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Mass-Movement Stationary Hazard Maps of Georgia Including Precipitation Triggering Effect: Fuzzy Logic Approach

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Each year landslides cause many disasters in mountainous areas all over the world. The territory of Georgia, due to the frequent reoccurrence of large-scale hazardous geological processes, growth of population, vulnerable infrastructure and land use as well as number of large engineering constructions, most vulnerable mountainous regions in the world. It is of great importance for disaster risk reduction to create reliable and accounting correctly for all important factors mass-movement stationary and dynamic hazard maps of Georgia, including precipitation. The precipitation is a strong triggering impact, which, after exceeding some threshold lead to initiation of mass-movement. In order to include precipitation factor we use the Fuzzy Logic approach. The resulting precipitation-accounting landslides/mudflows stationary hazard maps of Georgia are compiled.

landslides/debris-flows, hazard maps, precipitation, fuzzy logic

Each year landslides/mudflows (L/M) cause many disasters in mountainous areas all over the world. Thus, it is of great importance to create reliable and cost-effective early warning systems for monitoring mass-movements in potentially dangerous areas. The key elements in the solution of problem, as it is stressed in the Sendai Framework for Disaster Risk Reduction [1] are science and technology. The Sendai Framework calls for enhanced scientific and technical work on disaster risk reduction (DRR) and its mobilization through the coordination of existing arrays and scientific research institutions at all levels and all regions [2].

The territory of Georgia, due to the frequent reoccurrence of large-scale hazardous geological processes [3], growth of population, vulnerable infrastructure and land use as well as number of large engineering constructions, belongs to the most vulnerable mountainous regions in the world.

Thus, it is of great importance for disaster risk reduction (DRR) to create reliable and accounting correctly for all important factors, including precipitation, mass-movement stationary hazard maps of Georgia. The matter is that addition of the long-term precipitation data to time-independent spatial factors (slope steepness, lithology, land cover, etc.) should take into consideration strong triggering impact. According to many researchers, after exceeding some threshold, rainfall lead to initiation of mass-movement. The role of precipitation (soil moisture) factor is presented in papers [4-14]. Kirschbaum et al in [12, 13] show that there is very strong correlation between the monthly rainfall values and number of landslides in various regions of the world. For example, in Himalayan arc and in China landslides occur mainly from June to September. Such stationary precipitation-accounting maps are important for optimal planning of infrastructural objects.

For compilation of stationary L/M hazard maps one can use standard methodology of spatial multi-criteria evaluation (SMCE) considered in [15-18]. According to them, main factors affecting landslide initiation are slope steepness, elevation, lithology, land cover, long-standing (perennial) precipitation, seismic activity as well as human activity. Recently Gaprindashvili and van Westen [19] published multi-criteria stationary landslide hazard and risk maps of Georgia, which takes into account all above-mentioned factors, including 1-day maximal precipitation map, recorded for a century on the country territory. In our opinion, the weight, allocated to precipitation (0.03 from weights' total 1.0) is too small if we remember that landslide occurrence is highly correlated with both precipitation intensity and duration [7, 8, 12]. As a result of small weight, allocated to rainfall factor, the landslide hazard map of Gaprindashvili and van Westen [19] looks practically identical to the map, compiled without accounting precipitation. Besides, the probability of mass-movement increases strongly if rainfall is accumulating during several days. That is why in our version of stationary landslide/mudflow susceptibility map of Georgia we used 5-day precipitation map for the last century.

Standard Mass-Movement Hazard Map of Georgia Excluding Precipitation Factor

At the initial stage we built standard mass-movement hazard (or susceptibility) map of Georgia ignoring rainfall factor using the following list of factors with weights (Table), which is adopted in the European projects: "European Landslide Hazard Maps: Fostering European Harmonization of Slope Movement Hazard Assessment at various spatial scales" and "Pan-European and nation-wide landslide susceptibility assessment". The following dataset has been collected during the preparation period: 1. DTM (Digital Terrain Model) – The digital elevation model of the territory of Georgia (extracted from Aster Satellite mission (ASTER: Advanced Spaceborne Thermal Emission and Reflection) (http://asterweb.jpl.nasa.gov/); 2. Rivers network of territory of Georgia (the database was extracted from 1:50 000 topographic map); 3. Engineering geological structure's map of Georgia (the database was created based on the Engineering geological map of Georgia of 1:200 000 scale); 4. Active tectonic faults database of Georgia

Table. Model parameterization of factors' weights for landslides (%)

		1	2	3	4	5	6	7	8	9
1	Geology	20%	20%	20%	25%	20%	20%	20%	20%	20%
2	SLOPE	18%	18%	20%	20%	20%	20%	20%	18%	18%
3	Land_Use	15%	15%	15%	10%	10%	20%	10%	15%	15%
4	Soil	12%	12%	15%	15%	15%	10%	10%	12%	17%
5	Fault	5%	5%	5%	5%	5%	5%	5%	5%	5%
6	RIVER	5%	5%	5%	5%	5%	5%	5%	5%	5%
7	Dem	10%	10%	10%	10%	10%	5%	5%	15%	10%
8	ASPECT	5%				5%	5%	5%		5%
9	Water erosion	10%	15%	10%	10%	10%	10%	20%	10%	5%
	%	100	100	100	100	100	100	100	100	100

(created from geological map of Georgia 1:200 000 scale); 5. Soil-types map of Georgia (1:200 000 scale database); 6. Land use database (Terra modis dataset) (http://modis.gsfc. nasa.gov/); 7. Landslide inventory databases, compiled using different sources (around 500 events).

The next step, after collection and processing of data is parametrization of the factors' maps. For this goal, the analysis of different factors' maps was carried out, where the expert judgment and knowledge have been used. Each factor map was classified and for each classes the value from 0 to 100 have been graded, where 0 is absence of the class to produce mass movement and 100 is the highest value of formation, which should produce mass movement.

The parameterized maps have been reworked into raster type maps with 30 m resolution and the methodology have been tested using all (9) parameters. The combining of the selected parametrical maps was carried out using Arc-GIS. The maps were combined using different types of weight of each parameter. In the Table the numbers of models are shown with parameter's weights for landslides. Similar procedures were used to build mudflow hazard map.

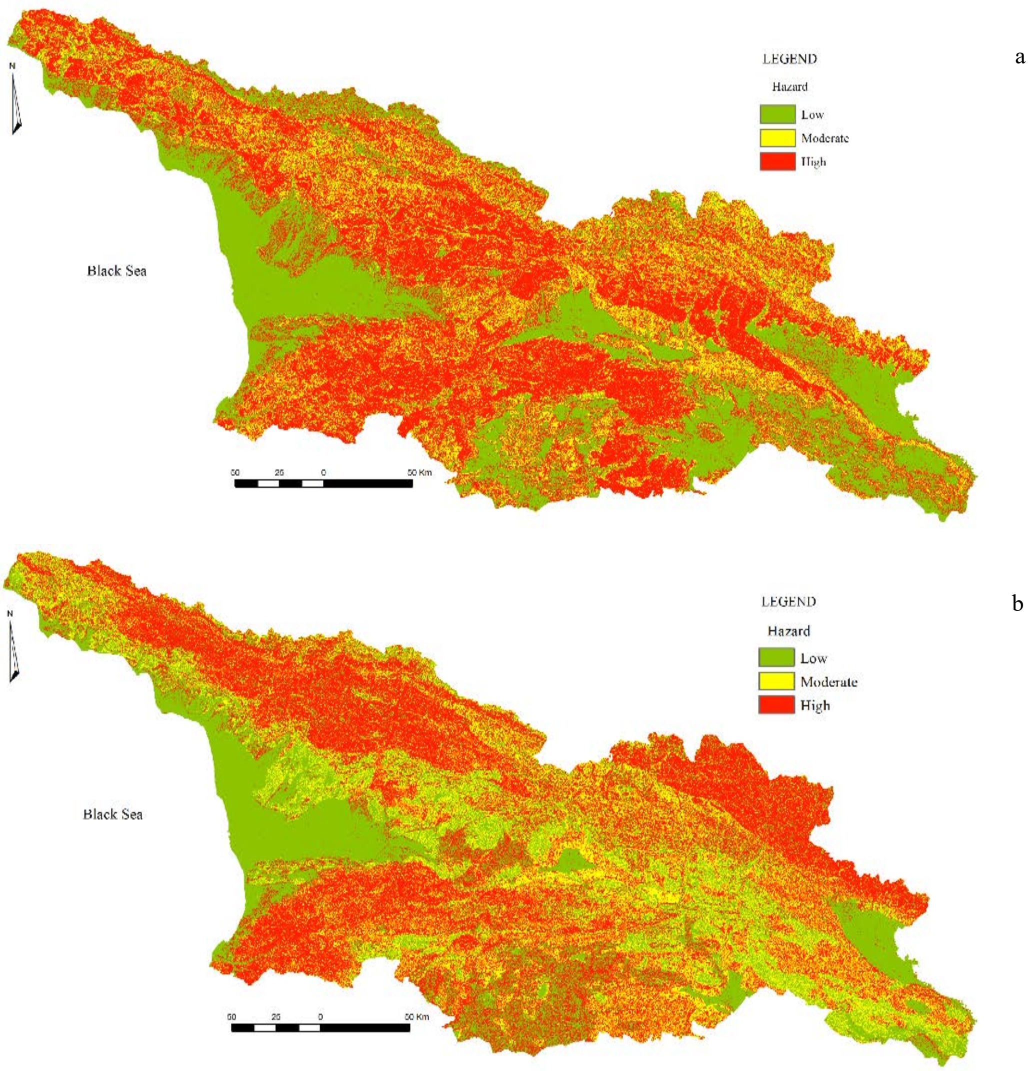

Fig. 1. Standard stationary landslide hazard map of Georgia excluding precipitation factor (a); stationary mudflow hazard map of Georgia excluding precipitation factor (b).

Fig. 1 shows the L/M susceptibility maps of Georgia with 3 gradations (low, middle and high): here precipitation factor is not taken into consideration.

Standard Stationary Mass-Movement Hazard Maps Including Precipitation Factor

Despite that at the present time we have not assessed the landslide/mudflow (L/M) precipitation threshold for Georgian environment, we made some steps in order to develop methodology for calculating rainfall-triggered stationary L/M hazard map. At this initial stage two types of maps are needed in order to develop rainfall triggered stationary L/M hazard map: a) L/M hazard map, Fig. 1 (where we do not foresee precipitation); b) long-standing (perennial) precipitation map, Fig. 2: we use the expected 5-day maximal precipitation map, or Rx5 for 100 years period. A century-long precipitation data set we consider as a stationary value of Rx5 precipitation.

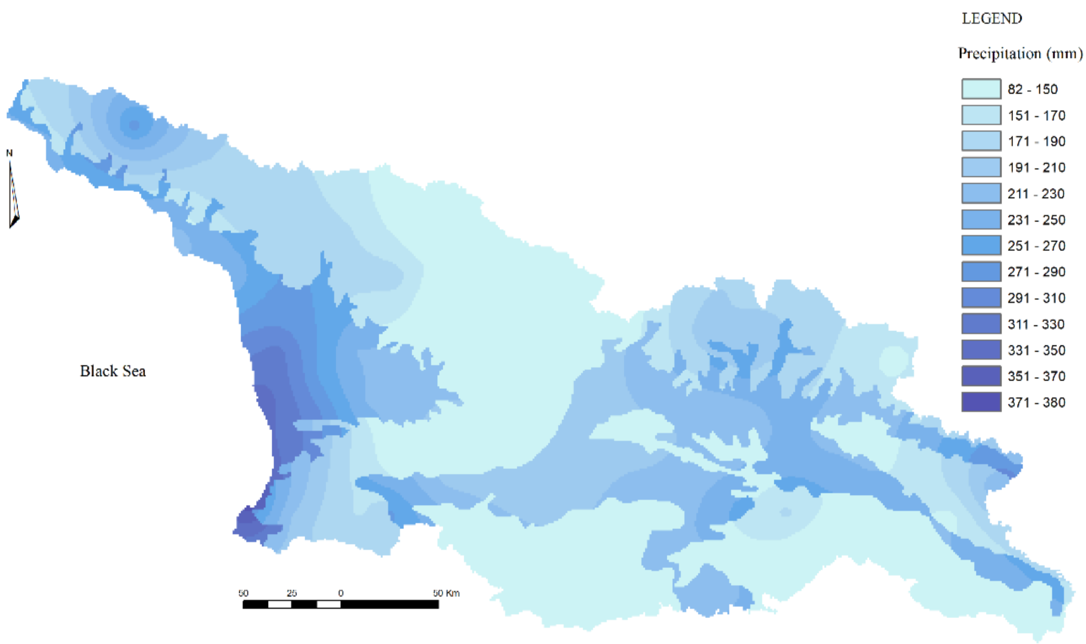

Fig. 2. The map of maximum 5-day (or Rx5) precipitation for 100 years return period in Georgia [20].

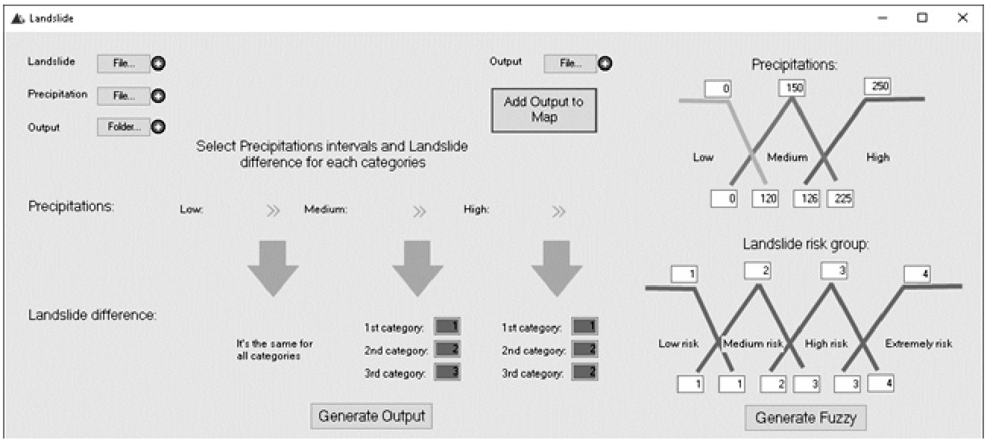

Fig. 3. The scheme of algorithm for merging standard L/M hazard and stationary precipitation maps using fuzzy logic approach.

We used one of artificial intelligence methods, "Fuzzy Logic System" (FLS) in order to combine L/M hazard maps with stationary rainfall (Rx5 for 100y) map of Georgia for 100y recurrence interval [20]. In contrast to classic logic, which considers only the assertion true-false and nothing in between, in FLS one considers intermediate truth (false) categories between zero and one, using the rule IF-THEN [21, 22].

Fig. 3 shows the scheme of developed algorithm for integrating landslide hazard and long-term precipitation maps. After adding above mentioned two maps into the software, we can choose thresholds for triggering landslide: a. minimum precipitation needed for landslide occurrence; b. amount of precipitation, which leads to landslide with high probability; when this information is combined with landslide hazard map (low, medium, high) using fuzzy logic method, as an output we get regions with high probability of landslide occurrence due to the precipitation.

As a result, of merging stationary maps of L/M hazard and precipitation the stationary maps of L/M hazards taking into account triggering factor – precipitation – were compiled (Fig. 4). It is evident that precipitation factor changes significantly

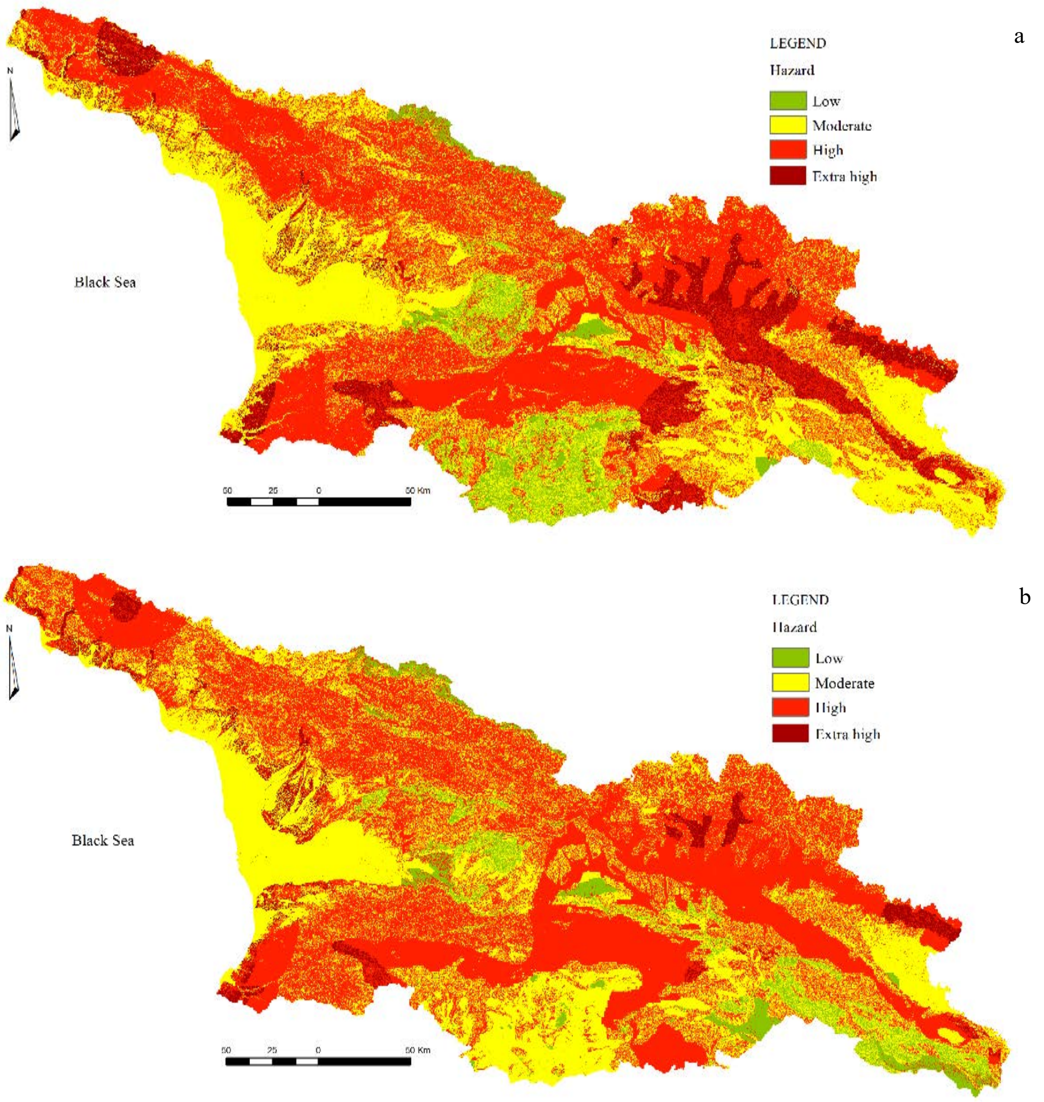

Fig. 4. Precipitation-accounted stationary landslide (a) and mudflow (b) hazard maps of Georgia.

configuration of hazardous zones, namely, due to precipitation factor some hazardous zones are upgraded from N-th to (N+1)th-grade higher hazard zone (i.e. middle hazard to high hazard etc). In the resulting maps one more gradation, taking into account precipitation factor – "extreme hazard" was added.

As we see, taking into account precipitation triggering impact delineates regions of extreme landslide and mudflow hazard, which occupy much less area than the high hazard space in contrast with the precipitation-accounting map of Gaprindashvili and van Westen [19]. These new maps (Fig. 4) are in good agreement with the existing data on mass-movement occurrences.

The described methodology will be used in the future research for compilation of the spatio-temporal susceptibility maps of Georgia on the basis of precipitation satellite data: i. In addition to stationary ones, such dynamical maps will be used for prevention of risks of impending catastrophic mass-movements, namely the probability of mass-movement will be assessed on the basis of intensity and duration of antedescent precipitation. For this it is very important to find the local threshold value of precipitation, which can initiate mass-movement [5, 8]. To assess the threshold precipitation value, it is necessary to accumulate the time-correlated statistical data on the antedescent precipitation and mass-movement events for territory of Georgia. In principle this became possible using NASA satellite data – namely, Global Precipitation Monitoring (GPM) 3-hourly data; ii. For assessing reliability of the existing mass-movement sustainability maps for Georgia they are compared with the statistical data of Ministry of Environment of Georgia, which take into attention only information obtained from local authorities. Such information is sent only in the case of damage of settlement, due to mass-movement. That means that L/M events are taken into account only when they cause damage of the settlement and mass-movements occurred in the nonpopulated area are ignored. According to maps, compiled on the basis of such data, the mass-movements take place in the populated foothills and are practically absent in adjacent mountaineous areas, which is illogical. In order to assess real susceptibility, it is necessary to use the objective space data on L/M sources – namely, satellite images. Such study has been carried out in Abkhazia – it shows that a lot of landslides occurred in non-populated areas, which means that they were not included into official local authorities' information. It is evident that the representative map of mass-movements should also include events occurred in non-populated areas. Otherwise the existing maps of occurred L/M reflect not the hazard, but mainly the risk in populated areas.

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გეოფიზიკა

საქართველოს მასების მოძრაობის სტაციონარული საშიშროების რუკები ნალექების ტრიგერული ეფექტის გათვალისწინებით: არაცხადი ლოგიკის მიდგომა

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ყოველ წელს მეწყრები იწვევს მრავალ კატასტროფას მსოფლიოს ყველა მთიან რეგიონში. საქართველოს ტერიტორია მოწყვლადია საშიში გეოლოგიური პროცესების მიმართ, ვინაიდან იზრდება მოსახლეობის სიმჭიდროვე, მოწყვლადი ინფრასტრუქტურის მოცულობა, სამეურნეო ფართი და დიდი საინჟინრო ნაგებობების რიცხვი. ამ მხრივ, საქართველო მიეკუთვნება მსოფლიოს ერთ-ერთ ყველაზე მოწყვლად მთაგორიანი რეგიონების რიცხვს. ამიტომ დიდი მნიშვნელობა უნდა მივანიჭოთ ამ საშიშროების რისკის შემცირებას. ამისათვის აუცილებელია სწორად იქნეს შეფასებული ყველა მნიშვნელოვანი ფაქტორი, რომელიც გავლენას ახდენს საქართველოს მეწყრების/ღვარცოფების სტაციონარული და დინამიკური საშიშროების რუკების აგების სისწორეზე. ინტენსიური ნალექი არის ამ მოვლენების ძლიერი მატრიგერებელი ფაქტორი, რომელიც გარკვეული ზღურბლის გადალახვის შემდეგ იწვევს მასების მოძრაობის ინიციაციას. იმისათვის, რომ გავითვალისწინოთ ნალექის ფაქტორი, ჩვენ ვიყენებთ არამკაფიო ლოგიკის (Fuzzy Logic) მიდგომას. შედეგად აგებულია საქართველოს მეწყრების/ღვარცოფების სტაციონარული საშიშროების რუკები ნალექების გავლენის გათვალისწინებით.

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