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Environmental assessment for natural resources revitalization in Solotvyno with an overarching view to preventing the further pollution of the Upper-Tisza Basin through the preparation of a complex monitoring system

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REVITAL I

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EUROPEAN UNION

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Partners of project:

Tisza European Grouping of Territorial Cooperation Limited Liability (Tisza EGTC), Hungary

University of Miskolc, Hungary

Solotvyno City Hall, Ukraine

Municipality of Sighetu Marmatiei, Romania

The Technical University of Kosice, Slovakia

Institute of Geological Sciences of the National Academy of Sciences of Ukraine, Ukraine

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PREFACE

The Project REVITAL 1 started in 2019 and encountered severe delays due to Covid-19 and Russia's war in Ukraine. Consequently, there were amendments made in the contract and a couple of prolongations of the project were made. The work (specifically the field work) has been an enormous sacrifice and self-motivation of all partners of the project as logistical challenges and security concerns prevented more efficient and effective work.

During the project a variety of data were collected (geological, hydrogeological water quality and quantity) providing exact information on the targeted area and revealing deterioration of the situation in Solotvyno.

For the implementation of the project 3 specific objectives were identified:

- to examine and evaluate the current environmental state of the Solotvyno salt mine and its wider surroundings with the aid of innovative technology,
- to set up investigative monitoring and to design an appropriate future complex monitoring system for tracking the surface and near subsurface water qualitative and quantitative changes and the soil movements.
- to raise awareness and promote the results of the project on different levels.

The consortium has been formed of University of Miskolc, Hungary, Solotvyno City Hall Ukraine, Sighetu Marmatiei Municipality, Romania, Technical University of Kosice, Slovakia, Institute of Geological Sciences of the National Academy of Sciences of Ukraine, and the Lead Partner TISZA EGTC (Ukraine/Hungary). There were also some valuable subcontractors supporting the project's activities.

The results have been achieved to some extent (with the hindering factors described already) and it will be up to local and regional authorities to push the suggested actions further. It is obvious that only with the joint effort by local, governmental authorities and involvement of scientific institutions the greater success can be achieved.

Tisza EGTC Team

CONTEXT AND SOLOTVYNO ANALYSIS

Central European Service for Cross-border Initiatives - CESCI's **tasks** was to

- prepare the territorial, economic and social analysis of the strategic concept supporting the revitalisation of the mining area in Solotvyno, in cooperation with the project's experts.
- identify the next steps of the revitalization, formulating proposals for the sustainable utilisation of the mining area and the region's heritage, within the framework of the strategic concept
- carry out interviews and data collection required for the analyses, obtaining field information.

The main **aim** of the chapter for which CESCI was responsible is to show the main challenges and potentials deriving from the local and locational endowments of Solotvyno. The analysis provides conclusions and recommendations by giving a comprehensive picture on the factors that shape the territorial, economic and social cohesion of the settlement. The upcoming analysis is important to give a deeper understanding of the context of the complex, cross-sectoral issues that shape the present of Solotvyno that are in strong connection with the salt mining and the environmental risks assessed throughout other parts of the document. The aforementioned analysis covers the topic of geographical and environmental features, the population structure and the economic structure of Solotvyno and its surroundings (its administrative unit and the Tiachiv Raion around the settlement).

To sum up the most important **results** of the study, it can be stated that the situation of the urban development of Solotvyno heavily depends on the utilisation level of local endowments and locational aspects. From a geographical point of view the settlement is situated on the westernmost part of Ukraine, in Transcarpathia.

Solotvyno has been in a disadvantaged peripheric situation as strong EU borders persist and major transport connections avoid the urban-type settlement. However, Solotvyno can capitalise from being a peaceful corner of Ukraine, its closeness to European markets, and the future decrease of the negative border effects (by the construction of a new bridge crossing to Romania in particular). Potentials lie in being in a stronger functional integration with Sighetu Marmației, Romania. Solotvyno is also the centre of its

surrounding settlements. Solotvyno has functions that make the urban-type settlement outstanding from the settlement network: health care facilities, spa tourism, a large number of organisations and institutions connected to the ethnic minorities.

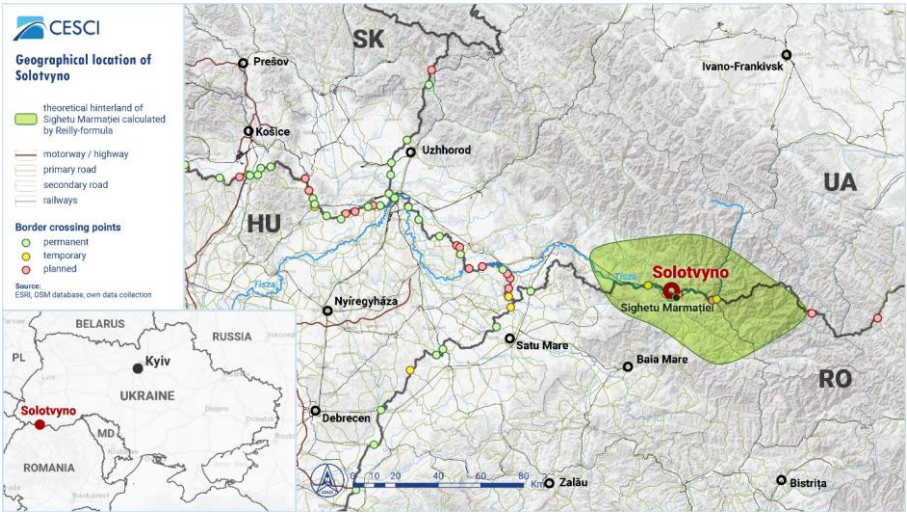


Figure 1: Geographical location of Solotvyno

Land movements connected to the results of mining activity push authorities and the local government to rethink land use planning and the relocation of functions and citizens, which could only be done with great care, especially on the ethno cultural implications. Environmental protection is of great importance since the pollution of the groundwater's and the Tisza itself impacts a wider transnational river basin which calls for joint initiatives in water management and environmental protection at least. Waste management is unresolved in Solotvyno that implies further calls for action.

The development of Solotvyno and any environmental intervention cannot be carried out without taking into account the multi-ethnic character of the urban-type settlement, which could be better addressed in the future as a basis for socio-economic improvements. Population retention force should be increased by effective and efficient policies and concrete actions that would keep the population at their homelands. With regard to economic structure after the collapse of salt mining, diversification could play an important role.

The lack of large enterprises after the shrinking mining industry could be counterbalanced by the support for SMEs in tourism in particular.

Mono-structural economy has been shifting towards an economy characterised by emerging tourism. In the economy a lot depends on the situation of the tourism and health sector. The emergence and quality shift to complex health and recreational tourism that is based on hospitals and the salt waters is of great significance. Water and ground pollution, waste, landslides and other movements and the well-being of the local population are inseparable areas.

The prosperity of Solotvyno including tourism, agriculture and mining is heavily dependent on decrease of environmental and man-made risks and hazards that hamper the success of Solotvyno in shifting to a more sustainable and new development path. Without comprehensive territorially integrated interventions Solotvyno will not be able to utilise its territorial capital and local endowments, and problems will be reproduced on a longer term.

Roland HESZ,
Chief Analyst CESCI

REGIONAL IMPACT AND OUTREACH 1

Project goals: the main goal of REVITAL I. for the Romaniai partner is to examine the current environmental impact of the Solotvyno salt deposit to Sighetu Marmatiei, tracking the surface and near subsurface water qualitative and quantitative changes and the soil movements.

Field measurements: in the first step electrical and electromagnetic geophysical measurements were carried out.

We carried out Surface Deformation Monitoring and Risk Mapping in Sighetu Marmatiei in Romania. The stability measurements is based on ERS (1992 - 2000), ENVISAT (2002 - 2010) and Sentinel-1 data set (2014 - 2021), ascending and descending equitation's. A similar processing method was executed, with the exception of grid-based analysis. We marked out a monitoring system in Sighetu Marmatiei. Water quality monitoring containe the following steps:

a. Examination of drilled and dug wells.

b. Examination of waterworks.

c. Examination of natural springs.

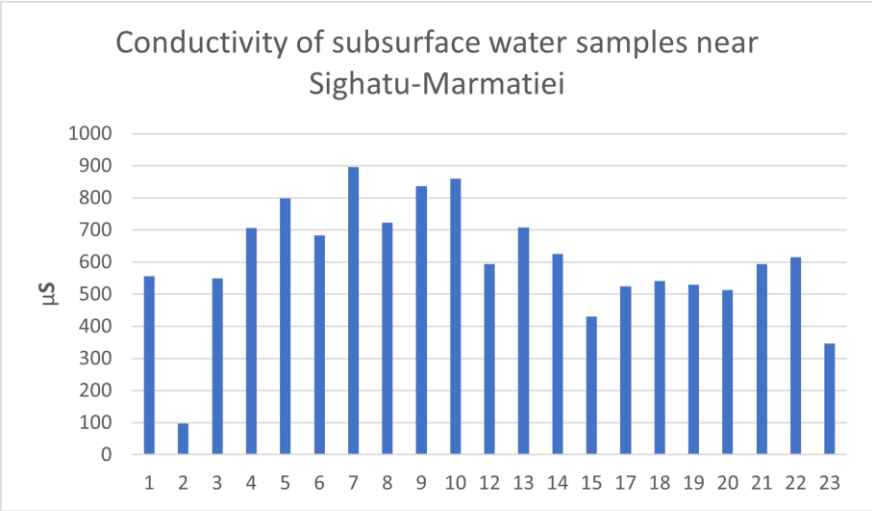
d. Examination of Tisza and Iza rivers.

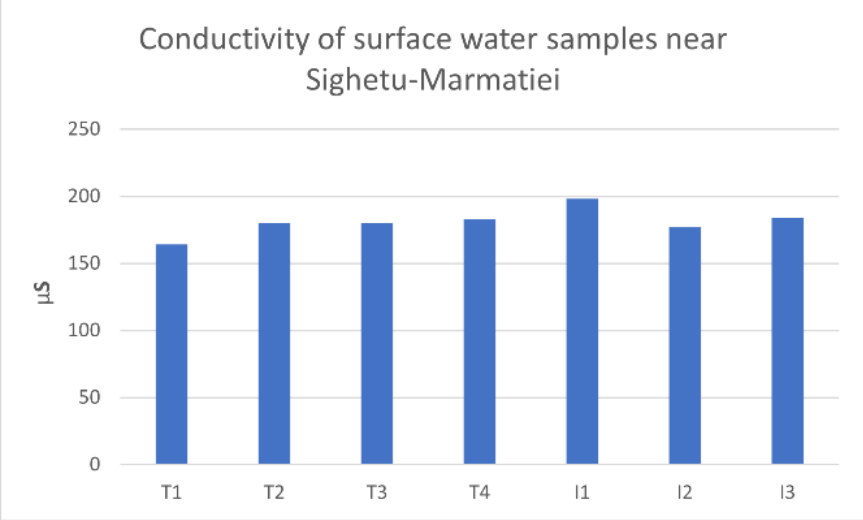
Outputs: According to the classification PSS-78 the salinity of all tested water samples is less than 0.5 ppt, so the tested waters around Sighetu Marmatiei are classified as fully fresh waters for the whole study period. As a result of the salinity studies carried out during the project period, it can be concluded that in Sighetu Marmatiei and its surroundings are not affected by salt pollution from the nearby Solotvino salt dome.

Among the various contaminants, heavy metals are of particular concern due to their environmental persistence, biogeochemical recycling and ecological risks. Heavy metals in sediments occur in different geochemical forms, which have a distinct mobility, biological toxicity and chemical behaviour. All of the bottom sediment samples from Iza and Tisza are not show exceedances of the acceptable limits.

The results of surface deformation analysis highlight a totally different situation, as it was detected in Solotvyno. The whole territory of Sighetu Marmatiei presents a stable condition, and there are not any districts of the town, which shows a geographically recognizable pattern of surface

movement. Scattered locations of few instabil points are detectable. It means that the revealed local instability most probably in connection with structural problems of a building, or slope conditions.





Peiter LENDEL
Sighetu Marmatiei Municipality, Doctor of Biology

REGIONAL IMPACT AND OUTREACH 2

Based on the fact that the prospects for the development of Solotvyno are associated by the local community with the use of minerals (the Solotvyno rock salt deposit) and technogenic brines that fill sinkholes above the mines, the studies of the Technical University of Košice (TUKE) were aimed at determining the prospects for the development of natural resources based on risk reduction

TUKE completed the tasks:

Monitoring of the morphological changes based on the interpretation of the recordings of the satellite images in the area of Solotvyno salt mine and its wider ambience

- **Collecting, ordering and reinterpreting the archive data that necessary for the other project activities.**

The complex of works included:

1) Preparatory work:

a. acquaintance with technical documentation;
b. reconnaissance of the territory and preparation of devices;
c. development of the project of performance of works.

2) Field works:

a. determining the coordinates of control and reference points;
b. aerial survey of the territory.

3) Processing of results:

a. construction of point cloud of a plot located in Solotvyno;
b. construction of digital elevation model of a plot located in Solotvyno;
c. construction of orthophotomap of a plot located in Solotvyno;
d. preparation of a technical report on the results of surveys.

Complex of works on construction of point cloud, digital elevation model and orthophotomap of a plot located in Solotvyno (Zakarpattia region) was carried out.

Aerial survey on a plot located in Solotvyno was performed in November 2021, in total as a result of aerial survey 1.154 images were taken.

Figure An orthophotomap of a plot located in Solotvyno

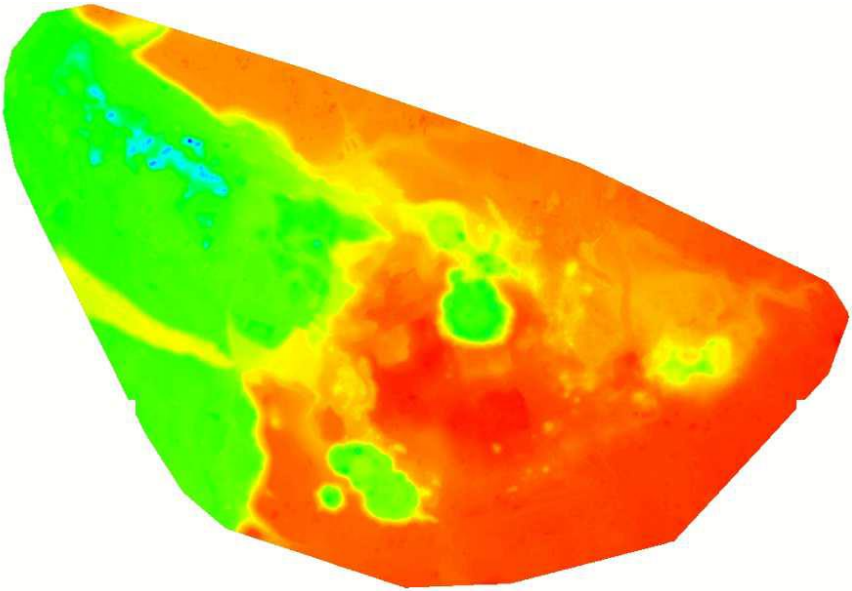


Figure. The digital elevation model of a plot located in Solotvyno

Performed: as a result of processing, an orthophotoplan, point cloud and digital elevation model with a resolution of 4 cm was created. The mean square error of their placement does not exceed 19 mm.

- **It will describe the current ecological state of the region, the planning of a future monitoring system and gives suggestions on the sustainable operation of it. The cost is for cooperating in compiling the final plan with every project partner.**

This part summarizes the works performed on the investigation of ground displacement using Multi-temporal satellite radar interferometry (MT-InSAR) technique and analysis of Signal-to-Clutter Ratio (SCR) in the area of Solotvyno mine located in Tiachiv region (Ukraine).

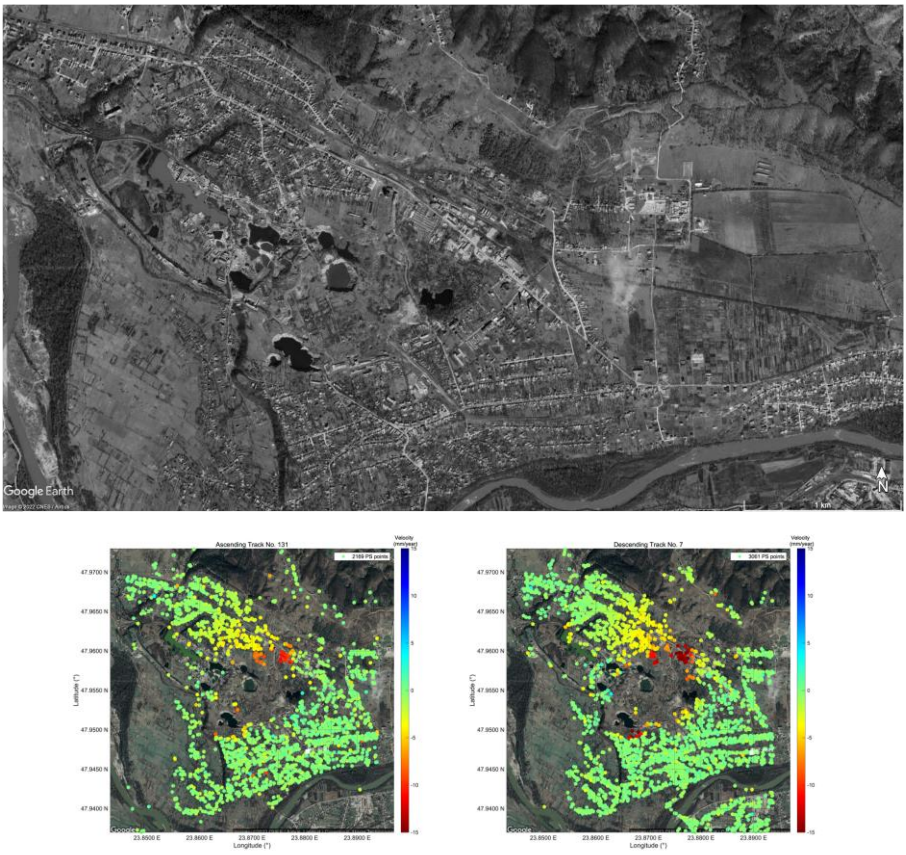


Figure Line-of-sight (LOS) displacement velocity map from Descending Track No. 7

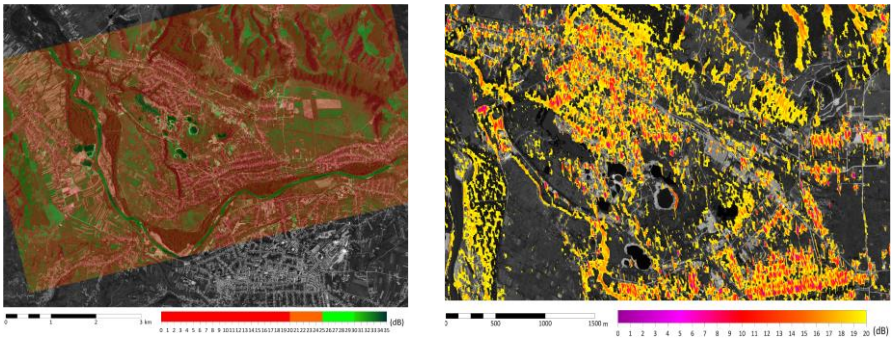


Figure Expected SCR from Descending Track No. 7 using last-year Sentinel-1 acquisitions for estimation (202012-202112), marked critical non-usage areas with SCR < 20dB

In this work, the area around Solotvyno mine in Ukraine has been analysed utilising Multi-temporal satellite radar interferometry (MT-InSAR) technique and Signal-to-Clutter Ratio (SCR) analysis. Two orbit paths of Sentinel-1A/B satellites have been analysed in monitoring periods from Oct 2014 to May 2021 with a total amount of 331 satellite radar images from Sentinel-1's Ascending Track 131 and 328 images from Descending Track 7.

The application of MT-InSAR technique with linear model assumption for deformation estimates has been capable of providing sufficient amounts of persistent scattering targets in the monitored area. Steeper displacement trends (> -2 cm) were recorded for the very central part of the Solotvyno progressing significantly also in recent monitoring periods of the year 2021. These measurements were confirmed via the independent analysis of both sensing geometries (ascending/descending).

The central area with no persistent targets might correspond to the significant physical changes of the surface exceeding motion detectable in one pixel (~2.8 cm per 6 days for Sentinel-1) induced by activities such as mining or digging, adding/removal of buildings or their parts, etc. Such areas shall be further analysed, validated and interpreted by geotechnical experts who are familiar with a monitored structure and its anthropological or naturally-induced changes that might have occurred during the monitoring period from Oct 2014 to May 2021.

Satellite monitoring using MT-InSAR techniques should be applied for the time-interval, or historical period, without the significant changes to objects' reflectance. For precise engineering tasks and analysis over the objects

with potential deformation risks, it is recommended to continue the monitoring with quarterly intervals, utilizing artificial corner reflector (ACR) measurements and higher-resolution satellite missions such as TerraSAR-X/PAZ. For more in depth observations and interpretation, it is suggested to refer to the results summarized in the Electronic File Repository delivered as Appendix 1 of this report.

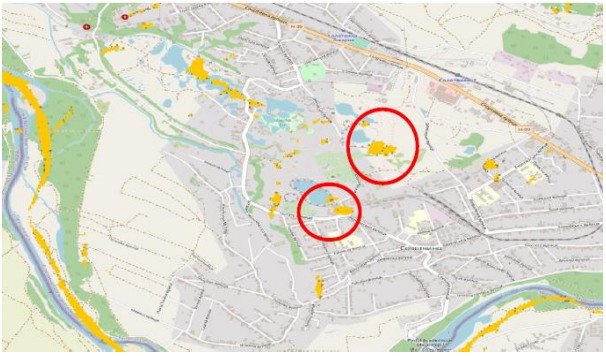
Expected SCR maps of stations should serve as an initial guidance for deciding the proper situation of artificial radar reflectors. SCR maps were produced using simulated corner reflector response of triangular trihedral with inner leg-length of 1 m (and corresponding RCS of 30dBm2).

Using simple thresholding on SCR maps, given the condition of single Sentinel-1 C-band phase measurement standard deviation of 0.5 mm, the SCR should be more than 20 dB. However, one has to be aware that the applied simulation does not consider the sensor's thermal noise and other InSAR-related noises, such as residual atmospheric path delay, unmodelled deformation or orbital errors. Additionally, the optimal installation location should not contain any strong point scatterers within plus/minus two Sentinel-1 IW SLC resolution cells (~40-50 m) in azimuth and range respectively. It is strongly encouraged to carry up a final decision on installation location in accordance with in-situ information. Reflectors should be collocated with GNSS stations monuments using minimal distance offsets.

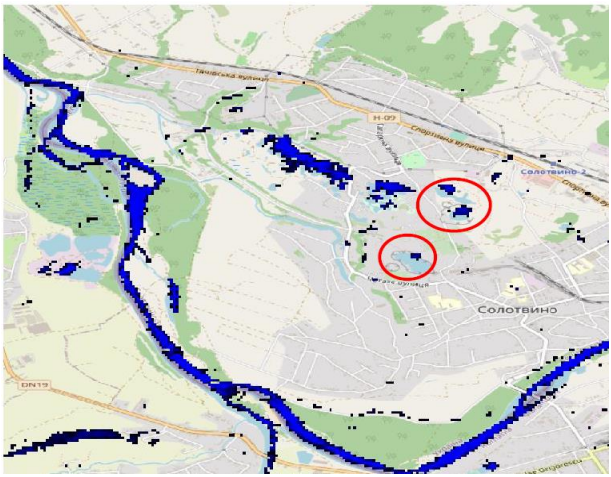
Monitoring ground movements, settlings with the interpretation of the recordings of satellite images.

This task was done using open street map images.

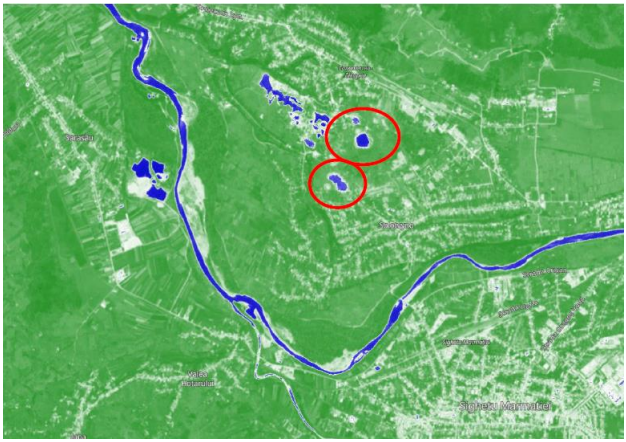
Display of OpenStreetMAp and NDWI_2014 images (Normalized Differential Water Index) from Multispectral image with resolution 10x10m, Družica Spot 5, Observation 5.12.2014



Display of NDWI_2008 images (Normalized Differential Water Index) from Multispectral image with resolution 10x10m, SPOT 4, Observation 28.10.2008



Display NDWI_2017 (Normalized Differential Water Index) from Multispectral image with resolution 10x10m, Sentinel satellite_2, ESA, Observation 9/29/2017



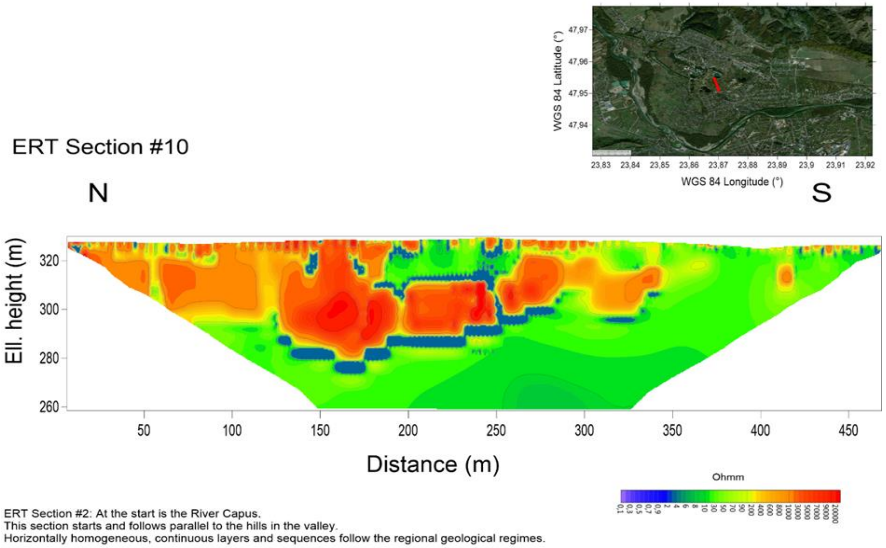
Display NDWI_2018 (Normalized Differential Water Index) from Multispectral image with resolution 10x10m, Sentinel satellite_2, ESA, Observation 10.12.2021

Martina ZELEŇÁKOVÁ,
Vice Dean for Marketing and International Relations
of Technical University of Kosice

FIELD STUDIES AND FINDINGS

The University of Miskolc, as part of the Revital project, was involved in several Activity Groups, mainly carrying out measurements related to the baseline survey with the involvement of subcontractors. The field measurements performed by the GeoGold Kárpátia Ltd.

Geophysical survey campaign has been carried out with the aim of extending the geological mapping of the Solotvyno salt mine area and to supplement the near-surface geophysical data of the region with several measurements from the southern side of the river. Multielectrode geoelectrical tomography (ERT), Very Low Frequency Radio-magnetotellurics (VLF-RMT), Horizontal Loop Electromagnetics (HLEM), gravimetric and seismic measurements. Among the applied geophysical methods, the most detailed and undisturbed results were obtained with electrical and electromagnetic measurements. The interpretations of the salt mine area's geology and structure was effectuated on base of these data, which were also the input parameters of the 3D geologic and hydrodynamic models.

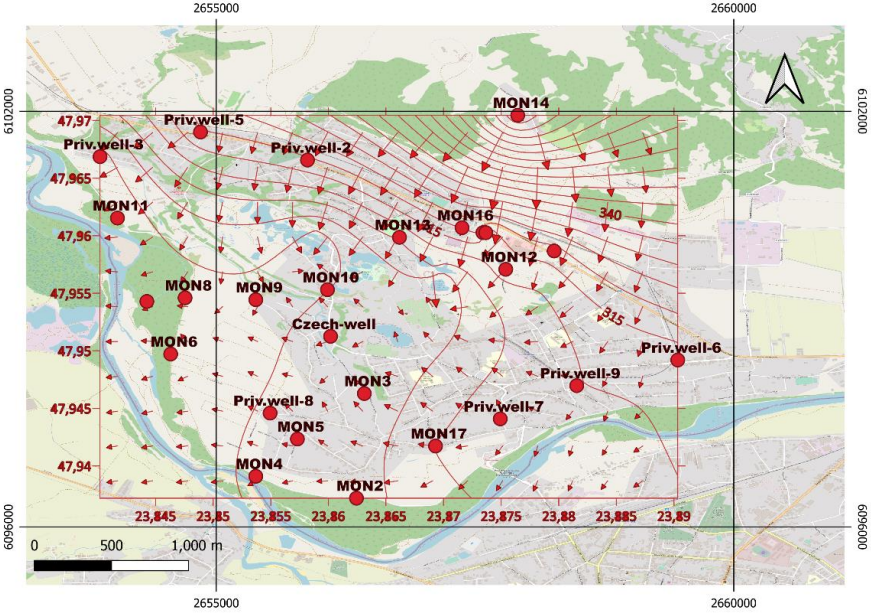


ERT Section #2: At the start is the River Capus.
This section starts and follows parallel to the hills in the valley.
Horizontally homogeneous, continuous layers and sequences follow the regional geological regimes.

Originally, the karstified salt dome was a genetically covered karst body protected from any contamination. During the centuries, due to the salt rock excavation made first on the surface, and later, due to the development of

mining and borehole techniques to the deeper ways, the protecting layers (palah) partly destroyed and disappeared. Because of these activities, the surface of the salt dome became open, contacting directly with the air humidity and precipitation, moreover is closer contact with the flowing surface and shallow groundwater, too, and the salt karstification processing has started here. Sinkholes, dolines, craters, and finally the disruption of the mines have been coming into play, and all these phenomena are the consequences of the salt dissolving.

To understand the hydrogeological conditions in the investigated area, a well-group consisting of 15 piezometer wells was established (wells marked MON), in which regular/continuous water level and water chemistry test measurements were carried out for a year. Private residential wells of similar depth (6-15 m) were also included in the measurements (a total of 8). The measurements detected seasonal differences. The flowing regime is North to South, the groundwater flowing from the slope of the Magura Mountains to Tisa river, but locally at the former mining area the direction changes and turns East to West.

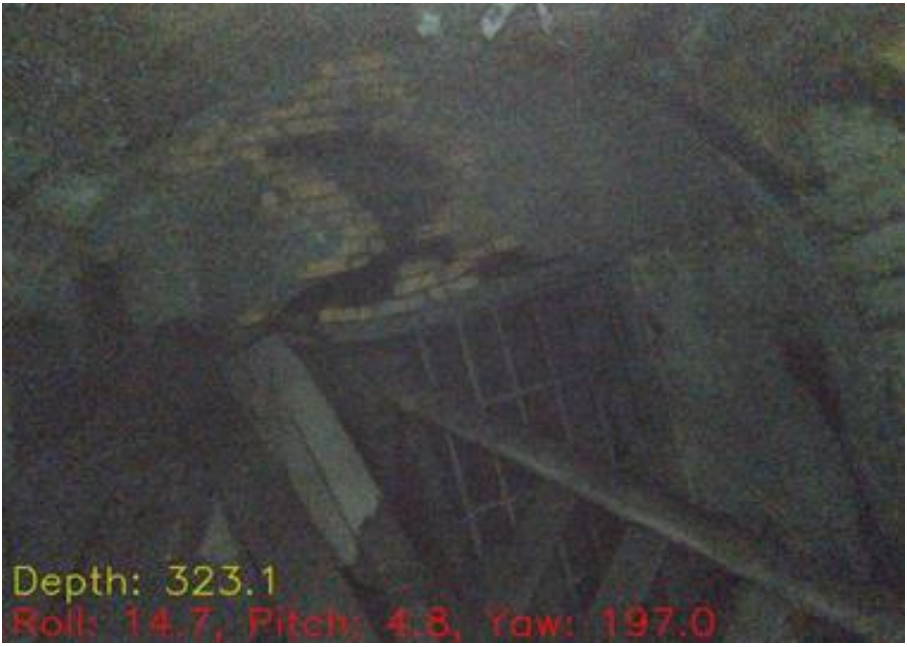


Several surface waters in the study area (Black Moor, crater lakes, mine shafts) were analysed for water chemistry.

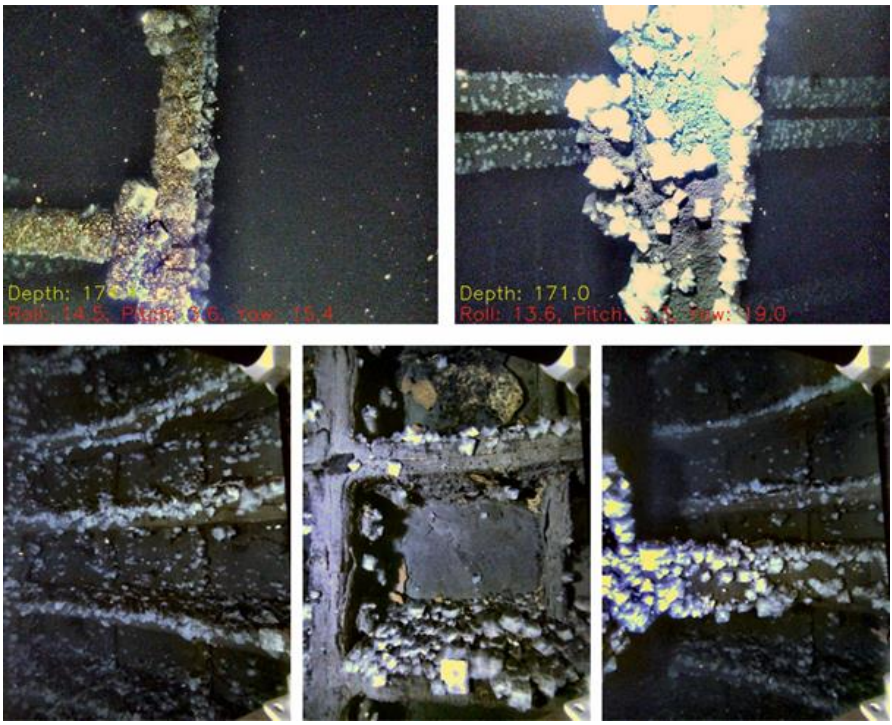
The EC values measured near the surface of the Black Moor- lake, therefore, seem to have practically not changed in 5 years. This apparently shows a state of equilibrium. Based on the measurements, we can assume a hydraulic connection between the Black Moor - lake and Shaft 10 of Mine 9.

In the crater lakes stabilised, close to salt-saturation conditions have most likely occurred in the depths, but in near the surface zone further surface movements are expected. Their intensity will decrease asymptotically over time, unless some sudden natural change occurs (e.g. extreme events. The Mine 7 water-filled crater lake is in direct contact with the lid of the salt dome, and thus the lake is completely saturated with salt. The water chemistry EC tests show that the crater lake formed at the site of Mine 8 has not yet reached its equilibrium state either from a static or water chemistry point of view.

With the help of the UX-1Nepo diving robot the UNEXMIN Georobotics Ltd. to produce 3D maps, capture high-resolution video footage in the Solotvyno mining area and evaluate the results of the dives. In addition, the robot carried out water sampling and water parameter measurements (electrical conductivity, pH, oxygen fugacity, temperature, pressure). The Shaft 10 was mapped to a depth of 435 m (47.5 bar), in total, there were 3 levels of side passage, of which only the access at 366 m is open from the shaft. The robot reach 55 m during the side passage mapping, but the passage was blocked.



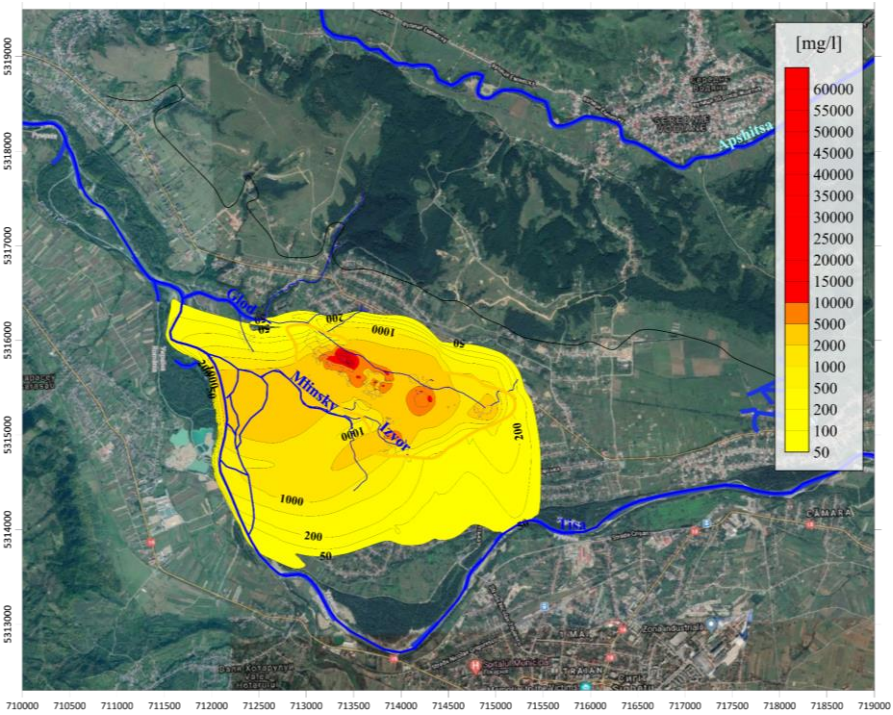
The Shaft 9 and 10 shafts appear to be structurally good, but the same cannot be stated for the side tunnels and beyond. In the saturated saline water body observed below 145 m, salt crystal formation is observed on the shaft wall and metal beams in the shaft at a depth of 158 m. The halocline level varies, shows seasonal differences, but never deeper than 158 m. The robot observed 1-1.5 bar pressure difference between the Shaft 9 and 10. This value assumes limited permeability between the two shafts, which is partly evidenced by the blockages observed in the side passages.



Based on the IGS NASU's hydrodinamical model, a chloride transport model developed by the Gáma-Geo Ltd and University of Miskolc.

Based on the numerical calculations, we can stated, that the current brine load on the riverbank layers therefore comes from two sources, the 13-15 m^3 of saturated brine seeping up from the mines and the water seeping through the ponds in the former collapsed mine cavities. Maximum of 4600 kg/d of NaCl is released from mines and 6600 kg/d from saltwater lakes, i.e. a

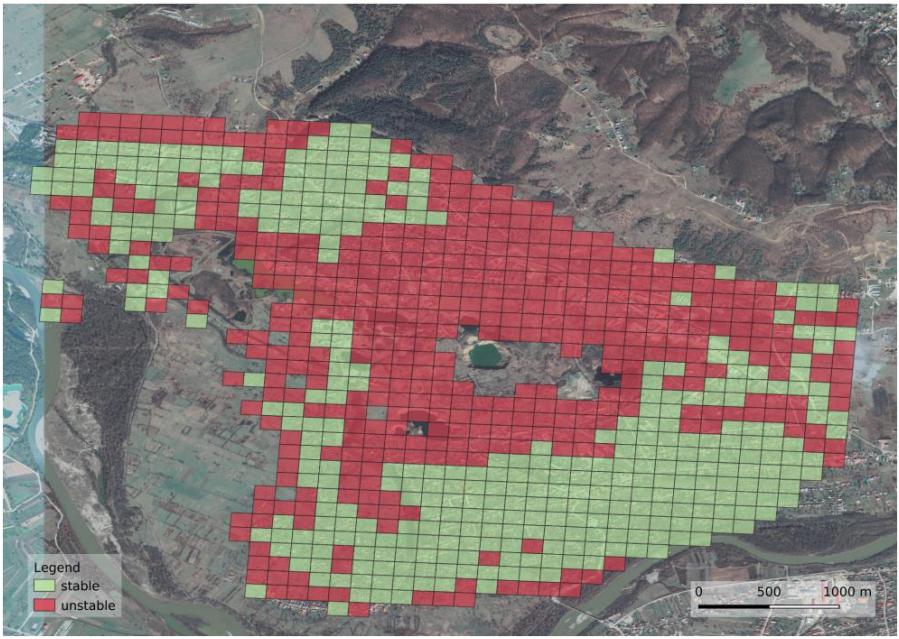
total of 11 200 kg of rock salt is loaded into the Tisa River. Assuming a rock salt density of 2100 kg/m^3, this would result in a daily leaching of 5-5.5 m^3 of rock salt per day, which would mean a maximum of nearly 2000 m^3 of cavitation below the surface per year. The estimated long term chloride concentrations can be seen on the Figure.



Archive data of the EU ENVISAT satellite system from the years 1992-2000 and 2002-2010 were used to monitor changes in surface movements in space and time. The evaluation performed by the Datelite Ltd. The mine ruptures with the largest surface movements can be linked to the latter period.

Based on the evaluation, there were no significant difference in land subsidence between 1992-2000, and 2002-2010 and and 2014-2021. In both periods, it is clearly visible that the very high-risk area is the former salt mine, the salt ponds, and the several hundred-meter strips bordering them if it affects built-up areas. This means subsidence of up to 25 mm/year (obviously, this shows higher values in the vicinity of the ruptured craters). The most endangered utility provider is the electrical distribution network plant located in the area of Mine 9 (near Shaft 10) in the NE part of the very high-risk area.

According to the indirect evidence of water chemistry tests, the subsidence process progresses asymptotically to the new equilibrium state, higher subsidence values are most likely no longer expected.



Stability map of Envisat scatters between 20014-2021 (DatElite Ltd)

Legend: green=stable, red=unstable

The whole territory of Sighetu Marmatiei presents a stable condition, and there are not any districts of the town, which shows a geographically recognizable pattern of surface movement.

As part of the project, a GIS database has been created which, in addition to the archive data, also contains the measurement results of the baseline survey carried out in the project. The database is available to project partners and the wider public also.

Prof. Dr. Péter SZŰCS, professor,
Vice Rector of the University of Miskolc

Dr. Viktória MIKITA, associate professor of the Institute of Water and Environmental Management, University of Miskolc

COMPREHENSIVE GEOMONITORING SYSTEM FOR SOLOTVYNO SUSTAINABLE DEVELOPMENT

Based on the fact that the prospects for the development of Solotvyno are associated by the local community with the use of minerals (the Solotvyno rock salt deposit) and technogenic brines that fill sinkholes above the mines, the studies of the IGS NASU were aimed at determining the prospects for the development of natural resources based on risk reduction

IGS NASU completed the tasks:

- development of a geological model with manifestations of hazardous exogenous geological and technogenic-geological processes in the Solotvyno settlement;
- assessment of the ground surface vertical displacements using interferometric processing of satellite radar monitoring data;
- hydrodynamic modeling;
- development of a conceptual scheme for Complex Monitoring of the territory for its revitalization and safe use of natural resources.

Construction of a geological model with manifestations of hazardous exogenous geological and man-made geological processes in Solotvyno settlement (Fig. 1)

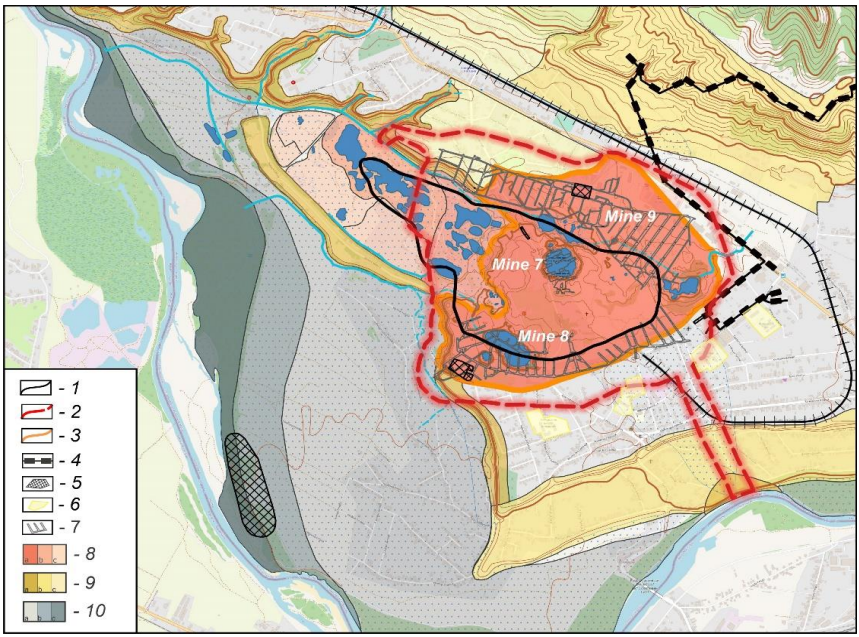


Figure 1. Situational plan of the Solotvyno salt mine area and its surroundings with zone of technogenic impact of salt mining operations and manifestations of hazardous exogenous geological processes: 1 – contour of the salt dome structure on the surface of alluvial sediments; 2 – the zone of technogenic impact of salt mines and development of the hazardous exogenous geological processes; 3 – the zone of active technogenic impact of salt mines and development of the hazardous exogenous geological processes; 4 – gas pipeline; 5 – critical infrastructure objects (power substation, water supply pumping station, sewage treatment facilities, landfill); 6 – preschool and school educational institutions; 7 – contours of mines. Risk of natural and natural-antropogenic hazards (8-10): 8 – karst processes: catastrophic (a), high (b), medium (c), low (d); 9 – slope erosion: high (a), medium (b), low (c); 10 – seasonal and flash floods: high (a), medium (b), low (c).

- *Field visual monitoring observations on the examination of the manifestations of hazardous exogenous geological and man-made geological processes in Solotvyno and verification of the results of the assessment of earth surface deformations;*
- *Monitoring of ground surface vertical deformations (subsidence) based on PS&SBAS interferometric techniques using DInSAR data (Differential interferometric synthetic aperture radar (DInSAR) technique);*
- *A complex geological model of the Solotvyno salt dome structure was developed.*

Zones with further development of ground surface subsidence (Fig. 2), sinkholes area expansion, and formation of shallow sinkholes above the galleries of the drainage tunnel system have been established; to refine the basic geological model for hydrodynamic modeling, fault zones in tuff outcrops were documented, maps of Quaternary formations were constructed, which shield salt rocks, and other elements of the basic integrational geological model.

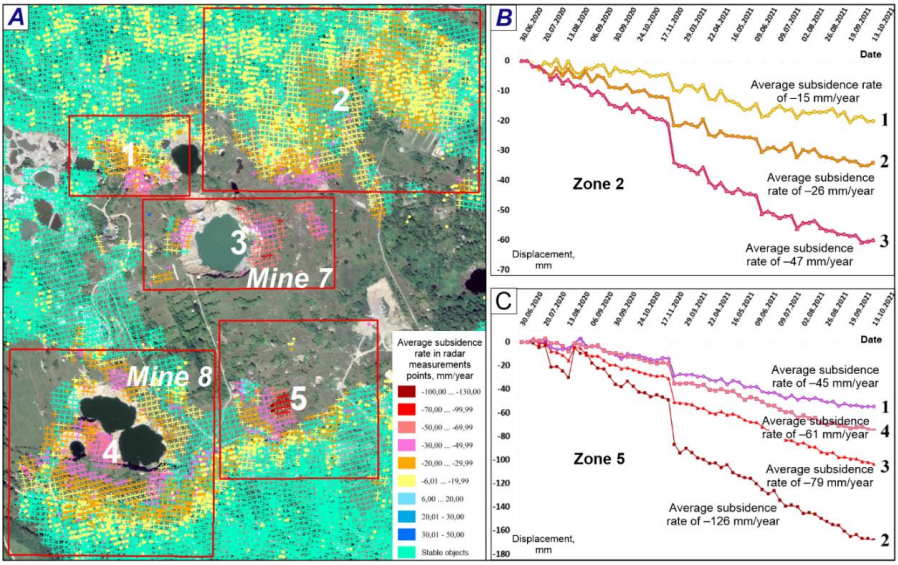


Figure 2. Assessment of ground surface vertical displacements using interferometric processing of satellite radar monitoring data (PS&SBAS) for the period from 06/2020 to 06/2021 (using data provided by the Center for receiving and processing special information and control of the navigation field, State Space Agency of Ukraine): A – zones of concentrated deformations; B – graph of vertical displacements for the zone of concentrated deformations #2, the maximum average subsidence rate is –47 mm/year; C – graph of vertical displacements for the zone of concentrated deformations #5, the maximum average subsidence rate is –126 mm/year.

Patterns of the distribution of ground surface vertical displacements, which are fixed not only in the contour of mining operations but also beyond them, are revealed (Fig. 3); the accumulated ground surface deformations in the areas of critical infrastructure facilities were assessed.

The map of manifestations of hazardous exogenous geological and technogenic-geological processes in the Solotvyno settlement has been updated.

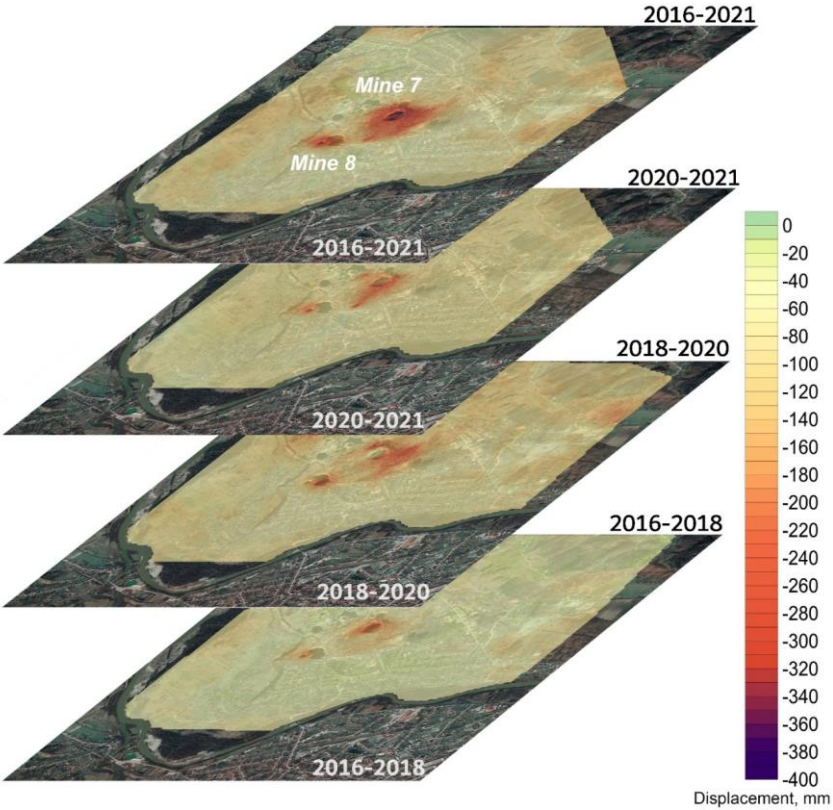


Figure 3. Dynamics of changes in the maximum vertical ground surface displacements

Hydrodynamic modeling

A modernized hydrodynamic model of the Solotvyno rock salt deposit and adjacent territories was created (Fig. 4), based on the refined filtration parameters of the suprasalt deposits of the Solotvyno salt dome structure and an updated geological database and basic integrational geological model.

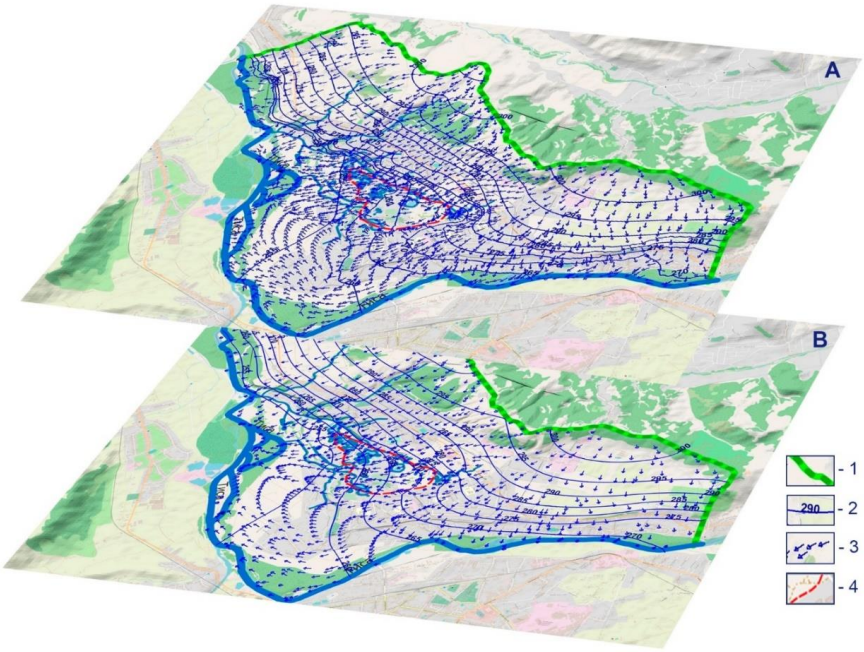


Figure 4. Hydrodynamic model of the Solotvyno salt mine area and its surroundings: A – the Quaternary aquifer with groundwater level isolines and actual flow velocity vectors; B – the Tortonian aquifer with groundwater level isolines and actual flow rate vectors. 1 – watershed; 2 – groundwater level isolines; 3 – actual flow rate vectors; 4 – salt dome structure contour on the surface of alluvial sediments.

Based on obtained studies results (field observations, remote sensing satellite radar monitoring data analysis, geological and hydrodynamic modeling) the complex monitoring system plan, which fits into the wider regional framework for tracking the surface and near subsurface water qualitative and quantitative changes and the ground surface deformations in Solotvyno area have been developed (Fig. 5).

Complex Monitoring System Plan

Operation of the monitoring system are required for the sustainable use of natural resources (brines and rock salt) and protection against transboundary spread of surface and underground water pollution.

Planned Complex Monitoring System includes: - monitoring of ground surface deformations using DInSAR; - hydrological and hydrogeological monitoring (water quantity & quality); geophysical survey (microgravity, geoelectric and seismic methods); - geodetic survey; - on-site inspection of hazardous geological processes development; - modeling (up-to-date improvement of hydrodynamic model); - risk assessment.

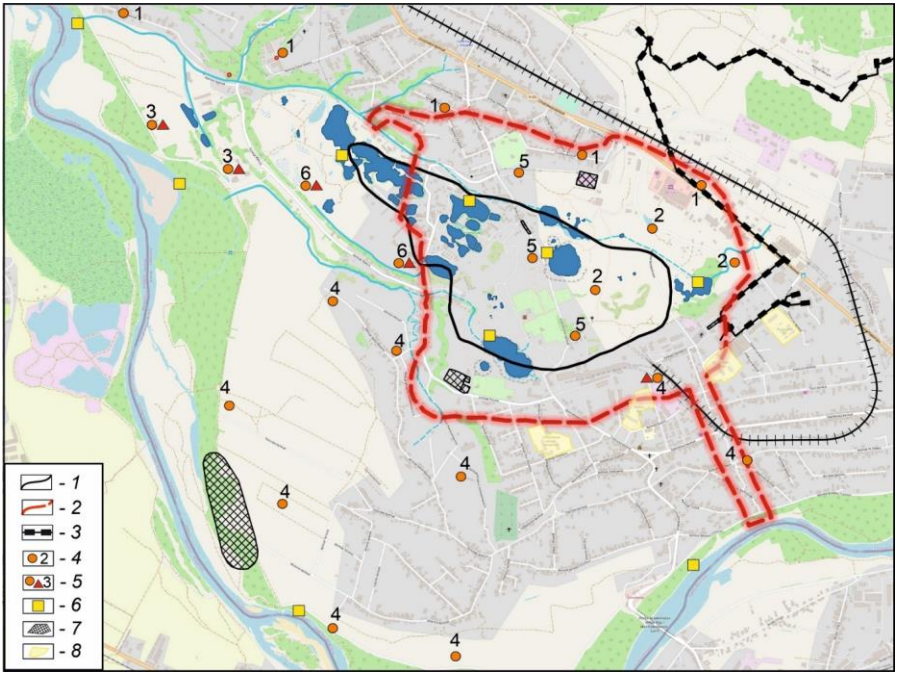


Figure 5. Complex Monitoring System Plan of the Solotvyno salt mine area and its surroundings: 1 – contour of the salt dome structure on the surface of alluvial sediments; 2 – the zone of technogenic impact of salt mines and development of the hazardous exogenous geological processes; 3 – gas pipeline; 4 – project monitoring hydrogeological observation point (well) and the number of the consolidated geological section type according to lithological data; 5 – project monitoring hydrogeological observation point (mine well, which consists of two wells: for the Quaternary unconfined and Tortonian fractured aquifers) and type number of the consolidated geological section according to lithological data; 6 – project monitoring hydrological

observation point; 7 – critical infrastructure objects; 8 – preschool and school educational institutions.

The implementation of a monitoring system with an integrated permanent hydrodynamic model should become a tool for managing the use of natural resources in the Solotvyno settlement – brines and rock salt.

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POSSIBLE FUTURE ACTIONS

The pearl of Transcarpathia Solotvino has been known since ancient times as a source of salt for many European nations. It is the mining settlement with a centuries-long history; salt has been mined in Solotvyno since the times of the Roman Empire.

The healing effect of salt water in lakes and baths has been used since the nineteenth century. In 1968, the first speleotherapy hospital was opened. As a result of mistakes made by the Soviet government in the operation of mines and salt production, the situation of the natural environment on the territory of the salt mine has deteriorated since the beginning of the 2000s, and due to its patterns, the situation was classified as a state emergency.

This project was very important for the settlement of Solotvyno because it allowed to find the solution to the environmental problems of the village, which had arisen as a result of the emergency situation on the territory of the Solotvyno salt mine. This is the first project aimed at the ecological assessment of the possibilities of restoration of natural resources in Solotvyno through the preparation of a comprehensive monitoring system.

The Solotvyno City Hall, as a part of the project, had to organize the stay of the project participants in Solotvino, obtain the necessary permits for scientific research on the territory of Solotvino, obtain access permits to the border zone, accompany the participants around the area, etc. The purchase of digital recorders for liquid level, conductivity and temperature indicators was very important for the project. A monitoring system was built up on the basis of these recorders.

This project serves as the beginning of the path to the restoration of salt production, and speleotherapy renewing!

Solotvyno City Hall

STRATEGIC CONCEPT NOTE

This Strategic Concept Note and a documentation on the complex monitoring system both are providing a good and important base for future actions and are supporting the decision makers at all levels. **The project activities build on several previously conducted missions by Hungarian authorities, EU Civil Protection Team and ImProDiReT project.**

The data collected should also serve as a base of the future developments and actions (new elements of the improved monitoring system, rehabilitation activities, new investment possibilities, disaster management, etc.), but must be planned according to the mid and long term with no harm to the environment and considering the safety issues for the inhabitants of the Solotvyno. There is an always present appetite to re-open the salt mining, but without a joint and coordinated effort no positive outcome is foreseeable.

Map of the studied salt dome area with lakes (fresh and salt), creeks, drainage system (GeoGold Ltd.)

As results of the Project activities numerous maps, data, reports etc, have been produced and the Strategic Concept Note captures the most important elements of the work performed by all project partners and

subcontractors. For the whole and complete picture, the interested party should get acquainted with the Strategic Concept Note and even study the specific results of the relevant activities.

The problems of the mining activity in Solotvyno, mainly started in the 60s and 70s. As the volume of salt extraction increased from 0.5 million tons per year to 1 million tons per year using explosives in deep mines, the amount and speed of harmful phenomena also increased.

Forced blasting extraction also increased the number of environmental disasters, the causes of which can be classified into three main groups.

1) Disruption of the natural water-tight layer near the surface (a layer of salty clay a few meters thick below the Quaternary cobble-gravel-sand alluvial sediment layer, locally known as 'palah') because of mining activity and research drillings

2) Complete lack of maintenance of the drainage gallery system (the dewatering system at an average depth of 30 m, which surrounds the cultivated mine area and aims to drain the groundwater of the Quaternary cobble-gravel- sand layer near the surface, located above the 'palah' layer that provides the natural protection of the salt dome) created about a hundred years ago. The absence of gallery and dewatering management started in the 70s, continuing with the incorrect handling of the resulting problems and the lack of further prevention.

3) Use of improperly performed and forced blasting procedures to increase salt production.

Consequences:

a) Water intrusions into mines, dissolutions processes in the salt dome

b) Formation of cracks and mine lakes that penetrate to the surface

c) Detectable annual ground level subsidence of 1-2.5 cm/year

The analysis deriving from the local and locational endowments of Solotvyno provides conclusions and recommendations by giving a comprehensive picture on the factors that shape the territorial, economic, and social cohesion of the settlement. It is important to give a deeper understanding of the context of the complex, cross-sectoral issues that shape the present of Solotvyno that are in strong connection with the salt mining and the environmental risks assessed throughout other parts of the document.

It can be said that in the current state, a maximum of 4600 kg/d of NaCl is released from mines and 6600 kg/d from saltwater lakes, i.e., a

total of 11 200 kg of rock salt is loaded into the Tisza River. Assuming a rock salt density of 2100 kg/m^3, this would result in a daily leaching of 5-5.5 m^3 of rock salt per day, which would mean a maximum of nearly 2000 m^3 of cavitation below the surface per year.

The overall methodology of the REVITAL 1 consists of desk research, use of statistics and conducting a series of interviews, site visits and measurements and data collection and analysis. During the desk research, information on Solotvyno was searched via finding and summarising, reviewing bibliography in the topic of Solotvyno's socio-economic life. Statistical data from the official sources of the Statistical Office of Ukraine as well as statistics from other databases built during the years in the frames of CBC[1] and transnational projects and regional analyses were also used to provide territorial evidence. Still, it must be noted that sometimes there are strong limitations owing to lack of latest data on settlement and regional levels.

It can be stated that the situation of the urban development of Solotvyno heavily depends on the utilisation level of local endowments and locational aspects.

Environmental protection is of great importance since the pollution of the groundwaters and the Tisza itself impacts a wider transnational river basin which calls for joint initiatives in water management and environmental protection at least. **Waste management** is unresolved in Solotvyno that implies further calls for action.

The development of Solotvyno and any environmental intervention cannot be carried out without considering the multi-ethnic character of the urban-type settlement, which could be better addressed in the future as a basis for socio-economic improvements.

Interpretation of satellite images was carried out to establish the basic patterns of earth surface deformations for further assessment of risks associated with the development of hazardous natural and technogenic geological processes within the Solotvyno salt dome structure and adjacent territories.

Assessment of vertical displacements of objects and the ground surface was carried out using interferometric processing of satellite radar monitoring data by means of satellite constellations Sentinel-1A and 1B (DInSAR analysis data for 2016-2021, SBAS approach, Copernicus EMSN-030, EMSN-064; PS+SBAS approach, Center of the Special Information Receiving and Processing

[1] Cross-Border Cooperation, also knowns as Interreg A

and the Navigating Field Control, Ukraine).

The research area was 33 sq. km. The final information products (raster and vector) were created, which made it possible to analyse changes in spatial and temporal dimensions. Remote sensing radar data preparation and pre-processing operations were performed in ENVI software, SarScape modules, and thematic processing operations based on interferometry results (ArcGis software) was done.

According to the latest satellite radar monitoring data (for the period 06/30/2020-10/12/2021) the assessment of the vertical deformations of the ground surface, buildings, and facilities within the Solotvyno was done. It was established that the subsidence zones near the mine No. 7, 8, 9 are significant in area and each has a significant subsidence mould, in which the largest subsidence is determined in its centre, and, when moving away from the centre, the intensity of subsidence of the ground surface gradually decreases. **The territory of mine No. 7 and the western and eastern parts of the mine No. 8 area was identified as unsafe.**

According to the results of retrospective processing in the study area, zones of concentrated deformations and the dynamics of subsidence in the points of radar measurements were determined.**, it was determined that mines No. 7, 8 and 9 pose a threat to the technogenic safety of the Solotvyno settlement.**

The results obtained from all data analysis should be used for continuous risk assessment of the Solotvyno rock salt deposit and adjacent territories. To ensure life safety in Solotvyno, the results need to be used for territory development and monitoring system establishment.

Using corner reflectors and InSAR technology an early warning system could be installed over the area. This InSAR-based monitoring system could improve the public safety conditions quite a lot, and provides an objective, transparent surface deformation information for anyone throughout a web gis application. **This application can be installed on local people's smart phones, and they will be able to receive direct information about their residential district**.

According to the hydraulic gradient, the water from precipitation and groundwater flow system continuously flows into the Tisza in the alluvial layers of highly permeable cobble, gravel, sandy gravel, and sand mainly from East to West, passing through the salt dome.

Originally, the salt dome was covered some few metres of salted clay layers (palah), protecting it against any humidity and/or water. But, **due to the mining activities, which finally caused serious surface destruction, this**

protecting layer became open providing so-called 'hydraulic windows' to harmful and fatal processes.

View of today's abandoned mines (white numbering) with the mining chambers and mine openings as potentially and really threatening underground spaces against water *(Geogold Ltd)*

InSAR measurements revealed the spatial and temporal distribution of historical surface deformations Solotvyno in Ukraine. ERS and Envisat SAR imagery archives covering the above-mentioned time frame have been processed and interferometric deformation history of the area was investigated concluding **the results,** some of them listed below:

- The central part of Solotvyno and adjacent southern slopes of the Magura were detected as fast-moving distinct surfaces during both decades, while other surfaces remained permanently stable.
- Risk levels were computed from interferometric and geological data, showing that high risk levels occur at the dome and surrounding area, while the level of risk decreases with the distance measured from the centre of the salt dome.

The continuous dissolution of the Solotvyno salt dome is influenced by the replenishment of fresh water, the amount and intensity of precipitation (especially the accumulation of winter precipitation), the flow of natural waters coming from the direction of the Magura mountain range, as well as anthropogenic effects, mainly water withdrawals and wastewater introductions.

The data show that the environment protection system in the Tiachiv Raion is underfinanced. Although **Solotvyno** has significant Badenian salt outcrops and salt karstic features – whose morphology transforms rapidly –, these heritages are not protected and not under any restrictions. Moreover, these **salt resources are not just a heritage or a tourist sight, but a vast environmental and hydrogeological hazard** as well.

With the UX-1Nepo diving robot the UNEXMIN Georobotics Ltd. the project partners produced 3D maps, captured high-resolution video footage in the Solotvyno mining area and evaluated the results of the dives. In addition, the robot carried out water sampling and water parameter measurements (electrical conductivity, pH, oxygen fugacity, temperature, pressure).

The prosperity of Solotvyno including tourism, agriculture and mining is heavily dependent on decrease of environmental and man-made risks and hazards that hamper the success of Solotvyno in shifting to a more sustainable and new development path. Without comprehensive territorially integrated interventions Solotvyno will not be able to utilise its territorial capital and local endowments, and problems will be reproduced on a longer term.

The sinkholes, the salt resource, the brine and the soil are **exposed to the threat of pollution.** Especially tourism (with the medical centres, the beaches, and the accommodations) and the agriculture, can fall into crises which directly affect the local community.

The spontaneous and uncoordinated management of the recreational area and the proximity of the abandoned mines cause hazards. The contamination of the sinkholes – by the illegal littering – has a direct effect on the water quality of the beaches. The incidental pollution of the water in the Lake Kunigunda would impair the reputation of Solotvyno and decrease the number of the future tourists. Unfortunately, due to the abandoned mines and the irresponsible behaviour of the locals, these **salt resources have been contaminated, which impairs the future potential of tourism.** To avoid this, it is crucial to create a well-working waste management system and to halt the illegal littering. Another hazard can be the unclosed territory of the mining area since the visitors frequently roam here between the sinkholes just because of interest or short cut. Furthermore, the **constant danger of landslide and subsidence deters the new investors and companies, as they do not want to invest in a risk zone**.

A modernised and improved hydrodynamic model of the Solotvyno salt mine area and its surroundings was created based on the refined filtration parameters of the suprasaline deposits of the Solotvyno salt dome structure

and an updated database, which made it possible to predict the direction and the speed of groundwater flow over time.

The area of influence cannot be reduced by wells, except by artificially reducing the flow of water through the bottom of the lakes formed by the collapse of the existing salt pits and continuously forming, by narrowing or blocking the exits of the pits and shafts even below the groundwater bodies, so that the salt water in the flooded mine pits is brought into full equilibrium by saturation, and in this way further desalination is induced only by fresh water infiltrating along the tectonic lines. This would not impede the use of salt ponds for tourism at all but would merely reduce the salinity load on the Pleistocene riverbank layer and the Glod and Mlinsky streams that discharges it. In this way, the salt concentration in the crater lakes (above collapsed mine chambers) would be reduced slightly, but the groundwater would be reduced substantially. Well water production should be eliminated or banned in the current area of influence of the salt dome.

Salt dissolution in deep layers must be curtailed, otherwise it will cause a steadily accelerating phenomenon, with increasing amounts of salt being dissolved along increasingly large, dissolved surfaces, causing ever larger underground cavities and accelerating subsidence. The process can only be stopped by a radical reduction in deep groundwater flow, which is possible because of the geological and hydrogeological conditions. Reasonable solutions can slow the process down, and significant artificial interventions can reduce it completely, but this should be started as soon as possible, while it is still possible to reduce the process and the environmental damage does not destroy the living conditions of the population in the area.

Considering the complicated geo ecological situation, development and functioning of the permanent complex monitoring system of the natural and man-made geosystem of Solotvyno is the priority objective, it would provide an opportunity for timely detection and assessment of dangerous changes in the state of the geological environment and factors of threats to the safety of life at the local and cross-border level. The SCN provides information on the Planned Complex Monitoring System, that includes monitoring of ground surface deformations using DInSAR (interferometric processing of satellite radar monitoring data with PS & SBAS techniques); hydrological and hydrogeological monitoring (water quantity (levels, flow rates), quality / chemical composition); geophysical survey (microgravity, geoelectric and seismic methods); geodetic survey (verification of remote studies of the ground surface deformations); on-site hazardous geological processes development (karst & suffosion

(subsidence, sinkholes, collapses), seasonal floods and flash floods, flooding, slope mass movement (erosion, landslides); modelling (up-to-date improvement of hydrodynamic model); risk assessment, preliminary substantiations of protective measurements.

Some of the conclusions:

- It could be concluded that some findings of the previous projects (ImProDireT) and even EUCPT mission (in 2016) **reiterate the previous conclusions that there is a deficiency in information exchange and sharing between all the stakeholders involved in (the consequences of) the mining in Solotvyno.** The state of emergency is still present and so far, no answers, senses, or solutions on how to lift the state of emergency can be found.
- **The settlement zone of Solotvyno is directly adjacent to or enters the geodynamically active part of the salt dome diapir structure, the core of which has exits to the surface.**
- **There are more than 140 local karst development sites with a total area of more than 11.22 hectares and a volume of karst sinkholes and mine collapses of more than 5 million cubic metres.**
- **The growth of the tourism sector cannot be achieved without preventing the spread of pollution**. The local salt resource is the most important value of the area, and currently it gives the brand of Solotvyno.
- In some areas relocation and building of new housing and infrastructure could be the only viable option. And badly planned relocation policy could cause uncontrolled negative impacts on the minority groups that would affect the whole society of Solotvyno.
- The labour market is very mono-structural with focus on tourism as the new main source of income after the collapse of the mining industry.
- Mining as an industry has collapsed, but **there is a chance to restart mining in Solotvyno further away from the older mines** that would disturb the urban areas less.

- It is unfavourable that just some parts of the generated waste are treated, but the **system of waste management**[2] does not work well either.
- **On the territory of flooded and non-working (abandoned) mines, there is an expansion of the subsidence area and a gradual flattening of the slopes around karst craters and sinkholes. At the same time, the existence of karst-suffosion sinkholes (collapses) with vertical walls is an indicator of the continuation of active karst-suffosion processes.**
- **In difficult economic conditions (military aggression of Russia, especially its acute phase from 2022 and to a certain extent COVID-19), the population of Solotvyno finds opportunities and resources to implement projects for the development of tourist infrastructure. There is an involvement in use, for building territories where vertical displacements are recorded. For balneological purposes, brine is pumped out of the sinkholes of mine No. 7.**
- **Based on the assessment of the vertical displacements of ground surface, obtained using interferometric processing of satellite radar monitoring data for the period 2016-2021,** the values of the accumulated deformations of the earth's surface reach -385.12 mm**, it was determined that mines No. 7, 8 and 9 pose a threat to the technogenic safety.**
- **The results highlight a totally different situation in the Romanian part, as it was detected in Solotvyno. The whole territory of Sighetu Marmatiei presents a stable condition, and there are not any districts of the town, which shows a geographically recognizable pattern of surface movement.**
- **A modernized hydrodynamic model of the Solotvyno rock salt deposit and adjacent territories was developed, which includes information on five layers (geological units – formations) with maps of the velocity vectors, isolines of groundwater level, flow lines provided for two aquifers (Quaternary and Tortonian) with and without considering tectonic disturbances of various ranks.**

[2] Waste management 2017, 2020:
http://www.uz.ukrstat.gov.ua/statinfo/navkol/2018/povod_vidhod_rajony-2017.pdf;
http://www.uz.ukrstat.gov.ua/statinfo/navkol/2021/povod_vidhod_rajony-2020.pdf

- **Hydrodynamic modeling with considering tectonic disturbances (faults) in the model showed the deformation of the model groundwater flow lines, that indicates an increase in water exchange in the fracture zones areas. This can accelerate and intensify the spread of saline water in aquifers.**
- **Based on results of solving several inverse problems, it has been established that that the hydrodynamic situation reproduced on the model reflects the natural conditions with sufficient probability thus the obtained model can be used to solve practical problems.**
- **Operation of the monitoring system are required for the sustainable use of natural resources (brines and rock salt) and protection against transboundary spread of surface and underground water pollution.**
- **Based on obtained studies results (field observations, remote sensing satellite radar monitoring data analysis, geological and hydrodynamic modelling) the complex monitoring system plan, have been developed.**

Some of the recommendations:

- **Considering the complicated geo ecological situation, development and functioning of the permanent complex monitoring system for the Solotvyno salt dome structure and adjacent territories is the priority objective.**
- **Ecological-technogenic and socio-economic parameters of Solotvyno settlement revitalization must be evaluated after the anticipatory creation of an informational and effective monitoring system with the possibility of a highly probable spatio-temporal assessment of the long-term (tens of years) transition to an equilibrium geodynamic state of the subsoil in this territory.**
- It is a topic of **further investigation to find out if it is environmentally and economically feasible to support the redevelopment of the salt mining sector.** Strict and improved monitoring should be deployed in case of positive answers.

- Mining can also be seen as a joint cultural heritage of the settlement and the wider region including the hromada of Solotvyno, which can support international tourism.
- Focus on urban functions, institutions, and services of regional importance (tourism facilities, hospitals etc.) and attraction to maintain and strengthen urban development.
- Encourage circular economy approaches, first by improving waste processing that can also provide additional jobs and income.
- Eliminate illegal ad hoc landfills and filled sinkholes along the floodplain of the Tisza in and around Solotvyno. Try to reuse or recycle the removed materials and waste.
- Establish a new modern landfill facility of EU standards further away from the river and the salt mines and protect the surface and ground waters from pollution and transmission.
- Support awareness raising activities (e.g., by waste collecting and recycling competitions)
- It is a topic of further investigation to find out if it is environmentally and economically feasible to support the redevelopment of the salt mining sector. Strict monitoring should be deployed in case of positive answers.
- The sources of pollution and the spread of it should be localised to avoid contamination to make tourism impossible or at least less attractive.
- **Create the conditions/system for the use of natural resources, for health tourism (medical, rehabilitation, recreational) within limits that do not pose additional risks to life and do not have negative consequences for the environment (primarily the spread of pollution).**
- **The hydrodynamic model became the basis for determining the number and spatial location of the network of monitoring hydrological observation points and hydrogeological wells in accordance with the developed plan of the monitoring system and observation regime.**
- **Apply the developed hydrodynamic model as the basis of a continuously updated hydrodynamic model as an element of the complex monitoring system of the Solotvyno rock salt**

deposit and surroundings for the purpose of sustainable management& use of natural resources.

- **It is recommended to establish a Complex Monitoring System, that includes monitoring of ground surface deformations using DInSAR; hydrological and hydrogeological monitoring (water quantity & quality); geophysical survey (microgravity, geoelectric and seismic methods); geodetic survey; on-site inspection of hazardous geological processes development; modelling (up-to-date improvement of hydrodynamic model); risk assessment, preliminary substantiations of protective measurements. The implementation of a monitoring system with an integrated permanent hydrodynamic model should become a tool for managing the use of natural resources in the Solotvyno settlement – brines and rock salt - as the main factor for its sustainable economic and social development.**

Finally, the first stage of the project has been done with aims of monitoring and investigation of the problem and detecting its causes and spread of the contaminants in the area.

We suggest a second stage of the project that could assess different techniques for management of salt-water in the study area and Tisza River. Then select and design the best technique that can be implemented to protect the area from contamination based on social, economic, and environmental aspects.

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