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INTEGRATING REMOTE SENSING AND GEOMORPHOLOGICAL ANALYSIS FOR LANDSLIDE HAZARD ASSESSMENT ADJACENT TO THE CHARVAK RESERVOIR

ABSTRACT

Landslide processes play a crucial role in geomorphological dynamics, significantly influencing the morphology of mountainous regions. Their impact is particularly evident in areas characterized by intense tectonic activity, such as the mountainous regions of Uzbekistan, where landslides dominate transformations of the Earth's surface. In inhabited mountainous zones, these phenomena cause significant damage and present severe risks to human life and property. Advances in remote sensing technologies and Geographic Information Systems (GIS) over the past two decades have greatly enhanced understanding of landslide processes. Building upon these developments, this paper presents a comprehensive framework for analyzing landslide dynamics at the slopes surrounding the Charvak Reservoir. The proposed methodology combines the relief plasticity technique with advanced remote sensing tools and GIS approaches. Drawing insights from prior studies and existing cartographic resources focused on lithodynamic flow analyses, it provides a robust foundation for identifying and predicting potentially hazardous landslide-prone areas. Additionally, the study explores key methodological aspects concerning territorial zonation based on varying levels of landslide risk. At its core lies an investigation of morphometric characteristics extracted from Digital Elevation Models (DEM/SRTM), complemented by the application of the second derivative method to topographic maps. From a practical standpoint, the results underscore the effectiveness of modern GIS applications and remote sensing data sets — including aerial and satellite images from Landsat — for accurate landslide mapping and assessment of their activity. As part of the research efforts, a detailed map of landform plasticity for the study region was created and converted into a digital format through geographic information systems (GIS). Furthermore, the analysis of lithodynamic flows within recognized landslide areas enabled reliable determination and delineation of morphological boundaries associated with distinct landslide flows.

KEYWORDS: landslide processes, remote sensing, geoinformation systems, digital relief model, Charvak Reservoir, landslide mapping

INTRODUCTION

Over the last two decades, the global scientific community has witnessed notable advancements in applying modern technologies for processing multispectral satellite imagery, enabling more efficient mapping of diverse exogenous geological processes, with particular focus on landslides [*Emelyanova*, 1972; *Crosta*, *Agliardi*, 2003; *Ghimire*, *Timalsina*, 2020]. Initiated by intricate interplay of geological, climatic, and anthropogenic elements, landslide phenomena present a severe challenge to infrastructure integrity and public safety, notably in vulnerable mountainous and hilly terrains [*Varnes*, 1978; *Niyazov*, *Minchenko*, 2003].

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A wealth of scholarly investigations documented worldwide underscore multifaceted approaches to studying landslide mechanisms, encompassing:

- mathematical simulations allowing quantitative depiction and prognosis of landslide mass movements;
- morphometric scrutiny of contour lines within topographic maps to reveal tell-tale signs of slope instability;
- robust utilization of GIS platforms facilitating integration and spatially-informed analysis of multiple variables driving landslide susceptibility [*Mandal*, *Mondal*, 2019; *Bekanov* et al., 2020; *Intrieri* et al., 2020; *Solari* et al., 2020].

These collective endeavors clearly illustrate how multidisciplinary collaboration yields marked improvements in predictive precision and surveillance efficiency concerning landslide activities, thereby playing a pivotal role in minimizing associated dangers while enhancing livability standards in affected regions [*Mandal*, *Mondal*, 2019; *Bekanov* et al., 2020; *Intrieri* et al., 2020; *Sharipov* et al., 2020a; *Solari* et al., 2020].

Unlike prior studies, the objective of this work is to integrate cartographic modeling techniques and detailed relief analysis utilizing the relief plasticity method, high-resolution digital elevation models (DEMs), remote sensing data, and GIS technologies for an in-depth exploration of landslide processes. The proposed integrated approach offers a qualitatively novel perspective on comprehending the conditions governing landslide initiation and evolution via the synergetic employment of diverse spatial data sources and analytical methods [*Elmasri*, *Navathe*, 2017; *Psomiadis* et al., 2020].

For this study, we selected the coastal slopes of the Charvak Reservoir — a man-made body created by damming the Chirchik River — as the primary subject of investigation. Geographically situated within the Burchmulla Basin, at the convergence point of the Chatkal and Pskem Rivers, hydrologically, this reservoir is categorized as a complex valley-type storage facility functioning under seasonal regulation of the Chirchik River flow. Its core function involves redistributing water discharge to meet integrated water usage requirements throughout the river basin, specifically augmenting irrigation supplies for agricultural lands spanning 164 000 ha in the Tashkent Region, addressing hydropower demands, and balancing peak electricity consumption across the network distributed along the riverbed and the Bozsu Canal. Runoff accumulation within the Charvak Reservoir drainage area covers approximately 10 000 km², primarily fed by three major tributaries — the Chatkal, Pskem, and Koksu rivers — which exhibit typical snow-glacier-fed regimes.

Our study area exhibits pronounced geological complexity attributable to its unique geodynamic location at the interface of extensive tectonic structures. Surrounded by the Karzhantau, Chatkal, and Kuramin mountain ranges, which display a gradual decline in altitude towards the southwest, this region reflects substantial tectonic disturbances manifested historically during different geological periods. As highlighted by Yarmukhamedov [1979], the defining characteristic of the local geology lies in the prevalence of thrust faulting and synclinal depressions. These structural anomalies signify vigorous tectonic shifts occurring across varied epochs, exerting profound effects on regional geological architecture. Consequently, the existence of these tectonic components assumes critical importance in elucidating landform generation patterns and assessing potential triggers for exogenous geological occurrences like landslides.

RESEARCH MATERIALS AND METHODS

The voluminous literature dedicated to the study of landslide processes both in Uzbekistan and the specific study area encompasses contributions from renowned scholars, including E. P. Emelyanova [1972], R. A. Niyazov [1999], R. A. Niyazov and B. S. Nurtaev [2004], among others. These studies span a broad spectrum of topics, encompassing stratigraphic, lithologic, engineering-geological, and seismic attributes of rocks forming the foundation for landslide slope genesis, alongside classifications of various landslide types, their dynamics, and mechanisms of rock mass movement.

E. P. Emelyanova's works [1972] serve as foundational references in landslide research, providing detailed insights into the geological conditions favoring landslide development. His research addresses both localized phenomena and larger-scale geological frameworks influencing slope stability, emphasizing the roles of stratigraphy and lithology in landslide formation. Additionally, Emelyanov introduced a systematic classification of landslides based on scale, triggering mechanisms, and environmental context.

R. A. Niyazov's contributions [1999] have significantly enriched landslide theory by focusing on engineering and geological parameters affecting landslide dynamics in Central Asian mountainous regions. His studies introduce predictive methodologies for estimating landslide activity grounded in geodynamic analysis, assess slope stability under varying rock mechanical properties, and propose strategies for evaluating landslide-related risks. Furthermore, Niyazov provided guidelines for optimized construction practices in hazard-prone zones.

Collaborative efforts by R. A. Niyazov and B. S. Nurtaev [2004] deepened comprehension of causal agents and contributing factors underlying rock mass displacements, advancing methods for seismic evaluation of slope stability. Their investigations scrutinized both natural and anthropogenic drivers responsible for landslide activation, enabling the formulation of more reliable recommendations for slope stabilization and mitigation of adverse impacts.

Collectively, these researches construct a cohesive picture of landslide dynamics in Uzbekistan, underscoring the necessity of adopting an integrated approach to their study. Beyond mere classification, they investigate the evolution of landslides contingent upon alterations in geological, climatic, and anthropogenic contexts. Moreover, these studies substantiate practical measures designed to reduce landslide-associated risks, a vital consideration in regions characterized by elevated seismic activity and intricate geological configurations. At the slopes of the Charvak Reservoir, landslide processes unfold amidst interplay with diverse natural and anthropogenic determinants, each exerting a profound influence on landslide activity and dynamics. Among the natural factors promoting landslide emergence are climatic conditions, topography, geological composition of slopes, hydrogeological attributes of the locale, and tectonic movements that set the stage for geological transformations [*Niyazov*, *Minchenko*, 2003].

Climatic conditions, particularly seasonal variations in temperature and precipitation, significantly influence soil moisture content and texture, thus exacerbating landslide risks [*Sharipov*, *Khayitmurodov*, 2024]. Alternating cycles of freezing and thawing, accompanied by heavy rainfall or snowmelt, accelerate erosion and degradation of slopes, diminishing their overall stability. Specifically, during rainy seasons and spring meltwater influx, mountainous regions experience increased gravitational loading due to water infiltration, amplifying the propensity for slope failure. Moisture-saturated soils lose cohesion between constituent particles, severely compromising their inherent strength. Upon saturation, unconsolidated and poorly cemented rocks undergo changes in rheological properties, decreasing shear resistance and becoming increasingly plastic, eventually reaching a semi-liquid state. Alterations in soil mechanics represent one of the principal catalysts activating landslide sequences.

Terrain configuration, notably steep inclines and elevations, constitutes another predominant determinant of landslide incidence and character. Steep gradients drastically heighten landslide probability owing to distinct hydrological and mechanical behaviors exhibited by soils. Accumulation of excess water increases soil mass and decreases rock strength, eroding particle adhesion and precipitating ground slippage. Findings from studies conducted on the Charvak

Reservoir shores corroborate this trend. According to [*Sabitova* et al., 2020], landslides predominantly occur on the reservoir's steeper coastal embankments, attributed to exposure to precipitation and fluctuating water levels that undermine soil stability. Research indicates that steep inclinations correlate directly with higher landslide frequencies and intensities, necessitating specialized precautions for monitoring and prevention.

Geological structure, inclusive of stratigraphic and lithological compositions, strongly influences landslide formation. Presence of soft or readily mobilizable rocks — such as clays, sandstones, or friable limestones — increases landslide susceptibility, particularly when overlain by disruptive features like tectonic faults or folds. Deformation-induced weaknesses compromise slope integrity, predisposing them to collapse. The geological profile of the Charvak Reservoir watershed critically shapes coastal slope stability. Areas with clay-rich sedimentary beds, structurally compromised zones, and fragmented formations exhibit the greatest frequency of landslides. Additionally, depositional environments, including alluvium, colluvium, and debris fields, frequently prove unstable and liable to disruption from external stimuli like precipitation or seismic tremors. Orientation of strata toward slopes or alignment with intersecting fracture planes further degrades slope resilience, magnifying landslide risks. Collectively, these observations underline the imperative need for thorough geological and hydrogeological evaluations to effectively mitigate landslide hazards.

In several regions, particularly those dominated by clayey soils in the upper layers of the geological section, flow-type landslides prevail as the dominant form of slope deformation. Research by R. A. Niyazov demonstrates that in areas with significant loess thickness, over 70 % of recorded landslides fall into the category of flow-type landslides, including mudflows, slumps, and solifluction. This highlights the critical role of clay deposits in the formation and activation of slope processes during extreme precipitation events.

Abnormal and intense precipitation typically trigger mass activation of slope failures in regions characterized by widespread clay deposits. At the Charvak Reservoir, active tectonic movements combined with loess distribution significantly influence landslide development. According to S. K. Khakimova [1992], nearly 99.8 % of landslide processes in the study area concentrate on deluvial and proluvial loess-loamy soils, reinforcing the link between these deposits and landslide activity.

Hydrogeological conditions, particularly groundwater levels and their fluctuations, profoundly affect the stability of the Charvak Reservoir slopes. Rising groundwater levels, especially during floods or following heavy rainfalls, induce substantial soil moisture retention. This excessive wetness reduces soil strength by lowering particle adhesion, thereby increasing the risk of landslides. Wetting of soils lowers the friction coefficient between particles, destabilizing slopes and facilitating landslide occurrences [*Zakirov* et al., 2022].

Periods of abrupt groundwater-level fluctuations are particularly hazardous because alternating soil saturation and desiccation may render soils more mobile, accelerating their degradation and activating landslide processes. This phenomenon is especially relevant for slopes adjacent to water bodies like the Charvak Reservoir, where water-level variations directly influence local hydrogeological conditions.

Tectonic movements and deformations of the Earth's crust within the Charvak Reservoir area play a pivotal role in regional geological activity, particularly in the interaction zones of large tectonic units. These processes generate new tectonic faults and enhance existing geological distortions, ultimately causing deterioration in slope stability. Stress and deformation induced by tectonics can initiate rock dislocations and fracturing, especially in pre-existing weak zones such as cracks, folds, or faults. These instabilities diminish slope strength and raise the likelihood of landslide activation. Thus, in conjunction with other natural and anthropogenic factors, tectonic and hydrological stresses exacerbate landslide formation, particularly in areas experiencing high tectonic activity and intense hydrological impacts.

Human activity represents an equally important factor influencing the development of landslide processes, either accelerating or altering natural geological dynamics. Construction projects such as road building, dam installations, housing developments, mining operations, and deforestation result in significant modifications to the regional water balance, impair natural drainage pathways, and degrade vegetative root networks. These alterations subsequently contribute to slope degradation, reduce their stability, and create favorable conditions for landslide activation [*Niyazov*, *Minchenko*, 2003].

Moreover, the Charvak Reservoir boasts a shoreline stretching approximately 100 km, much of which hosts recreational zones, guesthouses, and children's camps [*Sharipov* et al., 2020b]. Considering the anthropogenic pressure exerted on this area, compounded by its intensive recreational use, human-driven developmental activities and landscape modifications tend to exacerbate slope weakening and landslide incidences.

Since the establishment of the Charvak Reservoir in 1978, landslide processes along its banks have noticeably intensified. Persistent changes in the reservoir's hydrological regime, including fluctuations in water levels and their impact on the coastal zone, coupled with rising anthropogenic pressures, have disturbed natural drainage mechanisms and slope-stabilizing processes. Observations and studies validate this observation, highlighting an escalation in landslide frequency and severity in locations subjected to robust human intervention and areas exhibiting naturally fragile geological settings.

Mapping landslides on the coastal slopes of the Charvak Reservoir employed an integrated approach incorporating plasticity methods, high-resolution digital elevation models (DEMs), remote sensing, and geographic information systems (GIS). Remote sensing enabled efficient, high-quality detection and demarcation of landslides, considerably improving their localization accuracy and characterization. High-quality imagery and cartographic outputs served as cornerstones for subsequent research and analysis.

Additionally, remote sensing facilitated acquisition of quantitative metrics essential for comparing the intensity of landslide processes across different sections of the coastal slopes. This allowed for the estimation of landslide scales, distributions, and identification of patterns and trends in their dynamic progression based on geospatial data. Utilizing GIS technologies, detailed cartographic representations illustrating current and historical changes in the study areas were generated.

Fig. 1 depicts a landslide localization map derived from remote sensing data, offering a visual overview of their spatial distribution and highlighting the most vulnerable areas along the Charvak Reservoir slopes. These data serve as valuable instruments for ongoing monitoring, forecasting, and designing effective measures to prevent landslides in this region.

Special attention was given to the structural approach in modeling and analyzing relief, serving as a critical tool for understanding and predicting geological processes. Scientists such as A. V. Pozdnyakov, Z. B. Roykhvarger [1982], and Yu. G. Simonov [1976] highlight the central role of relief plasticity, morphography, and morphometry in controlling and maintaining relief forms. These elements allow us to discern the primary patterns of relief formation and transformation influenced by both natural and anthropogenic factors.

V. A. Nikolaev [1982] proposed establishing a new discipline called "analytical geomorphology" aiming to thoroughly explore relief plasticity. He argued for an analytical approach that incorporates both qualitative and quantitative traits, facilitating a more nuanced understanding of geological structure formation and its impact on slope stability, including landslide occurrences.

Fig. 1. Slopes of the Charvak Reservoir (photo by [Zakirov et al., 2022])

In his research, I. G. Chervanev [1982] stressed the necessity of conducting a structural analysis of relief, centered on identifying and examining structural lines known as the "relief skeleton". Elements such as thalwegs (valley bottoms) and watershed divides are critical in determining the primary geomorphological structures of any given territory. Structural lines constitute the backbone of an abstract invariant representation of relief — a stable structure maintained across different geological epochs and various natural processes.

Employing the structural-morphometric method for detecting tectonic structures represents a significant step in geomorphological analysis. Not only does this method enable the study of tectonic movements but also identifies their influence on relief formation, including landslides and other slope deformations. The collection of structural lines constituting the "relief skeleton" becomes the foundation for anticipating changes and evaluating slope stability under natural and anthropogenic influences.

V. P. Filosofov [1975] outlined a methodology for constructing and interpreting morphometric maps, relying heavily on detailed analysis of topographic maps. This method entails graphically breaking down the relief depicted on topographic maps into constituent parts, making it easier to recognize key relief elements and construct specialized maps depicting tectonic structures. This approach enhances comprehension of geomorphological processes and enables the identification of tectonic faults that contribute to landslide development.

The relief plasticity map, as noted in the works of Stepanov [2002] and Sabitova et al. [2020], serves as the primary instrument for evaluating landslide phenomena throughout every phase of the research process. From initial fieldwork to final thematic mapping (e. g., geomorphological, Quaternary deposit, and landscape maps), this map remains a critical component. Through its use, researchers achieve a more precise assessment of exogenous processes, such as landslides, and their correlation with natural and anthropogenic factors. Furthermore, the relief plasticity map proves indispensable for forecasting physical-geographical processes, enabling risk assessments and predictions of potential changes in specific areas. It provides a comprehensive visualization of relief and its transformations, which is essential for implementing measures to stabilize slopes and prevent landslides. For the Charvak reservoir case study, this map acts not just as an analytical tool but also as a foundation for developing comprehensive strategies to manage natural risks in the region.

The methodology for depicting relief plasticity is based on identifying key landforms, such as depressions and elevations, which are outlined using isolines of zero curvature on topographic maps. Analyzing combinations of these elevations and depressions leads to the formation of basins of different orders. A critical feature of this approach is recognizing visual inflection points along contour lines, which are linked by an isoline called a “morphoisograph”. This isoline, drawn through points of zero planar curvature, separates convex relief features from concave ones, providing a more precise and detailed representation of the terrain.

The morphoisograph divides the Earth’s surface into two distinct planes — foreground and background — which enables a deeper analysis of the relief structure. By utilizing a single isoline (the morphoisograph), the division of the landscape into convex and concave forms becomes possible. This technique contrasts sharply with conventional maps, which tend to be one-dimensional and do not adequately capture the complexity of relief variations. Two-plane models and three-dimensional representations make maps visually richer and more informative than classic relief maps [*Stepanova*, *Pikulenko*, 2014].

During specific phases of research focused on studying and mapping landslides within the coastal slopes of the Charvak Reservoir, geographic information technologies played a pivotal role. These technologies offer diverse methods for processing spatial data essential for addressing challenges related to landslide monitoring and prediction processes [*Konoplev* et al., 2014; *Osipov* et al., 2016]. Geospatial technologies deliver dependable and up-to-date data regarding study areas, serving as indispensable tools for gathering and organizing engineering-geological information.

In conducting a thorough evaluation of landslide hazards, the ArcGIS platform was employed, allowing for the integration of four dynamic variables: precipitation amounts, groundwater levels, vegetation coverage, and human impacts [*Ou* et al., 2016]. Such methodological approaches significantly enhance early warning systems for geological disasters and contribute to more effective risk management strategies regarding landslides.

Addressing challenges in physical geography and assessing exogenous processes through Geographic Information Systems (GIS) requires a comprehensive strategy incorporating various spatial analytical tools. These conclusions are supported by earlier studies on similar topics [*Fazilova*, *Arabov*, 2023; *Pirimov* et al., 2023; *Mirmakhmudov* et al., 2024], which highlight the necessity of integrated methods for robust hazard assessment.

A typical procedure during remote sensing and geospatial analyses includes utilizing specific combinations of spectral bands to generate false-color imagery. In this context, near-infrared (NIR) data is displayed as red, enhancing distinctions among diverse materials and vegetation types due to their distinct reflective characteristics in the infrared spectrum.

This particular band configuration provides richly informative outputs where geological formations, landscapes, and regions characterized by varying degrees of vegetation density, altered soil texture, or evidence of land-surface deformations appear across a broad color spectrum —

from deep blues to reddish-browns. Consequently, it becomes easier to visually identify areas susceptible to landslide activities, detect changes in vegetation health, monitor excessive moisture accumulation, or pinpoint accumulations of unstable rocks.

RESEARCH RESULTS AND DISCUSSION

The use of a Digital Elevation Model (DEM) is a key tool in assessing landslide activity and creating landslide hazard maps. A DEM provides a detailed analysis of the morphometric characteristics of the study area, enabling correlations to be established between various relief parameters and factors contributing to landslide initiation. Among the primary physical and geographical parameters considered in DEM-based analyses are slope steepness and length, as well as characteristics of the hydrographic network, particularly surface runoff density. These parameters exert considerable influence on slope stability and thus affect the probability of landslides. They serve as important indicators of vulnerability to landslide processes [*Cruden*, *Varnes*, 1996].

An equally vital factor is vegetation cover, which influences slope stability in dual ways. While vegetation may strengthen slopes through its root system, it can also cause instability when degraded or cut down. Multispectral space images like those provided by Landsat satellites, incorporating both standard RGB bands and a near-infrared band, are commonly used for comprehensive vegetation analysis and its impact on slope stability. Such datasets enable efficient assessments of vegetation density and type, which are crucial for understanding landslide risks.

One major indicator used for vegetation analysis is the Normalized Difference Vegetation Index (NDVI). Analysis of space imagery data using NDVI yields maps illustrating the condition of vegetation cover and its effects on soil moisture retention and slope mechanical strength. As a quantitative measure of biomass, NDVI directly correlates with soil water holding capacity and the stabilizing influence of vegetation on slope formations. Consequently, NDVI aids in more precisely estimating landslide susceptibility and designing preventive measures against exogenous geological processes [*Van Westen* et al., 2008].

Remote sensing data, encompassing aerial photography and satellite imagery, prove highly useful for detecting and mapping landslide movements. These data facilitate monitoring and analysis of landslide body dynamics and associated phenomena (Fig. 2).

Integration of remote sensing data, comprising aerial photography and satellite imagery, provides significant advantages for detecting, mapping, and analyzing landslide movements. These data sources enable comprehensive monitoring and evaluation of landslide dynamics and related phenomena. Peer-reviewed literature highlights the successful implementation of space-based imaging techniques for studying landslide processes [*Massonnet*, *Feigl*, 1998; *Fernandez* et al., 2008], underscoring how contemporary remote sensing technologies enhance the precision and efficiency of landslide mapping, monitoring, and prediction, thus supporting proactive measures to mitigate geological catastrophes.

For constructing the DEM in this study, we utilized SRTM1 radar imagery with a spatial resolution of 30 meters (one arc-second) (Fig. 3). Radar images provide information about geographical coordinates (x,y) and elevation values (z). With active radar systems, the terrain serves as the principal measurement target. Owing to their side-looking geometry, radar images highlight terrain details through elongated shadows, resembling aerial photos captured under conditions of low solar illumination. Final processing of identified landslide regions was completed using ArcGIS software equipped with the Spatial Analyst extension.

Statistical conversion tools such as “Raster to Polygon” were employed to transform raster data into vector polygon formats, whereas simplification tools (“Simplify Polygon”, “Aggregate Polygons”) reduced unnecessary detail, resulting in generalized outlines of the analyzed areas.

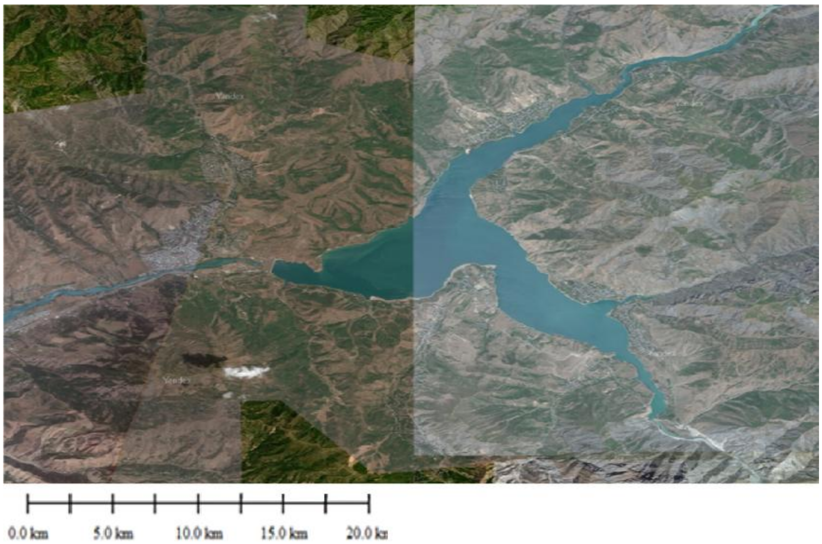

Fig. 2. Map of the Charvak Reservoir based on satellite images

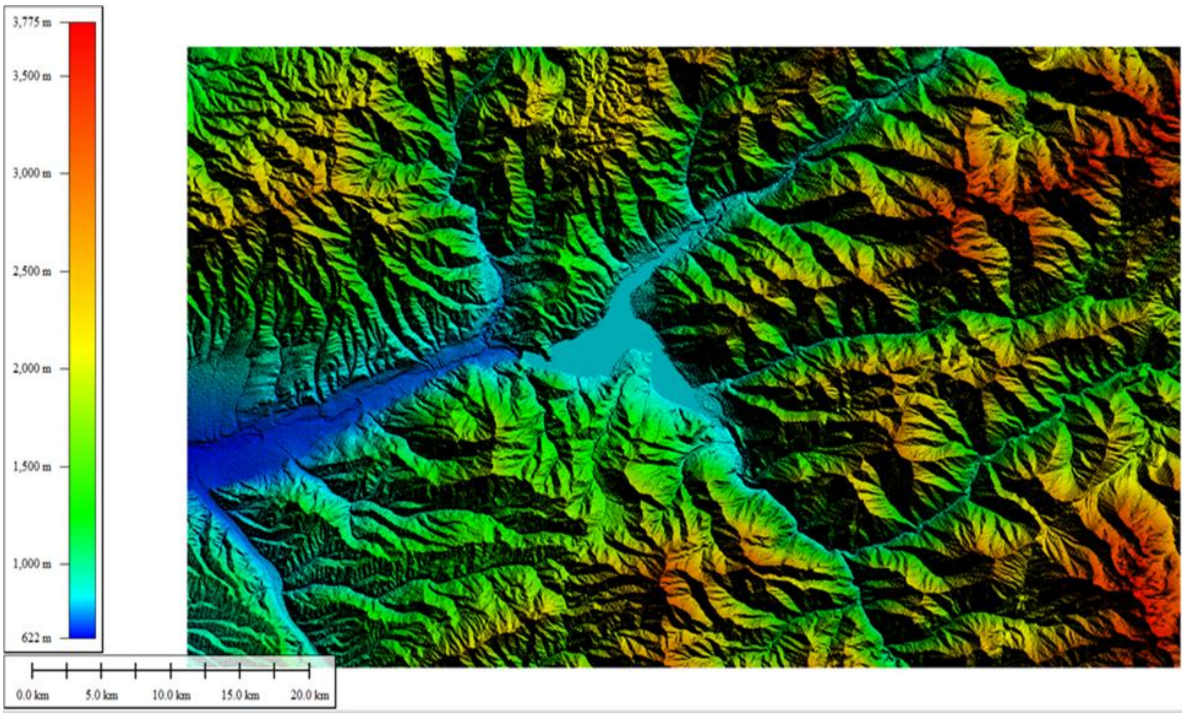

Fig. 3. DEM based on radar image

Morphography and morphometry constitute core elements in mathematically describing relief and morphogenetic processes. Relief morphology and morphometry are instrumental in qualitatively and quantitatively characterizing landform patterns derived from topographic map contours. Since the external appearance of relief reflects its origin and age, relief analysis is extensively utilized in interpreting satellite/aerial imagery and examining topographic maps. In our investigation of landslide occurrences, the relief plasticity method was adopted [*Stepanov*, 2006; *Sabitova* et al., 2022].

Initially, during the desk-bound phase of relief analysis, topographic map contour lines underwent transformation using the second derivative method.

This procedure identifies locations exhibiting pronounced curvature changes in contour lines, corresponding to areas with abrupt elevation shifts and potentially prone to landslide activations. Visualization of the transformation outcomes produces a relief plasticity map, facilitating recognition of morphologically diverse regions.

The topographic modeling of the water surface in the Charvak Reservoir Basin was undertaken to ensure proper consideration of the influence of the water factor on the stability of adjoining slopes. Fluctuations in the reservoir's water level can significantly alter hydrogeological conditions, leading to the activation of landslide processes in the coastal region. Based on the generated relief plasticity map, the spatial distribution of morphological elements (convex and concave forms) was visualized, enabling the identification of potential lithodynamic flow boundaries (Fig. 4).

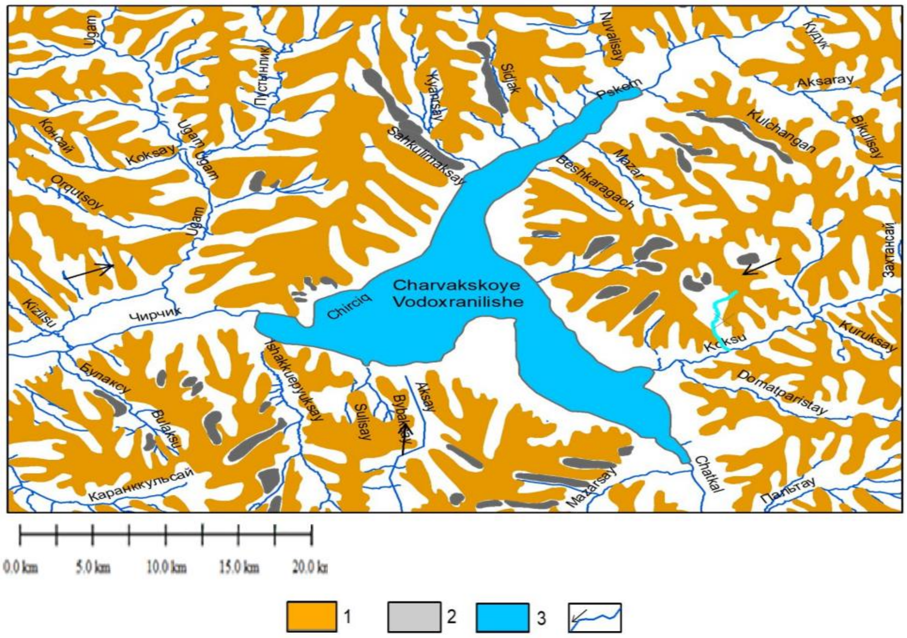

Fig. 4. Map of the relief plasticity of the studied area of the Charvak Reservoir.
1 — convexities (lithodynamic flows); 2 — landslides; 3 — reservoir; 4 — sais

On the relief plasticity map, convex and concave relief forms are clearly demarcated. Typically, convex forms correspond to ridges, slope edges, and other elements characterized by decreasing steepness and positive horizontal curvature of contours. These features might appear in distinctive colors or contrasting shades relative to concave forms. Within the context of landslide activity, the analysis of convex forms helps pinpoint potential landslide-prone zones, particularly where they about steep and unstable slopes. Concave relief forms consist of hollows, ravines, gullies, and tectonic/erosion-induced depressions, frequently representing either existing landslide beds or zones accumulating landslide debris.

Concave forms are characterized by increased steepness downslope and negative horizontal curvature of the contours. On the relief plasticity map, they would be highlighted in a different color or tone. As noted in the text, these concave forms serve as collectors of groundwater and atmospheric moisture, playing a crucial role in soil saturation and reducing stability, hence increasing the risk of landslide reactivation or new landslide development.

Boundaries separating convex and concave forms usually manifest as prominent linear elements on the relief plasticity map, reflecting zones of maximal curvature change. These boundary lines may signify active tectonic faults, erosional scarps, or landslide frontiers, all being indicative of potential slope instabilities.

The morphological criteria ensuring the validity of defined flow structure boundaries included extreme elevation markers, slope inclinations, surface configurations, and hypothesized directions of motion. Preservation of contour lines on the relief plasticity map and determination of material movement trajectories due to erosion-accumulation and gravity-driven processes permitted calculation of the morphometric parameters of landslide bodies, specifically their shapes and thicknesses.

Landslide detachment depths, calculated perpendicularly from the slope surface to the sliding plane within the identified concavities of lithodynamic flows, characterize the thickness of landslide masses. This approach enables not only the analysis of current relief states but also predictions of future morphological transformations, which is essential for assessing risks tied to landslides and other exogenous geological processes. All detected landslide bodies were delineated, and their boundaries, adjusted according to scale, were incorporated onto the relief plasticity map.

Analysis reveals that local depressions in the relief, acting as landslide cradles, function as repositories for groundwater and atmospheric moisture, potentially exacerbating landslide processes.

On the relief plasticity map of the Charvak Reservoir, lithodynamic flows (depicted in dark brown) are identified, indicating potential soil displacement (Fig. 4). Watersheds are shown in blue. These flows may serve as one criterion for landslide initiation, with potential landslide processes represented in dark gray on the map. Landslide areas are delineated within lithodynamic flow boundaries and may be considered predictive.

Considering the geological structure of the area, landslides are primarily composed of loams mixed with clastic material and are predominantly distributed on deluvial slopes. Based on formation conditions, manifestation characteristics, scale, and other features, the following types of landslides can be distinguished in the study area:

1. Flow-type landslides — large-scale displacements of earth masses resulting from saturation of cover loams by groundwater from below and atmospheric precipitation from above. Water-saturated rocks move downslope as a paste-like mass. These landslides are notable for their greater depth of involvement (typically 15–20 m) and larger dimensions (up to 250 m in width and 1 500 m in length). The slip surface usually occurs along the boundary between loose cover deposits and underlying bedrock red beds. The head sections have a semicircular shape, with scarp heights ranging from 2.0 to 15.0 m and slopes of 60–90°. Seepage outlets, such as springs and wetlands, are observed at the base of the scarps.
2. Slump-type landslides — rapid sliding or free fall of earth masses triggered by slope undercutting, surface water flow, or excavation activities. These occur during wet periods due to saturation by precipitation and occasionally groundwater. The depth of displacement is 5–10 m, with widths varying from 20 to 60 m and lengths along the slope of 15–50 m. Scarp slopes exhibit inclinations of 52–66°. The displaced material consists of deluvial loess-like loams with uneven inclusions of bedrock fragments.

The development and manifestation of landslide processes in the study area are facilitated by favorable combinations of natural factors — topographic, geological, hydrogeological, climatic, and others.

The coordinate systems and sheet nomenclatures used in cartography and topography form the foundational basis for geospatial referencing of all kinds of data integrated into Geographic Information Systems (GIS) [*Jensen*, 2015; *Fazilova*, *Arabov*, 2023]. Standardized coordinate systems guarantee precise location of objects, which is particularly important when performing multi-scale analyses, comparing disparate spatial datasets, and generating thematic maps, including landslide hazard maps.

Signs of landslide activity detected by remote sensing data include characteristic morphological features of relief and changes in the earth's surface. Such signs involve the presence of fault zones and cracks, elongated forms of slopes, deformation of vegetation and soil cover, anomalies in soil humidity, and changes in local albedo. Overlaying relief plasticity data with satellite monitoring results significantly increases the informative value of research. Important indicators include displacement of infrastructure objects, change in surface geometry, and formation of specific erosion structures.

To reliably determine landslide processes, various methods of satellite image processing are used, such as spectral analysis, digital elevation model processing, and synthesis of spatial data. The most effective tools are synthetic-aperture radar systems (InSAR), which provide precise measurements of ground displacements, as well as high-resolution multispectral images capable of detecting even minor landscape changes. An integrated approach combining remote sensing data and relief plasticity allows for a considerable increase in the accuracy of identifying landslide-hazardous territories and efficiently monitoring the dynamics of dangerous geological phenomena.

In this study, data from the Shuttle Radar Topography Mission (SRTM) digital elevation model was processed to produce gradient relief maps. The primary objective of this step was to compute slope gradients and orientations, which are crucial when evaluating the stability of slope surfaces. The processing relied on specialized digital image processing algorithms available in modern GIS platforms such as ArcGIS and QGIS.

The resultant derivative products, specifically the slope and aspect maps, were subsequently imported into the Geographic Information System (GIS) environment. Within this platform, a comprehensive visualization process was executed, utilizing a gradient color scale to represent the morphometric parameters. This approach allowed for a detailed depiction of the spatial distribution of these parameters, with particular emphasis on the alignment of slopes relative to compass directions, as illustrated in Fig. 5. This visualization technique is crucial for understanding the complex interplay between various environmental factors and their impact on landslide development. By highlighting the orientation of slopes, it becomes possible to analyze the influence of solar radiation, which can affect soil moisture levels and vegetation growth. Additionally, the visualization aids in assessing the accumulation of moisture, which is a key factor in landslide initiation and propagation. Furthermore, the method provides insights into other exogenous processes that may contribute to landslide dynamics, such as wind patterns and geological structures.

The image depicted in Fig. 6 prominently highlights areas affected by landslide processes, identifiable by their characteristic spectral signatures. These zones typically exhibit brownish-red tones, signaling poorly consolidated surfaces, diminished biomass, or ongoing slope erosion. Given the heightened sensitivity of the infrared range to vegetation health and soil moisture, this method proves invaluable for surveillance and spatial assessment of landslide activity within an integrated geoinformation framework.

Two primary algorithmic approaches are implemented in Geographic Information Systems (GIS) to determine slope aspect: the planar and geodetic methods [*Burrough*, *McDonnell*, 1998]. The decision to choose between them depends on the goals of the study, the characteristics of the analyzed area, and the desired accuracy of computations. The method-selection parameter is generally set by users through the functional settings of respective GIS software.

The planar method utilizes trigonometric calculations within a two-dimensional projection of the terrain using a Cartesian coordinate system (2D). Within this framework, the aspect — the orientation of the slope — is defined as the angle between the direction of maximum gradient decline and the north-south axis in the horizontal plane. Notably, the widely adopted Horn model

[*Horn*, 1981] computes relief derivatives by averaging adjacent elevation points. Its strengths lie in computational simplicity and applicability for small-scale analyses where the curvature of the Earth's surface exerts minimal impact on results.

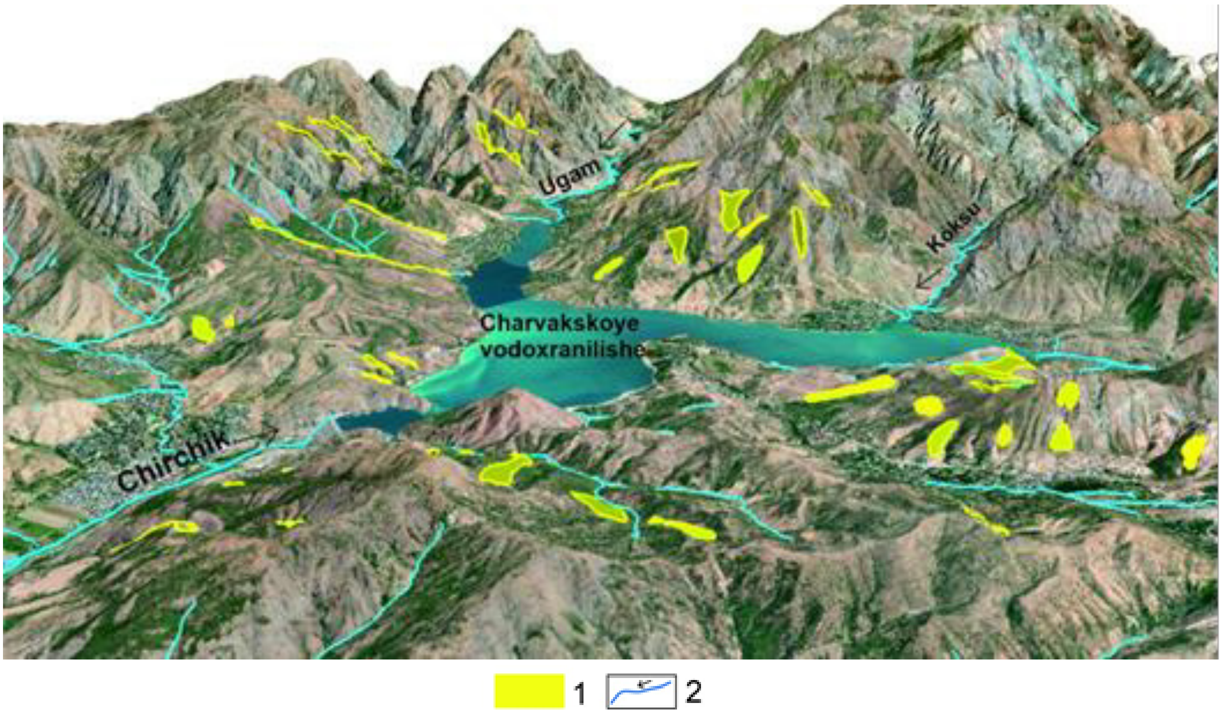

Fig. 5. Standard channel combination (Color Composition). 1 — landslides; 2 — river network

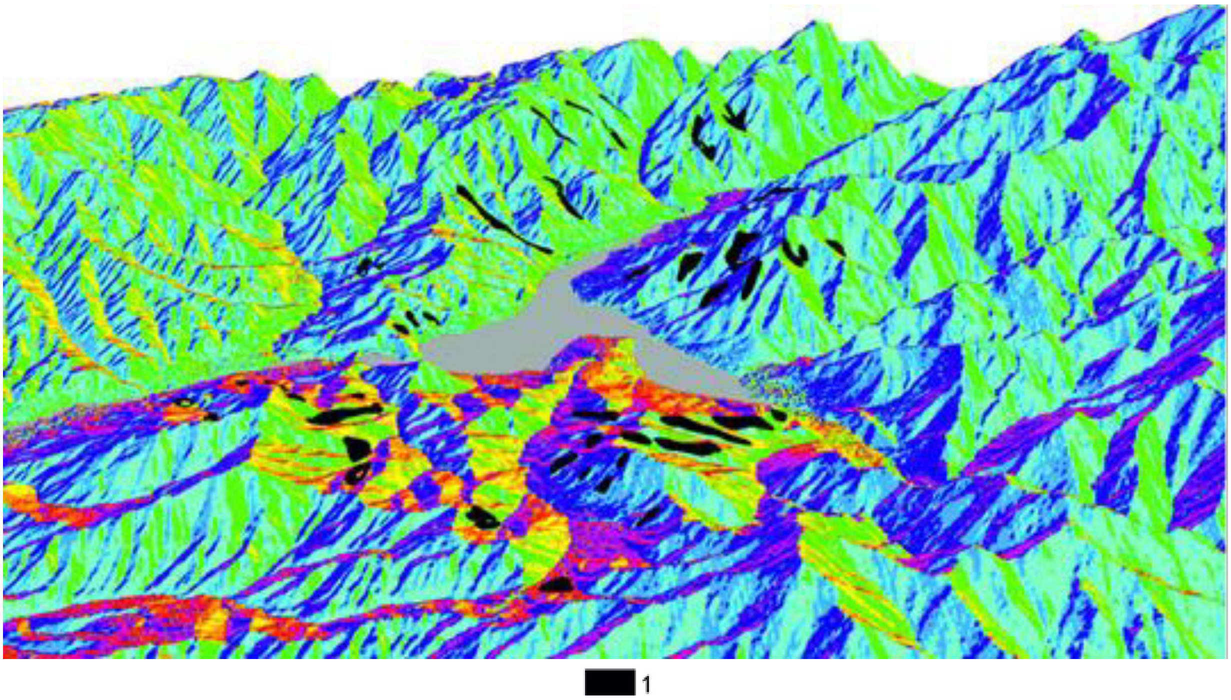

Fig. 6. Aspect Method Aspect Method. 1 — landslides and landslide processes

On the other hand, the geodetic method operates within a three-dimensional Cartesian coordinate system, accounting explicitly for the ellipsoidal nature of the Earth's surface. This approach achieves greater fidelity when representing actual terrestrial geometry, especially in larger regions or areas with pronounced relief undulations. As noted by [*Zevenbergen*, *Thorne*, 1987], adoption of the geodetic method proves beneficial for large-scale regional or interregional modeling tasks requiring high-accuracy spatial computation [*Richards*, 1999]. Furthermore, before interpreting high- and medium-resolution multispectral satellite images, certain preprocessing steps — such as radiometric calibration, atmospheric correction, and resampling — are necessary to optimize the information content and geometric integrity of the raw data [*Song* et al., 2001; *Mather* et al., 2011; *Lillesand* et al., 2015].

CONCLUSIONS

Areas susceptible to landslides are effectively mapped by utilizing a combination of relief plasticity analysis and remote sensing techniques. The workflow begins with preprocessing of space-borne images, involving atmospheric corrections and mosaicking procedures, resulting in high-quality spatial datasets suitable for both visual inspection and spectral interpretation. Enhanced classification outcomes were achieved by exploiting different band combinations and calculating specialized indices, such as Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Soil Adjusted Vegetation Index (SAVI), which help distinguish altered land cover indicative of landslide disturbances.

Relief plasticity refers specifically to the three-dimensional representation of topography, characterized by slope angles, aspect directions, curvature profiles, and shadow patterns. Detailed examination of these parameters yields essential insights into the structure and dynamics of landslide bodies. Through GIS-based morphometric analyses, relief plasticity data can be merged with remote sensing outputs to construct landslide susceptibility maps. Combining quantitative estimates of landslide body thickness with analyses of lithodynamic flow patterns greatly improves hazard assessments. Moreover, integrating variables like slope steepness, drainage density, and tectonic lineaments strengthens the reliability of predictions. This synergistic approach demonstrates the indispensable role of relief plasticity and remote sensing in accurately identifying landslide-prone regions.

REFERENCES

Abdunazarov U., Sabitova N., Stelmakh A., Kholdorova G., Kayumova M. Morphological Features of Buried Soils of Loess Formations of the Prytashkent Region of Uzbekistan. Journal of Critical Reviews, 2020. V. 7. Iss. 4. P. 361–370.

Bekanov K., Safarov E., Prenov S., Yusupov B., Uvraimov S. Creating Land Use Land Cover Map Using Methods GIS and Remote Sensing (On the Example the Chimbay District of the Karakalpakstan Republic). International Journal of Pharmaceutical Research, 2020. V. 12. Iss. 3. DOI: 10.31838/ijpr/2020.12.03.231.

Burrough P. A., McDonnell R. A. Principles of Geographical Information Systems. Oxford University Press, 1998.

Chervanev I. G. Modeling and Automated Analysis of Relief: Methodological Aspects. In: Problems of the System-Formational Approach to Understanding the Relief (The Main Directions in the Development of Geomorphological Theory). Novosibirsk: Nauka, 1982. P. 14–22 (in Russian).

Crosta G. B., Agliardi F. Regional Landslide Susceptibility Assessment using Physically Based Models. Environmental Geology, 2003. V. 45. Iss. 1. P. 66–81.

Cruden D. M., Varnes D. J. Landslide Types and Processes. Landslides: Investigation and Mitigation, 1996. V. 247. P. 36–75.

Dattilo M. C., Spezzano F. A. GIS-Based Landslide Susceptibility Mapping: A Case Study in Calabria, Southern Italy. Environmental Geology, 2003. V. 44. Iss. 6. P. 716–727.

Elmasri R., Navathe S. B. Fundamentals of Database Systems. 7th ed. Pearson Education, 2017.

Emelyanova E. P. Basic Patterns of Landslide Processes. Moscow: Nedra, 1972. 308 p. (in Russian).

Fazilova D., Arabov O. Vertical Accuracy Evaluation, Free Access Digital Elevation Models (DEMs): Case of Fergana Valley in Uzbekistan. Earth Sciences Research Journal, 2023. V. 27. Iss. 2. P. 85–91. DOI: 10.15446/esrj.v27n2.103801.

Fernandez T., Jimenez J., Fernandez P. E., Hamdouni R., Cardenal F. J., Delgado J., Cha da M. Integration of Remote Sensing and GIS for Landslide Hazard Assessment and Risk Management in the Tena Valley (Central Pyrenees, Spain). Natural Hazards, 2008. V. 46. Iss. 2. P. 229–247.

Filosofov V. P. Fundamentals of the Morphometric Method for Searching for Tectonic Structures. Saratov: University, 1975. 232 p. (in Russian).

Ghimire M., Timalsina N. Landslide Distribution and Processes in the Hills of Central Nepal: Geomorphic and Statistical Approach to Susceptibility Assessment. Journal of Geoscience and Environment Protection, 2020. V. 8. P. 276–302. DOI: 10.4236/gep.2020.812017.

Horn B. K. P. Hill Shading and the Reflectance Map. Proceedings of the IEEE, 1981. V. 69. Iss. 1. P. 14–47.

Intrieri E., Gigli G., Mugnai F., Fanti R., Canuti P. Landslide Early Warning Systems: Recent Advances and Future Perspectives. Earth-Science Reviews, 2020. V. 208. Art. 103242.

Jensen J. R. Remote Sensing of the Environment: An Earth Resource Perspective. 3rd ed. Pearson Education, 2015.

Khakimov S. K. Channel Processes on Mountain Rivers of the Western Tien Shan. Disssertation for the PhD in geographical sciences. Moscow: Lomonosov Moscow State University, 1992. 250 p. (in Russian).

Konoplev A. V., Kopylov I. S., Krasilnikov P. A., Kustov I. V. Geoinformation Support of the System of Engineering-Geological and Geoecological Safety of the City of Perm. Geoinformation Support of Spatial Development of the Perm Region: Collection of Scientific Papers. Perm: University, 2014. P. 56–78 (in Russian).

Lillesand T. M., Kiefer R. W., Chipman J. W. Remote Sensing and Image Interpretation. 7th ed. John Wiley & Sons, 2015.

Mandal S., Mondal S. Landslide Susceptibility Mapping using Geospatial Techniques and Statistical Models: A Review of the Recent Trends. Earth Systems and Environment, 2019. V. 3. Iss. 2. P. 307–327.

Massonnet D., Feigl K. L. Radar Interferometry and its Application to Changes in the Earth's Surface. Reviews of Geophysics, 1998. V. 36. Iss. 4. P. 441–500.

Mather P. M., Koch M. Computer Processing of Remotely-Sensed Images: An Introduction. 4th ed. John Wiley & Sons, 2011.

Mirmakhmudov E., Abzhaparova D., Tashbaltaeva Sh., Mamadaminova B., Xakimova M. Geophysical Research on a Landslide-Prone Slope in the Vicinity of the Village of Ayusay in the Republic of Kyrgyzstan. E3S Web of Conferences, 2024. V. 590. Art. 03007. P. 1–8.

Niyazov R. A. The Problem of Studying Dynamic Impacts on the Trigger Mechanism of the Beginning of Landslide Processes Formation. Geology and Mineral Resources, 1999. No. 6. P. 40–42 (in Russian).

Nikolaev V. A. Geomorphological Systems of Siberia. Dynamic Equilibrium in the Development of Relief Forms. In: Problems of the System-Formational Approach to Understanding the Relief (The Main Directions in the Development of Geomorphological Theory). Novosibirsk: Nauka, 1982. P. 108–123 (in Russian).

Niyazov R. A., Nurtayev B. S. Landslides Caused by Earthquakes in Uzbekistan. Geology and Mineral Resources, 2004. No. 6. P. 31–39 (in Russian).

Niyazov R. A., Minchenko V. D. Regional Assessment of Landslide Risk in Uzbekistan. Proceedings of the All-Russian Conference "Risk-2003. Assessment and Management of Natural Risks". Moscow, 2003. V. 2. P. 369–373 (in Russian).

Osipov V. I., Mironov O. K., Belyaev V. L. Permanently Operating GIS of the Geological Environment as a Tool for Substantiating Urban Planning of Infrastructure Facilities (On the Example of Moscow). Bulletin of MGSU, 2016. No. 2. P. 159–172 (in Russian).

Ou W., Zhao B., Dai Y. Information Quantity Model Applied in Hazard Evaluation of Landslides: A Case Study of Fuling, Chongqing. 6th International Workshop on Computer Science and Engineering, WCSE, 2016. P. 777–781.

Pirimov J., Safarov E., Abdullaev I., Abdullaeva N. Application of Orthophotomaps in Land Cadastre. E3S Web Conference, 2023. V. 386. Art. 05008. DOI: 10.1051/e3sconf/202338605008.

Pozdnyakov A. V., Roykhvarger Z. B. Dynamic Equilibrium in the Development of Relief Forms. Problems of the System-Formational Approach to Understanding the Relief (The Main Directions in the Development of Geomorphological Theory). Novosibirsk: Nauka, 1982. P. 9–14 (in Russian).

Psomiadis E., Nikos Ch., Nikolaos E., Konstantinos X., Soulis I. Earth Observation and GIS-Based Analysis for Landslide Susceptibility and Risk Assessment. ISPRS International Journal of Geo-Information, 2020. V. 9. No. 9. Art. 552.

Richards J. A. Remote Sensing Digital Image Analysis: An Introduction. 3rd ed. Springer, 1999.

Sabitova N. I., Stelmakh A. G., Tadjibaeva N. R. Mapping Landslides and Landslide Processes in Uzbekistan using the Relief Plasticity Method (Using the Chirchik Basin as an Example). InterCarto. InterGIS. Proceedings of the International Conference. Moscow: Lomonosov Moscow State University, 2020. V. 26. Part 1. P. 572–583 (in Russian).

Sabitova N. I., Stelmakh A. G., Tajibaeva N. R., Minchenko V. D. Application of GIS Technologies and Plastic Flow Map for Studying Landslides of the Chirchik Basin. InterCarto. InterGIS. Proceedings of the International Conference. Moscow: Lomonosov Moscow State University, 2022. V. 28. Part 1. P. 670–682 (in Russian).

Sharipov S. M., Gudalov M. R., Shomurodova S. G. Geologic Situation in the Aydar-Arnasay Colony and its Atrophy. Journal of Critical Reviews, 2020a. V. 7. Iss. 3. P. 461–468. DOI: 10.31838/jcr.07.03.85.

Sharipov S., Khayitmurodov A. The Impacts of Green Spaces on Mitigating the Urban Hot Island Effect in the City of Tashkent. BIO Web of Conferences, 2024. V. 105. Art. 06013. DOI: 10.1051/bioconf/202410506013.

Sharipov S. M., Shomurodova S. G., Gudalov M. R. The Use of the Mountain Kars in the Tourism Sphere in Cort and Recreation Zone of Chimgan-Charvak. Journal of Critical Reviews, 2020b. V. 7. Iss. 3. P. 475–481. DOI: 10.31838/jcr.07.03.87.

Shchukina O. G., Abdukarimov M. M., Ibragimov D., Ergashev M. Creation of a Three-Dimensional Model of a Landscape of the Left Bank of the Akhangaran Reservoir using a Phantom 4 Pro Quadrocopter. E3S Web of Conferences, 2024. V. 498. Art. 02012.

Simonov Yu. G. Analysis of Geomorphological Systems. Moscow Branch of the Geographers Society, 1976. P. 69–91 (in Russian).

Solari L., Cremonesi E., Ciervo F., Berti M., Aleotti P. Regional-Scale Landslide Susceptibility Assessment using Machine Learning Algorithms and Remote Sensing Data. Geomorphology, 2020. V. 355. Art. 107065.

Song C., Woodcock C. E., Seto K. C., Lenney J., Macomber R. T. Classification and Change Detection using Landsat TM Data: When and How to Correct Atmospheric Effects? Remote Sensing of Environment, 2001. V. 75. Iss. 2. P. 230–244.

Stepanov I. N. Theory of Relief Plasticity and New Thematic Maps. Moscow: Nauka, 2002. 230 p. (in Russian).

Stepanova V. I., Pikulenko O. V. Territorial Planning of Ecological Settlements using Relief Plasticity Maps. InterCarto. InterGIS. Proceedings of the International Conference. Moscow: Lomonosov Moscow State University, 2014. V. 20. P. 606–613 (in Russian).

Van Westen C. J., Rengers N., Terlien M. T. J., Soeters R. Analysis of the Influence of Land Use Change on Landslide Susceptibility in Cinque Terre (Liguria, Italy). Geomorphology, 2008. V. 94. Iss. 1-2. P. 58–79.

Varnes D. J. Slope Movement Types and Processes. Landslides: Analysis and Control, 1978. V. 176. P. 11–33.

Yarmukhamedov A. Modern Geodynamics of Eastern Uzbekistan. Tashkent: Fan, 1979. 145 p. (in Russian).

Zakirov M. M., Agzamova I. A., Begimkulov D. K., Ermatova Ya. S. Transformation of Geoecological Conditions in the Influence Zone of the Charvak Reservoir. Deutsche Internationale Zeitschrift für Zeitgenössische Wissenschaft (German International Journal of Modern Science), 2022. No. 30. P. 21 (in Russian).

Zevenbergen L. W., Thorne C. R. Quantitative Analysis of Land Surface Topography. Earth Surface Processes and Landforms, 1987. V. 12. Iss. 1. P. 47–56.