
# An AEM experience in Northern Italy. Innovative and multidisciplinary approach for a modern groundwater and land management

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## SUMMARY

Climate changes are strongly affecting water supply all around the world and Northern Italy does not make exception to this. In addition, pollutant contamination due to human, both industrial and farming, activities is increasingly spreading in the high Po Plain region and its lateral valleys. Hence, in 2021 an AEM survey has been conducted, aiming at the identification of unknown water reservoirs, on an area of about 200 $km^2$ located West of the Garda Lake. A time-domain transient EM system (SkyTEM) has been used to perform airborne measurements.

To address the complex depositional environments typical of the subalpine region, the resulting geophysical data, joint with lithological data collected from wells in the last decades, have been interpreted through a cognitive approach.

Where neither electromagnetic nor lithological data were available, a number of ground TDEM tests has been performed to cover the lack of knowledge.

The 3D geological model has been constructed manually as a voxel model with lithofacies attributes supplemented by several bounding surfaces. Two different modelling methods have been combined, namely smooth and sharp, allowing to get the geological complexity.

Starting from the geological model and based on an *ad hoc* piezometric campaign, carried out in the meanwhile on the same area, two 3D FEM flow models has been developed, namely a steady-state one and a transient one.

These achievements have allowed us to understand complex operational situations and to manage them with robust awareness.

In the light of these promising results, we have decided to extend the investigation on a wider area, covering further 1700 $km^2$. The whole activity will provide a detailed database, from which impressive multidisciplinary applications can be inferred. Amongst them, priority will be given in kettling drought effects, assessing groundwater vulnerability and evaluating geotechnical phenomena, such as saturated loose sand liquefaction.

**Key words**: airborne, cognitive approach, geological model, flow model, operational managing.

## INTRODUCTION

"*Ensure availability and sustainable management of water and sanitation for all*". This statement introduces the $6^{th}$ goal claimed by United Nations in the Sustainable Development Goals for 2030. Facing this goal requires, firstly, the identification of new water reservoirs for future generations. But this is not enough. The same importance does take the assessment of impacts arising from current land management, in terms of traditional and emerging pollutants, and the ability to predict how climate change scenarios could affect the hydrogeological cycle.

On all these themes depends not only drinking water availability, but also sanitation, hygiene and water-related ecosystems survival. Hence, the major scopes of the present work.

The region we live in, located between the Alps' piedmont district and the high Po Plain region, suffers from pollution induced by industrial activity, large-scale agriculture and intensive livestock farming. In addition, in the last years a lack of groundwater recharge during the fall and winter seasons is observed. This phenomenon can be related to the modified rainfall characteristics, since the usual long-duration moderate precipitations are increasingly replaced by short-duration intense events. In such situation, a numerical groundwater flow model becomes fundamental for a water public utility.

Usually, hydrogeological assessments and predictions are made on the basis of boreholes from wells. Even if hundreds of data from wells are available in the study area, they mainly concentrate near residential zones, along the Chiese river, hence large extensions of land are lacking information and, due to the peculiar complex geological structure, additional data within the deficient portions of land are needed.

We find that investigations by airborne electromagnetism of the time-domain type could be the more appropriate, detailed, time-saving and money-saving method to gain this target, following the remarkable examples all around the world (Auken et al., 2017; Ley-Cooper & Richardson, 2019; Munday, 2013; Kang et al. 2022; Knight et al., 2018).

As pioneering experience in our province, we conducted a first campaign in 2021, when 212 $km^2$ were flown in less than 15 days (Figure 1). This has led to a great amount of data, processed and interpreted by a cognitive approach, which involved a multidisciplinary team made of geophysicists, geologists and hydrogeologists.

As a result, we have got 120 thousand geophysical models (60 thousand with smooth inversion and 60 thousand with sharp one). From them a 3D geological model and two 3D flow models, for steady-state regime and transient one as well, have been obtained. These first results have provided insightful explanations of well-known operational problems, unresolved till now.

Given these promising achievements, a second campaign has been started in March 2023, covering further 1.717 $km^2$ in 97 days. This new survey aims at even more challenging targets, deemed essential for a sustainable and responsible management of land and geo-resources use. Hence, present and future efforts are oriented towards drought effects mitigation by artificial recharge of shallow aquifers (San-Sebastián-Sauto et al., 2018; Sendrós et al., 2020; Teatini et al., 2020) and groundwater protection (Thomsen et al., 2004). Geotechnical applications are in our sights as well, such as landslides mapping (Thiery et al., 2021; Pfaffhuber et al., 2010), seismic bedrock tracking (Christensen et al., 2015), evaluation of waste bodies conditions (Hammack et al., 2010) and liquefaction hazard assessment.

## METHOD

### Time Domain Electro-Magnetic method

To obtain information at basin scale and high depths, a helicopter electromagnetic survey was carried out, with the SkyTEM system (Sørensen & Auken, 2004). This is a time-domain helicopter electromagnetic system (TEM) designed for hydrogeophysical, environmental and mineral investigations (Viezzoli et al., 2012).

With the time-domain method, the signal amplitude is measured as a function of time. The system mainly consists of a transmitter coil (Tx) and a receiver loop (Rx). A current is transmitted in the Tx loop and is abruptly turned off. This generates an electromagnetic field, which induces an electrical current in the surroundings, which in turn induces a secondary magnetic field. The receiver coil records a series of voltages related to the change in the secondary magnetic field over time (dB/dt), which provide information on the electrical conductivity of the ground. The voltages are recorded through time windows (gates).

The sampling approach is based on using the same number of gates per decade of time. The gates have a width increasing logarithmically with time, a configuration called log-gating (Munkholm & Auken, 1996).

The raw data acquired in 2021 were processed and inverted by EMergo, who has been asked to develop two different geophysical models, in order to achieve the most reliable geological modelling, by means of two different inversion methods: *smooth* and *sharp*.

By the *smooth inversion* the half-space is discretised in several layers whose thickness logarithmically increases with depth. This inversion strategy gets the solution that involves a gradual variation of model parameters in space.

Figure 2a shows an example of *smooth inversion*. In the magnified boxes, the gradual transition between two different layers is shown: a shallower resistive layer (~ 200 $\Omega$·m) and deeper conductive layer (~ 1 $\Omega$·m). The resistivity of these two layers ranges gradually from 200 $\Omega$·m to 1 $\Omega$·m. Generally speaking, this condition is satisfied in sedimentary environments, with parallel sub-plane geometries, where facies exhibit broad lateral continuity and an effective vertical gradual variation.

The *sharp inversion* (Vignoli et al., 2014) promotes the reconstruction of blocky solutions, using a parametrisation characterised by several layers (like smooth inversion strategy), by minimising the volume where the spatial model variation is non-vanishing. *Sharp inversion* reconstructs electrical subdomains in which parameters are free to change under a certain threshold. This approach ensures that the results are consistent with the measured data while favouring, at the same time, the retrieval of horizontal abrupt changes. In addition, the focusing regularization can also be applied in the horizontal direction, in order to promote the reconstruction of lateral boundaries such as faults (Vignoli et al., 2014).

Figure 2b shows an example of *sharp inversion*. The magnified boxes show how the transition between two bodies can be defined, when a sharp contrast in electrical properties characterises them.

In general terms, this inversion strategy is more suitable than *smooth inversion* when the layer has an effective sharp spatial variation of model parameters. For example, it applies suitably where structural elements or magmatic intrusions do prevail in the investigation area.

### Data cognitive interpretation and overall framework

The geological model is developed with a cognitive approach, in which all available data (AEM data surface geological map, stratigraphic boreholes, etc.) and the overall conceptual geological knowledge are combined and translated into a manually interpreted 3D model (e.g., Sapia et al. 2015, Høyer et al., 2015, Jørgensen et al., 2013).

For the overall model construction, we used the software package GeoScene3D (https://geoscene3d.com/). This software promotes the visualisation of data by cross sections, horizontal sections, map views and 3D view (Jørgensen et al., 2015).

As stated by Jørgensen et al. (2015), the cognitive layer model is developed as a framework model consisting of layers that are defined as bodies between surfaces. These last are, in turn, controlled by interpretation points defined in space and manually digitised and attached to cross sections, horizontal sections, boreholes, geophysical sections, etc., according to the modeller's geological interpretations. Most interpretation points are attached to cross sections that were gradually moved through the model space and checked against perpendicular moveable cross sections. The interpretation points are instantaneously interpolated into surface grids, providing an instant overview of the surface or boundary being modelled.

In addition to the cognitive approach, the geological model takes its robustness upstream of the process, during the AEM survey itself. During the 2021 campaign, the continuous interaction between A2A geologists and EMergo geophysicists made possible to cope with the many difficulties inherent in the study area and to better plan the acquisition of the following days.

The information interchange between geologist and geophysicist during the survey has led to the best geological interpretation, achievable from the numerical processing of raw data. This interaction resulted in a good knowledge of the subsurface, which was used as a basis for geological modelling.

### Groundwater model with FeFlow

Three-dimensional numerical modelling was performed using FeFlow 7.4 software (*Finite Element subsurface Flow system - WASY GmbH*), based on the finite element method (FEM). The

Darcy's equation of flow is solved within a grid-discretised domain (mesh).

The choice of the FeFlow code is justified considering the complex geometries of the subsurface in the study area. With a finite element software, it is possible to implement a groundwater model without making simplifications to the geometries elaborated during the geological modelling phase.

In a first phase of the work, we set up a 3D-type problem in which a steady-state flow was simulated. In a second phase of the work the 3D-type problem considered a transient flow. Both models were implemented by considering a flow without mass and/or heat transport, within a saturated aquifer under unconfined conditions, considering a free water table surface.

For the implementation and calibration of the steady-state model, we used the piezometric values collected during the 2021 monitoring campaign. The hydraulic properties of the aquifer were defined from literature data and field tests, while the conductance of the riverbed was defined from literature values only (e.g., Chen et al., 2013; Naganna et al., 2017; Stewardson et al., 2016; Tang et al., 2018).

The transient model was implemented from the calibrated steady-state model, where the hydraulic conductivity of the aquifer and the conductance of the riverbed were automatically calibrated by a PEST analysis (J.E Doerthy & R.J. Hunt, 2010).

The transient modelling was carried out in two phases. In the first phase, the hydrological dynamics for the year 2020 was modelled, based on the time series coming from hydrological model returned by the software TOPKAPI. The purpose of this phase was to calibrate the model so that the groundwater recharge dynamics could be optimally reproduced. For the calibration, four representative reference points have been considered. In particular, the Pearson correlation coefficient (r) and the root mean square deviation (RMSE) were assumed as statistical criteria.

Whitin the second phase, three future climate scenarios models (RPC8.5, RPC4.5 and RPC2.6) was developed, for the years between 2071 and 2080, assuming as a starting point for the boundary conditions the time series modelled by TOPKAPI.

## RESULTS

### 3D geological model

The 3D geological model, developed by the AEM data, is shown in Figure 3.

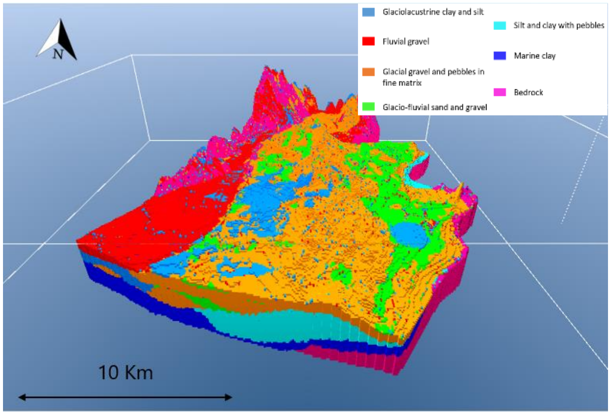


**Figure 3. 3D geological model.**

By developing the 3D geological model, we could identify two different geological domains: fluvial domain and glacial domain (Figure 3).

The glacial domain, covering the Eastern portion of the study area, is characterised by an alternation of heterogeneous deposits due to the presence of glacial depositional environments. The overall thickness is quantified in approximately 300 m and lays on the bedrock.

The fluvial domain, pertaining to the western portion of the area, is characterised by the recent fluvial deposits of the Chiese River, mainly composed of coarse gravels and pebbles, delimited in depth by deep fine deposits.

It is worth noting that, from the geological model, the two domains appear to be separated, due to bedrock rising. The only portion where the two domains come into contact is the southernmost part of the model where they overlap in angular unconformities.

Finally, by reconstructing the geometries of the glacial domain, we have observed that on the coast of Garda Lake (eastern limit of the geological model) the slope of the glacial deposits and the rise of the bedrock ensure that no interconnection between the lake and the aquifer is possible.

### Groundwater model results

The fluvial deposits of the Chiese River represent the main aquifer in the study area, therefore the 3D groundwater flow simulation focused on the recent and current fluvial deposits.

The 3D steady-state groundwater model has been initially calibrated manually by *trials and errors* and, successively, by an automatic procedure with PEST.

The achieved results return a RMSE of 0.53 m and an average absolute error of 0.42 m (Figure 4). The piezometry from the model and the data collected during the piezometric campaigns show a very good agreement. Moreover, the model is able to take into account the effects given by the geometry of the fluvial aquifer, by the external inputs related to surface water (Chiese River, percolation and lateral flow) and by the lateral inputs from the carbonate bedrock (West side of the studied area).

The 3D transient model was calibrated using *trials and errors*. Groundwater levels from the 2020 time series in the 4 observation wells were used as comparison data (Figure 5). The final calibration of the model resulted in an RMSE of 1.91 m and an average correlation coefficient (r) equal to 0.73. In particular, the model is able to reproduce the different recharge dynamics in the areas identified during the hydrogeological characterisation phase.

After this calibration phase, the three future climate scenarios were applied. Scenario RPC2.6 is considered the optimal scenario, close to the current meteo-climatic values. Scenario RPC8.5 represents the most unfavourable case, while the scenario RPC4.5 is intermediate between the two previous ones. As far as the modelled water balance volumes are concerned, variations consistent with the meteoclimatic forecasts are observed. In particular, for all three scenarios a negative aquifer storage (loss) is observed. The order of magnitude is approximately $10^3$ $m^3$/day. A 35% increase in loss between the RPC2.6 and RPC8.5 scenarios is obtained. This is mainly due to the reduction in volumes exchanged between the river and the aquifer (with a 10.5% reduction in the river's contribution) and between the bedrock and the aquifer (with a 3% reduction in the lateral water supply).

## SURVEY 2023

The recent campaign, started in March, has covered the major part of the district area (Figure 6). Inside it, we have distinguished four different compartments, according to different geo-lithological and structural peculiarities.

**Figure 6. District under investigation: province of Brescia, in Northern Italy (modified from www.originalmap.it).**

This new survey does not represent a mere aerial expansion of the previous one. In fact, thanks to progressive expertise, acquired in progress, we could focus on the several applications that deserve attention (Figure 7).

In the mountain zone, efforts are devoted to the identification of proper sites for perforating new drinking water wells in fractured rock masses.

In the Western Garda Lake area, opportunities for new enhancements in recent neotectonics activity come to the fore. In the plain portion, artificial recharge of shallow aquifers and groundwater protection are priority targets.

The southernmost part of the Po Plain, apart from drought problems affecting agriculture, suffers from poor geotechnical characteristics and coseismic effects, like loose sand liquefaction.

At present, all these targets are in progress. Hence, *in itinere* preliminary results will be presented.

## CONCLUSIONS

Starting from this pioneering experience for Italy, a great amount of work is in progress and an even greater quantity awaits us for the future.
The only conclusion, up to now, is that AEM methods together with cognitive interpretation for geological modelling do represent the most promising tool in facing environment-related problems and climate changes. From them, technicians, georesources managers and politicians can no longer escape.


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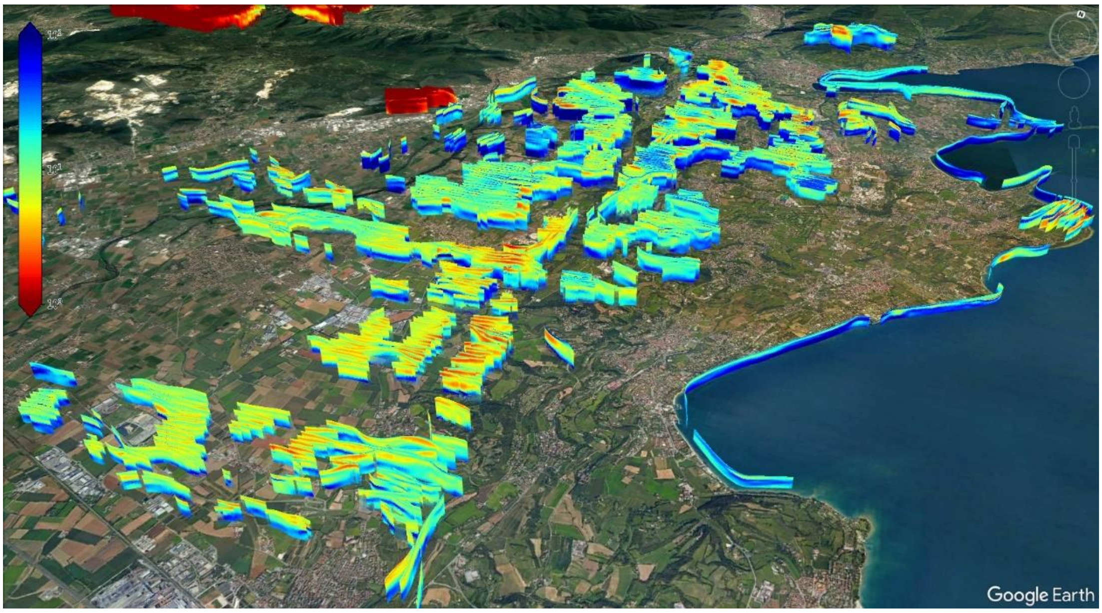


**Figure 1. Aerial overview of the flight lines from 2021 survey, with contour plots of the electrical sections (from Google Earth).**

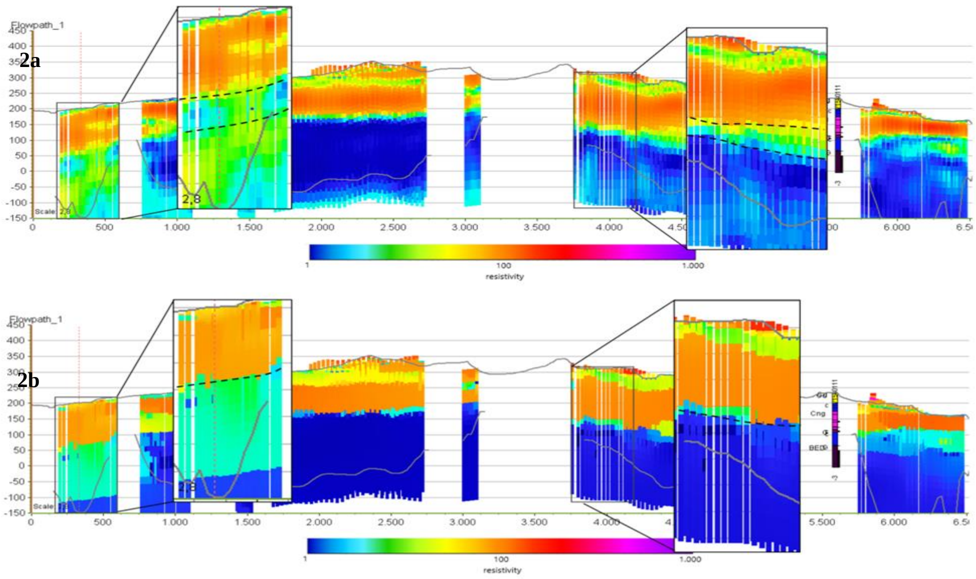


**Figure 2. 2D section of smooth (a) and sharp (b) electrical model. Grey curves represent DOI (Depth of Investigation).**

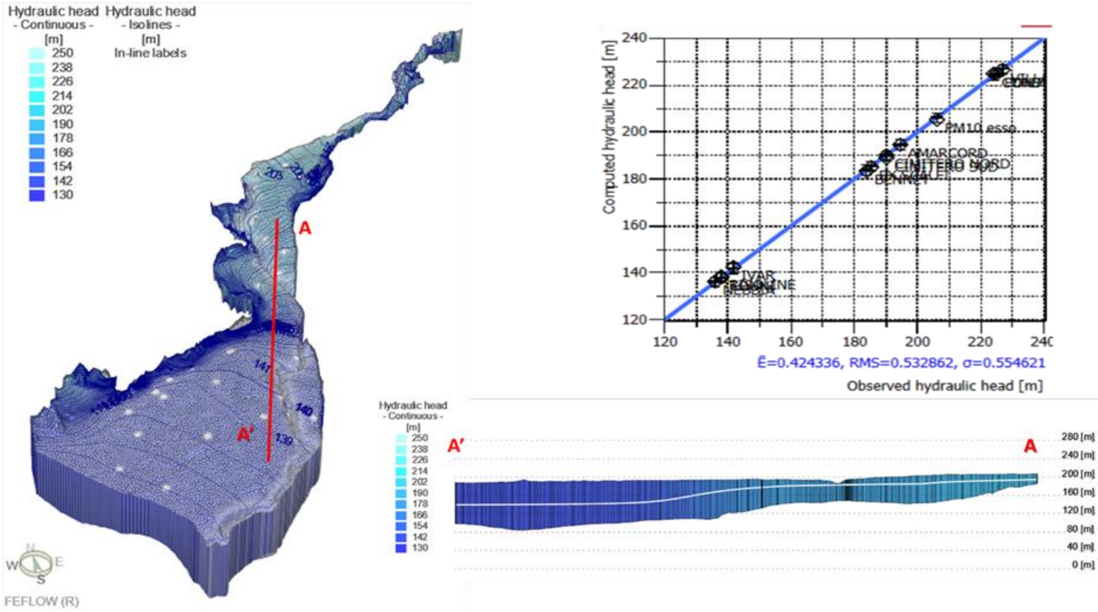


**Figure 4. Results of steady-state model calibration.**

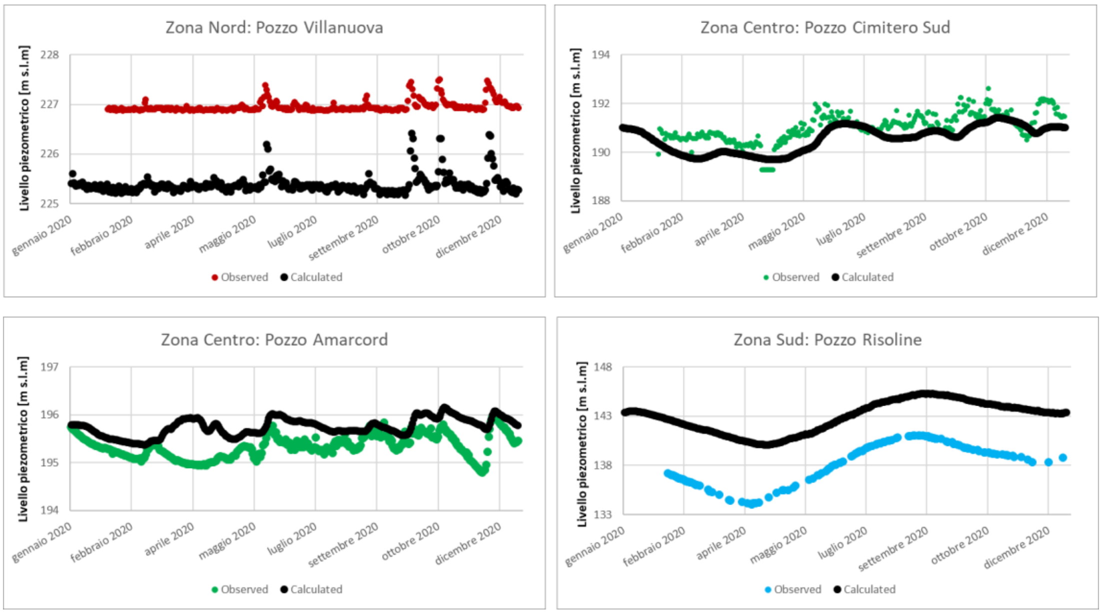


**Figure 5. Comparison between observed and model-measured time series at the 4 available observation points.**

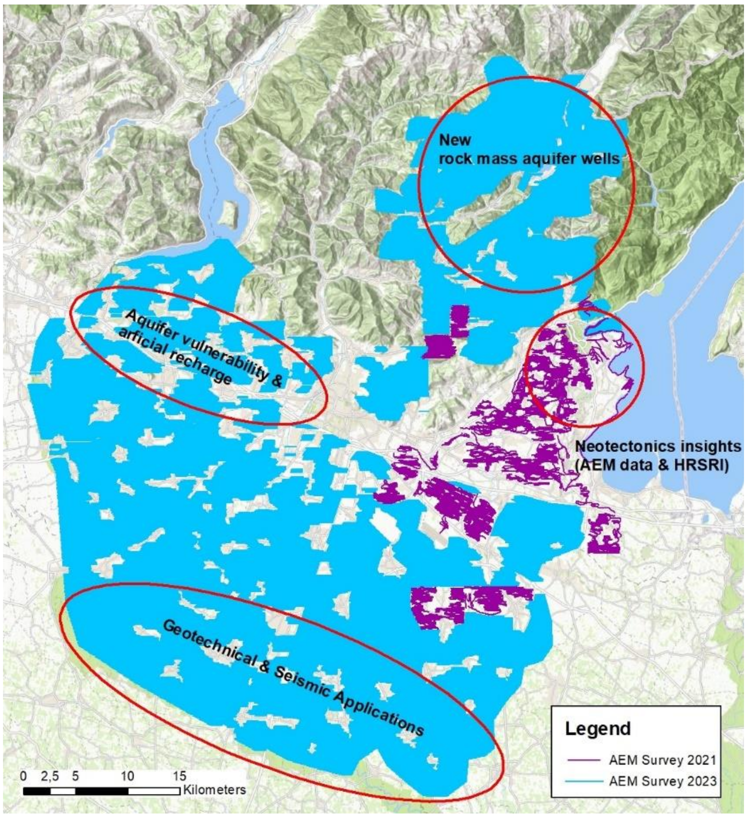


**Figure 7. Survey 2023. Flight zones and specific topics to deal with.**