SARforMINE. A 2D/3D Web Service for the Underground Gas Storage Impact Monitoring

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Abstract

Nowadays, satellite remote sensing produces vast amounts of Earth observation data, but without appropriate processing, visualization and interpretation, they are of limited use for a regular user. Web map applications are one of the approaches to share the data online. They allow not only for visualization, but also for analysis and interaction with geographic data. Such web services are used for a variety of purposes, fulfilling informational and educational roles. The SARforMINE is a geoportal service for monitoring, analysis and visualisations of predictive modelling of environmental impacts above underground gas storage facilities. The designed web map application represents information on selected environmental components, ground movements and vegetation condition derived from open-access satellite imagery, SAR and optical respectively. Additionally, historical data are analysed using machine learning for the purpose of predictive modelling of the potential future changes. The proposed approach outlines how web GIS services can augment traditional monitoring of underground gas storage sites.

1. Introduction

Subterranean engineering activities, such as underground mining or storage of energy sources, impact the land above in various ways. These impacts include among other things ground movements, triggering of seismic activity, leakages, environmental pollution and disturbance of land cover (Yi et al., 2005; Zhou et al., 2019; Benetatos et al., 2020). Nowadays, open satellite and airborne missions provide vast amounts of spectral and radar data at regular intervals and with spatial resolutions that are suitable for monitoring of these impacts (Rapant et al., 2020). Furthermore, data driven spatial statistics and machine learning based methods can be used to predict impacts such as ground movements and land cover disturbances (Ali et al., 2022).

A web map application is an interactive, online tool that allows users to view, analyse, and interact with geographic data through a web browser. The term is often used synonymously with web GIS, however the latter one emphasises analysis and processing of geographic data (Neumann, 2011). Web map services are used in fields like navigation, urban planning, or environmental monitoring, and depending on their purpose are equipped with various functionalities, such as zooming, querying, and data visualization. So far, there has been limited application of open web GIS services to map mining-related impacts, despite their potential to support monitoring of ground movements, groundwater changes, and land cover transformations. Integrating geographical data from open sources with project data in web map applications could significantly enhance the ability to assess, visualize, and manage the effects of underground gas storage activities on surrounding ecosystems and infrastructure.

Recently, there have been emerging web based services that provide information on ground movements and land cover conditions based on satellite data sources. However, their capabilities and functionalities are limited and inadequate in addressing the specific needs of monitoring individual mining or storage operations, as they are designed to deliver information generalised for a regional, e.g. the European Ground Monitoring Service (EGMS) (https://egms.land. copernicus.eu/) or a country, e.g. InSAR Norway (https://insar. ngu.no/), Dutch Bodemdalingskaart 2.0 (https://bodemdalingskaart.portal. skygeo.com) and German Bodenbewegungsdienst Deutschland (https://bodenbewegungsdienst.bgr.de) scale.

An example of web based map design intended for visualising and querying infrastructure of closed hard coal mines was proposed by Nowacka and Blachowski (2011). Recently, a web application in support of the open-cast mining industry supporting point cloud data, as well as querying and measuring geographical data was proposed by (Szujó et al., 2023). The other, available web map projects offer simple query and visualisation functions related to location of mining projects and mineral resources at regional, national or world scale. Examples include USGS Mineral Resources Online Spatial Data (https://mrdata.usgs.gov/) or the US National Mine Map Repository related to closed and abandoned mines (https://www.osmre.gov/programs/national-mine-map-repository).

In our study a demonstration web based GIS service for monitoring, analysis and predictive modelling of selected environmental impacts above underground gas storage sites was developed. In contrast to the InSAR derived ground movement data services presented earlier, our pilot is tailored to site specific characteristics and provides superior spatial resolution, data update capabilities and data querying options.

The geoportal offers a set of specifically designed functionalities for 2D and 3D geospatial data visualisations and an analytical dashboard providing verified and interpreted information on ground movements and vegetation cover condition changes in space and time domains. The application has been developed for two use cases in Poland (Kosakowo) and Germany (Etzel) cavern underground gas storage (CUGS) sites within the Polish National Centre for Research and Development and German Federal Ministry of Education and Research financed bilateral project CLEAR. In this paper, the results for the Polish site are presented. However, the presented functionalities are universal for both case studies, as well as any other site that can be integrated into the system.

2. Data and Methods

2.1 Case Study Site

The CUGS Kosakowo is located in northern Poland, close to the Baltic Sea and north of the cities of Gdańsk and Gdynia (Figure 1). The construction of the facility began in 2009 and the first cluster of 5 caverns started operation in 2014. This was followed by construction of the second cluster approx. 1 km east of the first one. The capacity of the gas storage site is approx. 295.2 Mio. m³. The facility is operated by the Gas Storage Poland sp. z o.o. The underground caverns used for gas storage were leached in the rock salt layer, with an average thickness ranging from 170 to 200 meters, lying at a depth of approximately 970 meters below ground level. The overburden is made up of Permian marine sedimentary rocks, as well as Mesozoic formations (Triassic, Jurassic, Cretaceous) and Cenozoic deposits. The land cover to the north and west of the CUGS Kosakowo consist of meadows and agricultural land. Forests and industrial areas dominate to the south, whereas in the east the main type of land use is residential and service development.

In accordance with national regulations, every CUGS operator is responsible for conducting ground movement measurements at least once every five years. In the study area, the observations are conducted in two perpendicular levelling lines located across the mining area.

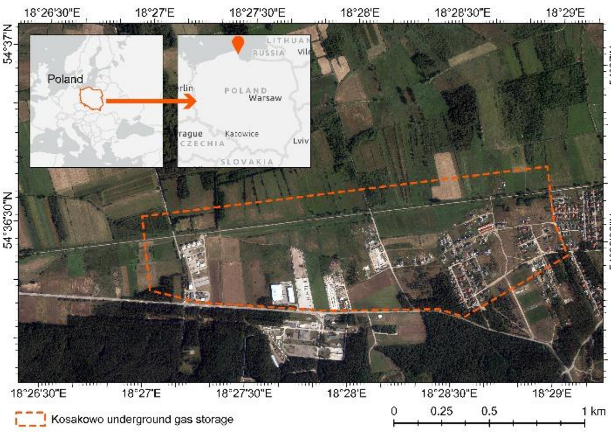

Figure 1. Location of the case study site.

2.2 Methodological Framework

The development of web GIS service is a part of the CLEAR project aimed at developing an intelligent system providing near real-time monitoring, analysis, prediction, communication and control of environmental impacts originating from underground energy storage infrastructures (Blachowski et al., 2024). Thus, the solution defined within the project assumes the following fundamental frames: (1) frequently updated spatial information on ground movements calculated from Sentinel-1 InSAR data using both the Small Baseline Subset (SBAS) and the Persistent Scatterer (PS) techniques to ensure high-precision deformation monitoring over time, (2) spatial information on land cover condition and change based on spectral indices such as Normalized Difference Vegetation Index (NDVI) to assess vegetation health and the Normalized Difference Water Index (NDWI) to monitor surface water changes over time, (3) analytical cockpit designed for user-friendly visualization of data, enabling intuitive analysis of spatial and temporal trends in the data, (4) prediction models with a horizon of up to 6 months (5) improved spatial coverage and resolution, and (6) presentation of interpreted data in comparison to available other public web based solutions, (7) 3D visualisation capabilities.

The ground movement monitoring data have been acquired through Multi-Temporal InSAR processing of Sentinel-1 SAR data. Due to the differentiated land cover characteristics, two methods have been tested and applied. The first one, modified Persistent Scatterer (PS) approach implemented in SNAP2StaMPS software (Foumelis et al., 2018), and a Small Baseline Subset (SBAS) technique with phase corrections (Yunjun et al., 2019). SAR data processing involves incorporation of 2 independent data acquisition orbits (ascending and descending), in order to decompose the Line of Sight (LOS) observations into vertical and horizontal (in the East-West direction) components, following the approach presented in (Fuhrmann & Garthwaite, 2019). Application of two InSAR methods for calculating time series of ground movements allows determination of surface deformations in both urban (PS) and rural (SBAS) areas. Seasonal variations of vegetation cover and soil moisture are considered to be the main limitation in attributing the measured ground movements to CUGS operations in the area. Further research on that matter is being conducted during the project.

The information on land cover condition and its spatiotemporal changes have been derived from multispectral data registered by the ESA Copernicus Sentinel-2 mission. The sensor registers reflected radiation in 13 spectral bands from the visible and infrared regions of the spectra with a temporal frequency of 5 days and spatial resolution of 10-60 m (Drusch et al., 2012). After initial processing, the images represent surface reflectance. However, the data are sensitive to atmospheric conditions such as clouds, snow or water vapour and thus, are of limited use in environmental studies. Approximately 10 to 15% of acquired imagery is free of the above mentioned effects. In our case, spectral indices such as NDVI and NDWI are applied as additional sources of data to assess the condition and track changes of the environmental components by highlighting selected features. It should be noted that analysis of spectral reflectance is prone to interpretation errors as various materials have similar properties, e.g., surface water and bright built-up features (Ma et al., 2019).

The processed thematic datasets are stored in the web GIS service database as multi-layer stacks. Where each layer in the stacks represents time step allowing for spatiotemporal queries, analyses and visualisations of ground movements and land cover alterations above and around the underground gas storage sites. At the moment the database on ground movements and land cover change is updated every 6 months, and the temporal horizon of the ground movement prediction model is also 6 months.

In the CLEAR project, in addition to classical ground movement forecasting methods, e.g. Knothe function (Knothe, 1984) learning algorithms suitable for the implementation of tasks including generating additional data in training sets, data clustering, data classification, spatiotemporal model of movements. and the target cause-effect model have been implemented (Blachowski et al., 2024). Optionally, generative adversarial networks (GAN) (Goodfellow et al., 2014) are used to increase the size of training sets. In the analysis of large data sets on new objects requiring an objective assessment of ground movement datasets, we strive to separate groups that differ significantly from each other but have similar values (or patterns) in a selected group of cases. These tasks are carried out using unsupervised learning techniques that do not require specifying a

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fixed number of classes. Analysis of the separated clusters can be the basis for their categorization, determination of model classes and qualitative analysis. The algorithms used in the system include Gaussian mixed models (GMM) (Reynolds, 2015; Zobay, 2014), the DBSCAN algorithm (Ester et al., 1996; Ma et al., 2023) and self-organizing feature maps (SOM) (Kohonen, 1982, 2013). To build more complex relationships between ground movements and potential causative factors, it is possible to build dependency models using classical statistical methods, including geographically weighted regression (GWR) (Brunsdon et al., 1996; Wheeler & Páez, 2010; Blachowski, 2016), machine learning algorithms, including random forest (Breiman, 2001), artificial neural networks (ANN) (Cieślik & Milczarek, 2022) or convolutional networks (CNN) (Zhang & Li, 2023). The system also implements prediction models based on historical data in the absence of complete data on the influencing factors (Cieślik & Milczarek, 2022) and models of the relationship between changes in causative factors and ground movements caused by them (Cieślik et al., 2024). Recurrent neural networks (RNN) or their combination with regression models are most often used to implement these models (Li et al., 2021). A simplified scheme of data processing is shown in Figure 2.

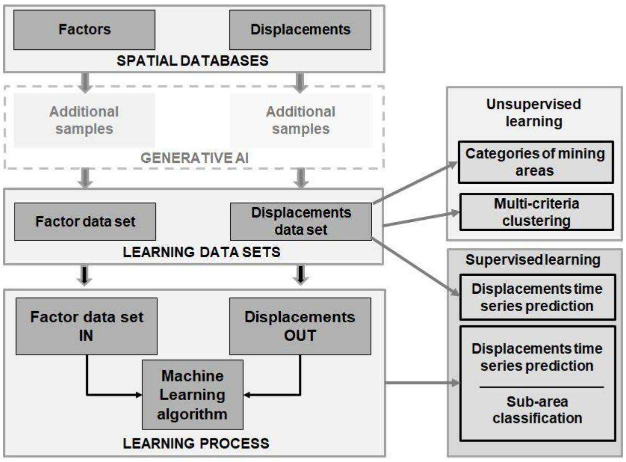

Figure 2. Simplified scheme of measurement data processing – the idea of using machine learning techniques (Blachowski et al., 2024).

The system's architecture has been depicted in Figure 3. showing main components and partially technologies utilised. In the storage layer, we mainly use NoSQL - Firebase and google cloud where we have defined user roles and permissions in the system. Spatial data are stored in dedicated containers for their specific handling. The application layer uses mechanisms of services, business logic, communication API and user interface components to support specialized views and support the geoportal tool. The system components communicate with each other using the http protocol.

In the design of the Web GIS application open-source libraries were used to render geospatial data. In particular, the Cesium.js technology for generating views of the globe, as 3D perspectives in a web browser environment. In addition, the service supports tools for generating 2D maps, analytical charts and static data sets. The views are presented in the form of a thematic geoportal equipped with a set of analytical and data management tools including business intelligence dashlets to present thematic datasets. To build layouts Vue.js with the Vuetify library framework was deployed as it allows building a responsive application.

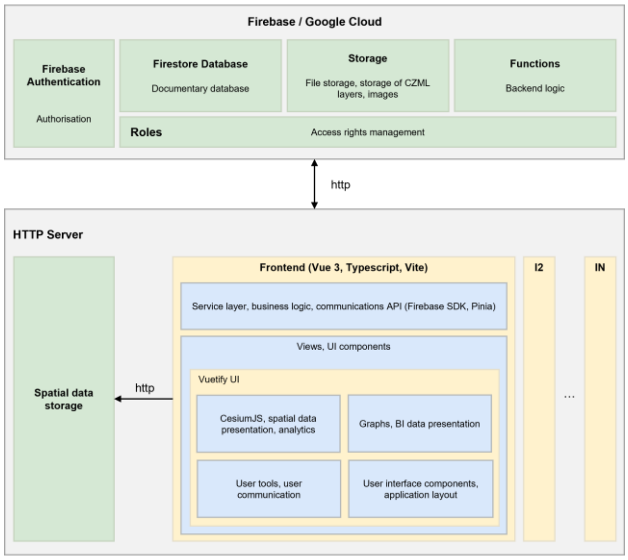

Figure 3. Web GIS service system architecture.

The designed data structure allows for flexible adaptation of the project while adhering to all rules regarding data access and project sharing with other users. By "project," we refer to an isolated, thematically prepared dataset intended for presenting both general views and specific phenomena. Users can configure the project's layer settings, compositions, and dedicated documents for displaying static data. These configurations can then be incorporated into the application's layout and tools, providing a tailored user experience. Once the project is configured, the application allows presentations of 2D/3D data in formats supported by the Cesium.js API. As a standard, raster base layers such as TMS, WMS, GEJOSON, CZML, tiled 3D data and NetCDF are supported.

3. Results

The web GIS service is one of the elements of a modular system for analysing and forecasting ground movements above underground gas reservoirs (Blachowski et al., 2024), one of the tasks of which is to collect data adapted to models with different levels of resolution, detail and completeness of data. The system for forecasting ground movements in mining areas requires collecting full information on the causative factor and ground movements, and analysing the resolution and uniformity of the spatial distribution of data. The GIS service has been equipped with tools for appropriate data processing to implement the construction of a spatiotemporal cause-and-effect model, as well as the implementation of intermediate tasks including generating additional data in training sets, data clustering, data classification, spatiotemporal model of deformation. More details of the system are presented in the work (Blachowski et al., 2024).

The graphical user interface of the Web GIS system has been shown in Figure 4 and Figure 5. These examples present InSAR derived ground movement data in 2D and 3D perspective respectively. In addition, analytical dashlet - ground movement graph for a selected location and as mean statistic for a selected area have been presented.

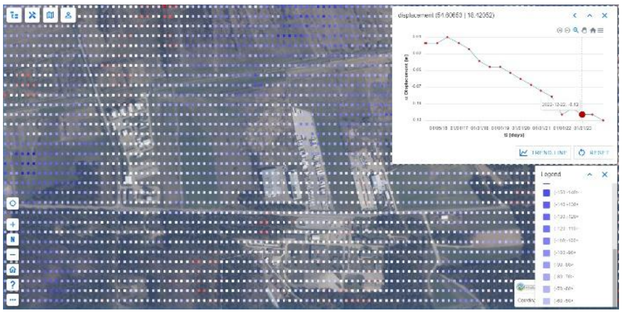

Figure 4. Interface of the web map in 2D mode with visualised ground movement data and displacement graph from the analytical cockpit.

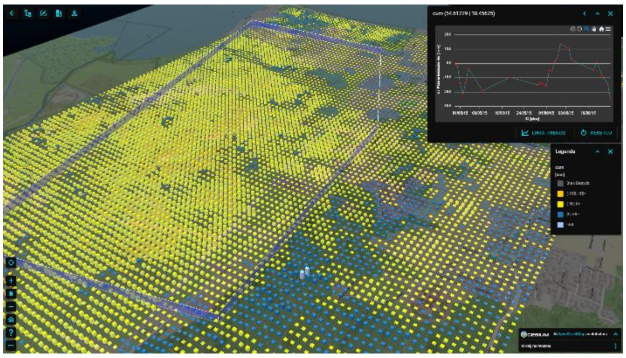

Figure 5. Interface of the web map in 3D mode with visualised ground movement data.

The web GIS application offers an integrated set of functions dedicated for importing various 2D and 3D geospatial datasets into the online system and geovisualisation of thematic layers in 2D and 3D modes. The latter include analytical tools for calculating basic and detailed statistics for full or subsets of data, and provide analytical dashboards with scalable and interactive graphs presenting descriptive statistics and time series of data for user defined locations and times. The thematic content of the web service includes, in particular, ground movements calculated from Sentinel 2 using PSI and SBAS InSAR techniques for both the LOS (Line of Sight) and vertical shifts, ground movements derived from prediction models developed for with machine learning algorithms, vegetation and water indices, e.g. NDVI or NDWI, derived from Sentinel 2 imagery and used as proxies for monitoring and predicting land cover condition and its changes.

The system supports data queries and measurements (line, area), as well as calculation of statistics for a user selected region or cross-section. Subsets of data selected for a given area can be exported to common formats such as CSV, GEOJSON for further processing and analysis. In addition, external data services (WMS, WMTS) can be added to create user defined maps that, in turn, can be saved locally as static graphics or shared via links. The data can be retrieved as a statically deposited file asset for layers, or as a cloud resource.

As the system stores large amounts of data with varying levels of detail and resolution, therefore it is important to use appropriate methods of presenting data that are readable to the user.

The developed web service integrates GIS and BIM features by combining large-scale geographical information (including a surface model, ground movement model, topographic data model, etc.) with 3D-BIM spatial models of engineering objects (cavern geometry, transmission system, buildings and other structures). The advantage of this solution is the combination of 3D models of technical infrastructure with other models, i.e.: geological, underground infrastructure, elevation data, topographical objects, and a model of ground movements and land cover changes detected by passive and active remote sensing methods. The developed system is a cheaper alternative to commercial systems by adapting and limiting the necessary functions of analysis, data visualization and reporting adapted to the specifics of the enterprise's operations. According to the adopted classifications (Wang et al. 2019; Wyszomirski & Gotlib, 2020), the developed system is an integration of BIM and GIS at the application server level and the client application level. The adopted solutions required the development of new and the expansion of existing applications and libraries at the application server level and the client application level.

Visualisation of BIM and GIS data, satellite and project data processing results and developed models require appropriate qualitative and quantitative generalization and their visualization. The developed service includes tools that implement proven cartographic presentation methods adapted to the capabilities of the Cesium JavaScript graphical environment used. Due to the lack of specific solutions in the field of mining areas, the model was based on solutions used in the visualization of buildings and technical infrastructure (Gotlib & Wyszomirski, 2018; Gotlib, Wyszomirski, Gnat, 2020, Bogusławski et al., 2022). The system has been adapted to the requirements of presenting data processing products and industry data adopted in mining companies. Independently, it is also being developed for applications on mobile devices for field reconnaissance, field data verification and assessment of the condition of buildings, structures and technical infrastructure located in impacted areas.

4. Concluding Remarks

The presented SAR4MINE web GIS service is a functional concept of a modern approach for presenting geospatial data in 2D and 3D domains with analytical functions tailored for supporting the management and control of underground gas storage impacts on the land surface. Application of InSAR derived ground movements provide temporal and spatial coverage that is much denser than classic levelling measurements. However, the InSAR-based results cannot yet be considered as a substitute for traditional geodetic methods due to potential limitations in accuracy, coherence loss, and the need for validation with ground-based observations. In the case of land cover changes monitoring, radar-based indexes could be considered an augmentation to optical remote sensing methods, particularly in areas with frequent cloud cover.

The system is an integrated environment for collecting, storing and disseminating geodata, in the cloud environment including structured presentations and documents. The web GIS service provides a novel approach for monitoring and machine learning based ground movement prediction methods designed for underground gas storage sites together with enhanced data assimilation methods for improved updating of model parameters for prediction of impacts of underground storage facilities.

Future development directions for ground surface monitoring web GIS services include semi-automatic or automatic updates of spatial data, integrating near real-time InSAR-based ground movement measurements, machine learning algorithms for trend analysis, and cloud-based processing. Additionally, enhancing analytical dashboards for user interactivity could further support monitoring and management of potential impacts of CUGS operations.

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