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ASSESSMENT OF LAND SURFACE DEFORMATION IN GEOLOGICALLY HAZARDOUS AREAS BASED ON GEODETIC MONITORING AND GIS TECHNOLOGIES

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Abstract

This article examines the assessment of land surface deformation in geologically hazardous areas through the integration of geodetic monitoring, geological observations and GIS technologies. The proposed approach combines GNSS observations, high-precision leveling, UAV/photogrammetric imagery, digital elevation models, geological maps and Sentinel-1 InSAR products within a unified GIS environment. In the conditions of Uzbekistan, earthquakes, landslides, mudflows, subsidence and waterlogging processes directly affect the stability of construction sites and transport infrastructure. Therefore, geodetic measurements should be considered not only as a means of determining coordinates and elevations, but also as a monitoring system for controlling the dynamics of geological processes. The paper proposes a procedure for scoring hazard factors, weighting them and calculating an integral hazard index. Using a 312 ha sample polygon, the areas of hazard classes, deformation rates and observation-point indicators are analyzed through tables and graphical materials.

Keywords: geodesy, geology, deformation monitoring, GNSS, leveling, InSAR, GIS, landslide hazard, engineering-geological assessment.

Introduction

In geologically hazardous areas, land surface displacement, subsidence, uplift or slow deformation of slopes is often not visible at the initial stage. Over time, however, these processes may threaten buildings, highways, railway facilities, irrigation networks and settlements. Geodesy records such processes through precise coordinate and elevation measurements, while geology explains the causes of deformation, including rock composition, faults, bedding, groundwater, seismic activity and relief conditions. For this reason, the two fields should be treated as a complementary scientific and practical system.

Although a large part of Uzbekistan consists of plains, the country is bounded by mountainous and foothill systems in the east and southeast. Disaster-risk profiles list earthquakes, drought, landslides, epidemics and floods among the main natural hazards for Uzbekistan, and landslides are reported to account for up to 10-12% of total losses associated with natural hazards [1]. This strengthens the need for continuous monitoring in territories with complex tectonic, irrigation and geomorphological conditions, including the Fergana Valley.

Studies of landslide processes in Central Asia commonly consider slope angle, soil type, previous mass movements, precipitation, reservoirs and earthquakes as key conditioning or triggering factors. A review of landslide studies for 2000-2020 analyzed 79 Scopus-indexed papers and showed that the role of GIS and remote sensing methods has increased considerably since 2013 [2]. This confirms that the integration of geodetic-geological monitoring with digital geotechnologies is a current scientific direction.

Aim and objectives of the study

The aim of the study is to develop a practical methodology for assessing land surface deformation in geologically hazardous areas based on geodetic monitoring and GIS technologies. To achieve this aim, the following objectives were defined: first, to systematize the geodetic and geological data sources used for detecting deformation; second, to generate hazard factors as GIS layers; third, to evaluate the relationship between deformation rate and geological factors; and fourth, to classify hazard zones and present the results as a map layout.

Table 1. Main data sources for geodetic-geological monitoring

Data type	Source	Indicator determined	Role in monitoring
GNSS observations	Static/RTK points	Horizontal displacement, mm/yr	Determination of deformation direction and rate
Leveling	Benchmark network	Elevation change, mm/yr	Control of subsidence or uplift
InSAR	Sentinel-1 SAR images	LOS deformation, mm/yr	Rapid screening of large territories
DEM and slope	UAV or SRTM/ASTER	Slope angle, aspect	Assessment of landslide susceptibility
Geological map	Lithology, faults	Rock type, distance to fault	Explanation of geological causes
Hydrogeology	Groundwater, drainage	Waterlogging and moisture zones	Assessment of slope-stability influence

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Methodology

The proposed methodology consists of three stages. At the first stage, field and remote data are collected: GNSS points, leveling benchmarks, geological maps, DEM layers, drainage networks, groundwater information and, when necessary, Sentinel-1 InSAR results. At the second stage, all data are brought into a unified coordinate system, GIS layers are normalized and each factor is scored from 1 to 5. At the third stage, the hazard index is calculated, compared with deformation rates and the territory is divided into low, medium, high and very high hazard classes.

Sentinel-1 radar data are used in InSAR analysis to monitor land deformation caused by subsidence, uplift, landslides, earthquakes and volcanic processes. According to the European Space Agency, the Sentinel-1 mission enables millimeter-scale monitoring of surface deformation through SAR interferometry [3]. Scientific literature also demonstrates that Sentinel-1 data are an effective layer for continuous and semi-automatic deformation monitoring over extensive areas [4].

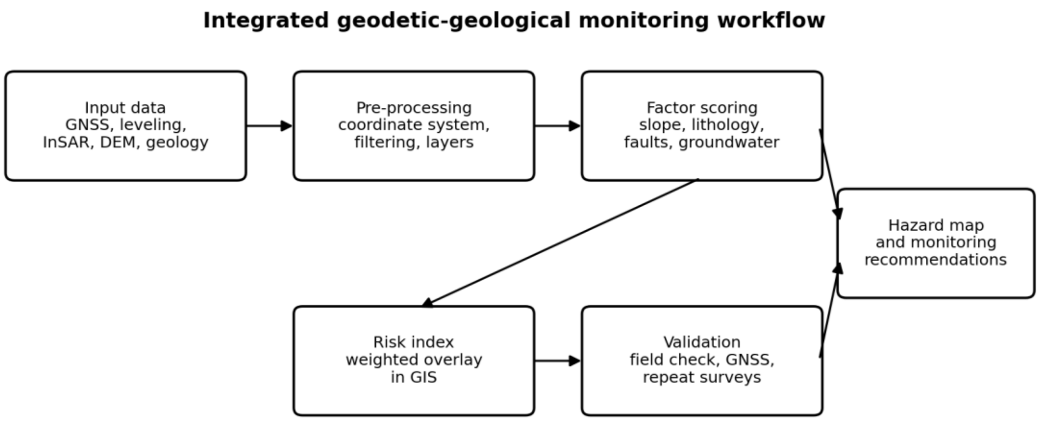

Figure 1. General workflow of geodetic-geological monitoring

The following generalized model may be used to calculate the hazard index:

$$R = 0.25S + 0.20L + 0.15F + 0.15D + 0.15W + 0.10A$$

Here R is the integral hazard index; S is slope angle; L is lithological stability; F is proximity to tectonic faults; D is proximity to drainage channels or ravines; W is groundwater and moisture influence; and A is anthropogenic load. The weights may be adjusted to local conditions;

however, slope and lithology were prioritized because they are among the most important stabilizing or destabilizing factors of geological hazard.

Table 2. Scoring criteria for hazard factors

Factor	1 point	2 points	3-4 points	5 points
Slope angle	<5°	5-10°	10-20°	>20°
Lithology	hard rock	semi-hard rock	loess-like / highly weathered	waterlogged clay, weak material
Distance to fault	>1000 m	500-1000 m	200-500 m	<200 m
Proximity to drainage	>500 m	300-500 m	100-300 m	<100 m
Groundwater	deep	medium depth	shallow	near-surface / waterlogged
Anthropogenic load	low	limited	medium	intensive construction, cut slopes, irrigation

Results and statistical analysis

To demonstrate the functioning of the methodology, a calculation was prepared for a 312 ha sample polygon corresponding to the foothill conditions of Fergana Region. These statistical data are presented as a methodological example; for a real article or engineering project, they should be replaced by field GNSS measurements, leveling logs and official geological archive materials. In the sample polygon, five observation zones were distinguished. For each zone, average slope, lithological conditions, linear deformation rate according to InSAR and the integral hazard class were calculated.

Table 3. Sample deformation and hazard indicators by observation zones

Zone	Area, ha	Slope, °	Lithological condition	GNSS/leveling, mm/yr	InSAR LOS, mm/yr	Hazard class
P-1	52	4-7	alluvial sandy loam	-1.8	-2.1	low
P-2	86	8-12	loess-like loam	-4.6	-5.2	medium
P-3	68	12-18	weathered clay-loam	-8.9	-9.6	high
P-4	42	18-24	waterlogged clay	-15.4	-16.1	very high
P-5	64	10-16	faulted loess-like layer	-7.2	-7.9	high

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According to the calculated results, 29.5% of the polygon was assigned to the low hazard class, 43.9% to the medium class, 18.9% to the high class and 7.7% to the very high class. The highest deformation was recorded in zone P-4, where the slope varies between 18 and 24°, the lithology is represented by waterlogged clay layers and the deformation rate is estimated at about 15-16 mm per year. This result indicates the presence of a causal relationship between geodetic measurements and geological factors.

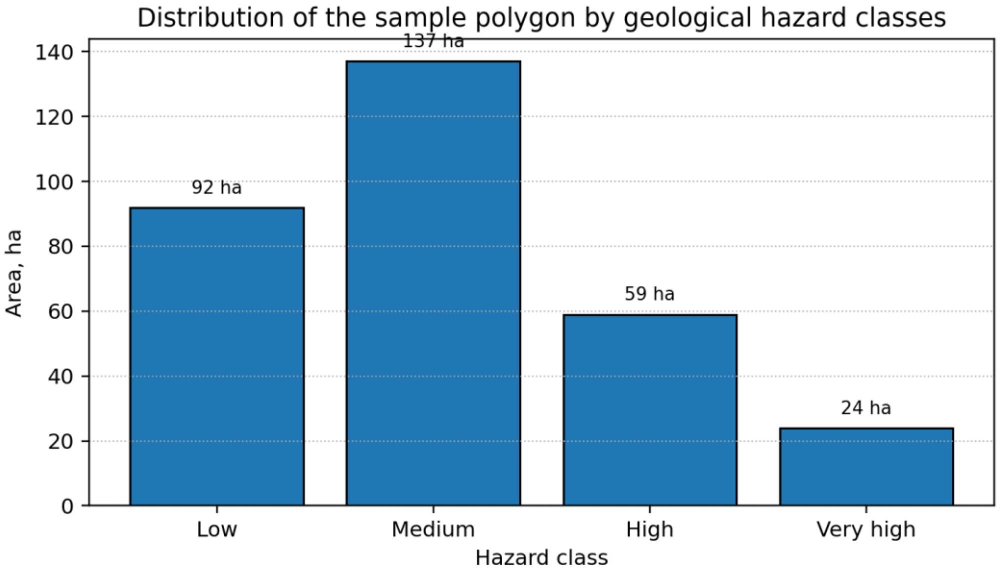

Figure 2. Area distribution by hazard classes

Table 4. Generalized area statistics by hazard classes

Hazard class	Area, ha	Share, %	Recommended measure
Low	92	29.5	Annual visual inspection and archive monitoring
Medium	137	43.9	Seasonal leveling and drainage control
High	59	18.9	GNSS points, geological section and slope stabilization
Very high	24	7.7	Continuous monitoring, construction restriction and engineering protection

When preparing the hazard map, each factor was entered into the GIS environment as a raster or vector layer. The slope map was derived from the DEM, distance to faults from the geological-structural map, proximity to drainage from the hydrographic layer, and deformation rate from GNSS/leveling and InSAR data. As a result, the hazard index was converted into a spatial layer and a map layout was prepared to support management decisions at the zone level.

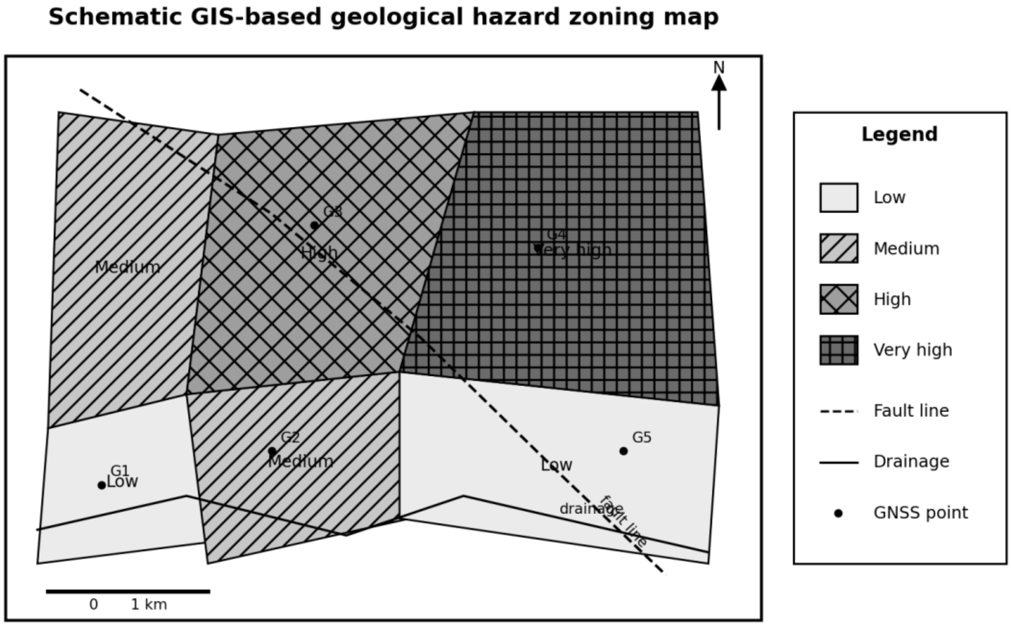

Figure 3. Schematic GIS-based geological hazard zoning map

Discussion

The advantage of geodetic monitoring is that it provides a quantitative expression of geological hazard: displacement can be measured in millimeters or centimeters, and subsidence rate can be expressed in mm/year. Geological analysis explains the causes of these displacements. For example, the same deformation rate may have different meanings in two different territories: in a flat area composed of strong rock, it may be associated with a technogenic factor, while on a slope composed of waterlogged clay it may indicate a pre-landslide condition. Therefore, neither geodetic measurement alone nor geological observation alone is sufficient. The scientific and practical conclusion becomes stronger when both are linked in a unified GIS system.

InSAR is important for preliminary screening of large areas. However, vegetation density, atmospheric effects, slope geometry and radar-signal decorrelation may limit accuracy in some locations [5]. Therefore, InSAR results must be calibrated with field GNSS points and leveling data. In the proposed approach, InSAR identifies potentially hazardous locations across a large territory, while GNSS and leveling provide refined monitoring at selected points. This saves resources and directs observations to the most hazardous zones.

In the conditions of the Fergana Valley, irrigation networks, foothill relief, loess-like deposits, faulted tectonic structures and dense settlement patterns make deformation monitoring especially important. On sites planned for construction, geodetic-geological analysis supports decisions such as selecting a foundation type, strengthening drainage systems, stabilizing slopes, restricting construction in hazardous zones and placing additional monitoring points. Thus, the proposed methodology may be viewed as a practical model for construction geodesy, engineering geology and territorial planning.

Recommendations for practical application

The use of geodetic-geological monitoring results requires a differentiated approach according to hazard class. In low-hazard areas, annual inspection may be sufficient. In medium-hazard areas, seasonal leveling and drainage inspection are advisable. In high and very high hazard zones, permanent GNSS points, repeated InSAR analysis, geological cross-sections, groundwater-level observations and engineering measures for slope stabilization should be carried out together. Monitoring points should not be placed only in convenient locations; they should be positioned near fault lines, waterlogged layers, cut slopes and important engineering structures.

The following sequence may be used in practical project documentation: first, geological archive materials and existing maps are collected; then slope and drainage layers are developed from DEM data; next, GNSS benchmarks are installed and measurements are conducted for at least two seasons. The results are entered into the GIS database, and the hazard-index map is updated quarterly or at the end of each season. Such an approach can be used in pre-construction investigations, safety assessment of operating facilities and prevention of emergency situations.

Table 5. Recommended monitoring plan by hazard class

Hazard class	Observation frequency	Main methods	Resulting document
Low	Once a year	Visual inspection, archive InSAR	Brief monitoring note
Medium	Every season	Leveling, drainage control, DEM comparison	Seasonal analytical table
High	Monthly or quarterly	GNSS, leveling, InSAR, geological section	Hazard cartogram and action plan
Very high	Continuous or weekly	Automatic GNSS, benchmarks, hydrogeological observation	Warning map and engineering-protection design

In practice, it is advisable to store monitoring results in a single geodatabase. If coordinates, elevations, measurement dates, deformation vectors, geological layer types and photographs are attached to each point, temporal changes can be monitored more reliably. In this way, geodetic and geological data are transformed from a simple report into a digital decision-support system.

Conclusion

- The integration of geodesy and geology makes it possible not only to detect land surface deformation in geologically hazardous areas, but also to explain its causes.
- GNSS, leveling and InSAR data are the main sources for quantitative assessment of deformation rate, while geological maps and DEM layers are essential for spatial interpretation of hazard factors.
- The proposed R hazard index enables the assessment of slope, lithology, distance to faults, drainage, groundwater and anthropogenic load within a single GIS layer.
- In the sample polygon, high and very high hazard zones accounted for 26.6% of the total area; such territories require permanent geodetic monitoring and engineering-geological mitigation measures.

- When supplemented with real field data, the methodology can be applied to foothill areas of the Fergana Valley, construction sites, road and railway corridors and irrigation structures for preparing hazard maps.

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Note: The statistical indicators in Tables 3 and 4 are illustrative calculations prepared to demonstrate the methodology. Before submission as a real scientific article, they should be replaced with exact values obtained from GNSS/leveling logs, official geological archive materials and field observations for the selected study area.