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BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 17, no. 2, 2023

Geophysics

Terrestrial and Satellite-Based Assessment of Rainfall Triggered Landslides Activity in Georgia, Caucasus

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Georgia, due to the mountainous relief, growth of population, vulnerable infrastructure and land use, as well as of number of large engineering constructions is one of the hardest landslides' (LS) prone regions in the world. For reduction of LS risk, it is important to create reliable mass-movement stationary and dynamic hazard maps of Georgia, including precipitation impact. The intensive precipitation is a strong LSs' trigger. The paper is aimed to assess the rainfall conditions, which can lead to initiation of mass-movement using limited terrestrial and satellite-based data on the summary rainfall and landslide occurrence. This approach can be useful for a lot of regions in the world, where LS and meteorological data are not detailed enough to calculate the standard rainfall intensity/ duration threshold graphs for landslide occurrence. *© 2023 Bull. Georg. Natl. Acad. Sci.*

landslides, rainfall triggering, terrestrial and satellite data

At present, by official data, on the territory of Georgia are registered 50000 landslide (LS) and 350 debris-flow sources are registered. In the high- and medium mass movement risk zone are located 1420 settlements. In this direction, some investigations are already carried out and corresponding LS stationary hazard maps were compiled [1,2]. The existing LS susceptibility maps of Georgia mainly take into consideration time-independent spatial factors (slope steepness, lithology, land cover, etc.) and ignore or give a very small weight to precipitation [2]. At the same time, last years' publications indicate that one of the main triggers of landslides' activation is intensive or extreme precipitation [3-7]. Recently, a number of studies have been carried out in Georgia to assess the long-term (secular) effects of precipitation on the initiation of landslides [8, 9].

In addition to precipitation data from the ground-based weather stations, satellite information has often been used in the recent decades to study various processes in the atmosphere and near the earth's surface, including landslides [10].

This work is a continuation of our previous studies on the association of precipitation with landslide activity in Georgia [8, 9]. The results of the study of the impact of atmospheric precipitation on the landslide activity both on the territory of Georgia as a whole and in its individual regions, using data from ground-based and satellite measurements of precipitation, are presented below. It should be noted, that in the present work significant attention is paid to satellite meteorological data, which, as we show below, can actually substitute the rain-gauge information.

Study Area, Methods and Data

Study area is Georgia (a mountainous country situated almost entirely in the South Caucasus) and its separate regions. The climate of Georgia is mild and rainy on the Black Sea coast and on the western plains. In the central and eastern interior regions, it is more continental and arid. The annual precipitation is ranging from 1000 to 4000 mm at the west and from 400 to 1600 mm at the east [2]. This paper presents the results of a study of the influence of atmospheric precipitation on landslide activity both in general on the territory of Georgia and in its individual regions (Table 1).

Methods

In the proposed work the analysis of data is carried out with the use of the standard statistical analysis methods. The determination of thresholds using empirical method has been carried out. The event rainfall is determined by the number of consecutive days of precipitation before the landslide. The rainfall events leading to LS are plotted in log(E) vs log(D) graph and the distribution fitted to the power law equation. Threshold equation: $E = a{\cdot}D^b$, where E is the total rainfall (mm), D is the duration (h), a is the intercept, and b is the slope of the threshold curve [3, 6]. The coefficients a and b were determined for the average values of precipitation, as well as their lower (Low) and upper (Upp) levels.

Landslide Data

The study used two types of landslide data of Georgian National Environmental Agency: 1 – data for 2014-2018 about 395 landslides with unknown exact coordinates and time of their activation; only the month and the area where the process took place are known; 2 – data for 2011-2020 about 174 landslides with established coordinates and time of their descent. By regions, these data are distributed as follows: Adjara (Adj, 41 LS); Imereti (Im, 25 LS); Racha-Lechkhumi and Kvemo Svaneti (R-L KS, 21 LS); Samtskhe-Javakheti (S-J, 17 LS); Samegrelo-Zemo Svaneti (S-ZS, 15 LS); Mtskheta-Mtianeti (M-M,12 LS); Guria (Gur, 9 LS) Shida Kartli (Sh K, 8 LS) Kakheti (Kakh, 4 LS) Kvemo

Table 1. Data on the mean accumulated sum of precipitation in Georgia and its individual regions (mm)

Region	1 day	3 days	5 days	7 days	10 days	20 days	30 days
Adj	50.6	87.0	96.9	110.2	126.3	218.9	286.6
Im	22.9	42.4	53.4	62.0	74.7	114.8	154.0
R-L KS	14.7	20.2	24.8	30.8	41.6	108.0	137.0
S-J	9.3	13.6	17.9	19.6	21.6	42.0	67.3
S-ZS	17.1	31.6	49.0	59.3	73.1	129.9	195.3
M-M	9.7	11.4	25.7	30.4	38.5	64.3	86.6
Gur	37.0	89.9	106.6	124.6	144.7	227.8	274.8
Sh K	12.1	19.6	26.1	29.5	46.5	74.2	99.7
Kakh	13.9	27.7	33.5	37.7	45.9	66.6	92.3
KK	0	0	0	0	15.4	20.6	23.3
Tb	14.5	21.2	27.4	37.0	40.5	62.5	74.8
All Reg	24.6	42.6	52.0	60.8	72.2	125.2	165.7

Kartli (KK, 1 LS); Tbilisi (Tb, 21 LS); All Regions (All Reg, 174 LS).

At this stage, only the fact of landslide occurrence is considered without detailing their scale.

Monthly Sum of Precipitation of Meteorological Stations and Satellite Data

The data of the Georgian National Environmental Agency and GPM Global Satellite Precipitation Data (http://svs.gsfc.nasa.gov/goto?11091) about the monthly sum of atmospheric precipitation for 26 locations in Georgia from January 2014 to December 2018 (60 months) are used. To study the overall effect of the monthly sum of precipitation on the activation of landslides throughout Georgia, data were averaged for a one meteorological station (or location with the same coordinates for the satellite data).

In Fig. 1 time-series of the average monthly sum of precipitation on 26 meteorological stations (Prec_MS) and corresponding satellite points (Prec_Sat) of Georgia from January 2014 to December 2018 are presented. As follows from Fig. 1, variations of the values of Prec_MS and Prec_Sat are close to each other. Note, that the coefficient of linear correlation between Prec_MS and Prec_Sat is very high – 0.94. Thus, the data of ground-based and satellite measurements of monthly precipitation in Georgia correspond quite well to each other.

Precipitation data of meteorological stations in days with landslide and for 3, 5, 7, 10, 20 and 30 days before their onset

In this paper, the data of the Georgian National Environmental Agency of 26 meteorological stations and 8 automatic weather stations for days with landslide and a few days before their onset are used. In Table 1, data of the mean accumulated (sum of) atmospheric precipitations in days with landslides (below – 1 day) and 3, 5, 7, 10, 20 and 30 days before landslides' onset in Georgia and its individual regions are presented.

As follows from the Table 1, on average, the largest amount of precipitation per one rain event with a landslide falls on Adjara (for 1 day – 50.6 mm, for the sum for 30 days – 286.6 mm), the least – on Samtskhe-Javakheti, respectively 9.3 mm and 67.3 mm. In the following the Kvemo Kartli region is not considered, as there was only one landslide.

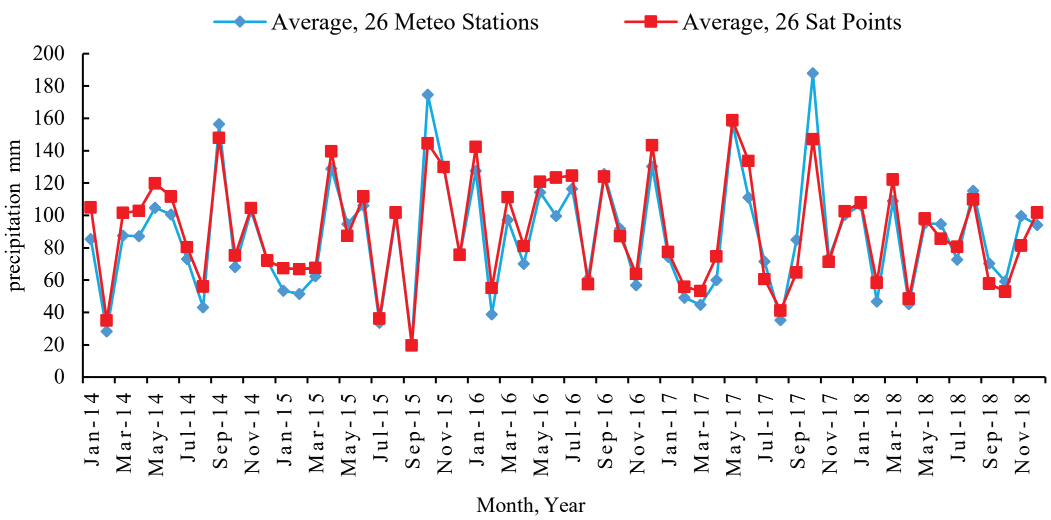

Fig. 1. Time-series of mean monthly sum of precipitation on 26 meteorological stations and in corresponding satellite points in Georgia from January 2014 to December 2018.

Results and Discussion

Monthly effects of precipitations on landslide activity. In Fig. 2 we show the graphs of the dependence of the average number of landslides on the average amount of precipitation according to ground-based and satellite observations. Averaging was performed for seven ranges of Prec_MS values and six ranges of Prec_Sat values in order of their growth.

As follows from the figure, in both cases, the dependence of the number of landslides on the monthly sum of precipitation has the form of the fourth order polynomial (sequentially: small growth – plateau – strong growth). For the ground-based observation network the average monthly plateau values of the amount of precipitation, after which a strong increase in the number of landslides began, covers the range from 46 to 78 mm, for the satellite data – from 59 to 93 mm (LS number ≈ 4-5).

Precipitation effects on landslides activity for 1, 3, 5, 7, 10, 20 and 30 days before their onset. In Fig. 3 we present the data on dependence of the accumulated sum of precipitation mm for 1, 3, 5, 7, 10, 20 and 30 days before landslides' onsets with the number of these days in Georgia and its individual regions (data of the Table 1 are used).

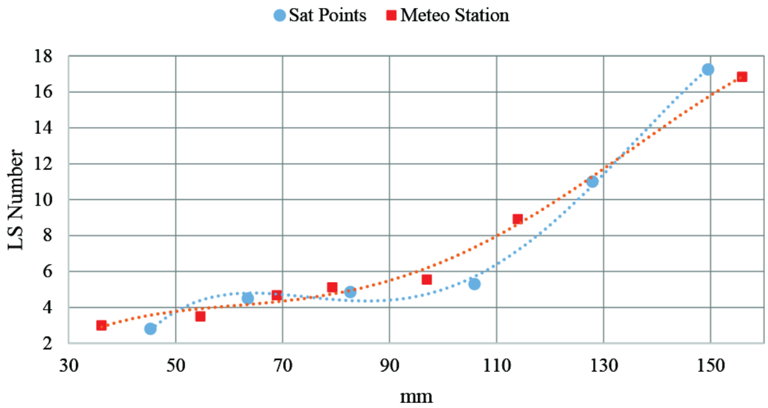

Fig. 2. Connection between the mean monthly sum of precipitation on 26 meteorological stations (red squares) and on satellite points (blue circles) and the mean monthly LS number in Georgia in 2014-2018.

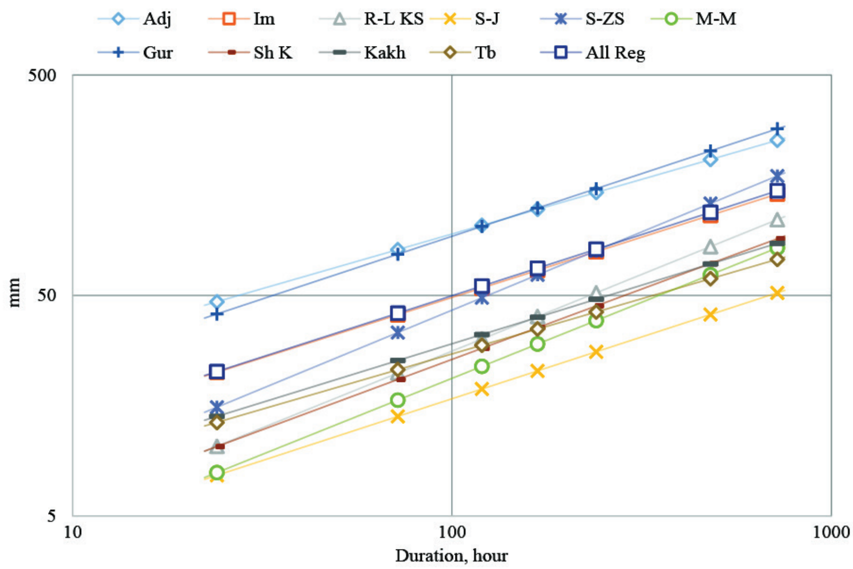

Fig. 3. Rainfall event thresholds (level, mm), versus rain event duration in hours before landslide activation for Georgia and its individual regions (Mean).

Table 2. Regression equation coefficients of rainfall event duration (ED) thresholds *D* for different regions of Georgia: $E=a \cdot D^b$, ($0.761 \le R^2 \le 0.995$)

Region, *a* and *b*	Adj	Im	R-L KS	S-J	S-ZS	M-M	Gur	Sh K	Kakh	Tb	All Reg
a (L)	2.79	1.21	0.43	0.62	0.39	0.36	2.28	0.02	1.34	0.10	0.13
b (L)	0.48	0.61	0.80	0.51	0.64	0.50	0.62	1.00	0.58	0.94	0.83
a (M)	9.70	3.94	1.13	1.29	1.63	0.88	6.77	1.36	2.61	2.71	3.88
b (M)	0.50	0.55	0.70	0.56	0.71	0.69	0.57	0.64	0.53	0.50	0.55
a (U)	69.0	32.4	7.4	30.8	6.7	31.5	13.8	11.5	11.2	36.5	69.0
b (U)	0.36	0.38	0.50	0.18	0.63	0.28	0.53	0.46	0.37	0.30	0.36

In the Table 2 we present information about coefficients of regression in equation: $E=a \cdot D^b$ between the days with landslides and accumulated sum of precipitation in 1, 3, 5, 7, 10, 20 and 30 days before landslides' onsets, where the numbers of these days in Georgia and its individual regions are also given (Low-L, Mean-M, Upper-U).

The values of the coefficients *a* and *b* vary in a wide range for different regions of Georgia according to the climate zones from the subtropical regions (Adjara, Guria) to areas with a continental climate (Shida Kartli, Kakheti) (Table 2). Note that the data on the values of *a* and *b* coefficients (Table 2) in some cases agree satisfactorily with similar data obtained by other authors for various regions of the world with a similar climate: World, Norway [3], Calabria [4], Chukha Dzongkhag, south-west Bhutan [6].

In future the obtained data will be used for calculating rainfall triggering thresholds of landslides, assessment and calibration for the territory of Georgia using satellite observations and receiver operating characteristic (ROC) approach in order to assess in a quantitative way correctness of the predicted critical precipitation values [7].

Conclusions

In the paper are assessed the rainfall conditions, which can lead to initiation of mass-movement using limited terrestrial and satellite-based data on the summary rainfall (mm) and its duration (h) obtained in Georgia. It is shown that satellite precipitation data allow to substitute for surface rain gauge data. The landslide activating precipitation threshold line follows the equation: $E=a \cdot D^b$, where E is the volume of accumulated precipitation, D is the duration of rain; a and b are parameters. The parameters of above equation for Georgia and its main regions as well as their statistical characteristics are calculated and compared to data for similar climatic zones in the world. The results obtained in this study indicate the prospects for further expansion of work for a more detailed study of the influence of precipitation on the activation of landslides in Georgia.

This work was supported by Shota Rustaveli National Science Foundation of Georgia (SRNSFG), Grant number FR-19-8190, "Assessment of landslide and mudflow hazards for Georgia using stationary and satellite rainfall data".

გეოფიზიკა

წვიმებით გამოწვეული მეწყრების აქტივაციის კრიტიკული ზღურბლის შეფასება სატელიტური და მიწისპირა მონაცემების საფუძველზე

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საქართველო, მთიანი რელიეფის, აქტიური მიწათსარგებლობის, მოსახლეობის ზრდის, მოწყვლადი საინჟინრო ინფრასტრუქტურული ნაგებობების პირობებში, მსოფლიოში ერთ-ერთ მეწყერსაშიშ რეგიონს წარმოადგენს. რისკის შემცირებისათვის მნიშვნელოვანია სტაციონარული და დინამიკური მეწყერსაშიში ზონირების რუკის შექმნა, მათ შორის, ნალექიანობის გავლენით. ინტენსიური ატმოსფერული ნალექი, მათი ხანგრძლივობა მეწყრული პროცესების ძირითადი მაპროვოცირებელი ფაქტორია. შრომა მიზნად ისახავს ნალექების რაოდენობის და ინტენსივობის იმ კრიტიკული ზღურბლის შეფასებას, რამაც შეიძლება მეწყრული პროცესების აქტივაცია გამოიწვიოს. ეს მიდგომა შესაძლოა გამოყენებულ იქნეს მსოფლიოს იმ რეგიონებისთვის, სადაც ატმოსფერული ნალექების მიწისპირა მონაცემები შეზღუდულია და შეუძლებელია მათი ინტენსივობისა და ხანგრძლივობების შეფასება.

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Received April, 2023