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Assessment of the Relationship Between Daily and Total Multi-Day Precipitation Sums and Landslide Activation in the Regions of Georgia

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ABSTRACT

A detailed statistical analysis of the relationship between daily and accumulated multi-daily precipitation sums and the number of landslides in 12 regions of Georgia is presented. Landslide data with a known days of activation were used (a total of 519 landslide events from 1968 to 2022). For the analysis, the precipitation sum for the day of landslide activation (P1) was determined, as well as the accumulated precipitation sum for 3 days (P3), 5 (P5), 7 (P7), 10 (P10), 20 (P20) and 30 days (P30) prior to landslide occurrence (including the day with landslide).
Specifically, the following results were obtained. The relationship between average precipitation values (threshold values) and daily precipitation duration during the day of landslide activation and before 3, 5...30 days of landslides activation in Georgia and its individual regions was determined. It was found that, overall, in eastern Georgia (including the Samtskhe-Javakheti region), landslide activation occurs with significantly lower precipitation sums than in western Georgia. The average P1 values are 8.8 and 11.9 mm, respectively, and the P30 values are 75.2 and 156.6 mm. The linear correlation between the number of landslides and the P1...P30 values across the regions of Georgia is high for P1,P3,P20 and P30 and moderate for P5,P7 and P10. For Georgia the sum of precipitation associated with landslides exceeds the general long-term mean daily precipitation sum by approximately 95%. For Georgia as a whole and its Eastern and Western parts, the dependence of the number of landslides on the P1 ... P30 values have the form of a third-degree polynomial (sequentially: slight increase – plateau – strong increase). For P1 values, the precipitation sum plateau, after which a strong increase in the number of landslides begins, covers the range from 6.3 to 30.8 mm, and for P30 – from 62.4 to 189.5 mm (the total relative number of landslides is ≈ 42.1–43.3%).

Keywords: *landslides, natural disaster, atmospheric precipitations, statistical analysis.*

Introduction

Landslides, as a type of natural disaster, are common almost everywhere [1–5], including in Georgia [6–12]. Landslides often lead to the destruction of residential buildings and utility infrastructure, serious damage to roads, railways, and bridges, the failure of various life support systems, significant material damage, threats to human life and health, etc. [9, 10, 13].

For example, according to data from the Geological Department of the Environmental Protection Agency of Georgia, the annual number of activated and newly formed landslides (LS) for the period from 1995 to 2024 ranged from 56 to 1,360, with an average annual value of 581 [10, 12].

Landslide activation is associated with many natural and anthropogenic factors, such as slope steepness, lithology, vegetation cover, seismic activity, construction work near landslide-prone areas, and others. Landslide formation is often accelerated by prolonged, intense, or extreme precipitation [14–15].

In recent years, a number of studies have been conducted in Georgia to identify the short-term (hours, days, months) [16–20] and long-term (years, climate scale) effects of precipitation on landslide and mudflow activation [21–28]. These studies used landslide and mudflow data presented in [9, 10], as well as ground-based, radar, and satellite precipitation data, taking into account their representativeness depending on the distance to the measurement point [29–33]. In particular, in our recent work [28], we conducted an initial statistical assessment of landslide hazard using 11 weighted objective factors (including annual precipitation). Using machine learning methods, we obtained a landslide hazard map that correlates well with observed data, confirming the reliability and robustness of the proposed model even in the case of unbalanced data.

In the paper [20] are assessed the rainfall conditions, which can lead to initiation of mass-movement using limited terrestrial data on the summary rainfall (mm) and its duration (h) obtained in Georgia. It is shown that 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 10 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.

A detailed statistical analysis of the relationship between monthly and accumulated multi-month precipitation sums and the number of landslides in 12 regions of Georgia is presented. Landslide data with a known month and year of activation were used (a total of 788 landslide events from 1961 to 2022) was presented in [21]. For the analysis, the precipitation sum for the month of landslide activation (P1) was determined, as well as the accumulated precipitation sum for the month of activation and for 1 month (P2), 2 months (P3), …, and 11 months (P12) prior to landslide occurrence.

Specifically, the following results were obtained. The relationship between average precipitation values (threshold values) and monthly precipitation duration during the month of landslide activation and before landslide activation in Georgia and its individual regions was determined. It was found that, overall, in eastern Georgia (including the Samtskhe-Javakheti region), landslide activation occurs with significantly lower precipitation sums than in western Georgia. The average P1 values are 76 and 156 mm, respectively, and the P12 values are 684 and 1588 mm. The linear correlation between the number of landslides and the P1…P12 values across the regions of Georgia is low for P1 and moderate for P2…P12. The sum of precipitation associated with landslides exceeds the general long-term average monthly precipitation by approximately 16%. For Georgia as a whole, the dependence of the number of landslides on the P1 and P12 values has the form of a fifth-order polynomial (sequentially: slight increase – plateau – strong increase). For P1 values, the precipitation sum plateau, after which a strong increase in the number of landslides begins, covers the range from 62 to 149 mm, and for P12 – from 914 to 1588 mm (the number of landslides is ≈ 108–114) [21].

This work is a continuation of previous studies [20, 21] related to the study of the relationship between precipitation and the activation of landslide processes on a time scale of 1, 3, 5, 7, 10, 20 and 30 days (or 24, 72, 120, 168, 240, 480 and 720 hours). 1 day (24 hour): sum of precipitation in the day with landslide occurrence; 3 days (72 hour) -30 days (720 hour): cumulative precipitation sums in the day and up to the day in which the landslide occurred.

Some results of statistical analysis of the relationship between daily and cumulative multi-daily sums of precipitation with the number of landslides in the 12 regions of Georgia are presented below.

Study area, material and methods

Study area is Georgia and their 12 regions (Abkhazeti; Samegrelo-Zemo Svaneti; Guria; Adjara; Samtskhe-Javakheti; Kvemo Kartli; Tbilisi; Kakheti; Mtskheta-Mtianeti; Shida Kartli; Imereti; Racha-Lechkhumi and Kvemo Svaneti) – Table 1, Fig. 1.

Data on the number of landslides with the known days of their activation were taken from the catalog [9]. Period of observation - from 1968 to 2022; landslide occurrence height – from 5 (Abkh) to 3773 (M-M) m; number of landslides - from 5 (KK) to 89 (Adj), total – 519 (Table 1, Fig. 1).

Data National Environmental Agency about daily sum of atmospheric precipitations for 68 meteorological stations are used. List of meteorological stations, their coordinates and locations in Table 2 and Fig. 2 are presented. Data from 80 meteorological stations on daily precipitation values for the period from 1960 to 1989 were also used for comparison with data on precipitation associated with landslides.

In the proposed work the analysis of data is carried out with the use of the standard statistical analysis methods [34].

The following designations will be used below: Max - maximal values; Min - minimal values; Mean - average values; P_M - average values of precipitation related to landslide processes; P* - average values of precipitation in 1960-1989; St Dev - standard deviation; St Err – standard error; R^2 – coefficient of determination; R – coefficient of linear correlation; R' - index of correlation for nonlinear equations; 99%(+/-) - 99% confidence interval of the mean; Lat - north latitude, N°; Lon - east longitude, E°; H – altitude above sea level, m; landslide – LS; P (or E for precipitations duration D in hour) - precipitation sum, mm; P1 – precipitation sum in day with LS activation, mm; P3, P5, P7, P10, P20 and P30 - cumulative precipitation sums in the day with landslide and 3…30 days up to landslide occurrence cumulative precipitation sums in the day and up to the day in which the landslide occurred; N(LS) – number of landslides; Eastern Georgia – E Geo; Western Georgia - W Geo.

Landslide activation thresholds were determined using two empirical methods.

1)The precipitation amount for Georgia, its eastern and western parts, and regions was determined by the precipitation amount for 30 consecutive days prior to the landslide and on the day of the landslide (30 days in total). The threshold equations are:

$P = a \cdot x + b$, where P is the total precipitation amount (mm), x is the duration (days), a is the slope of the threshold curve, and b is the free term of the equation;

$E = a \cdot D^b$, where E is the total precipitation amount (mm), D is the duration (hours), a and b are parameters.

The a and b coefficients were determined for average precipitation values.

2) The precipitation threshold for Georgia and its eastern and western parts was estimated by determining the number of landslides in seven precipitation ranges in ascending order. N(LS) = f(P), where N(LS) is the relative number of landslides, in %; f(P) is the precipitation function. All equations are represented by third-degree polynomials.

Table 1. Study regions, period and number of years of observation, number of landslides and their heights for known days of their occurrence in Georgia.

Region	Region, Abbr.	Observation period	Number of years	Number of landslides	Landslide occurrence height, m		
					Min	Max	Mean
1.Abkhazeti	Abkh	1968-1980	3	48	5	637	217
2.Samegrel	S-ZS	1979-2022	12	58	33	2278	696
3.Guria	Gur	2009-2022	11	40	30	1135	233
4.Adjara	Adj	1968-2022	11	89	15	1846	639
5.Samtskhe-	S-J	1973-2022	12	47	797	2468	1282
6.Kvemo	KK	2002-2022	5	5	668	1295	868
7.Tbilisi	Tb	2001-2022	11	47	435	1376	773
8.Kakheti	Kakh	2016-2022	5	9	500	1974	968
9.Mtskheta-	M-M	2013-2022	9	22	455	3773	1476
10.Shida	Sh K	2007-2022	10	16	548	986	781
11.Imereti	Im	1968-2022	13	75	29	980	416
12.Racha-Lechkhumi	R-L KS	2005-2022	13	63	372	1576	906
Georgia	Geo	1968-2022	28	519	5	3773	694

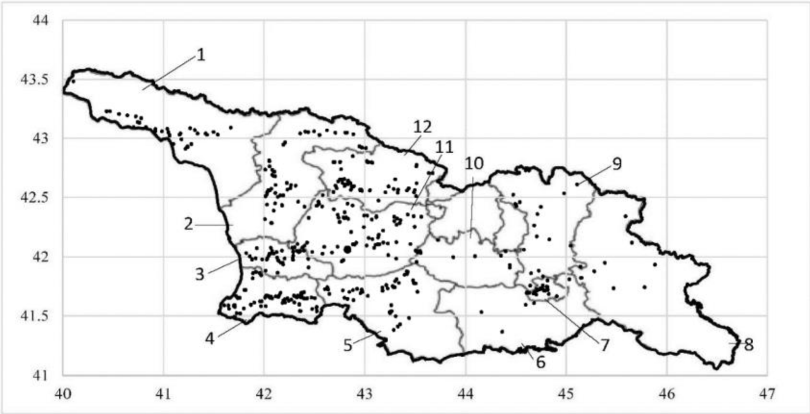

Fig. 1. Landslide distribution map for known days of occurrence. The numbers indicating the contours of the regions correspond to the numbers before the names of the regions in Table 1.

Table 2. List of meteorological stations whose precipitation data were used for known days of landslide occurrence. AWS - automatic weather station

Station	Lon, N°	Lat, E°	H, m	Station	Lon, N°	Lat, E°	H, m
Abastumani	41.75	42.83	1265	Legakhare	42.6	42.17	267
Achadara	43.04	40.99	1280	Luji	42.85	43.02	2587
Akhalkalaki	41.41	43.49	1716	Magaroskari	42.29	44.87	958
Akhaltsikhe	41.64	42.99	989	Martvili	42.38	42.28	176
Alpana	42.56	42.83	560	Martvili AWS	42.38	42.28	176
Ambrolauri	42.52	43.15	544	Mestia AWS	43.04	42.73	1441
Babushera	42.87	41.14	6	Mirveti	41.53	41.72	60
Bakhmaro AWS	41.85	42.32	1926	Mukhrani_AWS	41.93	44.58	550
Bakuriani	41.74	43.52	1665	Nokalakevi	42.36	42.19	115
Batumi_Airport	41.6	41.61	11	Orbeti_AWS	41.66	44.53	1306
Bichvinta	43.15	40.34	4	Orpiri_AWS	42.35	42.86	457
Borjomi	41.84	43.38	790	Pasanauri	42.35	44.69	1070
Chkhalta	43.1	41.68	544	Sabueti_Mta	42.03	43.47	1242
Chkhari AWS	42.27	43.02	465	Sachkhere	42.33	43.41	455
Chokhatauri	42.02	42.24	144	Sagarejo	41.74	45.33	802
Dimi AWS	42.12	42.85	200	Samgori	41.72	44.9	549
Dusheti_AWS	42.09	44.71	1038	Samtredia	42.16	42.34	28
Gagra	43.28	40.27	7	Samtredia_AWS	42.2	42.42	42
Glola	42.7	43.64	1280	Senaki	42.27	42.06	34
Gordi AWS	42.47	42.58	988	Senaki_AWS	42.31	42.12	388
Gori	41.98	44.11	609	Shovi	42.7	43.68	1509
Gudauri_AWS	42.5	44.51	2915	Sokhumi	43.01	41.04	116
Gudauta	43.1	40.64	46	Tbilisi	41.76	44.76	427
Gvandra	43.04	40.92	109	Telavi	41.92	45.48	568
Keda	41.6	41.94	256	Tianeti	42.11	44.97	1099
Khaishi	42.94	42.19	730	Tkibuli	42.35	43	593
Kharagauli AWS	42.03	43.23	597	Tsageri_AWS	42.64	42.79	621
Khashuri	41.99	43.6	690	Tsalka	41.6	44.09	1458
Khertvisi	41.48	43.29	1250	Tseva_AWS	42.12	43.17	448
Khulo	41.64	42.31	946	Tskaltubo_AWS	42.35	42.66	452
Kobi AWS	42.56	44.52	1973	Uravi_AWS	42.65	43.32	1742
Kobuleti	41.85	41.78	7	Zemo Chaladidi	42.22	41.79	4
Kutaisi	42.26	42.7	113	Zestafoni	42.1	43.05	160
Lata	43.03	41.48	299	Zugdidi	42.51	41.87	118

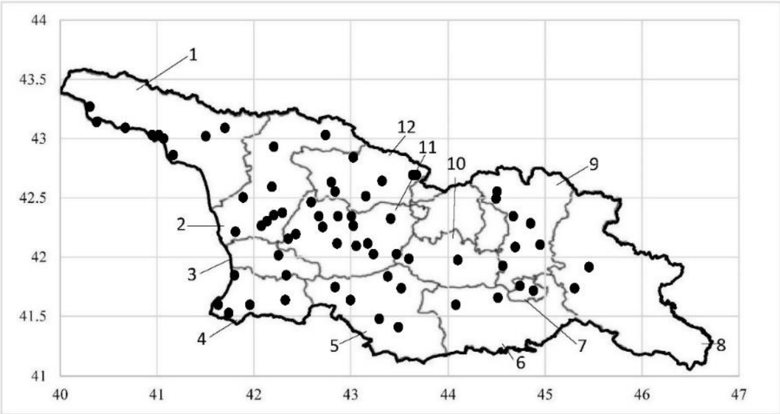

Fig. 2. Distribution map of meteorological stations for known days of landslide occurrence.

The degree of correlation was determined in accordance with [34]: very high correlation ($0.9 \le R \le 1.0$); high correlation ($0.7 \le R < 0.9$); moderate correlation ($0.5 \le R < 0.7$); low correlation ($0.3 \le R < 0.5$); negligible correlation ($0 \le R < 0.3$).

Results and discussion

Results in Tables 3 – 23 and Fig. 3 - 14 are presented. In Tables 3-18 statistical characteristics of the cumulative sum of precipitation related to landslide processes in Georgia, its regions as well as in its eastern and western parts are presented.

Table 3. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Georgia.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	0.1	1.8
Max	222.6	366.6	366.6	416.4	416.4	702.2	798.6
P_M	10.8	22.3	31.4	40.4	54.1	98.4	132.7
St Dev	22.1	39.5	44.5	51.3	59.1	90.5	105.0
St Err	1.0	1.7	2.0	2.3	2.6	4.0	4.6
Count	519	519	519	519	519	519	519
99%(+/-)	2.5	4.5	5.0	5.8	6.7	10.2	11.9
P*	3.3	9.9	16.5	23.1	33.0	65.9	98.9
P_M/P*	3.27	2.25	1.90	1.75	1.64	1.49	1.34

Georgia. P1 values vary from 0.0 mm (252 cases out of those observed) to 222.6 mm, with an average value of 10.8 mm; P30 values vary from 1.8 mm to 798.6 mm, with an average value of 132.7 mm (Table 3, catalog [9]).

The ratio P_M/P* varies from 1.34 (for P30) to 3.27 (for P1). Generally, cumulative sum of landslide-related (mean) precipitation in Georgia is higher than their average long-term values in 1960-1989 (P*). An example is shown in Fig. 3. The P_M/P* average value is 1.95.

Fig. 4 and 5 show examples of distribution maps of P5 and P30 values in the territory of Georgia. In particular, as can be seen from these Figures and Table 4, the distribution of P5 and P30 values in the study area is extremely uneven. Values of P5 vary from 0.0 mm (65 cases out of those observed) to 366.6 mm (Im, Kveda Gordi, landslides activation in October 07, 2013), with an average value of 31.4 mm (Table 3, Fig. 4, catalog [9]); P30 values vary from 1.8 mm (Sh K, Kaspi, February 01, 2019; Kakh, Manavi, January 14, 2020) to 798.6 mm (Adj, Keda, village lower Agara, October 16, 2017), with an average value of 132.7 mm (Table 3, Fig. 5, catalog [9]).

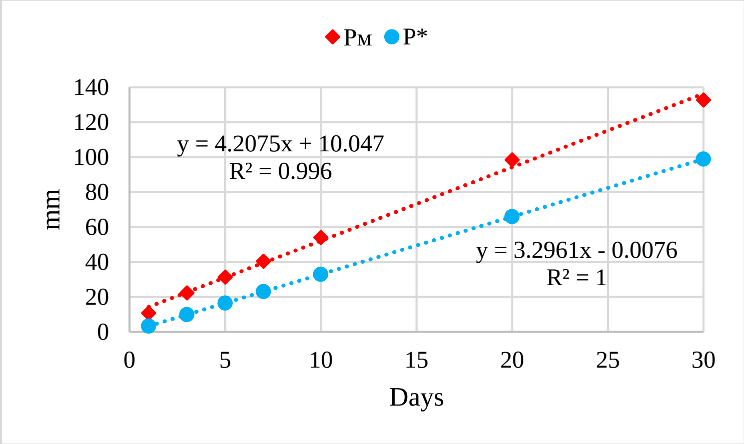

Fig. 3. Cumulative sum of landslide-related (P_M) and average (P*) precipitation in Georgia (very high correlation).

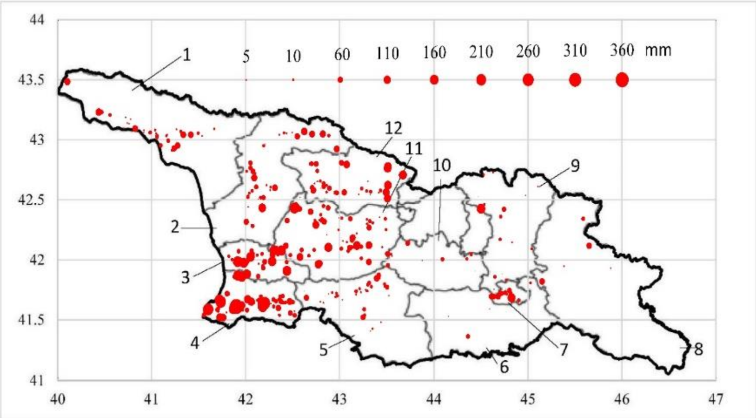

Fig. 4. Map of distribution of 5 days cumulative precipitation up to landslide occurrence (P5). (Total including the day of the landslide).

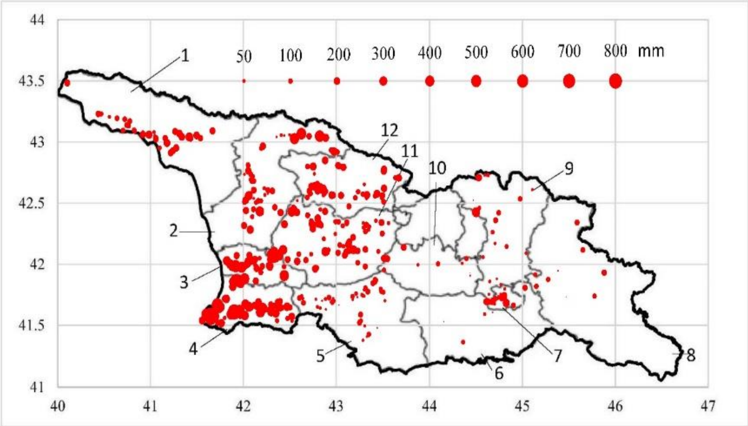

Fig. 5. Map of distribution of 30 days cumulative precipitation up to landslide occurrence (P30). (Total including the day of the landslide).

In Tables 4-18 statistical characteristics of the cumulative sum of precipitation related to landslide processes in 12 regions of Georgia, as well as in its eastern and western parts are presented.

Table 4. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Abkhazeti.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).					
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0.05	4.6	35.5
Max	37.8	78.4	87.2	127.9	194.7	267.3	273.3
P_M	4.1	12.5	22.8	32.3	44.3	93.9	122.9
St Dev	9.1	20.2	24.5	31.4	41.2	52.6	54.7
St Err	1.3	2.9	3.6	4.6	6.0	7.7	8.0
Count	48	48	48	48	48	48	48
99%(+/-)	3.4	7.6	9.2	11.8	15.5	19.8	20.5
P*	4.4	13.2	22.0	30.8	44.0	88.1	132.1
P_M/P*	0.93	0.95	1.04	1.05	1.01	1.07	0.93

Abkhazeti. P1 values vary from 0.0 mm (31 cases out of those observed) to 37.8 mm (Amtqeli, August 05, 1980), with an average value of 4.1 mm; P30 values vary from 35.5 mm (Aleksandrovka, July 20, 1980) to 273.3 mm (Zenobani, August 13, 1980), with an average value of 122.9 mm (Table 4, catalog [9]).

The ratio P_M/P* varies from 0.93 (for P1 and P30) to 1.07 (for P20). Generally, in Abkhazeti the specified parameters practical not differ from each other. The P_M/P* average value is 1.00.

Table 5. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Samegrelo-Zemo Svaneti.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).					
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	2	7
Max	52.6	75.4	126.0	205.7	226.9	285.4	448.9
P_M	6.5	16.3	22.0	34.7	48.8	97.1	133.7
St Dev	12.0	22.8	29.3	38.9	47.7	71.6	99.7
St Err	1.6	3.0	3.9	5.2	6.3	9.5	13.2
Count	58	58	58	58	58	58	58
99%(+/-)	4.1	7.8	10.0	13.3	16.3	24.4	34.0
P*	4.5	13.6	22.6	31.7	45.3	90.6	135.8
P_M/P*	1.44	1.20	0.97	1.09	1.08	1.07	0.98

Samegrelo-Zemo Svaneti. P1 values vary from 0.0 mm (34 cases out of those observed) to 52.6 mm (Mestia-Mulakhi-Ushguli road, village near Mulakhi, September 07, 2017), with an average value of 6.5 mm; P30 values vary from 7.0 mm (Chkvaleri, September 24, 2015) to 448.9 mm (Mestia-Mulakhi-Ushguli road, village near Mulakhi, September 07, 2017), with an average value of 133.7 mm (Table 5, catalog [9]).

The ratio P_M/P* varies from 0.97 (for P5) to 1.44 (for P1). Generally, cumulative sum of landslide-related precipitation in Samegrelo-Zemo Svaneti is slightly higher than their average long-term values. The P_M/P* average value is 1.12.

Table 6. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Guria.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).					
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	3	13.6
Max	70	160	187.4	208	244.3	498.2	498.7
P_M	12.2	31.0	44.9	58.2	75.5	132.0	179.6
St Dev	20.6	46.9	53.9	61.2	70.3	112.6	115.7
St Err	3.3	7.5	8.6	9.8	11.3	18.0	18.5
Count	40	40	40	40	40	40	40
99%(+/-)	8.5	19.3	22.3	25.2	29.0	46.4	47.7
P*	5.0	15.0	25.1	35.1	50.1	100.3	150.5
P_M/P*	2.44	2.07	1.79	1.66	1.51	1.32	1.19

Guria. P1 values vary from 0.0 mm (20 cases out of those observed) to 70.0 mm (Bayleti, Zoti, October 16, 2017), with an average value of 12.2 mm; P30 values vary from 13.6 mm (Mtispiri, August 09, 2015) to 498.7 mm (Konchkati, September 24, 2022), with an average value of 179.6 mm (Table 6, catalog [9]).

The ratio Pм/P* varies from 1.19 (for P30) to 2.44 (for P1). Generally, cumulative sum of landslide-related precipitation in Guria is higher than their average long-term values. The Pм/P* average value is 1.71.

Table 7. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Adjara.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	3	26.2
Max	222.6	366.6	366.6	416.4	416.4	702.2	798.6
Pм	20.3	41.1	55.1	65.8	82.6	154.5	210.3
St Dev	35.0	65.3	70.5	80.7	93.1	143.3	161.8
St Err	3.7	7.0	7.5	8.6	9.9	15.3	17.2
Count	89	89	89	89	89	89	89
99%(+/-)	9.6	17.9	19.4	22.1	25.6	39.4	44.4
P*	5.7	17.0	28.4	39.8	56.8	113.7	170.6
Pм/P*	3.56	2.42	1.94	1.65	1.45	1.36	1.23

Adjara. P1 values vary from 0.0 mm (31 cases out of those observed) to 222.6 mm (Keda, village lower Agara, October 16, 2017), with an average value of 20.3 mm; P30 values vary from 26.2 mm (Ghorjomeladzeebi, July 14, 2021) to 798.6 mm (Keda, village lower Agara, October 16, 2017), with an average value of 210.3 mm (Table 7, catalog [9]).

The ratio Pм/P* varies from 1.23 (for P30) to 3.56 (for P1). Generally, cumulative sum of landslide-related precipitation in Adjara is higher than their average long-term values. The Pм/P* average value is 1.95.

Table 8. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Samtskhe-Javakheti.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	2.9	6.35
Max	60.0	62.0	69.3	74.4	76.8	97.9	121.0
Pм	5.3	9.7	13.8	16.9	20.9	40.5	60.7
St Dev	11.1	12.6	16.2	18.0	20.0	24.1	33.5
St Err	1.6	1.9	2.4	2.6	2.9	3.6	4.9
Count	47	47	47	47	47	47	47
99%(+/-)	4.2	4.8	6.1	6.8	7.6	9.1	12.7
P*	2.0	6.0	10.0	14.0	20.1	40.2	60.2
Pм/P*	2.65	1.62	1.38	1.21	1.04	1.01	1.01

Samtskhe-Javakheti. P1 values vary from 0.0 mm (19 cases out of those observed) to 60.0 mm (Borjomi, August 04, 2016), with an average value of 5.3 mm; P30 values vary from 6.35 mm (Adigeni, February 06, 2020) to 121.0 mm (Aspindza, May 27, 1976), with an average value of 60.7 mm (Table 8, catalog [9]).

The ratio Pм/P* varies from 1.01 (for P20 and P30) to 2.65 (for P1). Generally, cumulative sum of landslide-related precipitation in Samtskhe-Javakheti is higher than their average long-term values. The Pм/P* average value is 1.42.

Table 9. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Kvemo Kartli.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	1.6	1.6	1.6	5
Max	1.0	20.2	33.8	38.0	58.8	101.2	131.8
P_M	0.2	4.4	10.4	20.1	27.1	47.2	55.6
St Dev	0.4	8.9	14.3	16.5	25.3	42.3	52.6
St Err	0.2	4.4	7.2	8.3	12.6	21.1	26.3
Count	5	5	5	5	5	5	5
99%(+/-)	0.6	11.4	18.4	21.3	32.6	54.4	67.7
P*	1.7	5.2	8.6	12.1	17.2	34.5	51.8
P_M/P*	0.12	0.85	1.21	1.66	1.58	1.37	1.07

Kvemo Kartli. P1 values vary from 0.0 mm (4 cases out of those observed) to 1.0 mm (Sagharasheni, April 11, 2019), with an average value of 0.2 mm; P30 values vary from 5.0 mm (Gomareti, February 09, 2022) to 131.8 mm (Martkhopi, September 02, 2002), with an average value of 55.6 mm (Table 9, catalog [9]).

The ratio P_M/P* varies from 0.12 (for P1) to 1.66 (for P7). Generally, cumulative sum of landslide-related precipitation in Kvemo Kartli is slightly higher than their average long-term values. The P_M/P* average value is 1.12.

Table 10. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Tbilisi.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	0.1	6.2
Max	93.5	126.2	129.4	214.2	221.5	228.6	237.6
P_M	12.4	16.4	20.3	26.1	43.4	71.8	84.9
St Dev	21.2	24.5	25.1	34.1	35.7	49.3	46.6
St Err	3.1	3.6	3.7	5.0	5.3	7.3	6.9
Count	47	47	47	47	47	47	47
99%(+/-)	8.1	9.3	9.5	13.0	13.6	18.7	17.7
P*	1.7	5.0	8.3	11.6	16.5	33.1	49.6
P_M/P*	7.29	3.28	2.45	2.25	2.63	2.17	1.71

Tbilisi. P1 values vary from 0.0 mm (24 cases out of those observed) to 93.5 mm (Krtsanisi ravine, May 13, 2012), with an average value of 12.4 mm; P30 values vary from 6.2 mm (Vere valley, new road, January 10, 2017) to 237.6 mm (Krtsanisi ravine, May 13, 2012), with an average value of 84.9 mm (Table 10, catalog [9]).

The ratio P_M/P* varies from 1.71 (for P30) to 7.29 (for P1). Generally, cumulative sum of landslide-related precipitation in Tbilisi is significantly higher than their average long-term values. The P_M/P* average value is 3.11.

Table 11. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Kakheti.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	1.8	1.8
Max	30.1	62.4	66.4	83.2	95.55	123.9	133.1
P_M	6.7	13.0	22.7	31.5	36.1	58.8	80.1
St Dev	10.6	21.3	27.6	31.8	32.6	44.1	46.0
St Err	3.8	7.5	9.7	11.2	11.5	15.6	16.3
Count	9	9	9	9	9	9	9
99%(+/-)	9.7	19.4	25.1	28.9	29.7	40.2	41.9
P*	2.0	6.1	10.2	14.2	20.3	40.7	61.0
P_M/P*	3.35	2.13	2.23	2.22	1.78	1.44	1.31

Kakheti. P1 values vary from 0.0 mm (4 cases out of those observed) to 30.1 mm (Gombori Pass, near Ujarma Castle, October 03, 2017), with an average value of 6.7 mm; P30 values vary from 1.8 mm (Manavi, January 14, 2020) to 133.1 mm (Kvareli, May 13, 2022), with an average value of 80.1 mm (Table 11, catalog [9]).

The ratio P_M/P^* varies from 1.31 (for P30) to 3.35 (for P1). Generally, cumulative sum of landslide-related precipitation in Kakheti is significantly higher than their average long-term values. The P_M/P^* average value is 2.07.

Table 12. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Mtskheta-Mtianeti.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	4.4	7.3
Max	59.6	154.8	157.6	176.2	180.4	230.4	329
P_M	8.2	16.8	22.3	29.2	39.7	56.0	81.2
St Dev	15.6	35.3	38.2	45.7	49.1	56.0	75.0
St Err	3.4	7.7	8.3	10.0	10.7	12.2	16.4
Count	22	22	22	22	22	22	22
99%(+/-)	8.8	19.9	21.5	25.7	27.6	31.5	42.2
P*	2.5	7.4	12.3	17.2	24.6	49.2	73.8
P_M/P^*	3.28	2.27	1.81	1.70	1.61	1.14	1.10

Mtskheta-Mtianeti. P1 values vary from 0.0 mm (12 cases out of those observed) to 59.6 mm (Gudauri-Kobi highway way, August 09, 2018), with an average value of 8.2 mm; P30 values vary from 7.3 mm (Gudauri-Kobi highway way, March 03, 2017) to 329.0 mm (Gudauri-Kobi highway way, August 09, 2018), with an average value of 81.2 mm (Table 12, catalog [9]).

The ratio P_M/P^* varies from 1.10 (for P30) to 3.28 (for P1). Generally, cumulative sum of landslide-related precipitation in Mtskheta-Mtianeti is higher than their average long-term values. The P_M/P^* average value is 1.84.

Table 13. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Shida Kartli.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	0.4	1.8
Max	39.4	39.7	55.1	70.7	86.3	164.7	170.9
P_M	6.8	11.2	16.9	21.2	31.8	57.5	76.1
St Dev	11.3	13.4	18.3	20.6	28.7	44.8	53.6
St Err	2.9	3.5	4.7	5.3	7.4	11.6	13.8
Count	16	16	16	16	16	16	16
99%(+/-)	7.5	8.9	12.2	13.7	19.1	29.8	35.7
P*	1.7	5.1	8.5	11.9	17.0	34.1	51.2
P_M/P^*	4.00	2.20	1.99	1.78	1.87	1.69	1.49

Shida Kartli. P1 values vary from 0.0 mm (8 cases out of those observed) to 39.4 mm (Abano, June 16, 2016), with an average value of 6.8 mm; P30 values vary from 1.8 mm (Kaspi, February 01, 2019) to 170.9 mm (Chumateleti, March 15, 2022), with an average value of 76.1 mm (Table 13, catalog [9]).

The ratio P_M/P^* varies from 1.49 (for P30) to 4.00 (for P1). Generally, cumulative sum of landslide-related precipitation in Shida Kartli is significantly higher than their average long-term values. The P_M/P^* average value is 2.14.

Table 14. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Imereti.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).					
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	23.2	32
Max	100.7	180.4	189.8	203.3	258.8	409.4	414.4
P_M	10.8	25.4	37.8	47.9	62.0	105.1	142.5
St Dev	21.5	38.9	42.1	45.8	52.0	78.0	79.6
St Err	2.5	4.5	4.9	5.3	6.0	9.1	9.3
Count	75	75	75	75	75	75	75
99%(+/-)	6.4	11.6	12.6	13.7	15.6	23.4	23.8
P*	3.7	11.1	18.5	25.9	37.0	74.0	111.0
P_M/P*	2.92	2.29	2.04	1.85	1.68	1.42	1.28

Imereti. P1 values vary from 0.0 mm (32 cases out of those observed) to 100.7 mm (Khoni, July 08, 2016), with an average value of 10.8 mm; P30 values vary from 32.0 mm (Kinchkha, May 21, 2013) to 414.4 mm (Samtredia, noga; Samtredia, village partial field, May 21, 2013), with an average value of 142.5 mm (Table 14, catalog [9]).

The ratio Pм/P* varies from 1.28 (for P30) to 2.92 (for P1). Generally, cumulative sum of landslide-related precipitation in Imereti is higher than their average long-term values. The Pм/P* average value is 1.93.

Table 15. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Racha-Lechkhumi and Kvemo Svaneti.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).					
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	8.4	19.3
Max	84.5	114.5	128.5	159.0	159.0	203.7	224.9
Pм	11.7	20.6	28.3	35.2	51.8	92.9	123.6
St Dev	23.4	31.9	36.5	40.1	43.5	55.6	58.2
St Err	3.0	4.0	4.6	5.1	5.5	7.1	7.4
Count	63	63	63	63	63	63	63
99%(+/-)	7.7	10.4	11.9	13.1	14.2	18.2	19.0
P*	3.2	9.5	15.8	22.1	31.6	63.2	94.7
P_M/P*	3.66	2.17	1.79	1.59	1.64	1.47	1.31

Racha-Lechkhumi and Kvemo Svaneti. P1 values vary from 0.0 mm (33 cases out of those observed) to 84.5 mm (Patara Ghebi, Ghebi, Nakieti, Shovi, July 29, 2020), with an average value of 11.7 mm; P30 values vary from 19.3 mm (Likheti, August, 13, 2017) to 224.9 mm (Komandeli, October 01, 2021), with an average value of 123.6 mm (Table 15, catalog [9]).

The ratio Pм/P* varies from 1.31 (for P30) to 3.66 (for P1). Generally, cumulative sum of landslide-related precipitation in Racha-Lechkhumi and Kvemo Svaneti is higher than their average long-term values. The Pм/P* average value is 1.95.

Table 16. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Eastern Georgia.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).					
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	0.1	1.8
Max	93.5	154.8	157.6	214.2	221.5	230.4	329.0
Pм	8.8	14.1	18.9	24.1	33.2	57.1	75.2
St Dev	16.4	22.4	24.6	30.3	33.6	45.4	50.6
St Err	1.4	1.9	2.0	2.5	2.8	3.8	4.2
Count	146	146	146	146	146	146	146
99%(+/-)	3.5	4.8	5.3	6.5	7.2	9.7	10.8
P*	2.0	6.0	10.0	13.9	19.9	39.9	59.8
P_M/P*	4.40	2.35	1.89	1.73	1.67	1.43	1.26

Eastern Georgia. P1 values vary from 0.0 mm (181 cases out of those observed) to 93.5 mm (Tbilisi, Krtsanisi ravine, May 13, 2012), with an average value of 8.8 mm; P30 values vary from 1.8 mm (Shida Kartli, Kaspi, February 01, 2019; Kakheti, Manavi, January 14, 2020) to 329.0 mm (Mtskheta-Mtianeti, Gudauri-Kobi highway way, August 09, 2018), with an average value of 75.2 mm (Table 16, catalog [9]).

The ratio Pм/P* varies from 1.26 (for P30) to 4.40 (for P1). Generally, cumulative sum of landslide-related precipitation in Eastern Georgia is significantly higher than their average long-term values. The Pм/P* average value is 2.10.

Table 17. Statistical characteristics of the cumulative sum of precipitation related to landslide processes in Western Georgia.

	Cumulative precipitation sum, mm. (1 - Day of landslide occurrence).						
Day	1	3	5	7	10	20	30
Min	0	0	0	0	0	2	7
Max	222.6	366.6	366.6	416.4	416.4	702.2	798.6
Pм	11.9	26.1	37.1	47.5	62.8	115.5	156.6
St Dev	24.2	44.2	49.5	56.3	65.0	98.3	112.6
St Err	1.3	2.3	2.6	2.9	3.4	5.1	5.8
Count	373	373	373	373	373	373	373
99%(+/-)	3.2	5.9	6.6	7.5	8.7	13.1	15.0
P*	4.4	13.3	22.1	30.9	44.2	88.4	132.5
Pм/P*	2.70	1.96	1.68	1.54	1.42	1.31	1.18

Western Georgia. P1 values vary from 0.0 mm (71 cases out of those observed) to 222.6 mm (Adjara, Keda, village lower Agara, October 16, 2017), with an average value of 11.9 mm; P30 values vary from 7.0 mm (Samegrelo-Zemo Svaneti, Chkvaleri, September 24, 2015) to 798.6 mm (Adjara, Keda, village lower Agara, October 16, 2017), with an average value of 156.6 mm (Table 17, catalog [9]).

The ratio Pм/P* varies from 1.18 (for P30) to 2.70 (for P1). Generally, cumulative sum of landslide-related precipitation in Western Georgia is higher than their average long-term values. The Pм/P* average value is 1.68.

Thus, on average, for individual regions of Georgia (with the exception of Abkhazeti, Pм/P* average value is 1.00, Table 4), Georgia as a whole and its eastern and western parts cumulative sum of landslide-related precipitation is higher, чем their average long-term values (Table 3, Tables 5-17, Fig. 3). The lowest value of the average ratio Pм/P* is observed in Samegrelo-Zemo Svaneti (Table 5) and Kvemo Kartli (Table 9) - 1.12 each, the greatest - in Tbilisi (3.11, Table 10). In Georgia this ratio is 1.95 (Table 3), in its eastern and western parts – 2.10 and 1.68 respectively (Tables 16 and 17).

A refinement of the results of work [20] shows that in order of increasing precipitation amount, based on P30 values, regions of Georgia can be grouped as follows (Tables 4-15): 1 – Kvemo Kartli (55.6 mm); 2 - Samtskhe-Javakheti (60.7 mm), 3- Shida Kartli (76,1 mm), 4-Kakheti (80.1 mm), 5- Mtskheta-Mtianeti (81.2 mm), 6- Tbilisi (84.9 mm), 7- Abkhazeti (122.9 mm), 8- Racha-Lechkhumi and Kvemo Svaneti (123.6 mm), 9- Samegrelo-Zemo Svaneti (133.7 mm), 10-Imereti (142.5 mm), 11- Guria (179.6 mm), 12- Adjara (210.3 mm).

In general, in eastern Georgia (including the Samtskhe-Javakheti region), landslide activation occurs with significantly lower precipitation amounts than in the west. Average P1 values are 8.8 and 11.9 mm, respectively, while P30 values are 75.2 and 156.6 mm (Tables 16,17).

In Fig. 6 graphs of connection of associated with landslide processes mean values of the cumulative sum of precipitation by individual regions of Georgia with mean values of the cumulative sum of precipitation for Georgia are presented. These relationships are linear. The corresponding regression equation coefficients are presented in Table 18.

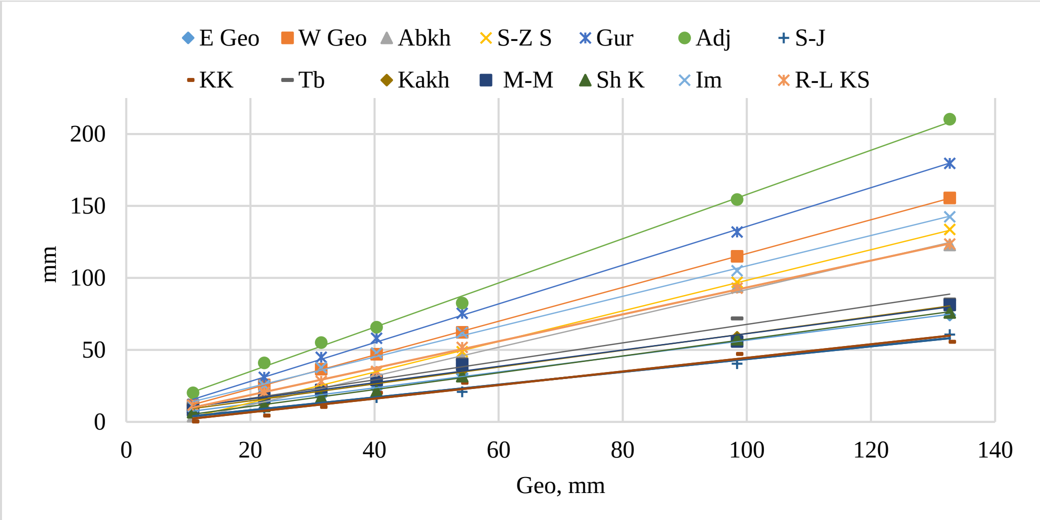

Fig. 6. Connection of associated with landslide processes (data from Tables 3-15) mean values of the cumulative sum of precipitation by individual regions of Georgia with mean values of the cumulative sum of precipitation for Georgia (linear regression, R≥0.94, very high correlation).

Table 18. The coefficients of the linear regression equation between mean values of the cumulative sum of precipitation by individual regions of Georgia with mean values of the cumulative sum of precipitation for Georgia (Fig. 6).

	Y = a·x + b			Y = a·x + b	
Region	a	b	Region	a	b
E Geo	0.5519	1.5341	KK	0.4723	-2.7517
W Geo	1.1754	-0.6005	Tb	0.643	3.4833
Abkh	1.0024	-8.323	Kakh	0.5842	2.9957
S-Z S	1.0628	-7.9381	M-M	0.5681	4.5294
Gur	1.3451	1.2306	Sh K	0.5841	-0.9199
Adj	1.537	4.287	Im	1.0556	2.8193
S-J	0.4446	-0.8057	R-L KS	0.935	-0.0996

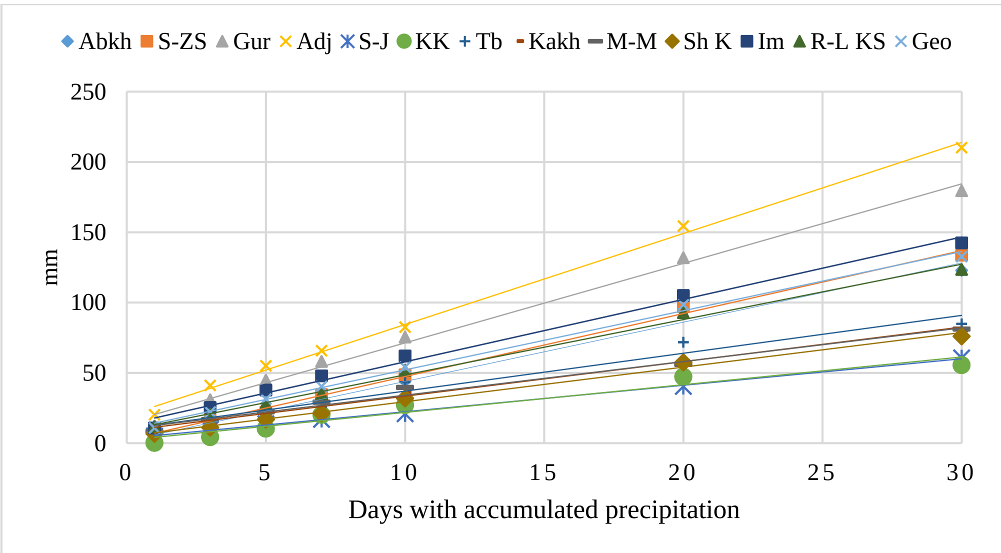

Fig. 7. Dependence of average precipitation values (threshold values) on precipitation duration in days on the day of landslide activation and before landslide activation in Georgia and its individual regions (linear regression).

In Fig. 7 graphs of dependence of average precipitation values (threshold values) on precipitation duration in days on the day of landslide activation and before landslide activation in Georgia and its individual regions in the linear approximation. In Fig. 8 graphs of dependence of average precipitation values (threshold values) on precipitation duration in hours on the day of landslide activation and before landslide activation in Georgia and its individual regions in the power approximation (data from Tables 3-15).

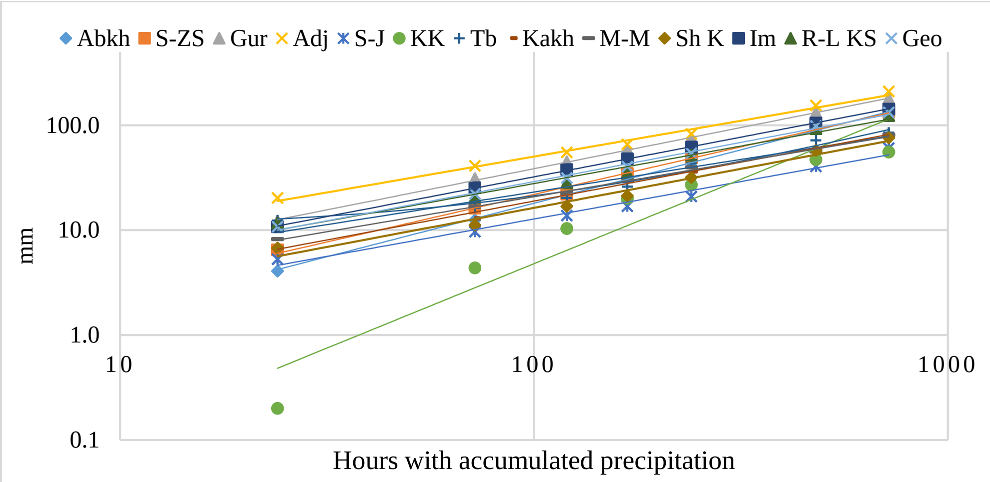

Fig. 8. Dependence of average precipitation values (threshold values) on precipitation duration in hours on the day of landslide activation and before landslide activation in Georgia and its individual regions (power regression).

The corresponding regression equation coefficients are presented in Table 19. For comparison, the same Table also provides previously calculated coefficients of the power regression equations for Georgia and its 10 regions for 174 cases of landslides [20].

Table 19. Coefficients of regression equation dependence of average precipitation values (threshold values) on precipitation duration in days and hours on the day of landslide activation and before landslide activation in Georgia and its individual regions.

Regions	Data from Tables 3-15				Data according to [20]	
	Regression equations					
	$P=a\cdot x+b$		$E=a\cdot D^b$			
	Regression equation coefficients					
	a	b	a	b	a	b
R^2, R, R'	($0.9479\leq R^2\leq 0.9982$), R ≥ 0.97		($0.9017\leq R^2\leq 0.9998$), R' ≥ 0.95		($0.761\leq R^2\leq 0.995$), R' $\geq$ 0.87	
Abkh	4.21	1.78	0.17	1.02	No data	No data
S-ZS	4.48	2.66	0.34	0.91	1.63	0.71
Gur	5.66	14.76	1.04	0.78	6.77	0.57
Adj	6.48	19.62	2.16	0.68	9.7	0.5
S-J	1.88	3.54	0.48	0.71	1.29	0.56
KK	1.97	2.18	0.003	1.61	No data	No data
Tb	2.69	10.07	1.32	0.62	2.71	0.5
Kakh	2.45	8.90	0.63	0.74	2.61	0.53
M-M	2.39	10.21	0.96	0.67	0.88	0.69
Sh K	2.46	4.94	0.53	0.74	1.36	0.64
Im	4.44	13.46	0.99	0.76	3.94	0.55
R-L KS	3.94	9.27	1.03	0.71	1.13	0.7
Geo	4.21	10.03	0.93	0.75	3.88	0.55

In particular, the values of the coefficients of a and b in in the equation $E=a\cdot D^b$ vary in a wide range for different regions of Georgia according to the climate zones from the subtropical regions (Abkhazeti, Adjara, Guria) to areas with a continental climate (Shida Kartli, Kakheti, etc., Table 19). Note, as in [20], the data on the values of a and b coefficients (Table 19) in some cases agree satisfactorily with similar data obtained by their authors for various regions of the world [35-37].

Fig. 9 shows dependence of average precipitation values (threshold values) on precipitation duration in days on the day of landslide activation and before landslide activation in Eastern and Western Georgia. Fig. 10 shows dependence of average precipitation values (threshold values) on precipitation duration in hours on the day of landslide activation and before landslide activation in the same parts of Georgia.

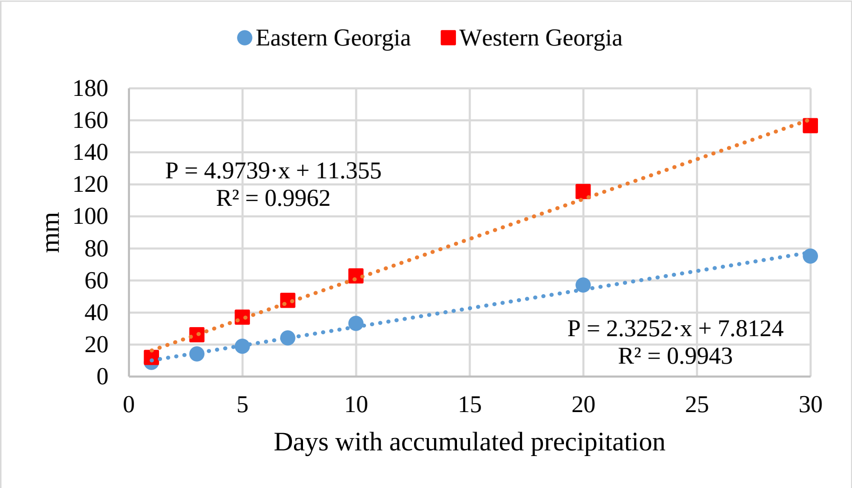

Fig. 9. Dependence of average precipitation values (threshold values) on precipitation duration in days on the day of landslide activation and before landslide activation in Eastern and Western Georgia ($R \approx 1.00$, very high correlation).

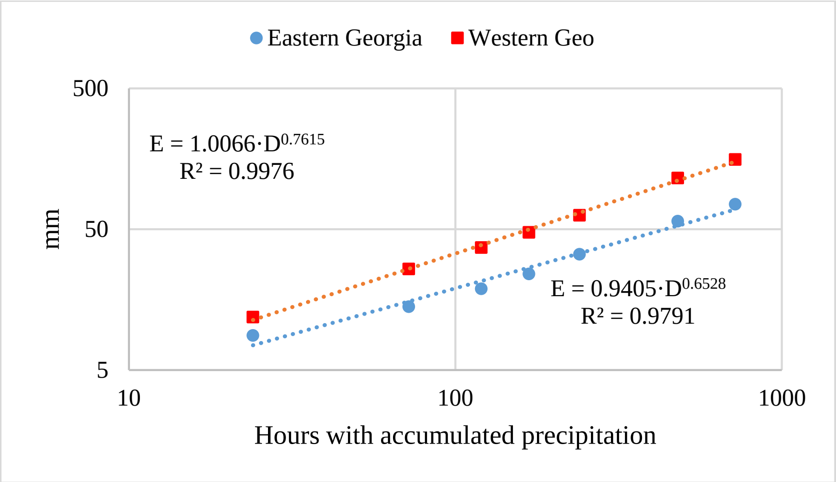

Fig. 10. Dependence of average precipitation values (threshold values) on precipitation duration in hours on the day of landslide activation and before landslide activation in Eastern and Western Georgia ($R' \geq 0.99$, very high correlation).

In the first case (Fig. 9), a linear relationship is observed between the parameters under study; in the second (Fig. 10), a power-law relationship is observed. Depending on the task at hand, both relationships can be used (e.g., comparison with similar works by various authors [35-37], etc.).

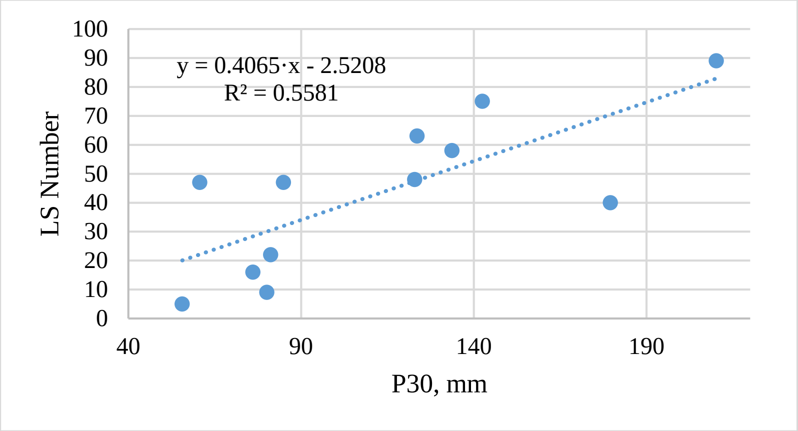

Fig. 11. Example of linear correlation and regression between the number of landslides and the cumulative sum of precipitation for 30 days related to landslide processes by regions of Georgia (data from Tables 4-15).

Fig. 11 shows an example of a graph of linear correlation and regression between the number of landslides and P30 values by region of Georgia. In Table 20 data on coefficients of the linear regression equation between the number of landslides (Y) and the cumulative sum of precipitation of different days (x) related to landslide processes by regions of Georgia are presented

Table 20. Coefficients of the linear regression equation between the number of landslides (Y) and the cumulative sum of precipitation of different days (x) related to landslide processes by regions of Georgia (data from Tables 4-15).

Cumulative precipitation sum	Coefficients of the linear regression equation $Y = a \cdot x + b$		R	Degree of correlation
P1	3.5964	11.76	0.70	high
P3	1.8775	9.1242	0.72	high
P5	1.3571	7.3696	0.68	moderate
P7	1.1149	4.3125	0.64	moderate
P10	0.9703	-2.3436	0.69	moderate
P20	0.5546	-3.292	0.74	high
P30	0.4065	-2.5208	0.75	high

In general, the linear correlation between the number of landslides and the values of P1…P30 by the regions of Georgia for change from 0.64 (P7, moderate correlation) to 0.75 (P30, high correlation)

Fig. 12-14, as an examples, present graphs of dependences the relative number of landslides (N(LS), %) from P1 values, respectively, for territory of Georgia and its Eastern and Western parts. Averaging was performed over seven ranges of P1 values in ascending order. The relationship between N(LS) values and P1, as well as P3, P5... P30, is a third-degree polynomial. The corresponding regression equation coefficients are presented in Table 21.

Table 21. Coefficients of the regression equation between the relative number of landslides (N(LS), %) and the cumulative sum of precipitation for 1, 3, 5, 7, 10, 20 and 30 days (x) related to landslide processes by Georgia and its eastern and western parts. $R' \geq 0.99$ (very high correlation)

Region	Cumulative precipitation sum	Regression equation
Georgia	P1	$N(LS) = 0.0001x^3 - 0.0126x^2 + 0.3121x + 12.007$
	P3	$N(LS) = 4E\text{-}05x^3 - 0.0052x^2 + 0.1974x + 12.008$
	P5	$N(LS) = 3E\text{-}05x^3 - 0.004x^2 + 0.1726x + 11.835$
	P7	$N(LS) = 4E\text{-}05x^3 - 0.0044x^2 + 0.1743x + 10.808$
	P10	$N(LS) = 1E\text{-}05x^3 - 0.0031x^2 + 0.2052x + 10.405$
	P20	$N(LS) = 3E\text{-}06x^3 - 0.0009x^2 + 0.0944x + 10.538$

	P30	$N(LS) = 7E\text{-}06x^3 - 0.0025x^2 + 0.3125x + 2.1577$
Eastern Georgia	P1	$N(LS) = 0.0003x^3 - 0.0213x^2 + 0.4195x + 12.075$
	P3	$N(LS) = 0.0002x^3 - 0.014x^2 + 0.309x + 12.204$
	P5	$N(LS) = 0.0002x^3 - 0.0137x^2 + 0.3348x + 11.986$
	P7	$N(LS) = 0.0003x^3 - 0.0192x^2 + 0.4168x + 10.738$
	P10	$N(LS) = 7E\text{-}05x^3 - 0.0068x^2 + 0.22x + 11.492$
	P20	$N(LS) = 1E\text{-}05x^3 - 0.0023x^2 + 0.1329x + 11.199$
	P30	$N(LS) = 1E\text{-}05x^3 - 0.0019x^2 + 0.1293x + 10.636$
Western Georgia	P1	$N(LS) = 8E\text{-}05x^3 - 0.0081x^2 + 0.2771x + 11.952$
	P3	$N(LS) = 3E\text{-}05x^3 - 0.0049x^2 + 0.1942x + 11.863$
	P5	$N(LS) = 2E\text{-}05x^3 - 0.0035x^2 + 0.1739x + 11.625$
	P7	$N(LS) = 3E\text{-}05x^3 - 0.0036x^2 + 0.1662x + 10.631$
	P10	$N(LS) = 7E\text{-}06x^3 - 0.0016x^2 + 0.1179x + 11.392$
	P20	$N(LS) = 2E\text{-}06x^3 - 0.0008x^2 + 0.0991x + 9.8761$
	P30	$N(LS) = 1E\text{-}06x^3 - 0.0005x^2 + 0.0907x + 8.7936$

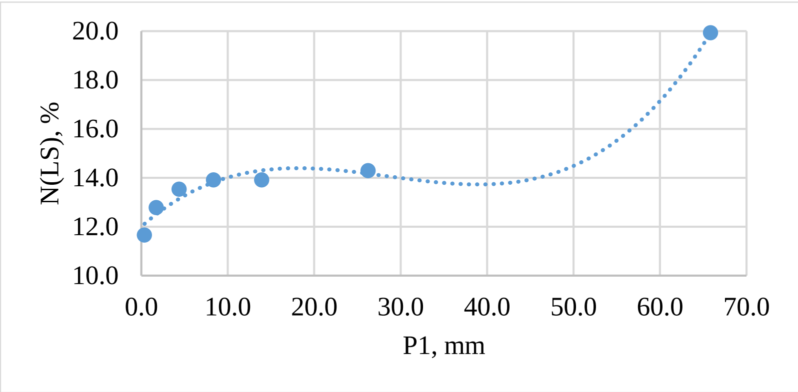

Fig. 12. Relationship between the relative number of landslides (%) and the 1-day total precipitation in the territory of Georgia (critical precipitation threshold).

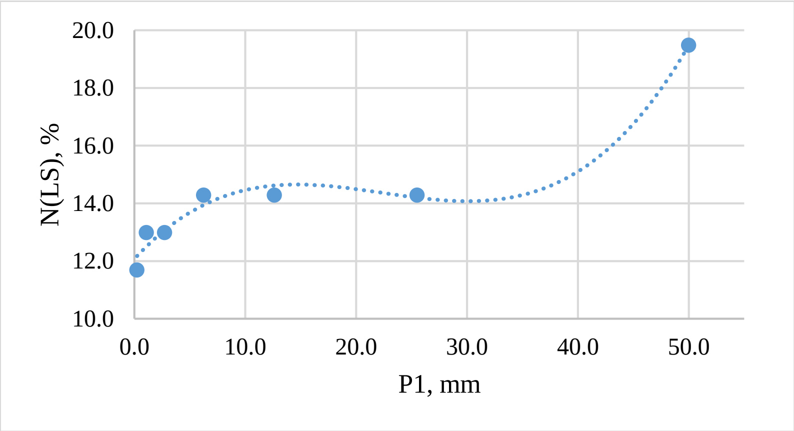

Fig. 13. Relationship between the relative number of landslides (%) and the 1-day total precipitation in the territory of Eastern Georgia (critical precipitation threshold).

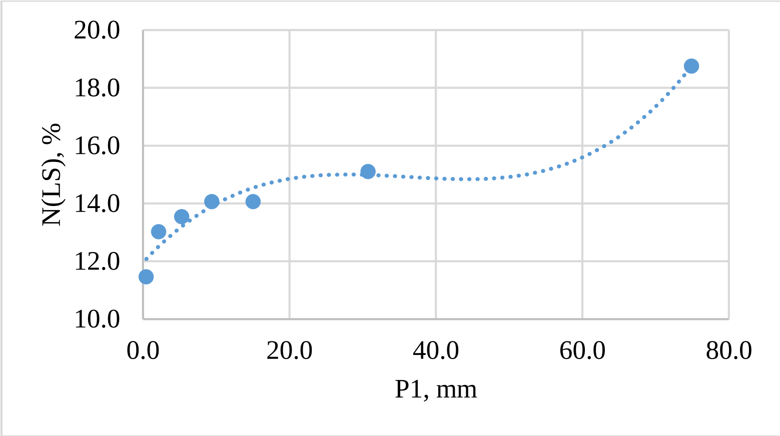

Fig. 14. Relationship between the relative number of landslides (%) and the 1-day total precipitation in the territory of Western Georgia (critical precipitation threshold).

Finally, Tables 21 and 22 presents data on critical threshold of 1, 3, 5, 7, 10, 20 and 30 - days precipitation sum for the activation of landslide processes in Georgia and its Eastern and Western parts (threshold start, threshold end, max precipitation sum).

Table 22. Critical threshold of 1, 3, 5 and 7-days precipitation sum for the activation of landslide processes in Georgia and its Eastern and Western parts

Region	Parameter	Threshold Start	Threshold End	Sum N(LS), %	Max	Sum N(LS), %
		P1, mm				
Georgia	Average	8.4	26.3	42.1	65.9	19.9
	99%(+/-)	0.6	2.2		10.3	
Eastern Georgia	Average	6.3	25.5	42.9	50.0	19.5
	99%(+/-)	1.2	4.6		10.0	
Western Georgia	Average	9.4	30.8	43.2	74.9	18.8
	99%(+/-)	0.7	3.4		13.0	
Region	Parameter	P3, mm				
Georgia	Average	13.7	36.5	42.1	99.4	19.7
	99%(+/-)	0.8	2.3		15.6	
Eastern Georgia	Average	11.4	28.4	42.0	59.4	19.0
	99%(+/-)	1.4	2.8		18.2	
Western Georgia	Average	14.7	39.7	41.8	109.6	20.4
	99%(+/-)	1.0	3.1		17.0	
Region	Parameter	P5, mm				
Georgia	Average	18.3	43.4	42.0	108.3	20.2
	99%(+/-)	0.8	2.3		15.0	
Eastern Georgia	Average	11.7	31.9	42.9	60.1	19.0
	99%(+/-)	1.9	2.5		11.8	
Western Georgia	Average	21.2	51.4	42.4	125.2	19.8
	99%(+/-)	1.1	3.1		18.1	
Region	Parameter	P7, mm				
Georgia	Average	21.3	44.9	39.1	109.8	25.8
	99%(+/-)	1.0	1.7		14.3	
Eastern Georgia	Average	12.6	31.3	40.6	56.4	23.3
	99%(+/-)	2.1	2.3		9.2	
Western Georgia	Average	25.6	52.1	39.3	125.0	25.7
	99%(+/-)	1.3	2.1		17.3	

Table 23. Critical threshold of 10, 20, and 30-day precipitation sum for the activation of landslide processes in Georgia and its Eastern and Western parts.

Region	Parameter	Threshold Start	Threshold End	Sum N(LS), %	Max	Sum N(LS), %
		P10, mm				
Georgia	Average	33.5	68.5	43.5	148.8	19.8
	99%(+/-)	1.0	2.1		17.9	
Eastern Georgia	Average	23.4	52.1	41.4	81.1	20.7
	99%(+/-)	1.9	4.1		18.7	
Western Georgia	Average	39.0	81.8	42.1	169.0	19.7
	99%(+/-)	1.3	3.1		21.3	
Region	Parameter	P20, mm				
Georgia	Average	67.3	124.7	42.0	234.4	20.2
	99%(+/-)	1.8	4.0		27.6	
Eastern Georgia	Average	40.3	78.6	41.8	129.5	19.9
	99%(+/-)	1.5	5.4		17.7	
Western Georgia	Average	81.1	142.5	42.1	265.2	20.1
	99%(+/-)	2.7	3.8		34.5	
Region	Parameter	P30, mm				
Georgia	Average	88.3	141.2	42.4	262.7	27.0
	99%(+/-)	2.1	3.3		25.3	
Eastern Georgia	Average	62.4	100.5	41.8	150.0	19.9
	99%(+/-)	3.9	3.4		22.4	
Western Georgia	Average	118.0	189.5	42.1	330.1	20.1
	99%(+/-)	3.1	4.1		37.1	

As can be seen from Fig. 12-14 and Tables 22, 23, for the P1 values, the precipitation plateau after which a rapid increase in the number of landslides begins covers the range from 6.3 to 30.8 mm, while for P30 it covers the range from 62.4 to 189.5 mm (total relative number of landslides ≈ 42.1-43.2%).

Conclusion

In the near future, the results of this study are planned to be used to assess the role of various factors in the activation of landslide processes (geological structure, topography, distance from roads and rivers, precipitation amount, etc.) using artificial intelligence methods in both steady-state and dynamic modes.

The results of this study may also be useful for hybrid risk assessment and the application of an integrated hybrid approach to forecasting various disaster-related events [38].

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საქართველოს რეგიონებში ყოველთვიურ და კუმულაციურ მრავალთვიან ნალექების რაოდენობასა და მეწყრის გააქტიურებას შორის კავშირის შეფასება

ა. ამირანაშვილი, ლ. ბროკა, თ. ჭელიძე, თ. ქირია,
$\boxed{\text{დ. სვანაძე}}$, თ. წამალაშვილი, ნ. ვარამაშვილი

რეზიუმე

წარმოდგენილია საქართველოს 12 რეგიონში დღიური და დაგროვილი მრავალდღიანი ნალექების რაოდენობასა და მეწყერების რაოდენობას შორის ურთიერთკავშირის დეტალური სტატისტიკური ანალიზი. გამოყენებული იქნა მონაცემები მეწყერების შესახებ ცნობილი გააქტიურების დღით (სულ 519 მეწყერის მოვლენა 1968 წლიდან 2022 წლამდე). ანალიზისთვის განისაზღვრა ნალექების რაოდენობა მეწყერის გააქტიურების დღეს (P1), ასევე დაგროვილი ნალექების რაოდენობა მეწყერამდე 3 დღის (P3), 5 დღის (P5), 7 დღის (P7), 10 დღის (P10), 20 დღის (P20) და 30 დღის (P30) განმავლობაში (მეწყერის დღის ჩათვლით).

კერძოდ, მიღებული იქნა შემდეგი შედეგები. დადგინდა კავშირი ნალექების საშუალო მნიშვნელობებსა (ზღვრულ მნიშვნელობებსა) და დღიური ნალექების ხანგრძლივობას შორის მეწყერის გააქტიურების დღეს და მეწყერის გააქტიურებამდე 3, 5 და 30 დღის განმავლობაში საქართველოში და მის ცალკეულ რეგიონებში. აღმოჩნდა, რომ აღმოსავლეთ საქართველოში (სამცხე-ჯავახეთის რეგიონის ჩათვლით) მეწყერის გააქტიურება ხდება ნალექების მნიშვნელოვნად დაბალი რაოდენობით, ვიდრე დასავლეთ საქართველოში. P1 საშუალო მნიშვნელობებია შესაბამისად 8.8 და 11.9 მმ, ხოლო P30 მნიშვნელობებია 75.2 და 156.6 მმ. საქართველოს რეგიონებში მეწყერების რაოდენობასა და P1…P30 მნიშვნელობებს შორის წრფივი

კორელაცია მაღალია P1, P3, P20 და P30-სთვის და ზომიერი P5, P7 და P10-სთვის. საქართველოსთვის, მეწყერებთან დაკავშირებული ნალექების რაოდენობა დაახლოებით 95%-ით აღემატება დღიური ნალექების საერთო გრძელვადიან საშუალო მაჩვენებელს. მთლიანად საქართველოსთვის და მისი აღმოსავლეთ და დასავლეთ ნაწილებისთვის, მეწყერების რაოდენობის დამოკიდებულებას P1…P30 მნიშვნელობებზე აქვს მესამე ხარისხის პოლინომის ფორმა (თანმიმდევრულად: უმნიშვნელო ზრდა - პლატო - ძლიერი ზრდა). P1 მნიშვნელობებისთვის, ნალექების პლატო, რომლის შემდეგაც იწყება მეწყერების რაოდენობის მკვეთრი ზრდა, მოიცავს დიაპაზონს 6.3-დან 30.8 მმ-მდე, ხოლო P30-ისთვის - 62.4-დან 189.5 მმ-მდე (მეწყერების საერთო ფარდობითი რაოდენობა ≈ 42.1–43.3%-ია).

საკვანძო სიტყვები: მეწყერი, სტიქიური უბედურება, ატმოსფერული ნალექები, სტატისტიკური ანალიზი.

Оценка связи суточных и накопленных многосуточных сумм осадков с активизацией оползней в регионах Грузии

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Резюме

Представлен подробный статистический анализ связи между суточным и накопленными многодневными количеством осадков и числом оползней в 12 регионах Грузии. Использовались данные об оползнях с известным днем активации (всего 519 оползневых событий с 1968 по 2022 год). Для анализа была определена сумма осадков в день активации оползня (P1), а также накопленная сумма осадков за 3 дня (P3), 5 (P5), 7 (P7), 10 (P10), 20 (P20) и 30 дней (P30) до возникновения оползня (включая день с оползнем).

В частности, были получены следующие результаты. Была определена связь между средними значениями осадков (пороговыми значениями) и продолжительностью суточных осадков в день активации оползня и за 3, 5...30 дней до активации оползней в Грузии и ее отдельных регионах. Было установлено, что в целом в восточной Грузии (включая регион Самцхе-Джавахети) активизация оползней происходит при значительно меньших суммах осадков, чем в западной Грузии. Средние значения P1 составляют 8.8 и 11.9 мм соответственно, а значения P30 — 75.2 и 156.6 мм. Линейная корреляция между количеством оползней и значениями P1…P30 по регионам Грузии высокая для P1, P3, P20 и P30 и умеренная для P5, P7 и P10. Для Грузии сумма осадков, связанных с оползнями, превышает общую долгосрочную среднюю суточную сумму осадков примерно на 95%. Для Грузии в целом и ее восточной и западной частей зависимость количества оползней от значений P1…P30 имеет вид полинома третьей степени (последовательно: незначительный рост — плато — сильный рост). Для значений P1 плато суммы осадков, после которого начинается резкое увеличение числа оползней, охватывает диапазон от 6.3 до 30.8 мм, а для P30 – от 62.4 до 189.5 мм (общее относительное число оползней составляет ≈ 42.1–43.3%).

Ключевые слова: оползни, стихийное бедствие, атмосферные осадки, статистический анализ.