Physical Geography

Modern Method of Analysis of the Factors of Catastrophic Floods on the Caucasus Mountain Rivers

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One of the peculiarities of mountain rivers is their narrow bed bordered with floodplain forests and blocked with boulders. An unpredictable flooding collapse following the river water rise forms a volley wave, which poses danger to hydraulic structures and settlements. The goal of the paper is to study the river floods and volley waves and to develop recommendations to avoid or mitigate them. Strong catastrophic flashfloods of the Rioni and Vere Rivers distinguished for their big size and water-abundance, were selected as a study object. Their scenarios give clear picture of the features of the volley wave formed by the flooding collapse. The study used the methods of mathematical statistics (analogue, the least square methods), high water level method, water velocity calculation methods and modernized calculation expressions. The reason for the Rioni flashflood was rain, firn degradation and landslide. As for the Vere catastrophic flood, it was related to the tunnels in Tbilisi, which failed to transport the phyto-sediment. The degree and frequency of catastrophes of mountain river flood are determined by the set of natural and anthropogenic factors with a long return period. When a facility's structural parameters do not comply with the parameters of the water discharge and sediment of a volley wave caused by the river flooding collapse, the flashflood becomes catastrophic. Therefore, for the purpose of safety of people, infrastructure and dams, the structure and parameters of hydraulic facilities must correspond to the properties of a potential volley wave.*

Volley wave, phyto-sediment, flooding level, flooding collapse

The main peculiarities of mountain rivers are: high velocity, coarse sediment and narrow riverbed bordered with floodplain forests and blocked with boulders. As the forest reaches its critical size, the risen river overflows its banks, captures plants and timber and forms flooded areas with this phyto-sediment in narrow riverbeds and near the bridges. The collapse of such unpredictable ponds forms a volley wave, a particularly dangerous hydro-element for people, dams and other hydraulic structures.

Sometimes, a human factor has a decisive impact on the formation of the catastrophic nature of floods and flashfloods of the mountain rivers. If during the design and operation of a hydraulic structure, particularly dangerous rare events and spontaneous processes are ignored, the flashfloods almost always end in catastrophes [1]. When such events develop under the impact of natural or anthropogenic factors of a rare provision, they almost always end in numerous victims and great damage.

Consequently, the goal of the paper is to study the reasons of catastrophic flashfloods and floods and accompanying volley waves of mountain rivers by considering the river scenarios. The issues of flood-water level estimation [2,3], quantified analysis of the probability of flooding under imaginable worst-case sea level rise scenarios [4], gravity-driven sediment transport near river mouths [5], flood alerts using short message service, as well as sediment transport and bed morphology at river channel confluences, adaptive flood level forecasting [6], simulation approach to the assessment of flood level frequencies [7], flood level indicator and risk warning system, natural sediment supply limitation and the influence [8,9], etc. have been comprehensively studied by many scientists from different regions of the world.

The studies were accomplished by using the monitoring data of flashfloods of rivers of the Caucasus and other mountainous regions. For illustrative purposes, the catastrophic floods of two rivers, which greatly differ from one another with their sizes and water regimes – the Rioni (28.07.2020) and the Vere (13.06.2015) with numerous victims and great material damage, were selected as a study object. Their scenarios clearly show the properties of volley waves formed by the flood collapse.

The study used the mathematical statistical (analogue, the least square) and high-water level method and water velocity calculation methods. Consequently, the sought values were calculated by using modernized calculation equations [8].

The reason for the Rioni flashflood was rain, firn degradation and landslide. The risen tributaries took the floodplain plant into the river torn out with their roots and sediment formed during the landslide processes. This combined sediment created blockades of various heights on five sites and flooded the river. A similar process near Utsera Bridge increased the river flow from 660 m^3/sec to 1360 m^3/sec at the expense of the flooding collapse and damaged or destroyed 12 bridges. The Vere River is known for numerous victims. The reason for this is the tunnels through which it crosses Tbilisi. According to the Vere catastrophic flood scenario, Tbilisi tunnels could not transport the phyto-sediment and there occurred flooding, with the discharge of its volley waves reaching 500 m^3/sec and having killed 21 people.

Consequently, the degree and frequency of catastrophic mountain river floods are determined by a combination of natural and anthropogenic factors with a long return period. The process develops as follows: heavy rains and its accompanying events cause river-rise and activation of the landslide hearths. There is no sufficient space in the riverbed for the river, as it is narrowed with floodplain vegetation, which grabs the plants and gathers the mudflow sediment, which forms blockades near the facilities with their structural parameters incompliant with the parameters of the risen river water discharge and sediment. As the level of flooded water reaches a critical value, there starts a flooding collapse to form a catastrophic volley wave. Therefore, in order to ensure the safety of people, infrastructure and dams particularly, the structure and parameters of the hydraulic facilities must be compliant with the properties of potential volley waves.

As mentioned above, the Rioni and Vere Rivers, as objects with outstanding catastrophic floods and hydrometry, were a subject of a particular interest. The Rioni River is one of the most water-abundant rivers of Georgia, the Caucasus. It is characterized by strong unexpected floods at any time of the year and strong unpredictable volley waves. Unlike the Rioni River, the Vere River is a small river even for Georgia. However, in terms of the combined human and natural factors, it is as dreadful as Rioni

River with its flooding regime and volley waves. As it flows across Tbilisi, quite often, its flashflood volley waves result in more victims and material damage than the Rioni River.

The study used the method of mathematical statistics (analogy, the least squares), high water level method and methods to calculate water velocities, as well as recent recommendations and expressions.

An important feature of the study river basins is fast-growing floodplain forests along their beds. Such forests make the riverbeds so narrow that in 40 or 50 years, there is no sufficient space in them for a high flashflood wave of a rare-provision. Then, the river flows over its banks and grabs the plants with their roots. Such a drift blocks the meanders, the sites near the bridge piers, tunnels and riverbeds narrowed by the blocks, and forms deep flooding. The collapse of such blockings forms a strong volley wave with its discharge (Q, m^3/sec) and volume (W, m^3) sometimes much exceeding its P≤1% flashflood parameters and has a great destructive power. The flashflood of the Rioni River of 2020 is also notable following the fact that as in the second half of summer, the seasonal snow supply disappears and the flashflood parameters are mainly determined by the rain properties and firn field runoff. This phenomenon was formed on July 28 as a downpour. The tributaries, together with a high runoff, transported the uprooted tall trees and other plants into the Rioni River and formed a 7-8 m pond near Ghebi Bridge. The rain caused stream rise of other tributaries on the right side, particularly the mud-prone Shkhilori River. The collapse of the Rioni flooding near the Shkhilori River formed such a high volley wave saturated with phyto-sediment that the bridge of Kutaisi-Mamisoni Military Road several kilometers below failed to discharge the water and as a result, a 0.7-km-long and 0.3-km-wide large flooding, the whirlpool, was formed. The water and phyto-sediment rotated in the whirlpool at such a high speed that the erosive processes caused by them increased the width of the river flashflood bed by three times and more. Following the collapse of the blocking, the river became so strong with the runoff of its lower tributaries that tore away the rope bridge in Utsera from the height of 4.5 m.

A semi-instrumental measurement of the high river water discharge was done with a high-level water reference item – the bunch of roots [8]. The bunch is hanging down the tree growing inclined on the rock, 3.2 m above the winter low-water surface. Following the passage, its width increased to 41 m. Consequently, the initial parameters of the wave passed across the bridge profile were: width: 41 m, depth: 3,2 m, effective cross-section: 118 m^2, and water discharge: 650 m^3/sec.

The riverbed, approximately 200 m below this profile Gverita, near the confluence of the Mushuani River, which was narrowed with massive blocks and concrete cubes, failed to convey the phyto-sediment transported there at once. Consequently, the river flooding was formed 25-30 m above the detrital cone of the Mushuani River. As the water level reached

the critical height, the water disrupted the block, flowed along an approximately 70-meter-long canyon-shape bed and, saturated with phyto-sediment, flashed onto an open plain where it started to flow through four different beds and approached a 5.0-meter-high and 120-meter-long bridge in village Zhamiereti.

The events there took a similar course, i.e., the bridge failed to convey the phyto-sediment, an approximately 5,0-5,3-meter whirlpool was formed and the water washed away the left wing of the bridge. Later, the river could disrupt the blocking, washed away high-voltage power towers 2.0-2.5 km below, the road and the right side of the bridge in village Gomi.

As the wave flowed through the canyon, it left the signs of high-water level behind. Based on them, the profile was selected and its parameters were measured. The width of the bed there was

35 m; its perimeter was 48 m; its area was 212 m^2; and the water discharge was 1362 m^3/sec what is twice as much the discharge measured through the bridge profile.

The same method and order were used to measure the volley wave parameters in the beds through which the wave formed near the block flowed. The total area of the measuring profiles of the given beds is 319 m^2 and the water discharge is 1353 m^3/sec.

It should be noted that the reference books and literary sources published before 2020 do not specify a flashflood volley wave of the Rioni River or its present-size parameters

According to these sources [10], the highest discharge (i.e., P≥1.0%) is ~400 m^3/sec and the maximum water level does not exceed 977.4 m asl. similar catastrophic flashflood occurred in August of 1953. It took a similar course and caused victims. It was caused by strong rain, which significantly activated the firn melting and landslide processes.

$$R = \frac{F}{P} m; C = \frac{1}{n} R^{y} m^{0,5} / sec; V = C\sqrt{R\,I} m / sec;$$

$$Q = FVm^{3} / sec; \varepsilon = \frac{1362 - 1353}{1362} 100\% = 0,7\%;$$

the error between the flashflood discharges calculated in the II and III profiles (sections).

The flashflood of the Vere River in 2015 had much severer consequences [1]. The highest discharge of this phenomenon near the entrance of the first tunnel was ~500 m^3/sec, what is almost three times less than the Rioni flashflood discharge, but had much severer consequences. The said natural calamity was formed as a result of the interactions of several natural and human factors. The natural cause of the flashflood was strong rain, which started two days earlier and lasted until the next day with small intervals. The degraded subgrade of the river basin failed to sustain the slope runoff formed with sediment. So, it rapidly flowed into the river as large currents and formed a flashflood wave with its discharge reaching 170 m^3/sec at the confluence of the risen mudflow current (the River Jokhoniskhevi). Such great water mass rushed towards Tbilisi at a high velocity down the much-inclined slope. A strong landslide formed in the basin of the said tributary, with much of it taken down to the Vere River bed by the flashflood wave, was flooded for some time what was critical

Table 1. Main parameters of the catastrophic flashflood of the Rioni River near Utsera

№	Transverse profile	B, m		P, ∂	I, ‰	n	y	R, ∂	C, $m^{0,5}$/sec	F, $∂^2$	V, m/sec	Q, m^3/sec	
1	Gverita Bridge	37(41)		43.4	0.03	0.07	0.34	2.72	19.7	118	5.48	650	
2	II, Mushuani Tributary	35(36)		48	0.02	0.080	0.37	4.41	21.6	212	6.43	1362	
3	III, Toll Tree section	Zhamiereti	27	50.2	0.01	0.067	0.08	1.04	14.9	52.0	1.52	79.0	1353
		Middle	28	41.2	0.01	0.070	0.37	5.32	23.8	219	5.47	1198	
		Khelosnianti	48	30.6	0.01	0.075	0.11	1.59	14.0	48.6	1.76	86.0	

Presumably, the projects developed in terms of lack of the reliable information are one of the reasons for the failure of the bridges, tunnels and other facilities designed by them to resist the floods and flashfloods of rare provision of the mountain rivers. As the facts evidence, as several rare natural events happen at once, the Rioni River flashflood may reach 1400 m^3/sec along Glola-Oni section. The flashflood volley wave of the river with the said regime destroyed 12 bridges and many sections of Kutaisi-Mamisoni military road and disrupted the road traffic for some time what inflicted a significant damage to the country, particularly to certain settlements, and expanded the list of risks of the Rioni River flashfloods. A for the flashflood waves of both rivers. They merged and the resultant river discharge reached ~300 m^3/sec. The mud mass diluted in the river runoff made the river into a mudflow current, which increased gradually as the tributaries and sediment joined it on its way and destroyed and grabbed the floodplain forests and different structures. They merged and the resultant river discharge reached ~300 m^3/sec. The mud mass diluted in the river runoff made the river into a mudflow current, which increased gradually as the tributaries and sediment joined it on its way and destroyed and grabbed the floodplain forests and different structures.

They merged and the resultant river discharge reached ~300 m^3/sec. The mud mass diluted in the river runoff made the river into a mudflow current, which increased gradually as the tributaries and sediment joined it on its way and destroyed and grabbed the floodplain forests and different structures. The mudflow volley wave formed in this way containing numerous tall root plants rushed onto the area in front of Vake-Saburtalo tunnel at 01 a.m., June 14, 2015, where the bed was quite narrowed with concrete dikes and other facilities, used as a car parking area. The rushed mudflow wave took all the things away from the area, including cars and washed them down into the tunnel. The tunnel design capacity is ~400 m^3/sec. However, the cars and the phyto-sediment jammed in it led to the river flooding and the water level in the tunnel raised so rapidly that the people living 10 m above the bed felt the danger only when the water flowed into their flats.

Later, the water pressure pushed the “plug” out of the tunnel, which was then stuck in Varaziskhevi tunnel at a lower level, where the same scenario developed, but with more victims and damage. The peak discharge of the volley wave in Varaziskhevi tunnel exceeded 500 m^3/sec (Table 2).

The water flashflood inflicted a great damage to the residents of both reaches of the tunnels: 21 people, mostly women and children, died; two people are still missing; TSU hydrometeorological laboratory with its database and study equipment was destroyed and Tbilisi Zoo was badly damaged. The idea to artificially close the riverbed between the tunnels and the design estimates of the authors of the structures turned out to be false and dangerous. It should be noted that due to the mistakes of the designers of the bridge projects, the country saw severe catastrophes with many victims and great material damage for three times (in 1960, 1980 and 2015).

A particular danger with these events is that all factors causing such catastrophes still exist, including anthropogenic (insufficient tunnel capacity, anthropogenic degradation of the sub-surface, narrowed bed, etc.) and natural (floodplain forests growing in the riverbeds, landslides, intense area rains, etc.) factors.

Followingthe review of the hydrological regime of the rivers and the reasons of catastrophic flashfloods, it is clear that a flashflood is

Table 2. Catastrophic flashfloods of the Vere River(the results of monitoring of TSU laboratory of 1960-2015)

Date of catastrophe	Flashflood catastrophic factors		Victims and material damage
	Natural volley wave discharge, m^3/sec	Human	
05.07.1960	259	Vake-Saburtalo and Varaziskhevi tunnels	Zoo exhibits, material damage
1963	150		Material damage
10.05.1980	127		
13.06.2015	512		21 people, Zoo exhibits, Material damage

catastrophic when the parameters of a flashflood with a long return period and the factors causing them are ignored. Consequently, the more thoroughly the rare natural phenomena (α_i) affecting this event will be described in the projects, the less the probability of a catastrophic flashflood (p) will be. The latter is inversely proportional to the number of rare natural phenomena envisaged by the projects:

$$p = \Phi\left(\frac{k}{n}\right), K = \{\alpha_i\}^{n}_{i=1}.$$

The Caucasus Rivers is a clear example. It crosses a number of settlements, but the probability of victims is minimal as the hydraulic facilities are built in its middle and lower reaches by considering the sufficient number of rare phenomena. The damage inflicted by the river in the upper reaches is greater, and the main reason for this is ignoring the multiple flooding and its resultant volley wave in the expression given above. The reason for the above-described catastrophe was multiple flooding of the Rioni River due to insufficient capacity of the bridges. Clearly, the anthropogenic factor must correspond to the natural factors, whose probability will further increase in the future in terms of the ongoing climatic fluctuations. In order to prevent such catastrophes, two big phyto-sediment trapping screens were provided across the Vere River to trap the coarse sediment before the first tunnel. These structures will reduce, though not eliminate the probability of catastrophic consequences of the flashfloods. Their limit water conductivity is as follows: $Q=350\,m^3$/sec for the upper screen and $Q=460\,m^3$/sec for the lower screen that is not sufficient to avoid catastrophes. Due to the fact that it is hard to forecast the behavior of the mountain rivers, the reasons for formation and the parameters of volley waves of the Rioni River (in 2020) and the Vere River (in 2015) must be specified in relevant reference and suggest for the course of designing and construction of hydraulic facilities in the mountain zones, particularly of water reservoirs.

Conclusion

The reasons for catastrophic flashfloods of the mountain rivers are the combined action of the natural and anthropogenic factors. Important natural factors are: rain and the firn field degradation provoked by it, landslides, permanent narrowing and blocking of the floodplain forests with phyto-sediment. Examples of the anthropogenic factors are: the structural defects of hydraulic structures or inappropriate building sites.

The analysis of the catastrophic flashfloods of the mountain rivers, the Rioni and the Vere, showed that the main reason is ignoring the volley wave and the resultant insufficient capacity and stability of the hydraulic structures.

The ongoing climate cycle significantly increases the probability and risks of flashfloods as it amplifies the factors causing them.

გეოგრაფია

თანამედროვე მეთოდი კავკასიის მთის მდინარეების კატასტროფული წყალმოვარდნების ფაქტორების ანალიზისთვის

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**ივანე ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტი, ზუსტ და საბუნებისმეტყველო მეცნიერებათა ფაკულტეტი, თბილისი, საქართველო*

(წარმოდგენილია აკადემიის წევრის თ. ჭელიძის მიერ)

ნაშრომის მიზანია წყალმოვარდნების ზალპური ტალღების გამოკვლევა. კვლევის ობიექტებად შერჩეულია სიდიდით და წყლიანობით მკვეთრად განსხვავებული მდინარეების – რიონისა და ვერეს კატასტროფული წყალმოვარდნები, რომელთა სცენარებში შეგუბების კოლაფსით წარმოქმნილი ზალპური ტალღის თვისებებია გამოკვეთილი. კვლევებისათვის გამოყენებულია: მათემატიკური სტატისტიკის მეთოდები (ანალოგიის, უმცირეს კვადრატთა), „მაღალი წყლის დონის (მწდ)“ მეთოდი და წყლის სიჩქარეთა საანგარიშო მეთოდები და მოდერნიზებული საანგარიშო გამოსახულებები. რიონის 28.07.2020 წყალმოვარდნის მიზეზი იყო ძლიერი წვიმით პროვოცირებული მეწყერი და ფირნის დეგრადაცია. ვერეს კატასტროფული წყალმოვარდნა თბილისის გვირაბებს უკავშირდება, რადგან მათ ვერ გაატარეს ფიტონატანით გაჯერებული ჩამონადენი. მთის მდინარის წყალმოვარდნის კატასტროფულობის ხარისხს და სიხშირეს განსაზღვრავს იშვიათი განმეორების ბუნებრივი და ანთროპოგენური ფაქტორების ერთობლიობა. წყალმოვარდნა კატასტროფულ ხასიათს იღებს, როცა ნაგებობის კონსტრუქციული პარამეტრები არ შეესაბამება ადიდებული მდინარის შეგუბების კოლაფსით წარმოქმნილი ზალპური ტალღის პარამეტრებს.

REFERENCES

1. Kereselidze D., Alaverdashvili M., Tsintsadze T., Trapaidze V., Bregvadze G. (2018) What happened on June 13, 2015 in the Vere River Basin? 64 p Tbilisi (in Georgian).
2. Dawson R.J., Hall J.W., Bates P.D., Nicholls R.J. (2005) Quantified analysis of the probability of flooding in the Thames Estuary under imaginable worst-case sea level rise scenarios. *Water Resources Development*, **21**(4): 577-591.
3. Best J.L. (1988) Sediment transport and bed morphology at river channel confluences. *Sedimentology*, **35**(3): 481-498.
4. Friedrichs C.T., Wright L.D. (2004) Gravity-driven sediment transport on the continentalshelf: implications for equilibrium profiles near river mouths. *Coastal Engineering*, **51**(8-9): 795-811.
5. Kuantama E., Setyawan L., Darma J. (2012) Early flood alerts using short message service (SMS). In 2012 International Conference on System Engineering and Technology (ICSET), 1-5.
6. Romanowicz R.J., Kiczko A. (2016) An event simulation approach to the assessment of flood level frequencies: risk maps for the Warsaw reach of the River Vistula. *Hydrological Processes*, **30**(14): 2451-2462.
7. Subramaniam S.K., Gannapathy V.R., Hamidon A.H. (2010) Flood level indicator and risk warning system for remote location monitoring using flood observatory system. *WSEAS Transactions on Systems and Control*, **5**(3): 153-163.
8. Tekhnicheskie ukazania po raschetam maksimal’nogo stoka rek v usloviakh Kavkaza. ZakNII. Tbilisi (1980) (in Russian).
9. Topping D.J., Rubin D.M., Vierra Jr L.E. (2000) Colorado River sediment transport: 1. Natural sediment supply limitation and the influence of Glen Canyon Dam. *Water Resources Research*, **36**(2): 515-542.

Received July, 2021