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GEODETIC SUPPORT FOR MONITORING LAND DEFORMATION IN THE CONTEXT OF TECHNOLOGICAL LOADS AND CLIMATE CHANGES

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Abstract. *The article addresses the issue of geodetic support for monitoring land surface deformations caused by anthropogenic pressure and climate change, which is an important prerequisite for preventing soil degradation and ensuring sustainable territorial development. The aim of the study is a comprehensive investigation of the geodetic support system as a fundamental basis for obtaining spatial data necessary for assessing and forecasting the dynamics of land resource conditions. Erosion-prone agricultural lands of the Mizoch territorial community in Rivne region were selected* *as the object for practical testing of the proposed solutions. The study analyzes the algorithm of geodetic monitoring, which includes preparatory and field work, data processing, GIS-based modeling of spatial changes, and the stage of managerial decision-making. Particular attention is paid to the fact that each stage requires the integration of specific instrumental methods and topographic-geodetic procedures to ensure high-precision recording of spatial shifts in terrain and soil cover over time. The principles of forming a monitoring framework are described in detail. In particular, the basic criteria for designing geodetic networks are formulated, including the layout of profile lines, reliable fixation of at least two reference benchmarks outside the zone of potential deformations, and the optimal placement of working stations directly within the risk area. The practical value of systematic ground-based geodetic measurements for the timely identification of erosion centers and soil displacements is demonstrated. The accumulated set of verified spatial data provides a reliable basis for the development of effective land reclamation measures and for making informed management decisions in the field of land protection within the community. Prospects for further research include the adaptation of deformation monitoring tools to other types of landscapes and specific land-use regimes..*

Keywords: *geodetic support, monitoring, land use, land deformation, anthropogenic load, climate change, GIS, GNSS, UAV.*

Introduction. In recent decades, land surface deformation has become a significant threat to the safe functioning of engineering infrastructure and the spatial development of territories, as it creates risks of structural damage and disrupts the conditions for economic activity. This widespread hazardous phenomenon can have several serious consequences, including an increased risk of flooding of coastal areas, damage to buildings and infrastructure, disruption of the hydrogeological regime of groundwater, and landslides. Hazardous processes associated with the deformation of the earth's surface are systematically recorded both globally and in Ukraine. In this context, continuous monitoring of deformation processes is a prerequisite for understanding the dynamics of the Earth's surface and for managing associated safety risks. This issue is particularly relevant in regions with complex hydrogeological conditions and a predominance of agricultural lands (for example, in the Forest-Steppe and Steppe zones of Ukraine), where water erosion and changes in the groundwater level directly affect land productivity. For the timely detection, assessment and prevention of these processes, continuous geodetic monitoring is required in potentially at-risk areas.

Analysis of recent researches and publications. The issues of geodetic support for monitoring and land protection have been addressed in the works of many Ukrainian and foreign scholars. An analysis of recent publications makes it possible to identify several key areas of research in this field. The theoretical and methodological foundations of geodetic monitoring are presented in studies [1, 2, 3], which define well-grounded approaches to recording deformations of the Earth's surface. D. Khaynus and co-authors [1] analyse modern methods of higher geodesy and their applied value for determining spatial displacements. O. Dobrokhodova and colleagues [2] summarise the theoretical aspects of deformation monitoring for both natural and anthropogenic processes. International experience and the evolution of approaches to observing land deformations are systematised in the review work of A. Ng et al. [3], which emphasises the global relevance of the problem. The article by N. Kolesnik and M. Kozhemiako details the importance of geodetic observations for calculating and analysing deformations of the Earth's surface in the zone affected by mining operations [4].

A significant body of research is devoted to studying the influence of anthropogenic loads and local geoprocesses on land deformation. Thus, O. Naminat [5] addresses a complex scientific and practical problem of geodetic monitoring of linear objects located in zones of directly affected by underground mining operations. The regional aspect of dangerous geoprocesses (in particular, landslides) is analysed by D. Bulysheva and co-authors [6] using the coastal strip of the Black Sea as an example, with the aim of preventing emergency risks. The monograph by R. Shevchenko [7] is devoted to urbanised areas subject to complex anthropogenic pressure, in which the tools of environmental monitoring are considered using the city of Kyiv as an example.

The defining trend of the modern stage is the transition from traditional geodetic measurements to the integrated use of spatial data arrays based on GIS technologies and remote sensing methods (RS). Thus, O. Braslavska [8] investigates the effectiveness of using GIS technologies and RS data to track the dynamics of land use changes over large areas. A more specialised but highly accurate tool, satellite radar interferometry, is considered by Y. Aimaiti et al. [9], who demonstrate its effectiveness in detecting millimetre-scale deformations of the Earth's surface. Monitoring under conditions of military aggression and post-conflict recovery has become a separate, relevant direction for Ukrainian science. The study by H. Domashchenko and co-authors [10] on the condition of land affected by hostilities substantiates the need for specialised geodetic support for monitoring land use changes under martial law and during post-conflict recovery of territories. The same issues are supplemented by M. Serbov, N. Danilova and V. Pylypiuk [11], who propose methodological principles for the application of remote sensing directly in combat zones, where traditional ground-based geodetic measurements are dangerous or impossible. Despite the significant number of thorough studies devoted to high-precision measurements, remote sensing and geoinformation analysis, most of them focus on industrial facilities (mining concessions, cities) or on macro-regional changes. At the same time, the issue of integrating these modern technologies directly into the practice of land management of agricultural lands for local monitoring of erosion processes and soil degradation remains insufficiently explored and requires further research.

Purpose of the article is to study the structure of geodetic support as a basic component for collecting spatial data, assessing and predicting deformations of land resources under conditions of technogenic and climatic influence.

The scientific novelty of the study lies in improving the geodetic support system for monitoring deformations at the local level, adapted to the needs of environmental and economic protection of agricultural land. Unlike traditional approaches, which are mainly focused on industrial and urbanized areas, this study substantiates the integrated use of high-precision ground-based geodetic measurements as a primary tool for recording spatial soil displacements and assessing the stability of anti-erosion hydraulic structures under conditions of changing climatic influence.

Methods. The information and material base of the study was the works of Ukrainian and foreign scientists in the field of land management, geodesy and geoinformatics. The study used a complex of general scientific and special methods. The system analysis method was applied to investigate the current state and structure of geodetic support for recording deformation processes. The comparative method was used to assess the effectiveness of integrating remote sensing data of the Earth with ground measurements. The conceptual modelling method was utilised to develop a structural-logical scheme for processing spatial data in an open GIS environment for predicting the development of erosion processes under conditions of climate change. The formation of conclusions and theoretical generalisations was formulated using an abstract-logical approach.

Results. Intensive agricultural land use, combined with climatic anomalies, including changes in precipitation patterns during the cold period, prolonged droughts, natural disasters. leads to the activation of exogenous processes such as sheet wash, ravine formation and soil subsidence. For the timely detection of these phenomena, it is necessary to monitor land deformations. Monitoring includes several stages that form a closed cycle of geoecological control: inventorying the current state of the land, instrumental recording of deformation landslides, mathematical modelling of their further development and development of land management projects aimed at ensuring the ecological and economic protection of agricultural landscapes (Table 1).

1. Stages of monitoring land deformations

Stages	Characteristics
Preparatory stage	analysis of archival cartographic and stock materials, data from previous soil surveys and design of an observation network.
Spatial data collection (field stage)	conducting high-precision geodetic measurements (GNSS surveys), aerial photography using UAVs, mobile laser scanning (LiDAR) and downloading current satellite images.
Camera processing and GIS analysis	processing data in specialised software (for example, QGIS or Digitals), building high-precision digital terrain models (DTM) and detecting spatial deviations by superimposing different time models.

Modelling and forecasting	spatial analysis of deformation dynamics, calculating the volume of lost or displaced soil and building predictive 3D models of the development of exogenous processes.
Decision-making (final stage)	forming thematic maps of spatial changes and developing substantiated recommendations for the implementation of anti-erosion and land reclamation measures.

Each stage requires geodetic support, which is understood as a complex of specialised topographic and geodetic works, instrumental methods and modern technologies aimed at systematic observation, high-precision measurement and spatial analysis of changes (displacements) of the Earth's surface, soil cover and engineering structures over time [1]. The basis of each stage is the performance of specialised topographic and geodetic works.

During the preparatory stage of monitoring land deformations, topographic and geodetic works are aimed at creating a monitoring base, namely designing, establishing and developing special reference (baseline) and deformation (working) geodetic networks within the studied territories.

The monitoring base is a specially created network of points fixed on the terrain, serving as a coordinate framework or a fixed base for all subsequent measurements. Reference points are a reliable base for the entire observation system and must maintain their spatial coordinates unchanged for a long time. Deformation (working) points are points (benchmarks, marks) that are installed directly in the area where the processes occur: on eroding slopes, in ravines or in areas of subsidence. They move together with the ground. By measuring the difference in their coordinates compared to the previous cycle, the speed and direction of deformation are determined. The observation network is designed with reference to the state geodetic network, which is used to determine point coordinates, and to the characteristics of the terrain, including the homogeneity of the geological structure of the rock layer, topography, technological zones and expected areas of maximum loading. The network is built in the form of profile lines. At each end of these lines, at least two reference points (benchmarks) are laid, which are established outside the zone of probable deformations, while working points are placed along the perimeter and directly within the studied area [6].

Spatial data collection (field stage) involves periodic (cyclic) measurements of spatial coordinates using GNSS technologies, electronic total stations and high-precision levelling to record even millimetre-scale displacements. Instrumental observations include levelling of all benchmarks, measuring distances between benchmarks along profile lines, surveying cracks formed on the surface, measuring deformations of objects. It should be noted that deformation is a change in coordinates over time; therefore, geodetic monitoring is characterised by cyclicity and precision. The reliability of geodetic measurements results directly depends on the accuracy of the methods used (Table 2) [12].

Plan coordinates (X,Y) are determined using dual-frequency GNSS receivers in static mode for baselines and in RTK mode for quick control of working marks. The root-mean-square error of planned measurements should not exceed 10–15 mm. For high-precision fixation of vertical subsidence, class II geometric levelling is used with digital levels on Invar rails, which ensures millimetre accuracy.

2. Comparative characteristics of the accuracy of instrumental geodetic methods in monitoring land deformations

Method / Device	**Measurement conditions**	**Expected accuracy**
High-precision level	Line levelling	0.3–0.5 mm/km
Digital level	Line levelling	0.3–1.0 mm/km
Medium-precision level	Line levelling	1.0–3.0 mm/km
Electronic total station	Line-angular measurements (up to several km)	1–5 cm
GNSS receiver (RTK / DGPS)	Availability of network corrections and good signal	0.5–3.0 cm
GNSS receiver (Standalone)	Single positioning without corrections	3–10 m
Terrestrial laser scanner (TLS)	Creation of high-precision 3D models of local areas	1–5 mm
Mobile scanning / UAV (LiDAR)	Depends on the quality of system calibration and survey range	1–10 cm

To increase the reliability and interpretative validity of the results obtained from satellite measurements and ground-based methods (tacheometry and geometric levelling), aerial photography from unmanned aerial vehicles is used. This makes it possible to refine the relief model and detect local changes in the shape of the terrain surface. UAV photography is carried out according to the following scheme: creating a network of ground control points, the coordinates of which are determined by a GNSS rover; performing a flight task with a longitudinal and transverse overlap of images of at least 75–80%; photogrammetric processing: building a dense cloud of points and generating a high-precision digital relief model (DRM) with a spatial resolution of 2–5 cm/pixel. The construction of high-precision and detailed digital relief models and terrain objects is carried out using laser scanning technology, or LiDAR (Light Detection and Ranging). This method is effective for analysing the consequences of earthquakes, landslides, mudflows and other hazardous processes. In addition, it makes it possible to track even minor slope deformations that may precede erosion processes [13].

Office processing and GIS analysis of observation results are carried out immediately after the completion of each series of measurements and include checking field logs, calculating the elevations of all benchmarks of the observation station, calculating horizontal distances between benchmarks of profile lines, determining the distances from the reference benchmark to each of the benchmarks of the station profile line, compiling information for each profile line (regarding vertical and horizontal displacements of benchmarks, as well as horizontal deformations - tension and compression), creating graphic materials. The benchmark marks after processing each series of observations are entered into the information on vertical displacements.

It should be noted that at the stage of spatial analysis, modelling and forecasting, the processed results of GNSS observations are aimed at obtaining reliable information about the nature and dynamics of deformations. To ensure this, the completeness of the initial data is checked, the stability of satellite solutions is analysed, and anomalous coordinate values are detected. In this case, special attention is paid to eliminating the influence of random errors, reflected signals, and short-term interference. Accordingly, the procedures for filtering and smoothing the time series of coordinates are applied. After cleaning the data of each point, the time dependences of vertical and horizontal displacements are formed. Based on the obtained time series, the accumulated deformations and average displacement speeds are determined. Dynamics analysis makes it possible to identify areas with accelerated subsidence or displacements, which may indicate adverse changes in the state of the array [12].

Calculation of the difference in the coordinates of the benchmarks between the zero (initial) and current observation cycles is determined by the formula.

Planned displacements:

$$\Delta X = X_i - X_0;\ \Delta Y = Y_i - Y_0, \quad (1)$$

where: $\Delta X, \Delta Y$ – the value of the difference in the coordinates of the benchmarks, mm;

Xi, Yi – the coordinate of the benchmark of the current cycle, m;

X_0, Y_0 – the coordinate of the benchmark of the zero (initial) cycle, m.

Vertical displacements:

$$\Delta H = H_i - H_0, \quad (2)$$

where: ΔH – the value of the difference in the height of the benchmark, mm;

H_i – the height of the benchmark of the current cycle, m;

H_0 – the height of the benchmark of the zero (initial) cycle, m.

Based on these data, displacement vectors are constructed that characterise the direction and speed of movement of soil masses.

At the final stage, the monitoring results are converted into a cartographic form for visual presentation of information. Deformation maps allow visually highlighting areas of increased activity and serve as the basis for making engineering decisions on adjusting technological processes and strengthening control.

The practical results of land surface deformation monitoring are presented using the example of erosion-prone lands of the Mizoch territorial community in Rivne region. The object of observation is a land plot belonging to agricultural lands. In 2020, anti-erosion hydraulic structures (water retention embankments) were built and ravines were filled. The purpose of monitoring is to check the areas for the presence of deformation processes (soil subsidence) in the places of filled ravines and to assess the spatial stability of the constructed hydraulic structures. For this purpose, a monitoring basis was created, which included reference (baseline) and deformation (working) geodetic networks within the studied territories (Figure 1). At the ends of the profile line, in the upper part of the gully at a safe distance (approximately 40 m from the gully edge and the zone of potential subsidence), two reference benchmarks (Rp1 and Rp2) were established. Their locations were selected to ensure that they would not be destroyed in the event of further gully expansion. The coordinates of the benchmarks were determined based on GNSS observations. The total length of the observation line along the constructed anti-erosion hydraulic structures and backfilled gullies is 1,210 m. During the survey, 3 pickets, 21 plus points (established at 50 m intervals), and 95 survey points (located at 10 m intervals) were used. The study of erosion processes and gully growth was carried out using the tacheometric survey method with an electronic total station. The elevation marks of the benchmarks along the profile lines were determined by third-order leveling.Office processing of the observation results was performed immediately after the completion of each measurement series. The calculated elevation marks were entered into the vertical displacement records. After control checks of the field measurements, surface displacements and deformations were calculated, and the corresponding graphs were constructed.

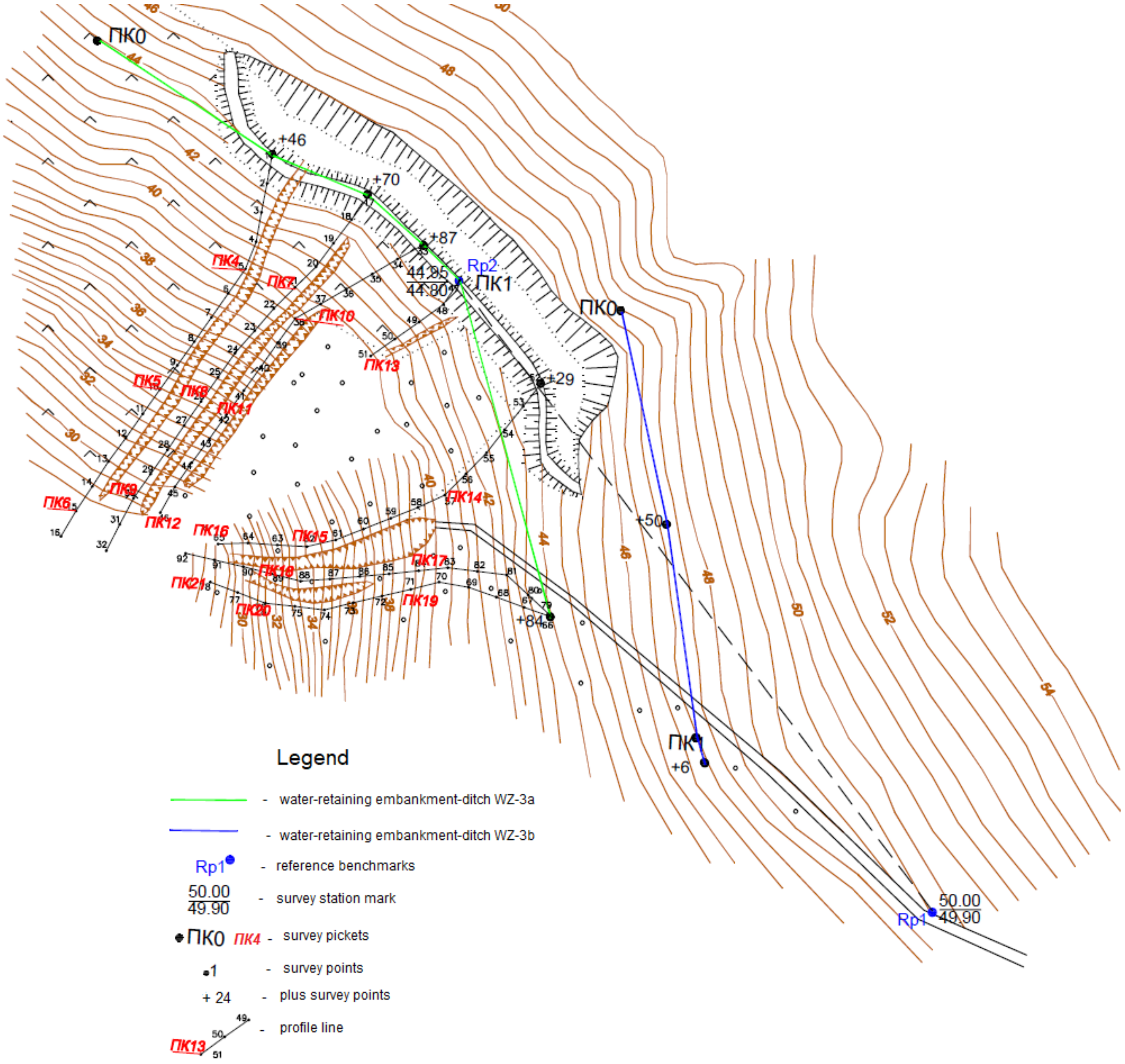

Figure 1. Scheme of breakdown of the monitoring base of erosion-hazardous lands of the Mizoch territorial community of Rivne region

The difference in the coordinates of the benchmarks (ΔX, ΔY, ΔZ) relative to their initial position determines the direction of the displacement vector in space, and the difference in horizontal alignments ΔS between the benchmarks makes it possible to estimate the deformation (compression or extension) of a section of the Earth's surface. For four years, systematic instrumental observations of the studied areas were carried out to identify the dynamics of displacements in time (Table 3).

3. Periods of instrumental observations on created control geodetic network

Cycle	Period	Cycle	Period
1st cycle	November 2022	5th cycle	August 2024
2nd cycle	May 2023	6th cycle	March 2025
3rd cycle	December 2023	7th cycle	October 2025
4th cycle	February 2024		

Observations of the first four cycles recorded uniform subsidence of the Earth's surface. According to the analysis of the graph of vertical displacement along all reference points of the profile lines, it was established that, after the maximum subsidence value had been reached, stabilisation of deformation processes occurred (Figure 2). This confirms the successful elimination of ravines and the spatial stability of the constructed anti-erosion hydraulic structures.

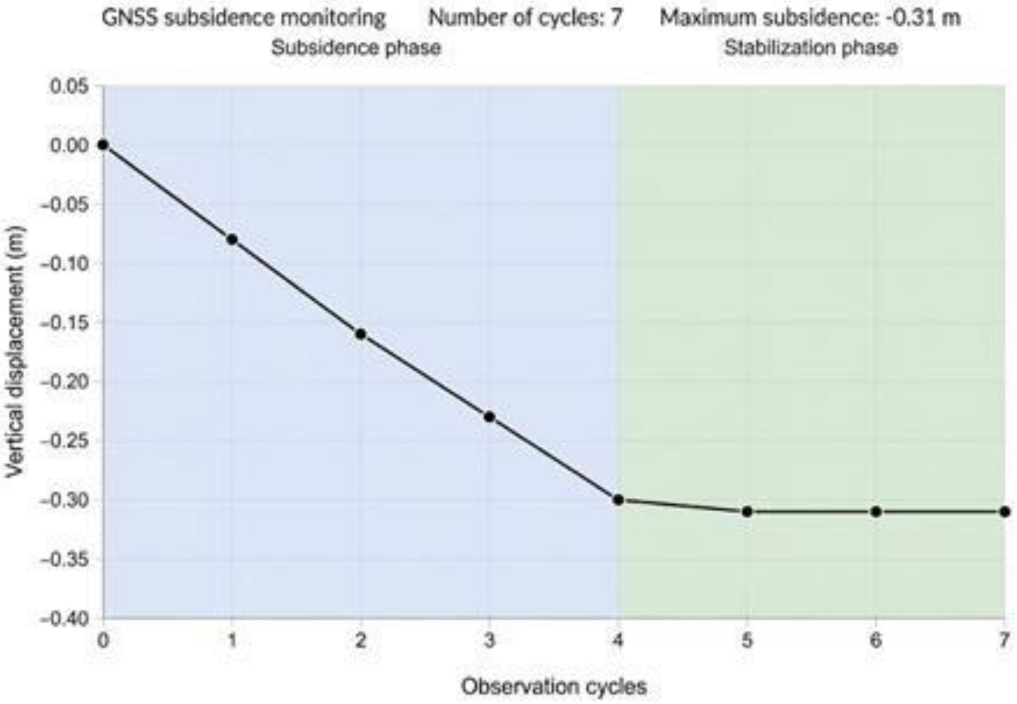

Figure 2. Results of monitoring vertical deformations on erosion-prone lands of the Mizoch territorial community

In addition to vertical displacements, planimetric movements (along the X and Y axes) were also necessarily investigated for a comprehensive assessment of the safety of the constructed anti-erosion hydraulic structures. Considering only vertical deformations is insufficient, since it is the horizontal pressure of soil masses that poses a risk of sliding and structural rupture of the water-retaining embankments. However, the analysis of GNSS observations and tacheometric survey results showed that horizontal displacements of the marks during all seven observation cycles did not exceed the permissible measurement errors (within 10–15 mm). This confirms the absence of hazardous lateral soil movements and demonstrates the complete planimetric (horizontal) stability of the constructed hydraulic structures.

Discussion. Comprehensive geodetic support, combining classical instrumental measurements (GNSS technologies, high-precision levelling) and modern methods of spatial analysis, forms the fundamental basis for monitoring deformations of the Earth's surface. It has been proven that the integration of the obtained spatial data into the GIS environment allows not only to record the current state of erosion-hazardous lands with high accuracy, but also to carry out spatial modelling and timely detection of negative exogenous processes caused by technogenic loads and climate changes. Practical testing of the proposed monitoring structure using the example of agricultural lands in the Mizoch territorial community confirmed the effectiveness of the applied methods. Systematic instrumental observations, carried out over seven cycles, allowed to track in detail the dynamics of vertical displacements in places of eliminated ravines and constructed hydraulic structures. It was established that after a period of uniform soil subsidence (the first four cycles), with the achievement of the maximum vertical displacement of -0.31 m, complete stabilisation of deformation processes occurs. The results obtained instrumentally confirm the successful consolidation of soils, the spatial stability of the constructed anti-erosion structures and the overall effectiveness of the land reclamation measures carried out. From a practical perspective, the results of instrumental geodetic monitoring serve as a basic metric layer for integration into decision support systems (DSS) in the field of land management. The use of verified geodetic data enables DSS algorithms to automate the assessment of soil degradation risks, model scenarios of erosion development, and calculate the required scope of preventive reclamation measures, thereby improving the overall efficiency of spatial management within territorial communities.

Further research is needed to adapt geodetic monitoring tools to the specific conditions of different landscape types and land-use regimes.

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ГЕОДЕЗИЧНЕ ЗАБЕЗПЕЧЕННЯ МОНІТОРИНГУ ЗМІН ДЕФОРМАЦІЙНОГО СТАНУ ЗЕМЕЛЬ У КОНТЕКСТІ ТЕХНОГЕННИХ НАВАНТАЖЕНЬ ТА КЛІМАТИЧНИХ ТРАНСФОРМАЦІЙ

Анотація. *У статті розглянуто геодезичне забезпечення моніторингу змін деформаційного стану земель у контексті техногенних навантажень та кліматичних трансформацій, що є актуальним завданням для запобігання деградації ґрунтів та забезпечення сталого просторового розвитку територій. Метою статі є дослідження структури геодезичного забезпечення як базової складової для збору просторових даних, оцінки та прогнозування деформацій земельних ресурсів в умовах техногенного та кліматичного впливу. Матеріалом практичного дослідження слугувало землекористування Мізоцької територіальної громади Рівненської області. Досліджено етапи моніторингу деформацій земель (підготовчий, польовий, камеральна обробка та ГІС-аналіз, моделювання та прогнозування, прийняття рішень (заключний)). Окрему увагу приділено геодезичному забезпечені кожного етапу як комплексу спеціалізованих топографо-геодезичних робіт, інструментальних методів та сучасних технологій, спрямованих на систематичне спостереження, високоточне вимірювання та просторовий аналіз змін (зміщень) земної поверхні, ґрунтового покриву та інженерних споруд у часі. Розглянуто побудову моніторингової основи, а саме: проєктуванню, закладанню та розвитку спеціальних опорних (вихідних) і деформаційних (робочих) геодезичних мереж у межах досліджуваних територій. Визначено вимоги до створення мережі (побудова у формі профільних ліній, закладання, що найменше двох опорних пунктів (реперів), які розташовують за межами зони ймовірних деформацій, розміщення робочих по периметру і безпосередньо в межах досліджуваної території). Практична важливість полягає у формуванні підходів до застосування наземних геодезичних вимірювань для оперативного виявлення зон ерозійного ризику і просторових зсувів ґрунту внаслідок кліматичних змін. Створена моніторингова мережа та накопичений масив геодезичних даних формують* *надійну базу для подальшого прийняття обґрунтованих управлінських рішень щодо раціонального використання та еколого-економічної охорони земельних ресурсів територіальної громади. Визначено, що подальші дослідження необхідні для адаптації інструментарію геодезичного моніторингу до специфічних умов різних типів ландшафтів і режимів землекористування.*

Ключові слова: *геодезичне забезпечення, моніторинг, землекористування, деформація земель, техногенне навантаження, кліматичні зміни, ГІС, GNSS, БПЛА.*