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Sustainability in Energy Storage - How Modern Geoscience Concepts can Improve Underground Storage Monitoring

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Abstract

The reuse of large-volume salt caverns for the intermediate storage of liquid and gaseous energy carriers is an indispensable step on the way to a sustainable energy economy. Continuous devel-opment of methods for monitoring these facilities is a crucial part of the social license to operate.

In the research project KaMonSys ("Monitoring system for the safety of cavern storage facilities using satellite and unmanned aerial vehicle (UAV) data"), safety solutions for critical infrastructures are implemented in an interdisciplinary approach of remote sensing and geoscientific methods. Using underground storage facilities (USF) as an example, multisensory approaches are being de-veloped to monitor the facilities as well as their surroundings by satellite and UAV-based monitor-ing to detect possible emissions, such as methane, hydrogen and carbon dioxide.

First results of the ongoing project show the initial evaluation of available spatial data (INSPIRE) and such of the project partners Uniper and SGW on the surface/subsurface situation. The integrated development leads to a 3D GIS for the spatiotemporal data evaluation. This is the basis to evaluate data and its usage for the development of 3D UAV flights, enabling the detection of primary and secondary damage to infrastructure and the environment.

It has already been shown that comprehensive safety monitoring requires the use of different data sources and sensor types [1]. These data must be analyzed together via a multi-stage process, merged and interpreted in a 4-dimensional context. This approach will be taken up for the further progress of the project and consistently implemented in a demonstrator.

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Introduction

Within the frame of the mining law and the operator's social license to operate [2], it is necessary to ensure site safety and integrity for both surface and underground facilities in order to minimize the impact on people, nature, agriculture, forestry and water management. Transparent communica-tion between the operators of underground storage facilities, policy makers and society is crucial for their acceptance (Figure 1). The aim of all stakeholders is to prevent hazardous substances es-caping from gas installations or to reduce them to an absolute minimum. This focus not only en-sures people's safety, but also limits the potential of methane emissions, which is second only to carbon dioxide in its overall contribution to climate change [3]. Furthermore, it provides a contribu-tion to energy security of large parts of the population and the industry in many countries e.g. Germany, where natural gas is the second most important primary energy source, after petroleum [4].

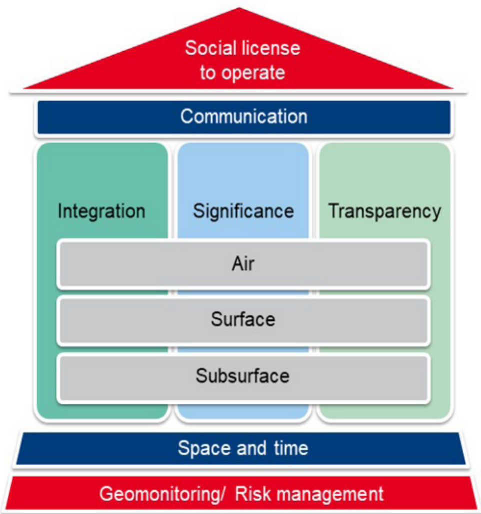

Figure 1: The double triad of geomonitoring as a basis for communication and social operator responsibility [2].

Underground storage facilities such as large-scale salt caverns greatly improve the security-of-supply, but at the same time also offer a target for manipulation or accidents. Safety, security, site integrity and functional integrity must be established throughout the entire mining and storage cycle, from exploration, development and construction, and maintained during operation and maintenance until the final abandonment of the storage site [2]. For this purpose, the operator has to set up a safety monitoring system with very different temporal and spatial resolutions and ob-jectives. Area-wide, safety-related and high-temporal monitoring of large-scale mining operations and underground gas storages is a difficult and expensive task that needs the integration of air-borne and satellite-based sensors as well as terrestrial and GNSS surveying and in-situ-sensors (Figure 2) [5, 6]. To achieve the goal of effective and efficient monitoring, the

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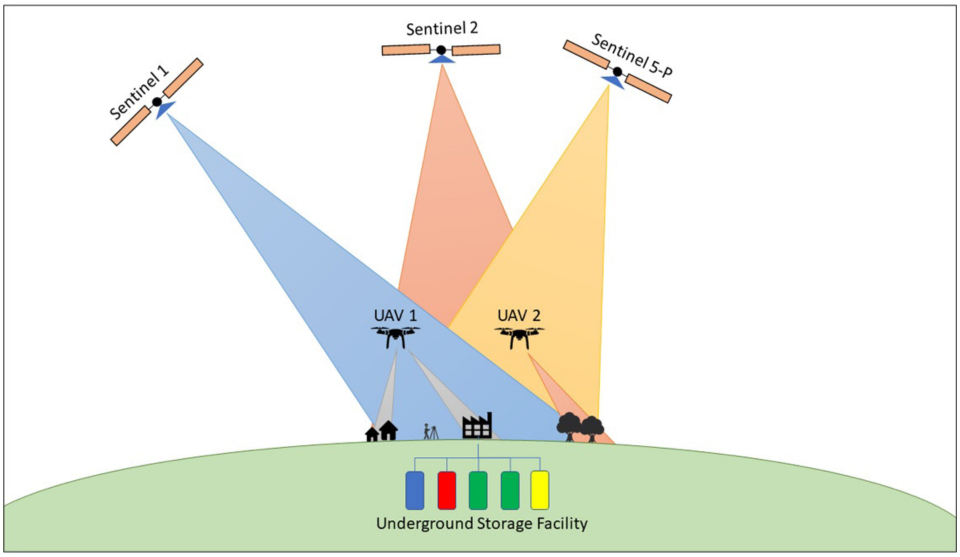

Figure 2: Multi-layered, spatio-temporal geomonitoring of an underground storage facility.

multi-dimensional and multi-temporal information needs to be integrated and evaluated in a geographic information system (GIS) [7].

Materials & Methods

The research conducted in project KaMonSys[1] consists of two sub-projects working on the data evaluation and integration. EFTAS Fernerkundung Technologietransfer GmbH uses, among others, the datasets of the Sentinel-1 (Radar), Sentinel-2 (Multispectral) and Sentinel-5P (Atmospheric gas) for different monitoring purposes in one sub-project [8].

This article will however focus of the second sub-project, which aims at the development of a 3D geo-graphic information system (3D GIS) to monitor the cavern site. Using the 3D GIS as a basis, the Research Center of Post-Mining fuses the spatio-temporal data sets, the information and the knowledge about the underground and surface situation as well as the operational business with UAV-airborne and satellite sensor datasets. The high-resolution GIS also enables the creation and modification of precise 3D-flight plans for UAVS. Together with real-time corrected GNSS position data, this allows the drone to deploy its sensors as close as possible to potential damage sites while maintaining a safe distance from infrastructure and hazard zones [7].

In addition, both teams are working together to develop an effective but inexpensive method for gas detection using drone-based thermal infrared sensor technology [9, 10].

Material

A wide variety of data sources were used for the initial creation of the 3D GIS. The largest part comes from open data sources provided by public institutions within the framework of the INSPIRE initiative of the European Commission [11]. From the geoportal of the state of North Rhine-Westphalia [12], a wide range of topographic, geological, hydrological, and other thematic maps, satellite and aerial images could be evaluated and used as basic data in the GIS. In addition, survey-ing data from the associated project partners on the surface, the company's own facilities and the underground conditions, as well as in-house surveys and UAV flights, improve and increase the dataset.

In addition to classic terrestrial surveying equipment, UAVs with various sensors were used for data acquisition. In addition to the GeoKopter prototype developed for the Research Center of Post-Mining with multispectral and thermal-infrared sensors, these included selected products from the manufacturer DJI (Figure 3):

Figure 3: DJI UAVs with different sensors and capabilities used in the Research Center for surveying and geomonitoring purposes.

- Phantom 4 RTK for high precision 2D and 3D surveying
- Phantom 4 Multispectral to capture images in different wavelengths [13]:
  - Blue (B): 450 nm ± 16 nm
  - Green (G): 560 nm ± 16 nm
  - Red (R): 650 nm ± 16 nm
  - Red Edge (RE): 730 nm ± 16 nm
  - Near-Infrared (NIR): 840 nm ± 26 nm
- Mavic 2 Enterprise Advanced for thermal-infrared images and videos
- Mavic Air 2 for indoor and outdoor test flights

The software products used for data capturing and processing include ArcGIS Pro, Drone2Map, Drone Harmony, PETREL, OpenDroneMap and Agisoft Metashape with different extensions.

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In later stages of the project, processed sentinel datasets from the European Copernicus program will integrated in the 3D GIS.

Methods

The research on the use of modern geomonitoring methods in the KaMonSys project is divided into different milestones, which are briefly explained here:

1. Data collection and development of an understanding of the geological, topographical and biogenic conditions at both surface and underground; Integration of the data in a 3D GIS
2. Extension of the 3D GIS with anthropogenic structures (buildings, technical facilities, pipeline routes, boreholes, caverns)
3. Extension of the 3D GIS with processed UAV and in-situ measurements (e.g. surface classifications, temperature base data, reflectance, identification of potential risk sources, wind edges, explosion protection zones)
4. Development of highly accurate 3D flight plans based on the acquired data, taking into account potential gas emitters and risk-based no-fly zones
5. Fusion of the 3D GIS with the evaluated satellite data from the first sub-project (EFTAS)
6. Development of workflows for a multi-level risk management from large-scale to point monitoring (satellite - UAV - in-situ)
7. Development of a WebGIS as demonstrator for the data presentation and processing of the workflows

Additionally, the project group works on new kinds of monitoring methods, e.g. gas detection with thermal-infrared UAV images and videos.

Results and Discussion

Initial data acquisition and evaluation

After defining an area of interest, the initial data collection and GIS-based evaluation was complet-ed within a short period. Due to the excellent availability of open geodata within the framework of the INSPIRE directive, a large number layers from data sources such as the Geoportal NRW [12] and Geoportal.DE [14] could be used. Most of the data is regularly updated by the responsible surveying authorities and often already available in GIS-enabled formats, OGC-compliant web layers or digitized and georeferenced maps. An exemplary compilation of available data is shown in Figure 4.

Initial data acquisition and evaluation

For the addition of man-made infrastructure, the use of free geodata could also be resorted. In addition to digital elevation models, the Geoportal NRW also contains Level-of-Detail-2 (LoD2) building models as 3D datasets. Additional data sets for pipelines, boreholes and caverns could be provided by the associated project partners and used to model the subsurface situation (Figure 5). Individual technical facilities were additionally rendered in photogrammetric software using images from UAV flights and inserted as textured LoD3 models (Figure 6).

Extension of the 3D GIS with processed UAV imagery and in-situ measurements

In addition to the aforementioned 3D models, other UAV-based information was also incorporated into the GIS. Based on several aerial flights, parts of the operating facilities as well as the surround ing

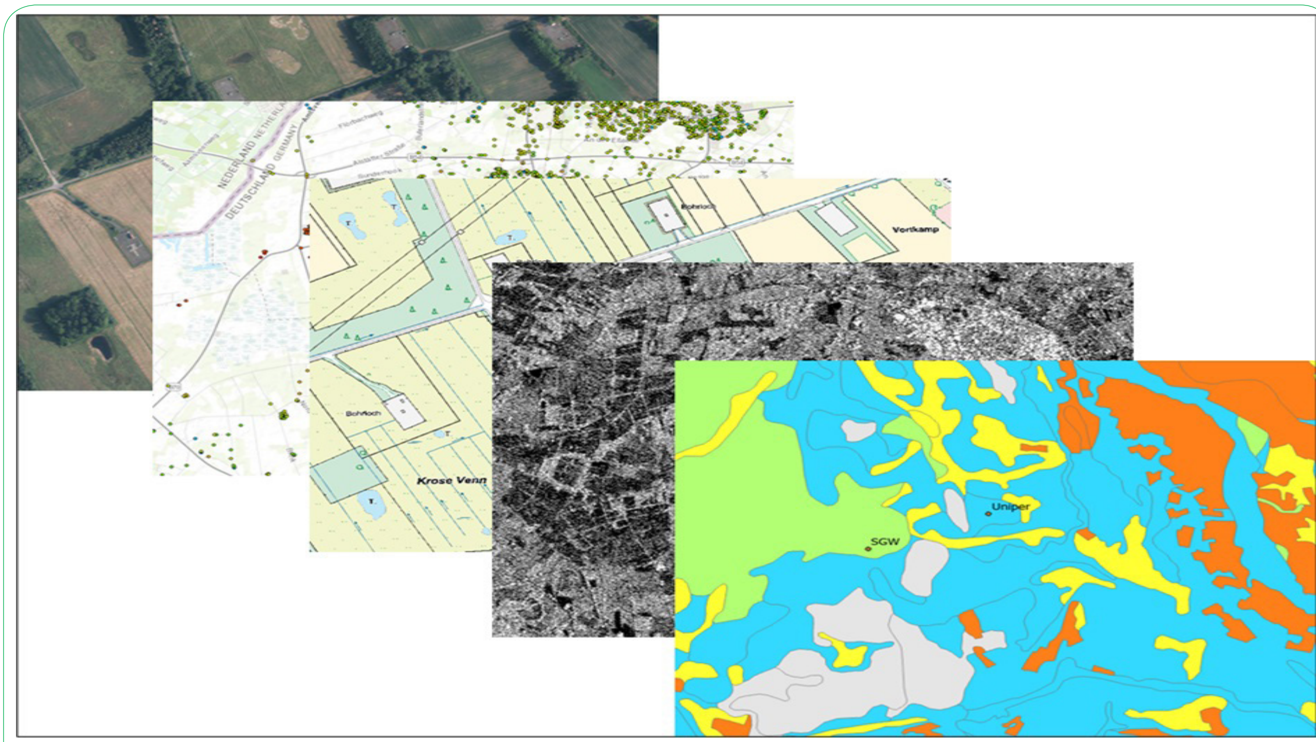

Figure 4: Exemplary compilation of free 2D geodata sets. From back to front: Digital orthophotos, ESRI base map with subsidence information from the Ground Motion Service Germany [13], Digital Topographic Map 1:10,000 (DTK10), radar image (Sentinel-1), soil map 1.

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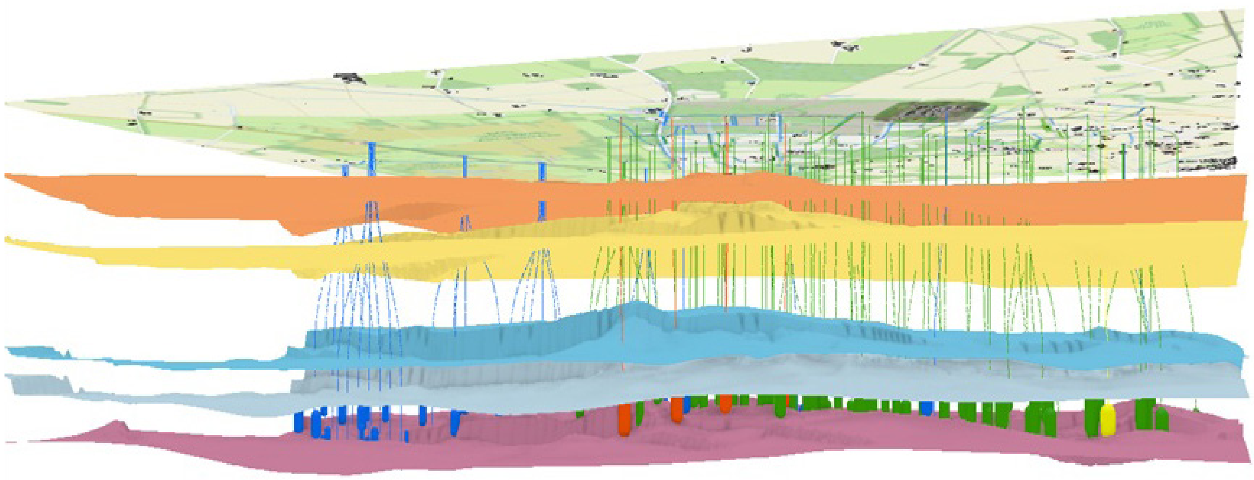

Figure 5: 3D GIS (bottom view) with various, exemplary information layers (borehole, geological strata and cavern storages in thick salt layer).

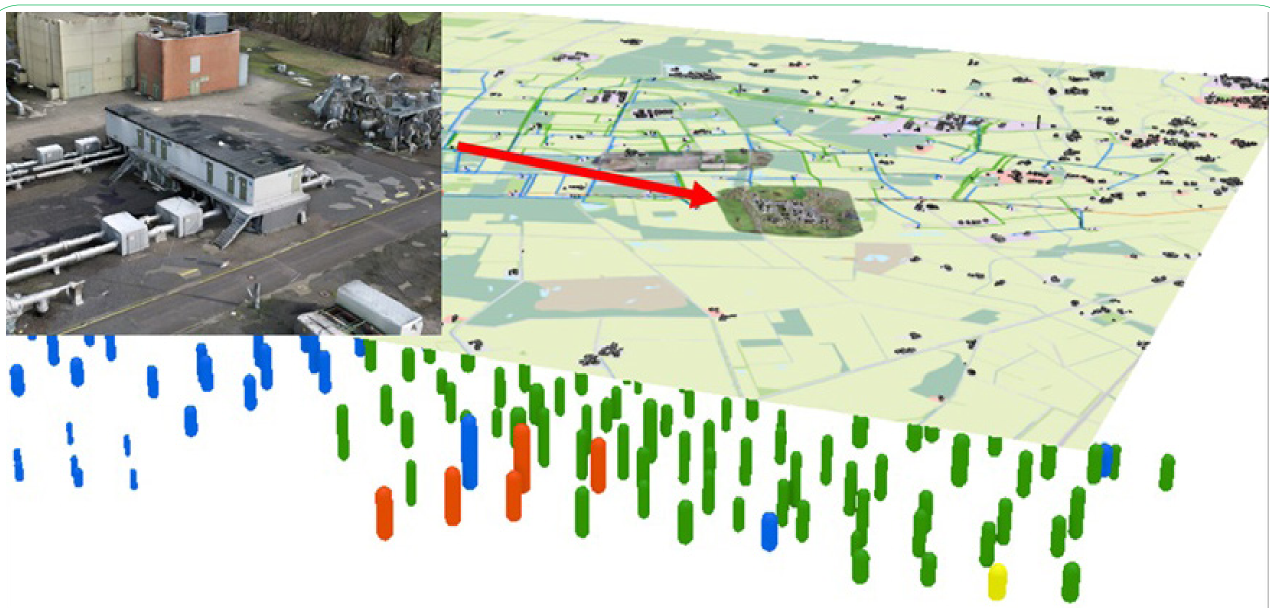

Figure 6: 3D GIS (top view) with various, exemplary information layers (land usage, pipelines, digital orthophotos, 3D build-ing models LoD 2 (grey) and LoD 3 (textured), cavern storages with type of filling (blue = sole, green = natural gas, red = oil, yellow = helium).

area were surveyed in different spectral ranges (Figure 7). By using previously terrestrially sur-veyed Ground Control Points (GCP) and Real Time Kinematic GNSS positioning of the UAVs, the resulting orthophotos could be georeferenced and overlaid with high accuracy. The measured GCP, in combination with other measured values, such as temperatures and surface spectrographs, were used to validate the subsequent flights.

The so-called "ground truth" created in this way is an essential component of the procedure and, together with the remote sensing results and the expert knowledge on site, forms an important triad. An example is shown in Figure 8.

The data collected in this way will, on the one hand, be used to calibrate and validate the satellite data from the other sub-project. On the other hand, it will create a baseline data set. This pre-serves the standard condition of the facilities and environment and is used as comparative values in the event of damage. In this step, it is especially important to consider biogenic factors too. Tem-perature as well as vegetation parameters change significantly over the course of the seasons, without this being attributable to damage or mining-related factors. Above all, multispectral aerial surveys to record plant vitality should therefore be carried out several times a year, creating a 4D-dataset. For example, Figure 9 shows significant vegetation changes over underground gas pipe-lines. However, these are not due to damage, but show seasonal fluctuations in the water balance of the cropland caused by the laying of the pipelines. These effects are only seen over a short peri-od of the growing season.

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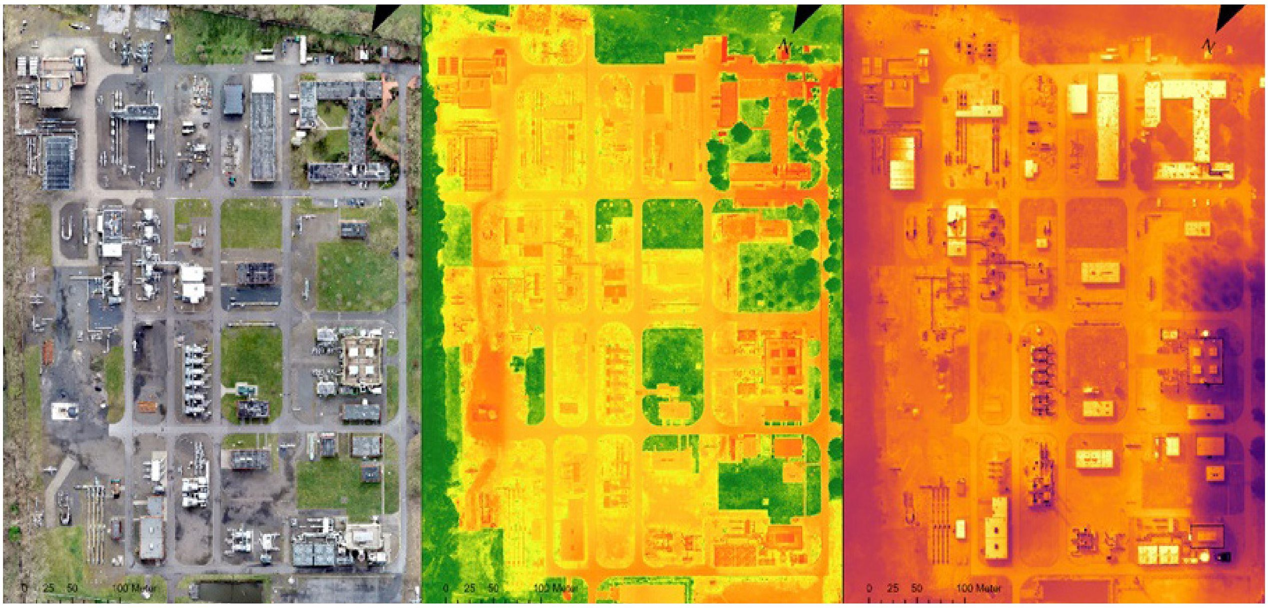

Figure 7: Comparison of orthophotos calculated with different UAV sensor technology and compared using highly accurate georeferencing. From left to right: RGB image, calculated Normalized Difference Vegetation Index (NDVI) from multispec-tral imagery, thermal infrared.

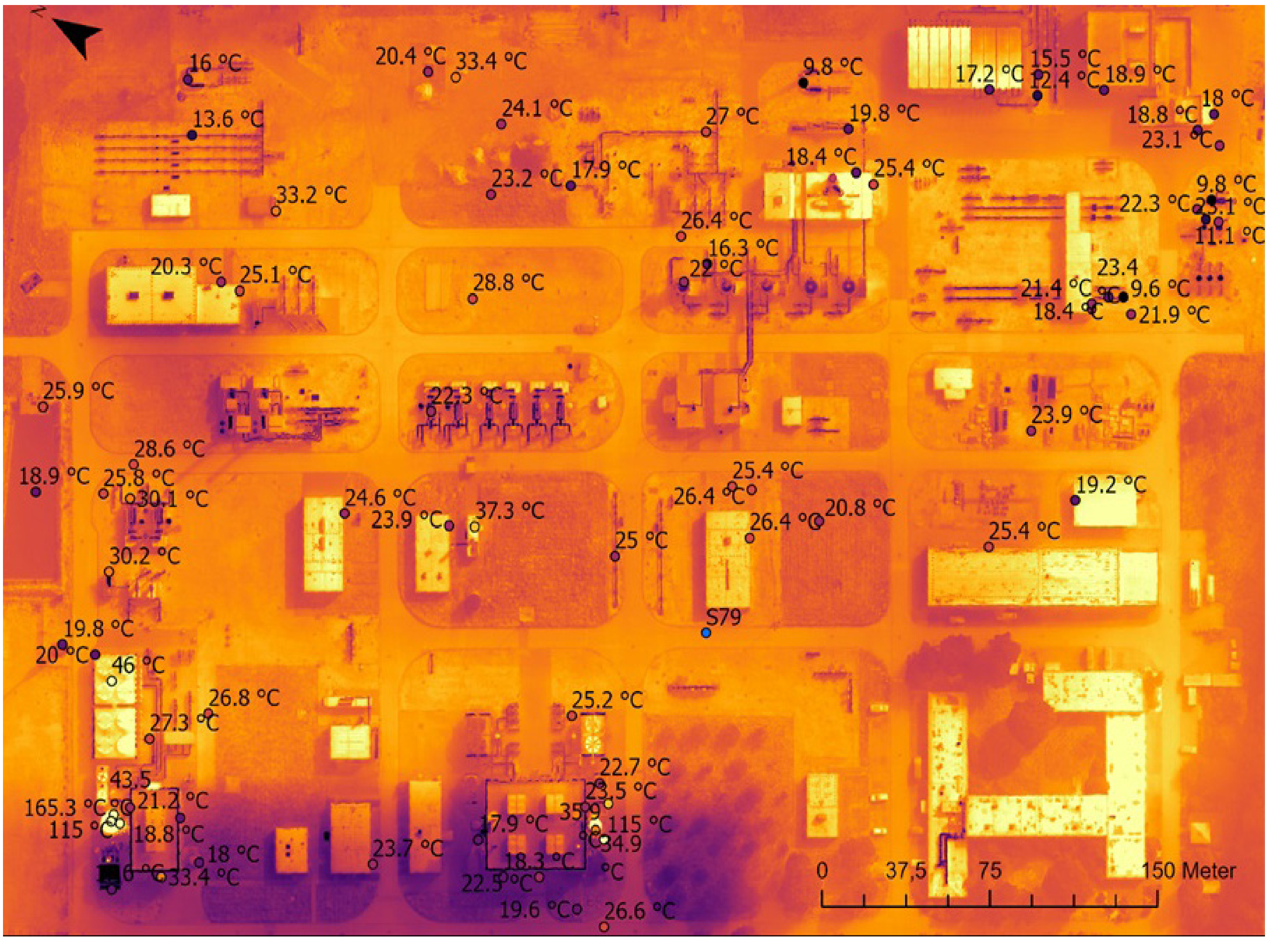

Figure 8: Temperatures measured with a mobile infrared thermometer as "ground truth" to validate UAV data. The west-ern area clearly shows the influence of solar radiation on the measurements, the dark area was caused by a cloud flyover during the mission.

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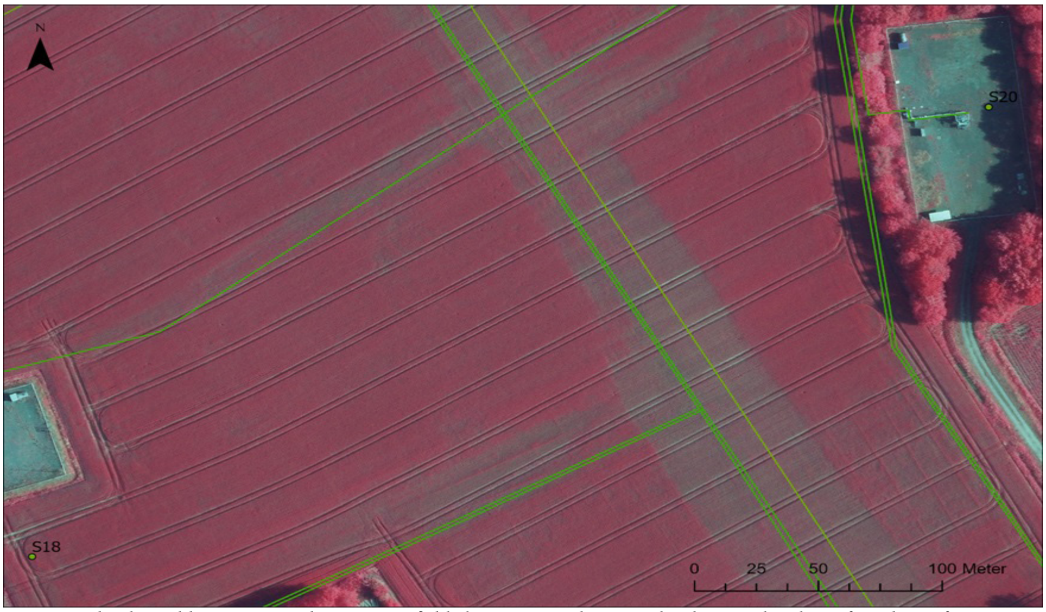

Figure 9: Clearly visible vegetation changes on a field above gas pipelines. Orthophoto with color infrared part from Geo-basis NRW [15] overlaid with pipeline courses from the study area.

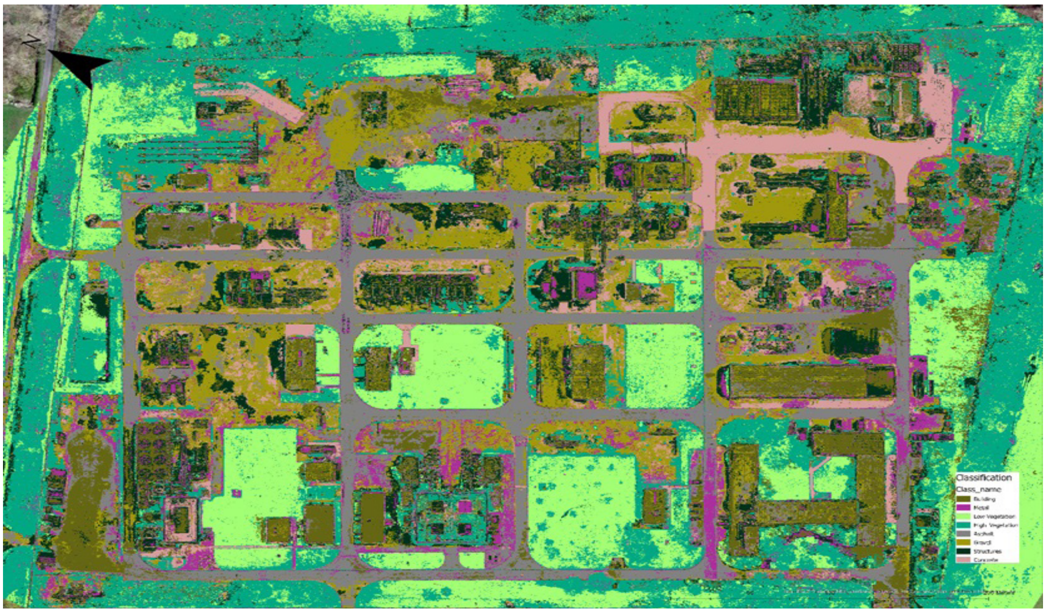

Figure 10: Surface classification using standard raster classification algorithms in ArcGIS Pro.

Ground movements such as uplift and subsidence may also be subject to seasonal and other varia-tions depending on the soil type [16]. For example, a large bog in the study area rises and falls over a large area with the annual variation of groundwater. Factors such as long-term dry periods have also been shown to have a large influence here [17]. Since mining-related ground movements in particular are a politically irritating topic among the interested public, it is imperative that such fac-tors are separated and openly communicated as part of transparency.

For the processing and analysis of the powerful infrared camera sensors for gas detection, it is also important to be able to make a statement about the surface models. A major limitation for the measurement of gas leakage is the lack of knowledge of the surface [10]. If a gas cloud has the same temperature as the surface, neither an IR camera nor the applied method can make escaping gas visible. A surface structure model can show under which weather conditions the method might fail. The enrichment of the 3D GIS with the surface structures is thus to be regarded as an im-portant component for the validation of the results of the UAV flights. Initially, surface area classifi-cation was performed using classical photogrammetry methods (e.g. Support Vector Machines). However, due to the extremely heterogeneous structures, these methods were not very reliable (Figure 10), so modern deep learning algorithms were used instead.

Since the Living Atlas [18] did not yet have models for high accuracy classification using drones, the "High Resolution Land Cover Classification - USA" model (8-bit, 3-band high-resolution

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(80 - 100 cm) imagery) was initially used [19]. While this provided better results, it did not allow identification of gas-related facilities as focal points for UAV monitoring (Figure 11). Other pixel-based algorithms based on U-Net [20] produced similar results.

Therefore, using the previously generated data sets, a new deep learning model was trained. In-stead of a pixel-based approach, an object-based Mask R-CNN approach was chosen to better rec-ognize the highly heterogeneous structures. Based on the marked training objects (yellow), it was possible to detect plant components on the entire site in the first test (Figure 12).

The hit rate determined based on the ground truth was 94%. False positives and negatives could be manually removed (red) or added (blue) to the correctly detected objects (green).

As possible sources of error, similar looking structures, coverage by trees and slight errors in the orthophotos could be identified. The model can be used as a result with the determined parame-ters also for other locations, but needs a manual recheck due to these influencing factors (Figure 13).

Development of highly accurate 3D flight plans based on the acquired data

The 3D flight plans required for highly accurate damage localization were created based on the data collected previously. The self-generated LoD3 building models and the object detection served as a basis for the identification of obstacles, wind edges, GNSS shadowing but also potential gas emit-ters. The operators supplemented these data with on-site explosion protection zones that are to be avoided when flying through the facilities (Figure 14).

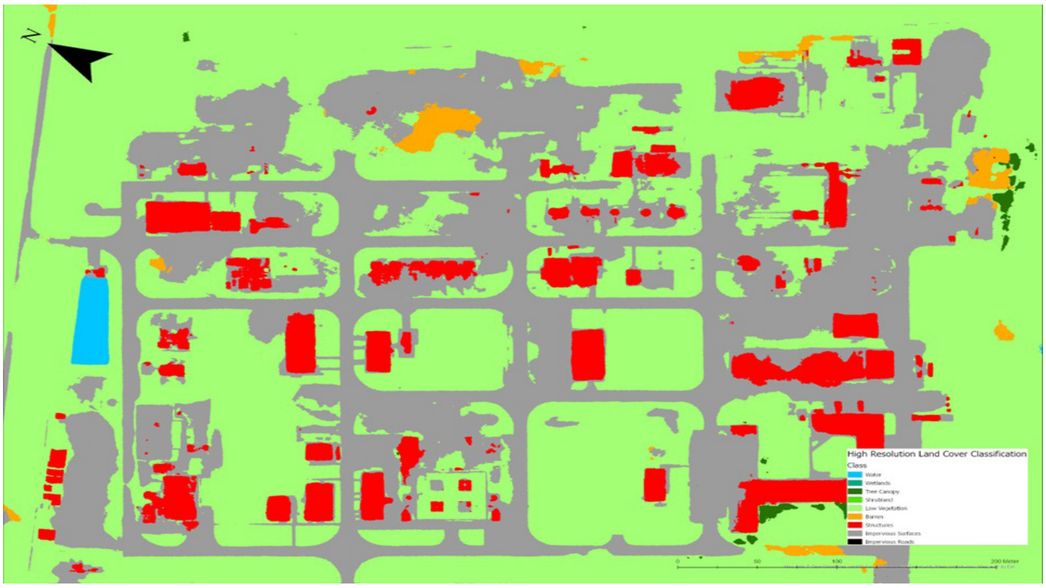

Figure 11: Surface classification using the High Resolution Land Cover Classification – USA model in ArcGIS Pro.

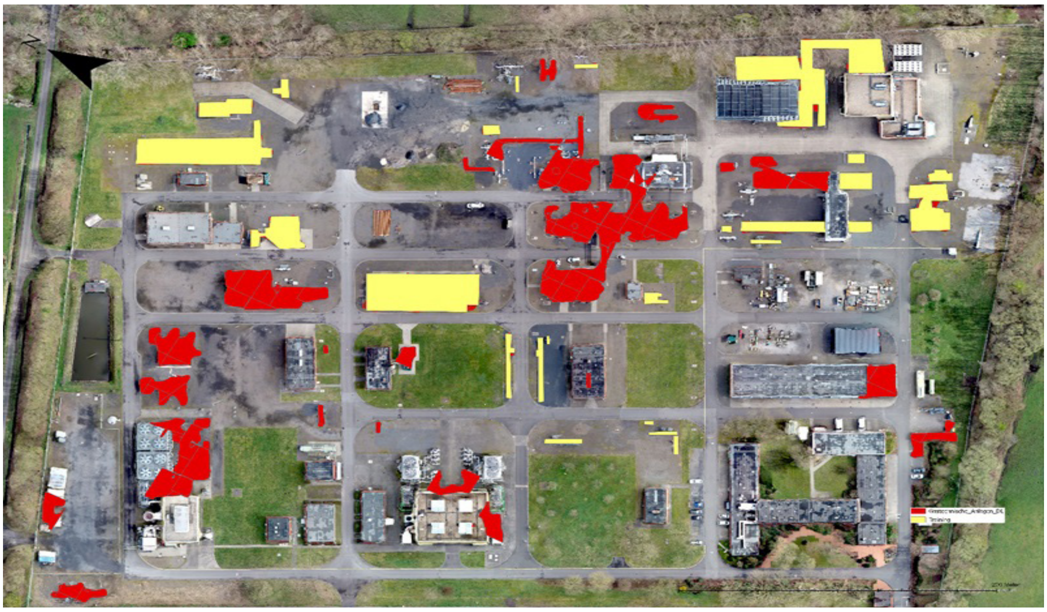

Figure 12: Detection of gas-technical equipment via Deep Learning in ArcGIS. Training objects are marked in yellow, de-tected objects in red.

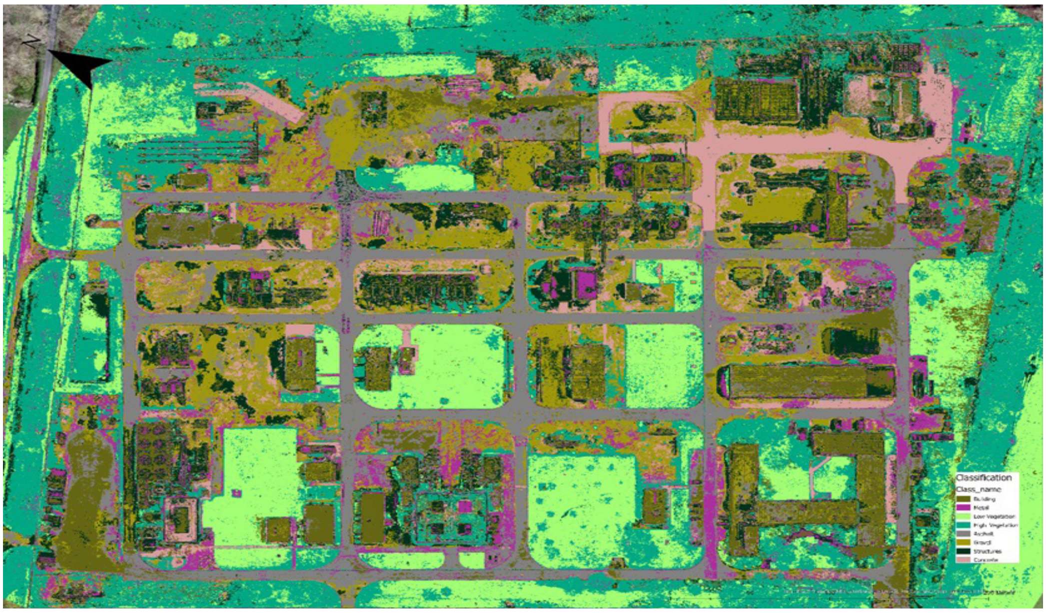

Figure 13: Manual post-processing of the automatic classification. Green = correctly detected, Red = removed False Positives, Blue = added False Negatives.

Figure 14: 3D flight planning taking into account infrastructure, risk and no-fly zones (Agisoft Metashape).

After several months of testing with different software products, the decision was made to use Drone Harmony [21], as it best met the requirements of the project. All data collected and evaluat-ed so far could be used to create a detailed 3D model of the site including buildings, potential emit-ters and no-fly-zones Figure 15). The data was tested for plausibility using the self-calculated digital elevation model (Figure 16) and the 2D data (Figure 17) and used for highly accurate flight planning.

The high-accuracy flights will be planned and tested based on the validated model as soon as the data from the gas detection work package is available.

Fusion of the 3D GIS with the Evaluated Satellite Data

Currently, data fusion is still undergoing. For this purpose, the satellite scenes are evaluated over a complete annual cycle and compared with previously placed ground sensors and the UAV flights carried out. Factors such as different resolutions, recording times, cloud cover and spectral ranges that are not identical must be compensated accordingly in order to ensure comparability.

Development of Workflows for a Multi-level Risk Management

Parallel to the development of the data fusion, the first workflows are already being designed. The multi-stage alerting process in the event of damage should basically work according to the following scheme:

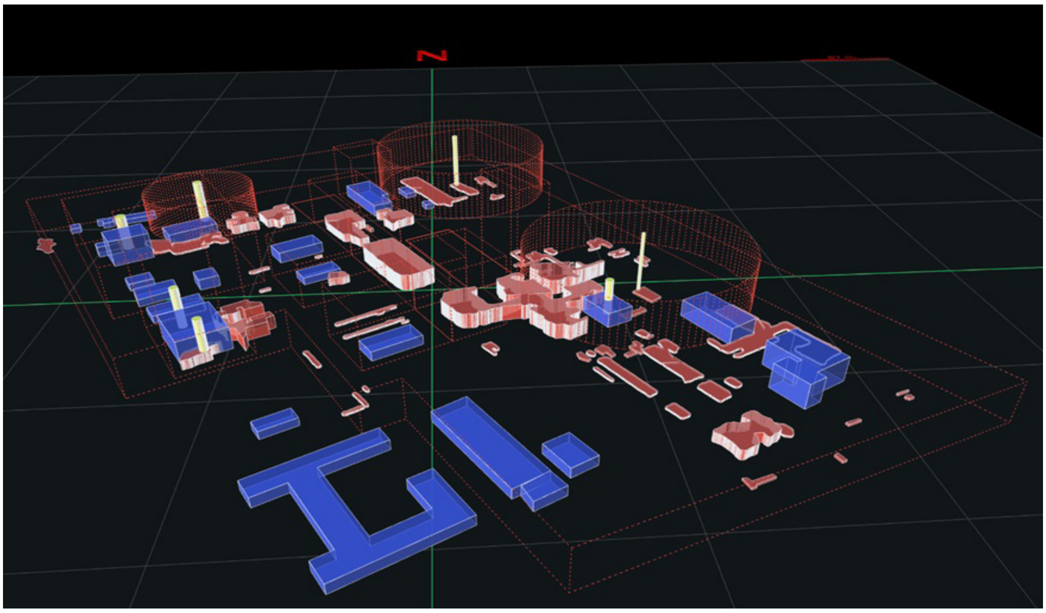

Figure 15: 3D-Model in Drone Harmony: Blue = Buildings, Red = gas-technical equipment as potential emitters.

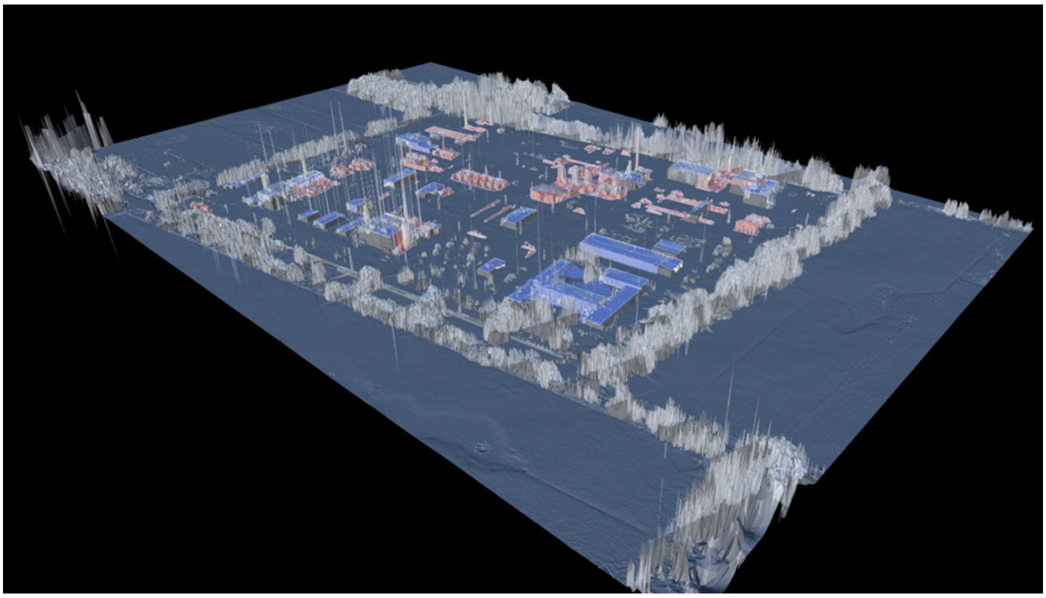

Figure 16: Validation of the 3D-Model by overlaying the digital elevation model.

1. Continuous satellite monitoring detects damage (e.g. gas emission, large area decrease in plant health).
2. Depending on the type of damage, a UAV equipped with appropriate sensor technology is launched for more precise localization and analysis of the damage. In the live feed of the drone images, false positives can already be ruled out if necessary or immediate measures can be initiated. The more detailed analysis takes place in post-processing.
3. After localization and analysis of the damage, teams can be dispatched for further assessment or damage repair.

As already explained in the previous subchapter, the workflow of the satellite segment itself is still being developed. In order to be able to accurately assess possible sources of danger in a risk man-agement process, the data obtained so far on the surface and subsurface situation were evaluated using geoanalysis tools (e.g. correlation of geological faults and pipeline trajectories).

Development of a WebGIS as Demonstrator

After the fusion of the previously collected and evaluated data, they are exported from the local GIS environment into a prepared WebGIS. In addition to the classic GIS functionality, the system architecture also provides interfaces to the cavern operator's site-bound sensors, a dashboard and an alarm function. The monitoring of the regularly updated satellite data will be at least partially automated. Currently, different free and proprietary options for the project period and the subse-quent use by storage operators are being examined.

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Figure 17: Validation of the 3D-Model by overlaying the processed 2D data.

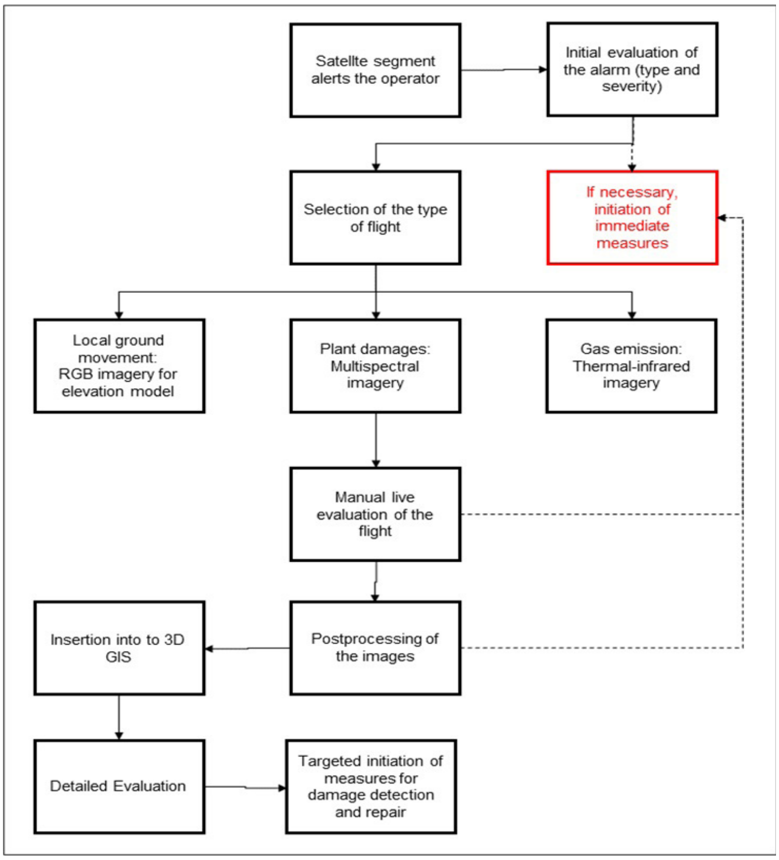

Figure 18: Workflow reacting to the satellite segment alerting the operator.

Conclusion

Coupling classical geological methods of subsurface assessment with innovative approaches from remote sensing shows a huge potential for further research. This integrative geomonitoring method will be the key to a successful energy transition and the enabler for the improvement of the social license to operate. For holistic geomonitoring, it is necessary to use a combination of differ-ent remote sensing systems to balance the weaknesses of individual sensors and platforms with the strengths of others. The data must be verified by local information and interpreted by expert knowledge.

For the topics of gas detection using thermal infrared cameras and high accuracy 4D data fusion of different sensor types, further research needs were identified and will be addressed either during the remainder of KaMonSys or in a follow-on project.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

Conceptualization, B.H., T.R. and B.B.; Methodology, B.H., T.R. and B.B.; Software, B.H. and B.B.; Resources B.H., T.R. and B.B.; Writing original draft, B.H., T.R. and B.B.; Review and editing, B.H., T.R., B.B. and J.B.; Visualization, B.H. and T.R.; Supervision, T.R. and J.B.; Project administration, B.H., T.R. and B.B.; All authors have read and agreed to the published version of the manuscript.

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