Predicting Erosive and Debris Flow Processes and the Innovative Measures to Control Them

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INTRODUCTION

The fund of the major fertile soils of the Earth, as well as inhabited areas, agricultural and industrial facilities and some roads and railway lines are located in the riverbank areas or on the alluvial fans of solid sediments and are subject to an impact of such natural disasters as debris flow processes.

Due to their unexpected nature and great destruction force, the debris flows change the environment drastically and inflict great damage to the people's economy. As the debris flow processes have become more active recently, the scientists were forced to study the physics of their formation and develop the engineering measures based on the study results to prevent them [1,2].

Today, in order to protect the buildings, infrastructures and the territories from the debris flows, debris flow-arresters and debris flow-guides, as well as debris flow stabilizing, preventing and technical-engineering measures are used. They are as follows:

- reinforced concrete debris flow-arresting rip-rap and ground dams: the debris flows are retained by forming debris flow-reserves in the surfaces.
- debris flow control channels and debris flow diversion structures diverting the debris flow around the object.
- debris flow-guide and blocking dams and heels: the flow is directed into the debris flow bed.
- a cascade of dikes, retaining walls, slope terraces and agrotechnical melioration: the movement of debris flows is arrested, or the dynamic properties of debris flows are mitigated.
- debris flow-diversion structures, debris flow regulation dams and debris flow diverters: the debris flows are prevented, and
- monitoring and reporting services, which predict the debris flows.

It should be noted that the first works to regulate the mountain flows were accomplished in 323 BC in Japan. Since then to the end of the XIX century, the scientists had studied the essence of the debris flow formation and made conclusions in order to decide on the right measures to prevent debris flows and to use the obtained data as a basis to classify the preventive measures into the following groups:

- **European:** The European approach is based on the French school; it prioritizes the forest melioration as a measure to prevent debris flows and recommends the construction of hydraulic structures, barrages, mass flood beds and weirs to regulate the second- and third-range tributaries of a hydrographic network. As per the recent recommendations of the European approach, open-end filtering barrages are expedient to use [3,5,6,12].
- **African:** The measures of the African approach, aiming at protecting the soil from erosion, imply terracing the slopes, growing forest reserves, and using barrages (as the most up-to-date measure) as transverse hydraulic structures to regulate watercourses [35].
- **American:** The American approach means regulating the debris flows by using the complexes of large hydraulic structures and the debris flow-retaining dikes. Recently, this approach have actively used such measures as forest melioration, barraging, weirs, etc. [36].
- **Asian**: The Asian approach uses a combination of the European and the African methods to prevent debris flows. Recently, it has widely used different kinds of transverse open-end structures.

Due to their abnormality, the kind of impact of the debris flows on the structures is directly associated with structural solutions. The work proposes the copyrighted engineering solutions, which are totally different from the existing ones [4,10].

Georgia is a mountainous country with the territory of 69 700 km^2 and with 25 074 small and big rivers, whose total length is 54 768 km. There are over 3000 catchment basins in the country and there are active erosive-denudation processes developed in them [8,9].

In the South Caucasus (Fig. 1), the major classical scientific studies of erosion and debris flow processes started in 1776 when in Georgia, a catastrophic glacial debris flow was formed as a result of the movement of the ice mass during the formation of Devdorak Glacier in the Tergi River basin. This mass blocked the Tergi (Terek) River bed and greatly damaged the territory of Russia, as the accumulated water mass outburst through the temporary dam.

Fig. 1. Map of South Caucasus [7, 36, 37]

Thus, the scientific studies of the erosion and debris flow processes in the South Caucasus have an over 200-year-long history. The Tsotne Mirtskhulava Water Management Institute of Georgian Technical University (GTU) (former Scientific and Research Institute of Hydraulic Engineering and Land Reclamation of Georgia) has been actively involved in these studies since 1929.

It should also be noted that in the 1950-1990s, in the former Soviet Union, the Scientific and Research Institute of Hydraulic Engineering and Land Reclamation of Georgia was a coordinator of scientific forecasts of debris flow processes and fought against them.

Fig. 2 shows the degree of damage by debris flows and risk of their activation in different municipalities of Georgia. Each municipality is given in a different colour denoting the hazard risk coefficients calculated by dividing the total length of the debris flow-forming watercourses by the total length of the river network in the basin [13].

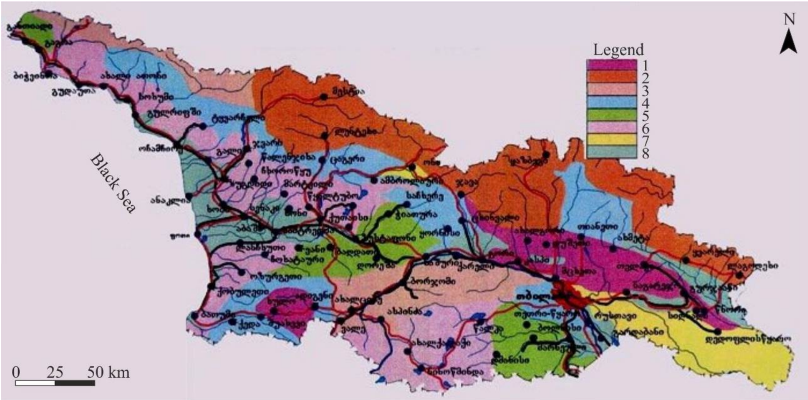

Fig. 2. Map of debris flow risks in Georgia [71].
***Legend*: 1 - very high risk of debris flow (8% of the territory of Georgia), 2 - high risk (19%), 3 – average risk (10%), 4 - significant risk (16%), 5 - limited risk (9%), 6 - negligible risk (20%), 7 – low risk (7%), 8 - mo risk (11%). The blue lines denote the rivers**

The map shows the least damaged municipalities in grey (Ninotsminda, Akhalkalaki, Dmanisi, the cities of Poti, Batumi and Kutaisi); the blue colour denotes more damaged municipalities (Adigeni, Kharagauli, Khashuri, Kareli, etc.) and the red colour denotes the municipalities with the highest risk of debris flow hazard (Kazbegi, Dusheti, Telavi, Kvareli, Gurjaani, Oni, Mestia, Lentekhi, Tianeti, etc.) [34].

As the Information Bulletins of the geological results of the National Environmental Agency of the Ministry of Environmental Protection and Agriculture of Georgia suggest, the manifestation of natural geological processes in the geodynamically stressed regions exceed the background value almost every year and consequently, cause significant economic damage (Table 1).

Table 1.
Statistics of damage inflicted by debris flows

#	Year	Number of debris flows	Approximate direct damage (mln. GEL)	Human victim	Total damage (mln. GEL)
1	1995	320	96	12	228,0
2	1996	162	27	5	107.3
3	1997	335	44	7	146,0
4	1998	173	20	6	87,0
5	1999	27	4.5	-	16.5
6	2000	23	3.0	-	16,0
7	2001	26	4.0	-	19,0
8	2002	23	2.5	2	16.3
9	2003	28	4.0	-	18.5
10	2004	258	28	2	175,0
11	2005	155	9.0	4	105,0
12	2006	63	9.0	-	79.5
13	2007	104	11.5	-	32,0
14	2008	126	15	8	63,0
15	2009	193	16.5	3	80,0
16	2015	85	35	23	45,8

NOTE: 1 Georgian GEL (Lari) equals 1.95 USD (2015 year)

Noteworthy modern methods used in recent years to combat debris flows are the construction of new reliable engineering-ecological structures in the riverbeds and coast-protecting weirs, terracing and foresting the slopes in erosive debris flow hearths and landslide zones, cleaning the detrital cones off the debris flow masses, etc.

PART I.

EROSIVE AND DEFORMATION PROCESSES IN MOUNTAIN LANDSCAPES

CHAPTER 1

ASSESSMENT OF THE ECOLOGICAL AND ECONOMIC LOSS OF THE FOREST MASSIFS BURNED DOWN FOLLOWING THE HOSTILITIES IN GEORGIA IN AUGUST 2008, AS WELL AS MEASURES TO PROTECT MOUNTAIN SLOPE SOILS AGAINST EROSION

1.1. An overall assessment of the burned-down forest massifs

The fires that erupted in Borjomi and Gori regions following the war in Georgia in August of 2008 covering nearly 1003 ha of forest massif, resulted in a catastrophic deterioration of the natural conditions of the regions and hydro-physical properties of soil, almost completely burning down its 2-10 cm humus layer in some areas.

The danger of erosive processes and formation of nallahs, ravines and landslides, as well as conditions conducive to debris flows and inundations have occurred, and environmental sustainability has worsened significantly.

As is well known, all of our planet's continents have forests that cover 30% of the total land area. Georgia is one of the most forested countries in Europe (forests cover 39.8% of the total terrain of the country), ranking fourth behind Finland (71%), Sweden (51%), and Lithuania (44%) [8, 12].

According to the researchers, a hectare of forest may absorb 13-17 tons of CO_2 and produce 10-15 tons of oxygen. Furthermore, it should be noted that 1 hectare of forest consumes 13-18 m^3 of water each year, returns 40-51 m^3 of water to the soil and has 150 m^3 of timber reserves. It is also interesting to note that during an 8-10-hour flight, a modern airplane absorbs 35 tons of oxygen, which is equivalent to the amount emitted by 1 hectare of forest in a year [17].

Forest fires caused by wars have an impact on the water output not just of mineral springs, but also of those contributing to the formation of local river discharges in Georgia during the next two or three years. All of the aforementioned have severely harmed the region's recreational resources, resulting in considerable ecological, social, and economic losses.

Figure 1.1 shows the burned-down forest territory near Gori; Figure 1.2 shows the burned tree remnants in the forest of village Daba near Tsagveri; Figure 1.3 shows the burned forest massifs in village Daba; and Figure 1.4 shows the sampling process of the burned soil.

Under Decree #252 of the Prime Minister of Georgia, as of 29 August, 2008, the Water Management Institute was actively involved in determining the environmental damage on the territory of Georgia caused by the hostilities of 2008.

Fig. 1.1. The territory near Gori after the fire

Fig. 1.2. Burned tree remnants in the forest of village Daba

Fig. 1.3. Territory near village Daba (Tsagveri) after the fire

Fig. 1.4. Sampling the burned soil in the forest of village Daba (right-to-left: Prof. T. Urushadze, Prof. G. Gavardashvili)

1.2. An integral estimate of the ecological and economic harm of the area following the burning of the forest massifs in Borjomi and Gori regions

To calculate the economic damage caused by forest fires, the following scholarly literature was used: [2, 17, 29]. Direct recalculation is used to calculate the losses caused by the destruction of the soil humus layer in the forest, as well as the reduction of water supplies (the number of destroyed resources multiplied by their value).

The losses resulting from the dramatic drop in the recreational capability of the natural forest landscape are estimated to last 50-100 years, which is the time, required for natural restoration of the original forest cover. The following formula [29, 44] can be used to calculate the total loss:

$$Y = \frac{\Pi \cdot S}{E}, \text{ (mln. GEL)} \qquad (1.1)$$

where, Y is the loss in sanatorium and health-resort economy; Π is the revenue generated by the operation of a recreational facility; S is a typical coefficient of input of recreational natural factors in income value; E is the time factor description rate (discount rate) (l/year). П is the value determined by the following expression [29]:

$$\Pi = I \times P \times Z \times T \,, \qquad (1.2)$$

where, I is the share of profit in the price of recreational facility services; P is the average number of visitors a day; Z is the price of recreational facility services; T is the duration of a visitor's stay at a recreational facility.

In addition to the economic damage, the social costs of the chemical pollution in the air basin and the deterioration of the aesthetic value of the landscapes must be considered.

Although the quantitative assessment of social loss is of a paramount importance, the methodology to calculate it has yet to be adopted.

Nowadays, the social loss (damage) can be computed by formula [17], which takes into account increased direct health expenditures:

$$Y\,soc = \frac{\alpha \cdot N \cdot K}{E} \text{ (mln. GEL)}, \qquad (1.3)$$

where, α is the health expenditure ratio; N is the number of local inhabitants; K is the average annual expenditure on population health in GEL/person; E is the discount rate.

1.3. Calculation of the economic losses in Borjomi Gorge

The fire burned down 950 hectares of forest, with 250 hectares totally destroyed. A total of 290 thousands m^3 of timber was destroyed, resulting in the following losses:

$$Y_F = 290{,}0 \text{ } thousand\,m^3 \times 500\,\text{GEL}/\text{m}^3 = 145{,}0\ \text{mln. G}EL \qquad (1.4)$$

where, 500 GEL/m^3 is the resource price of timber;

In 950 ha area, an average 0.2-m-thick soil cover was entirely or partially burned. Based on the calculated statistics, the following harm was caused by the removal of the humus layer: The damage caused by the loss of the humus layer based on the estimated data is as follows:

$$Y_F = 9\,500\,000\,\text{m}^2 \times 0{,}2\ \text{m} \times 100\,\text{GEL}/\text{m}^3 = 190{,}0\ \text{mln. G}EL; \qquad (1.5)$$

The damage caused by the reduction of water resources is as follows:

$$Y_F = 50\ \mathrm{m}^3 \times 850\ \mathrm{ha} \times 4{,}965\ \mathrm{GEL}/\mathrm{m}^3 = 0{,}235\ \mathrm{mln.}\ \mathrm{G}EL; \quad (1.6)$$

where, 4,956 GEL is the price of 1 m^3 water resource;

The sanatorium and health-resort loss is estimated using formulas (1.1) and (1.2):

$$Yhr = 0{,}3 \times 5{,}0\ \mathrm{t}hnperson. \times 50\ \mathrm{G}EL \times 90\ \mathrm{d}ays \times 1{,}0 : 0{,}01 = \\ = 675{,}0\ \mathrm{mln.GEL} \quad (1.7)$$

The value of the social loss is calculated by formula (1.3):

$$Y_{\mathrm{soc}} = 0{,}3 \times 5000\ \mathrm{p}ersons \times 150\ \mathrm{G}EL : 0{,}02 = \\ = 11.250\ \mathrm{mln.GEL} \quad (1.8)$$

Thus, the total loss caused by the deforestation of Borjomi Gorge is 1 021 485 million GEL.

1.4. Calculation of the economic losses in Gori region

Approximately 53 hectares of forest (including 50 hectares in Ateni Gorge) were damaged as a result of fire in Gori region. 16 thousand m^3 of timber was destroyed causing the following loss:

$$Y_F = 16{,}0\ thousand\ \mathrm{m}^3 \times 500\ \mathrm{GEL}/\mathrm{m}^3 = 8{,}0\ \mathrm{mln.}\ \mathrm{G}EL; \quad (1.9)$$

In 53 ha area, an average 0.2-metre-thick soil layer was entirely or partially burned. The loss caused by the disappearance of the humus layer according to estimated data is as follows:

$$Y_F = 530\,000\ \mathrm{m}^2 \times 0{,}2\ \mathrm{m} \times 100\ \mathrm{GEL}/\mathrm{m}^3 = 10{,}6\ \mathrm{mln.}\ \mathrm{G}EL; \quad (1.10)$$

The loss caused by the depletion of water resources is as follows:

$$Y_F = 50\ \mathrm{m}^3 \times 53\ \mathrm{ha} \times 4{,}95\ \mathrm{GEL}/\mathrm{m}^3 = 0{,}013\ \mathrm{mln.}\ \mathrm{G}EL; \quad (1.11)$$

The following is the sanatorium and health-resort economy loss estimated using formulas (1.1) and (1.2):

$$Yhr = 0{,}3 \times 1{,}0 \text{ th}npersons. \times 50 \text{ G}EL \times 90 \text{ d}ays \times 1{,}0 : 0{,}01 = \\ = 135{,}0 \text{ mln.GEL.} \quad (1.12)$$

Formula (1.3) is used to calculate the value of the social loss, which is as follows:

$$Y = \frac{0{,}1 \times 50000 \; persons \times 150 \text{GE}L}{0{,}02} = 37{,}5 \text{ mln.GEL.} \quad (1.13)$$

Thus, the total loss caused by the deforestation in Gori region is 191,113 million GEL.

1.5. Forecasting soil erosion processes in the burned areas

Expeditions were conducted by the scientific employees from the Water Management Institute from August to November of 2008 to investigate the geo-ecological conditions of burned soils in Borjomi and Gori regions. The burned soil was sampled on-site (Figs. 1.5, 1.6), and the following was determined based on the analysis of the laboratory study done at the Institute:

To study the situation following the fire in Borjomi Gorge (territory of Tsagveri and village Daba), a chemical analysis of a sample extraction was done, whose data confirm that the total concentration of highly soluble salts in the top soil sample layers is 2%; the content of humus in the soil is very low (1.25%). The soil is mostly carbonate and poor in nutrients. The amount of absorbed *Na* is 2.34% in total capacity, which exceeds the admissible limit. The soils have a low natrium concentration; the total alkalinity of the soil is quite high, reaching toxic levels; the chlorine concentration increases with depth and exceeds the hazardous limit for plants. According to these findings, the structure of the investigated soil has been disrupted, and the soil is extremely vulnerable to water and wind erosion.

The analysis of the published scientific literature dedicated to the study of erosion processes makes it clear that the maximum rate of annual precipitation in the catchment basins of the rivers Niagvris Ghele, so called MTS Ghele and Rusis Ghele, in village Daba and near Tsagveri, varies from 600 to 800 mm/year. The precipitation distribution in Borjomi region in different months is given in Table 1.1, and the precipitation distribution cyclogram is given in Fig. 1.7

Fig. 1.5. Burned soil surface near Gori

Fig. 1.6. Burned soil surface in village Daba

Table 1.1
Distribution of annual maximum precipitation by months

Station	1	2	3	4	5	6	7	8	9	10	11	12
Bakuriani	15,7	18,2	15,2	17,9	21,2	35,2	32	18,7	19,7	24,2	18,9	30,3

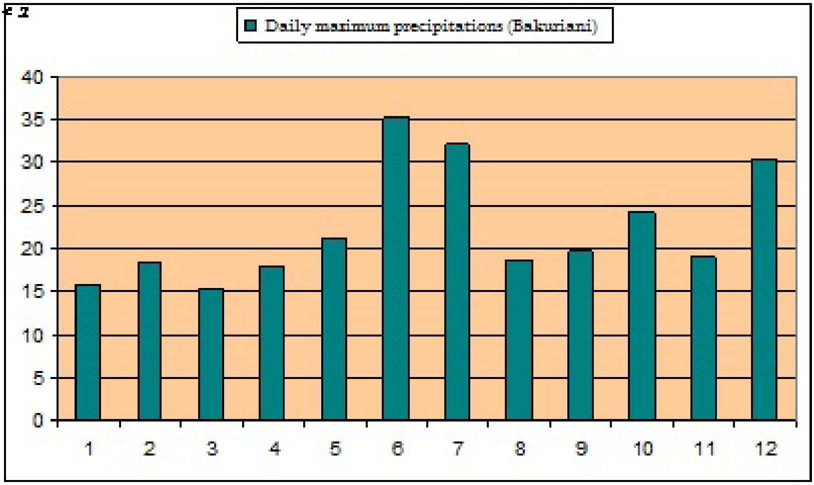

Fig. 1.7. Diagram of the precipitation distribution cycle

Field surveys and topographic map (Fig. 1.8) were used to calculate that the total area of the catchment basin of the River Naghvarevi is $F_0 = 4.313$ km², the burned area is $F_1 = 1{,}25$ km², and the sensitive area is $F_2 = 0{,}95$ km². Similar data of so called the MTS Ghele are: $F_0 = 1.656$ km², $F_1 = 0.52$ km², $F_2 = 0{,}41$ km², and those for the Rusis Ghele are: $F_0 = 2.375$ km², $F_1 = 0.66$ km² and $F_2 = 0{,}44$ km².

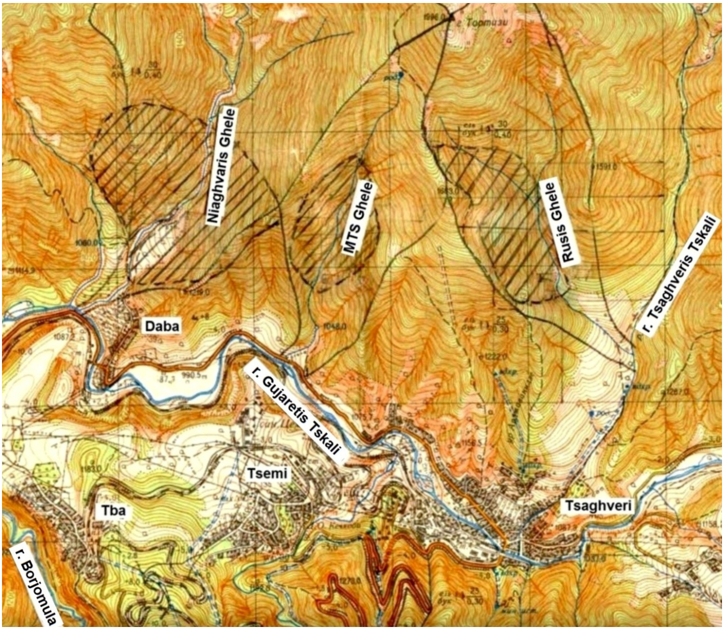

Fig. 1.8. Topographic map

So, as a result of the analysis of field reconnaissance surveys in Borjomi region, we can draw the following conclusion: 950 ha of forest massif were burned down in the catchment basins of the Rivers Naghvarevi, MTS Ghele and Rusis Ghele as a result of the fire in Borjomi region. The sensitive regions included 191 ha (1.91 km^2) of the 250 ha (2.50 km^2) entirely burned down forest (84%) (Table 1.2).

Table 1.2
Geometric values of the mountain slopes

Catchment basin	Slope projection	Slope initial and end levels asl (m)		Slope length (M)	Slope inclination	Slope inclination angle (degree)
Naghvarevis Ghele	Right	1475	1105	875	0,423	$25^0 00'$
	Left	1375	1105	625	0,432	$25^0 40'$
MTS Ghele	Right	1375	1125	500	0,500	$30^0 00'$
	Left	1425	1125	375	0,733	$47^0 10'$
Rusis Ghele	Right	1588	1250	575	0,587	$36^0 00'$
	Left	1450	1250	360	0,555	$33^0 40'$

The Erosion factor (E) is calculated using the formula [18,20]:

$$E = \left[0{,}58 + 1{,}40(F_2 / F_1)\right]\left(t / T\right)^{0{,}21}, \qquad (1.14)$$

where, F_1 is the burned-down area of the catchment basin (km^2); F_0 is the area of the whole catchment basin (km^2); t is the elementary period of the reporting period (year); and T is the entire forecast period (year).

Table 1.3 shows the results of the calculations performed using the English scientist Prof. R. Morgan's erosion scale [49] and relation (1.14).

Table 1.3
Erosion forecast

Erosion factor (*E*)	**2009**	**2015**	**2020**	**2025**	**2030**	**Erosion class according to R. Morgan [52]**	**Erosion intensity per year (t/ha)**
Catchment basin of the Naghvarevi River	0,95	1,11	1,21	1,27	1,34	3	5÷10
Catchment basin of the MTS Ghele River	0,56	0,65	0,71	0,75	0,79	2	2÷5
Catchment basin of the Rusis Ghele River	0,47	0,56	0,60	0,64	0,67	2	2÷5

According to Prof. R. Morgan's scale [52], the present-day erosion is of the second class, with an erosion intensity of less than 2÷5 t/ha a year. Given the heavy rainfall in the region (highest rainfall intensity anticipated equals K = 0,195 mm/s), water erosion processes in the soil may intensify, worsening the current ecological situation.

1.6. New resource-saving erosion control structures and methods to design them

Academician Tsotne Mirtskhulava [43-48], a world-renowned scientist, provided the foundation for the development of a system to foresee erosive processes and build countermeasures across the former Soviet Union, including Georgia. The formulation of "The State Target Program to Protect Georgia's Soils against Erosion" at the Water Management Institute (as approved by the relevant decree of the President of Georgia) under his direction and with his immediate participation is a significant event in the history of independent Georgia (1992).

Expedition research in the fire zones of Borjomi region have revealed that the region is situated in the upper forest belt, surrounded by average-height mountains, and covered with hornbeam-beech woods, with pine forests blooming in some areas. In terms of soils, the area is dominated by light and podzolized brown forest soils of average or little thickness [14,15].

The values of the angle of inclination of the mountain slopes located on the burned regions of the catchment basin of the rivers Naghvarevis Ghele, MTS Ghele, and Rusis Ghele were computed using a combination of field and cartographic data, and are listed in Table 1.3.