Author responses to review comments of "Sensitivity of airborne geophysical data to sublacustrine permafrost thaw" are detailed below.

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March 2015

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Received and published: 12 January 2015

General comments

The paper examines the potential of AEM to detect the thawing stage of talik structures in sublacustrine permafrost. The study is working purely with 2D (?) synthetic data. The geophysical approach presented here is of high interest and importance for near-subsurface geophysical surveys and can be considered an example for hydrogeophysical studies in different environments. Studies, such as the presented one, can be used to enhance interpretation of AEM surveys over permafrost terrain. I would like to see this paper published in TC, but would appreciate if the following comments could be addressed:

I summarize the workings steps of the presented approach. If I made a mistake here, you could consider changing your text to a better understanding of this fact:

1. Obtainment of a realistic subsurface model for a talik structure. A previously developed hydrological algorithm (SUTRA) is used, to simulate a 1000 years of talik development, for a couple of different starting models with different lake levels and hydraulic gradients.
2. Derivation of electrical conductivity from the hydrological model parameters. An advanced form of Archies law was used. A variety of parameters are considered, as for instance temperature and ice-content.
3. For the derived electrical conductivity models (for various Talik evolution stages) 1D AEM forward calculations were done, in order to calculate synthetic AEM surveying data. Such data were calculated for subsurface models of every time step of the Talik evolution within the 1000 years.
4. A study to examine, how accurate the synthetic AEM data can be inverted to true subsurface conductivity models, using statistical approaches. Goal is to obtain likelihoods for parameters such as: number of layers, thickness of layers etc.

Response: Thank you for your comments. Your above summary of the general working steps of our approach are correct.

Reviewer comment:

The Abstract and Introduction should more prominently state, that this paper describes a study with synthetic data ONLY. 2D or 3D?

Response:
The Abstract and Introduction already contain five references to 'synthetic' or 'simulated' results- two additional instances are described below, and we also added reference to the two-dimensional axis-symmetric modeling domain. We also clarify that the hydrologic model has a two-dimensional axis-symmetric geometry- while simulations are fundamentally 2D (radial distance & depth), they represent 3D physics under the assumption of radial symmetry.

Changes:
Two sentences modified in the Abstract: "Several *numerical modeling* scenarios are evaluated that consider the response to variable hydrologic forcing from different lake depths and hydrologic gradients", and "A final *synthetic* example compares AEM and ground-based electromagnetic responses for their ability to resolve shallow permafrost and thaw features in the upper 1-2 m below ground."

Introduction, last paragraph: "The coupled thermal-hydrologic simulations of Wellman et al. (2013) predict the evolution of lake taliks (unfrozen sub-lacustrine areas in permafrost regions) *in a two-dimensional axis-symmetric model* under different environmental scenarios (e.g. lake size, climate, groundwater flow regime).

Reviewer comment:
I understand, that the study examines the ability of AEM to detect not only Talik structures in general, but to detect different stages of a 1000 years of Talik evolution. If this is correct, please state this more clearly already in the Abstract and Introduction. However, I doubt, that in reality you can assign an inverted AEM resistivity model to a stage of a 1000 years of Talik evolution. You rather will obtain a general idea of where thawed areas are situated.

Response: We do not mean to suggest that we can assign any particular resistivity interpretation to a specific stage of talik evolution over the 1000 year simulation time. We do, however, demonstrate that general subsurface thaw conditions can be identified, and that this can give insight into whether talik formation at a particular location might be relatively new or if it has been established for some time. While geophysical data represent just one snapshot in time, a comparison across different lakes in one area may be able to identify relatively new versus older taliks.

Changes:
Added to end of 1st paragraph in Section 2.4: "*AEM-derived resistivity estimates for the simulations considered here will help guide interpretations of future field datasets, identifying the characteristics of relatively young versus established thaw under different hydrologic conditions.*"

Reviewer comment:

Can you explain in the text how the variance of 100'000 different resistivity models is created by the McMC appoach? Changing starting models? Changed inversion parameters?

Response:
McMC algorithms are well documented in the literature, and we did not want to distract from the talik simulation study to review the McMC method. A Markov chain is a mathematical framework for drawing samples from the model-space posterior distribution. Each of the 100,000 samples is drawn sequentially (starting from an arbitrary point in model-space) according to the Metropolis-Hastings algorithm (cited in the paper). In contrast with traditional inversion methods that find a single 'best' model given some starting model and inversion parameters, the McMC approach samples many (100,000 in our case) models consistent with the data in order to quantify model uncertainty.

Reviewer comment:
Please specify which kind of inversion the McMC approach uses. I understand that also the McMC study needs a "normal" inversion algorithm?

Response:
McMC is, itself, an alternate to "normal" inversion approaches. Instead of being an optimization algorithm that finds a single 'best' model that fits data (plus any model regularization), McMC is a sampling method that estimates the true posterior distribution of model parameters.

Changes:
Added to the 1st paragraph of section 2.4: "*This McMC approach is an alternative to traditional inversion methods that find a single 'optimal' model that minimizes a combined measure of data fit and model regularization (Aster et al., 2005). Although computationally more demanding, McMC methods allow for comprehensive model appraisal and uncertainty quantification.*"

Reviewer comment:
How large is the noise added to the synthetic data?

Changes:
Modified 2nd sentence in Section 3.2: "The simulated data are then used to recover estimates of the original resistivity values according to the approach outlined in Section **Error! Reference source not found.**, *assuming 4% data error with an absolute error floor of 5 ppm.*"

Modified last paragraph of section 3.3: "*An error model with 4% relative data errors and an absolute error floor of 75 ppm was used for the GEM-2 data.*"

Reviewer comment:
I would appreciate if the study addresses, how accurate the resistivity models would be, without the McMC method, just simple inversion with one result and one RMS value, as this is the standard you are going to improve.

Response:
McMC does not necessarily lead to a more accurate result, but rather a comprehensive assessment of model uncertainty. We recognize that any single model derived from a simple inversion can be misleading as choices of inversion algorithm and parameters can lead to many different results that fit the data equally well. By using the McMC approach we aim to be as transparent as possible with regards to linking possible geophysical models to true simulations. This is discussed in Section 2.4 (including new changes described earlier).

Reviewer comment:
I would appreciate, if the novelty in this approach is more clearly stated. For me as a reader it was not entirely clear, whether the novelty was in the combination of several other studies to a new approach or the application of other approaches in a series, or whether there was a significantly new calculation step involved?

Response:
There are several aspects in which this work is novel, building on existing studies: (1) Our incorporation of a surface conduction term in the electrical property model that facilitates modeling of changes both as a function of ice content and lithology, (2) coupling geophysical predictions to process-based hydrologic simulations is not new, but has not previously been done for simulations of permafrost impacted hydrologic systems, and (3) uncertainty quantification of AEM findings and their implications for permafrost interpretations.

Changes:
Modified in Abstract: "*A novel* physical property relationship connects the dynamic distribution of electrical resistivity to ice-saturation and temperature outputs from the SUTRA groundwater simulator with freeze/thaw physics."

Modified in Conclusions: "Coupled hydrogeophysical simulations using a *novel* physical property relationship that accounts for the effects of lithology, ice saturation, and temperature on electrical resistivity provide a systematic framework for exploring the geophysical response to various scenarios of permafrost evolution under different hydrological forcing... A robust uncertainty analysis of the geophysical simulations provides *important new* quantitative information about the types of features that can be resolved using AEM data given the inherent resolution limitations of geophysical measurements and ambiguities in the physical property relationships"

Specific comments

Reviewer comment:
I needed quite some time to extract important information about the study from the text (synthetic only, AEM study for a lot of stages throughout the 1000 years, . . .). I made suggestions to improve the text towards a quicker understanding of these facts. In italic are text passages from the paper, normal font are comments from my side, and in red text suggestions, where I think more stringent and exact writing could improve the understanding and clearness of the text.

Abstract Page 6080: Sorry for being pedantic but the abstract is the most important section of a paper, and I would like to understand it, without reading the entire paper:

Several scenarios are evaluated that consider the response (of what???) *to variable hydrologic forcing from* (better at?) *different lake depths and* for different *hydrologic gradients*.

Changes:
Several numerical modeling scenarios are evaluated that consider the *non-isothermal hydrologic* response to variable forcing from different lake depths and *for different* hydrologic gradients.

Reviewer comment:
The model includes a physical property relationship that connects the dynamic distribution of subsurface electrical resistivity based on lithology as well as ice-saturation and temperature outputs from the SUTRA groundwater simulator with freeze/thaw physics.
Can you break it into two sentences? It took me quite some time to get the meaning of the sentence . . . After I have read the entire paper, the sentence was easy to understand, but anyway, in the Abstract it should be easy to understand without any prior knowledge about the study.

Changes:
Modified abstract: "A *novel* physical property relationship connects the dynamic distribution of electrical resistivity *to* ice-saturation and temperature outputs from the SUTRA groundwater simulator with freeze/thaw physics. T*he influence of lithology on electrical resistivity is controlled by a surface conduction term in the physical property relationship.*"

Reviewer comment:

Electrical resistivity models are used to simulate AEM data in order to explore the sensitivity of geophysical observations to permafrost thaw. It is clear that you need electrical resistivity models as an input to simulate AEM data. Can you state more specifically what is special about the resistivity models? Something like a range of resistivity models, which reflect the progressing permafrost thaw, are used as an input to calculate synthetic AEM data in order to . . .

Changes:
Modified abstract: "*R*esistivity models*, which reflect changes in subsurface conditions,* are used *as inputs* to simulate AEM data in order to explore the sensitivity of geophysical observations to permafrost thaw."

Reviewer comment:
Synthetic geophysical data (Too general, what kind of data, the AEM data?) *are analyzed with a Bayesian Markov chain Monte Carlo algorithm that provides a probabilistic assessment of geophysical model uncertainty* (too general, what kind of model?) *and resolution*.

Changes:
Modified abstract: "Synthetic *AEM* data are analyzed with a Bayesian Markov chain Monte Carlo algorithm that quantifies geophysical *parameter* uncertainty and resolution."

Reviewer comment
Major lithological and permafrost features are well resolved (by the resistivity model inverted from the AEM data?) *in the examples considered*.

Changes:
Modified abstract: "Major lithological and permafrost features are well resolved *by AEM data* in the examples considered."

Reviewer comment:
A final example compares AEM and ground-based (on a lake? Maybe the title sublacustrine is not entirely correct?) *electromagnetic responses for their ability to resolve shallow permafrost* (still sublacustrine? .. After I have read the paper it was clear that this ground study was done for the regions outside the lake, however, then the title is not covering this part of the study) *and thaw features in the upper 1–2 m below ground.*

Changes:
Modified abstract: "A final synthetic example compares AEM and ground-based electromagnetic responses for their ability to resolve shallow permafrost and thaw features in the upper 1-2 m below ground *outside the lake margin*."

Modified title: "Sensitivity of airborne geophysical data to sublacustrine *and near-surface* permafrost thaw"

Reviewer comment:
Introduction: Page 6082
. . .expected for various permafrost hydrologic conditions occurring within the 1000 years of simulated Talik formation.

Changes:
Modified last paragraph of Introduction: "This is accomplished in three steps: … (2) *generation* of synthetic geophysical data that would be expected for various permafrost hydrologic conditions *that occur during simulated lake talik formation*; and …."

Reviewer comment:
Methods: 2.1. Is the model 2D or 3D? How is ice content calculated? I would appreciate a sentence or two describing the major factor responsible for thaw in the simulation?

Response:
We state in Section 2.1 that the model is axis-symmetric- so technically it is 2D, but accounts for the 3D geometry of flow surrounding a circular lake. Regarding ice content and simulating thaw, Wellman et al. (2013) state: "The US Geological Survey (USGS) SUTRA code (Voss and Provost 2002), which simulates unsaturated flow, groundwater (saturated) flow, and heat or solute transport, was extended to incorporate the phase change between ice and liquid water by McKenzie et al. (2007). The enhanced code simulates dynamic ice formation when subsurface temperatures fall below a specified maximum freezing temperature. Ice saturation, defined as the fraction of ice in the total pore volume, varies over a specified temperature range from 0 (thus, liquid saturation=1) at the maximum freezing temperature, to 1 minus a specified residual liquid saturation at the minimum freezing temperature. As ice forms or thaws, the code accounts for latent heat of fusion, changes in thermal conductivity and heat capacity for mixtures of liquid water and ice in the pore space, and changes in the effective permeability of the porous medium as impacted by ice content." The primary driver of thaw is the transition from terrestrial initial conditions to a lake system with greater average temperatures and reduced seasonal amplitude beneath the newly formed lake.

Changes:
Added to Section 2.1: "*The phase change between ice and liquid water occurs over a specified temperature range, and accounts for latent heat of fusion, as well as changes in thermal conductivity and heat capacity for ice-water mixtures. Ice content also changes*

the effective permeability, thereby altering subsurface flowpaths and enforcing a strong coupling between hydraulic and thermal processes"

Reviewer comment:
2.2. The theory seems to be well described and cited with literature. I could not see any major flaw on the theory how it is introduced, but must admit, that I am not an expert in the presented Theory. It might be good when a dedicated expert to electrical conductivity material relations is having a look on chapter 2.2.

Response:
Thank you for your comment- this section is mainly an adaptation of the theory presented by co-author Revil in his cited 2012 work.

Reviewer comment:
Page 6081: *However, few techniques are capable of assessing the distribution of permafrost, and most approaches only capture a single snapshot in time*. Are you talking about geophysical surveying techniques? In a 1000 years evolution, isn't every geophysical survey just a single snapshot in time?

Response:
This was a generic comment meant to refer to any sort of hydrologic/geophysical/remote sensing observation. While most observations represent a single snapshot in time, there are also examples of time-lapse surveys or data logging (though of course none of these would be relevant to a 1000 year time period).

Reviewer comment:
... physical properties (e.g. electrical resistivity) are only *indirectly sensitive to physical...*

Changes:
Modified sentence in Introduction: "A challenge with geophysical methods, however, is that geophysical properties (e.g. electrical resistivity) are *only* indirectly sensitive to physical properties of interest (e.g. lithology, water content, thermal state)."

Reviewer comment:
Chapter 2.2.
. . . *associated magnetic fields* created by *the transmitter coils induce electrical currents in the*

Changes:

Modified sentence in Section 2.3: "Oscillating currents and associated magnetic fields *created by* the transmitter coils induce electrical currents in the subsurface that, in turn, generate secondary magnetic fields that are recorded by the receiver coils (Siemon, 2006; Ward and Hohmann, 1988)."

Reviewer comment:
Data are simulated at the nominal survey elevation of 30m above ground surface using the one-dimensional modeling equations described in Minsley (2011). Please explain what is special about the equations in Minsley (2011), or add something like . . . which follow the standard theory given in e.g. Ward and Hohmann (1988)

Response:
The specific algorithm used for modeling was developed in Minsley (2011), though this follows the theory of Ward and Hohmann (1988) as you mention.

Changes:
Modified last sentence in first paragraph of section 2.3: "Data are simulated at the nominal survey elevation of 30 m above ground surface using the one-dimensional modeling *algorithm* described in Minsley (2011), *which follows the standard electromagnetic theory presented by Ward and Hohmann (1988).*"

Reviewer comment
2.4.:
resistivity values throughout the 1000 year lake talik simulations. . . . resistivity values for various (or yearly, what was the time resolution of the SUTRA model?) stages throughout the 1000 years of Talik evolution?

Response:
SUTRA models have a <1 year time resolution, but here we worked with outputs at 20 year intervals.

Changes:
Modified 1st paragraph of Section 2.4: "Here, we use a Bayesian Markov chain Monte Carlo (McMC) algorithm developed for frequency-domain EM data (Minsley, 2011) to explore the ability of simulated AEM data to recover the true distribution of subsurface resistivity values *at 20-year intervals within* the 1,000-year lake talik simulations.

Reviewer comment:
an ensemble of 100 000 resistivity models is inverted from the same synthetic AEM data set (did I understand this correctly?) *,according to the Metropolis–Hastings algorithm (Hastings, 1970; Metropolis et al., 1953).*

Changes:
Modified sentence in 2nd paragraph of section 2.4: "At every data location along the survey profile, an ensemble of 100,000 resistivity models is *generated* according to the Metropolis-Hastings algorithm (Hastings, 1970; Metropolis et al., 1953)."

Reviewer comment:
3.2.:
Geophysical data (not shown) are simulated AEM data? Please specifiy.

Changes:
Modified 1st sentence of section 3.2: "*AEM* data (not shown) are simulated for each of the electrical resistivity models (e.g. Figure 4) using the methods described in Section 2.3."

Reviewer comment:
Discussion Page 6095:
Understanding the hydrogeophysical responses to permafrost . . . You mean the AEM responses? Please specify.

Response:
I meant this comment to be broader than just AEM responses. It is really the coupled hydrologic and geophysical response we are interested in (hence the term hydrogeophysical).

Reviewer comment:
. . . coupling geophysical predictions . . . Please specify geophysical

... analysis of geophysical uncertainty ... Please specify geophysical

Changes:
Modified sentence in Discussion: "We have presented a general framework for coupling *airborne and ground-based electromagnetic* predictions to hydrologic simulations of permafrost evolution, including a novel physical property relationship that accounts for the electrical response to changes in lithology, temperature, and ice content, as well as a rigorous analysis of geophysical *parameter* uncertainty."

Reviewer comment:
as well as thermally and hydrologically induced changes in permafrost over time (Figs. 8 and 9). Are you talking about the 1000 years period? Can you dicuss how resistivity changes over 1000 years is of practical use in real surveys? . . . Okay,later

in the discussion chapter you address this issue. But the sentence confuses at this position in the text.

Changes:
Modified sentence in Discussion: "In the specific examples of lake talik evolution presented here, which are modeled after the physical setting of the Yukon Flats, Alaska (Minsley et al., 2012b), AEM data are shown to be generally capable of resolving large-scale permafrost and geological features (Figure 5), as well as thermally and hydrologically induced changes in permafrost (Figure 8, Figure 9)." [*deleted phrase 'over time'].*

Reviewer comment:
The Bayesian McMC analysis provides useful details about model resolution and uncertainty that cannot be assessed using traditional inversion methods that produce a single "best" model. I would appreciate a discussion about how wrong you are, when using traditional inversion, without McMC. Isn't traditional inversion also a part of the McMC analysis? See General comments as well.

Response:
See earlier response to general comment. McMC does not necessarily lead to a more accurate result compared with traditional inversion, but it does provide substantial information about parameter uncertainty that is typically not contained in traditional inversion results. In a traditional inversion, incorporation of a specific model regularization makes the inverse problem unique and solvable, but does not convey the degree to which other models are also consistent with the data (and should also be considered).

Reviewer response:
Summary:
. . . associated with the co-evolution of permafrost and hydrologic systems. . . The evolution happens over hundreds of years, how is AEM useful here. Are you saying, that the presented model study allows to assign inverted AEM resistivity models to a stage of permafrost evolution?

Response:
Correct, we do not suggest that geophysics would be useful in monitoring change over this timescale. But the resistivity data do provide insight as to the stage of permafrost evolution at a particular location.

Reviewer response:
Table 1: How is the difference between Unit 1 and 2 characterized? Both have the same porosity. Okay, at the end of chapter 2.2. you tell it is differentiated by Xi. You

could make this clearer in Table 1 and earlier in the text. I understand Xi to be the major controlling quantity and should be highlighted more prominent.

Response:
Correct, the difference in unit 1 and 2 is their cation exchange capacity. These values are noted in the 2nd to last row of table 2. We also state in Section 2.2, "Changes in χ, representative of bulk differences in clay mineral content, are used to differentiate the electrical signatures of the lithologic units in this study (Table 1)."

Reviewer comment:
Figure 10c. Can you comment on the deeper high conductivity artifact at app. r=750 m? How is this possible with synthetic data?

Response:
The data are synthetic, but have also had realistic noise added to them. This specific location probably represents a situation where incorrect model structure was fit to the noisy data.

Anonymous Referee #2
Received and published: 2 February 2015

Reviewer Comments :
This paper demonstrates the ability of airborne geophysical techniques (AEM) to characterize subsurface physical properties associated with talik formation beneath lakes. The results of this work can help to improve techniques to both identify and delineate taliks beneath lakes and also to monitor their evolution over time. This is important for development of ground water models which are required for example, for planning mining developments and the assessment of their environmental effects. Identification of hydraulic connections between mining project components such as open pit/underground mines and tailing impoundments and surrounding water bodies is a key consideration in planning mining projects.

The paper is appropriate for publication in The Cryosphere. A few comments, from a permafrost perspective, are offered for the authors' consideration.

Methods, Section 2.1 Additional information would be useful regarding the initial study conditions such as the initial ground temperature conditions and permafrost thickness.

Response*:* Initial permafrost conditions are detailed in Wellman et al. [2013]: "The permafrost structure that existed prior to the appearance of the lake was obtained by running the model to steady state under hydrostatic conditions with a constant temperature of −2.25 °C applied to the land surface. The applied surface temperature, thermal properties, and geothermal heat flux produces a laterally continuous permafrost layer extending to a depth of about 90 m. This is the initial condition, representing the system in a state prior to lake formation"

Changes: Added sentence to end of 1st paragraph in Section 2.1, "*Initial permafrost conditions prior to lake formation were established by running the model to steady state under hydrostatic conditions with a constant temperature of −2.25 °C applied to the land surface, which produces a laterally continuous permafrost layer extending to a depth of about 90 m.*"

Reviewer Comment:
Results/Discussion For fine-grained sediments such as silt and clay, a significant amount of unfrozen water may exist below 0◦C. The unfrozen water content curve (unfrozen water vs temperature) for fine-grained material therefore differs from that for coarser grained sands and gravels. Perhaps the authors could add a bit more about the range in temperatures for which the unfrozen water content may make it difficult to determine talik boundaries. For warm permafrost conditions where temperatures are close to 0◦C one could delineate a talik from the AEM survey (due to lower resistivity) in finer grained material which is larger than that which would be defined based on only temperature (i.e. permafrost at temperatures below 0◦C).

Response: We agree that the amount of unfrozen water, which differs as a function of temperature in different types of sediments, can complicate the interpretation of talik presence/absence. In part this is complicated by the term 'talik', which does not account for the warm permafrost conditions near 0◦C that you describe. The distinction between using resistivity data to infer the presence of a talik based on unfrozen water content versus temperature is an important one to consider.

Changes: Added to end of 3rd paragraph in Section 4 (Discussion), "*Finally, it is important to note that resistivity is sensitive primarily to unfrozen water content, and that significant unfrozen water can remain in relatively warm permafrost that is near 0 C, particularly in fine-grained sediments. Resistivity-derived estimates of talik boundaries defined by water content may therefore differ from the thermal boundary defined at 0 C.*"

Reviewer Comment:
The authors mention (page 6097) that AEM data are most likely to be useful for baseline characterization of subsurface properties as opposed to monitoring changes in permafrost. Perhaps the authors could comment more on the effectiveness of delineating through taliks which is a key consideration in the identification of hydraulic connections between water bodies. What are the limitations of the technique regarding permafrost conditions as presumably the

technique would not be as useful for identification of through taliks under colder conditions where permafrost is thicker.

Response: Difficulty in delineating fully through-going thaw conditions compared with partial thaw is discussed in detail in the Discussion section. We also discuss the fortuitous nature of the Yukon Flats geology upon which this study was based, where the gravel/silt resistivity contrast helps to identify when fully-thawed conditions exist. The challenge in identifying through-going conditions would be exacerbated in thicker permafrost conditions due to the decreasing resolution of AEM data with depth.

Changes: Modified 2nd paragraph in Discussion section, "If the order of these layers were reversed, if the base of permafrost were hosted in a relatively resistive lithology, *or if the base of permafrost was significantly deeper*, AEM data would not likely resolve the overall structure with such good fidelity."

Reviewer Comment:
I would agree with the authors that for the most part under natural conditions, changes in permafrost occur over a longer time period than is practical for repeat AEM surveys. However there are situations related to human activity where repeat surveys might be practical. One situation where use of AEM as a monitoring tool might be considered is where lakes are formed behind dams. This would be the case for water supply reservoirs and for mine tailing impoundments. Over several years a talik will form as there is a significant change in ground surface temperature conditions (rapid change from a mean ground surface temperature of several degrees below 0◦C to temperatures above 0◦C). There may also be situations either natural or related to human activity where (rapid) lake drainage may occur resulting in freezing of taliks beneath the former lakes and it is not clear whether AEM might be useful for monitoring these changes.

Response: We agree that there could be some value for AEM related to baseline characterization and monitoring impacts related to large-scale infrastructure projects that could cause permafrost change over short timeframes.

Changes: Added sentence to last paragraph of Discussion section, "*One exception could be related to infrastructure projects such as water reservoirs or mine tailing impoundments behind dams, where AEM could be useful for baseline characterization and repeat monitoring of the impact caused by human-induced permafrost change.*"