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STATISTICAL ANALYSIS OF THE RELATIONSHIP BETWEEN MONTHLY AND CUMULATIVE MULTI-MONTH SUMS OF PRECIPITATION WITH THE NUMBER OF LANDSLIDES IN THE REGIONS OF GEORGIA

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Introduction

Landslides are known to be a type of natural disaster and are widespread almost everywhere [1-4], including in Georgia [5-11]. These processes often lead to the destruction of residential buildings and utility structures, serious damage to roads and bridges, the failure of various life support systems, significant material damage, threats to human life and health, etc. [8, 9, 12].

For example, in [11] results of statistical analysis of data from the Geological Department of the Environment Agency of Georgia on the annual number of re-activated and newly formed landslides (LS) for the period from 1995 to 2024 are presented. The number of landslides varies in the range from 56 to 1360 with an average annual value of 581. The trend of the LS values has the form of a polynomial of the seventh degree.

Landslide activation is influenced by many natural and anthropogenic factors, including slope steepness, lithology, vegetation, seismic activity, construction work in landslide-prone areas, and others. Prolonged, intense, or extreme precipitation events often accelerate landslide formation [13].

Recently, a series of studies have been conducted in Georgia to identify the short-term (hours, days, months) [14-18] and long-term (years, climate scale) effects of precipitation on the activation of landslides and mudflows [19-23]. These studies utilized landslide and mudflow data presented in [8, 9], as well as ground-based, radar, and satellite precipitation data, taking into account their representativeness depending on the distance from the measurement point [24-28]. A detailed review of these studies is presented in [28].

In our last work [23] the results of statistical analysis of the number of re-activated and new cases of damaging landslides in 11 regions of Georgia and 59 municipalities included in them, as well as the relationship of landslide processes with atmospheric precipitation in the period from 2015 to 2024 are presented. The area of the municipalities varies from 56.7 km² (Kutaisi) to 3104 km² (Mestia). The total area under study is 56364 km². Over a ten-year period, 6998 damaging landslides were recorded (out of a total of 9978). In particular, the following results were obtained. Based on the number of landslides in year, normed to 100 km² (LS_{100}), it is proposed to introduce the following five danger categories: “Low” (LS_{100} = 0.02÷1), “Moderate” (LS_{100} = >1÷2), “High” (LS_{100} = >2÷3), “Very High” (LS_{100} = >3÷4), “Extreme” (LS_{100} = >4). It was found that 28 municipalities belong to the landslide hazard category "Low", 10 municipalities – to the category "Moderate", 9 municipalities – to the category "High ", 6 municipalities – to the category "Very High " and 6 municipalities – to the category "Extreme". As the average annual amount of precipitation increases, the number of landslides also increases. Connection of LS_{100} values with mean annual sum of atmospheric precipitation by municipalities and regions of Georgia have a power-law function.

This work is a continuation of previous studies related to the study of the relationship between precipitation and the activation of landslide processes on a time scale of 1-12 months (1: sum of precipitation in the month with landslide occurrence; 2-12: cumulative precipitation sums in the month and up to the month in which the landslide occurred).

Some results of statistical analysis of the relationship between monthly and cumulative multi-month 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 a known month of their activation were taken from the catalog [8]. Period of observation – from 1961 to 2022; landslide occurrence height – from 15 (Abkh) to 3773 (M-M) m; number of landslides – from 5 (KK) to 219 (Abkh), total – 788 (Table 1, Fig. 1).

Data from the National Environmental Agency about monthly sum of atmospheric precipitations for 78 meteorological stations are used. List of meteorological stations, their coordinates and locations in Table 2 and Fig. 2 are presented. Precipitation data from missing weather stations for some municipalities were compensated by data from the nearest weather stations, taking into account their representativeness [25].

In the proposed work the analysis of data is carried out with the use of the standard statistical analysis methods [29].

The following designations will be used below: Max – maximal values; Min – minimal values; Mean – average values; St Dev – standard deviation; St Err – standard error; R^2 – coefficient of determination; R – coefficient of linear correlation; Lat – north latitude, N°; Lon – east longitude, E°; H – altitude above sea level, m; landslide – LS; P – precipitation sum, mm; P1 – precipitation sum in month with LS activation, mm; P2…P12 – cumulative precipitation sums in the month with landslide and 1 month up to landslide occurrence, ..., P12 – cumulative precipitation sums in the month with landslide and 11 months up to landslide occurrence, mm. In the text below, the dimensions of precipitation (mm) are often omitted.

Table 1. Study regions, period and number of years of observation, number of landslides and their heights for known months 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	1961-1989	11	219	15	1846	670
2.Samegrelo-Zemo	S-ZS	1968-2022	13	62	33	2278	765
3.Guria	Gur	2009-2022	11	40	30	1135	233
4.Adjara	Adj	1968-2022	12	106	15	1846	670
5.Samtskhe-Javakheti	S-J	1973-2022	12	58	797	2468	1301
6.Kvemo Kartli	KK	2002-2022	5	5	668	1295	868
7.Tbilisi	Tb	2001-2022	11	47	435	1376	773

8.Kakheti	Kakh	1974-2022	9	22	440	1974	865
9.Mtskheta-Mtianeti	M-M	1968-2022	12	25	455	3773	1409
10.Shida Kartli	Sh K	1983-2022	14	25	548	1405	820
11.Imereti	Im	1963-2022	18	98	21	980	451
12.Racha-Lechkhumi and Kvemo Svaneti	R-L KS	1968-2022	15	81	372	1576	901
Georgia	Geo	1961-2022	39	788	4	3773	604

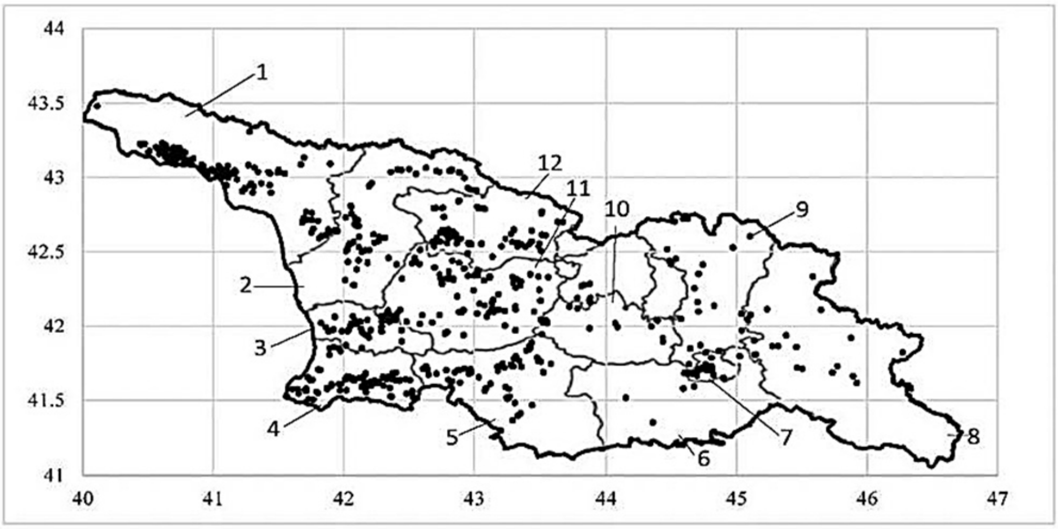

Fig. 1. Landslide distribution map for known months of occurrence. The numbers indicating the contours of the regions correspond to the numbers before the names of the regions in Table 1.

Table 2. List of meteorological stations whose precipitation data were used for known months 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	Magharoskari	42.29	44.87	958
Akhalkalaki	41.41	43.49	1716	Martvili	42.38	42.28	176
Akhaltsikhe	41.64	42.99	989	Martvili AWS	42.38	42.28	176
Akhmeta	42.04	45.21	545	Mestia	43.04	42.73	1441
Alpana	42.56	42.83	560	Mestia AWS	43.04	42.73	1441
Ambrolauri	42.52	43.15	544	Mirveti	41.53	41.72	60
Babushera	42.87	41.14	6	Mukhrani AWS	41.93	44.58	550
Bakhmaro AWS	41.85	42.32	1926	Nokalakevi	42.36	42.19	115
Bakuriani	41.74	43.52	1665	Orbeti AWS	41.66	44.53	1306
Batumi_Airport	41.6	41.61	11	Orpiri AWS	42.35	42.86	457
Bichvinta	43.15	40.34	4	Fasanauri	42.35	44.69	1070
Borjomi	41.84	43.38	790	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	Sakara	42.12	43.03	148
Dusheti AWS	42.09	44.71	1038	Samgori	41.72	44.9	549
Gagra	43.28	40.27	7	Samtredia	42.16	42.34	28
Gali	42.63	41.74	50	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	Sukhumi	43.01	41.04	116
Gudauta	43.1	40.64	46	Tbilisi	41.76	44.76	427
Gurjaani	41.74	45.8	410	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	Tsageri	42.65	42.77	474
Khertvisi	41.48	43.29	1250	Tsalka	41.6	44.09	1458
Khulo	41.64	42.31	946	Tseva AWS	42.12	43.17	448
Kobi AWS	42.56	44.52	1973	Tskaltubo AWS	42.35	42.66	452
Kobuleti	41.85	41.78	7	Tskhinvali	42.23	43.97	862
Kutaisi	42.26	42.7	113	Tskhratskaro	41.69	43.52	2466
Kvezani	42.84	41.69	268	Tsnori	41.65	45.97	223
Lagodekhi	41.77	46.24	429	Uravi AWS	42.65	43.32	1742
Lata	43.03	41.48	299	Zekari Gadasavli	41.83	42.86	2180
Legakhare	42.6	42.17	267	Zemo Chaladidi	42.22	41.79	4
Lentekhi	42.79	42.72	731	Zestafoni	42.10	43.05	160
Luji	42.85	43.02	2587	Zugdidi	42.51	41.87	118

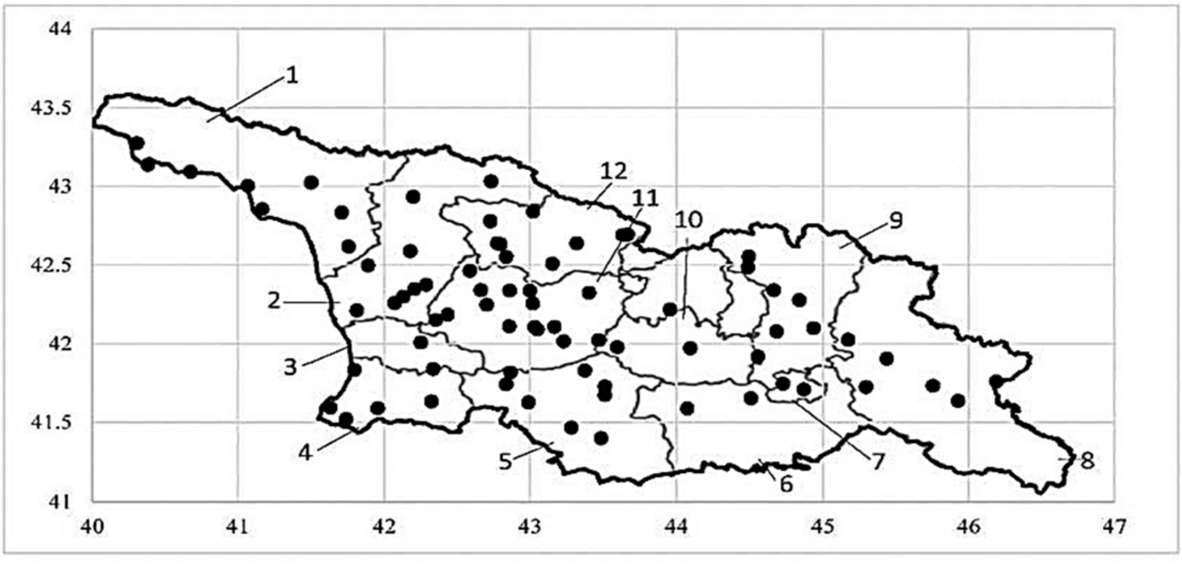

Fig. 2. Distribution map of meteorological stations for known months of landslide occurrence.

The degree of correlation was determined in accordance with [29]: very high correlation (0.9 ≤ R ≤ 1.0); high correlation (0.7 ≤ R < 0.9); moderate correlation (0.5 ≤ R < 0.7); low correlation (0.3 ≤ R< 0.5); negligible correlation (0 ≤ R < 0.3).

Results and discussion

Results in Tables 3 – 15 and Fig. 3 – 10 are presented. In Tables 3-15 statistical characteristics of the cumulative sum of precipitation related to landslide processes in Georgia and its regions are presented.

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	332	163	163	163	163	128	123	73	29	17	10	0.4
Max	3400	3236	3142	3061	2829	2647	1910	1800	1760	1520	1203	964
Mean	1378	1272	1163	1038	921	803	685	573	471	359	246	134
St Dev	583	543	498	447	409	368	323	282	248	207	155	106
St Err	20.8	19.4	17.7	16.0	14.6	13.1	11.5	10.0	8.8	7.4	5.5	3.8
99%_Low	1325	1222	1117	997	884	769	655	547	449	340	232	125
99%_Upp	1432	1322	1208	1079	959	837	714	599	494	378	261	144
Count	788	788	788	788	788	788	788	788	788	788	788	788
99%(+/-)	53.6	49.9	45.7	41.1	37.6	33.8	29.7	25.9	22.8	19.0	14.3	9.8

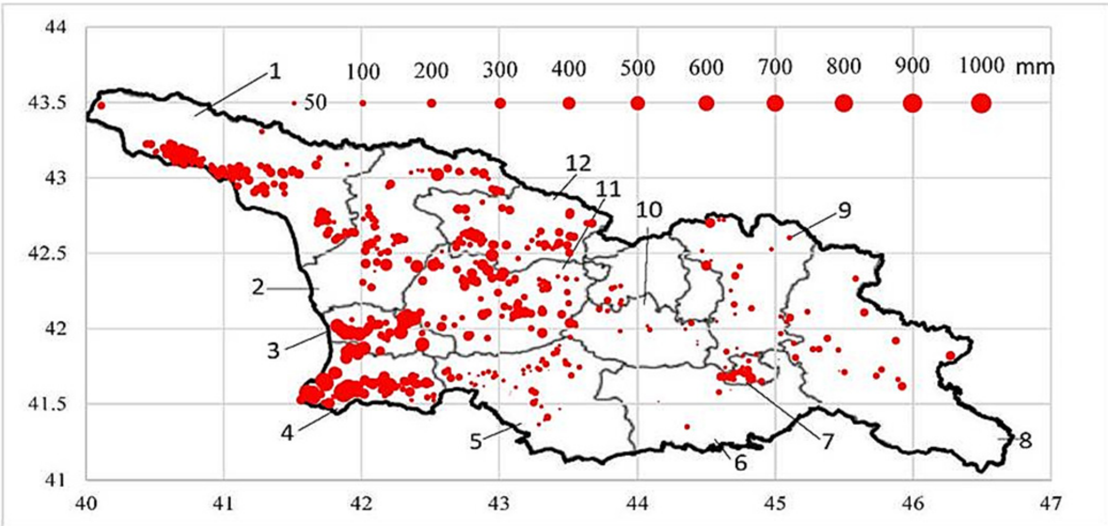

Fig. 3. Map of distribution of monthly precipitation sums in the months with landslides (P1).

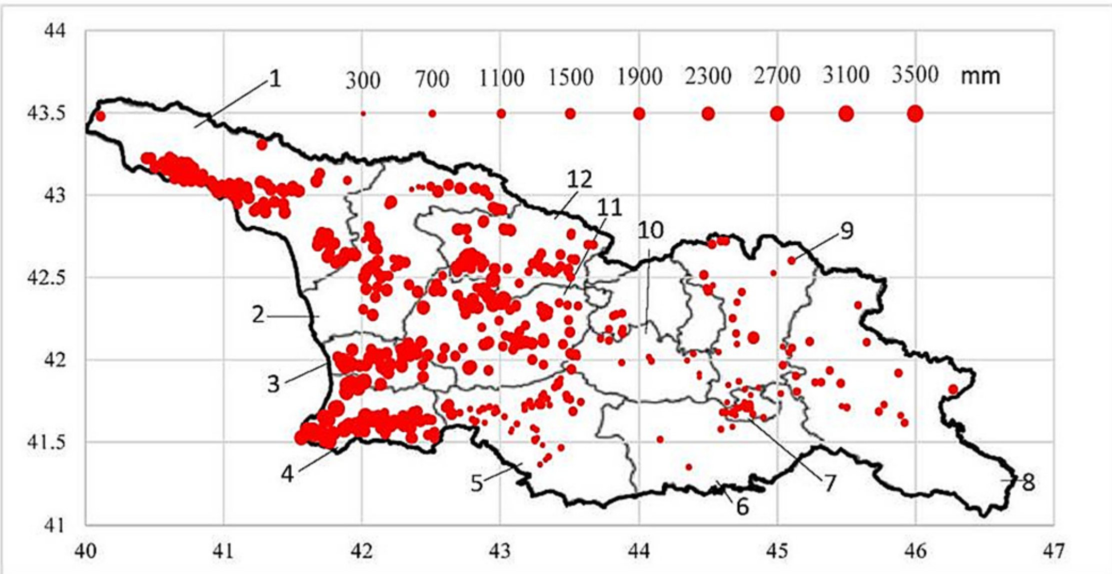

Fig. 4. Map of distribution of cumulative precipitation sums in the month with landslide and 11 months up to landslide occurrence (P12).

Fig. 3 and 4 show examples of distribution maps of P1 and P12 values in the territory of Georgia.

In particular, as can be seen from these Figures and Table 3, the distribution of P1 and P12 values in the study area is extremely uneven. Values of P1 vary from 0.4 (S-ZS, Jikhashkari village, landslide activation in August 2022) to 964 (Adj, Makhuntseti and Lower Agar villages, landslides activation in October 2017), with an average value of 134 mm (Table 3, Fig. 3, catalog [8]); P12 values vary from 332 (Sh K, Kavtiskhevi village, landslide activation in March 2019) to 3400 (Gur, Tkhinvali village, landslide activation in June 2022), with an average value of 1378 mm (Table 3, Fig. 4, catalog [8]).

In Tables 4-15 statistical characteristics of the cumulative sum of precipitation related to landslide processes in 12 regions of Georgia are presented.

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

	Cumulative precipitation sum, mm											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	627	564	553	502	468	438	335	306	269	111	56	17
Max	2171	2112	1755	1645	1515	1419	1312	1090	931	731	520	306
Mean	1580	1461	1319	1149	1005	864	735	613	513	378	258	136
St Dev	282	270	237	231	235	223	194	164	141	127	91	57
St Err	19.1	18.3	16.1	15.7	15.9	15.1	13.1	11.1	9.5	8.6	6.2	3.9
99%_Low	1531	1414	1277	1108	964	825	701	584	488	356	242	126
99%_Upp	1629	1508	1360	1189	1046	903	769	642	537	400	274	146
Count	219	219	219	219	219	219	219	219	219	219	219	219
99%(+/-)	49.2	47.1	41.4	40.4	41.1	38.9	33.8	28.6	24.5	22.2	15.9	9.9

Abkhazeti. P1 values vary from 17 (Saberio village, landslide activation in September 1984) to 306 (Pirveli Kopiti village, landslides activation in July 1983), with an average value of 136 mm; P12 values vary from 627 (Tsoukhva, Baghikita, Abakhuamcha, Bintkha, Primorskoe and Aualitsa villages, landslides activation in October 1982) to 2171 (Dikhazurga village, landslide activation in September 1982), with an average value of 1580 mm (Table 4, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	358	163	163	163	163	163	163	134	109	65	39	0.4
Max	2078	1843	1821	1772	1674	1470	1372	1225	1041	893	710	418
Mean	1340	1219	1137	1032	919	802	691	584	470	356	250	127
St Dev	446	423	400	374	349	325	306	278	237	204	161	93
St Err	57.2	54.2	51.2	47.9	44.7	41.6	39.2	35.5	30.3	26.1	20.6	11.9
99%_Low	1193	1079	1006	908	804	695	590	492	392	289	197	97
99%_Upp	1487	1358	1269	1155	1034	910	792	675	548	423	303	158
Count	62	62	62	62	62	62	62	62	62	62	62	62
99%(+/-)	147.2	139.6	131.8	123.5	115.1	107.2	100.9	91.6	78.1	67.2	53.0	30.6

Samegrelo-Zemo Svaneti. P1 values vary from 0.4 (Jikhashkari village, landslide activation in August 2022) to 418 (Hebudi village, landslides activation in August 2017), with an average value of 127 mm; P12 values vary from 358 (Nodashi village, landslide activation in November 2016) to 2078 (Obuji village, landslide activation in May 2012), with an average value of 1340 mm (Table 5, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	996	947	840	765	651	568	463	305	223	118	86	4
Max	3400	3236	3142	3061	2829	2647	1687	1480	1327	1036	818	519
Mean	1866	1755	1602	1400	1239	1073	863	714	581	438	320	198
St Dev	505	466	464	398	366	346	259	219	213	197	177	155
St Err	80.9	74.6	74.4	63.7	58.7	55.3	41.5	35.1	34.1	31.5	28.3	24.8
99%_Low	1658	1563	1410	1236	1087	931	756	624	493	357	247	135
99%_Upp	2075	1947	1793	1564	1390	1216	970	805	669	519	393	262
Count	40	40	40	40	40	40	40	40	40	40	40	40
99%(+/-)	208.4	192.2	191.6	164.2	151.2	142.5	107.0	90.3	87.9	81.1	72.9	63.9

Guria. P1 values vary from 4 (Nagomari village, landslide activation in September 2015) to 519 (Konchkati village, landslide activation in September 2022), with an average value of 198 mm; P12 values vary from 996 (Tkhinvali village, landslide activation in September 2021) to 3400 (Tkhinvali village, landslide activation in June 2022), with an average value of 1866 mm (Table 6, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	996	692	632	623	582	552	442	336	197	145	88	17
Max	3314	2779	2474	2376	2235	2042	1910	1800	1760	1520	1203	964
Mean	1939	1787	1636	1484	1329	1171	995	815	665	527	354	196
St Dev	594	516	461	404	386	370	372	369	367	331	262	189
St Err	57.9	50.3	45.0	39.5	37.7	36.1	36.3	36.0	35.9	32.3	25.6	18.5
99%_Low	1790	1657	1520	1383	1232	1077	902	722	573	444	288	149
99%_Upp	2089	1917	1752	1586	1426	1264	1089	908	758	611	420	244
Count	106	106	106	106	106	106	106	106	106	106	106	106
99%(+/-)	149.2	129.7	116.0	101.7	97.0	93.1	93.5	92.7	92.4	83.2	66.0	47.6

Adjara. P1 values vary from 17 (Akho, Baladzeebi and Chinkadzeebi villages, landslides activation in May 1968) to 964 (Makhuntseti and Lower Agar villages, landslides activation in October 2017), with an average value of 196 mm; P12 values vary from 996 (Zeda Makhuntseti, Takidzeebi, Chvana and Danisparauli villages, landslides activation in September 2021) to 3314 (Khala village, landslide activation in September 2016), with an average value of 1939 mm (Table 7, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	364	284	258	252	230	175	134	76	57	50	28	2
Max	1734	1692	1518	1427	1401	1349	1231	760	590	431	268	166
Mean	696	632	574	526	472	419	364	295	236	176	112	57
St Dev	277	257	233	224	201	187	168	122	100	80	56	38
St Err	36.7	34.0	30.8	29.6	26.6	24.8	22.2	16.2	13.2	10.6	7.4	5.0
99%_Low	601	544	494	450	404	355	306	253	202	149	93	44
99%_Upp	790	720	653	602	541	483	421	337	270	203	131	70
Count	58	58	58	58	58	58	58	58	58	58	58	58
99%(+/-)	94.5	87.6	79.5	76.3	68.5	63.9	57.3	41.7	34.1	27.2	19.0	13.0

Samtskhe-Javakheti. P1 values vary from 2 (Kodiani, Muskhi and Uraveli villages, landslides activation in October 1074) to 166 (Zarzma village, landslide activation in March 2018), with an average value of 57 mm; P12 values vary from 364 (Muskhi and Uraveli villages, landslides activation in October 1974) to 1734 (Zarzma village, landslide activation in March 2018), with an average value of 696 mm (Table 8, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	449	409	347	273	219	210	131	73	29	17	12	3
Max	620	560	528	503	500	494	473	349	295	185	136	91
Mean	553	489	437	397	354	324	270	190	148	105	77	36
St Dev	71	60	70	87	101	104	132	121	121	80	60	44
St Err	35.6	30.1	35.0	43.3	50.7	51.9	65.9	60.4	60.5	40.1	30.1	21.8
99%_Low	462	411	347	285	223	191	100	35	0	1	0	0
99%_Upp	645	566	527	508	484	458	440	346	304	208	155	92
Count	5	5	5	5	5	5	5	5	5	5	5	5
99%(+/-)	91.6	77.5	90.1	111.6	130.5	133.8	169.7	155.5	155.7	103.3	77.4	56.1

Kvemo Kartli. P1 values vary from 3 (Asureti village, landslide activation in March 2017) to 91 (Sagharasheni village, landslides activation in April 2019), with an average value of 36 mm; P12 values vary from 449 (Asureti village, landslide activation in March 2017) to 620 (Gomareti village, landslide activation in February 2022), with an average value of 553 mm (Table 9, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	373	286	210	187	164	128	123	104	58	23	20	3
Max	685	631	598	563	477	430	427	408	372	322	284	267
Mean	507	463	436	399	361	323	296	274	241	204	150	100
St Dev	72	81	102	101	102	98	102	112	110	99	67	55

St Err	10.7	12.0	15.1	15.0	15.1	14.5	15.0	16.6	16.2	14.6	9.9	8.1
99%_Low	480	432	397	360	322	286	257	232	199	166	124	79
99%_Upp	535	493	475	437	400	360	335	317	282	242	175	121
Count	47	47	47	47	47	47	47	47	47	47	47	47
99%(+/-)	27.5	30.9	38.9	38.5	38.8	37.3	38.6	42.6	41.8	37.7	25.5	21.0

Tbilisi. P1 values vary from 3 (landslide activation in January 2019) to 267 (Krtsanisi ravine, landslides activation in May 2012), with an average value of 100 mm; P12 values vary from 373 (landslide activation in October 2017) to 685 (landslide activation in June 2011), with an average value of 507 mm (Table 10, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	439	424	399	311	233	191	180	155	71	71	10	7
Max	1246	1090	1080	920	878	790	625	575	492	379	312	213
Mean	787	720	664	588	518	456	397	348	302	258	179	111
St Dev	169	154	154	139	154	142	120	110	108	92	77	54
St Err	36.9	33.7	33.7	30.3	33.7	31.1	26.1	24.0	23.6	20.2	16.9	11.8
99%_Low	692	634	578	510	431	376	330	286	241	206	135	81
99%_Upp	882	807	751	666	605	536	465	410	362	310	222	142
Count	22	22	22	22	22	22	22	22	22	22	22	22
99%(+/-)	95.1	86.7	86.7	78.0	86.8	80.0	67.3	61.8	60.9	52.0	43.5	30.4

Kakheti. P1 values vary from 7 (Manavi village, landslide activation in January 2020) to 213 (Lagodekhi, landslides activation in April 2007), with an average value of 111 mm; P12 values vary from 439 (Manavi village, landslide activation in January 2020) to 1246 (Lagodekhi, landslides activation in April 2007), with an average value of 787 mm (Table 11, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	394	380	321	286	228	192	152	97	72	56	41	14
Max	1869	1809	1600	1587	1445	1346	1197	901	744	540	392	248
Mean	761	697	611	543	491	437	391	336	278	211	147	81
St Dev	336	321	284	285	269	263	255	215	185	141	95	68
St Err	68.6	65.6	57.9	58.2	55.0	53.7	52.0	43.8	37.7	28.7	19.3	14.0
99%_Low	584	528	462	393	349	298	257	223	181	137	97	45
99%_Upp	938	866	760	693	633	575	525	449	375	286	196	117
Count	25	25	25	25	25	25	25	25	25	25	25	25
99%(+/-)	176.7	169.0	149.1	150.0	141.7	138.3	133.9	112.8	97.1	74.1	49.7	36.0

Mtskheta-Mtianeti. P1 values vary from 14 (Zemo Mleta village, landslide activation in January 2020) to 248 (Dariali village, landslides activation in May 2014), with an average value of 81 mm; P12 values vary from 394 (Mamkoda village, landslide activation in November 2004) to 1869 (Chinti village, landslide activation in May 2018), with an average value of 761 mm (Table 12, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	332	317	271	220	186	167	149	131	62	25	12	9
Max	1268	1223	1200	1141	925	917	899	748	633	539	341	253
Mean	798	733	669	604	534	474	411	343	273	203	140	71
St Dev	267	244	227	210	186	184	175	154	121	105	75	49
St Err	54.6	49.9	46.3	42.8	38.0	37.5	35.8	31.4	24.7	21.5	15.3	10.1
99%_Low	657	604	549	494	436	377	319	262	209	148	100	45
99%_Upp	938	861	788	714	632	570	503	424	336	258	179	97
Count	25	25	25	25	25	25	25	25	25	25	25	25
99%(+/-)	140.5	128.4	119.3	110.3	98.0	96.6	92.1	80.8	63.5	55.3	39.4	26.0

Shida Kartli. P1 values vary from 9 (Kaspi, landslide activation in February 2019) to 253 (Chumateleti village, landslides activation in March 2022), with an average value of 71 mm; P12 values vary from 332 (Kavtiskhevi village, landslide activation in March 2019) to 1268 (Khashuri, landslide activation in November 2016), with an average value of 798 mm (Table 13, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	843	707	669	596	550	431	400	314	236	103	80	28
Max	2806	2604	2401	2223	2024	1852	1525	1337	113	804	637	487
Mean	1550	1447	1334	1205	1091	960	828	709	575	430	296	161
St Dev	503	491	465	422	382	343	314	278	239	172	116	87
St Err	51.1	49.9	47.2	42.8	38.8	34.8	31.8	28.2	24.2	17.4	11.8	8.8
99%_Low	1418	1319	1212	1095	991	871	746	636	513	385	266	139
99%_Upp	1682	1576	1455	1315	1191	1050	910	782	637	475	327	184
Count	98	98	98	98	98	98	98	98	98	98	98	98
99%(+/-)	131.6	128.4	121.6	110.3	99.9	89.6	82.0	72.7	62.4	44.9	30.4	22.8

Imereti. P1 values vary from 28 (Sochkheti village, landslide activation in October 1966) to 487 (Samtredia, landslides activation in October 2017), with an average value of 161 mm; P12 values vary from 843 (Tsevari village, landslide activation in February 2019) to 2806 (Kisoreti and Sochkheti villages, landslides activation in October 1968), with an average value of 1550 mm (Table 14, catalog [8]).

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

	Cumulative precipitation sum, mm.											
Month	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1
Min	732	714	643	564	509	389	292	258	179	133	65	15
Max	2785	2529	2304	2131	1929	1584	1309	1099	897	747	662	394
Mean	1254	1143	1062	965	845	727	611	509	417	324	220	115
St Dev	341	308	289	274	251	207	179	160	141	125	111	76

St Err	38.1	34.5	32.3	30.7	28.1	23.1	20.0	17.9	15.8	14.0	12.4	8.5
99%_Low	1156	1054	979	886	773	668	559	463	376	288	188	93
99%_Upp	1352	1232	1145	1044	918	787	662	556	457	360	252	137
Count	81	81	81	81	81	81	81	81	81	81	81	81
99%(+/-)	98.1	88.8	83.2	79.0	72.3	59.6	51.6	46.1	40.7	36.1	31.9	22.0

Racha-Lechkhumi and Kvemo Svaneti. P1 values vary from 15 (Nasperi village, landslide activation in July 2022) to 394 (Tkhmori village, landslides activation in July 1968), with an average value of 115 mm; P12 values vary from 732 (Orbeli village, landslide activation in January 2020) to 2785 (Tkhmori village, landslides activation in July 1968), with an average value of 1254 mm (Table 15, catalog [8]).

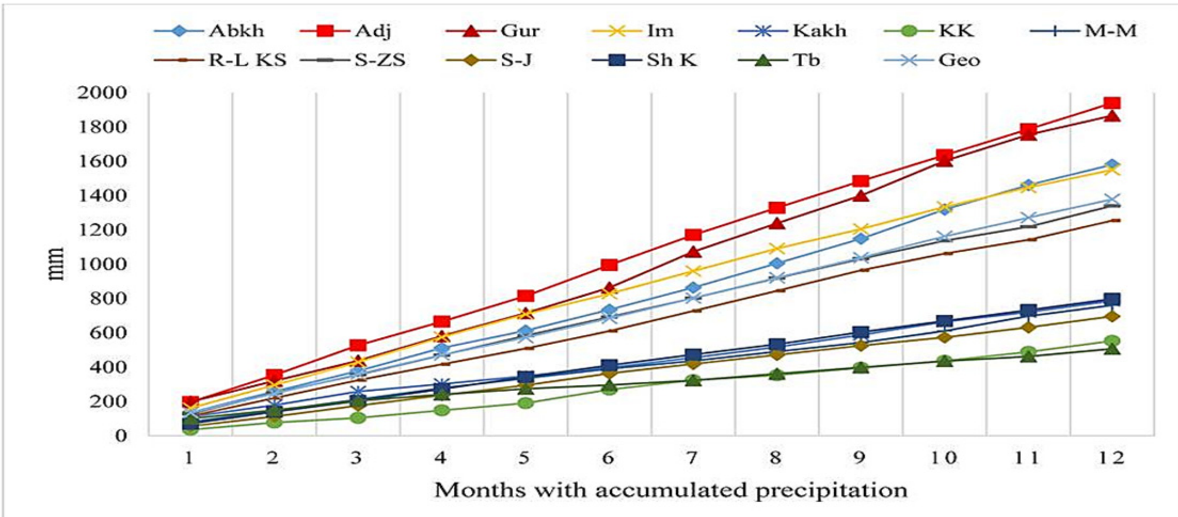

Fig. 5. Dependence of average precipitation values (threshold values) on precipitation duration in months during the month of landslide activation and before landslide activation in Georgia and its individual regions.

In Fig. 5 graphs of dependence of precipitation average values on P1...P12 values in Georgia and its individual regions are presented. These relationships are linear. The corresponding regression equations for Georgia and its regions are presented below.

Abkh: P = 132.11x – 24.539, (R^2 = 0.9972); Adj: P = 159.6x + 37.427, (R^2 = 0.9996); Gur: P = 158.34x – 25.095, (R^2 = 0.9955); Im: P = 127.25x + 55.091, (R^2 = 0.9988); Kakh: P = 59.958x + 54.417, (R^2 = 0.9963); KK: P = 47.259x – 25.518, (R^2 = 0.9943); M-M: P = 59.693x + 27.277, (R^2 = 0.9967); R-L KS: P = 104.43x + 3.9399, (R^2 = 0.9989); S-ZS: P = 109.97x + 29.213, (R^2 = 0.9994); S-J: P = 57.796x + 4.2483, (R^2 = 0.9989); Sh K: P = 66.026x + 8.4223, (R^2 = 0.9998); Tb: P = 34.936x + 85.708, (R^2 = 0.9933); Geo: P = 113.74x + 14.411, (R^2 = 0.9997). x – month.

In particular, Fig. 5 clearly demonstrates that different sums of precipitation are required to trigger landslides in different regions. In order of increasing precipitation amount, based on P12 values, these regions can be grouped as follows: 1 – Tbilisi and Kvemo Kartli; 2 – Samtskhe-Javakheti, Kakheti, Shida Kartli and Mtskheta-Mtianeti; 3 – Racha-Lechkhumi and Kvemo Svaneti, and Samegrelo-Zemo Svaneti; 4- Imereti and Abkhazeti; 5 – Guria and Adjara. 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 76 and 156 mm, respectively, while P12 values are 684 and 1588 mm (Tables 4-15, Fig. 5).

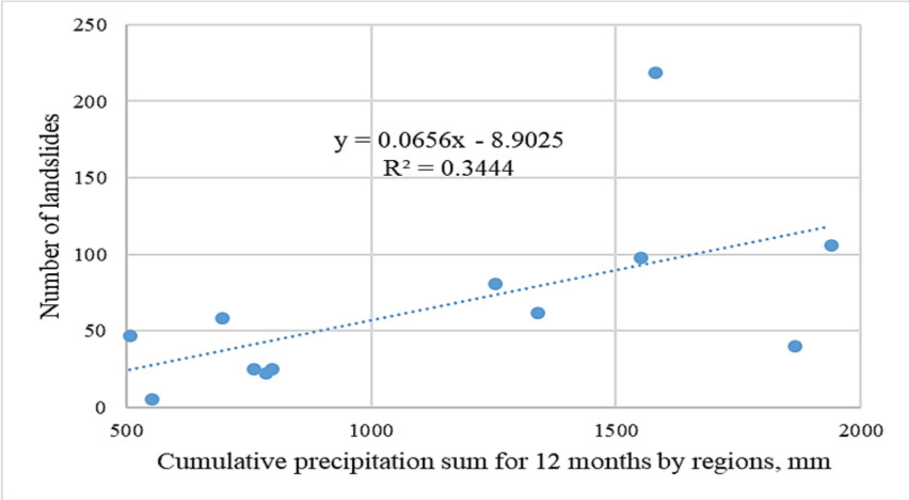

Fig. 6. Linear correlation between the number of landslides and the cumulative precipitation sum for 12 months by regions of Georgia (Table 3-14). R = 0.59.

Fig. 6 shows an example of a graph of linear correlation and regression between the number of landslides and P12 values by region of Georgia. As follows from this Figure, there is a moderate correlation between the studied parameters, ($0.5 \leq R < 0.7$).

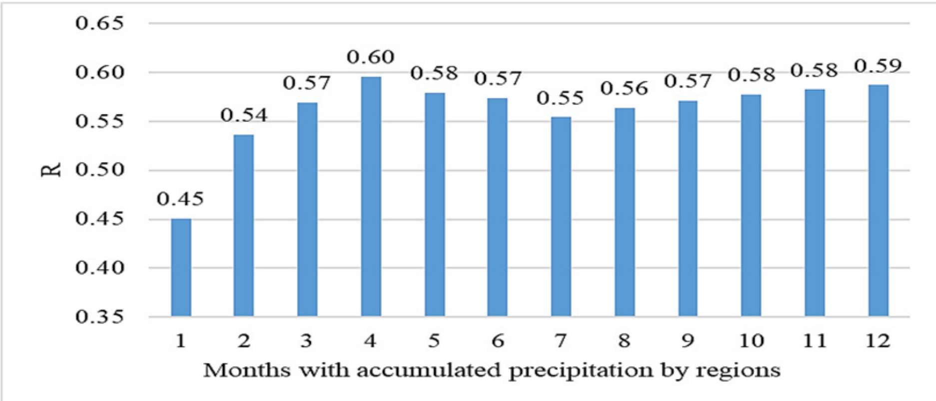

Fig. 7. Linear correlation between the number of landslides and the cumulative sum of precipitation by regions (Table 3-14).

In general, the linear correlation between the number of landslides and the values of P1…P12 by the regions of Georgia for P1 is low ($0.3 \leq R < 0.5$), for P2…P12 – moderate correlation (Fig. 6).

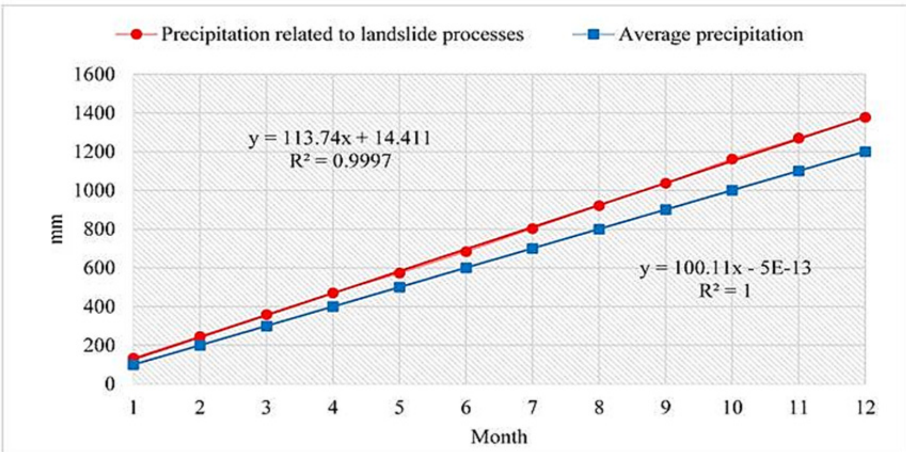

Fig. 8. Cumulative sum of landslide-related and average precipitation in Georgia.

Fig. 8 shows a graph of the relationship between average landslide-related precipitation amounts for Georgia and the P1…P12 values, as well as a graph of the relationship between average monthly precipitation amounts for Georgia (based on data from 1960-1989 for more than 80 meteorological stations). As can be seen from this Figure, landslide-related precipitation amounts are higher than the overall average precipitation amounts for individual months. On average, this difference is approximately 16%.

Finally, Fig. 9 and 10 present graphs of dependencies of the average landslide number from P1 and P12 values, respectively, for territory of Georgia. Averaging was performed over seven ranges of P1 and P12 values in ascending order.

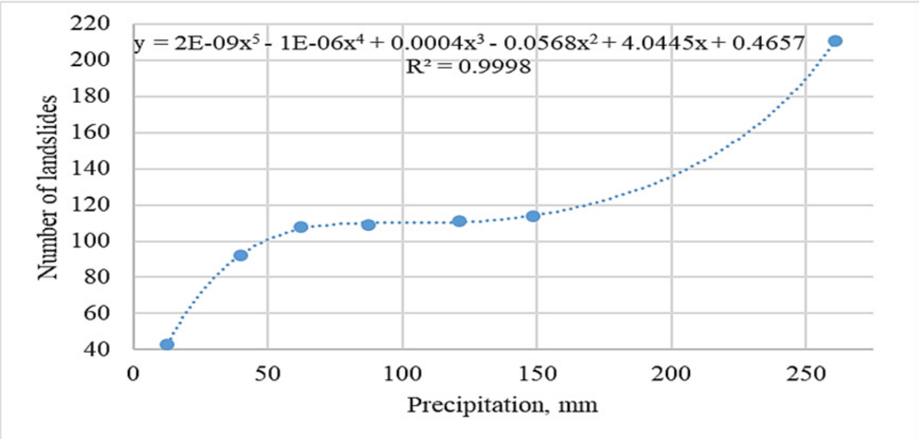

Fig. 9. Relationship between the number of landslides and the monthly sum of precipitation in Georgia.

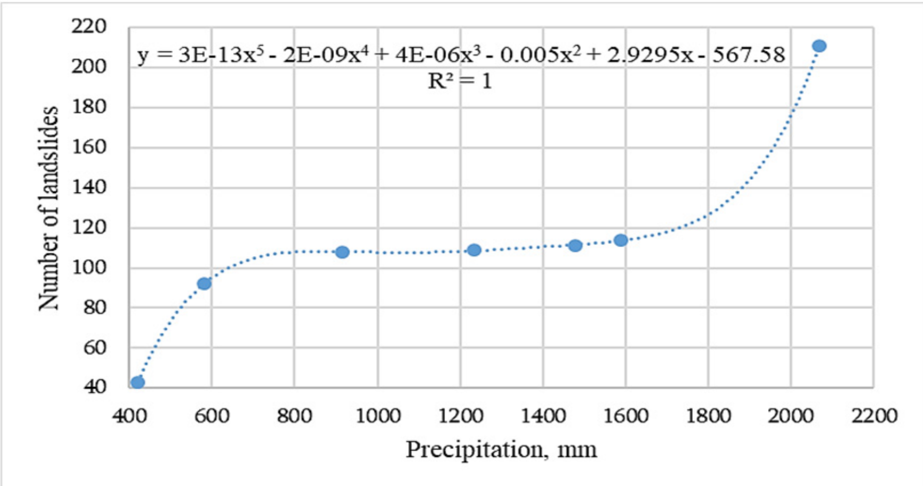

Fig. 10. Relationship between the number of landslides and the 12-month cumulative sum of precipitation on the territory of Georgia.

As can be seen from these figures, in both cases, the dependence of the landslide number on P1 and P12 values has the form of a fifth-order polynomial (sequentially: slight increase – plateau – strong increase). For P1 values, the precipitation plateau, after which a strong increase in landslides began, spans the range from 62 to 149 mm, while for P12, it spans from 914 to 1588 mm (LS number ≈ 108-114).

Conclusion

In the near future, it is planned to conduct research assessing the role of various factors in the activation of landslide processes (geological structure, terrain, distance from roads and rivers, precipitation amount, etc.) using artificial intelligence methods in both stationary and dynamic modes.

The results of these studies will also be useful for hybrid risk assessment and the application of an integrated hybrid approach to forecasting various events associated with natural disasters [30].

Acknowledgments

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STATISTICAL ANALYSIS OF THE RELATIONSHIP BETWEEN MONTHLY AND CUMULATIVE MULTI-MONTH SUMS OF PRECIPITATION WITH THE NUMBER OF LANDSLIDES IN THE REGIONS OF GEORGIA

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Abstract

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). 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).

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

საქართველოს რეგიონებში ყოველთვიური და დაგროვილი მრავალთვიანი ნალექების ჯამსა და მეწყერების რაოდენობას შორის კავშირის სტატისტიკური ანალიზი

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რეზიუმე

წარმოდგენილია საქართველოს 12 რეგიონში ყოველთვიური და დაგროვილი მრავალთვიანი ნალექების რაოდენობასა და მეწყერების რაოდენობას შორის ურთიერთკავშირის დეტალური სტატისტიკური ანალიზი. გამოყენებული იქნა მეწყერის მონაცემები გააქტიურების ცნობილი თვისა და წლის მიხედვით (სულ 788 მეწყერის მოვლენა 1961 წლიდან 2022 წლამდე). ანალიზისთვის განისაზღვრა მეწყერის გააქტიურების თვის ნალექების რაოდენობა (P1), ასევე, დაგროვილი ნალექების რაოდენობა გააქტიურების თვისთვის და მეწყერის წარმოქმნამდე 1 თვის (P2), 2 თვის (P3), ... და 11 თვის (P12) განმავლობაში.

კერძოდ, მიღებული იქნა შემდეგი შედეგები: განისაზღვრა ნალექების საშუალო მნიშვნელობებსა (ზღვრულ მნიშვნელობებსა) და ყოველთვიურ ნალექების ხანგრძლივობას შორის ურთიერთკავშირი მეწყერის გააქტიურების თვეში და მეწყერის გააქტიურებამდე საქართველოში და მის ცალკეულ რეგიონებში. დადგინდა, რომ, საერთო ჯამში, აღმოსავლეთ საქართველოში (მათ შორის სამცხე-ჯავახეთის რეგიონში), მეწყერის გააქტიურება ხდება ნალექების მნიშვნელოვნად დაბალი რაოდენობით, ვიდრე დასავლეთ საქართველოში. P1 საშუალო მნიშვნელობები შესაბამისად 76 და 156 მმ-ია, ხოლო P12 მნიშვნელობები 684 და 1588 მმ-ია. საქართველოს რეგიონებში მეწყერების რაოდენობასა და P1…P12 მნიშვნელობებს შორის წრფივი კორელაცია დაბალია P1-ისთვის და ზომიერი P2…P12-ისთვის. მეწყერებთან დაკავშირებული ნალექების რაოდენობა დაახლოებით 16%-ით აღემატება ზოგად გრძელვადიან საშუალო ყოველთვიურ ნალექებს. მთლიანად საქართველოსთვის, მეწყერების რაოდენობის დამოკიდებულებას P1 და P12 მნიშვნელობებზე აქვს მეხუთე რიგის პოლინომის ფორმა (თანმიმდევრობით: მცირე ზრდა – პლატო – ძლიერი ზრდა). P1 მნიშვნელობებისთვის, ნალექების პლატო, რომლის შემდეგაც იწყება მეწყერების რაოდენობის ძლიერი ზრდა, მოიცავს დიაპაზონს 62-დან 149 მმ-მდე, ხოლო P12-სთვის – 914-დან 1588 მმ-მდე (მეწყერების რაოდენობა ≈ 108-114-ია).

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

СТАТИСТИЧЕСКИЙ АНАЛИЗ СВЯЗИ МЕСЯЧНЫХ И НАКОПЛЕННЫХ МНОГОМЕСЯЧНЫХ СУММ ОСАДКОВ С КОЛИЧЕСТВОМ ОПОЛЗНЕЙ В РЕГИОНАХ ГРУЗИИ

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Реферат

Представлен подробный статистический анализ связи месячных и накопленных многомесячных сумм осадков с количеством оползней в 12 регионах Грузии. Использовались данные об оползнях с известным месяцем и годом их активизации (всего 788 случаев оползней в период с 1961 по 2022). Для анализа определялась сумма осадков в месяц с активизацией оползней (P1), а также накопленная сумма осадков в месяц с активизацией осадков и за 1 месяц (P2), 2 месяца (P3), … , 11 месяцев (P12) до возникновения оползня.

В частности, получены следующие результаты. Определена зависимость средних значений осадков (пороговых значений) от продолжительности осадков по месяцам в течение месяца активизации оползня и перед активизацией оползней в Грузии и ее отдельных регионах. Выявлено, что в целом, в восточной Грузии (включая регион Самцхе-Джавахети) активизация оползней происходит при значительно меньшем количестве осадков, чем в западной. Средние значения P1 составляют 76 и 156 мм соответственно, а значения P12 – 684 и 1588 мм. Линейная корреляция между количеством оползней и значениями P1…P12 по регионам Грузии для P1 низкая, для P2…P12 – умеренная корреляция. Количество осадков, связанных с оползнями, превышает общее многолетнее среднемесячное количество осадков примерно на 16%. В целом по Грузии зависимость количества оползней от значений P1 и P12 имеет вид полинома пятого порядка (последовательно: небольшой рост – плато – сильный рост). Для значений P1 плато количества осадков, после которого начинается сильный рост числа оползней, охватывает диапазон от 62 до 149 мм, а для P12 – от 914 до 1588 мм (число оползней ≈ 108-114).

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