Review comments on EGUSPHERE-2025-4567 (for Hydrology and Earth System Sciences)

Reviewer Comment 2: Anonymous Referee, 19 Jan 2026

Comment: This manuscript, titled "Proposing Sources for Discrete Groundwater Discharges to Patterned Pools in Three Regional Raised Northern Peat Bogs" addresses an important and timely topic by exploring the sources of discrete groundwater discharges to patterned pools in raised northern peat bogs using a combination of geophysical surveys (GPR and TEM), in-situ measurements (temperature and specific conductance), and geochemistry. The integration of geophysics with hydrochemical indicators is a promising approach, and the regional perspective across multiple bogs adds value to the study. The findings on discrete minerogenous groundwater upwelling linked to sub-peat glacial eskers are significant and contribute novel insights to peatland hydrology and carbon cycle science. However, the current version of the manuscript raises several methodological and interpretational concerns, particularly regarding temporal consistency, justification of measurement choices, and the strength of the linkage between geophysical responses and groundwater upwelling processes. While the results suggest differences between upgradient and downgradient zones, additional analysis and clarification are needed to strengthen the conclusions and improve the scientific rigor of the study.

I have highlighted some comments below that I think would strengthen the paper.

- Thank you for your recognition of the value of this study, below you will find your comments addressed accordingly.

Major Comment 1: Justification for Multiple Conductivity Meters

The study uses three different conductivity meters [Hach sensION 5 Conductivity Meter (+/- 0.86 µS/cm), YSI Pro30 Conductivity Meter (+/- 1.0 µS/cm), and EcoSense EC300A Conductivity Meter (+/- 2.0 µS/cm)] to measure specific conductance (SpC). The rationale for using multiple instruments instead of a single, standardized meter is not adequately explained. This raises concerns regarding data consistency, calibration differences, and potential measurement bias. The authors should clearly justify this choice and describe any intercalibration procedures used to ensure comparability across instruments.

- Use of multiple conductivity meters was warranted based on available resources for the fieldwork conducted. All three specific conductivity meters were calibrated across the same range of calibration conductivities at 25 ºC. This information is now available on Line 227 to Line 229 of the manuscript.
- Line 227 to Line 229: "All specific conductivity meters used for measurements were calibrated according to corresponding manufacturer instructions using standards of 84 µS/cm, 1413 µS/cm, and 12.88 mS/cm KCl solution standards at 25 ºC."

Major Comment 2: Temporal Mismatch Between Datasets

A major limitation of the study is the lack of temporal alignment between datasets. The GPR surveys were conducted in August and November 2023 and June 2024, the TEM survey in May 2025, while the in-situ temperature and SpC data were collected only in August 2023. Given the strong seasonal and yearly variability in peatland hydrology, this temporal mismatch could introduce significant uncertainty into the interpretation of groundwater discharge processes. The authors should more explicitly discuss how seasonal dynamics and year-to-year variability may affect the geophysical and in-situ signals. Ideally, the study would benefit from co-located, same-day measurements of TEM, temperature, and SpC to better constrain interpretations. At minimum, this limitation should be clearly acknowledged and its implications for the conclusions carefully addressed.

- Please find the reasoning for the geophysical interpretation addressed in the response to Major Comment 6. Temporal inconsistencies in the data are further addressed in the response to the comment on Line 215 to Line 225. While concurrent measurements would be ideal, the remote setting of these three peat bogs make this significantly difficult. The sensitivity of the geophysical methods to the subsurface structure rather than the electrical conductivity of water means that there is no issue with collecting these surveys during different time periods.

Major Comment 3: Quantification of Upgradient vs. Downgradient Differences

The manuscript demonstrates that upgradient and downgradient populations differ based on values; however, the magnitude of this difference is not quantified. Reporting effect sizes or percentage differences would strengthen the argument and allow readers to better assess the hydrological significance of the findings, beyond statistical separation alone.

- Thank you for this suggestion, this has been addressed below in the specific comment on Line 390 to Line 392 to update these magnitudes and clarify the statistical approach used.
- Line 373 to Line 392: " The magnitude of difference between the upgradient and downgradient populations was described by a rank-biserial correlation coefficient of 0.295, representing a modest but consistent tendency towards higher Gi values in the upgradient population."

Major Comment 4: Strength of Evidence for Minerogenous versus Ombrogenous Sources

L510-515: The discussion effectively presents evidence for upwelling but is cautious in attributing it solely to minerogenous groundwater, rightly noting the potential for peat pore water flow cells. This ambiguity is a strength scientifically, but could be sharpened. The aqueous geochemistry results (Fe, Mn) are particularly ambiguous in this regard. Strengthen this section by weighing the evidence for each source more directly. For example, the spatial correlation with eskers (GPR/TEM) strongly suggests a geological control. The T/SpC/TIR signals confirm vertical fluid movement. Do the Fe/Mn levels uniquely indicate a glacial aquifer, or could they be mobilized from peat? A paragraph explicitly comparing the likelihood of each source model, perhaps using the conceptual model (Fig. 10) as a framework, would be very helpful.

- These potential limitations are now addressed at the end of the Discussion section as avenues for future research. Line 705 to Line 710 particularly address the potential limitations of the Fe/Mn trace elements for tracking minerogenous groundwater. The ambiguity is retained to avoid overinterpretation of the data in qualitatively defining a likelihood of minerogenous vs ombrogenous sources for the upwelling signals observed. Line 638 to Line 641 further elaborate on the potential autogenic sourcing of the Fe and Mn trace elements.
- Line 638 to Line 641: "Given the complexity of the redox reactions occurring in peat bogs, the aqueous geochemistry could also indicate deeper circulation of ombrogenous peat pore water. Similar or higher concentrations of Fe and Mn have been reported in pools in bogs (Chauhan et al., 2024; Osborne et al., 2024) suggesting potential autogenic sourcing of these trace elements."
- Line 707 to Line 717: "Future research should target the origin of these TEAs from peat pipes or macropores facilitating preferential flow to the pools. We recognize the limitations of this study with the use of non-conservative trace elements of Fe and Mn to trace groundwater potentially originating from the underlying glacial aquifer. The presence of organic, acidic bog environments could alter the concentrations of these trace elements observed in the samples, potentially explaining the more variable results observed in this study. This warrants additional inquiry using other tracers, such as stable isotopes or environmental radon, in future studies to more confidently delineate groundwater sources to the pools."

Major Comment 5: Role of Geophysics: Structure vs. Process

As presented, the GPR and TEM data primarily provide a structural framework of the subsurface. While this framework is valuable, the manuscript sometimes implies a stronger process-based linkage between geophysical responses and groundwater upwelling than is currently supported by the data. The authors should clarify whether the geophysical results are intended to directly identify groundwater discharge pathways or simply constrain plausible structural controls. Future research directions should be explicitly recommended, particularly studies that quantitatively link geophysical parameters (e.g., bulk electrical conductivity) to groundwater fluxes or upwelling processes, rather than relying solely on point-scale in-situ measurements.

- Clarification has been added in Line 527 to Line 529 to highlight the geophysical sensitivity to the structure of the subsurface. A recommendation is made to implement induced polarization surveys to examine the electrolytic conductivity component and the surface conductivity components of the bulk electrical conductivity signal in Line 712 to

Line 714. Future work aims to examine the lack of relationship between the bulk electrical conductivity and the identified groundwater discharge locations.

- Line 527 to Line 529: "Corresponding electrical signals between the GPR and the TEM data are attributed to the subsurface structure based on the dominant ombrogenous hydrology of the bogs with low concentrations of dissolved ionic constituents in the saturating fluid (i.e., Theimer et al., 1994)."
- Line 712 to Line 714: "Implementing induced polarization to separate the contributions of the electrolytic conductivity component and the surface conductivity component to the bulk electrical conductivity could serve to further delineate these groundwater flowpaths from depth in future studies."

Major Comment 6: Interpretation of Equation (2) and TEM Conductivity

Equation (2) suggests a relationship involving specific conductance; however, the manuscript does not clearly demonstrate how SpC relates to the electrical conductivity derived from the TEM survey. Given that the TEM and in-situ datasets were not collected concurrently, it remains unclear which physical properties primarily control the TEM-derived conductivity (e.g., pore-water conductivity, saturation, lithology, or organic matter content). The authors should clarify the conceptual basis linking TEM conductivity to groundwater upwelling and patterned pool formation. If such a linkage cannot be robustly established with the available data, this limitation should be explicitly acknowledged.

- Structures observed in the inverse models of the TEM data correspond to the structure observed in the GPR data. GPR measures the displacement or polarization of the subsurface in low-loss media like peat, therefore typically representing the subsurface structures rather than the distribution of the saturating fluid (i.e. Theimer et al., 1994). Based on this visible correspondence between the GPR and TEM models, we infer that the bulk electrical conductivity measured in the bogs by the TEM is primarily sensitive to the subsurface structure rather than such saturating fluids. Additional clarification for this association is presented from Line 527 to Line 529.
  As you state, the TEM geophysical surveys are sensitive to the bulk electrical conductivity signal of the subsurface which for these surveys was primarily sensitive to the subsurface structure. Electrical conductivity from geo-electrical methods is typically represented by the summation of the electrolytic conductivity and the surface conductivity (i.e., Vinegar and Waxman, 1984). Given that these methods are sensitive to both components of the electrical signal, one component is typically dominant in the data collected in the field setting. The electrolytic conductivity component represents the conductivity of water (specific conductivity without the temperature correction) multiplied by one over the formation factor ($1/F$) representing the interconnected pore space of the media (Archie, 1942). There is no guarantee that the TEM would be primarily sensitive to the electrolytic conductivity component (and thus the specific conductivity), especially considering the dominantly ombrogenous hydrology of the peat

bogs. This is further amplified by the measurement footprint of the TEM system, which is on the order of meters compared to the highly localized upwelling (tens of centimeters) observed in the other datasets presented. By measuring *SpC* at a point scale, localized zones with contrasting water conductivity could be identified despite the larger influence of the ombrogenous hydrology.

Archie, G. E., (1942). The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. Trans. AIME 146, 54-67
Theimer, B. D., Nobes, D. C., & Warner, B. G. (1994). A study of the geoelectrical properties of peatlands and their influence on ground-penetrating radar surveying1. Geophysical prospecting, 42(3), 179-209.
Vinegar, H. J., and M. H. Waxman, 1984, Induced polarization of shaly sands: Geophysics, 49, 1267–1287, doi: 10.1190/1.1441755.

- Line 527 to Line 529: "Corresponding electrical signals between the GPR and the TEM data are attributed to the subsurface structure based on the dominant ombrogenous hydrology of the bogs with low concentrations of dissolved ionic constituents in the saturating fluid (i.e., Theimer et al., 1994)."

Comment: Line 215-Line 225: Why were three different conductivity meters used for the SpC measurements instead of relying on a single instrument? This choice requires justification in the study. Additionally, why were the geophysical surveys and the in-situ measurements (temperature and SpC) conducted in different years? If I understand correctly, the TEM survey was conducted on May 2 and 5, 2025; the GPR surveys were conducted in August and November 2023 and June 2024; while the in-situ dataset was collected only in August 2023. How would the results differ if temperature and SpC measurements were collected on the same day as the TEM survey? Substantial changes can occur within a single season, let alone over multi-year intervals, which raises concerns about temporal consistency.

- Reasoning for the geophysical survey sensitivity is addressed in Major Comment 6. The calibration of the *SpC* meters is now addressed in Line 227 to Line 229. Both the GPR and TEM surveys were deployed to examine the subsurface structure. Surveys in Caribou Bog over the past two decades particularly highlight the consistent depiction of subsurface architecture, supporting that such datasets are not affected by being collected in different years.
- Line 227 to Line 229: "All specific conductivity meters used for measurements were calibrated according to corresponding manufacturer instructions using standards of 84 µS/cm, 1413 µS/cm, and 12.88 mS/cm KCl solution standards at 25 ºC."

Comment: Line 225: This can be expressed/or converted to (mS/m) for consistency with TEM EC unit

- Units of μS/cm have been retained for the use of the Groundwater Indicator (*Gi*) variable throughout the manuscript.

Comment: Line 237: the U should be define; you can state A Mann-Whitney Unbiased(U)-Test. and why do you choose this test for this study?

- The U is now defined in Line 244 with additional reasoning added for the use of this approach justified in Line 245 to Line 247.
- Line 244 to Line 247: "A non-parametric Mann-Whitney Unbiased-Test (U-Test) was run comparing the non-Gaussian distribution of the Gi values of the two defined populations to produce a normalized U-statistic to establish statistical differences in the Gi values between the hydraulically upgradient and hydraulically downgradient sides of the pools. The U-statistic was normalized relative to the upgradient and downgradient populations to define a probability of superiority measure,"

Comment: Line 275: replaced with "using a filter size of 0.22..."

- Thank you for this correction, it has been implemented in Line 288.
- Line 288: "Water samples (n = 30 total) were prepared by filtering 10 mL of the raw sample using a filter size of 0.22 µm."

Comment: Figure 3: Why is there no data between 200 - 320 m positions (the white space) or what subsurface structure is present? Is it because of the filter applied to the dataset before the inversion process? this is not clear.

- The figure captions of Figure 3, Figure 4, and Figure 5 have been updated to reflect the filtering.
- Line 342 to Line 343, Line 358 to Line 359, and Line 373 to Line 374: "Sensitivity of the TEM inversion was filtered using a standard deviation of less than four to remove low sensitivity portions of the model (white)."

Comment: Line 330: delete (c)

- Thank you for this input, the © has been retained to comply with the requirements from the Hydrology and Earth System Science journal.

Comment: Line 373-Line 374: Yes, that is correct; however, by how much are the Gi values of the upgradient population larger than those of the downgradient population? An additional step is needed, as your results demonstrate that the upgradient and downgradient populations are statistically different, but the magnitude of this difference has not been quantified.

- This was invaluable for the manuscript thank you for calling attention to this issue. The normalized U-statistics represent probability of superiority measures between the two sides of the pools. Probability of superiority measures were used to calculate rank-biserial correlation coefficients for the three datasets to quantify the magnitude of difference.

Updates to the methods and nomenclature for these statistics are now presented in Line 244 to Line 254. The rank-biserial correlation coefficients are presented in Line 387 to Line 392, Line 410 to Line 417, and Line 426 to Line 428. Figure 6, Figure S7 and Figure S9 have been updated with the label for the probability of superiority value properly presented.

- Line 244 to Line 254: "A Mann-Whitney Unbiased-Test (U-Test) was run comparing the Gi values of the two defined populations to produce a normalized U-statistic to establish statistical differences in the Gi values between the hydraulically upgradient and hydraulically downgradient sides of the pools. The U-statistic was normalized relative to the upgradient and downgradient populations to define a probability of superiority measure, where a value of zero concludes that all Gi values on the hydraulically upgradient side of the pools were smaller than the Gi values on the hydraulically downgradient side of the pools. A value of one concludes that all Gi values on the hydraulically upgradient side of the pools were larger than the Gi values on the hydraulically downgradient side of the pools. A p-value was also produced to determine the statistical significance of the difference between the Gi values in the two populations, where a value of $p < 0.05$ was deemed significant. The magnitude of the difference between the hydraulically upgradient and hydraulically downgradient sides of the pools was calculated using rank-biserial correlation coefficient from the calculated probability of superiority measures."
- Line 386 to Line 392: "The Mann-Whitney U-Test comparing the Caribou Gi values of the upgradient and downgradient populations on either side of the major axis of the pool system produced a probability of superiority of 0.648 and $p < 0.001$ (Fig. 6). This test states that the Gi values of the upgradient population are statistically larger than the Gi values of the downgradient population, again corresponding to the direction of lateral spreading. Further, the p-value corroborates a statistically significant difference between the two populations. The magnitude of difference between the upgradient and downgradient populations was described by a rank-biserial correlation coefficient of 0.295, representing a modest but consistent tendency towards higher Gi values in the upgradient population."
- Line 410 to Line 417: "Comparison of the upgradient and downgradient populations, divided by the minor axis of the pool system, using the Mann-Whitney U-Test yielded a probability of superiority of 0.626 and a statistically significant $p < 0.001$ (Fig. S7). The probability of superiority states that the Gi values in the upgradient population are statistically larger than the Gi values in the downgradient population, corresponding to the direction of lateral spreading, and the p-value concludes there is a statistically significant difference between the two populations. The magnitude of difference between the upgradient and downgradient populations was described by a rank-biserial correlation coefficient of 0.252, representing a modest but consistent tendency towards higher Gi values in the upgradient population."

- Line 426 to Line 432: "The Mann-Whitney U-Test comparing the Gi values of the upgradient and downgradient populations, divided by the major axis of the pool system, produced a probability of superiority of 0.622 and a statistically significant $p < 0.001$ (Fig. S9). The probability of superiority demonstrates that Gi values in the upgradient population are statistically larger than the Gi values in the downgradient population, corresponding to the direction of lateral spreading, and the p-value shows a statistically significant difference between the two populations. The magnitude of difference between the upgradient and downgradient populations was described by a rank-biserial correlation coefficient of 0.244, representing a modest but consistent tendency towards higher Gi values in the upgradient population."

Comment: Line 420: Figure 7a and b background color are different from their respective zoom image. For instance there is green color background in the zoomed images while the underlaying image is showing another color be consistent.

- The green vegetation mask was used in the "zoomed in" sections of the TIR maps to highlight the localized zones of advective heat transport at a finer while still allowing the reader to see the greater "thermalscape" captured by the survey. Figure 7 has therefore been retained as is.

Comment: Figure 8: I suggest using the same temperature scale for Fig.8b and place the (single)color scale bar outside the figure as you did in Figure 8a (right image). This would help to capture or identify any localized discharge of groundwater spot flow patterned.

- Figure 8b was processed to emphasize the temperature contrasts from advective heat transport during the summer season and temperature ranges for each individual TIR photo were optimized to highlight such contrasts. For this reason, the figure has been retained.

Comment: Line 600: It should be Groschen et al., (2009)

- Thank you for catching this error, it has been corrected on Line 605.

Comment: Line 680-Line 681: Agreed. However, the GPR and TEM surveys in this study primarily provide a structural framework of the subsurface. Additional work is needed, and it would be beneficial to recommend future research aimed at quantifying and/or linking geophysical parameters to groundwater upwelling or its influence either directly or indirectly beyond the point-scale in-situ measurements of temperature and specific conductance. I am also concerned about Equation (2). Based on this equation, I expected specific conductance (SpC) to be more directly connected to the TEM dataset and potentially used to develop a conceptual groundwater upwelling model that explains the formation of the patterned peat pools. While I understand that the datasets used in this study were not collected concurrently an issue that has significant implications for the interpretation of the results, particularly the TEM response it raises an important question: what primarily controls the electrical conductivity derived from the TEM survey?

- Please find the reasoning behind the geophysical interpretation of these data in the response to Major Comment 6.