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

Reviewer Comment 1: Eric Rosa, 07 January 2026

Comment: This study focuses on identifying upwelling groundwater fluxes that could feed patterned pools in raised northern peat bogs in Maine, USA. It also considers the potential impact of these fluxes on the development of patterned pools. This topic is scientifically original and relevant to the readership of HESS. The methodological approaches include geophysical measurements (GPR and transient electromagnetic surveys), thermal imaging, in situ measurements of conductivity and temperature, and water sampling for Fe and Mn concentration analysis. These approaches are relevant to answering the research question. Overall, this is original and scientifically relevant work. However, I believe that some improvements are still needed before publication to maximise the manuscript's scientific impact.

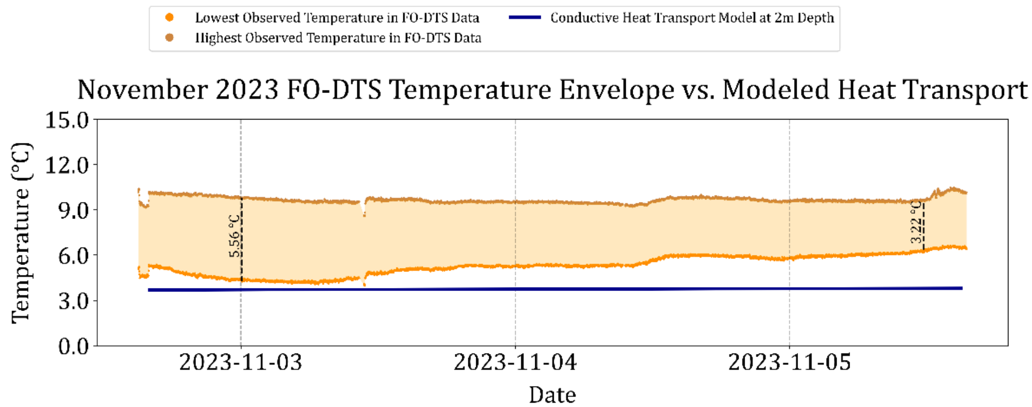
- Thank you for your in-depth, overall feedback on the manuscript and for your recognition of the value of the research body.

<u>*General Comment 1:*</u> I believe more details are needed in section 2 (Material and methods) to better explain the choices for sampling and in situ measurement points:

- Please find your specific concerns regarding the Materials and Methods section addressed in the comments below General Comment 1.

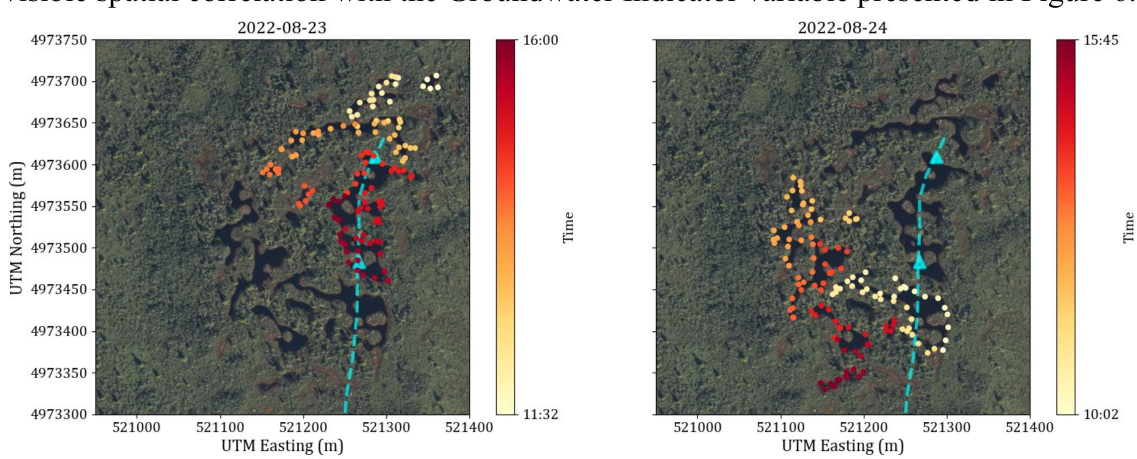
Comment: It is stated (L213) that specific conductivity and temperature measurements were conducted at a 25 cm depth a few centimeters from the pools perimeter. This choice is likely justified by the enhanced accessibility of the sites close to pool margins. However, it is important to consider the possibility that measurements taken in the immediate vicinity of the pool margins may not be representative of the conditions prevailing towards the centre of the pools, especially at greater depths. Could thermal stratification occur in some pools, with cold water at the bottom and warmer water at the surface?

- You are correct about the temperature and specific conductivity measurements being taken along the edges of the pools for the enhanced accessibility to the site to collect a representative sample size. This limitation is now recognized in Line 214 to Line 215 with the addition of "Due to the significant area of the pool systems, temperature and SpC data were not collected in the center of the pools.". Consistent measurements at 0.25 meters depth were conducted to limit surficial influences of the diurnal signal on the recorded temperature and *SpC* data. Thermal stratification is likely to occur in some of these pools, however the advective heat transport signal from groundwater discharges would still provide contrast along the pool margins due to the different heat transport processes occurring. Ongoing research, including preliminary FO-DTS observations, demonstrate that seasonal temperatures deviate from conductive heat-transport model predictions, indicating advective heat transport from depth. An example is provided below from FO-DTS data collected during the November 2023 season, where warmer water was expected to indicate advective heat transport along the base of the pools.

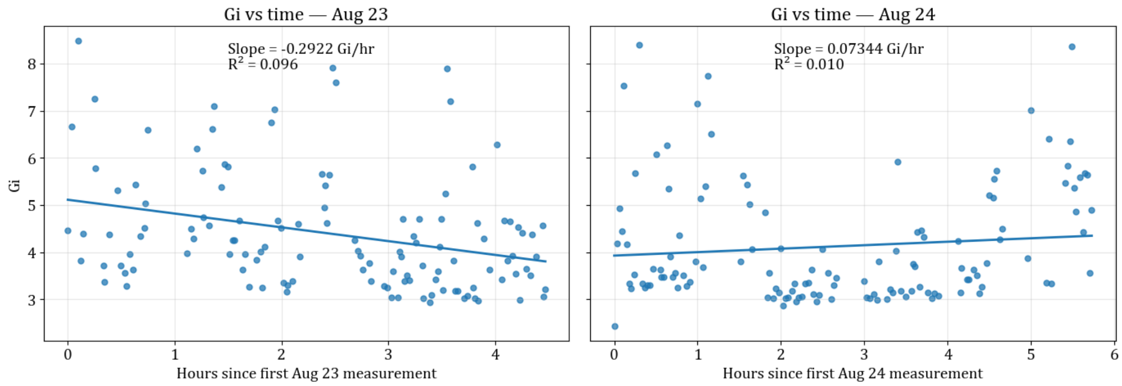


Comment: A variety of measurements were conducted on different days at multiple sites. It is to be considered whether there has been a change in the temperature of surface water in pools during the period of measurement. To illustrate this point, if measurements are conducted in August, can stable temperatures be expected between the early morning and the afternoon across all measurement points? The potential impact of temporal variability, i.e. variations in surface water temperature during the day of sampling, on the comparisons between different sampling points merits consideration.

- This is a valid concern regarding the temporal nature of the point measurements made, however the *Gi* variable defined from these measurements is emphasized to be used as a tracer for advective heat transport rather than a hard quantitative measure. The SpC measurements made would also be less susceptible to daily changes overall. It is further emphasized that collecting this representative sample size of points would not be feasible in such remote settings, and especially not in three separate regional bogs. This warrants the use of the *Gi* variable to display contrasts in space rather than in time. Provided below shows an example plot of the data collected with time in Caribou Bog, which shows no visible spatial correlation with the Groundwater Indicator variable presented in Figure 6.



A linear regression was carried out between the *Gi* variables over time to investigate any relationship and no statistical correlation was found, with visible spread of the *Gi* data.



Comment: The selection of Fe and Mn as analytical parameters could be expanded upon. Indeed, the hydrogeochemical behaviour of these two chemical elements is very sensitive to Eh-pH conditions and the presence of organic colloids. Consequently, utilising these two elements as tracers of groundwater flows without also considering Eh-pH values and the presence of organic colloids can result in a high degree of uncertainty. The use of other tracers, such as stable isotopes of the water molecule, could facilitate a more precise analysis of the sources of water feeding the pools.

- The use of iron and manganese as tracers is now further justified with the citation of regional glacial aquifers testing for heightened levels of these trace elements across the northeastern United States. An additional citation is now provided as well for this regional context. Additions have been made to the methods section that outline the assumption of relatively stable redox conditions during the geochemical sampling periods (Line 286 to Line 288). For this study, other geochemical tracers were not available due to funding limitations. The geochemical limitations as you describe are now recognized in the Discussion section (Line 705 to Line 710) as potential for future research directions. Environmental radon could also serve as another useful geochemical tracer in future work to identify water sources feeding the pools.
- Line 286 to Line 288: "It was assumed that redox conditions were relatively stable at 0.25 meters depth near the pool edges where the water was collected over the short sampling periods."
- Line 705 to Line 710: "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."

Comment: Here, the focus is set on advective transport but could diffusion from the underlaying inorganic sediments explain part of the spatial variability in pool water conductivity?

- The combination of advective heat transport signals corresponding with the heightened *SpC* observed near the surface suggests that water is plumbed from greater depths rather than simply diffusion from the underlying mineral sediment. Diffusion of ionic constituents from the underlying mineral sediments would take longer spans of time and advance through the peat matrix as a front, influencing the entire peat surface. Based on this diffuse movement, the localized contrasts observed would not occur and require the faster, localized process of advection. While there is a strong difference between the upgradient and downgradient signals, the localized nature of the signals (particularly the thermal infrared imagery) further suggest that water with higher *SpC* originates from discharges.

<u>*General Comment 2:*</u> Should it be feasible, it would be of interest to present the precise topographic contours for the peatlands under study. Some figures illustrate upgradient and downgradient areas (e.g., Figure 2); however, it is probable that the flow configuration is more intricate than what is visible in the image. The incorporation of topographic contours (e.g., derived from Lidar data) would facilitate enhanced comprehension of the surface flow paths between pools. This would further facilitate the comprehension of the hydraulic head data presented in Figure S16 and the general pattern illustrated in the conceptual model (Figure 10).

- Thank you for your suggestion, elevation profiles through the patterned pools investigated and to the nearest mapped surficial esker deposit are now presented in Figure 1. However, these elevation profiles do not change the basic interpretation of the hydraulically upgradient/downgradient pools. The flow configuration is likely more intricate as you describe, however this is now aimed at guiding the reader with additional support for the conceptual model in Figure 10.

<u>*General Comment 3:*</u> The conceptual model provided in Figure 10 is of particular interest. Nevertheless, further information could be pertinent:

- Thank you for your support of the new potential conceptual model presented in Figure 10, the further information recommended is acknowledged below.

Comment: If possible, it would be relevant to provide an estimate of the topographic gradient between the esker and the lagg and between the central part of the peatland and the lagg.

- Topographic profiles between the nearest esker deposit, corresponding lagg, and the center of the peatland (relative to the pools) are presented in Figure 1.

- Line 103 to Line 107:

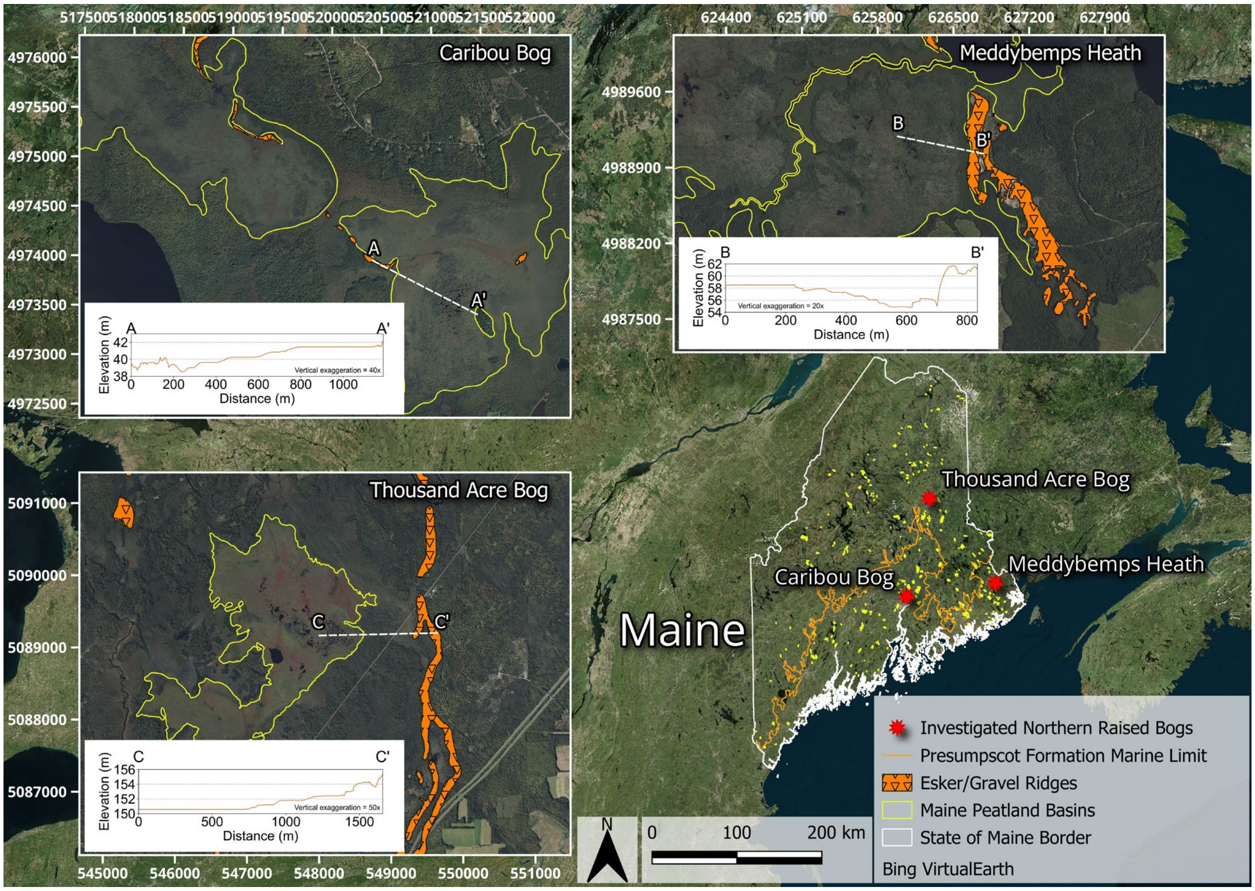


Figure 1: Images (© Microsoft) of Caribou Bog (central unit), Thousand Acre (Crystal) Bog, and Meddybemps Heath (southern unit) in Maine (USA) with nearby mapped glaciofluvial eskers/gravel deposits (Newman, 1980; Cameron et al., 1984; Shreve, 1985; Thompson & Borns, 1985). Elevation profiles (white) from the State of Maine (2020) between the patterned pools investigated and the nearest esker/gravel deposits are presented for the three peat bogs. All images are displayed using the WGS 84 / UTM Zone 19N (EPSG 32619) coordinate reference system, and tick marks are distances in meters.

Comment: If the necessary data are available, it would also be relevant to illustrate the hydraulic gradient between the esker and the peatland. Are there data confirming the higher hydraulic heads in eskers near the studied peatlands?

- Thank you for this inquiry, at this time, no well/piezometer data is available as evidence of higher hydraulic head in the surficial esker deposits around the studied bogs. At the end of the discussion section (Line 685 to Line 686) this is acknowledged as another direction for future research to investigate.

Comment: The available figures (e.g. 6, S7, S9) do not provide unequivocal evidence to determine whether the eskers are solely buried formations or if they are connected to topographically higher recharge areas. Can this be explained in more details or illustrated on a figure?

- It is recognized that the geophysical data does not provide unequivocal evidence for the hydraulic connection between the topographically higher, surficial esker recharge areas. GPR data is limited by the attenuation of the EM wave upon contact with the electrically conductive glaciomarine clay bounding most of the basin. Comas et al. (2011) traced the esker structures beneath Caribou Bog and shows evidence of the continuity of the deposits despite this limitation. Electrical structures in the new TEM data presented show some potential for hydraulic connections, however this cannot be definitively proven. Based on esker deposition patterns across glacial landscapes, and presented in Figure 1, there remains a possibility of connection between the surficial deposits and the underlying esker deposits beneath the bogs justifying the inclusion in the conceptual hydrostratigraphy. Even so, a sequence of discontinuous deposits could enhance flow and alter vertical hydraulic gradients in the center of the peatland (Reeve et al., 2009), leading to the flow cell model presented in Figure 10.

  Comas, X., Slater, L., & Reeve, A. S. (2011). Pool patterning in a northern peatland: Geophysical evidence for the role of postglacial landforms. Journal of Hydrology, 399(3-4), 173-184.
  Reeve, A. S., Tyczka, Z. D., Comas, X., & Slater, L. D. (2009). The influence of permeable mineral lenses on peatland hydrology. Geophysical Monograph Series, 184, 289-297.

General Comment 4: While the text on the methodological approaches and results is interesting, it can be difficult for readers unfamiliar with the study sites to follow. This is because several methods were used at different times for three sites. To optimise readability, I would suggest adding a summary table of the work carried out at the different sites to the Materials and Methods section. For example, in such a table, the rows could represent the methods and the columns could represent the sites. The information in the cells could provide information such as the number of measurements and the dates of the measurements. Similarly, a table could be added to the results section, summarising the highlights of the results (using a similar table structure).

- A table summarizing the methods used in each of the bogs studied is now presented as Table S1 in the supplemental data. The reader is further directed to this table at the beginning of the Materials and Methods section in Line 143 to Line 144. The Results section has been retained for interested readers to reference the supplemental data provided.
- **Table S1.** Hydrogeophysical methods conducted in the three surveyed peat bogs, the period of data collection, and the number of surveys and/or samples taken.

Method	*Caribou Bog*	*Thousand Acre Bog*	*Meddybemps Heath*
Ground-Penetrating Radar Surveys	Comas et al., 2011 (n = 2)	August 2023, June 2024 (n = 14)	November 2023 (n = 6)
Transient Electromagnetic Induction Surveys	May 2025 (n = 1)	May 2025 (n = 1)	May 2025 (n = 1)
Point Temperature and Specific Conductance Measurements	August 2022 (n = 247)	August 2023 (n = 888)	August 2023 (n = 324)
Uncrewed Aerial Systems Thermal Infrared Mapping	June 2023 (n = 1)	August 2023 (n = 1)	June 2023, August 2023, November 2023 (n = 3)
Handheld Thermal Infrared Imagery	None	None	June 2024 (n = 6)
Inductively-Coupled Plasma Optical Emission Spectrometry	November 2023 (n = 10)	August 2023 (n = 10)	August 2023 (n = 10)

- Line 143 to Line 144: “All hydrogeophysical methods implemented across the three bogs containing patterned pools for this study are summarized in Table S1 of the supplemental data provided for this study.”

Some additional specific comments on the manuscript:

Comment: L28 : I believe there is a missing apostrophe

- Thank you for catching this, the missing apostrophe has been added.
- Line 28: “Upwelling through the peat matrix is possibly partially facilitated by macropore, ‘peat pipe’ features that serve as preferential flowpaths of varying lengths to the surface.”

Comment: L111 + 112 : the expressions “glacial esker” and “glacial till” are used. Please double check if the term “glacial” is really needed. I believe both are, by definition, of glacial origin. The comment applies to the other appearances of these expressions.

- You are correct about this geological terminology, and the manuscript has been updated to remove the word “glacial” in reference to these specific deposits.

Comment: L230 (Eq. 2) : I believe this could be an oversimplification. Is the thermal regime of the pools dependent on their size and depth, as well as groundwater fluxes?

- Advective heat transport from groundwater discharge to the pools was anticipated to highlight stark contrasts compared to the otherwise assumed conductive heat transport processes expected in this system. While size and depth of the pools influence the thermal regimes of these pools, the pools (regardless of their size or depth) are still expected to primarily respond to the conductive heat transport from atmospheric temperature signals. The Groundwater Indicator parameter was developed as a qualitative spatial tracer, using both temperature and specific conductance, to identify areas with enhanced advective transport.

Comment: Figure 2: Would it be relevant to apply a topographic correction to the profiles? This also applies to other profiles shown.

- Thank you for your suggestion, given the minimal changes in the elevation (less than ~3 meters) over the surface of the bogs the topographic correction becomes problematic as the vertical resolution of the GPS used with the profiles was unable to resolve the fine scale changes in elevation. For this reason, the profiles without a topographic correction have been retained.

Comment: L380 (Figure 6):à I suggest adding the date of measurements in the figure caption.

- The dates of the paired temperature and specific conductance measurements have been added to the figure captions of Figure 6, Figure S7, and Figure S9.
- Line 395 to Line 401: **"Figure 6: Groundwater indicator (Gi) values (n = 247), in a) given as ratios of specific conductance (µS/cm) to temperature (ºC) collected at 0.25-meters depth along the perimeter of patterned pools (n = 13) of Caribou Bog (August 23, 2022 and August 24, 2022) with interpreted trends of underlying glacial esker deposits inferred from GPR data, and the inferred direction of lateral spreading for the pool system. Histograms in b) show the normalized frequency of Gi values of the upgradient and downgradient sections, split by the major axis of the system of patterned pools. In b), a Mann-Whitney U-Test shows a significant p-value for the difference between the two populations. A probability of superiority demonstrates that the upgradient side of the pools has statistically larger Gi values than the downgradient side of the pools. Basemap data from © Microsoft (2024)."**
- Supplemental Figure 7: **"Figure S7: Groundwater indicator (Gi) values (n = 888), in a) given as ratios of specific conductance (µS/cm) to temperature (ºC) collected at 0.25-meters depth along the perimeter of patterned pools (n = 37) of Thousand Acre (Crystal) Bog (August 8, 2023, August 10, 2023, and August 15, 2023) with interpreted trends of underlying glacial esker deposits inferred from GPR data, and the inferred direction of lateral spreading for the pool system. Histograms in b) show the normalized frequency of Gi values of the upgradient and downgradient sections, split by the major axis of the patterned pool system. In b), a Mann-Whitney U-Test shows a significant p-value for the difference between the two populations, and a probability of superiority demonstrates the upgradient side of the pools consists of statistically larger Gi values than the downgradient side of the pools. Basemap data: © Microsoft (2024)."**
- Supplemental Figure 9: **"Figure S9: Groundwater indicator (Gi) values (n = 324), in a) given as ratios of specific conductance (µS/cm) to temperature (ºC) collected at 0.25-meters depth along the perimeter of patterned pools (n = 15) of Meddybemps Heath (August 7, 2023, and August 17, 2023) with interpreted trends of underlying glacial esker deposits inferred from GPR data, and the inferred direction of lateral**

spreading for the pool system. Histograms in b) show the normalized frequency of Gi values of the upgradient and downgradient sections, split by the major axis of the patterned pool system. In b), a Mann-Whitney U-Test shows a significant p-value for the difference between the two populations, and a probability of superiority demonstrates that the upgradient side of the pools has statistically larger Gi values than the downgradient side of the pools. Basemap data: © Microsoft (2024).”

Comment: L441 : Please explain with more details the reported temperatures. Are all zones associated with temperatures below zero frozen?

- Those thermal infrared data do take some explanation, given areas known to be open water during the time of the drone flights present as below zero in the apparent surface temperatures. Reduced accuracy of thermal infrared cameras under cold weather conditions for GW/SW exchange studies was originally identified by Hare et al., (2015) (Figure 7, https://doi.org/10.1016/j.jhydrol.2015.09.059), which found a several degree negative shift (approximately -5 deg C) in apparent thermal infrared temperatures at known groundwater seepage areas, such that all water surface data appeared negative using a lower cost handheld camera of similar specification to the drone deployed instrument. However, that study found that even without local calibration of the data, the relative differences in bank and water surface temperature were still quite meaningful in geolocating points of seepage. In a similar manner, our Figure 8 is aimed to highlight the contrasts in temperature values in two specific pools during the winter of 2023 to indicate areas of seepage vs more those of reduced advective influence, even though all apparent pool surface temperatures are negative. Some of those areas were frozen, but we know there was open water in the (apparently) warmer zones. Temperature values from handheld TIR imagery in the summer 2024 season bolster the groundwater discharge interpretation of these winter contrasts with the opposite seasonal signals (colder zones in the same general areas of winter warm zones) of advective heat transport observed in summer.

  Hare, D. K., Briggs, M. A., Rosenberry, D. O., Boutt, D. F., & Lane, J. W. (2015). A comparison of thermal infrared to fiber-optic distributed temperature sensing for evaluation of groundwater discharge to surface water. Journal of Hydrology, 530, 153-166.

Comment: L618 : Can you please better explain point c)? Are there measurements/results directly representing this?

- In the Methods section, 2.4 Temperature Signals of Patterned Pools from Uncrewed Aerial System (UAS) Thermal Infrared Mapping and Handheld TIR Imaging, targeted periods for the TIR imagery following local precipitation are outlined with NOAA data

support. Clarification on this qualifier has been added to Line 618 and Line 619 with the inclusion of "observed in TIR imagery at the handheld and aerial scales".
- Line 644 to Line 645: "…c) changes in the temperature signal, observed in point measurements and TIR imagery directly following significant precipitation"

Comment: L634 (+figure 10) : It would be interesting to add information on the image (conceptual model) on how the parameters you have measured (with geophysics, geochemistry and temperature) help for constraining the model.

- Thank you for your recommendation. After experimenting with this idea, the conceptual figure became overcrowded and has thus been left as the original image to emphasize the hydrological implications.

Comment: L677 : Towards the end of the discussion, you would likely have an opportunity to recommend a series of measures to prioritize in future studies in order to test your conceptual model. What would you recommend to future researchers working on this issue? Such recommendations could inform future research.

- Thank you for suggesting this, a paragraph (Line 705 to Line 718) has been added to expand upon the future directions that researchers should take to test the conceptual model presented in this manuscript.
- Line 707 to Line 720: "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. Exploration into the presence, spatial orientation, and extent with depth of peat pipes also serves as an exciting new avenue for further research in understanding preferential flow to the surface of bogs. 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. Targeted deployments of piezometers or wells in the esker deposits beneath the bogs and in esker deposits in nearby surficial esker deposits could yield further insights into the hydrological responses of these systems. These measures will serve to test and improve the conceptual hydrological model presented based on the observations made in this study. Finally, the impacts of such preferential flows on carbon-cycling in the peat matrix should be explored to understand potential links between localized groundwater upwelling and carbon ebullition in pools."

Comment: Figures S5, S6, S8 : I recommend adding a line between both images and adding labels (A for temperature, B for Conductance).

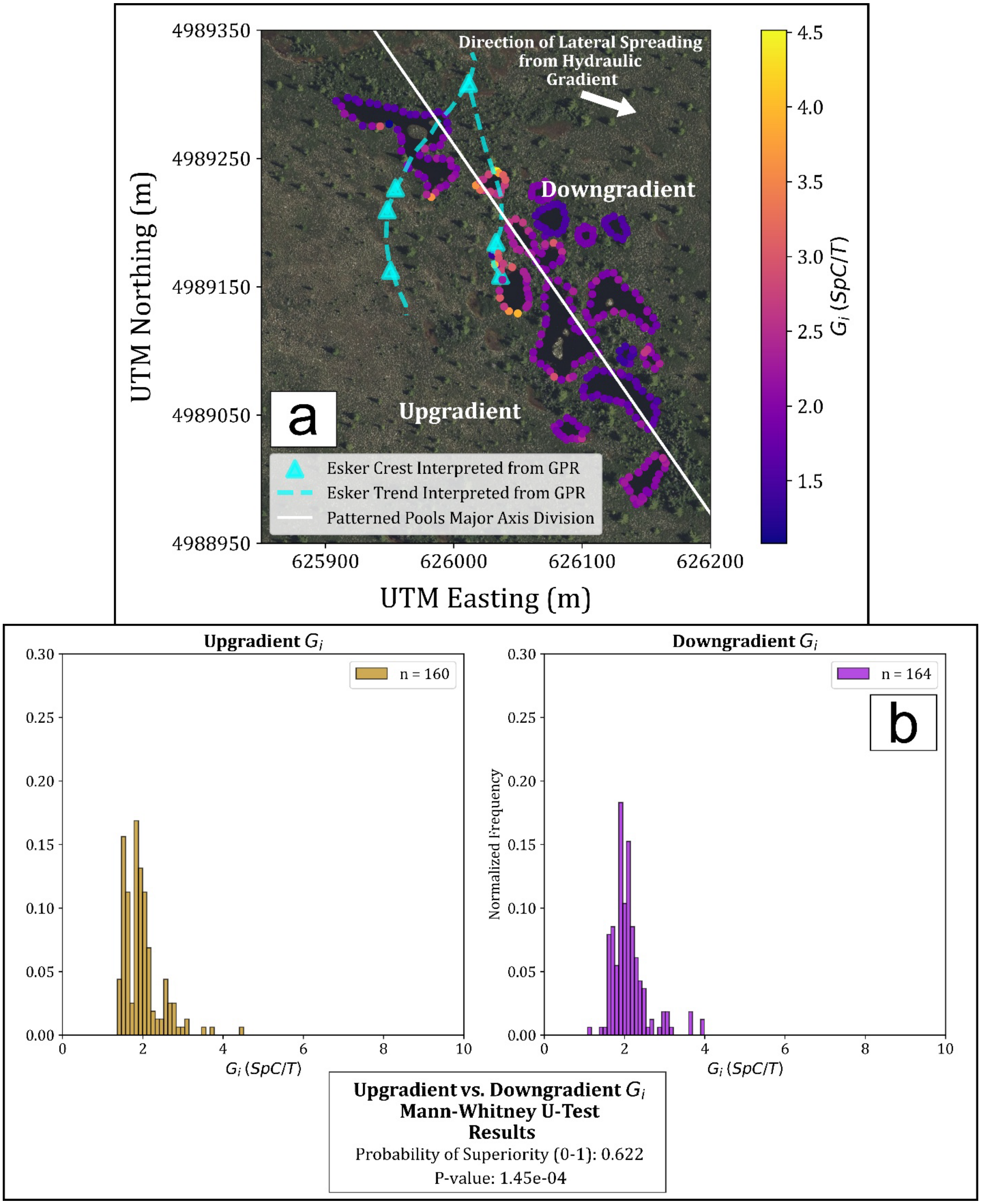
- The subsections of these figures have been implemented across Figure S5, Figure S6, and Figure S8, thank you for this recommendation.

Comment: Tables S1, S2, S3, S4, : Please carefully check how many decimals should be kept for the different values in these tables.

- Thank you for calling attention to the significant figures issue presented, Table S1, Table S2, Table S3, and Table S4 have been corrected accordingly.

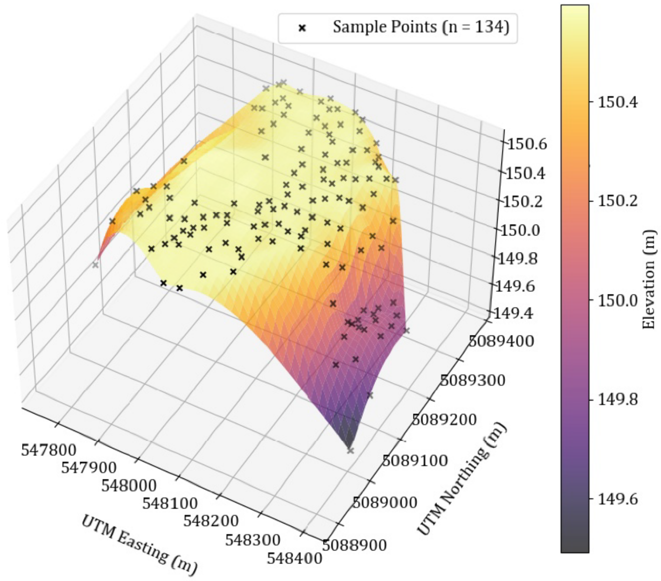
Comment: Figure S9 : I am having difficulty understanding how the arrow is oriented in relation to the up- and down-gradient areas. Please could you double-check this?

- After double-checking this arrow, the angle has been updated to reflect the direction of the downgradient side of the pools.

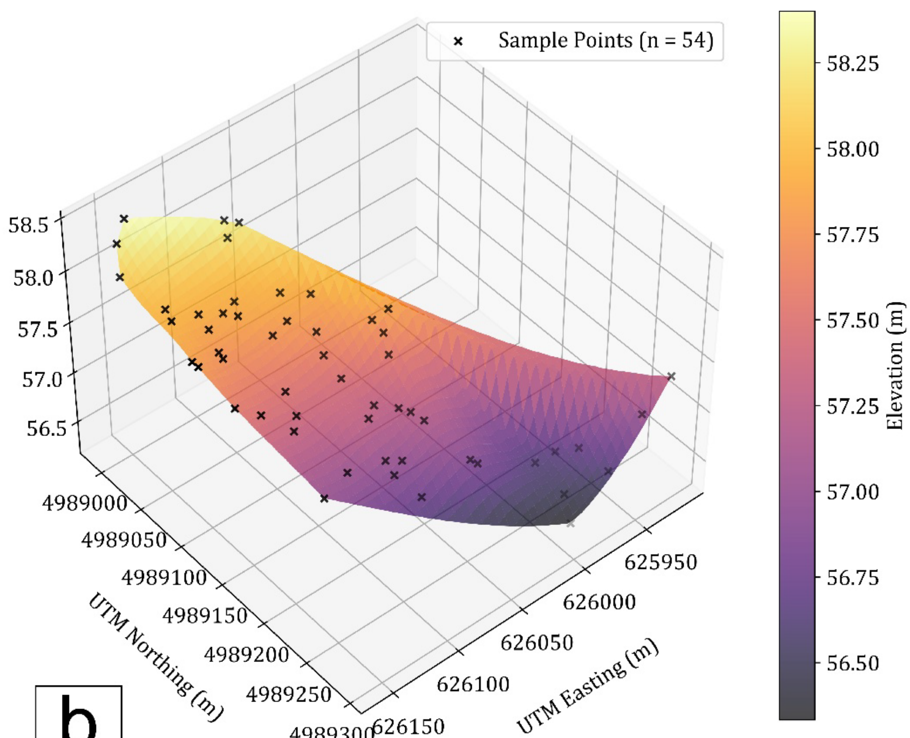
- 

Comment: Figure S15 : I recommend revising the text that appears on the images "3D Surface Plot of Hydraulic Gradient...". I believe the text in the caption should suffice.

- Agreed, thank you for this suggestion. The titles on the plots have been removed.



a



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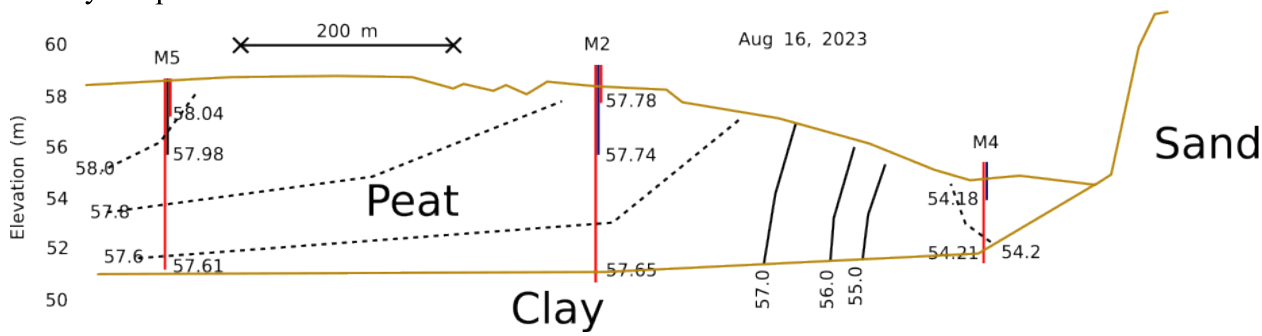
Comment: Figure S17 : The hydraulic head contours proposed therein appear to be oversimplified.

- An updated Figure S17 has been provided from ongoing hydrological modeling of the Meddybemps Heath based on well data.



- **Figure S17: Hydraulic head contours between wells MB5 and MB2 crossing the patterned pools of Meddybemps Heath on August 16th, 2023, showing downwelling between the wells. Downwelling patterns in the hydrological data persist until the lagg with the transition to esker sand.**

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.

Community Comment 1: Giacomo Medici, 31 October 2025

General Comment: Very good research in the field of groundwater hydrology. Please, follow my guidance and the specific comments to fix the minor issues.

- Thank you for your recognition of the value of this study, below you'll find responses to your suggestions.

Comment: Lines 76-78. "Glaciofluvial esker structures have been modelled to exert changes in the vertical movement of peat pore water, attributed to changes in the topography of the mineral sediment along the base of a bog and the hydraulic conductivity (K) contrasts between eskers and lower K peat". Insert review papers on flow heterogeneities in fluvial and glacial aquifers worldwide:

- Jansson, P., Hock, R., Schneider, T. 2003. The concept of glacier storage: a review. Journal of Hydrology, 282(1-4), 116-129.

- Agbotui, P.Y., Firouzbehi, F., Medici, G. 2025. Review of effective porosity in sandstone aquifers: insights for representation of contaminant transport. Sustainability, 17(14), 6469.

- Thank you for your comment, the current references for this statement have been retained due to specificity in the peatland environment rather than larger scale glacial sediment/sandstone aquifers.

Comment: Line 97. Clearly state the general aim of your research at the end of the introduction.

- Please find the research question addressed in this manuscript defined in Line 87 to Line 88.

Comment: Line 97. Describe the 3 to 4 general objectives of your research by using numbers (e.g., i, ii, and iii).

- Please find the research question addressed in this manuscript defined in Line 87 to Line 88.

Comment: Lines 99-139. Insert quantitative information on thickness of your sedimentary deposits.

- Thank you for your suggestion, currently thicknesses for the variable glacial deposits are not available for these specific sites.

Comment: Lines 99-139. Insert quantitative information from cores on proportion of sand, clay and gravel in your sedimentary deposits.

- Thank you for your suggestion, currently grain size proportions from cores of the variable glacial deposits are not available for these specific sites.

Comment: Line 679-690. Expand the conclusion. The general meaning/impact of your hydro-geophysical research is not evident in these lines.

- Thank you for your suggestion, the text has been retained to discuss the potential influences of such groundwater sources on the larger peat bog ecosystems rather than emphasizing the hydrogeophysical contribution.

Comment: Figure 2. Location not evident. Please, insert coordinates.

- The location of the patterned pools in Thousand Acre Bog is presented in Figure 1.

Comment: Figures 3 to 5. Distinguish a Figure A and B.

- Thank you for your suggestion, the figures have been retained due to the simple geospatial reference the maps provide.

Comment: Figure 6. The difference between Figure A and Figure B is not clear.

- Boxes around Figure 6a and Figure 6b have been emphasized to clarify the two different sections.

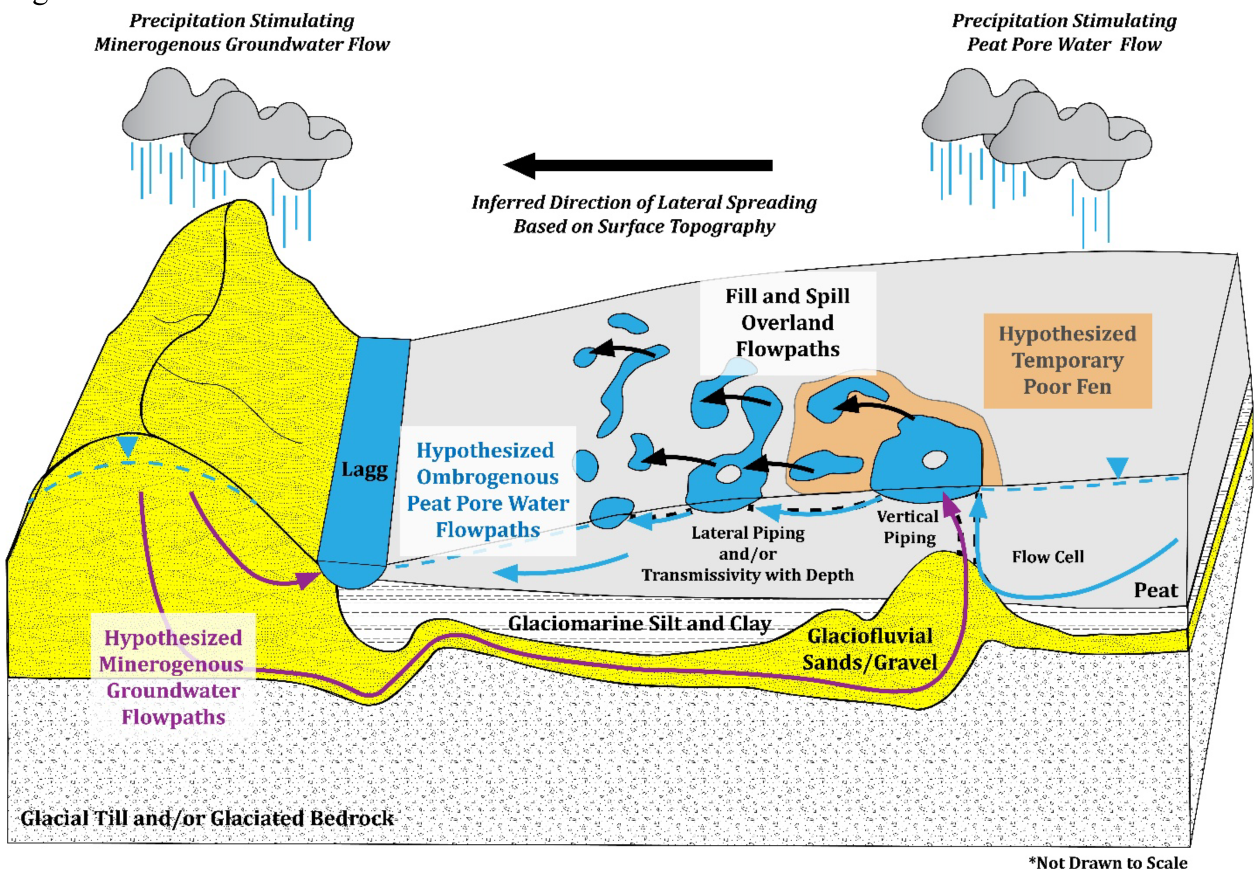
Comment: Figure 10. Insert a spatial scale.

- Thank you for the recommendation, a note has been added that the conceptual model is not drawn to scale.

Comment: Figure 10. Specify if a vertical exaggeration if present.

- Thank you for the recommendation, a note has been added that the conceptual model is not drawn to scale.

- Figure 10:


Precipitation Stimulating
Minerogenous Groundwater Flow
Precipitation Stimulating
Peat Pore Water Flow
Inferred Direction of Lateral Spreading
Based on Surface Topography
Fill and Spill
Overland
Flowpaths
Hypothesized
Temporary
Poor Fen
Lagg
Hypothesized
Ombrogenous
Peat Pore Water
Flowpaths
Lateral Piping
and/or
Transmissivity with Depth
Vertical
Piping
Flow Cell
Peat
Glaciomarine Silt and Clay
Glaciofluvial
Sands/Gravel
Hypothesized
Minerogenous
Groundwater
Flowpaths
Glacial Till and/or Glaciated Bedrock
*Not Drawn to Scale