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THE FIELD INVESTIGATION OF EROSION AND DEBRIS FLOW PROCESSES IN CATCHMENT BASIN OF THE DURUJI RIVER

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ABSTRACT

For the effective protection of the population of the town of Kvareli in Georgia from debris flow formed on the Duruji River, the critical places on the river-bed of Duruji, where overflow of debris flow is possible, were identified. Erosion coefficients of mountain slopes with debris flowing into the basin of Duruji River, which establishes links between the class of erosion and degree of damage of a slope, were explored. Maximum charges on debris flow of river Duruji in different provisions were established, through which, at a following stage of an ongoing project, anti-debris flow structures are planned and designed. Using the theories of reliability and risk, probability distributions of the maximum charges of debris flow formed on river Duruji were examined including the suitability of using the Weibull probability distribution.

The reliability of new springboard type debris flow protection structures and associated risk profiles in the case of joint and separate dynamic and statistic influences of debris flow on the structures were assessed. Results from this investigation enabled us to predict effectively erosive-debris flow processes in the river-bed of Duruji, and introduce new ecological measures engineered to ensure the effective protection of the population of the town of Kvareli in Georgia and contiguous territory of the Duruji River from debris flow.

Key words: Duruji River, Kvareli Town, erosion coefficient, debris flow.

INTRODUCTION

Taking into account that the scientific paper concerns the protection of Kvareli population (10-12 thousands) from debris flow on the Duruji River, the problem described in this paper is very important for Georgia. In accordance with this purpose and the assignment of the President's authorities (Letter No. 3/29, 20/11/2008), a working group was organized under the guidance of the Institute of Water Management.

The objective of this group is to develop an integrated general scheme for the protection of Kvareli population from debris flows using modern methods and technologies. This scheme will include the following: adjusted predictions of erosive - debris flow processes formed in the bed of Duruji River and, at the next stage, development of new safe and economic protective measures using the above-mentioned results; reviews of possibilities to use the mass of debris in rural economy on the basis of the appropriate cost-estimate.

The problem is complicated by the fact that the surface of debrisflow fan of the Duruji River is located 10-12 m above the Mountain (2994 m above sea level), the northern range of which borders on Dagestan (Russia), see Fig. 1). The total basin area of the Shavi and the Tetri Duruji Rivers is equal to 3,08 sq. km, including the area of 0,25 sq. km) located in subalpine and alpine zones, and 60-70 hectare located in forest line adjoining ground surface of the town of Kvareli. This difference is caused by accumulation of debris flow deposits after a protective dam was built along the river in 1949.

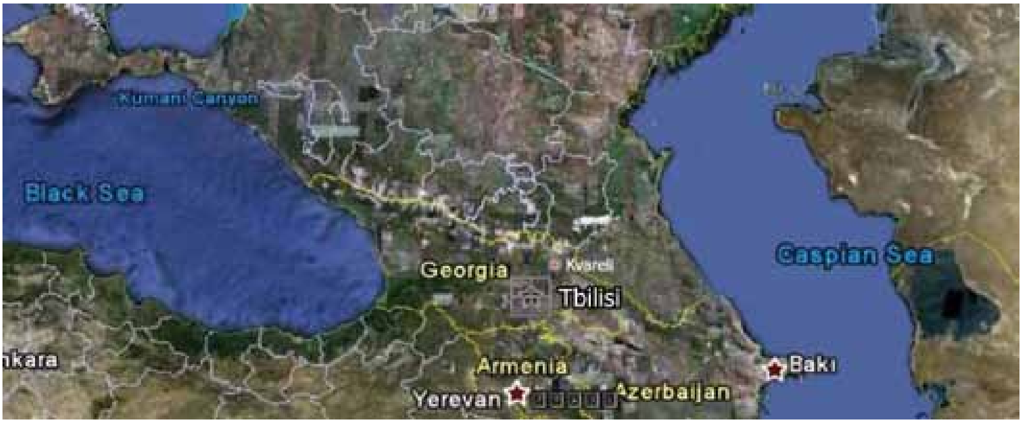

Fig. 1 - The catchment basin of the Duruji River

GENERAL DESCRIPTION OF THE CATCHMENT BASIN OF THE DURUJI RIVER

The Duruji River can be considered as one of the most active rivers with debris flow processes among the mountain rivers comprising the catchment basin of the Southern Caucasus (Georgia, Azerbaijan, and Armenia).

Field investigations during 2000 to 2009 implemented in the catchment basin of the Duruji River revealed that the ecologicalconditions are disastrous in the basins of the Tetri and the Shavi Duruji.

It is well known that the bed of Shavi Duruji is eroded because of the Shavi Mountain (2200 m above sea level), and the bed of Tetri Duruji is eroded because of the Southern range of the Pokhalo (Gagoshidze,1970; Tsereteli, etc. 2001; Gavardashvili, 2003).

The total area of the catchment basin of the Duruji river including its debris flow cone is equal to 116 km^2, among which the area of debris flow cone by itself is equal to -36 km^2.

The length of debris flow cone from the mouth of the Duruji River up to the so called Kherkheulidze structure is equal to 8.0 km, and the length of the river in the gully is equal to 18 km. Thus, the total length of the river is equal to 26 km, and its average gradient is i=0.222.

The average width of the catchment basin of the Duruji River is about 4.3-4.5 km, and the maximum is equal to 6.5-7.0 km (Gagoshidze, 1970, Gavardashvili & Chakhaia, 2002).

Geology. The catchment basin of the Duruji River is subdivided into two geographical parts: the Main Caucasian Range and Alazani Valley (Gagoshidze, 1970). In accordance with the lithological section, the catchment basin of the Duruji River is subdivided into the following parts: 1. shale stratum; 2. strata with inclusions of clay-shales and sandstones, and: 3. quaternary sediments.

Climate. The average annual temperature of the Duruji River basin varies within +12.2-14 oC, is this 12.2 to 14 mm, the average Soils. Generally, the following six types of soils are distributed in the basin of the Duruji River: cinnamonic forest soils, brunisol, outwashed soils (slopes), soils of mountain-forest-valleys, light chestnut soils, which can be observed generally in alpine and subalpine zones, proalluvial and deluvial soils (Gavardashvili & Chakhaia, 2002).

Plants. The whole area in the catchment basin of the Duruji River is subdivided in the following sequence: forests 76% (0.0066 sq. km), without forests 4.3% (0.00039 sq. km), summer pastures 16 % (0.0014 sq. km), rocks 4.3 % (0.00033 sq. km).

Fig. 2 - Boulder (63.1 ton) in the Duruji Riverbed (Photo G.Gavardashvili)

Fig. 3 - Tectonic fault zone, Pokhalo Mountain. 22 June, 2001 (Photo G.Gavardashvili)

PREDICTION OF EROSIVE - DEBRIS FLOW PROCESSES IN THE BED OF THE DURUJI RIVER

Implemented field investigations confirm that in the future the power of debris flow formed in the Duruji riverbed will not be only under the influence of erosive and landslide processes, but also under the influence of avalanches. During the expedition, we have noticed a big boulder of 63.1 tons (see Fig. 2), which has been moved downwards for the distance of 200 m as a result of flood and average debris flow in the Shavi Duruji riverbed during the period of 2 months. The implemented investigation revealed that the above-mentioned boulder belongs to the catchment basin of the Savepkho-Gori river (the left tributary of the Duruji River).

The tectonic break of mountainous strata has been observed on the Pokhalo Mountain (springs of the Tetri Duruji River), 2990 m above sea level (see Fig. 3). In the future, this break can activate annual temperature is - 3.7 oC in winter, and the highest temperature is +25 oC in summer.

The average annual quantity of precipitations in the Duruji River basin is equal to 960 mm, and 901 mm in Kvareli (Gavardashvili, 2002). The maximum quantity precipitations is observed in spring-summer periods (May-June).

In accordance with the data of meteorological station the maximum quantity of precipitations (1/4) can be observed in May-June.

landslide processes, which can be considered as the initial stage intensify the erosive-debris flow processes (Gavardashvili & Chakhaia, 2002).

The influence of avalanches can be added to the erosive-debris flow and landslide processes in the basin of the Duruji River. On the 22 June 2001, the catchment basin of the Duruji River was covered by the avalanche (5-6 m thickness, 150 m long) slipped from the gully of the Tsipel Gori River (the left tributary of the Shavi Duruji River) (see Fig. 4). In accordance with the longitudinal profile of the Duruji River, the gradient of this section is equal to 17°, the width of channel -4.6 m, and the depth of water flow -0.32 m (Gavardashvili, 2003; Gavardashvili & Chakhaia, 2002).

Fig. 4 - Avalanche in the Shavi Duruji valley, 2001 (Photo G.Gavardashvili)

The field surveys implemented in the catchment basins of the Shavi and the Tetri Duruji Rivers have produced a conclusive evidence that the ecological conditions of the mentioned areas as disastrous, which requires immediate implementation of appropriate measures.

To assess the erosive processes for the gullies with active erosive - debris flow processes in the catchment basin of the Duruji River,

the erosion coefficient (E) has been calculated on the basis of dependence obtained as a result of field works and interpretation of aerial and satellite images (Gavardashvili *et alii*, 2006):

$$E = [0,58 + 1,40\,(F_1 / F_0)] \cdot (t / T)^{0,21} \qquad (1)$$

NN	River	Values of erosion coefficient				Erosion class (2010)	Intensity of Erosion annually (t / ha)
		1980	1990	2000	2010		
1	Nakhechi Gully	0.077	0.08	0.195	0.207	second	2-5
2	Samali Gully	0.05	0.061	0.072	0.171	second	2-5
3	Salesavi Gully	0.30	0.45	0.68	0.75	third	5-10
4	Utkhovari Gully	0.84	0.92	0.98	1.00	fourth	10-50
5	Mshrali Gora Gully	0.76	0.94	1.00	1.05	fourth	10-50
6	Savepkhvo Gora Gully	0.82	0.96	1.11	1.15	fourth	10-50
7	Tsipel Gora Water	0.83	0.99	1.21	1.23	fifth	50-100
8	The Upper Duruji (Shavi Klde)	1.00	1.45	1.95	2.01	sixth	100-500

Tab. 1 - Erosion coefficient and erosion class of mountainous slopes in the catchment basin of the Duruji River

where, F_1 - erosive area (km^2) in the catchment basin of the river, F_0 - area (km^2) of the whole catchment basin, t - time interval surveyed (year), T - total observation period (in our case T=30 years).

(1) - limit dependencies are as follows:

$0.061 \leq (F_1/F_0) \leq 0.24$; $0.1 \leq (t/T) \leq 1.0$ (2)

The values of erosion coefficient for the mountainous slopes of the Duruji river basin are calculated by the dependencies (1) taking into account the appropriate values of damage rate given in Table 1.

The frequency of ravines and flumes observed in some sections of so called "Black Mountain" in the upper reaches of the Duruji River (2002) is equal to 15-20 m. In accordance with the classification of Prof. R. Morgan (MORGAN & HANN, 2001), this value is appropriate to the 7th class of erosion with the intensity of erosion more than 500 (t/ha) per year.

As about the association (Table 1) between the erosion class and the erosion coefficient, it has been calculated in accordance with the scale of Prof. R. Morgan (MORGAN & HANN, 2001)].

To assess the stability of the Duruji riverbed, we have measured the widths of Tsotskhali section (b) and Noga channel (B), depths of water flow (h), gradients of the riverbed (α) and flow velocities (V). Then, we have measured the discharges of water flow (Q_0). The number of statistical measurement is equal to 177 points.

The empirical values have the following forms:

$(h / b) = 0,3\ (\alpha)^{-0,62}$ (3)

$(b / B) = 0,001(\alpha\ )^{2,11}$ (4)

Limitations on the dependencies (3) and (4) are as follows:

$$\begin{cases} 0.01 \leq (h/b) \leq 0.185; & 4° \leq \alpha \leq 25° \\ 0.01 \leq (b/B) \leq 0.75; & 2° \leq \alpha \leq 22° \end{cases} \quad (5)$$

To assess the reliability of dependences (3), the resulting values have been compared with the collected data, and we found that their error varies between 5-20% in case of 0.95% probability, which are considered as satisfactory values for hydrological calculations.

Fig. 4 - Erosional Slopes of Shavi Klde. 21 June, 2001 (Photo G.GAVARDASHVILI)

To predict the quantity of debris mass collected in the catchment basin of the Duruji River, we have measured general features of mass slid from the mountainous slopes in the Noga riverbed. These features are as follows: geometrical dimensions of talus train, slope angles of solid fractions on the talus train and internal friction angles, average diameters of fractions etc.

Fig. 4 shows general view of eroded slopes in 700 m from Shavi Klde near the upper reaches of the Shavi Duruji River, and Fig. 5 shows the erosional slope of Pokhalo mountain in the upper reaches of the Tetri Duruji river, 2800 m above sea level.

The results of granulometric analysis concerning the samples of solid composition obtained from the talus train of the Duruji river are given in Tab. 2 (GAGOSHIDZE, 1970). The chemical analyses of colloidal mass needed to use debris mass in production (GAVARDASHVILI & CHAKHAIA, 2002) are given in Table 3 (value of chemical elements is given in %).

Fig. 5 - Erosional Landslide Slope of Pokhalo Mountain. 2001 (Photo G.GAVARDASHVILI)

No	Dimensions of Factions (mm)	Weight (kg)	Percentage (%)
1	Stones >30	116.0	42.0
2	Breakstone 30-10	48.9	17.7
3	Gravel and Coarse Sand (10-1)	43.4	15.7
4	Fine-Grained:	68.0	24.6
	(1-0.05)		8.4
	(0.05-0.005)		8.8
	(0.005-0.001)		4.0
	< 0.001		3.4

Tab. 2 - Mechanical composition of debris mass obtained on the Debris Flow Cone of the Duruji River

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	MnO	NaO	K_2O
49.5	27.0	12.02	0.29	0.90	2.90	0.80	1.08	5.60

Tab. 3 - Chemical analysis of colloidal mass of the Duruji River

As for the mass slid from the mountainous slopes in the catchment basin of the Shavi Duruji River, it is equal to 300 000 m^3 according to the data of June-July, 2001. This value can be considered as an average one for the conditions of this channel.

Thus, the field investigations implemented in summer (2001-2009) in the catchment basin of the Shavi and the Tetri Duruji Rivers revealed that

the condition of erosion processes on the mountainous slopes are disastrous and, in some sections, it can be considered as equal to the 7th class of erosion.

DETERMINATION OF MAXIMUM DISCHARGES OF DIFFERENT PROVISION FOR DEBRIS FLOW FORMED IN THE DURUJI RIVERBED

To determine maximum discharges of different provision for debris flow formed in the Duruji Riverbed, we have used scientific literature (GAGOSHIDZE, 1970; GAVARDASHVILI, 2003; GAVARDASHVILI & CHAKHAIA, 2002; MIRTSKHOULAVA, 1998; NATISHVILI & TEVZADZE, 1996; TAKAHASHI, 1994) and statistic line developed and restored by the author on the basis of data obtained in hydrometeorological observatory.

The accumulative value of relative maximum discharge for the debris flows passed in the Duruji Riverbed (1899-1999) is equal to $\sum_{i=1}^{46} Q_i/Q_{\max} = 7{,}856$ (m^3); the statistical value based on the field observation is equal to $N = 46$ points.

The average value (Q_i / Q_{max}) of relative discharge for the debris flow is equal to:

$$(\bar{Q_i/Q_{\max}}) = \frac{\sum_{i=1}^{46} Q_i/Q_{\max}}{N} = \frac{7{,}856}{46} = 0{,}187 \quad (6)$$

The coefficient of variation of debris discharge is equal to (AYYUB, 2003):

$$C_v = \sqrt{\frac{\sum_{i=1}^{N}[(Q_i/Q_{\max}) - 1]^2}{N-1}} = \sqrt{\frac{57{,}34}{45}} = 1.128 \quad (7)$$

The coefficient of asymmetry was calculated on the basis of the following dependences:

$$C_S = 2 \cdot C_V = 2 \cdot 1{,}128 = 2{,}256 \quad (8)$$

Using the values obtained, we have calculated debris discharges of different provisions of the Duruji River. These values are given in the Table below (see Tab. 4)

To assess field data, which will allow us to predict maximum debris discharges of different provision for the Duruji river; we have used the following empirical dependence (GAVARDASHVILI *et alii*, 2006):

$$Q_{max} = A \cdot (34 \dotplus 400 \cdot i) \cdot F^{0,61} \text{ (m}^3\text{/sec)} \quad (9)$$

where, A - coefficient, which is given with the coefficient of discharge in Table 5; i - average gradient of the Duruji River, which is equal to i=0.222; F - area of the catchment basin of the Duruji River, F = 80.0 sq. km;

Recurrence once n per year	1000	100	33	20	10	4
Provision P(%)	0.1	1	3	5	10	25
Field data	3094.89	1967.62	1421.06	1216.09	891.57	491.90
(9) Formula	4267.55	1778.14	1244.69	1066.88	889.07	533.44
Error P (%)	27.5	9.6	12.4	12.3	2.8	7.8

Tab. 4 - Discharges of Different Provisions of the Duruji River

Provision P (%)	0.1	1	3	5	10	25
(A) - Coefficient	2.4	1.0	0.7	0.6	0.5	0.3

Tab. 5 - Association between the coefficient (A) and the discharge provision (P%)

The average square error of maximum debris discharge has been calculated on the basis of the following dependence (AYYUB, 2003):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{46}\left[(Q_i/Q_{\max})_j - (Q_i\bar{/}Q_{\max})\right]^2}{N}} = \sqrt{\frac{1{,}6873}{46}} = 0{,}1915 \ (m^3/sec) \qquad (10)$$

The data needed to plot histogram are given in Table 6.

Intervals of debris discharge $(Q_i/Q_{\max})$	0 - 0,25	0,25 – 0,50	0,50 – 0,75	0,75 - 1,00
(m_i) Frequency	41	2	1	2
$f(Q_i/Q_{\max})$	0,891	0,044	0,022	0,044

Tab. 6 - Relative Values of Debris Discharge per appropriate Intervals

The mathematical expectation is determined on the basis of the following formula (AYYUB, 2003; GAVARDASHVILI & CHAKHAIA, 2002):

$$m_* = \sum_{i=1}^{46} f(Q_i/Q_{\max})\cdot(Q_i\bar{/}Q_{\max}) = 0{,}891\cdot 0{,}125 + 0{,}044\cdot 0{,}375 + 0{,}022\cdot 0{,}625 + 0{,}044\cdot 0{,}875 = 0{,}1801 \qquad (11)$$

The histogram of values relative to the maximum discharges of the Duruji river and the curve of appropriate theoretical distribution are given on Fig. 6.

The Weibull distribution (AYYUB, 2003) appropriate to the curve given on Fig. 6 is as follows:

$$f(Q_i/Q_{\max}) = 0{,}035\cdot(Q_i/Q_{\max})^{-0{,}82}\cdot\exp[-0{,}192\cdot(Q_i/Q_{\max})^{0{,}18}] \qquad (12)$$

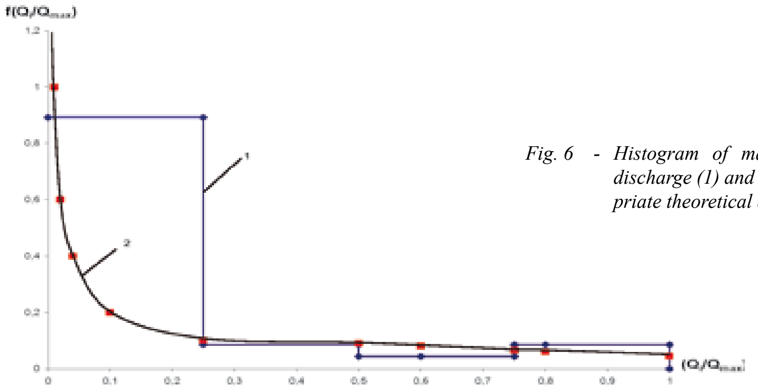

Fig. 6 - Histogram of maximum debris discharge (1) and curve of appropriate theoretical distribution (2)

If we calculate the maximum discharges of the Duruji River using Weibull distribution, the reliability of values obtained on the basis of dependence (12) should be calculated by the following formula:

$$P(Q_i/Q_{\max}) = \int_0^1 0{,}035(Q_i/Q_{\max})^{-0.82}\cdot\exp[-0{,}192\cdot(Q_i/Q_{\max})^{0{,}18}]\cdot d(Q_i/Q_{\max}) \qquad (13)$$

Solving the equation (13) we receive the following value $P(Q_i/Q_{\max}) = 0{,}549$, and the non-performance probability is as follows:

$$R = 1 - P(Q_i/Q_{\max}) = 1 - 0{,}549 = 0.461 \qquad (14)$$

We have determined that to predict the maximum discharges of the Duruji river, the values calculated on the basis of dependences (9) are correspond more closely to the data of natural debris discharge than to the values calculated on the basis of Weibull formula (see Table 5).

The results were compared with the methodology developed by Acad. Tsotne Mirtskhulava (MIRTSKHOULAVA. 1998), who determined the pattern of change in maximum debris discharges using the mathematical simulation, especially, probability theory. The coincidence between them is satisfactory.

No	Year of Debris Flow event	Debris Discharge Q_{max} (m^3/sec)	Duration of Debris Flow T (sec)	Capacity of Debris Flow W (m^3)		Error (%)
				Field Data	By Formula (15)	
1	**2**	**3**	**4**	**5**	**6**	**7**
1	1899	434.8	1380	600024	689361	12.9
2	1906	2000.0	900	1 800000	1096675	39.6
3	1947	1666.6	960	1 599936	1058926	33.8
4	1949	370.4	1620	600048	782448	23.3
5	1956	253.2	900	227880	242579	6.1
6	1957	199.2	960	191232	224600	14.8
7	1961	159.6	900	143640	173197	17.1
8	1961	210.0	660	138600	132055	4.7
9	1961	740.0	1560	1 154400	1224423	5.7
10	1961	250	2160	540000	909388	40.6
11	1963	172.0	960	165120	201774	18.2
12	1963	132	420	55440	47341	14.6
13	1963	703	1740	1 223220	1 392487	12.2
14	1963	144	840	120960	144673	16.4
15	1963	73	420	30660	30722	0.2
16	1963	470	3300	1 551000	2 745691	43.5
17	1963	103	180	18540	10896	41.2
18	1963	1244	720	895680	552387	38.3
19	1963	443	1380	611340	698827	12.5
20	1963	288	300	86400	50172	41.9
21	1963	150	360	54000	41115	23.8
22	1963	262	720	188640	177167	6.1
23	1963	446	360	160560	91091	43.3
24	1963	205	900	184500	207926	11.3
25	1963	82	300	24600	20053	18.5
26	1963	62	1020	63240	105050	39.8
27	1973	200.6	900	180540	204658	11.8
28	1976	240.2	840	201768	210185	4.0
29	1977	167.6	720	120672	127863	5.6
30	1981	264.0	1200	316800	387263	18.2
31	1982	458.0	300	137400	70394	48.7
32	1983	229.0	720	164880	160585	2.6
33	1984	162.0	960	155520	193142	19.5
34	1986	282.0	720	203040	186942	7.9
35	1986	160.0	1500	240750	377177	36.2
36	1986	321.0	900	288900	288454	0.2
37	1990	114.0	1200	136800	209785	34.8
38	1992	330.2	1500	495300	640086	22.6
39	1997	221.1	1080	239868	289889	17.3
40	1999	333.3	1500	500000	644477	22.4

Tab. 7 - Coincidence of Debris Mass transported by Debris flow of the Duruji River

PREDICTION OF DEBRIS MASS TRANSPORTED IN THE DURUJI RIVERBED

To predict debris mass transported by debris flow of the Duruji River, we have used the results of field surveys implemented in the summer of 2001-2009 and the scientific literature published during the recent period of time (Gagoshidze, 1970; Gavardashvili, 2003; Natishvili & Tevzadze, 1996; Tsereteli *et alii*, 2001).

The statistical line of debris flows in the Duruji riverbed revised and, in some cases restored, is published in the paper (Gavardashvili, 2003); processing the above-mentioned statistical line we receive empirical dependence, which allows us to calculate the volume of debris flow transported by debris flow in the Duruji riverbed (W).

The mathematical expression is of the following type:

$$W = 0{,}138 \cdot T^{1,52} \cdot Q_{max}^{0,73} \quad (m^3) \qquad (15)$$

where, T - travelling time of debris flow in the riverbed; Q_{max} - maximum discharge of debris flow (m^3 / wm).

Limitations on dependencies (15) are as follows:

$$180 \leq T \leq 2160 \quad (sec)$$
$$100 \leq Q_{max} \leq 2000 \quad (m^3 / sec) \qquad (16)$$

Using the dependencies (15) we have calculated the values of debris mass (*W*) transported by debris flow in the Duruji riverbed, which were compared with the natural data; the percentage indices of their coincidence are given in Table 7).

Tab. 7 comparison between the values of debris capacity transported by the debris flow in the Duruji riverbed and the data calculated by formula (15) gives us errors of 0.2 - 40 %, which can be considered as satisfactory for hydrological calculations.

CONCLUSIONS

The following general conclusions and recommendations can be drawn on the basis of field investigations implemented in the catchment basin of the Duruji River (2001-2009) and scientific literature:

• To provide effective protection of Kvareli population against debris flow in the Duruji riverbed, we have determined those critical sections, where debris flow can break the riverbed;

• We have studied erosion coefficients for the mountainous slopes of debris tributaries sliding in the catchment basin of the Duruji River. These coefficients allow us to determine the coincidence between the class of erosion and the damage rate of slopes;

• We have determined the maximum discharges of different provision regarding the debris flow of the Duruji river, which allow us to design structures against debris flows;

• Using the theory of reliability and risk, we have determined distribution law for the function of maximum debris discharges formed in the Duruji riverbed, which has a form of Weibull;

• We have obtained empirical dependence, which allow us to calculate the capacity of debris mass transported by debris flow in the Duruji riverbed;

• The results obtained in ceramics plant regarding the chemical analysis of debris mass (10 - 20 M m^3) collected in the Duruji riverbed allow us to use Duruji debris mass in construction works (facing slabs, bricks, mortar, glass making etc.), in agriculture (increase in output of Kindzmarauli wine, increase in stability of farmlands located on the mountainous slopes, which are under the influence of erosion processes), in production of ceramics and other products.

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