

## Exploring groundwater salinization using drone-based electromagnetics in the North Sea region, Germany

B. Blanco Arrué<sup>1</sup>, R. Rochlitz<sup>1</sup>, T. Günther<sup>1</sup>, M. Ronczka<sup>1</sup>, W. Mörbe<sup>2</sup>, and M. Müller Petke<sup>1</sup>

<sup>1</sup>LIAG Institute for Applied Geophysics, Hannover, Germany

<sup>2</sup>Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany

---

### SUMMARY

The Blue Transition project accounts for the complex and cross-cutting relationships between climate adaptation and water management. In the framework of this project, a drone-based electromagnetic study targeting groundwater systems in northern Germany was performed. This research seeks to improve and advance the use of multi-patch drone-based EM inversion for groundwater exploration and aids in the development of a hydrological model to evaluate the impacts of climate change on groundwater. Data was collected over a 4 km<sup>2</sup> area, divided into seven flight patches and measuring with four different transmitter locations. Initial inversion results using data from two of the transmitter, including Bx and Bz components, show promising outcomes, identifying the fresh/saline water boundary between 50 and 150 m depth and resolving the conductive zones with deep salinization. The survey area exhibits signs of salinization with 3D conditions, making sAEM a preferred method for investigating deep salinization zones.

**Keywords:** CSEM drone-based, groundwater systems, 3D inversion, conductivity models.

---

### INTRODUCTION

In times of climate change, Blue Transition (BT) is an *Interreg Europe* North Sea Region project aiming for a systematic change by integrating water and soil management and balancing urban, agricultural, and natural activities. This interdisciplinary project aims to ensure the quality and quantity of water for the future while helping revitalize natural habitats and reduce CO<sub>2</sub> emissions.

Electric or Electromagnetic (EM) methods can provide valuable data to feed into hydrological models by imaging subsurface structures and characterize processes based on physical properties, especially when imaging conductivity subsurface structures. Geophysical techniques at various scales, integrating airborne spatial data with sparsely distributed geophysical and borehole data, have been successfully employed to map saltwater intrusion (Gottschalk et al. 2020), as well as to study freshwater lenses and hydrogeological conditions in the coastal areas of northern Germany (e.g., Siemon et al. 2009, 2015). EM methods such as semi-airborne electromagnetic (sAEM) have proven very effective and accurate in deep mineral exploration (Becken et al. 2020) using helicopters. In contrast to purely airborne electromagnetic (EM) methods, sAEM offers better penetration depth due to a strong-grounded source and larger transmitter-

receiver offsets, which is crucial for targeting deep salinization. Recently, the rapid development of drones as carriers for geophysical sensors such as magnetometers provides a cost-effective alternative to the helicopters (Kotowski et al. 2022). While previous investigations focused primarily on mineral exploration targets, applying these methods on exploring groundwater resources has yet to be fully promoted.

We present a case study utilizing a multi-patch 3D inversion of drone-based sAEM data recorded in the Minstedt region in northern Germany. The objective is to enhance the understanding of groundwater systems by delivering 3D conductivity models down to a depth of approximately 300 meters at this specific site, facilitating the identification of the fresh and saline groundwater boundary and the occurrence of clayey sediment layers. The results obtained from the drone-based controlled-source EM is compared with geological information and existing wells in the study area, and will be integrated with electrical resistivity tomography (ERT) and SkyTEM data. This integration will aid in the creation and enhancement of a comprehensive hydrogeological structural model for the region.

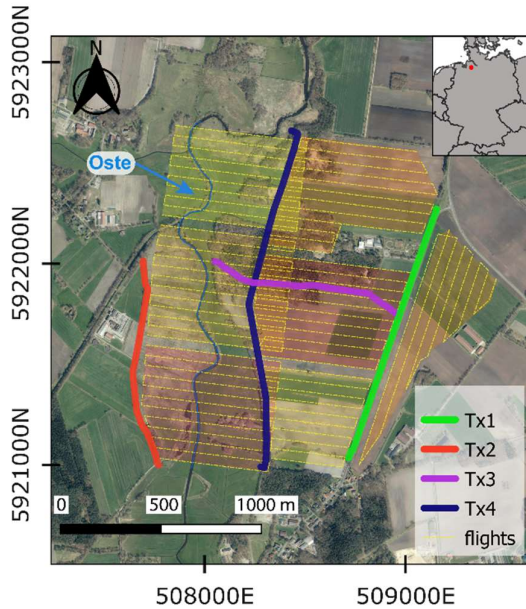
---

EMIW2024 abstracts are distributed under the Creative Commons Attribution 4.0 Unported License. Authors retain the copyright of the abstract but grant any third party the right to use the abstract freely as long as its original authors and citation details are identified.

To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>

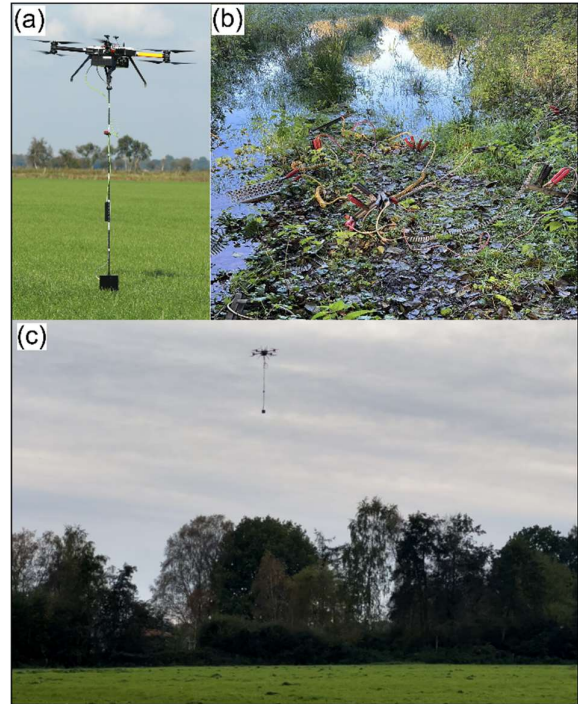
### SURVEY AREA

The Minstedt area is part of the Geest Adaptation pilot in Lower Saxony, Germany (GE2 Geest Adaptation, 2023). In this area, it is anticipated that climate change will adversely affect the groundwater's quality and volume. Specifically, the Minstedt region shows signs of groundwater systems' salinization at approximately 120 m depth (chloride concentration > 250 mg/L), rendering them unsuitable for drinking water provision. Figure 1 illustrates the study region in Minstedt, which was segmented into seven distinct flights, from here called patches, to enhance the efficiency of drone flight operations. Within the study area, sAEM measurements were conducted, covering a region approximately 2 km x 2 km in size.



**Figure 1.** Survey area with drone-flight patches (colored areas) located in the Minstedt region in Germany. The thick lines are four different grounded dipoles transmitters.

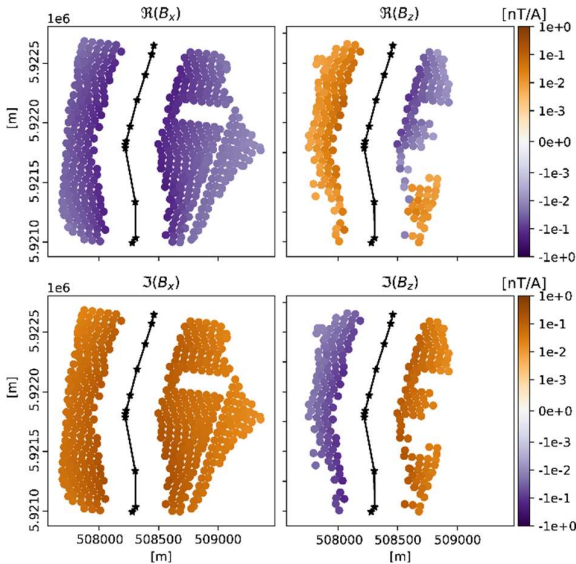
The entire Minstedt region was surveyed using various grounded transmitter dipoles (Figure 1): Tx1 (1.32 km), Tx2 (1 km), Tx3 (0.98 km) and Tx4 (1.76 km). Figure 2 presents the drone, encompassing their sensors and part of the fieldwork conducted in the study area. During the course of four days, an amount of 27 flights missions (each about 20 min) were recorded, surveying over 48 km densely covered with a line spacing of 50 m. The altitude for the drone flights was set at 40 m above the ground with an average constant speed of about 6 m/s.



**Figure 2.** (a) Drone equipped with IMU, ADU, and SHFT sensors. (b) Grounding electrodes installation. (c) Minstedt area.

### DRONE-BASED EM DATA

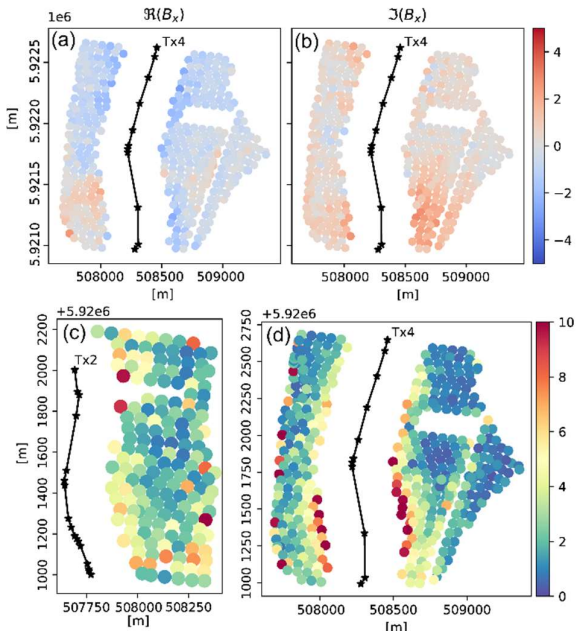
Data processing consisted of calculating the transfer functions, including noise removal and total signal recovery, steps previously outlined in the contribution presented by Becken *et al.* (2020). The multi-patch inversion was performed with *custEM/pyGIMLi* (Rochlitz *et al.* 2023). Within the data processing, frequencies under 55 Hz and over 16 kHz, along with frequency bands showing clear drone noise were excluded. In addition, data within 200 meters distance to the transmitters was disregarded. After the post-processing stage, the data for each transmitter were inverted separately and the quality of all components was assessed. Ultimately, 16 frequencies were selected for the inversion process. Errors are estimated, including a relative contribution of 5% and a minimum error floor of 2.5 nT/A. Data entries with absolute errors above 0.1 nT/A and relative errors exceeding 50% were excluded. This analysis offers a clearer insight into the locations with the highest errors. The preliminary findings include a display of the spatial distribution of the components  $B_x$  and  $B_z$  of the Tx4 data set at 2048 Hz shown in Figure 3. In order to validate the quality of each transmitter data set, we included in the inversion the high-intensity components  $B_x$  and  $B_z$  using the good-quality transmitter data sets. Here, the  $B_y$  components were excluded in subsequent inversion runs, which only used the north-south transmitters.



**Figure 3.** The spatial distribution of the magnetic transfer functions at 2048 Hz for transmitter Tx4 in Bx (left) and Bz (right) components. The complex-valued estimates are illustrated in real (top) and imaginary parts (bottom).

**RESULTS**

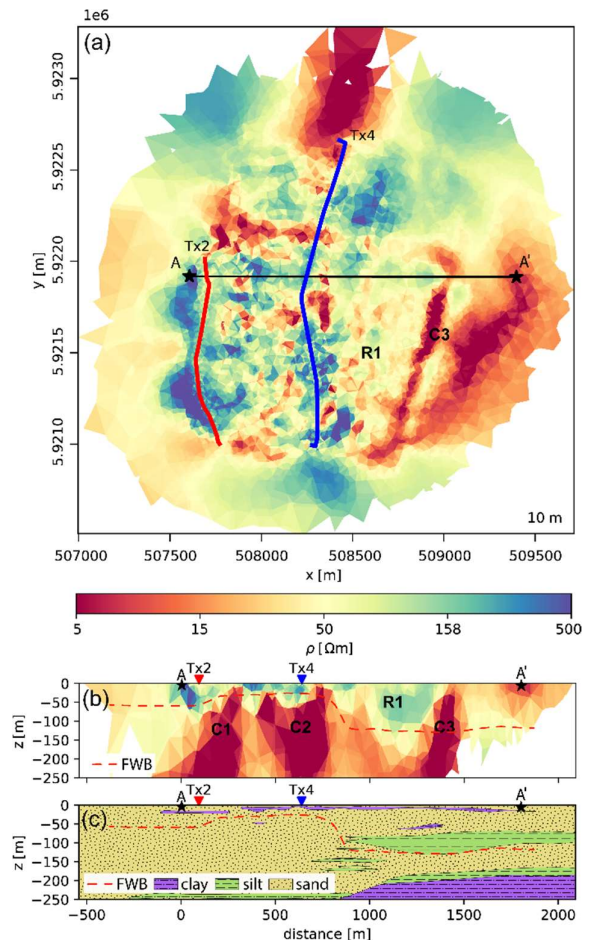
The multi-patch inversion results presented here include Bx and Bz components of Tx2 & Tx4 data exhibiting already fast convergence with less than ten iterations. Figure 4 illustrates the misfit distribution of the Tx4 data set at 2048 Hz.



**Figure 4.** The error-weighted spatial misfit distribution of the magnetic transfer functions at 2048 Hz for transmitter Tx4 in (a) Bx and (b) Bz components. Global misfit of (c) Tx2 and (d) Tx4.

The summary of component versus frequency misfit statistics indicates consistent distortions in the processed data when some combinations do not align well with most others. This will be examined in more detail and improved in the future. However, most receiver points show overall misfits below 2, suggesting that the data is well-fitted.

Figure 5 shows the inversion results for the multi-patch inversion of the Tx2 & Tx4 data sets. A chi-squared data fit of 2.75 was obtained after 7 iterations. At a depth of 10 meters, the plan view reveals multiple minor resistive features, and a strong conductor C3 that coincidentally follows one of the roads in the study area. Therefore at this stage, is not considered for geological interpretations.



**Figure 5.** Inversion results using Bx and Bz components of Tx2 & Tx4 data sets. (a) Z-plane view at 10 m. Black line shows profile A-A'. (b) X-plane view along profile A-A'. (c) Lithology of the study area. FWB: freshwater boundary.

The section along profile A-A' reveals that conductors C1 and C2 are dominant and exhibit high conductivities of around 5 ohm-m, suggesting the presence of substantial deep salinization. Furthermore, only very shallow fresh water levels

are observed in the west, with a slight transition at approximately 50 m depth. Conversely, in the east, a deeper fresh water zone between 700 and 1300 m, labeled as R1, is prominent. This finding was validated and aligns well with the geological characteristics of the area, where the boundary of the fresh water matches closely with the C1 and C2 zones (see Figure 5b and c). Lateral variation are also observed in the top of the FWB zone, especially where conductors C1 and C2 emerge at the surface (~400 meters from A along A-A' profile). On this regard, further analysis is needed to determine whether there is a link between the conductor bodies and the deep salinization.

Additionally, the ultimate model needs to be combined with borehole data to more effectively distinguish between silt layers, clay lenses and salt water. Future studies will incorporate topography, as the lowest elevation is where the Oste River is located and where C1 appear on the surface. In the next inversion stage, the transmitters oriented East-West will be also included in an overall multi-patch inversion to provide more detailed 3D subsurface conductivity structures.

#### CONCLUSIONS

The presented resistivity models based on a four-day drone-based sAEM survey in a region of about 4 km<sup>2</sup> provide detailed 3D information about the subsurface structure and in particular, salinization zones, with penetration capabilities down to at least 200 m depth. Consequently, the sAEM technique is regarded as highly promising for efficiently imaging groundwater systems in 3D. The initial results presented here show that comprehensive multi-patch inversion involving two transmitters already offers a nice 3D model with promising features, identifying the fresh water border between 50 and 150 m depth. It is expected that an inversion with all transmitter data sets and all components can produce an even more detailed subsurface model. A thorough analysis of these results, considering existing boreholes and evaluate these inversions with other geophysical data, such as SkyTEM and ERT measurements is planned. Validating these findings through well data is essential, particularly in wells that have shown deep salinization. This research aims to enhance and solidify the application of groundwater exploration using drone-based EM surveys and contributes to the hydrological model assessing the effects of climate change on groundwater.

#### ACKNOWLEDGEMENTS

We would like to express our sincere gratitude and appreciation to Philipp Kotowski from the University of Münster for all the data processing support. We

thank the LIAG crew that helped in the field and all those who contributed to the development of this contribution: Frank Oppermann, Carlos Lehne, and Saeed Nazari. This project is co-funded by the Interreg North Sea Region (Blue Transition, project number 41-2-12-22).

#### REFERENCES

- Becken, M., Nittinger, C.G., Smirnova, M., Steuer, A., Martin T., Petersen H., Meyer U., Mörbe W., Yogeshwar P., Tezkan B., Matzander U., Friedrichs B., Rochlitz R., Günther T., Schiffler M., Stolz R., and the DESMEX Working Group. (2020): A novel system development for semi-airborne electromagnetic exploration. *Geophysics* 85(6): E253-67. doi: 10.1190/geo2019-0336.1
- GE2 Geest Adaptation: Effects of peatland renaturation on groundwater system. Blue Transition | Interreg North Sea. <https://www.interregnorthsea.eu/blue-transition/pilots/ge2-geest-adaptation> Accessed June 2024.
- Gottschalk, I., Knight, R., Asch, T., Abraham, J., & Cannia, J. (2020). Using an airborne electromagnetic method to map saltwater intrusion in the northern Salinas Valley, California. *Geophysics*, 85(4), B119-B131.
- Kotowski, P. O., M. Becken, A. Thiede, V. Schmidt, J. Schmalzl, S. Ueding, and S. Kligen, 2022, Evaluation of a Semi-Airborne Electromagnetic Survey Based on a Multicopter Aircraft System: *Geosciences*, 12, 26.
- Rochlitz, R., Becken, M., & Günther, T. (2023). Three-dimensional inversion of semi-airborne electromagnetic data with a second-order finite-element forward solver. *Geophysical Journal International*, 234(1), 528-545.
- Siemon, B., Christiansen, A. V., & Auken, E. (2009). A review of helicopter-borne electromagnetic methods for groundwater exploration. *Near Surface Geophysics*, 7(5-6), 629-646.
- Siemon, B., Costabel, S., Voß, W., Meyer, U., Deus, N., Elbracht, J., Günther, T. & Wiederhold, H. (2015). Airborne and ground geophysical mapping of coastal clays in Eastern Friesland, Germany. *Geophysics*, 80(3), WB21-WB34.