Highly Detailed Landfill Mapping and Zoning Based on Multi-sensor Data and Its Analysis

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Abstract: The problem of household waste is becoming increasingly relevant in the context of the growing anthropogenic impact on the environment. Many countries are faced with the need to establish an effective system of waste collection, storage, and utilization. However, for decades, this system has not been properly organized in various states, leading to the formation of spontaneous dumps and landfills that are poorly controlled. The Republic of Armenia was not an exception: 174 dumps and landfills of domestic waste were identified on its territory. Of these, only 9 are official municipal landfills, where waste records are kept, and control and reclamation activities are carried out. When the whole sphere of waste management remains in the «grey zone», remote sensing becomes the only effective tool for monitoring the condition of dumps and landfills. Various remote sensing techniques and data types are used to monitor and analyze landfills and landfill sites. Both satellite and unmanned aerial vehicles (UAV) technologies and ultra-high resolution data provide long-term observation and more detailed studies of sites. At the level of individual dumps and landfills, not only waste volumes and other spatial indicators are analyzed, but also a component-by-component study of the waste itself is performed. In addition, the processes occurring on the landfill body are monitored, and the areas surrounding the landfill are studied. This is particularly important as the main environmental impact occurs in this buffer zone. In our study, we examined an urban landfill that has been in operation for over 40 years and found out how the processes taking place there affect the surrounding landscape. Optical, multispectral, and thermal imagery from UAVs were used for detailed analysis and mapping. A series of satellite imagery was also applied to create a long-time series. The optical imagery data served as the basis for creating an orthophoto of the terrain and a digital elevation model, which became the basis for morphometric analysis. Using morphometric indices, thematic maps of exogenous processes occurring in the landfill body and surrounding area were created. Erosion, accumulation processes, and zones of material movement were identified. Multispectral imagery helped to assess the vegetation cover condition and to identify affected areas. Thermal imagery contributed to assessing atmospheric pollution by identifying direct combustion sites, places of landfill gas emission, and the decomposition of domestic waste. Ground geochemical studies, spectroscopy, bioindication, and thermal imaging confirmed the remote sensing results. Based on the data obtained, maps of the territory zoning were created according to various criteria: functional, geochemical, hazards, impact on vegetation cover, and atmospheric pollution. These studies allowed for a comprehensive assessment of the environmental condition of the landfill and the surrounding area, combining remote sensing data with the results of their careful processing.

1. Introduction

In the middle of the last century, when the technology and techniques for producing goods and services were developing rapidly, many controlled and uncontrolled landfills and solid municipal waste (MSW) disposal sites appeared in many countries. These facilities became the basis for forming the modern waste management industry.

However, the pace of development of this industry has not kept up with the rate of growth in the amount of waste and changes in its composition. As a result, the number of waste disposal sites has increased dramatically, which has led to the deterioration of the environmental situation at the existing waste disposal facilities.

State reports and analytical reviews on the territory of Armenia for different years provide information on the amount of annually generated waste in the country. The tendency of the increase in the amount of waste generated compared to the indicators of each previous year is from 90 to 120%, and in some years (2011) by 160%. In Armenia, the reports record stable positive dynamics regarding the amount of waste generated (Republic of Armenia Solid Waste Management…). This fact can be related to the improvement of primary waste accounting at the municipal level, strengthening of reporting discipline, expansion of the number of reporting facilities, and several other factors of organizational and statistical nature. In Armenia, a one-stage scheme is used for waste accumulation in settlements, i.e., waste from territories is collected in special containers located in approved places - container sites, then the accumulated waste is loaded into specialized vehicles and delivered to disposal facilities. In addition, in some settlements, there are unauthorized landfills where the uncontrolled accumulation of waste takes place.

In most cases, landfills were formed spontaneously in waste pits, various excavations, trenches, ravines, and gully networks without considering environmental protection requirements and planning restrictions. In particular, the geological structure, hydrogeological and landscape-geochemical conditions, and the existing socio-economic situation were not considered. These circumstances contribute to the highly negative impact of the landfills on the environment, especially on groundwater, which is a source of water supply, and the air basin of the territory, creating a real threat to public health.

Most waste studies have focused on the areas adjacent to landfills and dumps. However, the processes occurring on the landfill soil-like bodies, which are a mixture of natural and anthropogenic materials, are neglected.

Usually, landfills are considered part of an industrial area with clear functional zoning, where only technical elements and working maps are emphasized. However, it is not taken into account that inside the landfill bodies, processes of migration of chemical elements form areas with homogeneous composition. These areas arise according to natural patterns.

In addition, waste is not always carefully sorted or not sorted at all before disposal. Because of this, along with non-hazardous waste, there is toxic and flammable waste, as well as valuable resources that can be used as raw materials for the production of new goods—secondary material resources.

Landfills and waste dumps are open-loop systems that negatively impact the environment. They pollute natural resources and contribute to the formation of greenhouse gases, which in turn can cause climate change. In addition, these facilities are closely related to human economic activities.

The main factors affecting the environment at landfills and dumps are leachate and landfill gas. Filtrate is a liquid waste formed by the interaction of natural sediments with plant and animal wastes and their decomposition products during storage, compaction, and decomposition.

The composition of seepage water depends on various factors, including geological, hydrogeological, meteorological, topographical conditions, waste morphology, landfill life cycle stage, and storage conditions. However, it is mainly determined by landfill processes, including degradation.

Landfill gas is a mixture of methane and carbon dioxide with small amounts of impurities such as nitrogen, oxygen, hydrogen, silica, sulfur, and hydrogen sulfide. It is produced by the anaerobic decomposition of organic waste and can contain dozens of different organic compounds as trace impurities.The process of decomposition of organic matter in landfills and dumps, as well as the formation of landfill gas, includes two main phases of destruction: aerobic and anaerobic.

Many factors determine the formation of biogas in landfills and dumps:
1. Waste characteristics: total mass, organic matter content, moisture level, presence of nutrients, and methanogenic inhibitors.
2. Waste treatment technologies: crushing and leachate recycling methods.
3. Landfill characteristics: terrain, mode of operation, leachate and biogas disposal arrangements, and level of ground cover.
4. Natural conditions: precipitation, temperature, and evaporation rate.

Vegetation growing near landfills and dumps is predominantly composed of ruderal species. Pollutants affect plant communities in two main ways: directly and indirectly.

Direct effects occur near the landfill body and are manifested through the following processes:
1. Formation of a halo of landfill gases (LFG) dispersion creates permanent conditions of increased air dustiness.
2. Weathering of fine particles from the surface of the landfill, which leads to the formation of stable dust conditions.
3. Leachate enters the soil, accumulates, and then enters water bodies through surface runoff.

Indirect impacts are realized through other components of the environment, e.g., phytotoxic soils. When assessing the condition of vegetation in landfill conditions, researchers note that it is enriched with almost the same chemical elements as the soil.

Disturbance of plant mineral nutrition leads to a number of negative consequences: changes in leaf color (yellowing, brown or purple spots, and so on), growth arrest (dwarfism), and the formation of cracks and holes on leaves, which, in turn, can lead to the death of species.

The degree of landfill gas influence on phytocenoses depends on its source and the content of components in atmospheric air. This influence manifests in changes in plants' linear parameters and leaf necrosis lesions.

Thus, it can be concluded that the territory near landfills is subjected to a complex impact of various factors. Landscape components need separate monitoring of their condition. To solve such problems, it is not enough to use only one remote sensing method or data type; a detailed component-by-component analysis is required.

2. Methodology

2.1 Study area

Our focus is a landfill located a few kilometers from Vanadzor, the third largest city in Armenia (Figure 1) and the administrative center of Lori Marz. This landfill is an urban dump where domestic and industrial waste from the surrounding areas is dumped. According to archive images and old photographs, the landfill has operated since the middle of the last century. It is located on a slope in the valley of the Pambak River, at the foot of the Bazum and Pambak ridges, which creates favorable conditions for the active development of exogenous processes.The altitude is about 1650 meters above sea level, and the valley's location provides a moderately continental climate with cold winters and warm summers. Most precipitation falls in the spring-summer period, which in turn contributes to erosion processes and the transport of substances. In the study area, the slopes are steep and covered with herbaceous vegetation, mainly steppe species. The study site is under control, and the landfill was still accepting waste for disposal at the time of the study. Because the area is industrialized, a process road to the mining site is near the site, creating an opportunity for intermittent dumping of industrial waste. At the time of the survey, spontaneous waste disposal was not limited to a single site. Litter was observed in several areas along the country road to the site. The landfill is located almost 200 meters away from the residential area (Archut village) (Figure 2.1), towards which air masses migrate. Nearby irrigated agricultural fields may also contribute to the spread of pollutants.

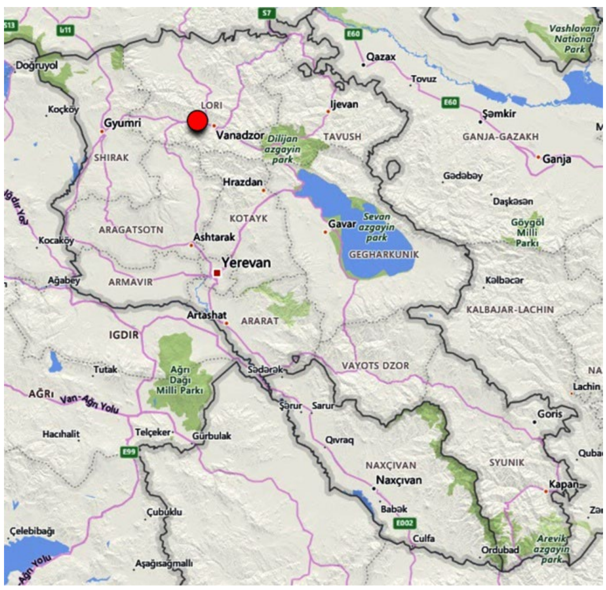

Figure 1. Study area.

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2.2 Data and processing

The primary research method is monitoring waste disposal sites based on effective and efficient strategies and technologies for obtaining information. Specifically, data from unmanned aerial vehicles (UAVs) and satellites, geographic information systems (GIS), and mapping techniques are used (Mager et al., 2022).

Remote sensing is a practical tool for monitoring disturbed dumps and detecting unauthorized landfills. This study used remote sensing in two ways: first, space imagery data was used to identify landfills and illegal dumps, and second, a detailed survey using UAVs (Filkin et al., 2022) was conducted in a key area to analyze the morphometric, bioindication, thermophysical, and geochemical characteristics of an urban landfill. It is also worth noting that high-resolution satellite imagery was used to trace the formation and boundary changes chronologically at the test site (Karimi et al., 2022).

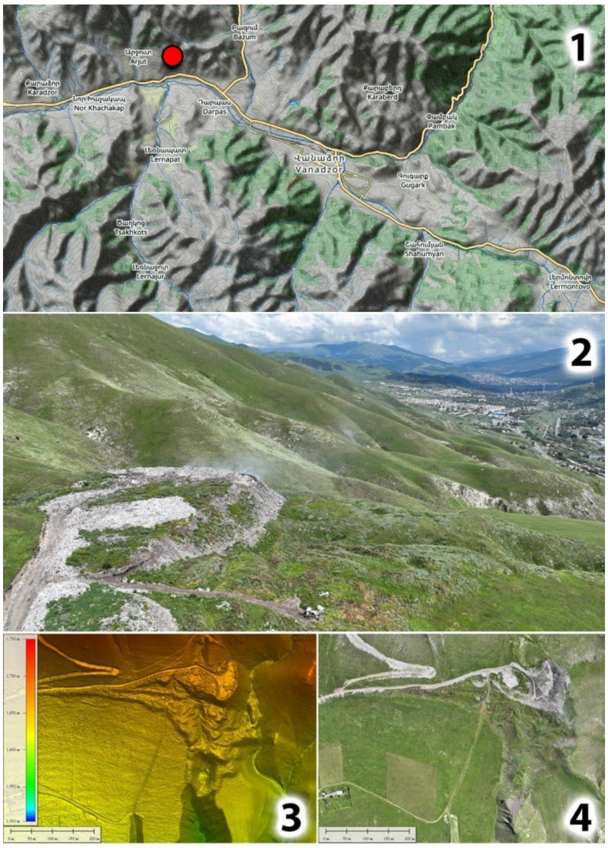

Figure 2. 1) Location of the study area in river Pambak valley, 2) View from site to city Vanadzor, 3) DEM, 4) Orthomosaic

Remote sensing techniques were used to obtain highly detailed data (Torres et al., 2021) from the test waste disposal site using DJI Mavic 3 Pro, Mavic 3M (multispectral), and Mavic 3T (thermal) drones. The imagery was collected at altitudes of 100, 150, and 200 meters, as the site is located on a valley slope and it was necessary to consider the terrain when flying. A ground-based RTK base station was used, and the drones were equipped with appropriate antennas. The aerial imagery underwent photogrammetric processing to produce orthophotos, digital surface model (DSM) and digital elevation model (DEM), tiled, and 3D models (Figure 2.3 and 2.4). All spatial data were projected in the UTM coordinate system, zone 38 on the WGS-84 ellipsoid, and integrated into a single geospatial project.

Based on the collected data (Figure 3), the following tasks were performed using automated software modules such as Agisoft Metashape, Pix4D Mapper, ArcGIS Pro, Global Mapper, and SagaGIS:
1. Retrospective analysis of archived space images using analysis and comparison techniques was performed (Garofalo and Wobber, 1974).
2. Photogrammetric processing and creation of three-dimensional digital products including point clouds.
3. Performed recognition and classification of waste disposal site features using interpretation methods, focusing on existing benchmarks and interpretation features.
4. Calculate metric parameters of the landfill body, such as distance, area, perimeter, and volume.
5. Morphometric data, including land surface steepness and slope angle of the landfill body, were collected.
6. Thermal characteristics such as land surface temperature (LST), vegetation cover condition based on spectral indices (NDVI, GNDVI, SAVI and GSAVI) were studied (Koda et al., 2022).

Pre-processing included different types of correction: geometric, radiometric calibration, and atmospheric influence correction. In addition, aerial and satellite images were subjected to image enhancement: missing pixels were restored, contrast was enhanced, and filtering was performed.

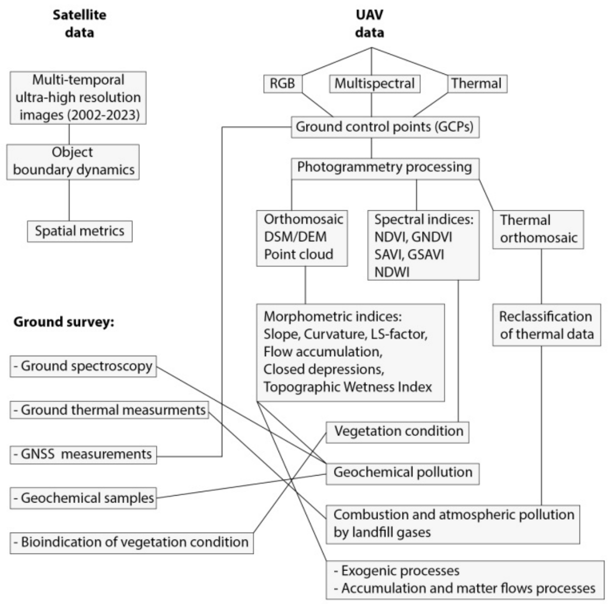

Figure 3. Data and processing steps

The thematic processing depended on the objectives of the study and consisted of the following steps:
* interpretation - the process of recognizing and understanding images;
* color transformations - changing the color of images for more straightforward perception;
* index images - creation of unique maps reflecting various characteristics of the study area;
* principal component analysis - a method allowing to highlight key factors determining the features of the investigated area;
* spectral separation - allocation of different spectral ranges for more profound analysis;
* classification - grouping of objects based on their properties and characteristics.

In addition to ultra-high resolution remote sensing data, traditional research methods were used at the key test site (Youme et al., 2021). These included ground-based field and laboratory work, the results of which became the basis for geo-ecological assessment of the site and the environment in the zone of its influence.

The field methods were based on geo-environmental studies of the area. They included vegetation assessment, geochemical sampling, ground-based spectroscopy using a NaturaSpec hyperspectrometer, and ground-based thermal imaging surveys. Soil samples were collected during the route surveys, and their coordinates were determined using a GNSS.

The study of chemical element distribution in the waste disposal area was carried out at the local level. Geo-ecological assessment was performed using an X-ray fluorescence spectrometer, which allowed the evaluation of multi-element contamination and the level of environmental risk. In addition, a compositional data analysis method was applied to identify geochemical associations of potentially toxic elements (Wang et al., 2022).

The vegetation of adjacent landscapes and the landfill body was described using standard geobotanical methods, including bioindication and phytocenology.

Optical survey data, such as highly detailed digital elevation models and orthophotos, were invaluable for morphometric analysis of the LFB and affected vegetation. Morphometric indices were used to identify processes such as waste sliding down the landfill slopes, formation of surface ponds due to runoff filtration, landfill surface failures, no-drain accumulation zones, and landfill runoff and movement of substances from the landfill.

The results of the remote sensing surveys and their analysis provided the basis for zoning the landfill. The zoning was conducted using cluster analysis, spatial statistics, and mathematical analysis.

3. Results

3.1 Functional zoning of the landfill

One of the first tasks that the remote sensing data from the landfill accomplished was delineating functional zones. The landfill has been reclaimed several times during its operation, and waste is regularly moved around the active storage area. Therefore, optical imagery and a digital elevation model were used to perform the zoning. The accurate elevation data made it possible to identify some elements that stand out against the artificial forms.

Several zones can be distinguished on the landfill site:
- Excavation zone, where the extraction and movement of waste takes place.
- The open storage zone is where the waste is unprotected.
- The primary overgrowth zone, where the waste begins to be covered by vegetation.
- The reclaimed waste zone is where vegetation covers the already processed soil.
- Technological access roads appeared both during the landfill operation and as a result of natural processes.

This approach to functional zoning of landfills is quite typical for such facilities. Despite the presence of the necessary infrastructure for operation, the landfill cannot be said to be managed in a planned manner. Operational tasks of waste storage and movement are mainly addressed, but there is no long-term planning and normal waste distribution.

Waste first accumulates in the active excavation area and then moves to fill the bottom of the landform. The highest concentrations of garbage are found in the slope areas of the landfill body. The remediation areas where waste has been mixed with brought soil and conserved have the lowest concentrations of contamination.

3.2 Analysis of topography and exogenic processes

Optical aerial survey and its processing became the basis for studying the terrain and the landfill body. The process of creating a DEM can be divided into three consecutive tasks:
1. Gathering a sample of surface elevations: Collection of terrain elevation data using photogrammetry techniques, particularly the currently popular Structure-from-Motion (SfM) method.
2. DEM Creation: Creating a three-dimensional elevation model based on the resulting elevation sample.
3. Error and Artifact Correction: Correcting inaccuracies and distortions in the generated model to maximize accuracy.

Since the modeling is based on aerial photography data in our work, we use photogrammetry methods, particularly SfM, to obtain a sample of land surface elevations. This method allows us to get a dense point cloud describing the three-dimensional geometry of the terrain, including objects located on the surface. We exclude this information to create a terrain model, leaving only elevation data. This step also included the outlier filtering procedure, which usually precedes the land surface point classification step. The classification resulted in point clouds, which were then converted to a DEM by interpolation to create a continuous land surface model. Also, at this stage, the resulting DEM was post-processed to ensure its hydrological correctness.

The study of the landfill's morphometric properties began with the study of basic geometric parameters that describe the shape of the relief surface. These parameters include slope, exposure, curvature, and other characteristics. If we consider the DEM as a scalar field, slope and exposure represent the two components of the elevation gradient: the length of the vector and its direction.

The direction of surface water flow and the movement of substances, including sediment, was determined based on slope. The D8 (Deterministic 8) and MFD (Multiple Flow Direction) algorithms, which allow the determination of both single and multiple flow directions, were used to calculate the matter flow.

Morphometric indices and indices were used to evaluate exogenous processes on the landfill surface. Based on a set of indices, in particular, the LS factor, the following types of such processes were identified: weathering; waste movement with loss of contact; waste screen and landslides; suffosion and subsurface erosion are caused by flushing and internal burning.
DEM and morphometric indices were also used to identify micro-relief changes resulting from reclamation activities. As the site was surveyed several times a year, it was possible to compare elevation models, assess the effectiveness of reclamation, and identify areas where hazardous processes were

developing. Modeling of relief changes was used to monitor long-term processes such as overgrowth and slope stabilization.

3.3 Vegetation condition assessment

The landfill's vegetation is dominated by ruderal species, with introduced species also occurring. Waste's impact negatively affects plants' condition, causing defoliation (leaf fall), shortening of the vegetation period, and disruption of photosynthesis and mineral nutrition. These changes can lead to plant mortality.

Multispectral survey results, spectral vegetation, and soil-vegetation indices were used to assess the vegetation condition. Special attention was paid to the near-infrared channel, which was considered the most informative for studying the degree of vegetation disturbance (Figure 4).

Analysis of the spectral index images identified two main types of pollutant impacts on plant communities: direct and indirect.
Direct impacts occur near landfills and can be caused by several factors:
* The dispersion halo of landfill gas affects air composition and creates stable dust conditions.
* The weathering of fine particles from the landfills' surface also results in dusty air and a stable environment.
* Leachate enters the soil, accumulates in the soil, and can be leached to non-drainage areas through surface runoff.

Indirect impact is through environmental components, such as toxic soils, which can lead to complete plant death. Disturbance of mineral nutrition of plants is manifested in color change (yellowing of leaves, etc.) and cessation of growth.

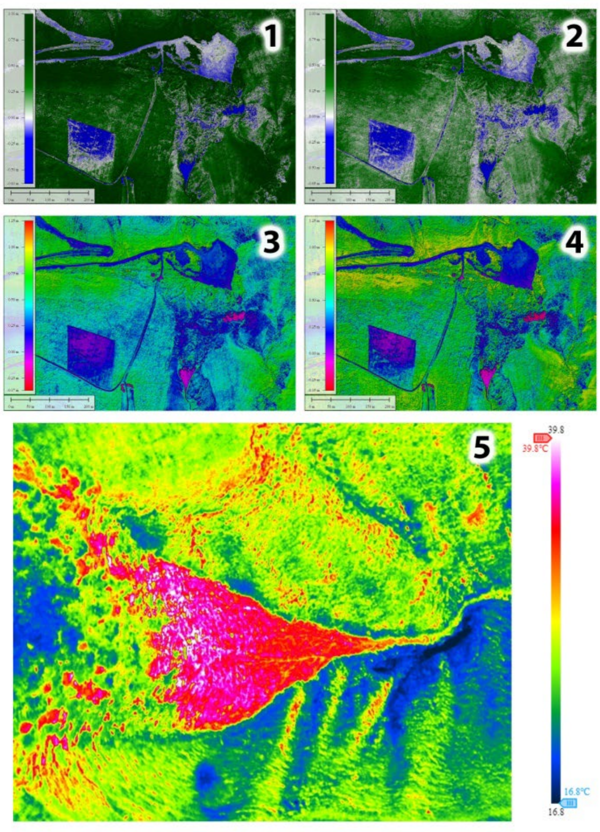

Figure 4. Spectral indices; 1) NDVI, 2) GNDVI, 3) SAVI, 4) GSAVI, 5) Fragment of thermal orthomosaic.

If we consider the condition of vegetation as a whole, the most problematic areas are areas where active waste decomposition occurs and places with a high level of geochemical pollution.

However, it should be noted that active overgrowth is observed in areas where reclamation works have been carried out and waste is mixed with soil. Vegetation indices in these areas demonstrate high values, indicating favorable plant growth conditions.

3.4 Atmospheric pollution

One of the main problems this facility faces is the constant burning of waste, which results in atmospheric pollution (Grondona et al., 2022). When burning, the waste emits smoke gases and odors that can travel up to several kilometers.

On the site, there are areas where waste burns openly and areas where it smolders. Burning occurs both on the landfill's surface (open burning) and in the thickness of the landfill body (latent burning). Latent burning heats the surface layers of the waste and may be visible over a wider area. The only direct indication of such burning is smoke.

Monitoring a landfill fire is problematic because it is difficult to identify possible hotspots due to the different specific heat capacities of the waste. Therefore, monitoring is only possible with a thermal survey, which has been selectively verified with ground-based thermal imaging. Large voids are formed under the waste strata, resulting in subsidence of the waste layers.
Another important source of pollution is landfill gas, which is emitted from waste decomposition. This gas's peculiarity is its ability to move long distances under the influence of pressure gradient and molecular diffusion.

Based on thermal ortho mosaics, areas with temperature anomalies were identified — areas where the registered thermogram shows a higher temperature compared to the reference area. The presence of an elevated temperature anomaly at the landfill indicates the release of heated biogas from the waste column into the atmosphere. Temperature anomalies were recorded on the landfill slopes and in the area of active waste movement.

4. Discussion and conclusion

Waste burial on unequipped land plots in mountainous terrain has a direct negative impact on nature, disrupting natural processes. Large areas of landfills are covered with waste. Although the location of dumps is smaller than that of landfills, their number is much larger than that of the latter. The impact zones of landfills are wider because they are often located in valleys and gully systems, which facilitates the migration of pollutants.

Uncontrolled and unzoned sites spontaneously create new places for waste storage and littering, and the area occupied by garbage continues to grow. Although such sites are known to the local authorities and unofficially have the status of "authorized landfills," this does not solve the waste management problem.

The study of landfills and their comprehensive zoning has identified many indicators that characterize the environmental impact (without considering the economic aspect). Such indicators include: morphological characteristics of the landfill body and morphodynamic processes that can alter the

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anthropogenic topography of the site and lead to contaminant migration; geochemical characteristics - the presence of hazardous properties significantly exceeding permissible concentrations; bioindication characteristics - influence on the state of plant communities on the territory of the landfill and in its vicinity; chronological (dynamic) and functional characteristics - describe the history of waste accumulation, stages of reclamation, and operational management of new arrivals (Figure 5).

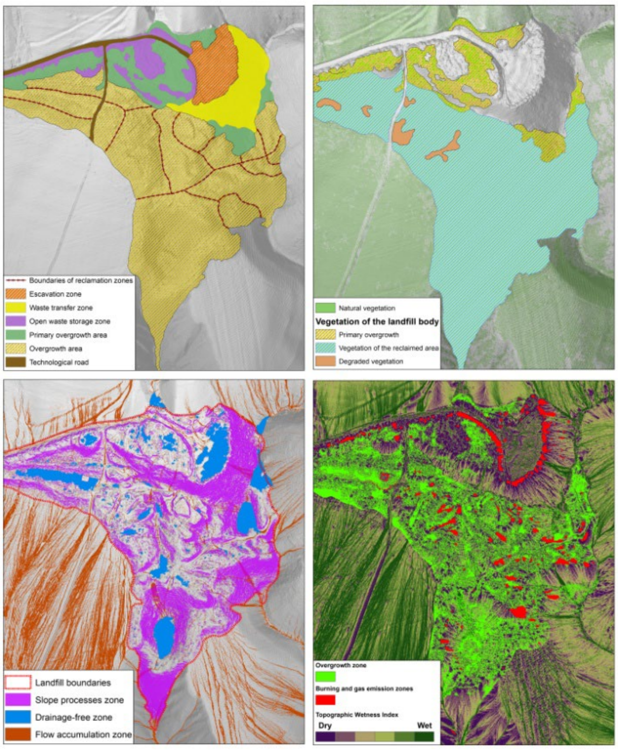

Figure 5. 1) Map of functional zones, 2) Map of vegetation types and condition, 3) Map of exogenous processes, 4) Map of combustion and landfill gas emission zones.

Modern remote sensing methods allow continuous monitoring of landfills and waste dumps. Using space and aerial imagery, we obtain qualitative and quantitative data not only on the waste itself but also on how it affects the environment.

In-depth analysis and classification of ultra-high spatial resolution data make it possible to study individual processes in real-time and model the state and movement of pollutants. For the investigated object, not only was a comprehensive assessment of its condition carried out, but also all possible variants of territory zoning were considered.

Ultra-high resolution images and geoinformation analysis, the following conclusions can be drawn:
- a methodological approach for integrated study and zoning of waste landfills based on RS and GIS data has been developed;
- chronological, morphodynamic, bioindication, thermophysical, and functional analyses of landfill parameters on the plane and in space were carried out using GIS, space, and aerial photographs;
- such processes as waste sliding and landslides, formation of surface water bodies formed by filtration runoff, subsidence and collapses, fires and smoldering, and littering of adjacent landscapes with waste were identified on the landfill body using images and highly detailed digital elevation models;
- analyzing the state of natural environment components based on remote sensing data at the site and the adjacent territory allowed assessing the disturbance of natural vegetation cover by calculating soil-vegetation indices;
- the use of remote sensing and GIS data showed the effectiveness of their application in the study of waste landfills, especially when using multi-temporal imagery, as it allowed to analyze the object not only in dynamics, but also to identify individual components and elements of the underlying surface in more detail.

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