SWAN System Configuration Recommendations for Detecting Permafrost Degradation in Canadian Beaufort Sea

1 Subsurface Models

The models used are based on:

- Riedel et al., 2015
- Sherman et al., 2017
- Indications obtained by Charly Paull

Typical structure:

- **Bathymetry:** 20–150 m
- **Top of permafrost:** 5–50 m below seafloor (b.s.f.)
- **Typical electrical conductivity for Ice Permafrost:** 0,001 S/m
- **Electrical conductivity of permafrost depending on the degree of melting:** 0.01-0.1 S/m

2 Tested Frequencies

Several source frequencies were simulated: **0.02 Hz, 0.05 Hz, 0.5 Hz, 1 Hz, 10 Hz**

3 1D Modelling Results

Model 1

Table 1 – Depths and conductivity values for a 1D subsurface model with and without an ice-rich permafrost layer.

	Model 1 with Perm	**Model 1 without Perm**
Water depth, h	100 m	100 m
SED thickness, k-h	8 m	8 m
PERM-ICE Thickness, l-k	100 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM-ICE, conductivity, σ_2	0.001 S/m	0.7 S/m
SED BOTTOM, conductivity, σ_4	0.7 S/m	0.7 S/m

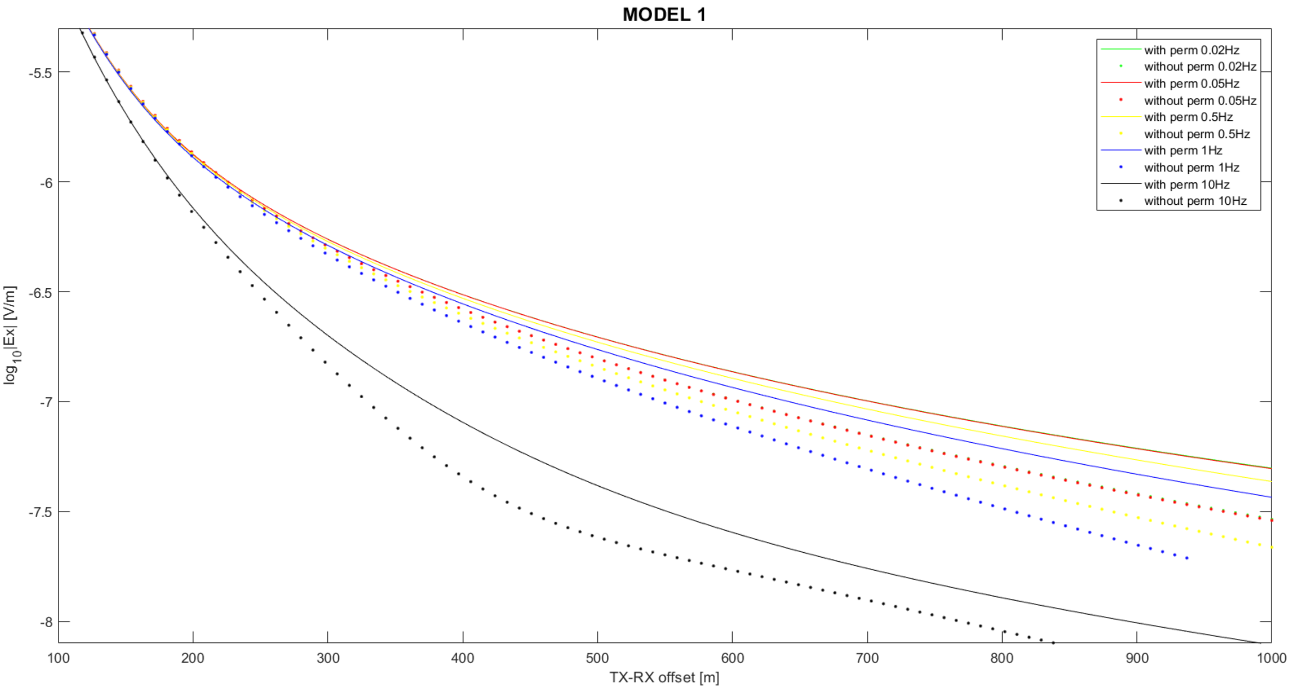

Figure 1 – Ex responses of Model 1 at different source frequencies. Solid lines represent the response of Model 1 with an ice-rich permafrost layer, while dashed lines represent the response without a permafrost layer.

Model 2

Table 2 – Depths and conductivity values for a 1D subsurface model with and without a melting permafrost layer.

	Model 2 with Perm	**Model 2 without Perm**
Water depth, h	100 m	100 m
SED thickness, k-h	8 m	8 m
PERM-ICE Thickness, l-k	100 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM ice-bearig1, conductivity, σ_2	0.01 S/m	0.7 S/m
SED BOTTOM, conductivity, σ_4	0.7 S/m	0.7 S/m

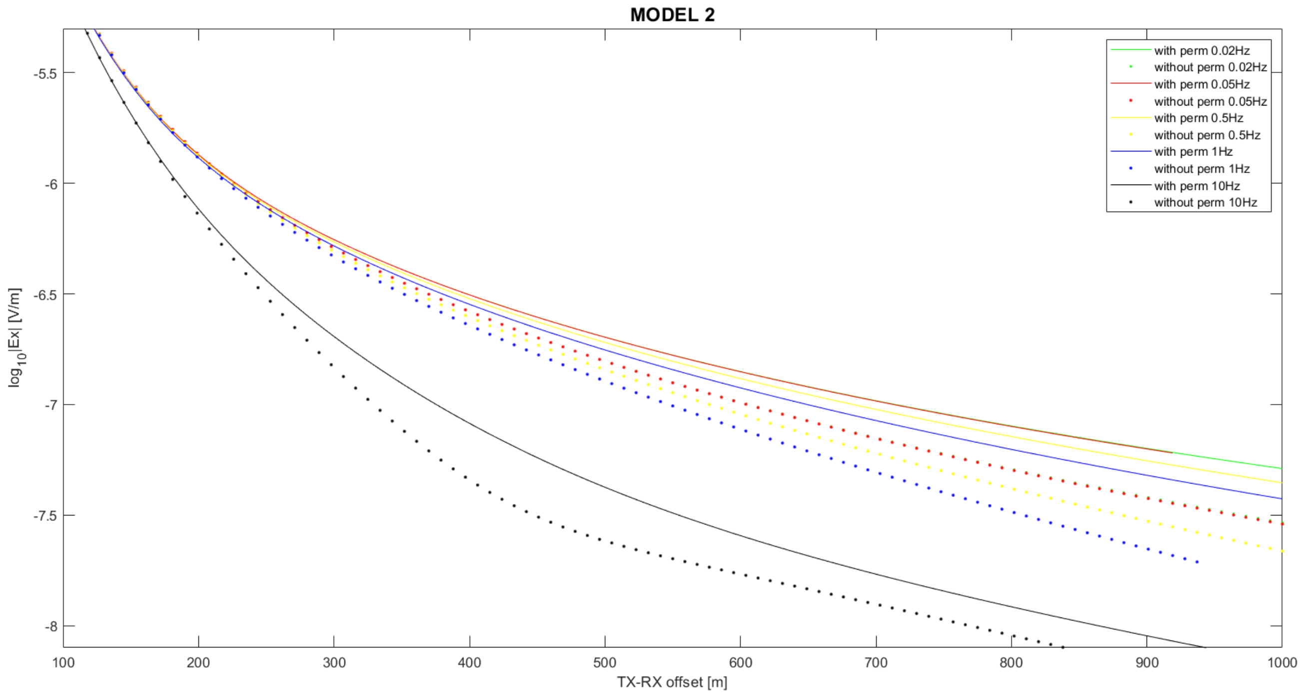

Figure 2 – Ex responses of Model 2 at different source frequencies. Solid lines represent the response of Model 2 with an melting permafrost layer, while dashed lines represent the response without a permafrost layer.

Model 3

Table 3 – Depths and conductivity values for a 1D subsurface model with and without a strong melting permafrost layer.

	Model 3 with Perm	Model 3 without Perm
Water depth, h	100 m	100 m
SED thickness, k-h	8 m	8 m
PERM-ICE Thickness, l-k	100 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM ice-bearig1, conductivity, σ_2	0.1 S/m	0.7 S/m
SED BOTTOM, conductivity, σ_4	0.7 S/m	0.7 S/m

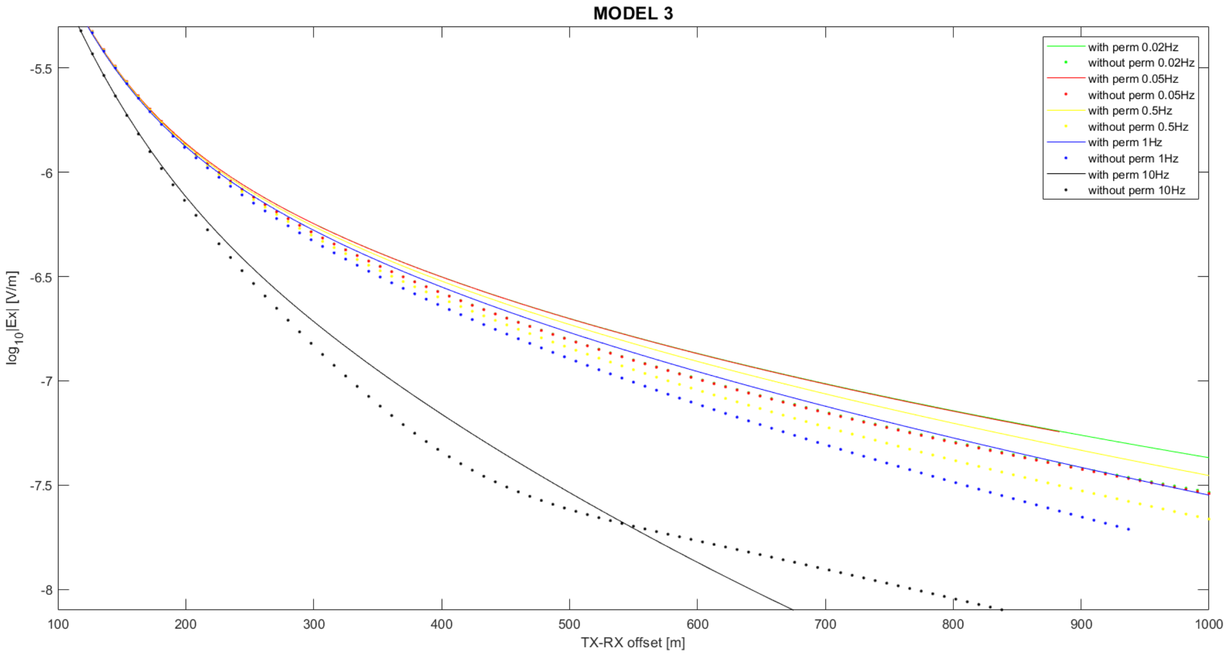

Figure 3 – Ex responses of Model 3 at different source frequencies. Solid lines represent the response of Model 3 with a strong melting permafrost layer, while dashed lines represent the response without a permafrost layer.

Model 4

Table 4 – Depths and conductivity values for a 1D subsurface model with and without an ice-rich permafrost layer beneath 80 m water depth.

	Model 4 with Perm	Model 4 without Perm
Water depth, h	80 m	80 m
SED thickness, k-h	8 m	8 m
PERM-ICE Thickness, l-k	100 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM-ICE, conductivity, σ_2	0.001 S/m	0.7 S/m
SED BOTTOM, conductivity, σ_4	0.7 S/m	0.7 S/m

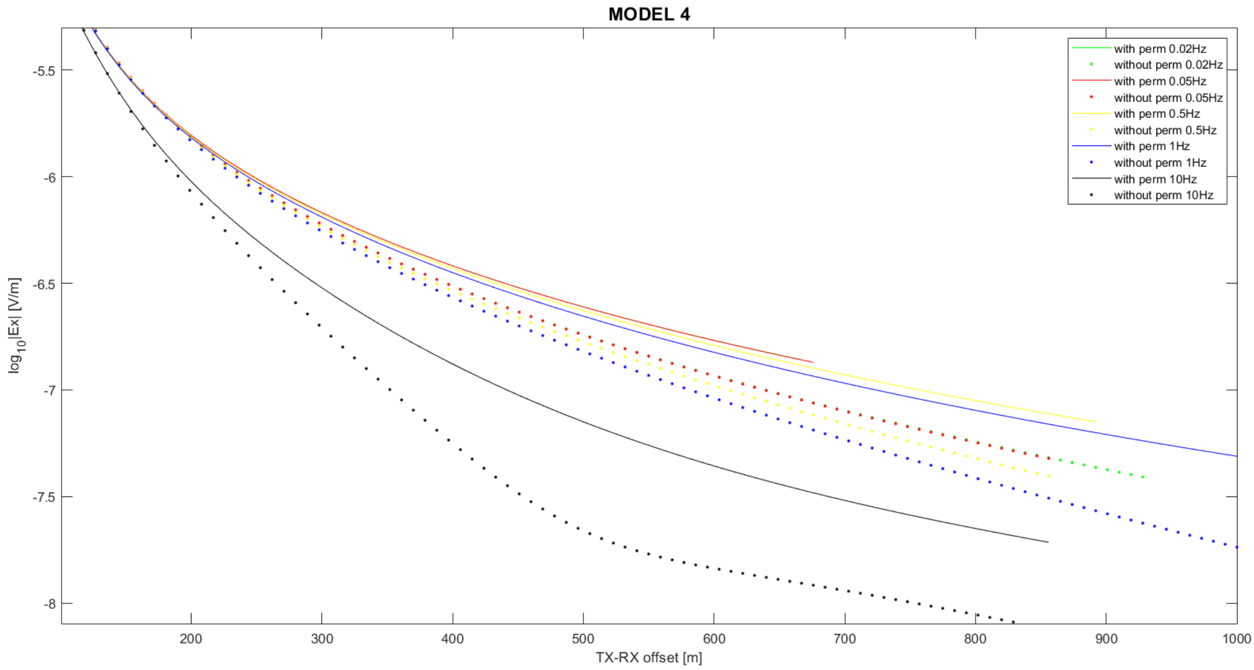

Figure 4 – Ex responses of Model 4 at different source frequencies. Solid lines represent the response of Model 4 with an ice-rich permafrost layer, while dashed lines represent the response without a permafrost layer.

Model 5

Table 5 – Depths and conductivity values for a 1D subsurface model with and without a melting permafrost layer beneath 80 m water depth.

	Model 5 with Perm	Model 5 without Perm
Water depth, h	80 m	80 m
SED thickness, k-h	8 m	8 m
PERM-ICE Thickness, l-k	100 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM ice-bearig1, conductivity, σ_2	0.01 S/m	0.7 S/m
SED BOTTOM, conductivity, σ_4	0.7 S/m	0.7 S/m

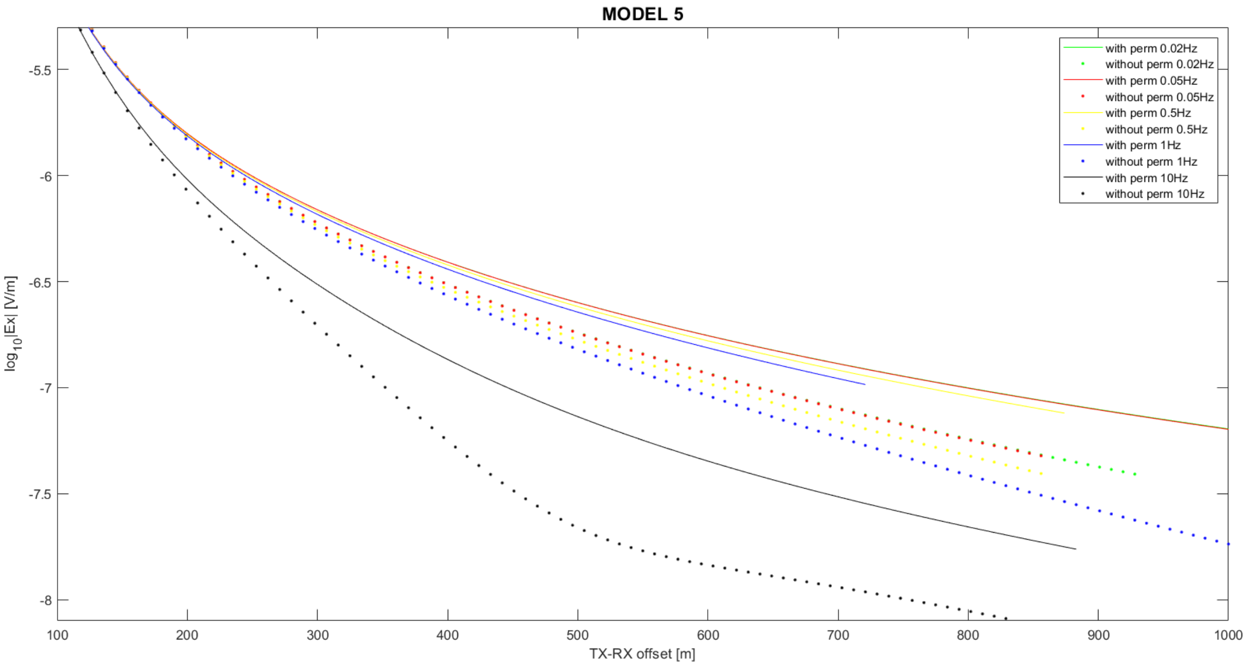

Figure 5 – Ex responses of Model 5 at different source frequencies. Solid lines represent the response of Model 5 with a melting permafrost layer, while dashed lines represent the response without a permafrost layer.

Model 6

Table 6 – Depths and conductivity values for a 1D subsurface model with and without a strong melting permafrost layer beneath 80 m water depth.

	Model 6 with Perm	Model 6 without Perm
Water depth, h	80 m	80 m
SED thickness, k-h	8 m	8 m
PERM-ICE Thickness, l-k	100 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM ice-bearig2, conductivity, σ_2	0.1 S/m	0.7 S/m
SED BOTTOM, conductivity, σ_4	0.7 S/m	0.7 S/m

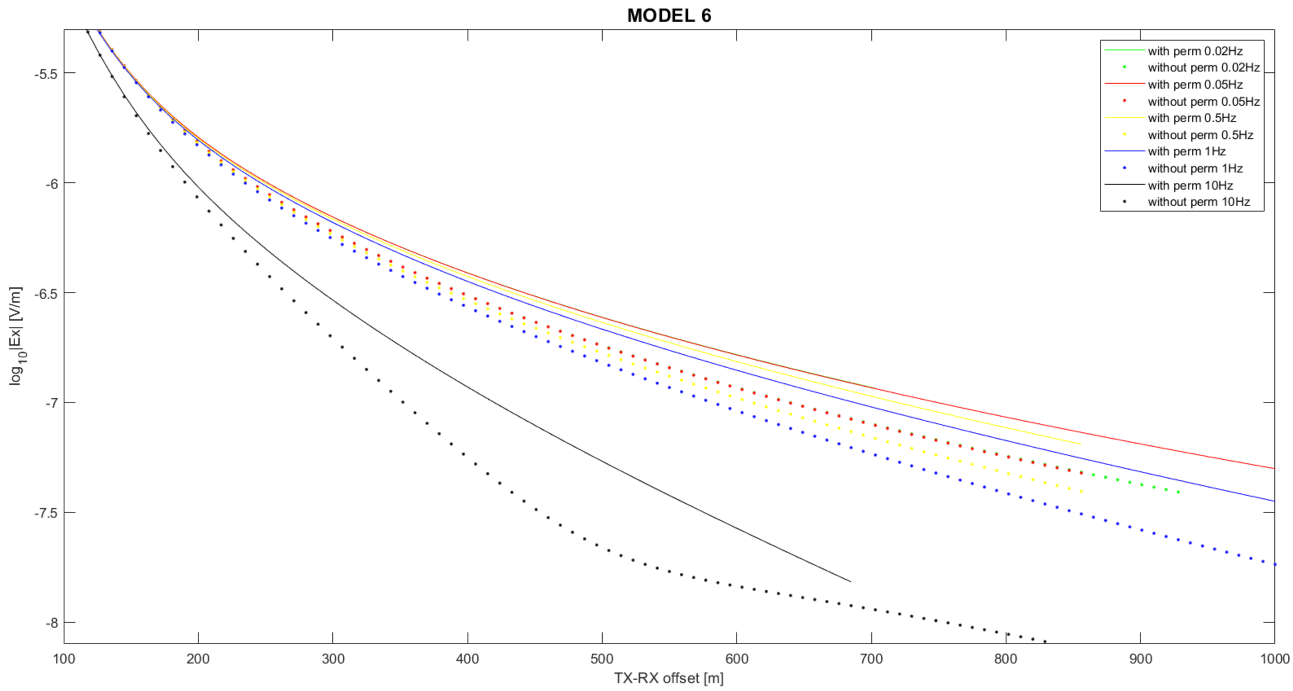

Figure 6 – Ex responses of Model 6 at different source frequencies. Solid lines represent the response of Model 6 with a strong melting permafrost layer, while dashed lines represent the response without a permafrost layer.

Model 7

Table 7 – Depths and conductivity values for a 1D subsurface model with and without a melting permafrost layer, characterized by an overlying 20 m-thick sediment layer.

	Model 7 with Perm	**Model 7 without Perm**
Water depth, h	100 m	100 m
SED thickness, k-h	20 m	20 m
PERM-ICE Thickness, l-k	100 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM ice-bearig1, conductivity, σ_2	0.01 S/m	0.7 S/m
SED BOTTOM, conductivity, σ_4	0.7 S/m	0.7 S/m

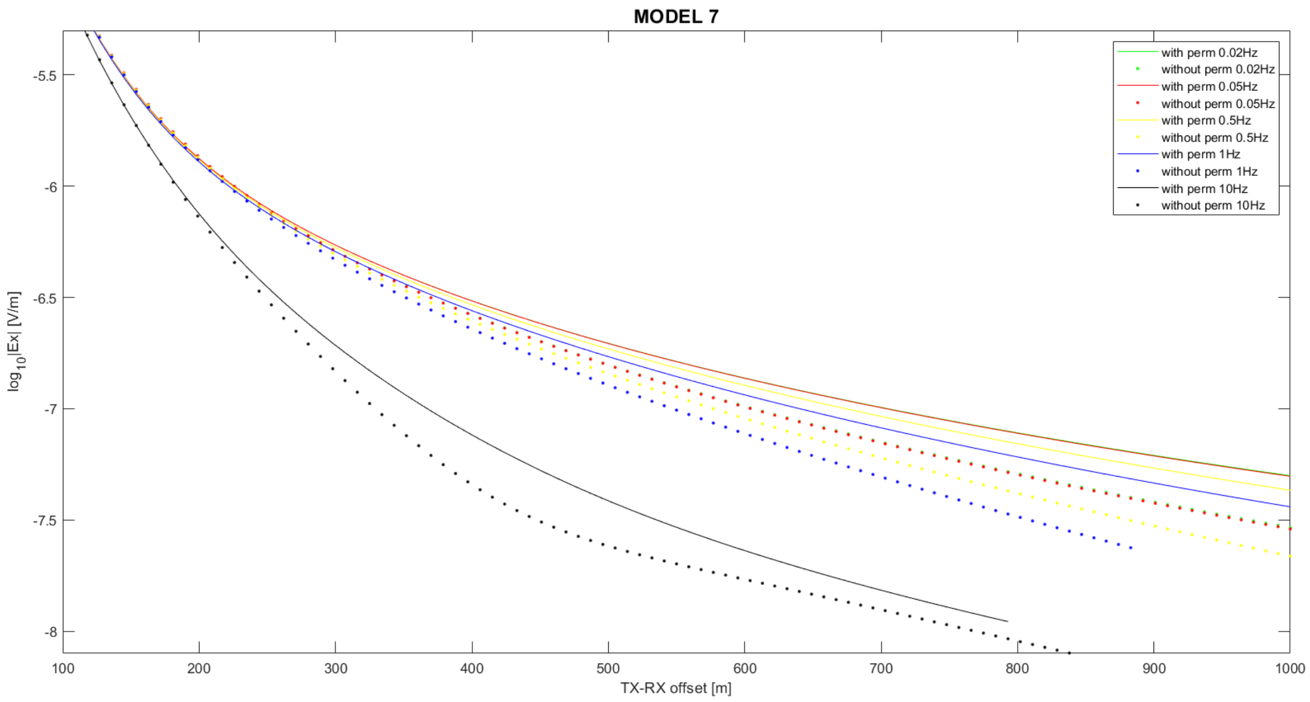

Figure 7 – Ex responses of Model 7 at different source frequencies. Solid lines represent the response of Model 7 with a melting permafrost layer, while dashed lines represent the response without a permafrost layer.

Model 8

Table 8 – Depths and conductivity values for a 1D subsurface model characterized by a 1 m-thick ice-rich permafrost layer overlying a strong melting permafrost stratum, beneath a water depth of 160 m (from Charly Paull indications).

	Model 8 with Perm	Model 8 without Perm
Water depth, h	160 m	160 m
SED thickness, k-h	8 m	8 m
PERM-ICE Thickness, l-k	1 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM-ICE, conductivity, σ_2	0.001 S/m	/
ice-bearing permafrost, conductivity, σ_4	0.1 S/m	0.1 S/m

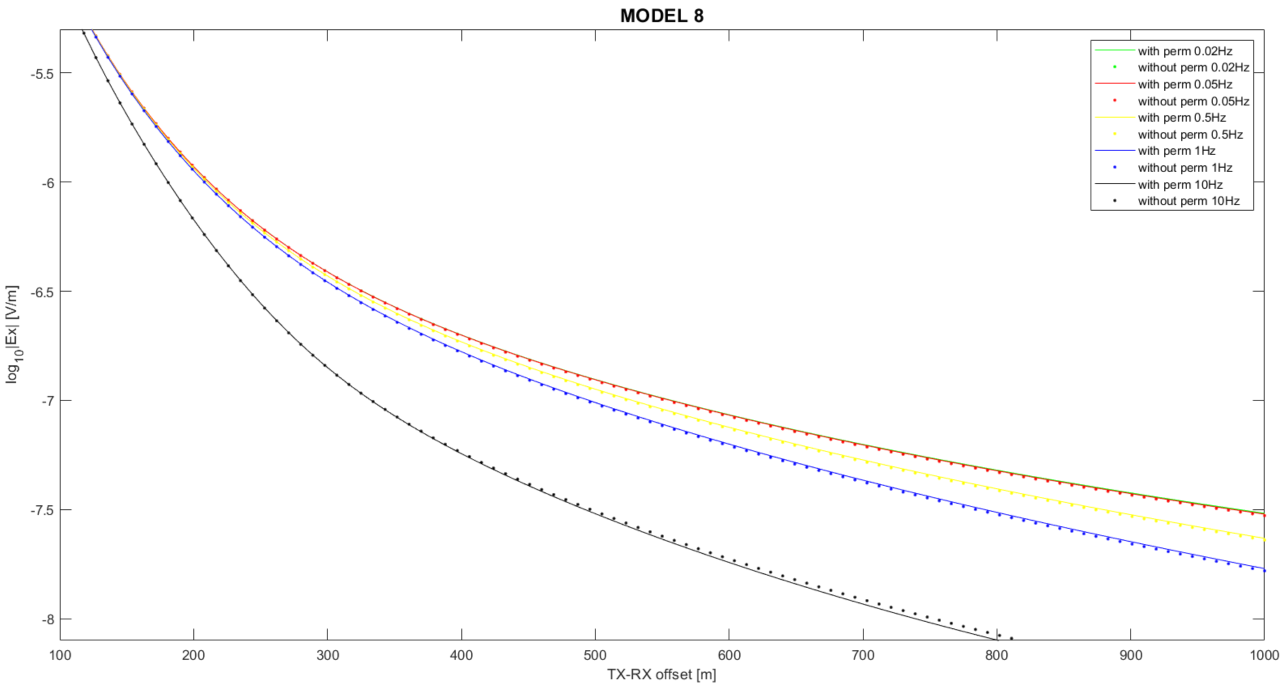

Figure 8 – Ex responses of Model 8 at different source frequencies. Solid lines represent the response of Model 8 with a ice-rich permafrost layer, while dashed lines represent the response without a permafrost layer.

Model 9

Table 9 – Depths and conductivity values for a 1D subsurface model with and without a melting permafrost layer beneath 120 m water depth.

	Model 9 with Perm	Model 9 without Perm
Water depth, h	120 m	120 m
SED thickness, k-h	8 m	8 m
PERM-ICE Thickness, l-k	100 m	/
SED TOP conductivity , σ_1	0.7 S/m	0.7 S/m
PERM ice-bearig1, conductivity, σ_2	0.01 S/m	/
SED BOTTOM, conductivity, σ_4	0.7 S/m	0.7 S/m

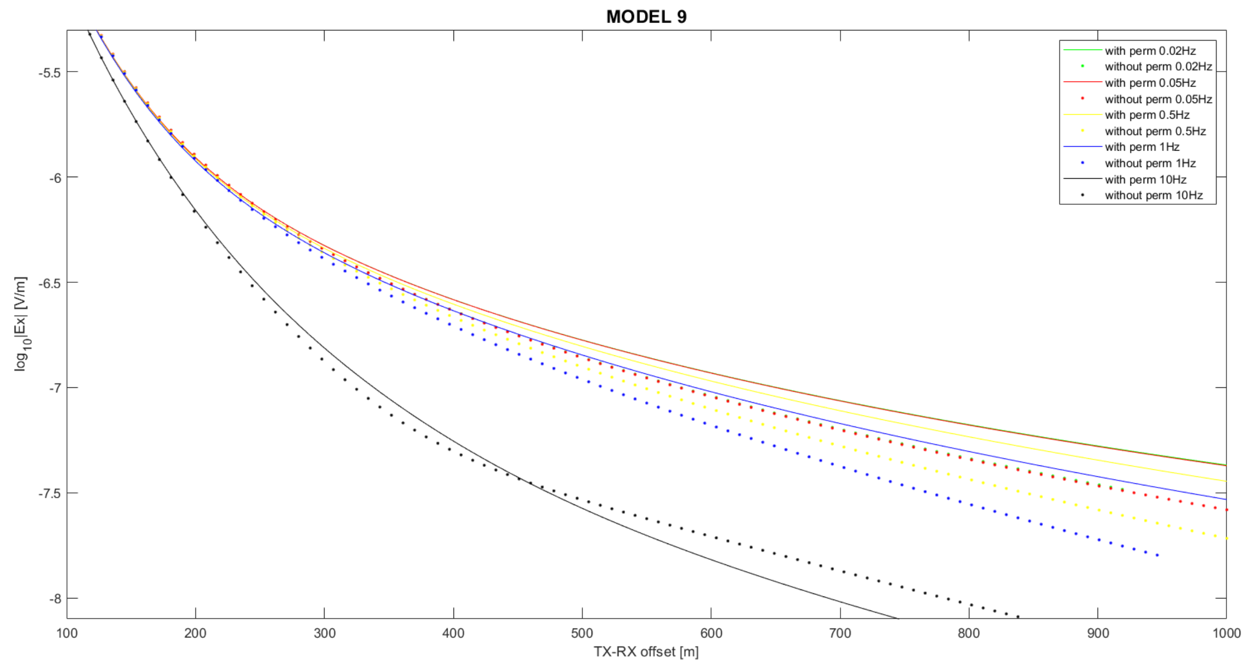

Figure 9 – Ex responses of Model 9 at different source frequencies. Solid lines represent the response of Model 9 with a melting permafrost layer, while dashed lines represent the response without a permafrost layer.

4 Analysis of the Ex-Responses in the Models

- **Short Offsets (100–300 m):**

- Across all models (1–9), the Ex responses at short offsets do not show strong sensitivity to the presence or absence of permafrost, regardless of the frequency.
- For instance, in Models 1, 2, 3, and 7, the difference between the "with" and "without permafrost" cases is minimal at short offsets, even at higher frequencies like 10 Hz.
- This implies that short offsets are not effective for resolving shallow permafrost degradation.

- **Longer Offsets (≥500 m):**
  - The difference in Ex responses between permafrost vs no-permafrost models becomes more apparent at longer offsets, particularly in melting permafrost scenarios (e.g., Models 5, 6, 9).
  - This suggests that the EM field needs more propagation distance to capture the integrated conductivity differences that arise from permafrost degradation**.**

- **Source Frequency Dependence:**
  - In nearly all the subsurface models analysed, the electric field (Ex) responses show the greatest contrast between models with and without permafrost at a source frequency of 10 Hz, particularly within the top 80–100 meters below the seafloor.
  - This holds true for both ice-rich permafrost and melting permafrost layers, even in more complex stratigraphies (e.g., with a surface sediment layer).

Table 10-Effect of Frequency on Ex Contrast

Frequency	**Ex Contrast Between Permafrost / No-Permafrost Models**	**Sensitivity to Shallow Layers**
0.02 – 0.05 Hz	Weak or negligible	Low
0.5 – 1 Hz	Moderate	Medium
10 Hz	**High**	**High**

5 Updated Recommendation:

- Recommended source frequency: 10 Hz
- To be used in combination with short to mid-range offsets (300–500 m) to maximize sensitivity to shallow conductivity contrasts.