

# STATISTICAL ANALYSIS OF THE NUMBER OF DAMAGING LANDSLIDES IN MUNICIPALITIES AND REGIONS OF GEORGIA AND THEIR RELATIONSHIP WITH ATMOSPHERIC PRECIPITATION IN 2015-2024

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## Abstract

*Landslides are one of the most widespread types of natural disaster, occurring almost everywhere, including in Georgia. Landslides can destroy residential buildings and other structures, damage roads and bridges, disable utility lines and pose a threat to human life and health. They can also cause significant material damage. The occurrence of landslides depends on various stationary factors, such as slope steepness, lithology, soil and vegetation cover. At the same time, intense or extreme precipitation can be a key factor in landslide activation. Furthermore, precipitation can have both short-term (hours, days or months) and long-term (years or the climate scale) effects on landslide activation. This work presents the results of a statistical analysis of re-activated and new cases of damaging landslides in 11 Georgian regions and their constituent municipalities, as well as the relationship between landslide processes and atmospheric precipitation from 2015 to 2024. The municipalities vary in size from 56.7 km<sup>2</sup> (Kutaisi) to 3,104 km<sup>2</sup> (Mestia). The total area under study is 56,364 km<sup>2</sup>. Over a ten-year period, 6,998 damaging landslides were recorded out of a total of 9,978. The following results were obtained in particular. Based on the number of landslides per year, normalized to 100 km<sup>2</sup> (LS100), the following five danger categories are proposed: 'Low' (LS100 = 0.02–1), 'Moderate' (LS100 = 1–2), 'High' (LS100 = 2–3), 'Very High' (LS100 = 3–4) and 'Extreme' (LS100 = 4). It was found that 28 municipalities belong to the "Low" landslide hazard category, 10 to the "Moderate" category, 9 to the "High" category, 6 to the "Very High" category, and 6 to the "Extreme" category. As the average annual precipitation increases, so does the number of landslides. The connection between LS100 values and the mean annual sum of atmospheric precipitation in municipalities and regions of Georgia follows a power-law function.*

**Keywords:** landslides, natural disaster, risk assessment, atmospheric precipitations, statistical analysis

## I. Introduction

Landslide processes, as one of the types of natural disasters, are widespread almost everywhere [1-3], including in Georgia [4-7]. Landslides destroy residential buildings and

structures, damage roads and bridges, disable utility lines, pose a threat to human life and health, cause significant material damage, etc. [8-10].

For example, some results of statistical analysis of parameterized landslide (LS) data (the number of landslides and their areas) for 11 regions of Georgia from 1900 to 2022 are presented in [7]. Landslides count for Georgia is 1325, total area - 526.3 km<sup>2</sup>. The area of individual landslides varies in the range from 0.0005 km<sup>2</sup> (Imereti, Samegrelo-Zemo Svaneti, Samtskhe-Javakheti) to 12.0 km<sup>2</sup> (Shida Kartli). In particular, the following results were obtained. Map of distribution of landslides number and their areas for different regions of Georgia is presented. Repeatability of the number of landslides and also their total area for different ranges of LS areas is study; the highest frequency of landslides in the study area falls on the range of their areas 0.0005-0.05 km<sup>2</sup> (41.5%), the smallest - on the range 5.01-12.0 km<sup>2</sup> (0.38%); the highest frequency of the total area of landslides falls on the range of their areas 1.01-2.0 km<sup>2</sup> (26.1%), the smallest – on the range 0.0005-0.05 km<sup>2</sup> (1.8%). The average annual shares of the total area of landslides from the area of study regions is calculated; this share in Guria (0.288%) and Adjara (0.281%) is significantly higher than in other regions - respectively, 5.05-4.9 times more than in Shida Kartli and 28.8-28.1 times more than in Samegrelo-Zemo Svaneti, etc.

The activation of landslide processes depends on many stationary factors - slope steepness, lithology, soil and vegetation cover, etc. At the same time, intense or extreme precipitation can be one of the main reasons for the activation of landslides [11].

Recently, a number of studies have been conducted in Georgia to assess the short-term (hours, days, months) [12-15] and long-term (years, climate scale) impact of precipitation on the occurrence of landslides [16-18].

For example, in [16] preliminary results of the study of the relationship between the variability of the mean annual sum of atmospheric precipitation and landslide processes in Georgia for 32 years are presented. In particular, it was found that with an increase in the annual sum of atmospheric precipitation, the tendency of increase in the number of landslides is observed in accordance with a second power of polynomial.

This work is a continuation of previous studies. Below are presented 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.

## II. Study area, material and methods

Study area – 11 region of Georgia including 59 municipalities with registered re-activated and new of damaging landslide number: Autonomous Republic of Adjara – /Adj/ - (Keda, Khelvachauri, Khulo, Kobuleti, Shuakhevi); Guria – /Gur/ - (Chokhatauri, Lanchkhuti, Ozurgeti); Imereti – /Im/ - (Baghdati, Chiatara, Kharagauli, Khoni, Kutaisi, Sachkhere, Samtredia, Terjola, Tkibuli, Tskaltubo, Vani, Zestaphoni); Kakheti – /Kakh/ - (Akhmeta, Dedoplistskaro, Gurjaani, Kvareli, Lagodekhi, Sagarejo, Signagi, Telavi); Kvemo Kartli – /KK/ - (Bolnisi, Dmanisi, Gardabani, Marneuli, Tetritskaro, Tsalka); Mtskheta-Mtianeti – /MM/ - (Dusheti, Kazbegi, Mtskheta, Tianeti); Samegrelo-Zemo Svaneti – /S-Z S/ - (Chkhorotsku, Khobi, Martvili, Mestia, Senaki, Tsalenjikha, Zugdidi); Racha-Lechkhumi and Kvemo Svaneti – /R-L KS/ (Ambrolauri, Lentekhi, Oni, Tsageri); Samtskhe-Javakheti – /S-J/ - (Adigeni, Akhalkalaki, Akhaltsikhe, Aspindza, Borjomi), Shida Kartli - /Sh K/ - (Gori, Kareli, Kaspi, Khashuri), Tbilisi - /Tb/.

The data of Department of Geology at Georgian National Environmental Agency about registered re-activated and new of damaging landslide number and annual sum of atmospheric precipitations for these municipalities are used [9,19]. It should be noted that the analysis of precipitation data in relation to this study was carried out in the work [19]. Period of observation: 2015-2024 (10 years).

The area of the municipalities varies from 56.7 km<sup>2</sup> (Kutaisi) to 3104 km<sup>2</sup> (Mestia). The total area under study is 56364 km<sup>2</sup>. Over a ten-year period, 6998 damaging landslides were recorded (out of a total of 9978) [9].

In the proposed work the analysis of data is carried out with the use of the standard statistical analysis methods [20].

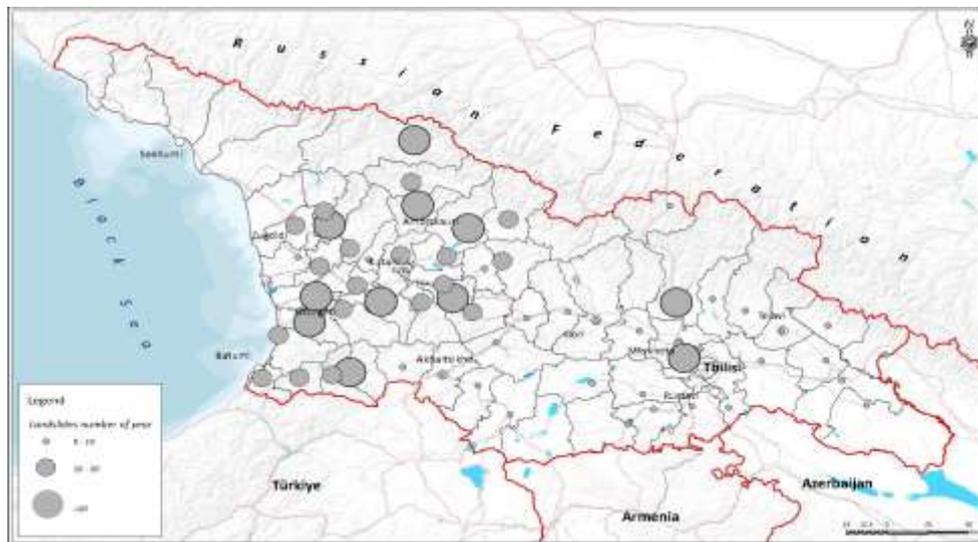
The following designations will be used below: Mean – average values; Max - maximal values; Min – minimal values; St Dev - standard deviation; St Err - standard error;  $C_v$ , - coefficient of variation, %;  $LS_N$  – landslide number in year;  $LS_{100}$  – landslide number in year normed to 100 km<sup>2</sup>;  $R^2$  – coefficient of determination;  $R$  – coefficient of linear correlation;  $R'$  - correlation index for nonlinear regression;  $\alpha$  - the level of significance; Lat - north latitude, °N; Lon - east longitude, °E.

The degree of correlation was determined in accordance with [20]: very high correlation ( $0.9 \leq R \leq 1.0$ ); high correlation ( $0.7 \leq R < 0.9$ ); moderate correlation ( $0.5 \leq R < 0.7$ ); low correlation ( $0.3 \leq R < 0.5$ ); negligible correlation ( $0 \leq R < 0.3$ ).

Based on the number of landslides in year, normed to 100 km<sup>2</sup>, it is proposed to introduce the following five danger categories: “Low” ( $LS_{100} = 0.02 \div 1$ ), “Moderate” ( $LS_{100} = >1 \div 2$ ), “High” ( $LS_{100} = >2 \div 3$ ), “Very High” ( $LS_{100} = >3 \div 4$ ), “Extreme” ( $LS_{100} = >4$ ).

### III. Results and discussion

Information on landslides number in year and landslides number in year normed to 100 km<sup>2</sup> by municipalities of Georgia in Fig. 1 and Table 1 are presented.



**Figure 1:** Distribution of landslides number in year by municipalities of Georgia in 2015-2024.

As follows from Fig. 1 and Table 1 values of  $LS_N$  change from 0.2 (Akhalkalaki, S-J) to 45.9 (Ozurgeti, Gur) and values of  $LS_{100}$  – from 0.02 (Akhalkalaki, S-J) to 7.00 (Lanchkhuti, Gur).

The various municipalities are characterized by the following landslides danger categories (Table 1):

$LS_{100} = 0.02 \div 1$  (“Low” category, 28 municipalities): Akhalkalaki (S-J), Dedoplistskaro (Kakh),

Kvareli (Kakh), Lagodekhi (Kakh), Gori (Sh K), Marneuli (KK), Kareli (Sh K), Bolnisi (KK), Kaspi (Sh K), Signagi (Kakh), Tsalka (KK), Akhmeta (Kakh), Dmanisi (KK), Telavi (Kakh), Kazbegi (M-M), Sagarejo (Kakh), Akhaltsikhe (S-J), Aspindza (S-J), Gardabani (KK), Borjomi (S-J), Gurjaani (Kakh), Tianeti (M-M), Mestia (S-ZS), Tetrtskaro (KK), Khoni (Im), Dusheti (M-M), Oni (R-L KS), Mtskheta (M-M).

$LS_{100} = >1\div 2$  ("Moderate" category, 10 municipalities): Khashuri (Sh K), Lentekhi (R-L KS), Adigeni (S-J), Khobi (S-ZS), Sachkhere (Im), Chiatura (Im), Kobuleti (Adj), Martvili (S-ZS), Tskaltubo (Im), Kutaisi (Im).

$LS_{100} = >2\div 3$  ("High" category, 9 municipalities): Chokhatauri (Gur), Ambrolauri (R-L KS), Tsalenjikha (S-ZS), Kharagauli (Im), Baghdati (Im), Shuakhevi (Adj), Senaki (S-ZS), Keda (Adj), Zugdidi (S-ZS).

$LS_{100} = >3\div 4$  ("Very High" category, 6 municipalities): Khelvachauri (Adj), Chkhorotsku (S-ZS), Terjola (Im), Tsageri (R-L KS), Khulo (Adj), Tkibuli (Im).

$LS_{100} = >4\div 7$  ("Extreme" category, 6 municipalities): Vani (Im), Tbilisi (Tb), Samtredia (Im), Zestaphoni (Im), Ozurgeti (Gur), Lanchkhuti (Gur).

**Table 1:** Data on landslides number in year and landslides number in year normed to 100 km<sup>2</sup> by municipalities of Georgia in 2015-2024.

Location	LS Numb in year	LS Numb in year/100 km <sup>2</sup>	Location	LS Numb in year	LS Numb in year/100 km <sup>2</sup>
Keda (Adj)	12.7	2.88	Gardabani (KK)	4.6	0.44
Khelvachauri (Adj)	11.3	3.03	Marneuli (KK)	1.1	0.12
Khulo (Adj)	26	3.76	Tetrtskaro (KK)	9.5	0.81
Kobuleti (Adj)	11.6	1.55	Tsalka (KK)	2.4	0.23
Shuakhevi (Adj)	15	2.60	Dusheti (M-M)	26.8	0.90
Chokhatauri (Gur)	16.7	2.04	Kazbegi (M-M)	3.1	0.29
Lanchkhuti (Gur)	39.2	7.00	Mtskheta (M-M)	7	0.95
Ozurgeti (Gur)	45.9	6.87	Tianeti (M-M)	6.7	0.74
Baghdati (Im)	19	2.35	Chkhorotsku (S-ZS)	21.3	3.34
Chiatura (Im)	8.4	1.53	Khobi (S-ZS)	7.7	1.12
Kharagauli (Im)	19.5	2.15	Martvili (S-ZS)	14.7	1.64
Khoni (Im)	3.4	0.84	Mestia (S-ZS)	23.7	0.76
Kutaisi (Im)	1.1	1.94	Senaki (S-ZS)	15.1	2.85
Sachkhere (Im)	10.7	1.18	Tsalenjikha (S-ZS)	14.2	2.15
Samtredia (Im)	16.6	4.78	Zugdidi (S-ZS)	19.8	2.99
Terjola (Im)	12.7	3.59	Ambrolauri (R-L KS)	24.3	2.13
Tkibuli (Im)	18.3	3.86	Lentekhi (R-L KS)	14.8	1.10
Tskaltubo (Im)	12.1	1.75	Oni (R-L KS)	15.4	0.90
Vani (Im)	26	4.44	Tsageri (R-L KS)	27.9	3.69
Zestaphoni (Im)	28.6	6.57	Adigeni (S-J)	8.9	1.11
Akhmeta (Kakh)	6	0.25	Akhalkalaki (S-J)	0.2	0.02
Dedoplistskaro (Kakh)	0.6	0.02	Akhalsikhe (S-J)	4.2	0.42
Gurjaani (Kakh)	5	0.59	Aspindza (S-J)	3.5	0.42
Kvareli (Kakh)	0.6	0.06	Borjomi (S-J)	5.7	0.48
Lagodekhi (Kakh)	0.9	0.10	Gori (Sh K)	1.5	0.12
Sagarejo (Kakh)	4.4	0.29	Kareli (Sh K)	1.6	0.15
Signagi (Kakh)	2.8	0.22	Kaspi (Sh K)	1.6	0.20
Telavi (Kakh)	3.3	0.28	Khashuri (Sh K)	6.2	1.10
Bolnisi (KK)	1.5	0.18	Tbilisi (Tb)	23.1	4.58
Dmanisi (KK)	3.3	0.28			

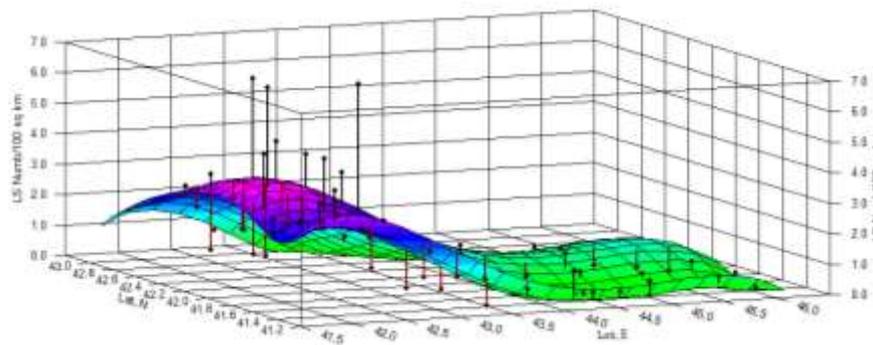
With a high level of reliability, relationship between the values of  $LS_{100}$  by municipalities and the latitude and longitude of the area in Georgia can be represented by the following regression equation (the corresponding regression coefficients are presented in Table 2):

$$Y = a + b \cdot x_1 + c \cdot x_1^2 + d \cdot x_1^3 + e \cdot x_1^4 + f/x_2 + g/x_2^2 + h/x_2^3 + i/x_2^4 + j/x_2^5$$

$x_1$  – Lon °E,  $x_2$  – Lat °N,  $R^2 = 0.524$ ,  $R' = 0.88$ , high correlation.

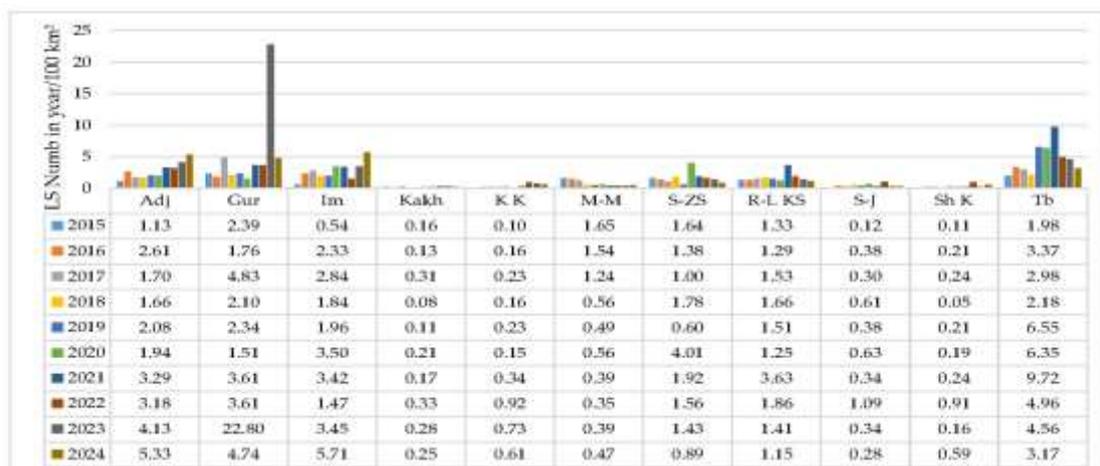
**Table 2:** Coefficients of the equation for the relationship between the landslides number in year normed to 100 km<sup>2</sup> by municipalities and the latitude and longitude of the area in Georgia in 2015-2024.

Coefficient	Value	Coefficient	Value
a	-8.70E+08	f	1.84E+11
b	4.22E+04	g	-1.56E+13
c	-1.44E+03	h	6.58E+14
d	2.17E+01	i	-1.39E+16
e	-1.23E-01	j	1.18E+17



**Figure 2:** Calculation model of distribution of landslides number in year normed to 100 km<sup>2</sup> by municipalities of Georgia in 2015-2024.

In Fig. 2 calculation model of distribution of landslides number in year normed to 100 km<sup>2</sup> by municipalities of Georgia is presented, the actual data of which are given in Table 1. This Figure clearly demonstrates the decrease in the  $LS_{100}$  values in the eastern direction of the study area.



**Figure 3:** Data on landslides number in year normed to 100 km<sup>2</sup> by regions of Georgia in 2015-2024.

Data on landslides number in year normed to 100 km<sup>2</sup> by regions of Georgia in 2015-2024 in Fig. 3 are presented and the statistical characteristics of these data in Table 3 are presented.

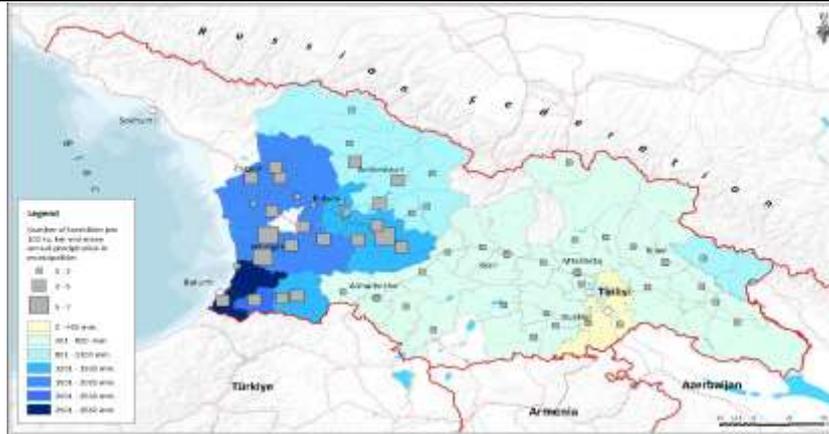
In particular, generally in the separate regions of Georgia the range of change and average of landslides danger categories is a following (Table 3): Adj: "Moderate" – "Extreme", "High"; Gur: "Moderate" – "Extreme", "Extreme"; Im: "Low" – "Extreme", "High"; Kakh: "Low" – "Low", "Low"; KK: "Low" – "Low", "Low"; M-M: "Low" – "Moderate", "Low"; S-ZS: "Low" – "Extreme", "Moderate"; R-L KS: "Moderate" – "Very High", "Moderate"; S-J: "Low" – "Moderate", "Low"; Sh K: "Low" – "Low", "Low"; Tb: "Moderate" – "Extreme", "Extreme".

**Table 3:** Statistical characteristics of the landslides number in year normed to 100 km<sup>2</sup> by regions of Georgia in 2015-2024. NC - negligible correlation ( $0 \leq R < 0.3$ ).

Variable	Adj	Gur	Im	Kakh	KK	M-M	S-ZS	R-L KS	S-J	Sh K	Tb
Max	5.33	22.8	5.71	0.33	0.92	1.65	4.01	3.63	1.09	0.91	9.72
Min	1.13	1.51	0.54	0.08	0.1	0.35	0.6	1.15	0.12	0.05	1.98
Mean	2.71	4.97	2.71	0.20	0.36	0.76	1.62	1.66	0.45	0.29	4.58
St Dev	1.29	6.38	1.43	0.09	0.29	0.51	0.94	0.72	0.27	0.26	2.41
St Err	0.43	2.13	0.48	0.03	0.10	0.17	0.31	0.24	0.09	0.09	0.80
Cv, %	47.8	128.3	52.8	42.8	78.9	66.3	57.7	43.5	60.7	89.4	52.5
Correlation Matrix											
Adj	1	0.47	0.77	0.42	0.73	-0.53	NC	NC	NC	0.52	NC
Gur	0.47	1	NC	0.43	0.53	NC	NC	NC	NC	NC	NC
Im	0.77	NC	1	0.30	NC	-0.44	NC	NC	NC	NC	NC
Kakh	0.42	0.43	0.30	1	0.71	NC	NC	NC	NC	0.63	NC
KK	0.73	0.53	NC	0.71	1	-0.59	NC	NC	0.48	0.78	NC
M-M	-0.53	NC	-0.44	NC	-0.59	1	NC	-0.33	-0.49	-0.36	-0.55
S-ZS	NC	NC	NC	NC	NC	NC	1	NC	0.31	NC	NC
R-L KS	NC	NC	NC	NC	NC	-0.33	NC	1	NC	NC	0.73
S-J	NC	NC	NC	NC	0.48	-0.49	0.31	NC	1	0.61	NC
Sh K	0.52	NC	NC	0.63	0.78	-0.36	NC	NC	0.61	1	NC
Tb	NC	NC	NC	NC	NC	-0.55	NC	0.73	NC	NC	1

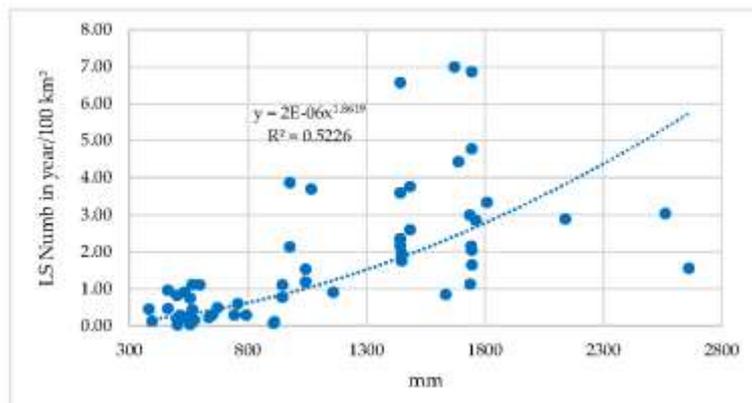
The linear correlation coefficients between the regions of Georgia according to the LS<sub>100</sub> values are significant only for 22 pairs of regions out of 55 ( $R \geq 0.30$ ,  $\alpha \leq 0.40$ ). Moreover, a positive correlation is observed for 15 pairs of regions, and a negative one for 7. High correlation observed for 5 pair of regions, moderate correlation - for 7 pair of regions and low correlation - for 10 pair of regions. The largest positive value of R is observed for the pair Sh K÷KK (0.78 - high correlation), the largest negative K- for the pair M-M÷KK (-0.59 - moderate correlation).

In general, the processes of landslide formation in different regions of Georgia are weakly connected with each other - local conditions prevail. However, a common factor in the activation of landslides is atmospheric precipitation.

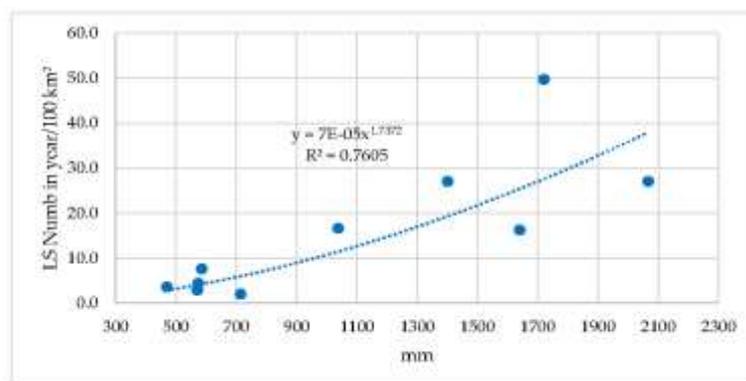


**Figure 4:** Distribution of landslides number in year normed to 100 km<sup>2</sup> and mean annual sum of atmospheric precipitation by municipalities of Georgia in 2015-2024.

In Fig. 4 distribution of LS<sub>100</sub> values in the background of mean annual sum of atmospheric precipitation by municipalities of Georgia in 2015-2024 is presented. This Figure clearly shows the general tendency of decreasing LS<sub>100</sub> values with decreasing annual sum of precipitation in eastern Georgia compared to western Georgia. Connection of LS<sub>100</sub> values with mean annual sum of atmospheric precipitation by municipalities and regions of Georgia have a power-law function (Fig. 5 and Fig. 6 respectively).



**Figure 5:** Connection of landslides number in year normed to 100 km<sup>2</sup> with mean annual sum of atmospheric precipitation by municipalities of Georgia in 2015-2024.  $R' = 0.72$ , high index of correlation.



**Figure 6:** Connection of landslides number in year normed to 100 km<sup>2</sup> with mean annual sum of atmospheric precipitation by regions of Georgia (excluding Tbilisi) in 2015-2024.  $R' = 0.87$ , high index of correlation.

It should be noted that Tbilisi is the densely populated capital of Georgia. Therefore, there are significantly more landslide-vulnerable areas (buildings, roads, communications, etc.) per unit of area. Accordingly, the number of registered destructive landslides here is higher than the average in other regions of Georgia. Taking this fact into account, Fig. 6 does not contain corresponding data for Tbilisi.

However, even when including data for Tbilisi in this Figure, the power law relationship between LS100 values and annual sum of precipitation remains, albeit with a lower level of correlation index ( $y = 0.0039 \cdot x^{1.173}$ ,  $R' = 0.58$ , moderate index of correlation).

## V. Conclusion

In the near future, it is planned to conduct a similar study by the areas of destructive landslides in municipalities and regions of Georgia. The results of the conducted and planned studies will be used to assess the role of various factors in the activation of landslide processes (geological structure, terrain, distance from roads, precipitation, etc.) using artificial intelligence methods.

The results of these studies can also be useful for hybrid risk assessments and the application of a comprehensive hybrid approach to forecasting various events related to natural disasters [21].

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### CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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