Slovak Geol. Mag., 19, 1 (2019), 19 – 32

2. Use of Applied Geophysics in Monitoring of Environmental Burdens

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Abstract: Old environmental burdens represent a societal problem that must be addressed urgently. Generally, this term refers to old waste dumps, old mining works, various heaps, tailings ponds and other objects (not only) of old mining works, areas contaminated by military activity, but also other sources of pollution (industry premises, various pipelines, (agricultural) yards, manure yards, ...), which may pose a significant source of groundwater and surface water, rock environment and air pollution. This can ultimately result in a threat to human and animal health, but also in the deterioration of the stability of the landscape ecosystem.
When investigating old environmental burdens, the methods of applied geophysics are advantageously used for their efficiency and speed of screening in the area of objects of interest. The results of these works provide information about the studied area indirectly – based on the analysis of various (geo)physical fields and physical parameters of the rock environment.
Outputs of interpretation of geophysical measurements enable to optimize localization of other activities (sampling and drilling works, etc.) and thus can significantly contribute to the solution of the problem of environmental burdens.

Key words: applied geophysics, environmental burden, monitoring

2.1 Introduction

The issue of creation and protection of the environment is very extensive and to varying degrees it concerns practically all activities of the human population. However, it can be stated that in the last decades it has been ranked among priority areas, which is an undeniably positive trend from the environmental point of view.

In the study and monitoring of various environmental parameters geosciences dealing with the survey of the geological environment are widely used. Several of the problems can be effectively solved by a rational and economically designed set of geophysical (GPH) methods and methodologies.

However, this issue cannot be more generalized and each GPH measurement at a particular site/object should be modified according to specific field, structural-geological, hydrogeological, engineering-geological, etc. conditions.

The geophysical methods provide information about the surveyed area indirectly – based on the analysis of a number of physical fields and parameters of the geological environment. We rank them mostly in the so-called group of non-destructive methods that do not require significant interventions in the natural environment.

When researching various environmental burdens (landfills, tailings ponds, contaminant leaks, etc.), the GPH works are used mainly due to their effectiveness and the possibility of relatively rapid point/profile/area survey directly in the area of an environmental burden (EB), or in its (wider) neighbourhood.

Thus, in the first phase, they can help to optimize the situation of other exploratory works (probes, wells, sampling points of different types of samples, etc.) and in the next stages allow interpolation/extrapolation of information obtained from direct methods of valuation of the EB.

2.2 Methodology and solution procedures

Due to the large scale of the GPH measurements – 161 localities situated unevenly across the whole territory of Slovakia (Kordík & Slaninka et al., 2015) – the works were divided into five sites within which individual organizations carried out the GPH survey work.

In parallel, five organizations participated in the geological task solution: SENSOR, s.r.o. Bratislava (Bratislava + Trnava regions); ESPRIT, s.r.o. Banská Štiavnica (Banská Bystrica region); BHF environmental, s.r.o. Bratislava (Trenčín + Žilina regions); KORAL, s.r.o. Spišská Nová Ves (Košice + Prešov regions) and DEKONTA Slovensko, s.r.o. Bratislava (Nitra region). In addition, the employees of AG&E, s.r.o. Bratislava participated in the GPH work.

As all geosciences the methods of the applied geophysics have also their limits, which have to be handled in searching and exploring not only the old EBs. The limits often result from the physical fundamentals of the individual methods, and under unfavourable circumstances, some methods and methodologies may be virtually unusable, or they will not provide relevant results (Bláha et al., 2009).

Among the more or less significant factors limiting the possibilities of using the GPH survey works, we generally include:

- urbanization and industrialization of surveyed sites;
- presence of line objects (fences, rails, power lines, etc.); asphalted areas, underground structures (various pipelines, tanks, etc.), or other metal scrap on a larger scale;
- low and high frequency electromagnetic interference;
- insufficient contrast of physical parameters within contaminated deposits, landfill fluids and unpolluted geological environment (rocks, water);

- significantly dropped groundwater table level and low groundwater flow rate;
- accessibility, morphology and trafficability of the terrain;
- required depth range and measurement detail;
- time consumption of some methods;
- insufficient depth of borehole (well), steel (to some extent PVC, as well) casing, deep-seated groundwater table, dry well;
- low gas permeability of the geological environment below the landfill or a landfill material;
- the landfill covering with various sealing foils and (separating) geotextiles;
- ambiguity of interpretation of the GPH measurements.

These limitations must be taken into account in the design as well as in the interpretation of the survey results in the areas of the environmental burdens.

The Tab. 2.1 presents a brief overview of the suitability of using selected methods of the applied geophysics in various fields of research work. It was compiled on the basis of many years of experience of solvers in various activities (not only) in the area of the EB (Gregor & Vybíral, 2015).

As a rule, the aim of the GPH exploration work is to specify the spatial structure of the rock environment, to determine the thickness of the coverings, the relief of the impermeable subsoil and the course of the failure zones, to determine the direction and rate of groundwater flow.

In the wider surroundings of most of the surveyed sites (objects), a relatively large number of the GPH works had been carried out in the past with different focus and scale of research. In terms of the requirements of the solution of the old EBs, the results of geoelectric methods were of particular interest. However, the vast majority of them were of regional character, or they were part of other (detailed) surveys and were mostly of marginal importance for the purposes of dealing with the EB.

From the point of view of the GPH works methodology, these regional works were interesting:

- Monitoring the Impact of Environmental Burdens on Geological Factors of the Environment in Selected Regions of the Western Carpathians (Vybíral et al., 2005);
- Use of Remote Sensing in Monitoring the Environmental Burdens on Geological Agents in Selected Regions of the Slovak Republic (Gregor et al., 2008).

In order to maintain the sequence of individual works and activities, the GPH's operations were divided into several stages:

- preparatory work – archival excerption, field reconnaissance;
- field work – stage 1 (CMD screening; draft of works in stage 2);
- field work – stage 2 (implementation of the additional GPH measurements at selected locations);
- preparation of partial final reports for surveyed location/object.

2.2.1 Preparatory work

A significant part of the preparatory work was focused in the detailed excerption of archived **documents**, their summarization, re-evaluation and possible reinterpretation. They were obtained from the archives of Geofond Bratislava, Department of Geophysical Research, SGIDŠ

Tab. 2.1 Suitability of the GPH methods applied to investigate the EB and their environmental impact

Suitability of applied geophysics methods at survey of the environmental burdens and their impact upon the environment	**CMD screening (DEMP)**	**Multicable (ERT)**	**Georadar (GPR)**	**Method SP**	**Method CBM (HG-variant)**	**Logging**	**Radiometry (SG/RVA)**
Localization of buried environmental burdens	suitable	suitable	suitable	conditionally suitable	conditionally suitable	less suitable	conditionally suitable
Mapping of geological setting in horizontal pattern	less suitable	suitable	less suitable	unsuitable	unsuitable	conditionally suitable	suitable
Mapping of geological setting in vertical pattern	suitable	suitable	less suitable	unsuitable	unsuitable	suitable	conditionally suitable
Lithological composition and thickness of cover deposits	less suitable	suitable	less suitable	unsuitable	unsuitable	suitable	less suitable
Lithological composition and morphology of (impervious) subsoil	conditionally suitable	suitable	conditionally suitable	unsuitable	unsuitable	suitable	conditionally suitable
HG regime in cover deposits	suitable	suitable	suitable	suitable	suitable	suitable	unsuitable
HG conditions of geological environ	conditionally suitable	suitable	conditionally suitable	less suitable	conditionally suitable	suitable	unsuitable
Groundwater table level	conditionally suitable	suitable	suitable	unsuitable	unsuitable	suitable	unsuitable
Direction and rate of groundwater flow	unsuitable	unsuitable	unsuitable	conditionally suitable	suitable	suitable	unsuitable
Extent and character of contaminants spread	less suitable	suitable	less suitable	conditionally suitable	unsuitable	suitable	unsuitable
Localization of subsurface technical facilities	less suitable	suitable	suitable	conditionally suitable	conditionally suitable	conditionally suitable	unsuitable

suitable | less suitable | conditionally suitable | unsuitable

Map Server, professional publications, information sources on the Internet, etc. An important source of relevant information was also Enviroport, Envirofond, landfill register, old mining works register and old environmental burdens register.

Increased attention was paid to the **terrain reconnaissance**. In the first stage, the base documents were used along with available large scale orthophotomaps. Subsequently, in cooperation with the coordinators of individual sites, field reconnaissance was carried out, which served mainly to assess the possibility of realization of the field GPH, to get acquainted with the geological structure of the site and the content of the ecological burden itself.

In the terrain reconnaissance, directions and assumed lengths of profiles/routes for CMD screening were also proposed at individual sites.

2.2.2 Field work – stage 1

CMD screening – measurement of electromagnetic conductivity of local repositories (DEMP – Dipole Electromagnetic Profiling) – was the focal point of the 1st stage of the GPH field work. The CMD screening belongs to active GPH electromagnetic methods. The measuring devices used allow fast and operative measurement of resistivity, or conductivity from 3 to 14 depth levels at the same time, with a depth range of up to approx. 10 m (under optimum conditions up to ~ 15 m). The measurements are non-destructive, i.e. without interfering with the natural environment. It is not necessary to lay out the profiles, to drive-in the electrodes or to dig the probes and the measurements are carried out in the form of walks across the evaluated area (Fig. 2.1).

The measurement outputs indicate conductive bodies, resistivity division of rocks and deposits within the investigated area (sand, gravel, clay, ...). The conductive anomalies detect tectonic faults and failure zones that may indicate contaminated waterways at the site. The measurements also register metal objects, engineering networks (cables, pipelines, ...), various types of anthropogenic fillings, etc.

The basic CMD screening was carried out at all localities (objects) with the aim to determine the electromagnetic conductivity and susceptibility of local rocks, soils and deposits using a CMD-explorer (GFinstruments, s.r.o., Brno) at three depth levels (2.2 m, 4.2 m and 6.7 m) simultaneously. A measuring interval of 1 second was used.

The second device used (only for the Košice and Prešov regions) was the AEMP-14 Electromagnetic Profiler (NEMFIS, Moscow), enabling non-contact measurements at 14 depth levels simultaneously (only 2.2 m, 4.2 m and 6.7 m were entered for further processing) with a measuring step of 5 m.

The measured quantity was the apparent resistivity (apparent specific conductivity) and the “in-phase” component, which is proportional to the magnetic susceptibility of local rocks and deposits.

Each measurement was recorded along with the position of the measured point using a GPS receiver. The distance of the profiles – according to the possibilities of realization and availability of the terrain – was in the range up to 50 m and the measuring step up to 5 m. A separate **assessment report** was subsequently prepared for each site/object (group of close-lying objects) with an interpretation of the measurements by the CMD screening, including a proposal for further GPH work at the site/object.

2.2.3 Field work – stage 2

Within this stage, geophysical profiles were identified and surveyed in selected locations according to the conclusions of the evaluation reports and the measurements were carried out using one of the other methods of the geological task project: multicable (ERT), georadar (GPR), spontaneous polarization (SP), charged-body method – hydrogeological variant (CBM – HG), gamma spectrometry (SG), emanation measurements (RVA – ^{222}Rn volume activity) and logging in selected boreholes.

Fig. 2.1 Field measurements by CMD screening (source: www.gfinstruments.cz)

Prior to the GPH works were carried out, the GPH profiles were laid out (the routes were cut to the necessary extent if necessary), with pins staggered by 50 m. Using the GPS receiver (accuracy up to 1 m), the survey profiles were then geodetically surveyed. Their number at a site (object), length and distance between profiles were determined individually as needed to achieve the set goals of the geological task. In setting the profiles, in cooperation with the site coordinator and the responsible geological task solver, the results were based mainly on the results of the CMD screening, but also on other available knowledge about the site setting.

The Multi-Cable Method (ERT – Electrical Resistance Tomography) is currently one of the most widely used geoelectric methods in environmental studies. It is a system of complex resistance measurement with a larger number of electrodes. The distance between the electrodes is determined depending on the detail and the desired depth range. The electrodes serve alternately as the source and receiver ones.

Considering the fact that the measurements are carried out by means of a series of electrodes configured with small spacing (max. approx. 5.8 m) and by computer-controlled addressing of current transmission and voltage reception, it is possible to obtain a relatively detailed picture of vertical distribution of apparent resistivity in vertical section along the measured profile.

The field measurements were performed using the ARES geoelectric apparatus (GFinstruments, s.r.o., Brno) and multielectrode sections with N * 8 electrodes (Fig. 2.2). The electrode spacing was chosen in the range of 2.0 – 5.8 m with a depth reach of up to 50 m.

Subsequent computer processing allows the measured data to be transformed into a set of real values of resistivity and through them to obtain a picture of the real structure of the rock environment along the measured profile.

RES2DINV (Company GEOTOMO SOFTWARE, Malaysia – a standard 2D inversion application) software was used to interpret resistivity images, which assumes that the apparent resistances change only in the profile direction (X axis) and depth (Z axis). The programme generates a model whose calculated values are as close as possible to the measured values. It uses the smoothing method to solve the system of linear equations.

Fig. 2.3 Georadar measurement on designated geophysical profiles

georadar is limited by the depth of the conductive layer. The antenna was selected according to the particular situation along the measured profile and the requirements for the size of the details to be monitored.

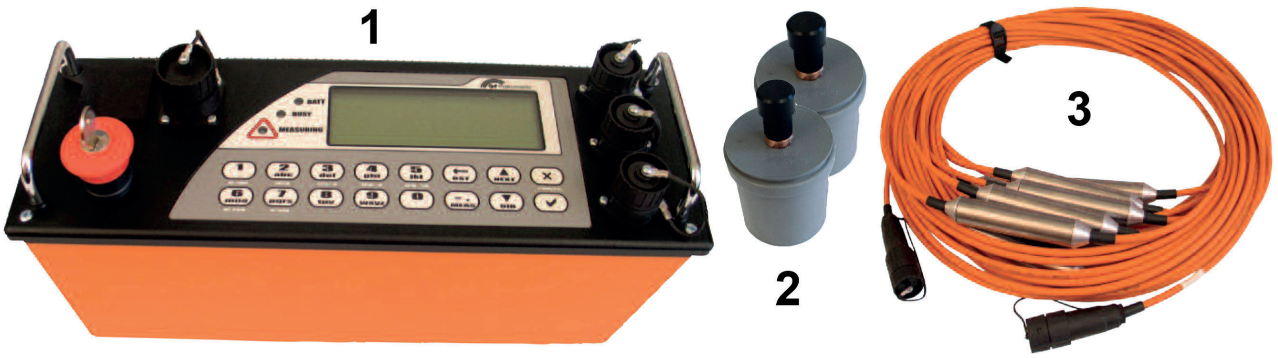


Fig. 2.2 ARES Geoelectric Apparatus (1); non-polarizable electrodes (2); active multi-electrode cable (3) (source: www.gfinstruments.cz)

Georadar (GPR – Ground Penetrating Radar) utilizes the reflection of high-frequency electromagnetic waves transmitted and received by the measuring apparatus from the interfaces of various subsurface natural/anthropogenic layers and interfaces with different conductivity and permittivity (Fig. 2.3). By the georadar it is possible to study the geological environment relatively quickly and effectively to the depth of the first units (up to tens of meters).

For the georadar measurements, the depth range and resolution of the method are determined by the use of antennas with variably radiated frequency. Measurements on the old EBs used 500 MHz and 350 MHz antennas with depth range of 2.5 – 3 m at the first (resolution > 5 cm), or 5 – 6 m for the second antenna (resolution > 20 cm).

In the case of shallow auriferous conductive layers, or any layers with high conductivity, the depth reach of the

The **spontaneous polarization method** (SP) is one of the oldest GPH methods. It investigates local electrochemical fields arising from groundwater flow (hydraulic conductivity potentials), ion movement on contact of various mineralized/contaminated groundwaters (diffusion potentials), or on contact of groundwater and ore minerals (oxidation-reduction potentials). Elevated SP values may also have anthropogenic origin, e.g. corrosion of various pipelines, electrical noise (stray currents, electrification, railways, etc.).

The potential difference in the electric field between two points at the surface is measured. The method is used to indicate various types of leaks and escapes, for detailed measurements in the inspection of sealing walls, etc.

The field measurements were carried out using the ARES geoelectric apparatus (GFinstruments, s.r.o., Brno) and non-polarizable electrodes (Fig. 2.2) in a potential configuration. The use and scope of the SP measurements were determined individually according to the possibilities and conditions at a particular site/object.

The **charged-body method** (CBM) is a special variant of the SP method. It is designed to monitor the direction and speed of groundwater flow around the borehole (well), the course of underground streams, leakage of sealing foils below a landfill, etc. One of the current electrodes is placed in the well below the water surface, whose conductivity is increased by adding a salt. The measurements at the surface can then monitor the rate and direction of movement of the salt-enriched medium.

The use of the CBM method was possible only under favourable conditions and was used selectively also according to the possibilities of its implementation at a specific site (object). The method has a relatively low depth reach and its use is not possible in environments with increased conductivity of the geological environment (clays, clays, tuffs, heavily mineralized groundwater, etc.) and its practical use is therefore considerably limited. Good results can be obtained e.g. in gravel-sand sediments with a small thickness of coverings.

The field measurements were performed using the MRS-256 geoelectric apparatus (Fig. 2.4), or by ARES (Fig. 2.2). In the vicinity of each borehole 8 radial profiles with a length of 15 m were laid out, on which the sensing (potential) electrodes were grounded in steps of 1 m. The artificial electric field was created by current electrodes placed in the borehole and in the so-called “infinite” position (approx. 140 m from the borehole). Changes in resistance ratios were observed within a few (to tens) days of the start of the addition of salt to groundwater.

Logging (geophysical measurements in a borehole) is probably the largest set of geophysical methods and methodologies, the results of which provide detailed relevant information on the physical properties of the geological environment along the well axis: lithology, radioactivity, porosity and pore fill, electrical resistance, polarization, magnetic susceptibility, density, technical condition, course of the borehole axis, temperature, inflows and direction of water flow in the borehole and many other parameters.

Fig. 2.4 Geoelectric apparatus MRS-256 (source: www.gfinstruments.cz)

The logging works were carried out in new (or other available) survey boreholes: cavernometry (CM), thermometry (TM, 2 measurements), resistivimetry (RM), 5 measurements of RM after dilution, gamma-carotage (GC) and electro-carotage if possible).

The logging results were processed, visualized and interpreted at a scale of 1: 100 and a separate evaluation report was prepared for each borehole (group of boreholes). An example of a logging apparatus is shown in Fig. 2.5.

Fig. 2.5 Logging equipment for borehole measurements (source: www.koral.sk)

Pedestrian **gamma spectrometry** (SG) is mainly used in mineral exploration, geological mapping, environmental radioactivity monitoring (including indicative determination of natural and/or artificial radionuclide concentrations at various landfills and repositories), assessment of radioactivity of building materials, etc. The most important natural sources of rock gamma radiation are potassium (K), uranium (U) and thorium (Th). The artificial radionuclides then e.g. ^{137}Cs, which entered the natural environment after the Chernobyl nuclear power plant accident in 1986.

In order to determine the basic parameters of natural radioactivity (potassium concentration K, equivalent uranium eU, equivalent thorium eTh, total natural

Fig. 2.6 Gamma spectrometer GAMMA Surveyor (source: www.gfinstruments.cz)

radioactivity eUt and dose rate of gamma radiation), gamma spectrometry spot measurements were performed in the immediate vicinity and also in the area of the EBs in a configuration of 5 points in the area of EB and 5 points outside the building of EB. A GAMMA Surveyor (GFinstruments, s.r.o., Brno) and a measurement time of 3 minutes were used (Fig. 2.6).

Emanation (radon) exploration is mainly used for geological mapping, searching for tectonic lines, assessing radioactivity of the environment (e.g. determining the radon risk of a building plot), searching for energy resources (uranium), assessing the radioactivity of building materials, etc.

Simultaneously and at the same positions as the natural radioactivity (SG) parameters were measured, soil air was extracted from a depth of up to 0.8 m to determine radon volume activity (RVA). RVA measurements were performed with a metrologically verified and calibrated LUK-4 measuring instrument (manufactured by Ing. J. Plch, Prague) with 125 ml Lucas type (LC) scintillation chambers (Fig. 2.7).

Fig. 2.7 Apparatus LUK-4 and Lucas Chamber volume 125 and 600 ml (source: www.geology.sk)

All the ground documents and data (measured and interpreted), obtained during the solution of the geological task in question (Kordík & Slaninka et al., 2015), are stored in the approved structure and physical content of individual sites, types of work and methods on the SGIDŠ data server and archived on optical media (more than 13,000 files; 15x DVD-R).

2.3 Overview and results of realized work

Detailed knowledge of the geological structure of the investigated EB area helps to identify potential impacts and possibly the spread of contamination. Applied geophysics can help in defining the extent of coverings, determining the depth of the (impermeable) subsoil, determining the horizontal (areal) and vertical character and delimiting of the lithological complexes, in mapping the failure zones, etc.

The areal (to some extent also spatial) extent of individual lithotypes was surveyed by profile measurements, where the GPH methods were applied, mainly in which mapped rocks and deposits showed sufficiently contrasting physical properties (specific electrical resistance, magnetic susceptibility, but also natural radioactivity) against uncontaminated environment.

Differentiation of lithotypes is important e.g. also in differentiation of their hydrogeological function. Impermeable deposits with a predominant clay component are electrically conductive due to the bound water and thus have lower resistances. Coarse-grained sediments with high inter-granular permeability are characterized by higher resistances unless they saturated with mineralized/contaminated water.

2.3.1 CMD screening

The **CMD screening** (DEMP) was used at all 161 solved sites/objects in the first phase of the GPH works (altogether approx. 1,088 km of routes), which aimed to delineate local rocks and deposits according to their electromagnetic properties.

However, an important limiting factor in the performance of this type of exploratory work is urbanization and industrialization, and more or less significant electromagnetic interference. At several localities, this led to the situation that the methods of geoelectric survey (multicable, georadar, SP method, CBM method) were not recommended at the next stage, because the relevant results could not be expected.

However, this fact can be considered rather positive because there was no waste of funds that could – to some extent – be used at other, more appropriate locations/objects.

Based on the CMD screening results, environments with reduced apparent resistivity corresponding to clay-type rocks, deluvial sediments, landfills with an increased proportion of clay fraction, etc. were indicated. It was often possible to observe mostly hidden old oxbows and meanders of watercourses (Fig. 2.8). Low resistances reflect both anthropogenic effects (various pipelines, utility networks, etc.), but also contamination of deposits with increased/high content of decomposed petroleum substances.

Higher apparent resistances set aside areas with a lower clay content and an increase in the proportion of gravel and sand, or landfill material with increased specific resistance (rubble, construction waste, etc.).

Since it was simultaneously mapped for three different depth levels, the thickness of the mapped geoelectric layers can also be determined from the visualized outputs to some extent.

It was possible to identify various metal materials in the examined areas, or in landfill material, based on the results of the in-phase component measurements, which is proportional to the magnetic susceptibility of local rocks and deposits. Such material is reflected in the visualized measurement results by expressing higher values (Gluch in Kordík & Slaninka et al., 2015).

In a smaller number of objects, where the electromagnetic properties of the surveyed geological environment did not show the necessary contrast, or they were affected

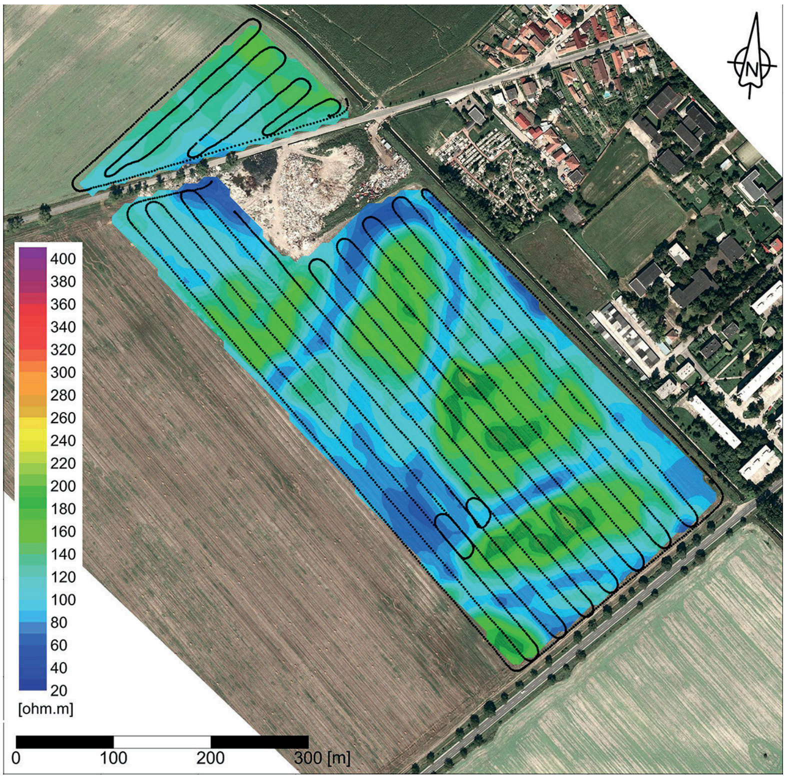


Fig. 2.8 CMD screening results – locality 108 Zlaté Klasy (apparent resistivity [ohm.m] for effective depth range 4.2 m; CMD measurement paths) (compiled by Company Sensor, spol. s.r.o. Bratislava, modified by Gluch & Zeman, 2019)

to varying extents by civilization interference, the results of CMD screening were not sufficiently demonstrable, and – based on the principle of this method they could not be representative.

In general, it can be stated that better readable results of the CMD screening (but also the other GPH works) were achieved at most sites (objects) in case of their processing in the form of maps of the measured component. Measurement outputs presented in the form of individual profiles had a slightly lower level of information.

2.3.2 Multicabel

The multicable (ERT) method is used for geoelectric research along marked and surveyed GPH profiles. The presentation of results in the form of inverse resistance models and geophysical-geologically interpreted sections is currently the standard for detailed work in the explored areas (Fig. 2.9).

One of the basic problems of all geoelectric methods is the ambiguity of

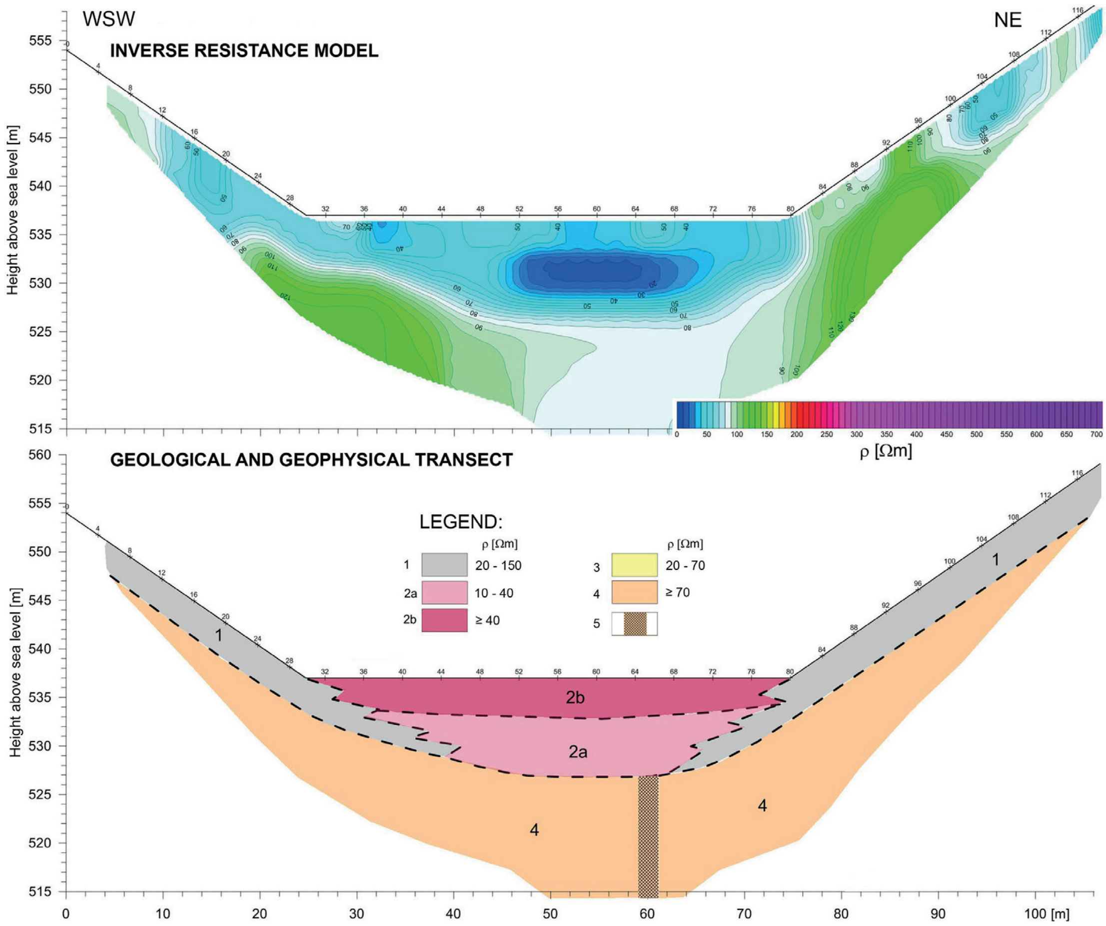


Fig. 2.9 Multicable measurement results – locality 51 Medzibrodie nad Oravou. Legend: 1: surface layer, eluvial-deluvial sediments; 2a: anthropogenic fill, prevalence of municipal waste; 2b: anthropogenic fill, predominance of coarse-grained component; 3: predominance of claystone; 4: limestone, or sandstone, siltstone; 5: failure zone/tectonics (compiled by Company BHF Environmental, spol. s.r.o. Bratislava, modified by Gluch & Zeman, 2019)

interpretation of measurement results. In general, the so-called principle of equivalence, but also anisotropy of the geological environment are significant, so the computer-generated model is the only one possible solution. The refinement of the geophysical-geological interpretation can be achieved by supplementary data obtained e.g. from logging results in available supporting boreholes.

In spite of the above, the results obtained from the ERT measurements sufficiently illustrate the suitability and justification of their use – detailed and relevant information on the geometry and stratigraphy of rocks and deposits on the premises of objects/locations up to the first tens of meters depth. However, the multicable has found application e.g. even with the unexpected detection of unknown subsurface spaces (Gluch in Kordík & Slaninka et al., 2015).

2.3.3 Georadar

The georadar uses a different principle compared to a multi-cable, but the measurement outputs in a similar way – but with a significantly higher resolution (depending on the antenna transmitting/receiving frequency) – indicate interfaces with different conductivity and permittivity (Fig. 2.10).

The advantages of georadar are simplicity and speed of measurement, high resolution and relatively simple

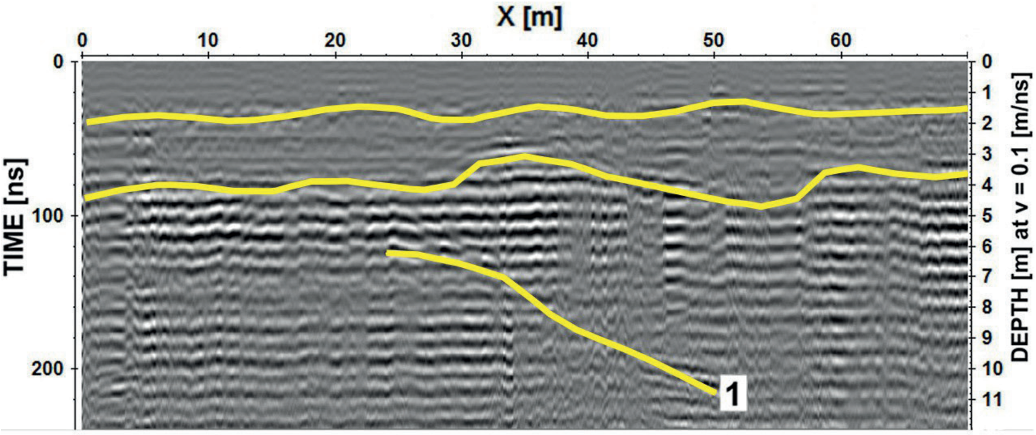


Fig. 2.10 Results of georadar measurements – locality 71 Lučenec (1: interpreted interface) (compiled by Company Sensor, spol. s.r.o. Bratislava, modified by Gluch & Zeman, 2019)

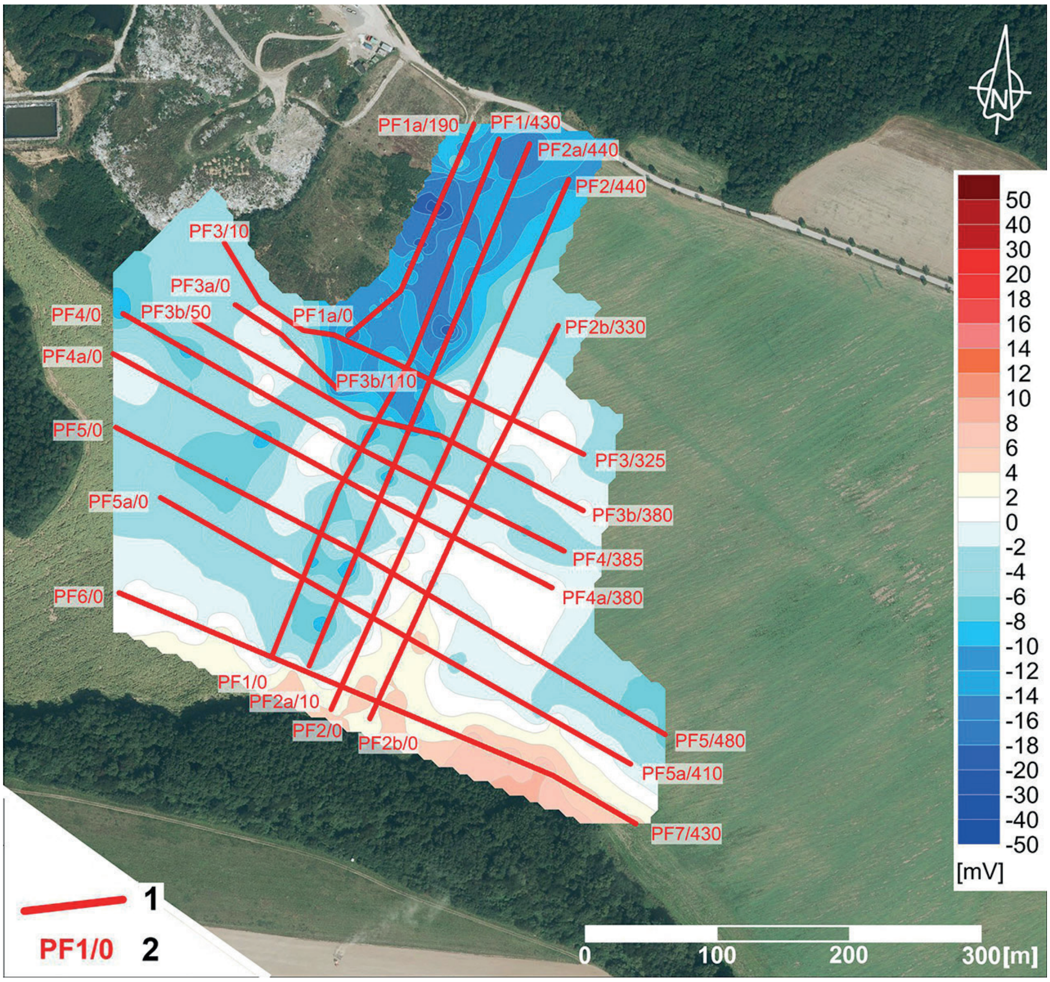


Fig. 2.11 Measurement results by the SP method – locality 85 Bojná (1: measured profile; 2: profile number and length) (compiled by Company DEKONTA Slovensko, spol. s.r.o. Bratislava, modified by Gluch & Zeman, 2019)

interpretation. The limiting factors are in particular: the transmitted frequency, determining the resolution of details, specific conductivity of geological environment, but also water content, density of rocks and deposits, etc. A necessary assumption is a sufficiently different permittivity, or specific conductivity of individual lithotypes, but also a reasonably large reflective surface of explored structures.

Despite the fact that the georadar was used only at 5 sites/objects, it confirmed its justification. Combination with another suitable GPH method, e.g. using the multi-cable method (if allowed by environmental parameters and measurement conditions) and ideally with logging results on the supporting boreholes is the optimum utilisation of the georadar.

2.3.4 Spontaneous polarization method

The SP method could be used only at 25 localities/objects in a total of 8,770 measured points. This method measures the potential difference between two points on the profile, or within the exploration area, generated by various local electrochemical fields. The advantage of the SP method is its simplicity and speed of measurement. The limiting factor is the presence of various disturbances caused mainly by civilization factors. The possibilities of its use in urbanized areas on a larger scale are thus significantly limited. The negative SP values indicate the areas of possible ground/landfill contamination. From the results of measurements it is possible to determine the spatial extent and to some extent also the level of contamination

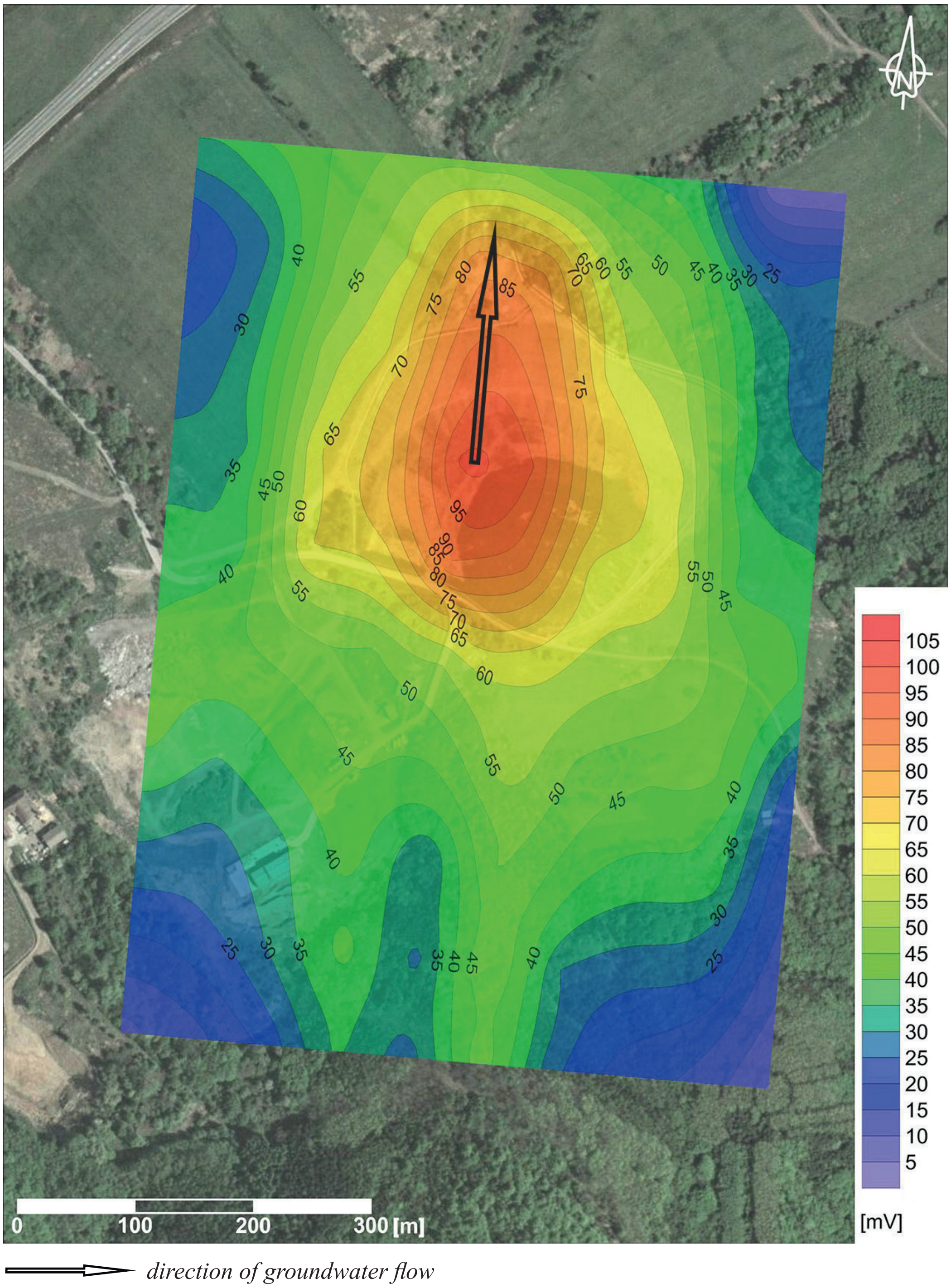


Fig. 2.12 Charged-body method measurement results – locality 168 Žiar nad Hronom (compiled by Company Sensor, spol. s.r.o. Bratislava, modified Gluch & Zeman, 2019)

of the environment around the environmental burden (Fig. 2.11). Under specific conditions, it is also possible to determine the direction of groundwater flow from the SP measurements.

Despite the fact that the SP method could only be used on a relatively small number of sites, its merits and benefits are undeniable.

2.3.5 Charged-body method

Due to the very specific conditions of the possibility of realization of the CBM (HG variant) method, it could be used basically only in 7 localities. From the results of time-consuming measurements it was possible to determine the direction and speed of the groundwater flow. The limiting factors are mainly: relatively low effective depth reach, impossibility to use the CBM method in a rock environment with high conductivity, depth of the groundwater level (decimetres up to the first meter) and last but not least the longevity of measurements in the order of tens of days, depending upon the groundwater flow rate. When selecting suitable objects (boreholes, wells), the CBM measurement results provide reliable data (Fig. 2.12).

The results of the measurements of the charged body method at the site (Fig. 2.12) confirmed the propagation of the electric field in the geological environment, and this field was deformed. The deformation was caused by the spread of contaminated groundwater in the direction shown by the arrow.

2.3.6 Logging

The geophysical measurements in a borehole (logging) are probably the most extensive set of methods and methodologies, the results of which give detailed and relevant information about the physical properties of the geological environment along the well axis. The limiting factors of logging work are mainly too low depth of the well, steel casing of the borehole (to some extent also PVC), deep groundwater table level or dry well, etc. One of the limitations in the implementation of this project was the fact that a significant number of boreholes were drilled only during the first half of 2015, but the logging (part of the GPH works) was contractually concluded in early January 2015. The logging outputs allowed to separate lithological boundaries of rocks caught by borehole, hydrogeological aquifers and aquitards, places of inflows and losses in the borehole, hydraulic conductivity values, temperature and specific resistance of drilling mud, etc. (Fig. 2.13).

2.3.7 Radiometric methods

The radiometric methods – gamma spectrometry (SG) and radon survey (RVA) – were used at all 161 sites in a number of 10 points SG and RVA in the vicinity, but also directly in the EB object. Results of the radiometric determination of concentrations of natural radionuclides "in situ" by measurements of SG, or the radon volume activity in the soil air indicate their very good mapping

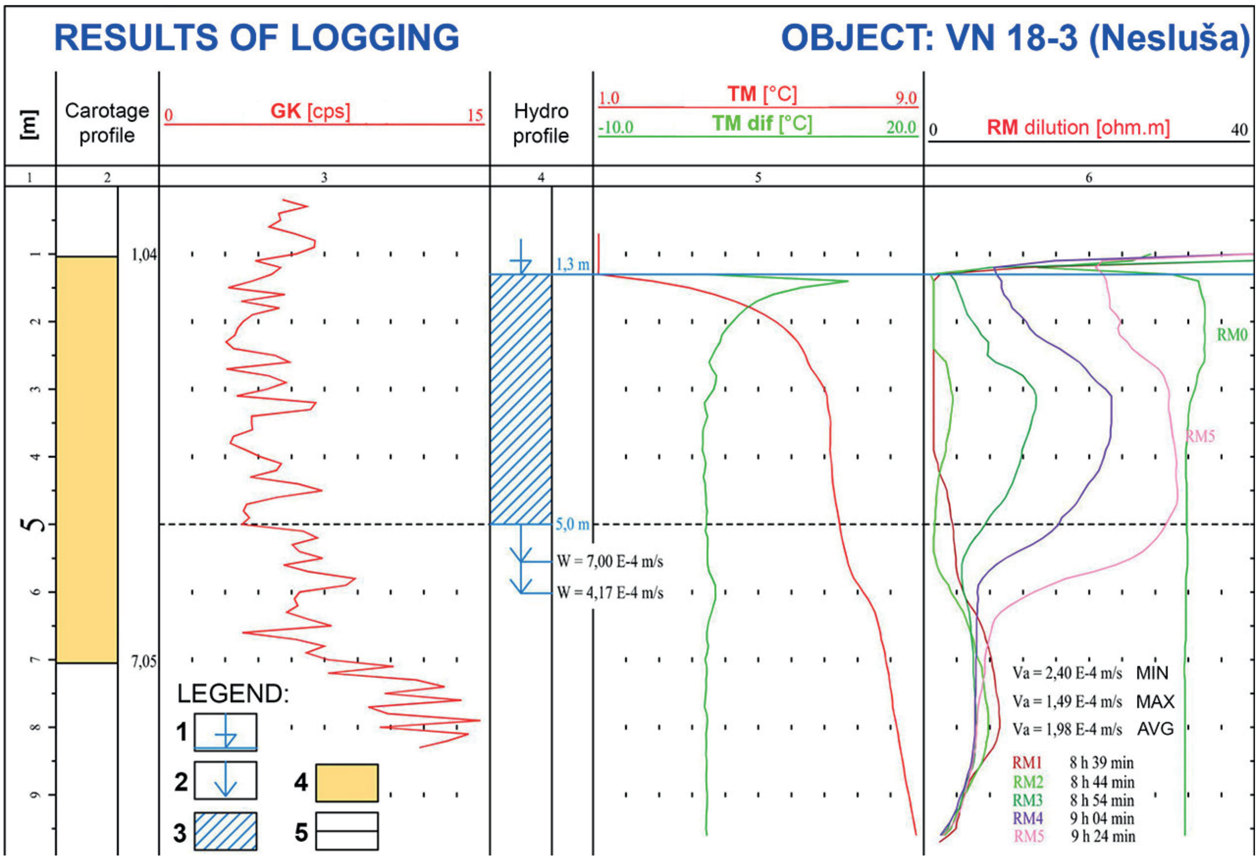
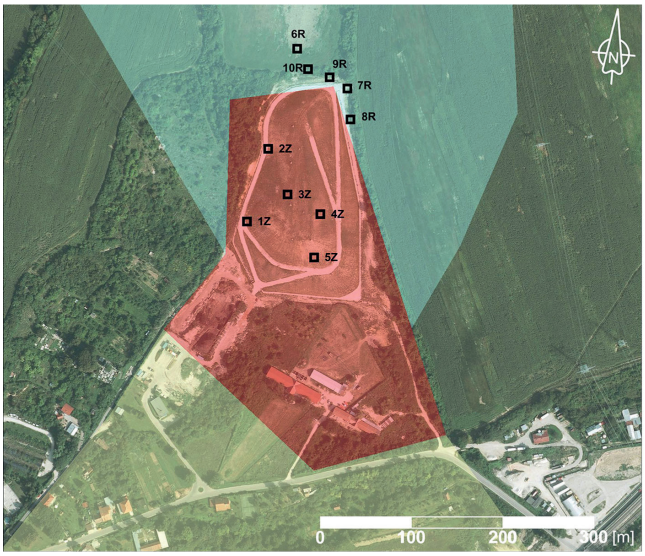


Fig. 2.13 Logging results – location 18 Nesluša. Legend – 1: water level; 2: vertical movement of water; 3: filtration of water over time; 4: permeable rocks, collectors; 5: rock interface; GK: gamma logging [cps]; TM: thermometry [°C]; RM: resistivimetry [ohm.m]; W: vertical rate [m.s^{-1}]; Va: hydraulic conductivity coefficient [m.s^{-1}] (compiled by Company KORAL, spol. s.r.o. Spišská Nová Ves, modified by Gluch & Zeman, 2019)

capability, which was also confirmed by the results of measurements at several locations/objects. Significantly increased levels of equivalent uranium (eU = 9.0 – 12.3 ppm), which correspond to increased (eU ≥ 4.0 ppm) to high (eU ≥ 10.0 ppm) natural radioactivity of the rock environment, were identified, e.g. in clay and loess clays at 21 Nové Mesto nad Váhom – KO Mnešice – Tušková landfill (Gluch in Kordík & Slaninka et al., 2015; Fig. 2.14).

2.3.8 Atmogeochemistry

The atmogeochemical measurements were not part of the design work and were not carried out experimentally until the second half of 2015 at several selected locations. The advantage of atmogeochemistry is the rapid and sufficiently accurate determination of the detected gas concentrations (depending on the equipment of the detectors) in the landfill air. The limiting factors are mainly



Point	K [%]	eU [ppm]	eTh [ppm]	eUt [ur]	Da [nGy.h^{-1}]	OAR [kBq.m^{-3}]
1Z	1.1	12.1	8.6	19.3	104.6	12
2Z	0.9	11.4	7.8	17.8	96.6	12
3Z	1.1	10.8	6.9	17.4	93.8	15
4Z	1.5	12.3	7.6	20.2	109.0	16
5Z	1.1	11.7	4.5	17.0	92.4	14
6R	0.8	10.0	1.2	12.8	70.5	11
7R	0.9	9.7	1.9	13.2	72.0	15
8R	1.0	10.2	1.6	13.8	75.4	11
9R	0.9	9.4	1.0	12.5	68.4	11
10R	0.9	9.0	1.3	12.1	66.1	7
Limits	≥ 2.0	≥ 4.0	≥ 12.0	≥ 17.0	≥ 80.0	≥ 20

LEGEND:

1 ▫1Z

Conceptual model:

2 3 4

Fig. 2.14 Radiometric survey results – locality 21 Nové Mesto nad Váhom. 1: measurement point SG and RVA; 2: source zone (Z); 3: indication zone; 4: reference zone (R) (compiled by Company BHF Environmental, spol. s.r.o. Bratislava, modified by Gluch & Zeman, 2019)

Source zone represents the source(s) of the pollution, in this case environmental burden; indicative zone denotes the area where the pollution occurs/could occur from the EB; the reference zone delineates the territory not affected by the EB (natural conditions).

High concentrations of soil radon were found e.g. in the area of the EB 117 Sliač (Kordík & Slaninka et al., 2015). All 10 points, measured in both the reference and source areas (RVA = 30 – 208 kBq.m^{-3}), are bound to the failure zone, overlain by polymictic coarse and medium-grained, sand-covered gravel. Pursuant to Annex no. 6 of the Decree of the Ministry of Health of the Slovak Republic no. 528/2007, which lays down the details of the requirements for limiting the exposure from natural radiation, the object falls under high radon risk.

An overview of field geophysical measurements carried out in the course of the project is shown in Tab. 2.2.

the thickness of the overburden, the high groundwater level and the use of sealing foils for landfill reclamation.

The Dräger X-am 7000 measuring unit (of the Company Drägerwerk AG & Co. KGaA) was used for measurements, equipped with detectors for the determination of CH_4, CO_2 and O_2 content [vol. %], which was connected to the sampling probe (Fe-pipe, ϕ = 12 mm, length approx. 1 m) via silicone tubing through a washer (to prevent water from entering the instrument). The landfill air was continuously pumped by an integrated pump from a depth of 70 – 80 cm and subsequently "in situ" analyzed by the evaluation unit.

The measured or the support points on the profiles/routes were geodetically levelled by the professional GPS receiver Trimble Geo 7X (Trimble Navigation Limited, USA); the levelling accuracy reached about 10 cm in the X and Y directions, up to 25 cm in the Z axis. The assay results were then processed and visualized in the SURFER

Tab. 2.2: Overview of realized geophysical field measurements

Region	CMD [m]	SP [points]	ERT [m]	GPR [m]	SG [points]	RVA [points]	Karotáž [m]
Bratislava and Trnava	222,683	1,775	29,909		320	320	
Banská Bystrica	231,954	1,768	25,673		350	350	285.3
Košice and Prešov	180,709	2,176	29,043		400	400	211.2
Nitra	200,121	1,520	23,415		270	270	310.9
Trenčín and Žilina	252,249	1,531	23,353		290	290	292.8

software application environment (GoldenSoftware Inc, USA; Fig. 2.15).

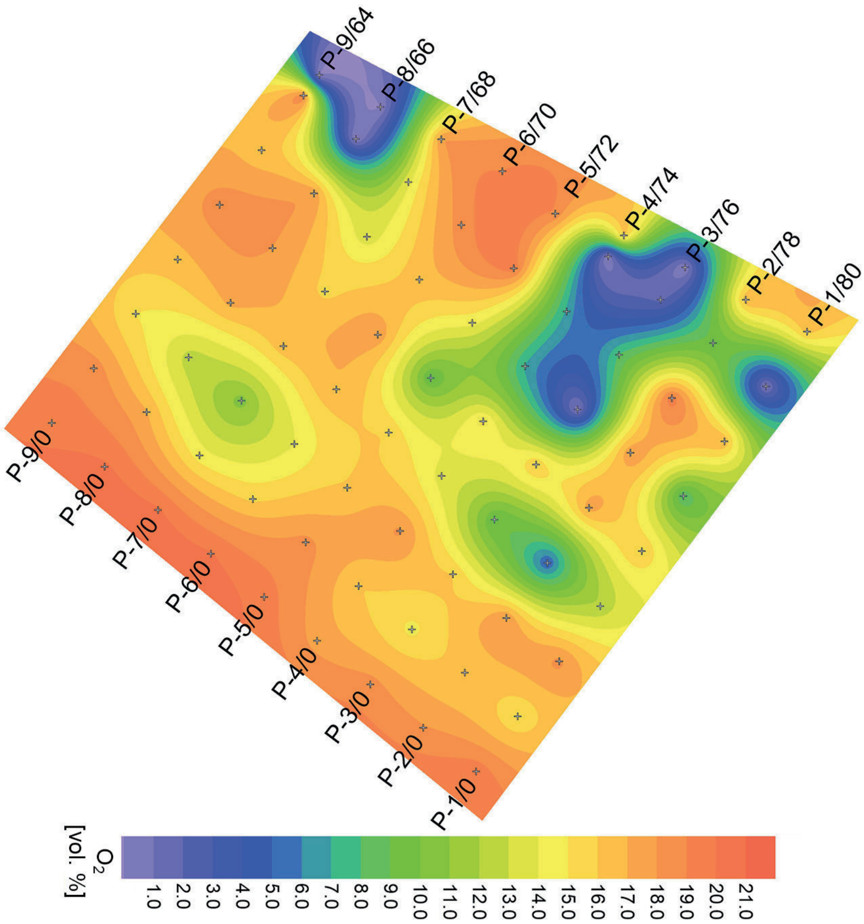


Fig. 2.15 Atmogeochemistry results – location 144 Spišská Belá (O_2 concentration [vol. %]) (compiled by Gluch & Zeman, 2019)

At the locality 144 Spišská Belá the atmogeochemistry was realized at a distance of about 120 m southeast of the old reclaimed landfill in a regular network of measured points (10 x 10 m). The results of the “in-situ” determination of oxygen concentrations in landfill air are documented in Fig. 15.2.

The measurements confirmed good detection capabilities of the measuring apparatus for the above mentioned (landfill) gases. Based on the acquired knowledge, it was recommended in the future to purchase a Smart PID sensor, which would enable to significantly increase the usability of “in situ” atmospheric chemistry determinations, e.g. in areas of various chemical plants and treatment plants, fuel storage and handling, etc.

2.4 Conclusions

The environmental burden is defined in terms of the Geological Act (Act 569/2007 Coll.) as contamination of the area caused by human activity, which represents a serious risk to human health or the rock environment, groundwater and soil. The solution of the issue of environmental burdens came to the attention especially in the early 1990s in connection with their elimination in the territories abandoned by the former Soviet Army troops. At present, the environmental burdens and information on their location and potential risks are recorded in the Information System of Environmental Burdens (ISEZ), which is part of the public administration information system.

The output of the geological task, the geophysical part of which is the subject of this article, is a set of geological-geophysical data and information used in the creation and implementation of an optimal monitoring system of the selected environmental burdens in the Slovak Republic.

The use of the applied geophysics methods has been limited in many cases by civilization influences to various extents, but in most cases the structure of the GPH exploration works has been operatively modified so that the requirements, objectives and goals of the project were met as far as possible.

Based on the analysis of the described GPH works, including a critical assessment of possible adverse impacts on these activities, it can be concluded that the project-designed and realized complex of the GPH measurements proved to be suitable, rationally designed and to some extent also generally applicable in monitoring (not only) of the old EBs.

In similarly structured exploratory projects we recommend for the future:

- in the methodology of the GPH survey to use so-called complex profiles on which all project-specified GPH methods and methodologies would be implemented, including the use of the logging results from suitably situated supporting boreholes;
- to include the atmospheric chemistry in a standard set of monitoring works (at least on the complex profiles);
- in justified cases, to include works the profile and/or area magnetometry in the range of the GPH (at least on complex profiles);
- to increase the share of multi-cable (ERT) and/or georadar (GPR) measurements in the EBs;
- to make more extensive use of radiometric measurements (SG and RVA).

References

Bláha, K., Kačabová, P., Gruntorád, J., Bárta, J., Kněz, J., Kobr, M. & Dostál, D., 2009: Možnosti geofyzikálních metod při ověřování nejasných strukturně geologických, popřípadě jiných vztahů na lokalitách při průzkumu a nápravě starých ekologických zátěží, aktualizácia metodickej příručky [*Possibilities of geophysical methods for verification of* *unclear structural geological or other relations at sites during exploration and remediation of old ecological burdens, update of methodological manual*]. Ministry of Environment of the Czech Republic. In Czech.

Gregor, T., Zlocha, M., Vybíral, V., Čapo, J., Lanc, J., Kováčik, M., Bednarik, M., Hrabinová, J. & Piovarči, M., 2008: Použitie diaľkového prieskumu Zeme pri sledovaní environmentálnych záťaží na geologické činiteľe životného prostredia vo vybraných regiónoch [*Use of remote sensing in monitoring of environmental burdens impact upon geological environmental factors in selected regions*]. Final report, Ministry of Environment SR. In Slovak.

Gregor, T. & Vybíral, V., 2015: Použitie geofyzikálnych metód pri prieskume a monitoringu environmentálnych záťaží [*Application of geophysical methods in survey and monitoring of environmental burdens*]. Proceedings Environmentálne záťaže 07/2015, p. 106 – 113. In Slovak.

Kordík, J. & Slaninka, I. (Eds.), Bačová, N., Bahnová, N., Benková, K., Bottlik, F., Dananaj, I., Demko, R., Fajčíková, K., Frajkor, V., Fričovský, B., Gluch, A., Gonda, S., Gumáňová, J., Iglárová, Ľ., Jankulár, M., Jelínek, R., Kováčik, M., Kúšik, D., Lenhardtová, E., Liščák, P., Marcin, D., Mašlár, E., Mašlárová, I., Mikušová, J., Olšavský, M., Ondrášiková, B., Pažická, A., Pešková, I., Petro, Ľ., Pramuka, S., Šimeková, J., Zlocha, M., Zvarová, I., Mikita, S., Pauditš, P., Fordinál, K., Šefčík, P., Michalko, J., Bodiš, D., Repčiak, M., Grolmusová, Z., Kronome, B., Kováčik, M., Černák, R., Siska, M., Mackových, D., Repková, R., Findura, Ľ., Vabcová, J., Tupý, P., Jasovská, A., Mihalkovič, J., Jasovský, Z., Ilkanič, A., Lučivjanský, L., Olejník, M., Fekete, M., Jezný, M., Čopan, J., Keklák, V., Seres, Z., Machlica, A., Igondová, S., Soboňová, S., Binčík, T., Urban, O., Kolářová, J., Zavadiak, R., Bednarik, M., Polák, M., Veleba, P., Chovanec, J., Štefánek, J., Pospiechová, O., Pospiech, Ján, Pospiech, Juraj, Jurkovič, B., Kriváček, J., Méry, V., Urbaník, J., Gregor, T., Vybíral, V., Jurčák, S., Ďurovič, R., Filo, J., Gretsch, J., Hrubý, V., Krajňák, M., Zverka, P., Komoň, J., Hojnoš, M., Daniel, S., Ujpál, Z., Kultan, V., Bašista, J., Vaník, J., Hodál, M., Zvara, I., Pauk, J., Babiš, P., Hudec, A., Chovan, J., Ivanič, B., Kočický, D., Maretta, M., Špilárová, I., Švec, P., Turaček, D., Vazan, V. & Zigo, T., 2015: Monitorovanie environmentálnych záťaží na vybraných lokalitách Slovenskej republiky [*Monitoring of environmental burdens at selected sites of the Slovak Republic*]. Final report. SGIDŠ Bratislava. 252 p. In Slovak.

Vybíral, V., Hrabinová, J., Gajdoš, V., Matys, M. & Némethyová, M., 2005: Monitorovanie vplyvu environmentálnych záťaží na geologické činitele životného prostredia vo vybraných regiónoch Západných Karpát [*Monitoring the impact of environmental burdens on geological factors of the environment in selected regions of the Western Carpathians*]. Ministry of Environment SR, SENSOR, Bratislava. SENSOR, s.r.o. Archive, Bratislava. In Slovak.

Decree of the Ministry of Health no. 528/2007 Coll. on details of requirements for irradiation limitation from natural sources, Annex no. 6.

Act 569/2007 Coll. on Geological Works (Geological Act).