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Development of the Integrated Flood Hazard Index (FHI) for a Multi-Criteria Assessment of Mudflow Hazard

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Abstract: The article presents a comprehensive approach to the quantitative assessment and mapping of debris-flow hazard at the regional scale (using Samarkand Region as a case study) through the development of an integrated Flood Hazard Index (FHI). The index is constructed using a Multi-Criteria Analysis (MCA) framework and incorporates six key thematic layers: precipitation intensity (CHIRPS), flow accumulation (HydroSHEDS ACC), terrain slope (SRTM), distance to surface water bodies (JRC Global Surface Water), vegetation index (MODIS NDVI), and global land-cover data (ESA WorldCover). Data processing was carried out within the Google Earth Engine (GEE) environment, while layer integration was performed using normalization procedures and the Weighted Linear Combination (WLC) technique. The resulting FHI map delineates four hazard classes (very low to high) and reveals the spatial concentration of high hazard levels in the mountainous and piedmont catchments of the Middle Zarafshan. The methodological principles and datasets employed in the study are aligned with contemporary practices in satellite remote sensing and GIS-based hazard assessment.

Keywords: debris flows, precipitation intensity, flow accumulation, terrain slope, distance to water bodies, vegetation index, global land-cover map, layer integration, hazard class.

INTRODUCTION. Mudflows are dynamic and often catastrophic natural processes that form when intense precipitation in mountainous and foothill areas combines with steep slopes and insufficient vegetation cover. To manage risks and plan measures to reduce damage, spatial-temporal debris flow hazard maps based on objective physical indicators and reproducible methodology are required. In recent decades, multi-criteria methods integrating remotely sensed products and digital terrain models have become the standard for regional hazard assessments [1;2].

The aim of the study is to develop an integrated multi-criteria Flood Hazard Index (FHI) for assessing and mapping debris flow hazards in the Samarkand region, to show the methodology for preparing and normalising input layers in GEE, and to demonstrate the spatial distribution of risk classes with an indication of areas of increased hazard.

LITERATURE REVIEW. Since the global data sets for assessing hydrological and landscape factors include CHIRPS, HydroSHEDS (Flow Accumulation), SRTM DEM, JRC Global Surface Water, MODIS NDVI, and ESA WorldCover, in their study "Infrared precipitation monitoring stations - a new environmental record for monitoring extreme events" (2015), Chris Funk and his colleagues presented the CHIRPS algorithm, the results of global and regional validation, and showed how CHIRPS can be used to quantify the hydrological consequences of reduced precipitation and increased air temperatures in the Greater Horn of Africa. Using a variable infiltration capacity model, they demonstrated that CHIRPS can support effective hydrological forecasting and trend analysis in southeastern Ethiopia [3].

In the 2008 technical documentation on hydrological networks, author Bernhard Lechner et al. note that Hydro SHEDS (Flow Accumulation) and related products provide global hydrography and runoff accumulation indicators, which are key to identifying drainage structures and surface runoff concentration zones [4].

During the Shuttle Radar Topography Mission, Tom Farrar and his colleagues (2007) created the most complete digital model of the Earth's relief with the highest resolution. Dual radar antennas were used to collect interferometric radar data, which was converted into digital topographic data with a resolution of 1 arc second [5].

The location and stability of surface waters (inland and coastal) depend on both climate and human activity, and also influence climate, biodiversity and human well- being. Global datasets documenting the location of surface waters and seasonality can be obtained from cadasters and national inventories, statistical extrapolation of regional data, and satellite imagery, but measuring long-term changes at high resolution remains a challenge. In a study by Jean-François Pechel, Andrey Kottam, Noel Gorelik, and Alan Belward (2016), three million Landsat13 satellite images were used to map global surface water with high resolution and its long-term changes, where they quantified changes in the state of surface water worldwide over the past 32 years with a resolution of 30 meters. The authors recorded the months and years during which water was present, where its content changed, and what changes took place in terms of seasonality and permanence, thus proving that JRC Global Surface Water provides quality information on the location and seasonality of water bodies, which is important when calculating the distance to water bodies and assessing water storage potential [6].

MODIS NDVI is a proven time series of vegetation indices for assessing the condition of vegetation cover and the area of exposed (poorly protected) areas, which is one of the factors influencing the formation of debris flows. The MODIS NDVI product suite is currently being used successfully in all studies on ecosystem, climate and natural resource management, as well as in operational research, as evidenced by the ever-growing number of publications by specialists [7].

In the literature, MCA (including AHP, WLC and their variants) is recognized as convenient and flexible for regional mudflow hazard assessment maps, where WLC is particularly often used to integrate quantitative map layers with expert weighting. Recently, variable weighting and sensitivity analysis methods have also been used to assess the robustness of results to the choice of weighting coefficients [2;3].

Combining the above-described high-quality global products with proven MCA approaches and cloud computing (GEE) allows for the production of reproducible, scalable landslide hazard maps suitable for spatial planning and monitoring [2].

METHODOLOGY. The area of this study is the Samarkand region, with a focus on the mountainous and foothill areas of the Middle Zarafshan (Amangutansay, Urgutsay, Akdarya, Aktepasay), where historical data indicate the highest debris flow activity. The study used the study area boundary prepared in GIS and loaded into GEE. The input layers are precipitation intensity data - CHIRPS (time series/seasonal averages), flow accumulation - Hydro SHEDS ACC (Flow Accumulation) calculated from DEM Hydro SHEDS/SRTM, relief slope - SRTM DEM (calculation of slope angle and exposure), distance to water bodies - JRC Global Surface Water (distinction between permanent/seasonal waters), NDVI - MODIS (averaged NDVI for the growing season and minimum values for assessing potentially hazardous areas) and land cover - ESA World Cover 10 m (reclassified into categories relevant to debris flow hazard - forest, shrub, arable land, open areas). All layers are converted to a single projection and resolution of 1 km (by reprojecting in GEE), which is optimal for regional risk analysis and comparable to the scale of available event inventories.

Google Earth Engine (GEE) was selected for processing large time series and global products in the cloud, as it is consistent with remote sensing and risk mapping practices [2]. The following tasks were performed in GEE: loading of source products, calculation of morphometric indicators (slope), calculation of runoff accumulation, aggregation of NDVI for the season, distances to water bodies, normalization, and final WLC.

Normalization was performed by linear scaling (min-max) to ensure uniformity of ranges.

Weights were assigned by experts based on a review of the literature and local expertise (approximate scheme: precipitation 0.25; slope 0.20; runoff accumulation 0.20; NDVI 0.15; distance to water bodies 0.10; WorldCover 0.10). Sensitivity testing of weight changes was performed to verify stability [1].

Integration consisted of a weighted linear combination (WLC), which gives the final FHI according to the formula:

$$FHI = \sum_{i=1}^{n} w_i * S_i$$

where: w_i – weight of factor i, S_i – normalized value of factor. After calculating the FHI, a classification into four risk classes was carried out: very low, low, medium, high (Fig. 1).

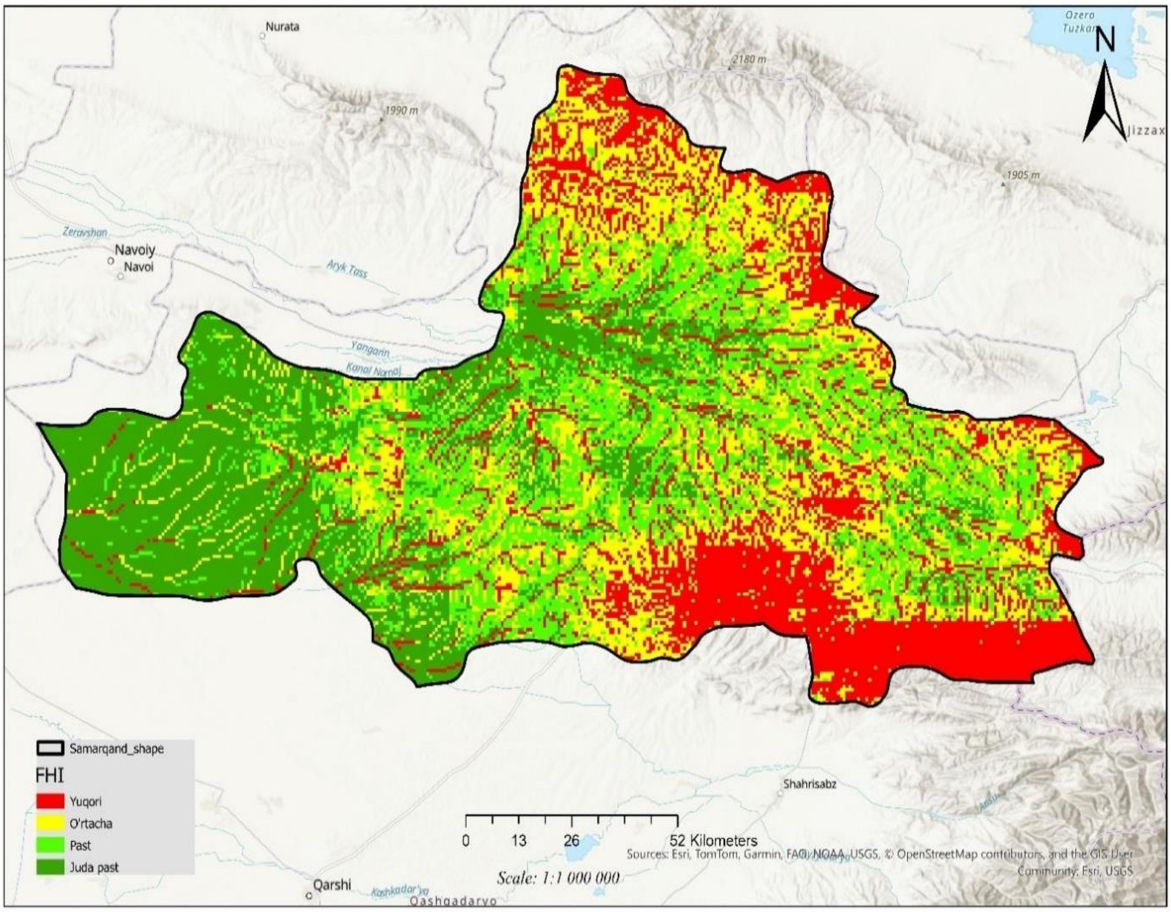

Fig. 1. FHI map, according to their degree of influence on the selepavod process in the Samarkand region

DISCUSSION AND CONCLUSIONS. The final FHI map shows a distinct concentration of high values in the upper parts of the mountain catchments of the Middle Zarafshan, which include the Amankutansay, Urgutsay, Akdarya and Aktepasay. The spatial structure of the FHI correlates with a combination of intense precipitation, steep slopes and significant runoff accumulation. The identified areas of high FHI coincide with the registered mudflow-prone basins and the results of regional studies in Uzbekistan, which confirms the correctness of the selection of factors and the advantages of the integrated MCA approach [8;9;10].

The use of representative global products (CHIRPS, Hydro SHEDS, SRTM, JRC GSW, MODIS, ESA World Cover) provides reproducibility and scalability; the use of GEE ensures computational reproducibility and easy adaptation of time intervals [3].

The limitations are a spatial resolution of 1 km, which is suitable for regional assessment, but for local planning (engineering protection projects, detailed maps), more detailed DEMs and local observation networks are recommended; the accuracy of the results strongly depends on the quality of the event inventory for calibrating weights and verification (distortions are possible in areas with low registration density) [11].

CONCLUSION AND RECOMMENDATIONS. The developed integrated Flood Hazard Index (FHI) demonstrates the practical applicability of the MCA approach for mapping flood hazards in the Samarkand region. The approach provides a reproducible, scalable and transparent methodology suitable for inclusion in the territorial risk planning and monitoring system. For practical application, it is recommended to conduct detailed validation using local debris flow event inventories, integrate FHI results into early warning and engineering planning procedures, and use finer resolution and local observations for maps with high FHI values.

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