and widths between 3 m and 9 m (Figure 5a). Most domes are situated along a fault line in a northwest-southeast direction, shown in a geological map of the area, but some are also aligned in an east-west direction (Figure 5b).
Vegetation description

From the TWINSPLAN analysis, three major plant communities were identified (Figure 6). The three major communities are briefly described below:

1. *Andropogon eucnemicus–Aristida canescens* community. Most of the elevated peat domes were covered with this vegetation community. This vegetation community contained the largest number of species, with common wetland species as well as species generally associated with drier conditions.

2. *Kyllinga melanopserma–Miscanthus junceus* community. This community occurred in the wettest part of the mire and was closely associated with peat deposits. A stand of *Phragmites australis* reeds on transect B at B3–B4 was found in this vegetation community.

3. *Pteridium aquilinum* community. This community occurred along the edges of the mire and is characterised by species-poor patches dominated by the fern *Pteridium aquilinum*.

Figure 6: Vegetation map of the mire showing the three dominant vegetation types.

\[ \text{\textsuperscript{14}C} \text{ dating} \]

Table 1 lists the results of the radiocarbon dating of the 14 peat samples, their \( \delta^{13} \text{C} \) content and descriptions of the depth intervals; the ages are given as median calibrated age. The mire’s oldest basal peat sample, with a radiocarbon age of 11\,160 \text{CalBP}, was taken from point B4f, which is the second lowest point in altitude. The valley flank basal peats all had younger ages, ranging between 5120 \text{CalBP} on the southeastern side (AB), 3860 \text{CalBP} on the western side (W1) and 690 \text{CalBP} on the northeastern side (C3b). Modern dates with bomb values were observed at point B4a (-55 \text{CalBP}) and point C3a (-6.5 \text{CalBP}), while point B3a dated to 130 \text{CalBP}. The \( \delta^{13} \text{C} \) values show that C3 plants were limited to the top layer in core B4 (point B4a), whereas the rest of the samples had values indicating C3 plants.

\[ \text{Groundwater flow} \]

The groundwater phreatic head in the peat layer showed a decrease from east to west along transect B (Figure 7a). At transect C, however, there was a downward direction of the phreatic head isohypse with most of the flow being directed to point C5, which is at the head of a permanent channel. The channel at C5 was shown to be draining from points C4 and C6, which had higher phreatic heads (Figure 7b).

Differences between the piezometric head and the phreatic head were + 0.01 to 0.04 m at B2 and B3, respectively. Such differences indicate potential seepage of groundwater, in line with the depressions visible on the ground surface. The head differences were largest at B4, where differences in the sand piezometric head and peat phreatic head equalled 0.14 m. Similar differences in head were observed along transect C, with the highest piezometric head found under one of the peat domes at point C4. In contrast, the piezometric heads in the sand were lower (c. 0.03 m) than those in the peat further west from B4 and C4 at both transects. At C5, the head difference was also significantly lower at 0.4 m.

Lastly, the water levels in the peat domes were found 30–50 cm below the surface. This depth is different from that of other parts with no dome structures, where the water levels were close to the surface. In the south to north direction, the phreatic head decreased northwards following the height gradient of the mire surface and the drainage direction of the surface water channels.

\[ \text{Peat temperature} \]

Peat temperature showed an increase with depth, with the temperature gradients generally following the gradient of the peat surface slope. However, the discharging groundwater at B4 showed input of warmer water about 1.5 m from the surface: >14 °C when the ambient temperature was 10 °C (Figure 8). These measurements were taken at night during the dry and cold season in August 2013. Such patterns were also found along transects A and C, where warmer temperatures appear to be associated with discharging groundwater flows.

Table 1: Results of \( \text{\textsuperscript{14}C} \) dating of the peat samples taken from transects A, B, C on the eastern side and point W1 on the western side

<table>
<thead>
<tr>
<th>Code</th>
<th>Sample depth (cm)</th>
<th>Altitude (m a.m.s.l)</th>
<th>Sample description and Von Post scale (H1–H10)</th>
<th>( \delta^{13} \text{C} ) (‰)</th>
<th>Median age (CalBP)</th>
<th>Thickness (m)</th>
<th>Accumulation rate (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>200</td>
<td>1590.4</td>
<td>Peat with gradual increase of clay content with increasing depth in the 50-cm core, low water content</td>
<td>-12.22</td>
<td>3860</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>AB1</td>
<td>250</td>
<td>1564.65</td>
<td>Decomposed peat (H6)</td>
<td>-13.26</td>
<td>5120</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>B3a</td>
<td>37</td>
<td>1579.7</td>
<td>Decomposed peat (H6)</td>
<td>-11.62</td>
<td>130</td>
<td>1.00</td>
<td>1.56</td>
</tr>
<tr>
<td>B3b</td>
<td>136</td>
<td>1578.03</td>
<td>Peat with high clay content (&gt;H6)</td>
<td>-10.33</td>
<td>590</td>
<td>0.72</td>
<td>0.61</td>
</tr>
<tr>
<td>B3c</td>
<td>208</td>
<td>1577.31</td>
<td>–</td>
<td>-11.43</td>
<td>1780</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>B4a</td>
<td>35</td>
<td>1577.63</td>
<td>Red amorphous peat (H1–H3)</td>
<td>-25.88</td>
<td>-55</td>
<td>0.46</td>
<td>1.31</td>
</tr>
<tr>
<td>B4b</td>
<td>79</td>
<td>1577.17</td>
<td>Recomposed peat (H6)</td>
<td>-12.29</td>
<td>295</td>
<td>1.42</td>
<td>1.76</td>
</tr>
<tr>
<td>B4c</td>
<td>227</td>
<td>1575.75</td>
<td>Radicel peat (H1–H3)</td>
<td>-13.31</td>
<td>1100</td>
<td>0.62</td>
<td>0.66</td>
</tr>
<tr>
<td>B4d</td>
<td>282</td>
<td>1575.13</td>
<td>Radicel peat (H1–H3)</td>
<td>-14.46</td>
<td>2040</td>
<td>1.18</td>
<td>1.37</td>
</tr>
<tr>
<td>B4e</td>
<td>399</td>
<td>1573.95</td>
<td>Peat with clay and sand interval at 415–425 (&gt;H6)</td>
<td>-15.92</td>
<td>2900</td>
<td>1.00</td>
<td>0.12</td>
</tr>
<tr>
<td>B4f</td>
<td>499</td>
<td>1574.95</td>
<td>–</td>
<td>-13.97</td>
<td>11160</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>B5</td>
<td>155</td>
<td>1575.31</td>
<td>Peat with high clay content (&gt;H6)</td>
<td>-11.53</td>
<td>1225</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>C3a</td>
<td>80</td>
<td>1575.52</td>
<td>Decomposed peat (H6)</td>
<td>-10.07</td>
<td>-6.5</td>
<td>1.15</td>
<td>1.65</td>
</tr>
<tr>
<td>C3b</td>
<td>195</td>
<td>1574.37</td>
<td>Peat with high clay content (&lt;H6)</td>
<td>-12.96</td>
<td>690</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Ion composition

Chloride ion concentrations changed by three- to fourfold with season in the top 1–2 m of the peat layer. In deeper layers, the changes in concentration were smaller and less than onefold, e.g. at the sand piezometer at B4 (Figure 9a to c). Calcium ion concentrations also increased in the dry seasons, with magnitudes of change similar to patterns in the chloride ion. Calcium values increased by more than threefold within the top 2 m, while it remained one- to twofold higher in the deeper parts, except for B6 which showed higher calcium values in the deeper layers (Figure 9d to f).

In transect C, the calcium-rich and chloride-poor groundwater remained in the deeper soil layers. In the central peat dome, relatively large changes in ion composition occurred. During the wet season the calcium values were low under the peat dome (point C4), while in the dry season the calcium values were higher. There was also an increase in nitrate concentrations (0.73 mg/L relative to the average of 0.16 mg/L) in the...
groundwater below the peat domes at points C2 and C4 during the wet season (Supplementary table 1).

Stable isotopes

The stable isotope content in the water sampled in March 2015, which was at the end of the hot summer season, was significantly enriched compared with that of the water sampled in October 2017, which was at the end of the cold winter season (Figure 10). The samples from March 2015 had δ18O values ranging from -4 to -6‰ and δD values ranging from -20 to -30‰, while the samples from October 2017 had δ18O values ranging from -4 to -3‰ and δD ranging from -10 to -20‰. Samples from the western side of the mire appear to be mostly below the global meteoric water line, with more indications of enrichment.

Carbon isotopes

Table 2 shows that four water samples (A2b, B6b, D4b and W5b) had uncorrected 14C values above 100%, indicating infiltration after 1950. By the Mid-Holocene, lateral expansion of peat formation had occurred in the higher parts of the valley bottom in the south and west, possibly as a result of a mixture of both autogenic and allogenic factors. These samples include the clogging effects of peat accumulation on the slope of transect B, with a low hydraulic conductivity leading to a higher water table upslope at transect A in the south and point W1 in the west. With respect to allogenic factors, expansion to the north occurred because of the shift to a wetter climate during the Late Holocene.34

In the current vegetation, the wettest vegetation type, which possibly contributes to peat formation, is dominated by the large tussock species Miscanthus junceus and also includes stands of Phragmites australis at B3 to B4, although Kyllinga melanosperma and Thelypteris confluenta are also abundant. However, the plant remnants in the peat cores were dominated by δ13C values of C4 plants, which indicates lower water availability.33,35 However, the recent vegetation shows shifts to C3 plants in the best developed and wettest parts of the mire (B4). This modern shift in δ13C values highlights the role that stable isotope content in groundwater flow coupled with the maturity of the peat development plays in sustaining wetter conditions in the mature parts of the mire.

Natural dynamics: water origin and flow

Piezometric head data indicate that groundwater discharge is limited to the central eastern parts of the mire, e.g. at B2 to B4 and C2 to C4. Three major water flows were shown to control mire development (Figure 11). The first water flow is sheet flow over the peat surface that occurs in the wet season when precipitation exceeds peat infiltration capacity and the peat is often already saturated. The second is the phreatic groundwater flow in the peat layer, which is often also supplied by the intermittent channel in the south that flows in the mire during the wet season with relatively high energy flows, i.e. sand deposits in the soil profiles at transects A and B. The third is the seepage discharge of deeper groundwater at certain points in the mire, e.g. B4 and C4, which is stable and shows little change over the seasons.

The ion composition indicates that the groundwater in Matlabas is stable and shows little change over the seasons.

<table>
<thead>
<tr>
<th>No.</th>
<th>Code</th>
<th>Lab no. (GrM)</th>
<th>14C uncorrected (%)</th>
<th>Error ±</th>
<th>δ13C (‰; IRMS)</th>
<th>Error ±</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A2b</td>
<td>11547</td>
<td>104.26</td>
<td>0.19</td>
<td>-14.27</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>B4b</td>
<td>11548</td>
<td>95.42</td>
<td>0.18</td>
<td>-13.38</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>B6b</td>
<td>11549</td>
<td>104.91</td>
<td>0.19</td>
<td>-10.10</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td>D4b</td>
<td>11550</td>
<td>106.3</td>
<td>0.19</td>
<td>0.43</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>D5b</td>
<td>11552</td>
<td>95.31</td>
<td>0.18</td>
<td>-13.06</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>W5b</td>
<td>11554</td>
<td>105.25</td>
<td>0.18</td>
<td>-6.31</td>
<td>0.15</td>
</tr>
</tbody>
</table>

IRMS, isotope ratio mass spectrometry
isotopes, especially during the wet season when the occurrence of rainwater lenses in the top peat layers increases. After a dry period, higher mineral concentrations are evident as a result of concentration by evapotranspiration, particularly in the top layers.

The effects of evaporation could also be observed in the stable isotope values. The variations at the end of the wet period were minor, indicating the stable upward flow of groundwater that is not affected by evaporation. This was, however, not the case for the water flows in the western side of the mire, which has lower hydraulic conductivity in its peat layer. Hence, signs of evaporation were observed in the samples taken from its middle parts during both the hot-wet periods and the cold-dry periods, where the hillslope water enters from the sides, showing a slower flow subject to evaporation processes, and follows the relief to the east side of the mire.

The observed discharges of deep groundwater flow generally had short residence times; however, they had longer flow lines and deeper origins than the phreatic ones. This deeper flow origin is indicated by the radiocarbon values of the water samples. Hence, the sources of these deep discharging groundwater flows are most likely the adjacent hillslopes, which consist of unsorted rock boulders and coarse fragments that form highly permeable layers acting as recharge areas for subsurface water flow to the mire. The groundwater discharges are diluted in the wet period by input from the phreatic and sheet flows, resulting in low calcium and chloride concentrations. However, their chemical characteristics are more nuanced in the dry period with their resulting in low calcium and chloride concentrations. Hence, the sources of these deep discharge groundwater flows are most likely the adjacent hillslopes, which consist of unsorted rock boulders and coarse fragments that form highly permeable layers acting as recharge areas for subsurface water flow to the mire. The groundwater discharges are diluted in the wet period by input from the phreatic and sheet flows, resulting in low calcium and chloride concentrations. However, their chemical characteristics are more nuanced in the dry period with their resulting in low calcium and chloride concentrations. Hence, the sources of these deep discharge groundwater flows are most likely the adjacent hillslopes, which consist of unsorted rock boulders and coarse fragments that form highly permeable layers acting as recharge areas for subsurface water flow to the mire. The groundwater discharges are diluted in the wet period by input from the phreatic and sheet flows, resulting in low calcium and chloride concentrations. However, their chemical characteristics are more nuanced in the dry period with their resulting in low calcium and chloride concentrations. Hence, the sources of these deep discharge groundwater flows are most likely the adjacent hillslopes, which consist of unsorted rock boulders and coarse fragments that form highly permeable layers acting as recharge areas for subsurface water flow to the mire. The groundwater discharges are diluted in the wet period by input from the phreatic and sheet flows, resulting in low calcium and chloride concentrations. However, their chemical characteristics are more nuanced in the dry period with their resulting in low calcium and chloride concentrations. Hence, the sources of these deep discharge groundwater flows are most likely the adjacent hillslopes, which consist of unsorted rock boulders and coarse fragments that form highly permeable layers acting as recharge areas for subsurface water flow to the mire. The groundwater discharges are diluted in the wet period by input from the phreatic and sheet flows, resulting in low calcium and chloride concentrations. However, their chemical characteristics are more nuanced in the dry period with their resulting in low calcium and chloride concentrations. Hence, the sources of these deep discharge groundwater flows are most likely the adjacent hillslopes, which consist of unsorted rock boulders and coarse fragments that form highly permeable layers acting as recharge areas for subsurface water flow to the mire. The groundwater discharges are diluted in the wet period by input from the phreatic and sheet flows, resulting in low calcium and chloride concentrations. However, their chemical characteristics are more nuanced in the dry period with their resulting in low calcium and chloride concentrations.