



Issue 154, 2024

WSL Berichte

ISSN 2296-3456

Natural Debris Flows and Field Experiments in Kazakhstan

Edited by
Dieter Rickenmann
Roza K. Yafyazova
Brian W. McArdell
Boris Stepanov

Swiss Federal Institute for Forest, Snow and Landscape Research WSL

Issue 154, 2024
WSL Berichte
ISSN 2296-3456

Natural Debris Flows and Field Experiments in Kazakhstan

Edited by
Dieter Rickenmann
Roza K. Yafyazova
Brian W. McArdell
Boris Stepanov

Swiss Federal Institute for Forest, Snow and Landscape Research WSL
CH-8903 Birmensdorf

Publisher
Swiss Federal Institute for Forest, Snow and Landscape Research WSL

Responsible for this issue: Manfred Stähli, Head of Research Unit Mountain Hydrology and Mass Movements

Managing Editor: Sandra Gurzeler, Groupleader Publications, WSL

Citation
Rickenmann D., Yafyazova R.K., McArdell B.W., Stepanov B.(2024) Natural Debris Flows and Field Experiments in Kazakhstan. WSL Ber. 154. 142 p.

ISSN 2296-3448 (Print)
ISSN 2296-3456 (Online)

Cover photos by D. Rickenmann, August 2000

Photo 1: Prototype experiments: gate structure at the ancient glacial lake
Photo 2: Prototype experiments: lake outflow into the upper erosion reach
Photo 3: Prototype experiments: lower part of steep erosion reach in morainic material
Photo 4: Prototype experiments: lowest part of erosion reach and flatter deposition reach in background
Photo 5: Debris-flow protection structure in Kazakhstan

Natural Debris Flows and Field Experiments in Kazakhstan

Edited by Dieter Rickenmann[1], Roza K. Yafyazova[2], Brian W. McArdell[1], and Boris Stepanov[2]
Translated from Russian by C.E. Bartelt

[1]WSL Swiss Federal Research Institute, Zurich, Switzerland
[2]National Hydrometeorological Service of Kazakhstan (Kazhydromet), Astana, Kazakhstan

Abstract

Natural Debris Flows and Field Experiments in Kazakhstan brings together numerous papers on debris flow research that were originally published in Russian between 1976 and 1992. Topics range from large-scale field experiments at the Chemolgan test site and the use of passively recorded seismic signals to estimate debris flow discharge to the documentation of unusually large-scale natural debris flows in Kazakhstan, which were mainly triggered by glacial lake outburst floods. Many new concepts on debris flow research were developed in the Soviet Union but until now were only available in hard to find Russian-language literature. This volume presents careful translations of the original Russian-language publications, assembled into themes of *Field Experiments at the Chemolgan Test Site* and *Natural Debris Flows in the Zailiysky Alatau Mountains*. Two additional contributions summarize the geologic setting and the evolution of debris flow activity in the past and give an overview of the main observations at the field experiments.

Table of Contents

Part A: Chemolgan Field Experiments

Table of Contents [continued]

Part B: Natural Debris Flows in the Zailiysky Alatau Mountains

Preface

Debris flows are a rapidly flowing mixture of water and granular material, including particles up to boulder size, and occurring in steep terrain. The mountain regions of Kazakhstan are characterised by a steep topography, the highest peaks exceeding 4600 meters above sea level (the highest peak is Talgar, 4979 meters). At high altitudes, parts of the catchments are covered by glaciers. In the past, many debris flow occurred in the Zailiysky Alatau mountains in the southeast of Kazakhstan, including disastrous events caused by glacier lake outburst floods (GLOFs). Due to their large magnitude, these granular-type debris flows travel over relatively long distances and reach the debris fans at the foot of larger catchments. For example, a large debris flow was initiated by rainfall in the Malaya Almatinka River basin in 1921, travelled over 20 km down to Almaty, the former capital of Kazakhstan, caused destruction of parts of the city and claimed the lives of about 500 people. In 1973, a large debris flow caused by a GLOF occurred in the same catchment but the entire sediment load of about 3.8 million m^3 was stopped by a dam upstream of Almaty.

Scientists in the Soviet Union documented and studied many debris flows caused by GLOFs or initiated by rainfall. To better understand the mechanics of debris flows, they performed controlled laboratory and field experiments. Starting in 1972, field experiments were carried out at the Chemolgan test site situated some 30 km west of Almaty. Debris flows were artificially triggered by releasing water from a reservoir at an altitude of 2900 m a.s.l. Until today these field experiments are unique in the world, and they provide interesting observations on debris flow initiation, propagation and deposition.

Between 1998 to 2001, the Kazakh Research Institute for Environmental Monitoring and Climate (KazNIIMOSK), which was part of the National Hydrometeorological Service of Kazakhstan (Kazhydromet) in Almaty, and the Swiss Federal Research Institute WSL established a cooperation in several projects. Within the program "Netherlands climate change studies and assistance programme – Kazakhstan climate change study" a special project "Assistance on climate change effects on mudflows and avalanches in Kazakhstan" has been performed in 1998/1999. A follow-up project on the same topic was supported by the Swiss Agency for Development and Cooperation and carried out in 2000/2001.

In 1972–1978, the Kazakh Institute for Hydrometeorological Research (KazNIGMI), which was renamed KazNIIMOSK in 1995, conducted the field experiments described above. A few scientists who carried out parts of the field experiments participated in the recent cooperation projects. Articles in Russian related to both natural debris flows and the Chemolgan field experiments were made available by these scientists to WSL. Since not much related information about these debris-flow investigations is available in English, some of the more important articles were translated into English. The translations were done by C. E. Bartelt, who also provided additional information on the use of debris-flow related expressions in the Russian language.

This publication entitled *Natural Debris Flows and Field Experiments in Kazakhstan* brings together numerous papers on debris flow research that were originally published in Russian between 1976 and 1992. Topics range from large-scale field experiments at the Chemolgan test site and the use of seismic signals to estimate debris flow discharge to the documentation of unusually large-scale natural debris flows in Kazakhstan, which were mainly triggered by glacial lake outburst floods. Many new concepts on debris flow research were developed in the Soviet Union but until now were only available in hard to find Russian-language literature. This volume presents careful translations of the original Russian-language publications, assembled into themes of “Field Experiments at the Chemolgan Test Site” and “Natural Debris Flows in the Zailiysky Alatau Mountains”. Additional contributions summarize the geologic setting and the evolution of debris flow activity in the past and give an overview of the main observations at the field experiments.

We would like to acknowledge the support of all colleagues and institutions that made this publication possible. A special thank is due to the late Charles E. Bartelt for the very careful translations of the Russian-language articles into English.

The editors: Dieter Rickenmann[1], Roza K. Yafyazova[2], Brian W. McArdell[1], and Boris Stepanov[2]

[1]Swiss Federal Research Institute WSL, Birmensdorf, Switzerland
[2]National Hydrometeorological Service of Kazakhstan (Kazhydromet), Astana, Kazakhstan

Notes on the Translations of C.E. Bartelt

Below are statements from C.E. Bartelt in a letter to D. Rickenmann regarding the translations: As you can see, I took to heart your admonition that the flows described in these papers are more correctly labeled as "debris flows." The Russian noun sel', its adjectival form *selyevoy* and the adjective-noun combination *selyevoy potok*, used throughout these papers to refer to what I had previously translated as "mudflows"(or "mudslides"), are now duly rendered as "debris flows." Yet I must point out that there is a potential problem with this treatment of these Russian terms whose meaning resists precise translation. Basically, the problem is this: After some study of the way *sel*', *selyevoy* and *selyevoy potok* are used in these papers and defined elsewhere, I have found that they actually refer generally to all types of rapidly and turbulently flowing sediment-water mixtures while other terms are used for the particular types of flows, namely, *nanosovodniy po*tok ("alluvium-water flow"), *vodokamenniy potok* ("water-rock flow"), *gryazevoy potok* ("mudflow") and *gryazekamenniy po*tok ("debris flow"). Of these, "mud-rock flow" appears to match what you have defined as "debris flow" and is indeed the particular term the authors often use in reference to the "granular-type" flows of the Chemolgan experiments and other natural events. Thus, unless a satisfactory alternate translation can be found for *sel*' and its adjectival form (and I cannot think of one), all such particular types of flowing sediment-water mixtures, that is, both "mudflows" and "debris flows" but including the more "watery" mixtures, will appear to the reader of these translated papers as subcategories of "debris flows." That of course seems wholly inconsistent with the way such flows are categorized by you and in the English-language papers you provided. The following describes what I found in a little more detail:

There appears to be no appreciable difference in meaning between *sel*' and *selyevoy potok* (the latter a combination of the adjectival form of *sel*' and the term for "flow). The Russians also use the adjectival form of *sel*' as a modifier when referring to a great many things, ranging from the various elements of the flow path such as the initiation zone and channel to the names of organizations and periodicals dealing with such flows. While my Russian-to-English dictionaries render both *sel*' and *selyevoy potok* as a "mud-laden torrent" or "mudflow," my more authoritative four-volume Dictionary of the Russian Language (published by the USSR Academy of Sciences) defines *sel*' as a "mud or debris flow (*gryazevoy ili gryazekamenniy potok*) occurring suddenly in a mountain riverbed as a result of a flash flood induced by vigorous snowmelt or heavy cloudbursts and other causes" and states that it derives from the Arabic *sail*, which in Russian means *burniy potok* - "turbulent flow" or "torrent." This definition is consistent with the way these terms often appear in the papers, for instance " … *selyeviye potoki* of high density (mud and debris flows with a density of around 2000 kg/m^3 and higher) … " If one assumes correctly that the boundary between what are called mudflows and debris flows in Russian is the same as that between mudflows and debris flows in English, then one finds that sel' and *selyevoy potok* apply to both of the latter. But the authors sometimes use *sel*' and *selyevoy potok* with additional modifiers describing a particular type of flow, and in these instances it is quite evident not only that they can apply to virtually all types of sediment-water flows but that these terms should be translated simply as "torrent" (which is, after all, the meaning of the Arabic word from which *sel*' is derived): *nanosovodniy sel*' and *nanosovodniy selyevoy potok* ("alluvium-water torrent"), *vodokamenniy sel*' ("water-rock torrent"), *gryazevoy selyevoy potok* ("mud torrent"), and *gryazekamenniy sel'* ("debris torrent"). It is convenient to translate *selyevoy* as "torrent" in some cases such as *selyevoye ruslo* ("torrent channel") or *selyevoy basseyn* ("torrent catchment") because it is understood that the torrent can convey different types of sediment-water mixtures. Uncertainty arises when *selyevoy* is used to modify *pavodok* - should it be "mud flood" or "debris flood"? – or an organization such as the Department of *selyeviye potoki* of the Kazakh institute – should it be "Department of Debris Flows" or the equally valid "Department of Water, Soil and Rock Movements"? –that more accurately covers the full range of meanings of *selyeviye potoki*. (I arbitrarily chose the former in both cases.)

Apart from a substantial revision of the texts of the papers (or a more clever job of translating than I am capable of), my only suggestion for dealing with this problem would be to make a brief explanatory statement about this Russian terminology in the preface to your publication.

I must note that in your paper on debris flows [Rickenmann, 1999, Natural Hazards] I found (I think) some language supporting the notion that mudflows are a subcategory of debris flows, that is, seemingly in contradiction to your definition of debris flows and mudflows as independent but parallel categories: On pages 53/54 of your paper you refer to "granular type debris flows" and "muddy type debris flows" and "debris flows with predominantly fine material" whereas I deduced from the statements in your letter that all debris flows are predominantly granular in character and only in mudflows do fine materials predominate. Or is all this beyond my layman's depth of understanding?

Another problematic term is what the Russians use throughout these papers to refer to the peculiar kind of channel cut into a hillslope or riverbed by the erosive force of the debris flow - *selyevoy vrez*. You will note that whereas in the previous work this term was translated as "mudslide ravine" it now appears as "torrent gully." *Vrez* is the noun form of the verb *vrezat'* – "to cut into" – and would ordinarily be translated simply as a "cut." But I was unable to find the noun "cut" anywhere as a valid term for referring to a particular kind of channel. I could not evade this issue by simply using the more neutral "channel" because the authors occasionally refer to "channels of the *selyevoy vrez* type." In my recent book acquisition "Fluvial Processes in Geomorphology" (by Leopold, Wolman and Miller, 1964) I found that cut channels matching the description of those in the papers are referred to only as "trenches" and "gullies" (no "cuts" or "ravines" anywhere). Of these, "trenches" appeared to relate more to channels cut into relatively flat surfaces. Hence my choice of "gullies" in the translated papers. For the reasons discussed above I rendered *selyevoy vrez* and *selyevoye ruslo* as the more neutral "torrent gully" and "torrent channel" (rather than "debris-flow gully / channel"). I was gratified to see "torrent channel" in your paper.

Still another term of somewhat less uncertainty is *selyevoy ochag* which I had previously translated as "mudslide origination site" but now render as "debris-flow initiation zone." In the papers it appears as the location in the channel where the flow initiates but also as the location of the "potential debris-flow mass" - the latter undoubtedly what you refer to in your paper as the "sediment source potential." The Russian *ochag* (of Turkic origin) is defined in the four-volume as the "place where something originates, or source of the propagation or spread of something." Both "source area" in Costa's (1984) paper and "initiation zone" in your paper are consistent with this definition. I settled on the latter in the belief that it is somewhat more descriptive of what takes place there.

…

If the authors review these translations, I would ask them to look carefully at my expansions of Russian organizational abbreviations and contractions. In some cases such as "Kazglavselezashchita" I am not sure they are completely correct. In one case–"UGKS"–I was unable to provide any expansion.

Charles E. Bartelt, 31 January 2001

Table with the translated papers, authors, translator, and the original publication source

Part A: Chemolgan Field Experiments			
English Title	**Authors**	**Translator**	**Original publication series of article**
The experimental site in the Chemolgan river basin and the history of its founding	R. V. Khonin, V. P. Mochalov and A. E. Zems	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 7–25
The principal physio-mechanical properties of debris flow-forming soils and debris-flow deposits in the Chemolgan river basin	V. N. Vardugin	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 25–35
The solid/liquid material balance in the debris flows of 1972–1973 in the Chemolgan river basin	A. E. Zems, R. V. Khonin and V. I. Laptev	CEB	Published originally in *«Debris Flows»*, Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 35–43
The velocity characteristics of experimental debris flows	M. D. Spektorman	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 44–48.
The debris flow of 10 June 1972 in the upper reaches of the Chemolgan river	V. N. Vardugin and M. D. Spektorman	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 48–53.
Determining the age of debris-flow deposits in the Chemolgan river basin by the dendrochronological method	R. I. Belogrivtseva	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 53–59.
The third experiment on the artificial replication of a debris flow	R. V. Khonin, V. A. Keremkulov and V. P. Mochalov	CEB	Published originally in *«Debris Flows»*, Collected Papers, Kazakh Institute for Hydrometeorological Research (1977) No. 2, pp 57–63.
Results of an experiment on the artificial replication of a debris flow in the Chemolgan river basin in 1976	T. S. Stepanova, R. V. Khonin, N. I. Krzhechkovskaya and A. Kh. Khaydarov	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1978) No. 3, pp 86–92.
Results of tests of a seismic system for warning of debris-flow hazard	P. I. Kovalenko, V. A. Krasyukov, M. Ya. Novikov and B.S. Stepanov	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1978) No. 3, pp 92–96.
"Chemolgan-78"	T. L. Kirenskaya, T. S. Stepanova and F. G. Balabayev	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1980) No. 5, pp 64–71.
Results of the experiment Chemolgan-91	V. P. Mochalov, A. K. Kim and A. Kh. Khaydarov	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1992) No. 12, pp 101–109.
Post-debris flow phenomena in the Chemolgan riverbed, 12–22 September 1991	Ye. I. Svetlakov	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1992) No. 12, pp 110–112.

Part B: Natural Debris Flows in the Zailiysky Alatau Mountains			
English Title	**Authors**	**Translator**	**Original publication series of article**
The debris flow of 15 July 1973 in the Malaya Almatinka River	Yu. B. Vinogradov, A. E. Zems and R. V. Khonin	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 60–73.
The meteorological conditions attending the formation of the debris flow of 15 July 1973	R. S. Golubov	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 73–74.
Some quantitative characteristics of the Zharsay debris flow of 1963 in the Issyk River	A. E. Zems	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No 1, pp 75–85.
The causes for the formation of the catastrophic debris flow of 7 July 1963 in the upper reaches of Zharsay Creek	B.A. Paramonov	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, 86–87
Formation of the solid phase of debris flow of 7 July 1963 in the Issyk River	B. A. Paramonov	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1976) No. 1, pp 88–92.
The debris flow of 19 August 1975 in the Bol'shaya Almatinka River	T. L. Kirenskaya, B. S. Stepanov and R. V. Khonin	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1977) No. 2, pp 115–119.
The debris-flow events of 3–31 August 1977 in the Bol'shaya Almatinka River Basin	V. I. Popov, B. S. Stepanov, V. P. Mochalov, R. V. Khonin, I. N. Markov, V. A. Golubovich and V. Ye. Bekarevich	CEB	Published originally in *«Debris Flows»,* Collected Papers, Kazakh Institute for Hydrometeorological Research (1980) No. 4, pp 57–63.

Part A: Chemolgan Field Experiments

The experimental site in the Chemolgan river basin and the history of its founding*

R. V. Khonin, V. P. Mochalov and A. E. Zems

We can investigate the processes of debris-flow formation and movement when objective techniques for measuring and computing the characteristics of the flows are available. However, the development of such techniques, just as in the case of forecasts of debris-flow events and the most rational means of protecting against them, is significantly encumbered by an extreme dearth of factual data. Because of the suddenness and infrequency of debris flows, the lack in most instances of any kind of measurements, and the complexity of organizing largescale and qualitative observations, we cannot rely on obtaining the required data in the near future.

Numerous literature sources often abound in ascertaining the facts of debris-flow events and the destruction caused by them in various regions. The characteristics of debris flows presented in the literature usually are derived from surveys of their traces. They are frequently unreliable because of the use of inadequate techniques which very approximately evaluate flow velocity and do not take into account channel deformation during the travel of the debris flow. Visual observations of the movement of debris flows, particularly by chance eyewitnesses, as a rule are notable for their extreme subjectivity and abound in fantasy and speculation.

The need to verify theories being developed on debris flows on the basis of factual data required the creation of artificial debris flows. The first steps in this direction were in the modeling of mud floods by N. S. Dyurnbaum [6] and I. V. Yegiazarov [7] and mudflows by M. S. Gagoshidze [5] and S. M. Fleishman [13]. Unfortunately, these investigations solved particular problems, and the lack of fullscale data made it difficult to evaluate whether the models reliably replicated the natural process.

The next step was the creation of small debris flows under natural conditions. The first experiments of this kind were those conducted by I. P. Smirnov [11] on the artificial replication of debris flows in 1951–1952 in the channel of the Chimbulak River – the righthand tributary of the Malaya Almatinka River. The principal deficiency of this work, from the standpoint of current thinking, was the unfortunate selection of the experimental tract. The experiments were conducted not in natural debris-flow initiation zones but in a channel with a mean slope of 8° (0.140). The release from an artificial reservoir of large discharges of water up to 7 m^3/s led only to the forming of an alluvium-transporting flood of low density (on average 1150 kg/m^3). I. P. Smirnov and S. P. Kavetskiy took these floods to be typical debris flows and extended their views to the natural debris flows (1950 - Bol'shaya Almatinka and 1956 - Malaya Almatinka) that formed in conditions markedly different from those of the experiments.

Original experiments on the replication of small alluvium-water (or water-rock) torrents and debris torrents on colluvial slopes were undertaken in the 1950's by G. V. Ivanov [8], who shed light on some qualitative features of the debris-flow processes. But that investigator came to the conclusion that the debris-flow process is basically the water transport of alluvium. Similar experiments, but with quantitative evaluations, were conducted in 1967 in the Mamsko-Chuyskaya Expedition of Moscow State University by A. Yu. Vlasov and I. Ya. Boyarskiy [1]. Debris flows with densities between 1550 and 2390 kg/m^3 were produced on slopes of between 9–10° (0.158–0.176) and 17° (0.306) and more. Although the investigators referred to these as water-rock flows, the high density of the flows (greater than 2000 kg/m^3) formed on slopes of about 0.300 and characterizes them more as typical debris flows.

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 7–25

Experiments in creating small artificial mud floods under natural conditions were conducted by Kazgidroproyekt [Kazakh Institute for the Design of Hydrofacilities] during 1965-1970. M. S. Kolyada [1] modeled alluvium-water torrents in the basin of the former Lake Issyk.

These works, while throwing light on particular issues, on the whole enlarged the body of information on debris-flow occurrences. Yet because of the lack of reliable criteria for the similitude of the models to the debris-flow process it was not possible to use the results obtained either for understanding the laws of formation and movement of natural debris flows or for computing their quantitative characteristics. It was essential to replicate debris flows in full scale, that is, in a scale exceeding that of previous experiments by a factor of 1-2. Of particular interest here was the problem of the formation of debris flows because it is precisely such flows of high density that have the greatest destructive force. To uncover the mechanism by which such debris flows are formed an experiment had to be conducted on a scale making possible a debris flow with a discharge of the order of 100 m^3/s because at smaller scales it is improbable that large boulder material, which comprises about half the spectrum of the granular composition of the deposits, would be entrained in the debris-flow process.

In 1967 Yu. B. Vinogradov of the Department of Debris Flows at KazNIGMI [Kazakh Institute for Hydrometeorological Research] advanced and scientifically verified the hypothesis that debris flows (mud and debris flows with densities of around 2000 kg/m^3 and above) form in specific sections of torrent catchments [3, 4]. Observations and measurements of natural debris flows in the basin of the Kokcheka River (basin of the Bol'shaya Almatinka) served as the starting point of the hypothesis.

As a result of preliminary surveys of the mountain systems of Central Asia and the south of Kazakhstan factual data were collected which confirmed the hypothesis that debris flows form only in initiation zones or at the same time as the latter originate. By this time the view was finally formulated that the initiation zone is the section of the torrent catchment where the direct formation of a mudflow or debris flow occurs. The principal area of the initiation zone is where it is supplied with loose rock fragments which as a result of denudation processes are carried to the negative contours of the initiation zone where the potential debris-flow mass (PDFM) also forms. The PDFM plays a direct role in the formation of debris flows. Several types of initiation zones are identified, classified by the particular way the debris flows form in local and dispersed initiation zones [10]. Torrent gullies were identified as the most characteristic among the local initiation zones. In them develop the largest debris flows which sometimes lead to catastrophic consequences.

One of the large initiation zones of the torrent gully type is Kyzylzhar [9] in the basin of the Chonaksu River, the southern slope of the Kungey Alatau mountains, cutting through Upper-Quaternary glacial formations to a depth of up to 150 m. In 1967 this gully was surveyed by staff of the Department of Debris Flows of KazNIGMI. But its considerable distance from Alma-Ata (now Almaty) (more than 500 km) and denial of permission to conduct experiments in the Chonaksu River basin made it necessary to continue searching for a suitable site.

In 1970 a gully in the upper reaches of the Chemolgan River was selected as the appropriate site. The basin of this river is located in the western part of the northern slope of the Zailiysky Alatau. Extending from the south to the north in the shape of a narrow strip 30 km in length, the basin of the Chemolgan River is contiguous in the west with the basin of the Uzunkargaly River and in the east with the basin of the Kaskelen River. Its southern boundary passes partially along the Zailiysky Alatau mountains and then along a watershed of the second order separating the basin of the Chemolgan River from the basin of the Uzunkargaly River.

In the upper part of the Chemolgan River basin at a height of 2300 m the valley of the river is partitioned by a regional terrace which may be taken as the apparent boundary of maximum glaciation. This boundary separates the erosion-denudation forms of relief from the glacial. The terrace is cut by six ancient gullies. Three of them are fairly highly pronounced in relief, and at the present time the Right and

Left Chemolgan Rivers flow along the bottom of these gullies. The Middle Chemolgan River flows along the bottom of the modern gully (the main torrent gully), which falls into an ancient one. A quick examination of the relief of the regional terrace gives the impression that a lateral tributary flows into the lower reaches of the torrent gully. Study of aerial photos in a stereomodel of the terrain showed that the modern torrent gully flows into the older one. It is probable that in the past the Middle Chemolgan River had a different channel, as indicated by traces of a past bifurcation in its upper reaches. A change in the course of the river led to the forming of a new debris-flow initiation zone. A similar process was observed in 1972 when the course of the river was changed artificially [2].

At a height of 2900 m the regional terrace changes to a plateau-shaped section slightly inclined to the north forming an upper level of terrain in the basin of the Chemolgan River. The latter is made up of Upper-Quaternary glacial formations. The surface of the upper level is complicated by crests of meridional direction that continue on the terrace, separating the ancient gullies. The space between the crests has a slightly hilly surface, typical for ancient moraine relief, abounding in closed basins. One of these basins is located in the upper reaches of the main torrent gully. Judging by its bottom deposits, a lake was located in it at one time, the outburst of which appears to have caused the formation of the torrent gully.

The preliminary surveys made it possible to conclude that the main torrent gully is suitable for solving the problems formulated. The region of the torrent gully is relatively accessible to vehicles with cross-country capability, and by road it is not more than 80 km from Alma-Ata.

Having received permission in the Kazakh SSR to organize an experimental site in the basin of the Chemolgan River, staff of the Department of Debris Flows of KazNIGMI began preparatory work in the summer of 1970. This work included specialized surveys of the torrent gully, torrent channel and lower gully and improving existing and laying out new dirt roads. Carried out during the specialized surveying of the debris-flow path were a largescale (1:1000) topographic survey and electrogeophysical exploration of the loose-debris deposits of the PDFM of the initiation zone to determine its depth. Data from the topographic survey became the basis for designing the dam outlet works and debris-flow measuring and other facilities. This design work was done by staff of the Department of Debris Flows and the Special Design Bureau of Kazgeofizpribor [Kazakh Geophysical Instruments Plant]. Some parts of the dam outlet works were designed while construction was in progress. A survey plan of the basin of a future reservoir was used for constructing a bathygraphic curve (Fig. 1).

A system of cross-sectional profiles was established to determine the volumes of removals and deposits in the main torrent gully, the torrent channel and the debris field. In 1972 28 cross-sectional profiles were marked and their levels taken in the main torrent gully, 10 in a section of the torrent channel, 19 in the lower gully and 27 in the debris field. In 1973 the system of cross sections was increased by 16 profiles in a torrent channel below the debris field.

The cross-sectional profiles are situated 20-30 m apart in the main torrent gully and in the lower gully. In the torrent channel between the two gullies the cross-sectional profiles are marked in characteristic places, and in the debris field they are situated on average 100 m apart. The system of geodetic profiles presently covers 6.8 km of the Chemolgan River.

The main initiation zone is an immense morphological formation and has the typical configuration of torrent gullies (Fig. 2). It is located in the steepest part of the regional terrace of Upper-Quaternary moraine with heights above sea level ranging from 2644 to 2900 m. In plan view (Fig. 3) the torrent gully has a characteristic elongated form with the meandering lines of the cliff brows forming narrowed and widened areas. The torrent gully is 930 m in length along the thalweg and has an area of 70,400 m^2.

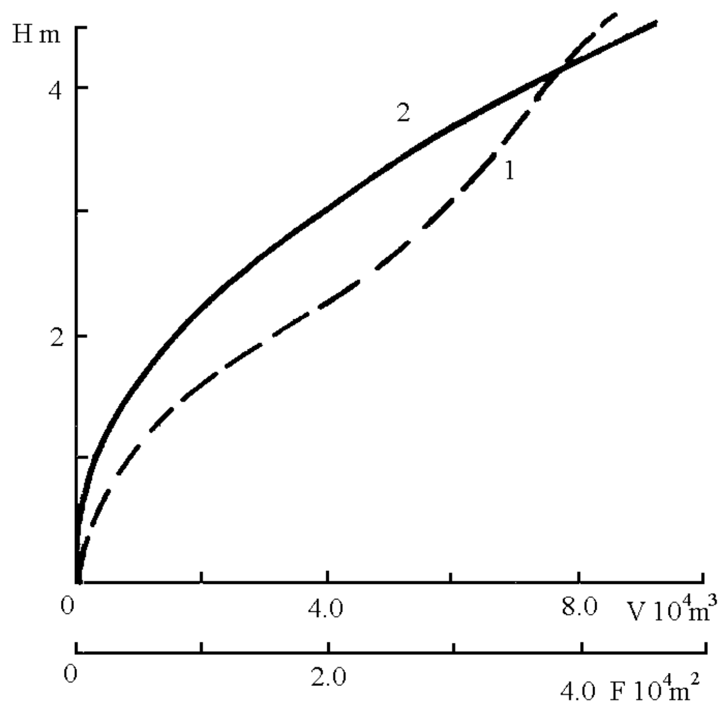


Fig. 1. Plots of the area of the water table (*1*) of the reservoir and its volume (*2*) as a function of level.

The steep sides of the torrent gully are composed of consolidated Upper-Quaternary glacial formations whose angles of inclination vary from 35 to 80° and more. The relatively flatly sloped sections of the sides are cut by channels forming an unusual relief with steep and sharp ridges in the spaces between the channels. Micro-debris flows usually form in these channels during intensive cloudbursts. Vertical inclinations and negative slopes are found on steep sections of the sides.

The mean depth of the torrent gully is 45 m and the maximum, 75 m. The mean distance between opposite brows of the cliffs is 95 m. The greatest width of the torrent gully is 150 m. In the upper and lower parts of the main torrent gully the brows come together by as little as 20 m. The total volume of the torrent gully is 3.17 million m^3.

The cross-sectional profile of the initiation zone has a trough-shaped form with a comparatively flat bottom made up of denudation products from the gully sides. This material consists of loose rock debris of highly diverse sizes. The largest boulders are located on the thalweg of the gully, while sand-pebble fractions make up the upper part of peculiar plumes at the foot of the cliffs. Redeposited glacial material on the bottom of the torrent gully forms the initiation zone's potential debris-flow mass which is involved first in the debris-flow process.

The mean width of the potential debris-flow mass is 40 m, increasing in places to 60 m. The mean slope of the PDFM along the thalweg is 16° (0.287), and the characteristic slope is 18°30' (0.333). The total area of redeposited loose-debris formations is 35,000 m^2, that is, it takes up around 50% of the area of the entire torrent gully. The mean depth of the PDFM from geophysical data is 10 m. The morphometric characteristics of the initiation zone and the depth and mechanical makeup of the loose-debris formations of the PDFM ensure that a large number of debris flows can develop in the gully.

Fig. 2. The main torrent gully in the Chemolgan River basin.

In the lower part of the initiation zone at a height of 2690 m there are outcroppings of bedrock which form a waterfall up to 10 m in height. Underneath it by 80 m is a second waterfall, after which the Middle Chemolgan River flows in an unusual channel created by debris flows containing granitoid rocks. Within 100 m of the lower waterfall a small stream flows into the river bed from the right, flowing along the bottom of an ancient gully and precipitating as waterfalls from a height of up to 30 m. The mouth of this stream may be considered the starting point of the torrent channel (2644 m above sea level).

Characteristic of the torrent channel are numerous outcroppings of bedrock forming more than 10 waterfalls at different heights. The bedrock outcroppings stabilize the channel, impeding its deformation during the movement of the debris flow. On the other hand, they increase the bending of the channel (the coefficient of bending is 1.3) causing violent turbulence in the debris flow. In the sections between the bedrock outcroppings that form the waterfalls loose-debris deposits are intensively entrained by the flow. Thus, the debris flow formation process would to a considerable extent continue to develop in the torrent channel if it was not impeded by the numerous outcroppings of bedrock.

The overall length of the torrent channel is 760 m with a mean slope of 11°30' (0.202). At a height of 2484 m the channel is broken up by a stepped waterfall up to 12 m in height, which morphologically can be considered part of the lower gully. The region of the waterfall is almost an non-deformable section and is suitable for carrying out debris-flow measuring observations. A "control cross-section" site for debris-flow monitoring was set up at this place.

The lower gully replicates to a considerable extent the morphological features of the main torrent gully with the exception of the longitudinal slope of the thalweg which on average is 7°30' (0.133). Such small slopes usually are not observed in existing initiation zones. Hence, despite its external similarity with the main gully, the lower gully cannot be considered an initiation zone. The latter is confirmed by the redistribution of loose rock debris after passage of the debris flows. Thus, after the experiments of 1972–1973, deposition of the solid part of the debris flows predominated in the lower gully. It is probable that when this gully was formed debris flows occurred in it, but they ceased with the decline in the longitudinal slope of the thalweg. At the present time the lower gully is a continuation of the torrent channel in which the debris flow becomes transformed, and the debris-flow deposits are redistributed (Fig. 3).

The overall length of the lower gully along the thalweg is 510 m. The 61st cross-sectional profile (the second cradle crossing) is taken as its lower boundary. The central point of the profile has a height above sea level of 2413 m. Below this point the Middle Chemolgan merges with the Left Chemolgan. In this place the lower gully after a turn to the north by 60° loses its specific character. The debris field extends below it by more than 2.5 m. In 1972 the main part of this field was covered by observations to a channel elevation of 2140 m above sea level. In 1973 an additional 2.1 km was covered by observations. The slope of the upper part of the debris field on average was 6° (0.103), the lower part, 4° (0.07). In 1973 an additional 2.1 km was covered by observations. In this section the longitudinal slope of the valley bottom maintains the same value.

The mean width of the debris field is 150 m, the maximum width reaching 260 m. Morphologically the debris field is an inhomogeneous surface intersected by dry channels and debris-flow embankments. In its upper part there are accumulations of rubble resembling the "head" of the debris flow. In the middle part of the debris field are islands with grass-covered surfaces which divide the floodplain of the river into three arms. Here there is a local increase in the longitudinal slope, and a narrowing of the channels between the islands leads to an increase in the eroding power of the debris flow.

Below the field, beginning at a height of 2140 m, the Chemolgan River has a single channel situated in the lefthand part of a fairly wide floodplain. At a height of 1980 m the channel of the river begins to press to the right side of a ravine. In 1973 observations of the debris flow terminated at this place.

Thus, in all 6.7 km of the total extent of the initiation zone, channel and debris field were covered by observations. In all 104 cross-sectional profiles were selected and marked. On them multiple levels were taken after each experiment artificially replicating debris flows.

A large volume of construction and research had to be done before conducting the first experiment in this poorly accessible region at heights above sea level ranging from 2500 to 3000 m with the complex climatic conditions that are typical for high mountains. It was necessary to make and install debris-flow measuring instruments, select and outfit observation points, and so on. In addition, while work setting up the experimental site was in progress new problems arose whose solution required additional work. In particular, after a new torrent gully developed in one of the tributaries of the Left Chemolgan and a debris flow initiated in it [2], it was decided to construct a low-pressure dam in a lake in the upper reaches of this gully. This construction was carried out in 1972 by staff of the Kazgeofizpribor Plant. The damming of the lake together with solving other problems made it possible to study the conditions under which a new torrent gully originates.

In setting up the experimental area it was planned to outfit two debris-flow measuring sites. The primary measuring site – the "control cross section" – was situated in the lower part of the torrent channel 1.7 km from the dam outlet works. The slope of the channel in the 100 m section located above it measures 0.200. The second measuring site was selected at the mouth of the lower gully 2.2 km from the dam. The slope of the channel in the region of this site changes after passage of each debris flow and ranges around 0.150. This site was activated only in 1973. This was the point for measuring the velocity of individual boulders and the place for installing the second transducer of a seismo-flowmeter.

In autumn of 1970 work began on outfitting the future debris-flow measuring sites. At each site standard cradle crossovers were constructed for servicing the contactless debris-flow measuring devices, anchors and supports for the crossovers were laid in concrete and cables were suspended. The cradles were installed, and the cables finally tightened shortly before the first experiment.

In 1972 work was carried out to improve the riverbed at the "control cross section" site. A 4.0 X 3.5 m section of the debris-flow measuring site was leveled by monolithic reinforced concrete and covered with 5-mm sheet steel.

In the same year on the eve of the experiment on the artificial replication of debris flows the measuring devices at the "control cross section" were calibrated. For this, hydrometric measurements were made of small releases of water into the improved bed in parallel with the measuring of these releases by a debris-flow level gage and velocity meter. The discharges of these releases did not exceed 3 m^3/s. It should be noted that even with such discharges (maximum natural discharges of the Middle Chemolgan River at this site usually are on the order of 1.0–1.5 m^3/s) the quantity of suspended and entrained alluvium increases sharply, that is, an alluvium-water flow begins to form. It becomes difficult to measure even the surface velocity of this flow with hydroflowmeters. In 1972 the "control cross section" measuring site was outfitted with instruments for measuring the level and surface velocity of the debris flow without direct contact with the flow. A density meter was installed in a special housing in the bottom part of the site. In 1973 an experimental model of a seismoflowmeter and new version of a density meter were tested here [12].

In 1970 at a location 170 m upstream of the "control cross section" construction began on a facility for measuring the dynamic action of the debris flow on an obstacle. With the aid of small explosive charges a trench 1 m deep and 5 m long was dug in the bedrock. A hollow steel structure covered with 4-mm steel sheet was installed in this trench. The trench and structure were filled in with high-quality concrete to form a monolithic reinforced concrete facility. In all about 12 m^3 of concrete were laid in this facility.

The frontal wall of the facility was 1.85 m in height and 0.35 m in width, the middle part was 1.2 m in height and 0.60 m in width and the rear wall was 0.75 m in height and 0.2 m in width. The facility was 4.0 m long. Cylinders with massive pistons were mounted on its frontal part. The upper cylinder was located at a height of 1.5 m and the lower, 0.75 m. Pistons having a diameter of 200 mm and length of 400 mm transmitted dynamic pressures to standard tensometer units. The latter transmitted signals through embedded cables to a recording dynamometer set up outside the action of the debris flow. The lower and upper tensometers were designed for impact forces of up to 10^3 and up to $6 \cdot 10^5$ N, respectively.

When interacting with a debris flow in 1972, this facility functioned normally for several tens of seconds but then was partially destroyed. But the recording dynamometer read off-scale in the first seconds, so that it was not possible to judge the debris flow's impact force on the facility. After the experiment 1/3 of the upper part of the facility was as if cut off at an oblique angle from below upward. The foundation of the facility and the cables embedded in the rock bottom and sides of the channel were practically undamaged. The remainder of the facility was demolished almost to its base during the debris-flow event in 1973.

In 1972, in addition to the primary facility for measuring the dynamic action of the debris flow, an apparatus was constructed for measuring dynamic pressures within the debris flow. On the left bank of the Middle Chemolgan River a massive concrete anchor was laid 100 m upstream from the primary debris-flow measuring site. An aluminum sphere 0.5 m in diameter was connected to the anchor by means of a traction link on a steel cable 30 m in length. The density of aluminum and that of granitoid rock are very close. The traction link was designed for a load of 10^5 N.

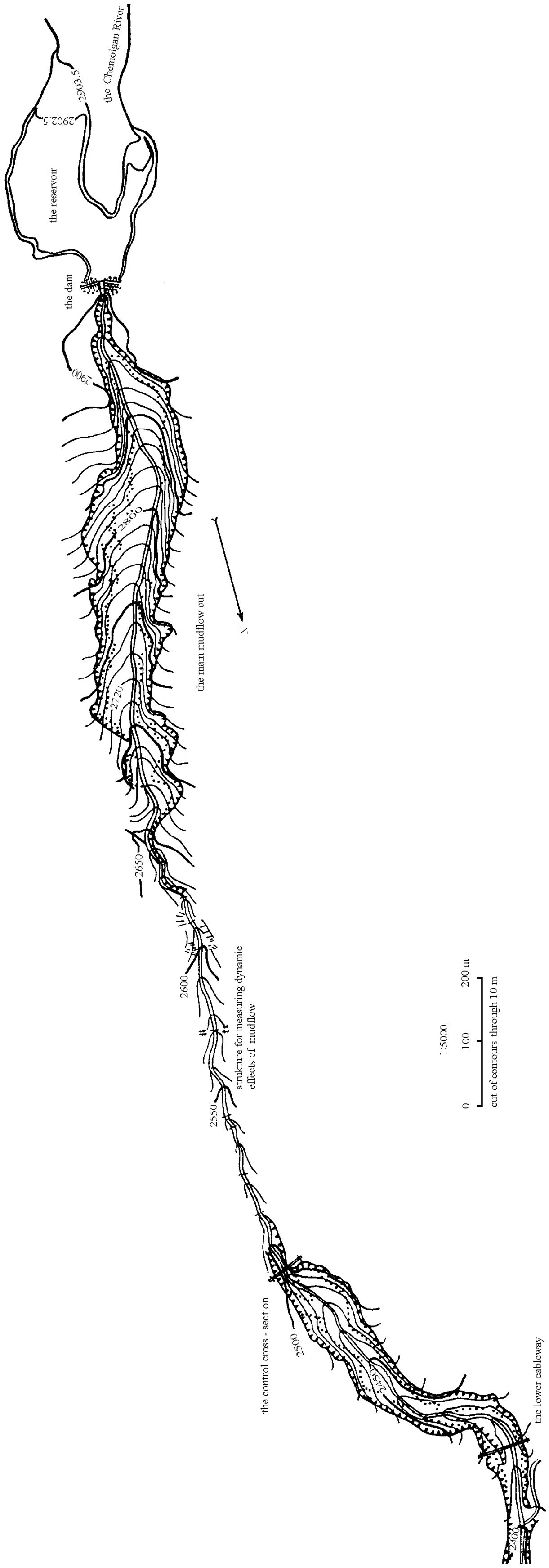


Fig. 3. Plan view of the main torrent gully, channel and lower gully.

One of the requirements of the apparatus was to maintain the anchor-sphere line parallel to the main direction of the channel. Measuring dynamic action on such a system is of interest because within the space limited by the surface of the channel and the sphere, the radius of which is determined by the length of the cable, the sphere may be regarded as free from connections if the mass of the cable is much less than the mass of the sphere. In this case the mass of the cable amounted to 20 kg and the mass of the sphere, 186 kg. Large rocks lying on the bottom of the channel can be of this size.

During the first experiment (1972) measurements were conducted over a period of 301 s, but the sphere remained directly in the flow only 148 s. On two occasions the flow ejected it to the riverbank, where the sphere lay 153 s. At 301 s at the moment when the sphere came in contact with the debris flow a heavy impact was recorded, after which the 18-mm cable broke, and the sphere was carried away by the flow. The recorder readings could not be deciphered because a standard dynamograph was used that was quite sluggish and the impacts on the sphere were of exceptionally short duration. By improving the recording instrumentation, it will be possible to obtain a continuous recording of the action of the debris flow on the sphere-cable system.

On 7 July 1971 in the upper reaches of the main torrent gully construction was started on the dam outlet works which required substantial shipments of construction materials and a large volume of preparatory work. It was necessary to excavate a pit for the foundation of the spillway part of the dam. For this the normal flow of the Middle Chemolgan River was diverted to the neighboring channel. The bifurcation of the river made this diversion much easier.

All construction work was done by hand as the use of machinery was made difficult owing to the scant electric power and transportation resources available. During the construction period in 1971–1972 a T-75 bulldozer was operated no more than 1.5 months at the site mainly to fill the impervious part of the dam. During 2.5 months of 1971 75 m^3 of concrete were poured in the reinforced concrete parts of the dam. Reinforced concrete rings and slabs weighing a total of 26 t and steel structural members weighing more than 3 t for the upper and lower gates of the dam (Fig. 4) were used in constructing the spillway part of the dam. The main construction work on the dam outlet works in 1971 was done by a group headed by B. S. Stepanov of the Special Design Bureau of Plant Geofizpribor.

At the beginning of the field season of 1972 a second apron was constructed (Fig. 5) of rubble-filled concrete and steel-reinforced concrete. In all about 100 t of rubble of varied diameter and 38 m^3 of concrete were poured in the second apron. This completed the work of reinforcing the lower reach of the dam outlet works for the initial releases.

The dam outlet works consist of a dam with water release openings, a water jet apron, and an inlet portal with a hydrometric bridge and system for measuring water velocity. Four sites for measuring water level were set up and fitted with recorders at various locations in the reservoir.

The dam outlet works were constructed at the narrowest place in the floodplain of the Middle Chemolgan River above the main torrent gully. They close a lake-shaped basin located at a height of more than 2900 m and made up of Upper-Quaternary glacial formations. The facility is intended for releases of water into the debris-flow initiation zone with a peak discharge of up to 80–100 m^3/s and releases lasting up to 30 min. The reservoir capacity required for this purpose was assessed as 70-75 thousand m^3. This volume can be attained by filling the reservoir to the 2903.5 m elevation. The creation of such a reservoir required a dam 4.5 m in height with a margin of 0.5 m above the level of maximum fill. The reservoir formed by this dam, at a depth of 4 m above the lower gates, has a water table area of 38 thousand m^2, with a reservoir capacity of 73 thousand m^3.

Fig. 4. Construction of the dam outlet works in the Chemolgan River basin.

The dam consists of impervious and spillway parts. The former consists of two earth embankments (a right embankment about 10 m in width and a left bank embankment up to 20 m in width) made up of ancient glacial deposits. Fluvioglacial deposits with inclusions of large boulders form the base of the dam. The height of the impervious part of the dam varies from 0 to 4.5 m, upper and lower slope gradients are 1 : 2.0 and 1 : 2.5, width along the crest is 2–2.5 m. The low value of the filtration coefficient, on average up to 0.5 m/day, made it possible to make the body of the impervious part uniform, without special antifiltration devices.

The spillway part of the dam consists of a flowbed with a two-stage system of gates and a two-step apron (Fig. 5). The 6X6 m slab of the flowbed is made of 30 cm-thick reinforced concrete and joins with the impervious part of the dam with the aid of two vertical reinforced concrete buttresses of variable height. Two vertical reinforced concrete counterforts strengthened by metal braces made of rails divide the spillway opening into three parts. Each part is covered by two planar gates, an upper and lower one. The upper gates are panels 3.0 m in height and 2.0 m in width with a vertical rotation axis. The width of the spillway opening is 1.75 m. The gates are operated by winches permanently installed on the banks of the reservoir. The lower gates are in reserve and are opened if it becomes necessary to sharply increase the discharge of the release. They are 1.43 X 1.43 m-metal panels with a horizontal axis of rotation in the lower part of the panel and with a stop latch on the upper part. Pulling out the latch pin causes the gates to fall in the direction of the downstream wall. The lower gates are presently replaced by impervious steel panels.

A two-step apron is situated beyond the backwater part of the spillway. The upper step of the apron is a widening (from 5.83 to 7.03 m) reinforced concrete chute 7.3 m in length terminating as a massive reinforced concrete tooth sinking to a depth of more than 2 m. In order to locate the zone of erosion farther away from the dam the apron in 1972 was lengthened by 11 m in the direction of the downstream wall. Thus, the total length of the water jet trough was 18.3 m.

Laid underneath the backwater part of the dam and the upper apron is a tubular reinforced concrete water conduit with a regulating water discharge fitted with a flat sliding gate. The water conduit is designed for discharges of not more than 5 m^3/s and is intended for the continuous draining of the reservoir and normal river runoff in the periods between debris-flow experiments.

Three (a fourth in 1973) limnographic manholes were installed to continuously record change in water level in the reservoir during its draining by water release. Three of them were located in one line at distances of 1, 30 and 70 m from the dam, and the fourth manhole is located east of the primary limnographic line at a distance of 172 m from the dam. Height of the three manholes is 4.5 m and the fourth, about 3 m. The horizontal cross section of the manholes is 0.5 X 0.5 m. The manholes are set on a concrete base, and their upper part is reinforced by two strands of cable braces. Installed on the upper cross section of each manhole is a wood floor with a limnographic booth in which a "Valday" water level recorder is located. Correspondence between the water levels in the manholes and the reservoir is achieved by 0.7 X 0.5 m holes in the lower part of the manholes.

The water level recorder located in the immediate vicinity of the dam is serviced from the inlet portal of the dam outlet works. A "Sig" boat and flexible ladders fastened to the limnographic manholes are used to service the other recorders.

Water levels are recorded by the "Valday" on a scale of 1 : 2 with 3- and 12-hourly recordings. The 12-hourly recording is accomplished with a standard clockwork drive. To obtain the 3-hourly recording the clockwork drives were modified in the workshop of KazNIGMI. In 1973 the clockwork drives were used only with 3-hourly recordings because the expanded time scale makes it possible to determine change in water level in greater detail at the moment of the reservoir's draining.

A system of hydrometric current meters at various points on seven vertical lines makes it possible to directly measure and continuously record water velocity during the releases. The vertical lines are located in the intervening spaces between the spillway openings and in the center parts of the latter. The points for measuring velocity on the vertical lines are arranged so that reliable values of mean velocities may be obtained at different water levels in the reservoir during releases. Signals of the current meters, except for one check meter, were recorded by a PO-19 undulator. Signals from the check current meter were recorded by an observer in the usual manner.

Observational data from the water meters make it possible in various ways and with high accuracy to compute a hydrograph of the release from the reservoir and its volume. In addition, it is possible during the release to obtain a continuous picture of changes in the slope of the reservoir water surface.

During the dam's construction in 1971 a seven-meter pit was dug in the bottom part of the main torrent gully. The granulometric composition and soil density of the potential debris-flow mass of the initiation zone were determined over its entire depth. In the same year a 0.2 m diameter casing pipe was installed in the pit for determining the level of the ground waters of the PDFM of the initiation zones during the formation of the debris flow. After the pit was filled in, a seven-meter deep well was installed and fitted with a remote electric water-level meter with automatic recording. No changes occurred in the ground water level in the well during test releases and at the moment at which the debris flow formed. These data were also verified indirectly by computations of the debris-flow liquid/solid balance.

The main work preparatory to conducting the experiment on the artificial replication of debris flows was completed in the middle of August 1972. After the reservoir was preliminarily filled for testing the operation of the lower gates of the dam outlet works, work was begun on filling the reservoir for the experiment.

By this time, besides the dam outlet works, the following were fitted out and made ready for observations at the experimental site: the system of hydrometric facilities in the reservoir and before the water-

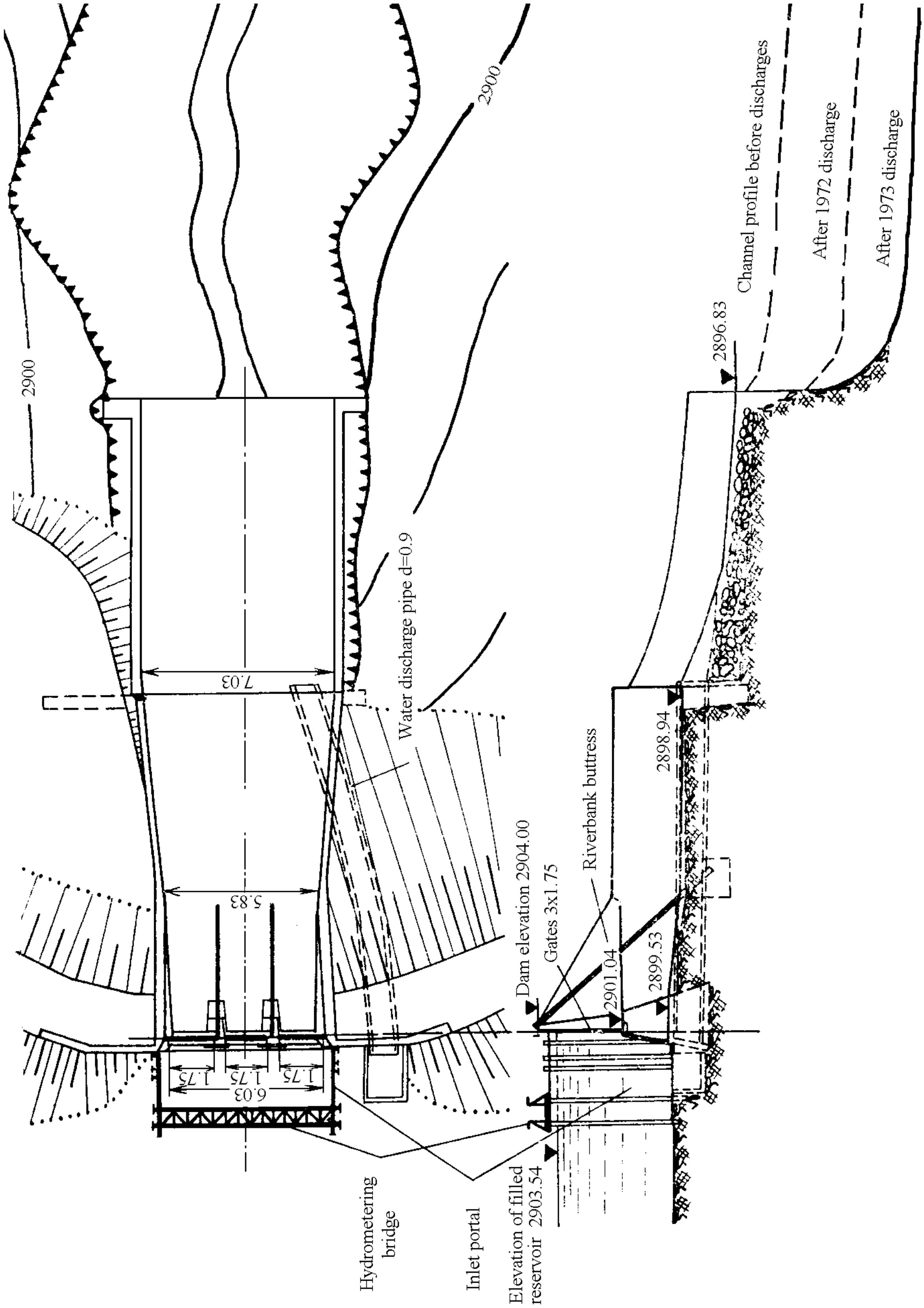


Fig. 5. Plan view and longitudinal section of dam outlet works.

release openings of the dam outlet works, the "control cross section" debris-flow measuring site, facilities for measuring the dynamic effect of the debris flow, an additional debris-flow measuring site, the well for measuring the level of ground waters in the bottom of the torrent gully, the system of cross-sectional profiles for measuring the solid material balance in the debris flow, places for observing the velocity of the front of the debris-flow wave, places for motion picture filming of the debris flow, and a place for removing samples of debris-flow mass from the moving flow.

Attempts to measure debris-flow density by scooping debris-flow mass with a measuring vessel proved to be ineffective because the samples could be removed only from the side offshoots of the flow which were insufficiently representative. In 1973 several samples of debris-flow mass were taken from the main channel but on the falling limb of the debris-flow wave.

Motion picture filming of the debris flow on 35-mm colored negative film was widely employed during both experiments. Sixteen motion picture cameras were located at various places in 1972 and eight in 1973. Two of these cameras were fixed in the direction of a selected point in the channel. The frames of these cameras were used to measure the velocity of flow and the velocity of individual boulders.

In conclusion it should be noted that the creation of an experimental site equipped with unique debris-flow measuring instrumentation under such difficult conditions and in such a short time required tremendous efforts and a fair amount of ingenuity. Naturally, the first experiments on artificial replication of debris flows expanded our notions about this terrible phenomenon of nature. Problems arose that can be solved during new experiments and in the laboratory modeling of the debris-flow process and its individual elements. These data will help us to analyze the conditions under which debris flows of high density form and move and to compute and forecast debris flows - a problem whose solution is so necessary for the national economy.

REFERENCES

1. Boyarskiy, I. Ya., Vlasov, A. Yu., Kolyada, M. S. A device for measuring the surface velocity of water-rock flows. *Vest. MGU* (1970) No 3 pp 82–87.
2. Vardugin, V. N., Spektorman, M. D. The debris flow of 10 June 1972 in the upper reaches of the Chemolgan River (in this collection of papers).
3. Vinogradov, Yu. B. Some issues regarding the formation of debris flows and techniques for computing them. *Tr. KazNIGMI* (1969), No.33, pp 5-29.
4. Vinogradov, Yu. B. Models of the debris-flow formation process. *Tr. KazNIGMI* (1971) No 51 pp 26–44.
5. Gagoshidze, M. S. and Natishvili, O. G. An experimental facility for studying debris flows and mud floods. *Tr. GruzNIIGiM* (1965) No 23 pp 175–184.
6. Dyurnbaum, N. S. *Protection of Populated Areas against Debris Flows.* Moscow, Leningrad (1949) 176 pp.
7. Yegiazarov, I. V. Modeling mountain flows entraining bottom alluvium. *DAN Arm. SSR* (1948) Vol 8 No 5 pp 193–202.
8. Ivanov, G. V. *The Passage of Debris Flows through Channels*. Irkutsk: Knizhn. izdat. (1955) pp 3–44.
9. Iveronova, M. I. A lake at the location of a debris flow. *Priroda* (1963) No 1 pp 94–95.
10. *Guide to Techniques for the Study of Debris Flows* (*draft*). KazNIGMI, GUGMS, Alma-Ata (1972) 91 pp.
11. Smirnov, I. P. Knowledge gained from the study of debris flows through their artificial replication. *Tr. KazNIGMI* (1953) No 4 pp 39–54.
12. Krasyukov, V. A., Stepanov, B. S., Stepanova, T. S. Instruments for contactless measurement of some debris-flow characteristics (in this collection of papers).
13. Fleishman, S. M. Investigation of the viscosity and suspensibility of a debris-flow mass. *Tr. VNIIZhdSiP* (1952) No 7 pp 132–149.

The principal physio-mechanical properties of debris flow-forming soils and debris-flow deposits in the Chemolgan river basin*

V. N. Vardugin

The largest debris flows in the Chemolgan River basin develop in the upper reaches of the river on a terrace of Upper-Quaternary moraine. The debris flow-forming loose rock debris consists of moraines as well as rocks of the potential debris-flow mass (PDFM) which are moraines reworked by gravitational and rockslide-slopewash processes. During the formation of the PDFM there is a significant reduction in the content of clay-silt fractions (<0.05 mm) in comparison with the original moraines (washout by water flows and erosion by wind, Fig. 1*a, b*).

The granulometric composition of course debris soils determines all other physio-mechanical properties (density, porosity, strength characteristics, etc.).

Observations of the travel and deposition of the debris-flow mass in artificial and natural debris flows in the Chemolgan in 1972 and 1973 established that when the debris-flow surges stop mud suspension containing fragments up to 20 mm in size runs out from them. The same may be said about mud splashes during the travel of the debris flows in the Issyk River in 1963 and in the Malaya Almatinka River in 1973. Thus, the mud suspension of the debris-flow mass consists mostly of particles smaller than 20 mm. The remaining part of the debris-flow mass consists of fragments larger than 20 mm.

Henceforth we shall arbitrarily refer to the sum of fractions larger than 20 mm as course debris and to the remaining part of the soils as filler. Consequently, we shall be talking about the granulometric composition of course-debris soils as well as about course debris, the character of their distribution and the quantity of filler and its granulometric composition.

Of greatest importance in the composition of filler are fractions smaller than 0.05 mm which are highly cohesive, adhesive and hydrophilic. When the debris flow-forming loose rock fragments contains no such particles, the probability of the onset of a debris flow is very small. But when it contains a large quantity of these particles (when $p \rightarrow 1$) the probability of the onset of a debris flow also decreases because debris with a large content of clay-silt fractions will be highly cohesive and difficult to wash away.

Consequently, one can say that a specific range of content of clay-silt fractions in soils exists within which the rock can become debris flow-forming, that is, $p_{min} \leq p \leq p_{max.}$

The granulometric composition of debris flow-forming loose rock fragments of the main Chemolgan torrent gully is most fully presented in Fig. 2 (curve *1*). Shown here is the content in the soil of fractions ranging in size between less than 0.001 mm and 10,000 mm. Fragments larger than 10,000 mm are practically not encountered in the moraine soils of the Zailiysky Alatau, although the probability of finding them is not zero. According to the integral curve of the granular composition, the content of fractions smaller than 20 mm (filler) on average is not more than 45%, and the content of clay-silt fractions is less than 1%. When there is such a low content of this most important part of the debris flow-forming loose rock fragments, it is very difficult to graphically portray the granular composition of different types of rock because it is practically impossible to see any difference in the plots.

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 25–35

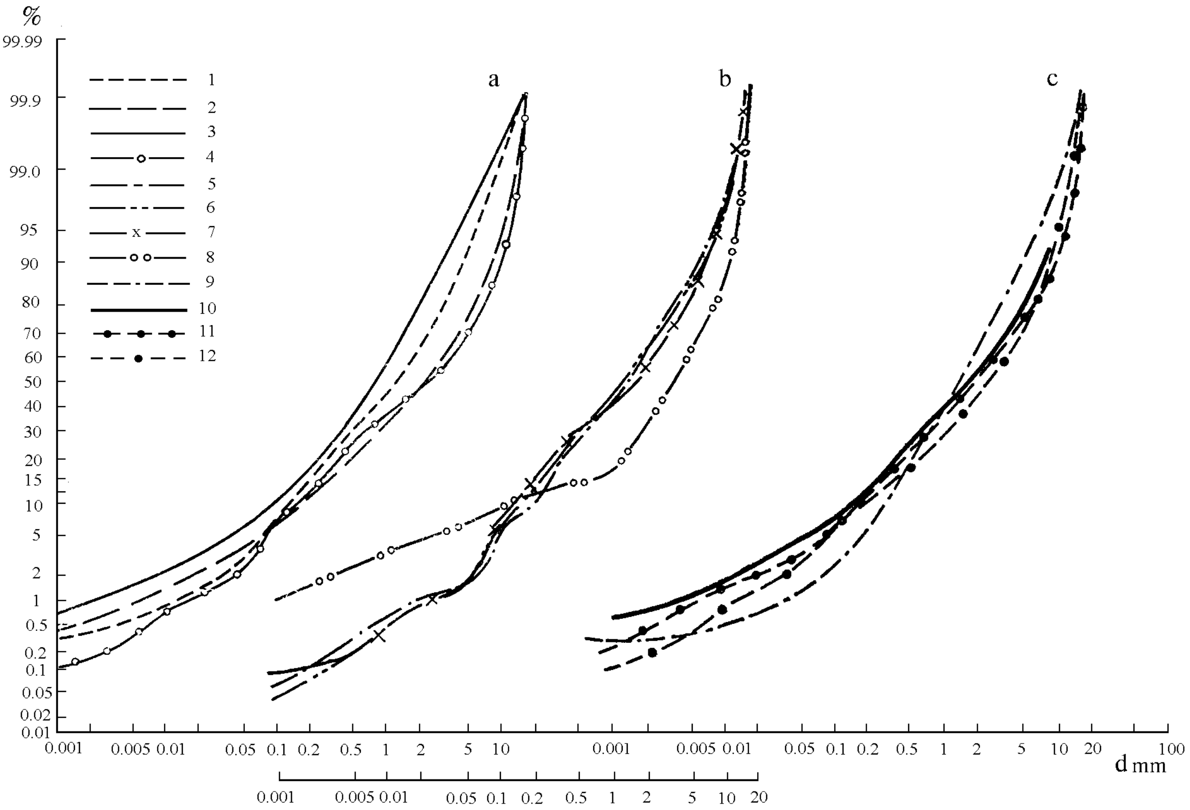


Fig. 1. Integral plots of the granulometric composition of filler in debris-flow deposits and in debris flow-forming soils: *a* - data from the 1973 experiment; *b* - 1972; *c* - particle size for debris-flow deposits of 1973 experiment 0.3 km below mouth of the initiation zone; *1* - debris-flow deposits at mouth of torrent gully; *2* - debris-flow deposits 300 m below mouth of torrent gully; *3* - debris-flow deposits 3 km below mouth of torrent gully; *4* - filler in PDFM; *5* - ancient debris-flow deposits; *6* - debris-flow deposits of 1972 experiment; *7* - debris-flow deposits of 10 June 1972 debris flow; *8* - filler in moraine soils; *9* - deposits from residual flood; *10* - lower debris-flow terrace; *11*- upper debris-flow terrace; *12* - ancient debris-flow deposits.

To more graphically display the granular composition of some types of debris flow-forming soils it is much more convenient to use the granular composition of the filler. In Fig. 2 (curves *1*–*5*) one clearly sees that the granular composition of filler in all types of debris flow-forming soils of the main Chemolgan torrent gully is the same regardless of age and genesis. The content of clay-silt fractions will fluctuate within 4.5–6.5% and on average is 6%. Note that in the filler of debris flow-forming soils of the Zharsay initiation zone (Issyk River) the total content of fractions smaller than 0.05 mm on average is not more than 2%. The filler consists mostly of small and medium gravel (2–10 mm fragments). Nevertheless, it has been shown more than once in practice that debris flows can occur here (1958, 1963).

Debris flow-forming soils in the debris-flow formation process are transformed into debris-flow mass and after it stops are referred to as debris-flow deposits. The granulometric composition of the soils changes substantially in the process of this transformation. Fig. 1*a* presents integral plots of the granular composition of the filler in soils of the PDFM (the debris flow-forming soil) and debris-flow deposits. By analyzing these plots one can come to the following conclusions:

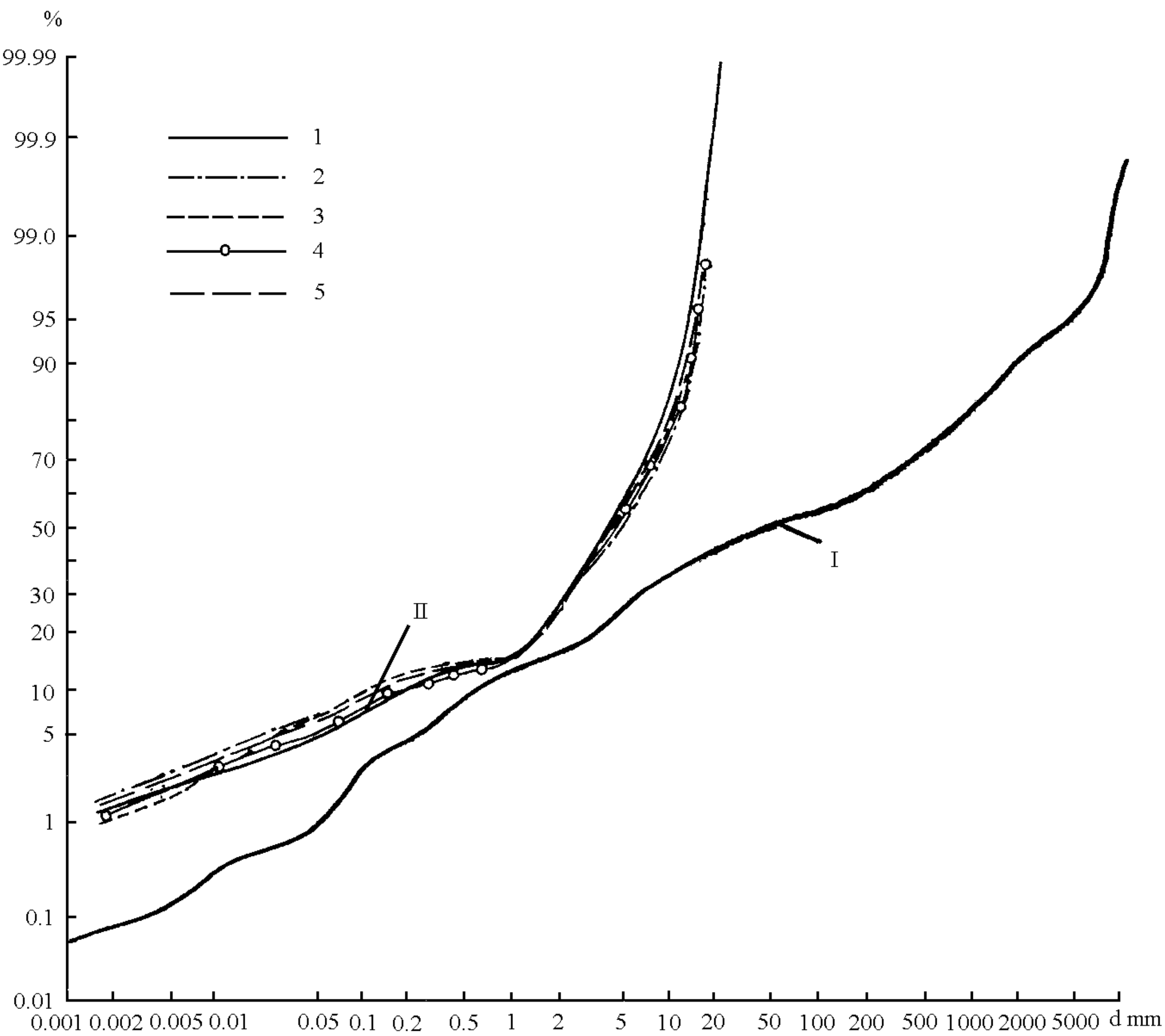


Fig. 2. Integral plots of the granulometric composition of debris flow-forming soils of the Chemolgan torrent gully: *I* - the granulometric composition of the PDFM; *II* - the granulometric composition of filler in the principal debris flow-forming soils; *1* - alluvial-proluvial, debris-flow soils; *2* - proluvial soils of side tributaries; *3* - Upper-Quaternary moraine soils (upper terrace); *4* - washout-gravitational and gravitational (slope) soils; *5* - Upper-Quaternary moraine soils (lower terrace).

(1) the smallest quantity of clay-silt particles is contained in the soils of the PDFM;

(2) the quantity of clay-silt particles in the debris-flow deposits changes in proportion as the flow travels downslope;

(3) the longer the flow travels, the more clay-silt particles in its deposits;

(4) in the first stages of debris-flow formation and movement of the debris-flow mass the content of all filler fractions increases (Fig. 1*a*); then at a certain stage the content of small particles (smaller than 0.1 mm) increases and that of the larger particles decreases; thenceforth the plots of the granular composition move as if in parallel upwards;

(5) debris in the debris flow-forming soil can break up into smaller sizes only in a turbulent flow regime.

It is interesting to compare the granulometric composition of the filler in variously-aged debris-flow deposits and in moraine soils (Fig. 1*b*). The granular composition of the filler in debris-flow deposits of different ages is very uniform, although the debris flow-formation mechanisms were basically different [1]. There are considerably more clay-silt fractions in moraine soils than in debris-flow deposits (Fig. 1*b*). If we accept the notion that the debris flow of 10 June 1972 was initiated as a landslide [1], we are justified in expecting an increased content of smaller particles in the debris-flow soils in comparison with the debris flow-forming soils. The content of fractions smaller than 0.1–0.2 mm in debris-flow soils decreases because of the passage of previous mud floods, whose formation mechanism we have described previously [1]. It should be noted that soil samples were collected directly at the mouth of the torrent gully. Borings made by the Zailiysky party of the MG KazSSR [Ministry of Geology of the Kazakh SSR] under the author's supervision in 1968 at locations 2–3 km below the mouth of the torrent gully in ancient debris-flow deposits characterize the filler as very similar to the filler of the moraine soils, that is, owing to the turbulent regime of the debris flows the debris-flow mass underwent a grinding process which resulted in the rapid formation of a large quantity of clay-silt fractions and fine sand (Fig. 1*b*).

The granulometric composition of debris-flow deposits is very diverse across both valley length and width. Deposits of the experimental debris flow of 1973 were studied on the basis of three borings (Fig. 3).

Boring No 5 was made in the body of the lead debris-flow surge which stopped on a flattened section of the channel; boring No 6 was made below the mouth of the torrent gully at a location approximately 2 km on a debris-flow terrace with a height of about 1 m in the wide part of the valley where the debris flow spread out to 80-100 m in width; boring No 7 was made in the rocky part of the initiation zone at a sharp turn of the channel. The morphological conditions of the flow channel in many respects determine the granulometric composition of the debris-flow deposits. The smallest quantity of course debris is contained in boring No 6 (Table 1), which is located in the widest and most leveled-out part of the torrent channel. The largest quantity of course debris is contained in boring No 5, made in a deep debris-flow surge. Also observed here is the smallest quantity of filler (fractions less than 20 mm in size), which spilled out as mud suspension after the surge stopped. Boring No 7 represents an averaged particle composition of the debris flow because the terrace was reformed several times by the debris flow during its travel.

Table 1
Granulometric composition of debris-flow deposits, %

Loc. of sample	Sample weight, kg	Size of fractions, mm					
		1000–500	500–200	200–100	100–50	50–20	< 20
B-7	1162	10.4	16.9	6.6	5.8	6.0	54.3
B-5	16408	8.7	50.9	9.7	1.9	2.1	26.7
B-6	1965	11.1	5.1	1.6	4.5	6.0	71.7

Along with boring No 5 in this same surge we estimated the quantity of fragments larger than 200 mm in an area of about 1000 m^2 and determined the percentage of each fraction not by its weight but by the quantity of fragments (Table 2). This was done to give a more complete picture of the granulometric composition of debris-flow deposits with a significant quantity of fragments larger than 1000 mm, the content of which could not be determined in the borings.

Table 2
The granulometric composition of a debris-flow surge, %

Location of experiment	Total quantity of debris, pcs	Size of fractions, mm				
		5000-2000	2000-1000	1000-500	500-200	< 200
Debris field No. 1	5126	0.5	7.4	32.7	54.9	4.5

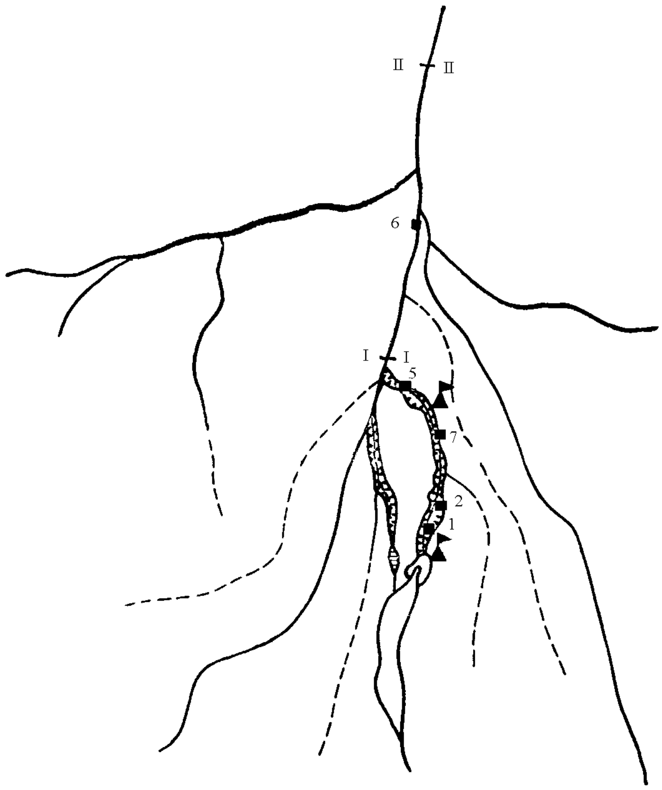


Fig. 3. Locations of borings in the Chemolgan initiation zone.

For the characteristics of the granular composition of debris-flow deposits in a direction perpendicular to the movement of the flow, we collected several samples at cross sections *I–I* and *II–II* (Figs. 3, 1*c*, 4*a*). The granular composition of the deposits in cross section *II–II* was more uniform; apparently, the debris-flow mass by this time was more thoroughly mixed.

Always observed after the passage of the experimental debris flows were residual mud floods which deposited alluvial-type terraces along the sides of the torrent channel. Fig. 4*b* presents plots of the granular composition of deposits of the residual mud flood after the debris flow of 1973. Here, unlike the debris-flow deposits, we see a reverse pattern in the granular composition: the greater the distance separating the deposit from the initiation zone, the smaller the quantity of clay-silt fractions. Therein lies the fundamental difference between the deposits of alluvium-transporting water flows and those of debris flows. And although the turbulent regime of movement of mudfloods is much more sharply pronounced, clay-silt particles do not form–the flow lacks the rigid skeleton of rock fragments.

Debris-flow soils and debris flow-forming soils are multicomponent systems. The properties of these soils are composed of the totality of the properties of the individual components. Of interest therefore are such indices as moisture content, porosity, density, and the petrographic composition of course debris larger than 20 mm). Investigations have established that in the area of action of the main Chemolgan torrent gully the most common among debris of varied sizes are granite and diorite (Table 3). Moisture content and density of course debris are practically independent of fragment size and shape, and hence Table 4 presents the characteristics of the properties of course debris without indicating their sizes.

The moisture content and porosity of course-debris soils in natural deposits are dependent on the granulometric composition of the soils, the petrographic composition of course debris and the percentage of individual petrographic species (Table 5).

One sees from Table 5 that the density of absolutely dry soil is dependent on both the content of course fragments in the rock and their petrographic composition. The lower density of the rocks in boring No 1 is attributed to the very loose texture of the rocks (the very weakly pronounced diagenesis of the soils of the PDFM)

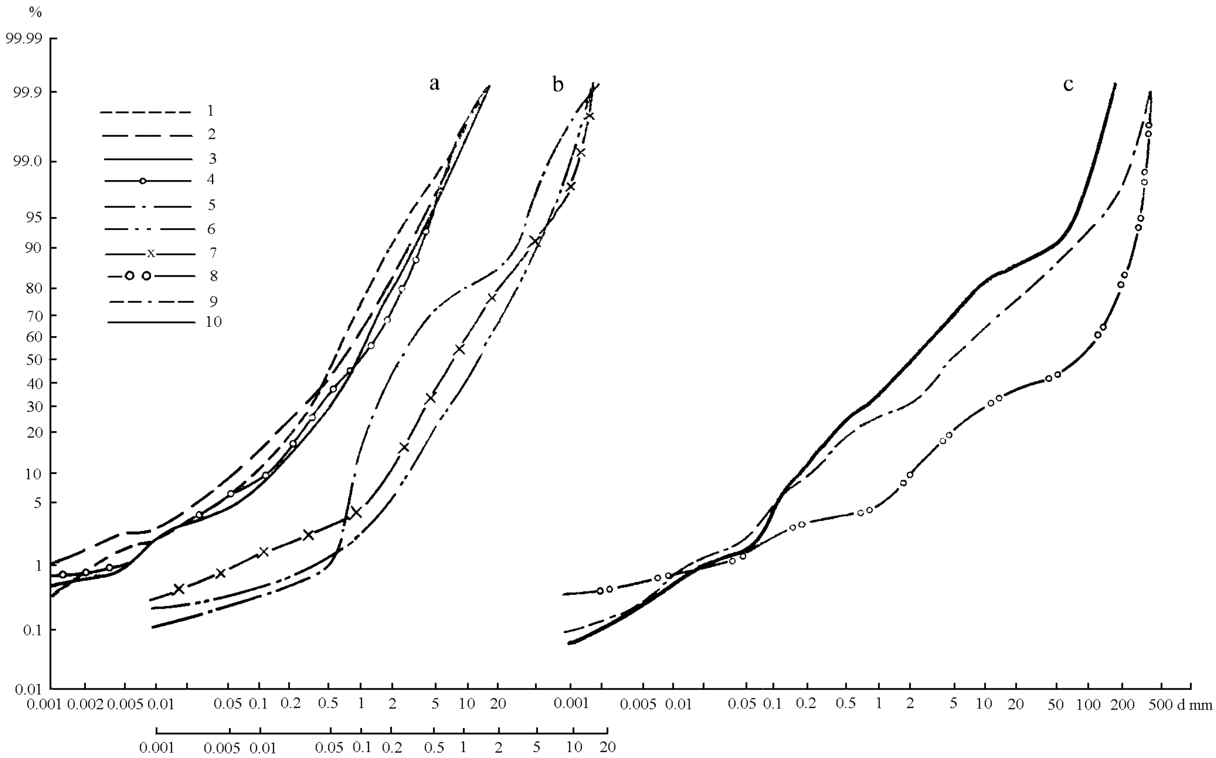


Fig. 4. Integral plots of granulometric composition: *a* - filler in debris-flow deposits of 1973 experiment for cross section 3 km below mouth of torrent gully; *b* - filler in deposits from residual floods; *c* - soils of PDFM, morainic and debris-flow deposits; *1, 2, 3, 4* - debris-flow deposits from east to west by cross section; *5* - mouth of torrent gully; *6* - at 0.3 km below mouth of torrent gully; *7* - at 3.5 km below mouth of torrent gully; *8* - moraines; *9* - PDFM; *10* - debris-flow deposits.

Table 3
Percentages of diorite debris of varied sizes

No of boring	Size of fractions, mm				Average	Average by weight and quantity
	20–50	50–100	100–200	> 200		
B-1	15.3/15.8	22.7/21.5	- /18.5	- / -	19.0/18.6	18.8
B-2	22.7/19.3	25.7/29.1	- / -	25.2/26.0	24.5/24.8	24.7
B-5	14.1/14.6	8.4/10.6	8.1/16.7	- / -	10.2/13.6	11.9
B-6	23.9/21.6	24.2/25.1	27.0/28.4	- / -	25.0/25.0	25.0
B-7	18.3/16.8	17.1/19.6	11.7/18.6	- / -	15.7/18.3	17.0
Average	18.9/17.6	19.6/21.2	15.6/20.6	25.2/26.0	19.4/20.8	19.5
Combined average	18.2	20.4	18.1	25.6	20.6	20.0

Note: Percentage of diorites in the total quantity of debris: numerator by weight, denominator by quantity

Among the debris flow-forming soils and debris-flow deposits, based on data from the granulometric composition of samples collected from the borings, the percentage of filler is more than 50% (except for boring No 5).

Table 4

Physical properties of course debris of varied petrographic composition

Petrogr. species	Density for natural moisture content, kg/m^3	Natural moisture content (by weight) %	Density			Porosity, %
			Absolutely dry debris kg/m^3	Fine earth material, kg/m^3	Material according to ref. data, kg/m^3	
Granite	2540	0.6	2520	2700	2650	5
Diorite	2800	0.6	2780	2700	2900	4

When we examine data on granulometric composition derived by photo techniques or by sifting large quantities of soils, we see that course debris (larger than 20 mm) nevertheless make up more than 50%. Consequently, data on granulometric composition derived from borings may be regarded only as a component part of granulometric analysis ending with the photo and sifting techniques with which we study a considerable volume of soils in a representative sample.

As already mentioned, debris-flow deposits are referred to as stopped debris-flow mass. One sees that this term is not quite accurate because the granulometric composition of the debris-flow mass differs substantially from that of debris-flow deposits, which is shown in Table 6.

Table 5

Physical-mechanical properties of loose rocks in natural structure

Bor-ing No	Vol. of remov. rock, dm^3	Wgt of remov. rock, kg	Moisture content, %			Soil density, kg/m^3		Granulometric Fraction composition, % size, mm											Total fract. >2mm	Total fract. >20 mm	% of diorit. in course debris
			Fine earth. >2mm	Debris <2mm	Soil in mass	In natur. strat.	Absol. dry soil	1000-500	500-200	200-100	100–50	50–20	20–2	2–0.05	0.05–0.01	0.01–0.005	0.005–0.002	>0.002			
B-1	1307	2672	12.0	0.6	3.6	2040	1970	2.3	20.0	7.1	6.7	5.9	30.7	24.8	1.5	0.5	0.3	0.2	73.7	43.0	18.8
B-2	1089	2440	15.6	0.6	4.0	2240	2150	2.2	15.4	3.0	5.6	5.9	44.1	21.3	1.8	0.1	0.1	0.4	77.4	33.3	24.7
B-5	7375	16408	11.5	0.6	2.3	2200	2170	8.7	50.3	9.5	1.8	1.9	10.2	14.7	1.8	0.5	0.3	0.3	83.5	73.3	11.9
B-7	518	1162	8.8	0.6	2.9	2250	2190	10.4	16.8	6.6	5.8	5.9	26.0	26.5	1.6	0.2	0.1	0.1	71.7	45.7	17.0
B-6	892	1965	9.7	0.6	3.2	2200	2130	11.0	5.1	1.6	4.4	5.8	43.6	26.2	1.7	0.2	0.3	0.1	71.9	28.3	25.0

As we see from Table 6, the content of clay-silt particles in the debris-flow mass of the experimental debris-flow of 1973 is more than 10 times greater than the quantity of these fractions in debris flow-forming soil and 6 times greater than their content in debris-flow deposits!

Table 6

Granulometric composition of filler in loose rock debris and debris-flow mass, %

Soils	Fraction size, mm											
	>10	10–5	5–2	2–1	1–0.5	0.5–0.2	0.2–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.002	< 0.002
Soils of the PDFM	10.5	19.2	30.3	13.5	13.0	7.3	2.5	1.5	1.4	0.3	0.2	0.3
Debris-flow deposits	9.5	15.1	24.4	13.8	13.5	11.7	4.7	3.2	2.8	0.6	0.4	0.3
Debris-flow mass	0.8	3.9	3.9	5.0	12.3	12.5	18.6	17.5	17.1	3.1	2.8	2.5

This fact shows that when the debris-flow mass stops the liquid part very rapidly separates from it to carry away a considerable quantity of clay-silt particles. Consequently, the process by which the experimental debris flow formed can be classified as an erosion-shear process with the former dominant when an excess of the water component has an effect. Still, one can point to a certain deficit of clay-silt fractions in the debris flow-forming soil that could, thanks to their strong hydrophilic nature, hold a large quantity of water. This is confirmed by the fact that after the samples of debris-flow mass are collected the water very rapidly separates from the solid particles.

These facts indirectly confirm the hypothesis that in the debris-flow process the grinding action produces a large quantity of small fractions which we call clayey not on the basis of their mineral composition but their particle size, that is, they possess the same chemical and water-physical properties as particles of the same size formed in the soil through the chemical conversion of plagioclases and other minerals into clayey ones.

REFERENCE

1. Vardugin, V. N., Spektorman, M. D. The debris flow of 10 June 1972 in the upper reaches of the Chemolgan River (in this collection of papers).

The solid/liquid material balance in the debris flows of 1972–1973 in the Chemolgan river basin*

A. E. Zems, R. V. Khonin and V. I. Laptev

During the experiments the volumes of water and soil involved in the debris-flow process were measured in order to analyze the material composition of the debris flow, evaluate its mean density and study the laws of spatial distribution of material entrained and deposited by the flow.

The liquid part of the debris flow was composed of water discharged from the reservoir and interstitial water entrained along with the loose rock debris. A rough evaluation of the moisture content of loose-debris formations is presented in a paper by V. N. Vardugin [1]. The negligible (less than 1%) volume of channel water entrained by the flow was not taken into account.

Release of water from the reservoir in 1972 began on 27 August at 12:15 hours when it was filled to a level of 3.06 m, which corresponded to a volume of 42 thousand m^3 of stored water. The release lasted 18 min and 30 s. Of these, 12 min and 15 s were with the gates fully open. Two min were spent on opening the gates and 4 min and 15 s, on closing them. After the release the reservoir level dropped to 0.4 m.

The 1973 experiment was begun on 22 August at 13:00 hours with the reservoir water level at 3.04 m, which corresponded to a volume of 39.2 thousand m^3. A total of 15.7 thousand m^3 of water was dumped from the reservoir in the three main releases. The length of the releases and their volumes and peak discharges are given in Table 1.

Table 1

Year of experiment	No of releases	Period of releases, min	Volume of releases, 1000 m^3	Peak discharge of releases, m^3/s
1972	1	18.5	11.8	16.0
1973	1	2.5	1.7	16.2
	2	10.0	7.3	15.8
	3	9.0	5.3	12.1
	4	222.0	24.9	2.1

The volumes of the releases from the reservoir were determined by a bathymetric curve [8]. But the runoff velocity obtained by this method was not in accord with reality because a substantial slanting of the water surface was observed in the reservoir during the releases, thus upsetting the relationship between water volume and level. The largest errors in determining water volumes and, consequently, discharges occurred during the closing of the dam gates.

During the experiment on artificial replication of debris flows in 1973, when the dam gates were repeatedly opened and closed, the reservoir surface was very complex in form. This was registered by four water-level recorders set up at various points in the reservoir. Hence the volume of water drawn off the reservoir in each release could not be determined by a bathymetric curve. These volumes, as well as the hydrographs of the releases, were computed from hydraulic formulae (Fig. 1). As a check the velocity of water outflow was measured with current meters during the releases from the reservoir.

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 35–43

The spatial distribution of volumes of solid material was computed on the basis of topo-geodetic measurements which in 1972 covered 4.6 km of the initiation zone, channel and debris field. Trigonometric levels were taken at 84 cross-sectional profiles, of which 28 were located in the main torrent gully, 10 in the torrent channel, 19 in the lower torrent gully and 27 in the debris field (Fig. 2).

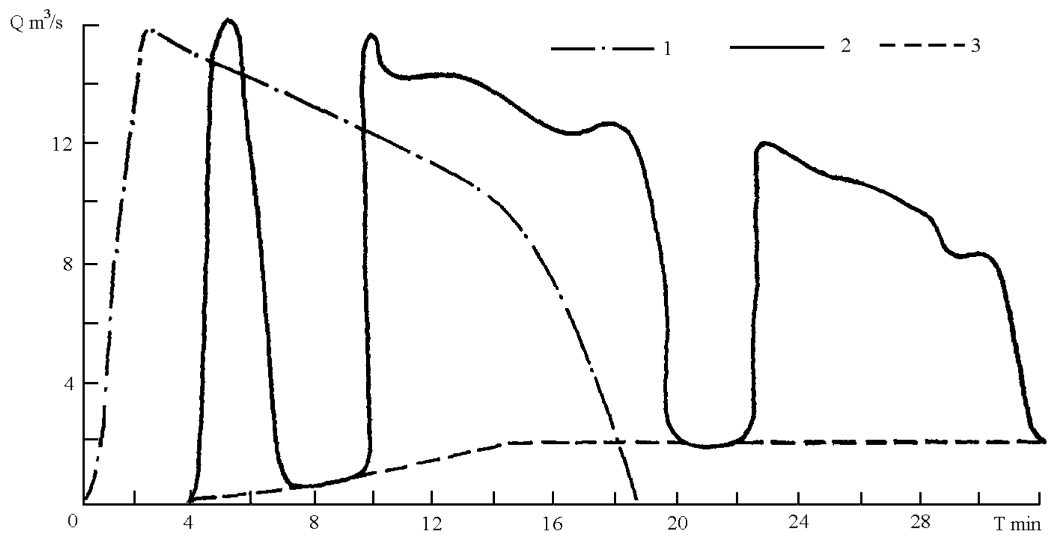


Fig. 1. Hydrographs of water releases from the reservoir in 1972 and 1973 computed according to hydraulic formulae: *1* - hydrograph of the 1972 release; *2* - hydrograph of the 1973 release; *3* – hydrograph of the release from the tubular water conduit in 1973.

In 1972 after the experiment was conducted and levels were again taken of the cross-sectional profiles, it was established that a total of 24.2 thousand m^3 of loose rock debris was removed from the initiation zone. Despite the gradual decrease in the slope of the potential debris-flow mass, loose rock debris in different sections of the cross-sectional profile of the initiation zone was entrained in motion rather erratically (Fig. 3). Fifty percent of the debris mass of the debris flow formed in the upper part of the PDFM of the main torrent gully down to the 15th cross-sectional profile. Below this profile a gradual reduction in the intensity of the debris-flow formation process was noted. The volume of debris flow increased down to the 47th cross-sectional profile (Table 2), after which there was considerable deposition of debris-flow mass.

One can attribute the accumulation of debris-flow deposits between the 47th and 62nd cross-sectional profiles (18000 m^3) more to a sharp 60° bend in the lower torrent gully in the region of the 59th–61st cross sections and less to the decrease in its longitudinal slope. A similar pattern in smaller scale was observed at a bend in the torrent channel between the 33rd and 34th cross-sectional profiles.

Below the 62nd cross section in the debris field sections of deposits from the debris flow alternated with places where there was a predominance of loose-debris formations which had been entrained in the flow from the channel (Fig. 2). Deposits generally predominated down to the 78th cross section, below which an increase in the volume of debris flow was noted (Fig. 3). Below the 88th cross-sectional profile deposits from typical debris flow were observed for a distance of 6 km.

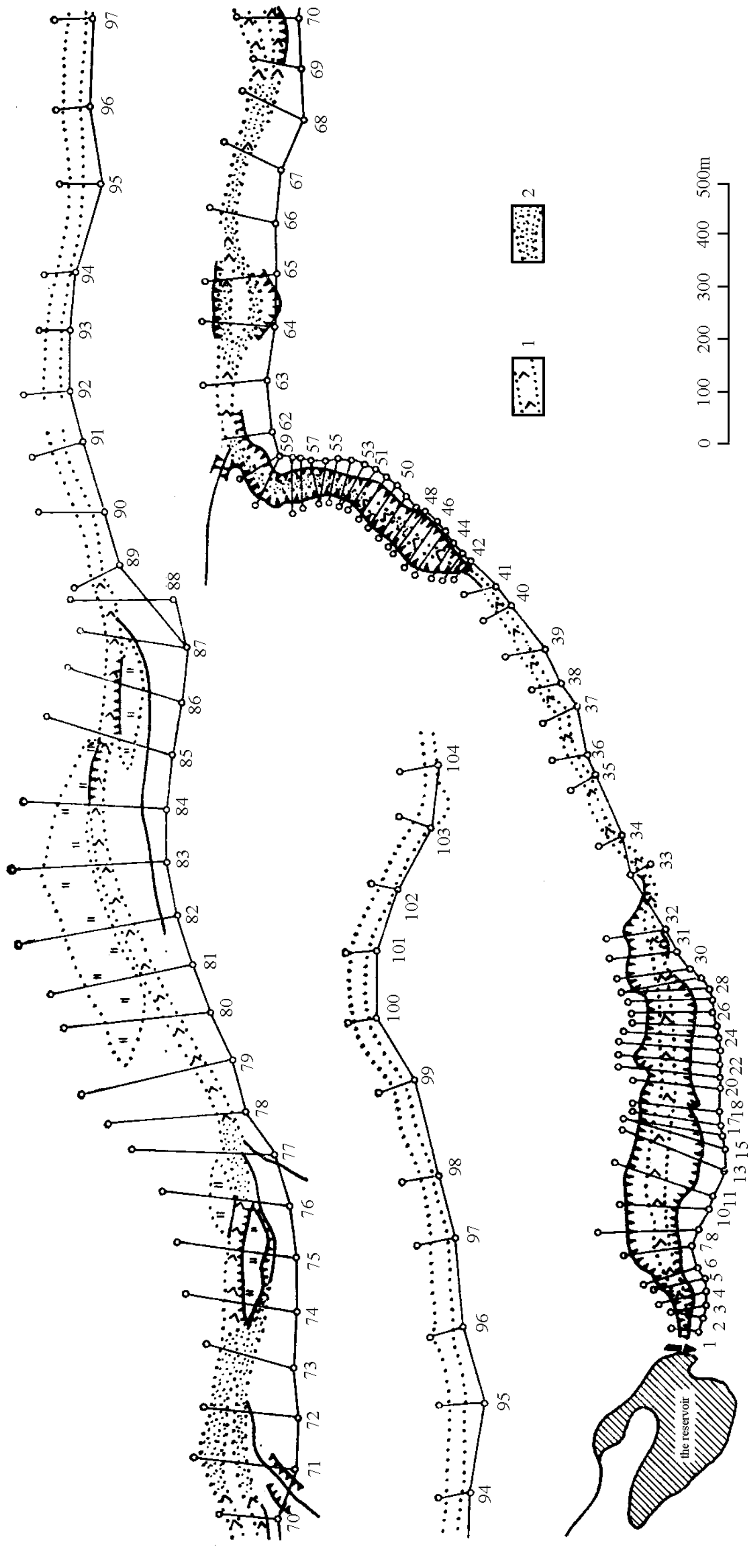


Fig. 2. Diagram of cross-sectional profiles and locations of sections of washout (*1*) and deposits (*2*) of the 1972 debris flow in the Chemolgan River basin.

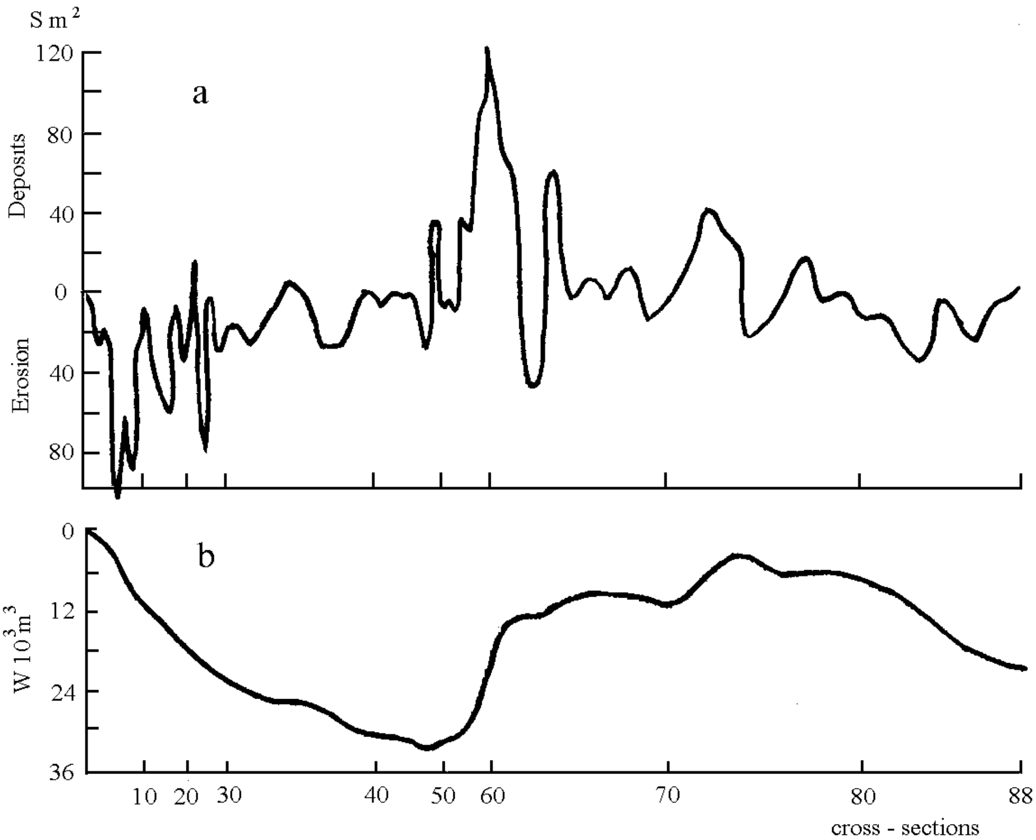


Fig. 3. Plot of areas of washout and deposits (*a*) according to data from levels taken of the cross-sectional profiles and an integral curve of volumes of washout and deposits (*b*) in 1972.

Table 2

No of cross-sectional profile	15	32	42	47	62	78	88
Distance from dam to profile, km	0.41	0.80	1.57	1.70	2.11	3.69	4.71
Volume of soil passing through cross section location, 1000 m^3	16.4	24.2	31.5	32.8	14.8	7.9	23.5
% of total volume of the solid component of the debris flow	50.0	73.8	96.1	100.0	45.1	24.1	71.7

In 1972 the morphological complexity of the debris field was analyzed in order to elucidate the reasons for the peculiar way in which the debris flow was regenerated below the 78th cross-sectional profile. Because the slope of the debris field in some sections fluctuated only slightly against the background of a general decline in slope, the fact that the volume of the solid component of the debris flow (Table 2) increased cannot be attributed to a change in the channel's slope. As geodetic measurements showed, debris-flow deposits were observed in places where the floodplain widened, at bends in the flow and when it branched out, that is, where the depth and velocity of the flow decreased (Fig. 2).

In sections where the flow narrowed its depth and velocity increased. Loose rock debris was entrained in the flow at such places. The debris flow had the greatest eroding power after the front of the debris-flow wave or the largest debris-flow waves passed, when the depth and velocity of the debris mass increased substantially. Debris-flow mass usually was deposited between the debris-flow waves, when flow depth decreased.

The immense eroding power of the debris flow is shown by the removals of loose-debris deposits from positive contours of the debris field, that is, from those sections where washout only by a post-debris flow flood is ruled out. Observations of the debris flow in the regions of the 70th and 80th cross-sectional profiles showed that the debris flow was being continuously "merged" into the channel deposits.

The artificially triggered debris flow of 1973 was substantially different from the debris flow of the previous year (Table 3).

One sees from the data in Table 3 and Fig. 4 that in 1973 the debris flow formed in a longer section in comparison with the previous year. If in 1972 the solid component of the debris flow increased up to the 47th cross-sectional profile, in 1973 the maximum volume of loose debris moved through the line of the 73rd cross section. As in the previous year, in the section between the 46th and 61st cross sections, 18 thousand m^3 of soil was deposited, which comprised only 15% of the total volume of the solid component of the debris flow. Debris-flow deposits also accumulated below the 73rd profile. Even though the section under observation by instruments was extended by 2 km (to the 104th cross section), the main deposits of debris-flow mass were noted beyond it.

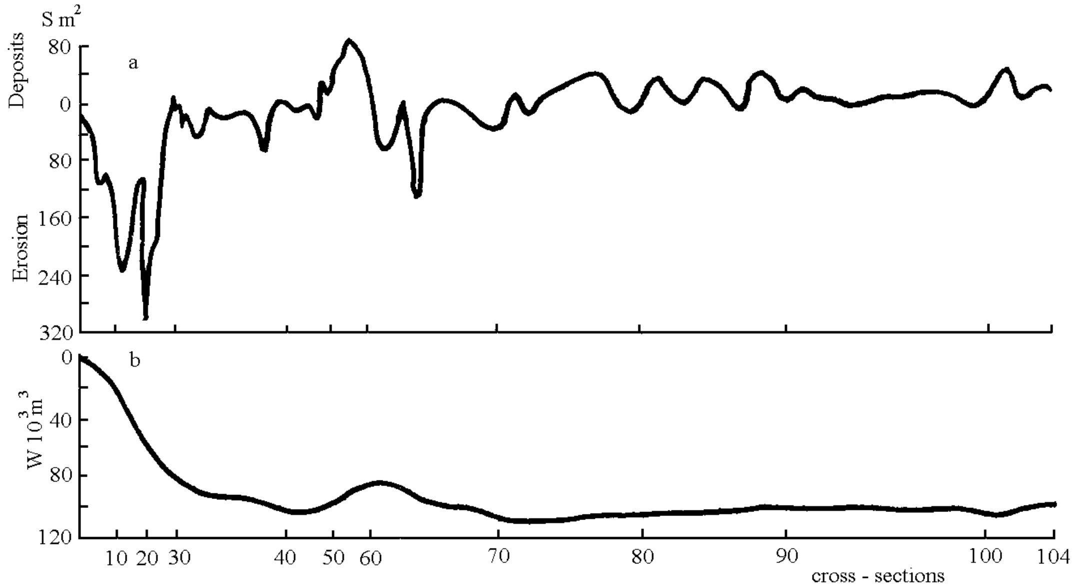


Fig. 4. Plot of areas of washout and deposits (*a*) according to data from levels taken of the cross-sectional profiles and curve of volumes of washout and deposits (*b*) in 1973.

According to the data of Vardugin [1], a substantial increase in silt-clay particles is noted in the debris-flow deposits in comparison with the original soil of the potential debris-flow mass. Externally this manifests itself in the greater "cementation" of the debris-flow deposits. A similar increase in cementation of debris flow deposits downstream was observed in surveying the debris flow of 15 July 1973 in the Malaya Almatinka.

If data on the volumes of solid and liquid components of the debris flows are available, one can estimate the mean values of their density by the balance method. Table 4 presents a computation of the mean density of the entire flow as a whole, that is, including the post-debris flow floods. Initial data for the computation were taken from [1 and 4]. The computation was done for the "control cross section" location (42nd cross-sectional profile).

Table 3

No of cross-sectional profile	15	32	42	46	61	65	73	78	91	100	104
Distance from dam to profile, km	0.41	0.80	1.57	1.67	2.07	2.41	3.23	3.69	5.01	6.28	6.77
Volume of ground passing through cross section location, 10^3 m^3	50.0	87.0	102.0	103.5	85.5	106.0	119.0	110.0	102.0	110.0	105.0
% of total volume of the solid component of the mudflow	42.0	73.1	85.7	87.0	71.8	89.1	100.0	92.4	85.7	92.4	88.2

Table 4

Year of experiment	Ground					Water				Mudflow		
	Density of rock waste (spec.wgt), kg/m^3	Density of ground in absolut. dry state, kg/m^3	Porosity n	Volume of transported ground (loose), 10^3 m^3	Volume of poreless ground matter, 10^3 m^3	Degree of water satura-tion of ground pores α	Volume of water entrap. in pores, 10^3 m^3	Volume of dischar-ges from reserv., 10^3 m^3	Total volume of water compon. of mudf. 10^3 m^3	Total volume of flow, 10^3 m^3	Total weight of flow, 10^3 m^3	Average density, kg/m^3
1972	2700	2210	0.181	32	26.2	0.65	3.8	11.8	15.6	41.8	86.4	2070
1973	2700	2210	0.181	102	83.5	0.65	12.0	40.6	52.6	136.1	278.0	2040

As is seen from the data in Table 4, the values of mean flow density for both experiments exceed 2000 kg/m^3. One is easily satisfied that the approximate character of the evaluation of coefficient α [1] is of little significance: thus, when it varies within 0.50–0.80 the density value will differ from that computed in the table (when α = 0.65) by less than 1.5%.

The given density evaluations, as shown above, are gross, relating to the flow as a whole, including the post-debris flow floods. The density of the main debris flow was substantially higher, as shown for example by the unit measurement in 1973 of flow density by the densimeter of the Kazgeofizpribor Plant, which gave 2300±100 kg/m^3 as the mean density value for a minute interval [4].

The heterogeneity of the flow was particularly high in the 1973 experiment, when because of the opened gate of the tubular water outlet the three main water releases with discharges of 8–16 m^3/s (for a total volume of 15.7 thousand m^3) were accompanied by a long plume-release for a period of 3.5 h with a discharge of 1–2 m^3/s (for a total volume of 24.9 thousand m^3). The debris flow induced by the plume of the releases bore the character of an alluvium-transporting water flow, in the background of which only isolated pulsating movements of debris-flow masses were noted. An attempt was made to separate the main from the plume part of the 1973 debris flow. This was done by comparing a hydrograph of the water releases with the readings of a seismo-flowmeter which operated for 110 min [4], whereas the main part of the debris flow lasted only 29 min [2]. On the assumption that the relation of the level of seismic noise to the discharge is linear in character, the total volume of the debris flow – 136.1 thousand m^3 – can be divided into two parts: a main volume of 63.3 thousand m^3 (lasting the first 29 min) and a plume volume of 72.8 thousand m^3 (lasting 110 min). Mean density values corresponding to these volumes amount to 2120 kg/m^3 for the main part and 1970 kg/m^3 for the plume part.

When the seismo-flowmeter readings are interpreted as nonlinear, the volume and density of the main part of the debris flow will increase (with a corresponding decrease in the plume part).

Because the geomorphological conditions and physio-mechanical properties of the rock in the region under study are fairly characteristic for the entire central part of the northern slope of the Zailiysky Alatau, the results obtained refute the commonly accepted notion that under the conditions of the Zailiysky Alatau cloudburst and outburst floods cause formation of only the so-called turbulent (in the terminology of the III All-Union Debris-Flow Conference) debris flows, regarded as the water-transport of solid material, the content of which in the flow is less than 40% [3, 5–7].

REFERENCES

1. Vardugin, V. N. The principal physio-mechanical properties of debris flow-forming soils and debris-flow deposits in the Chemolgan River basin (in this collection of papers).
2. Vinogradov, Yu. B. Artificial replication of debris flows at the experimental site in the Chemolgan River basin (in this collection of papers).
3. Duysenov, Ye. D. Debris Flows. Alma-Ata: *Kazakhstan* (1966) pp 217.
4. Krasyukov, V. A., Stepanov, B. S., Stepanova, T. S. Instruments for contactless measurements of some characteristics of debris flows (in this collection of papers).
5. Smirnov, I. P. The formation and dynamics of debris flows. *Tr. KazNIGMI* (1959) Vol 11 pp 52–61.
6. Smirnov, I. P., Degovets, A. S., Zhirkevich, A. N. Techniques for computing the principal characteristics of cloudburst-induced debris flows in the Kazakh SSR. *Debris flows and Mountain Riverbed Processes.* Yerevan: Izdat. AN ArmSSR (1968) pp 135–148.
7. Sokolovskiy, D. L. Debris flows, their hydrological features and computational techniques. *Meteorology and Hydrology* (1947) No 5 pp 65–75.
8. Khonin, R. V., Mochalov, V. M., Zems, A. E. The experimental site in the Chemolgan River Basin and the history of its founding (in this collection of papers).

The velocity characteristics of experimental debris flows*

M. D. Spektorman

During the replication of experimental debris flows in the Chemolgan River basin we measured the velocities at which the front of the flow moved in various sections of the channel and surface velocities at a stationary site.

Fig. 1 presents a histogram of the velocities at which individual waves moved.

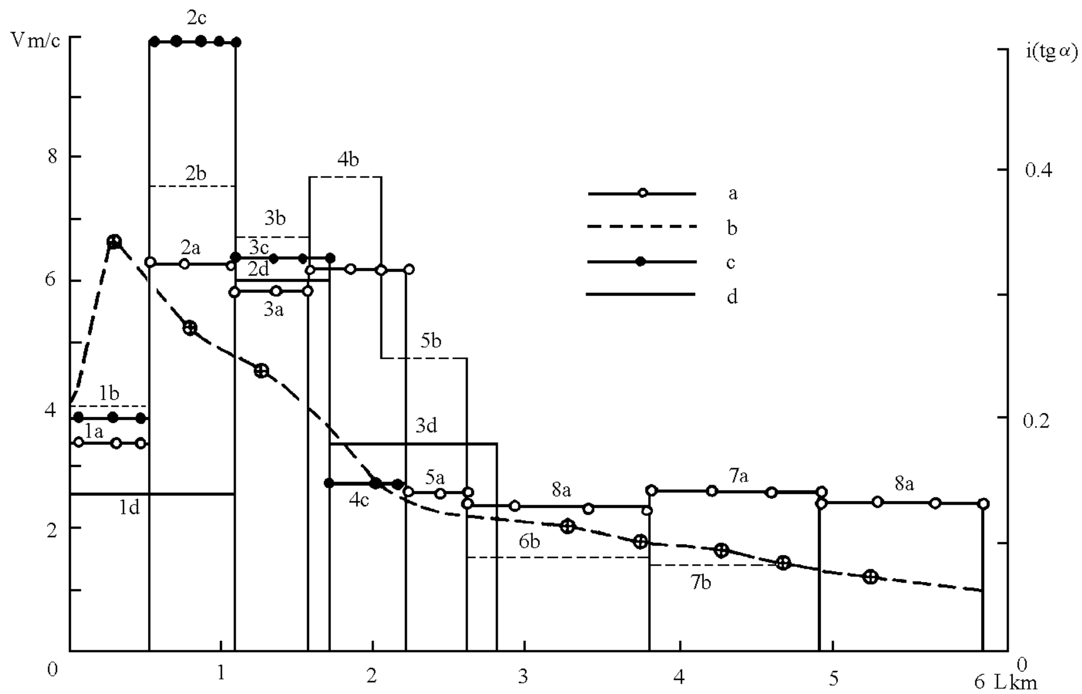


Fig. 1. Velocities at which the front of the flow *v* moves in various sections of the initiation zone and torrent channel: *a, b, c* - respectively the 1st, 2nd and 3rd waves in the 1973 experiment; *d* - the 1972 experiment: dotted line - slopes of the channel.

Because of the frequency with which the velocity of the flow front was measured we were able for the first time to characterize comparatively completely the evolution of the velocity of the debris flow over almost the entire course of its formation and deposition. Certainly, information on the conversion of a purely water flow into an alluvium-carrying one and then into a debris flow is contained in the velocity values measured at various distances from the dam. During the transformation of the water flow into debris flow the maximum of velocity does not coincide with the maximum of the slopes (Fig. 1), and one sees that its coordinates are dependent on the intensity with which channel material is entrained. Fig. 2 presents the relation between the measured wave velocities and the slopes in individual sections.

The group of points which deviated sharply from the primary dependence belongs to sections of the channel in the upper part of the initiation zone, where the flow on average contained little solid material, and is appreciably separated from the general set. The other points are grouped together comparatively closely and characterize a process where depth of flow and concentration of solid material varied relatively slightly. In these cases, velocity is basically a function of the slopes. The statistical processing of the data (without points with the numeral *1* which belong to the first interval of length) (Fig. 1) showed that the best correspondence (that is, the minimum of the slopes squared) is obtained with an approximation of their linear dependence $v = a(i - i_0)$ where a = 41.8, i_0 = 0.050 The magnitude of i_0 may

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 44–48.

be treated as the least possible value of the slope at which the debris-flow process takes place with a given concentration of solid material in the flow, and the value of a is a function of the depth of flow and the concentration and roughness of the channel.

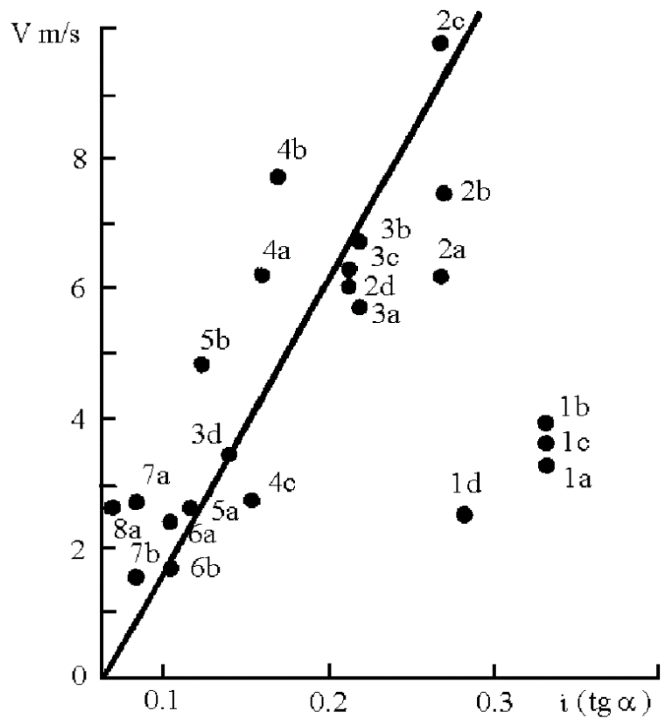


Fig. 2. The relation between velocity of debris-flow wave fronts *v* and channel slopes: *a, b, c, d* - see Fig. 1.

Debris-flow surface velocities were obtained at the stationary site with an automatic velocity meter. The site is located at a distance of 1700 m from the dam. The channel in the region of the site consists of rock partially covered by a thin mantle of loose debris deposits. The slope of the channel on the previous 30-meter section on average is 0.20. A waterfall with a height of about 7 m begins several meters below the site.

Fig. 3 presents a curve of the continuous recording of velocities in the 1972 experiment. The operating principles of the automatic velocity meter were described in a paper by B. S. Stepanov [2].

The most important characteristic of the flow is its volumetric discharge. For its computation we found the coefficient for the transition of surface velocity to mean velocity, the coefficient equaling the relation of the integral $\int_0^\tau v_{surf}\omega dt$ to the sum of the volumes of released water and entrained channel material passed through the site (τ is duration of flow at the site, *t* is time). The relation computed in this manner $\frac{\bar{v}}{v_{surf}}$ = 0.64.

Non-trivial results are obtained when measured velocities are compared with debris-flow depths. In a plot of the relation between v_{surf} and *h* (Fig. 4) one clearly sees that the process in question is not the same in the domain of the high and low values of level. This manifests itself first in a regular increase in the dispersion of velocities with an increase in level. Here observations during any value of level are equally accurate, and an increase in the spread of points at large depths is not associated with a systematic decrease in accuracy. Magnitudes of velocity dispersion are presented in Table 1. Another characteristic feature in the plot of the relation between v_{surf} and *h* in the domain of large discharges is a regular decrease in velocity with a rise in flow depth, and, conversely, an increase in velocity with a

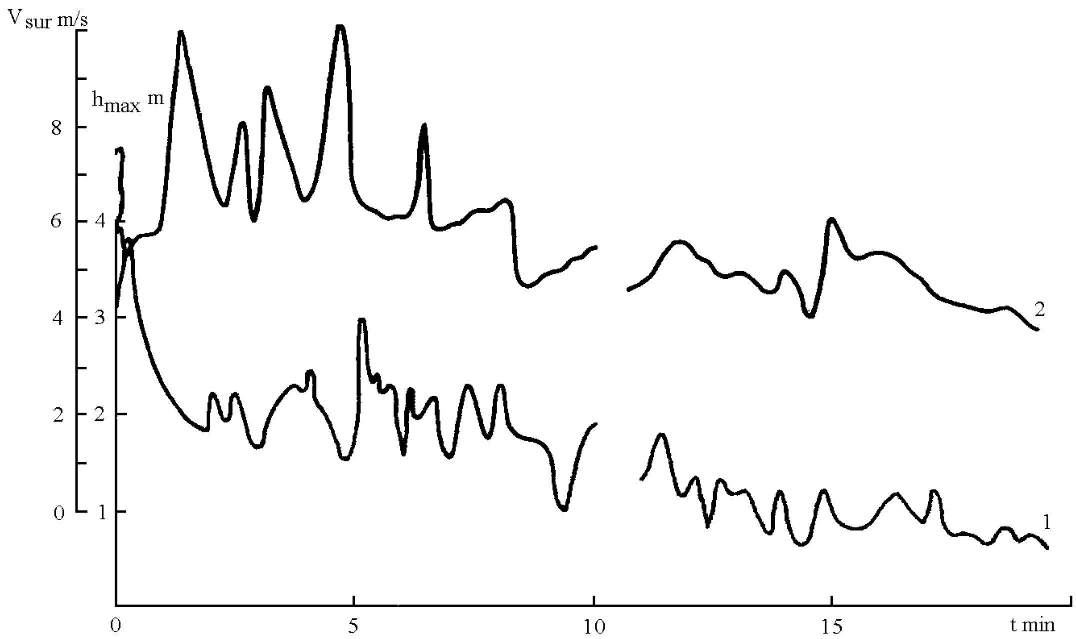


Fig. 3. Collated plots of continuous recordings during maximum depth h_{max} (*1*) and surface velocity v_{surf}(*2*) at the stationary site.

decrease in level. Here the reverse proportionality is observed only with some critical value of flow depth, approximately equaling *h* ≈ 1.5 m (*R* ≈ 1.10 m). One can naturally attribute such "nonstandard" behavior of velocity as a function of depth to cyclical change in the composition and properties of the debris-flow mass that are associated with surge formation.

Table 1

Velocity Dispersion of partial samples (time interval Δ*T* = 270 s)

Interval	1	2	3	4
σ^2(v)	1.41	0.52	0.24	0.20
$\bar{h}$ m	2.25	1.83	1.03	0.82
Number of computational points	30	30	30	25
v. m/s	6.99	5.7	5.03	4.39
$C_v(_v)$	0.20	0.09	0.05	0.05

There are several empirical formulae for computing debris-flow velocity. A comparison of two of them—the formula of I. I. Kherkheulidze [3] $v_{max} = 10.75\bar{h}^{0.55}i^{0.33}$and the formula of V. V. Golubtsov $\bar{v} = 3.75\,\bar{h}^{0.5}i^{0.17}$ [1]—with measured velocities (with conversion in accordance with the relation $v_{max} = \bar{v}\,/\,0.64$) shows (Fig. 4) that based on the available data one cannot give preference to either one of them, or rather inevitably conclude that they express the relation between depths and velocities for flows with different properties, when the alluvium concentration in the debris flow is varied.

The movement regime of the experimental flows. The movement of the debris flows was distinguished by turbulence. Above the flow, particularly with large discharges, arose a dense shroud of spray formed by the collision of moving rocks. In sections of steep slopes, the spray was so intense that the solid surface of the flow was hardly visible. At times the appearance of the flow changed, which was associated with the travel of rock fields moving in a quasi-structural regime. A completely structured flow (movement as a type of solid body) did not occur; the bonds existing between individual elements were not sustained with time. Noted at times were particularly large clumps lagging behind the rest of the flow. The critical diameter of the rocks, above which the velocity of the debris is less than that of rocks average in cross section, obviously cannot be defined unambiguously because it is functionally associated with the density and discharge of the flow and with channel slope. With peak discharges of the order of 100 m^3/s, the critical diameter is approximately 2.5–3.0 m, that is, dimensions comparable to the dimensions of the channel, and hence during their motion such clumps are subjected to immense resistance which reduces their velocity.

The initiation zone was transformed appreciably by the debris flow moving over it. A deep narrow canyon with steep sides formed in places where there was intensive entrainment of channel material. Sections of deposits in the channel and in the valley bottom appeared both as wide, comparatively level fields and as long narrow strips of bank surges. The immense eroding power of the flow hampered large-scale measurement of depths. In particular, after the experiments it became clear that the popular method of computing debris flows according to so-called high-water markers is totally unacceptable if a channel with a steep longitudinal slope is composed of loose debris.

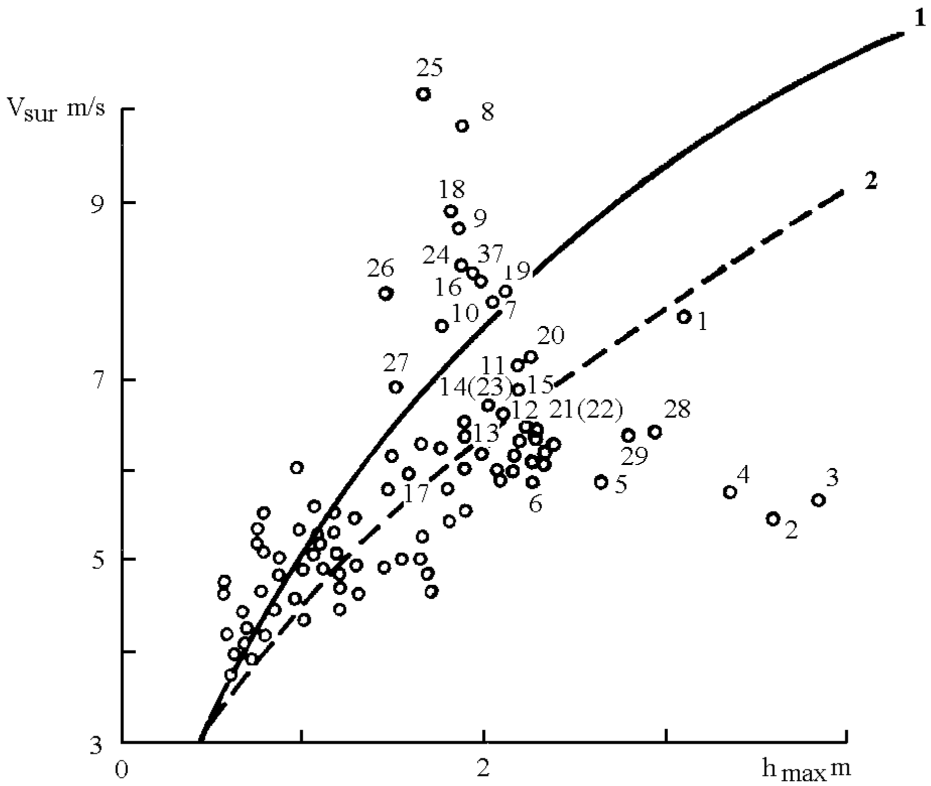


Fig. 4. Relation between surface velocity v_{surf} and maximum depth of debris flow as measured at a stationary site: *1* - based on the formula of I. I. Kherkheulidze, *2* - of V. V. Golubtsov.

REFERENCES

1. Golubtsov, V. V. Computation of the mean velocity of turbulent debris flows. *Collected papers of the Alma-Ata Hydrometeorological Observatory* (1969) No 4 pp 163–167.
2. Krasyukov, V. A., Stepanov, B. S., Stepanova, T. S. Instruments for contactless measurements of some characteristics of debris flows. (in this collection of papers).
3. Kherkheulidze, I. I. Computations of the principal characteristics of debris flows. *Collected papers of the International Symposium on Floods, Vol II,* Leningrad, Gidrometeoizdat (1969) pp 384–394.

The debris flow of 10 June 1972 in the upper reaches of the Chemolgan river*

V. N. Vardugin and M. D. Spektorman

A characteristic of the debris flow-hazardous rivers on the northern slope of the Zailiysky Alatau is that the largest initiation zones are confined to the steep (up to 30–35°) and deep (up to 300 m in height) terminal surges of Upper-Quaternary moraines (Zharsay, Kumbelsu, Kasymbek, Chemolgan, et al). Because the mechanism by which such initiation zones form has hitherto been largely undefined, we allow notions that these torrent gullies owe their origin both to a type of erosion by the forces of flowing water with gradual saturation of the water flow by a solid component and to a process of one or several successive landslides or slopewashes.

Of interest in this connection is that an initiation zone developed in the front of the terminal surge of ancient moraine next to the existing initiation zone on which staff of the Department of Debris Flows of KazNIGMI [Kazakh Institute for Hydrometeorological Research] conducted work beginning in 1970 to replicate artificial debris flows under natural conditions. For the period of construction, a stream which had been running into the initiation zone was moved somewhat to the west, and the water ran down depressions and wide hollows which lacked a developed channel.

The hydrologic regime of the stream was inadequately studied. One can say with certainty only that the stream has a particularly pronounced intra-daily change in level and discharge, reaching its peak at approximately 23:00. The minimum discharge occurs in the morning. The peak discharge was not more than 1 m^3/s. The movement of even this amount of water onto a slope with an inclination of up to 30–35° created the prerequisites for the creation of an initiation zone and formation of a debris flow.

The spring of 1972 in the high-mountain region was prolonged, cold and wet. On 10 June 1972 a slight (7 mm) rainfall of moderate intensity occurred with thick fog during the day and evening.

At around 22:30 staff of the field detachment heard a rumble and felt a slight vibration in the ground. The direction from which the rumble originated could not be determined. During that same night staff of the detachment located in the lower camp at the mouth of the main torrent gully heard a debris flow moving down the Chemolgan riverbed (a low powerful rumble, the crash of colliding rocks, ground vibrations).

The newly formed initiation zone appeared as a new torrent gully with a width ranging from 5–10 to 30–50 m, depth from 4–5 to 15–18 m and a length of about 2000 m. The maximum depth and width of the torrent gully are confined to the steepest parts of the slope (Fig. 1).

The initiation zone may be divided into three sections differing from each other by the morphometry of the torrent gully and separated by waterfalls confined in plan view to places where there is a sharp turn in the channel, and in profile, to sections where there is a sharp increase in slope. These waterfalls originally were very high: No *1*—12 m, No *2*—5 m, No *3*—18 m, but as erosion developed they rapidly degraded and in a week appeared simply as a steep channel composed of very large rocks. The sharp widening and deepening of the sections of the channel confined to the waterfalls bring to mind their landslide origin.

The mechanism by which the initiation zone and the debris flow formed is as follows:

As a result of the interaction of loose-detrital soil (coefficient of filtration about 1 m/day) with surface drainage (the complete saturation of pores with water and the resulting increase in weight, reduction in

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 48–53.

cohesive forces and in angle of internal friction, and hydrodynamic and hydrostatic effects) the equilibrium of forces holding and shearing the ground mass was disrupted in favor of the latter. The upper part of the moraine terrace with a slope of about 30° began to slide, the sliding surface apparently being the upper boundary of permafrost lying at a depth of 2.5–3.0 m. The sliding process developed very rapidly, facilitated by the penetration of surface waters into the landslide body through cracks which were preserved long after the debris-flow event. Because of the varied roughness of certain parts of the underlaying surface (protuberances of large rocks) the sliding body broke up into separate units moving at different velocities, causing agitation of the soil and formation of a liquid mass as a result of the dilution of the soils. The volume of the initial sliding mass apparently was not less than 50% of the volume of landslide basin No *1* (the volume of soil from the ground surface to the proposed sliding surface), that is, not less than 2000–2500 m^3. The dynamic action of the sliding mass on the underlying water-logged soils caused them to become diluted and set in motion. The flow grew more massive as it descended.

Thus, taking place in this case was a gravitational flow of water-logged, diluted soil. Let us introduce some facts indirectly confirming the hypothesis that a debris flow can develop like a landslide process.

During the inspection of the initiation zone and debris-flow deposits on 11 June 1972 one more debris flow formed in the initiation zone that, true, was smaller in scale than the first one. At about 17:00 observers in the upper part of the initiation zone recorded the collapse of part of the ground mass along an already existing crack in the volume of around 100 m^3. The broken-away ground turned before our very eyes into a liquid mass which rapidly descended down the initiation zone, transporting for some distance boulders up to 2–3 m in a cross section. At that time the authors of this paper were located below the area where the old and new initiation zones merged. At 16:55 we heard a powerful low rumble accompanied by slight vibration in the ground; sometime later at the widest part of the initiation zone (Fig. 1) a dark wave rose up and disappeared. Within 3 min a dark-brown wave carrying juniper brush and rock debris reached the wide part of the valley, broke down into separate arms and for the most part followed the path of the first debris flow. The height of the surge in the narrow part of the valley attained 2.5-3.0 m. In 3 min the surge traversed a distance of around 1500 m, that is, its mean velocity was 8-9 m/s. Behind the first wave, which was an alluvium-transporting water flow, moved a debris flow with a particularly pronounced leading surge consisting of a very large quantity of course debris which moved as a single body without revolving around its own axis and without the noise from colliding fragments. With a depth of 1.5-2.0 m the flow readily entrained in motion the previously deposited surge of the same height. The flow was close to laminar in character.

Within 7 min the discharge decreased markedly, and liquid mud with a large quantity of debris up to 30–50 mm in size rapidly ran out from the stopped waves. An alluvium-transporting water flow noisily rolling rock fragments up to 400–500 mm in size again ran down the channel.

A characteristic of the flow observed by us was the successive changing of its color and character of motion: the advance and residual alluvium-transporting water flows were dark-brown in color and turbulent in character of motion; the debris flow which ran between them was grey-green in color and near-laminar in character of motion. The discharge of one of the debris-flow arms was visually determined to be 7–10 m^3/s. But observers in the upper part of the initiation zone did not notice an increase in the discharge of the stream flowing into the initiation zone, and precipitation on 11 June was 0.2 mm in all. With a channel slope of 20–30° it is difficult to imagine the existence of major dams holding back a large quantity of water. Consequently, the debris flow formed not because of an increase, even for a short time, in the discharge of the water flow and its enrichment with solid material but rather because of the sliding of water-logged soil.

After the debris flow we conducted a tachometric survey of the initiation zone and constructed a schematic. The depth of the initiation zone was measured with a cable bearing a weight at its end. From the survey results we computed the volume of material removed, reducing the volume by 20% to account for erosion by the water flow after the debris flow. The volume of material removed in this case was 106 thousand m^3 (Table 1).

As pointed out by department staff from the lower camp located near the debris flow, the noise and crashing during the night of 10–11 June 1972 continued for 2–3 h. Consequently, the maximum duration of the debris flow was not more than 3 h. One should also take into account that during this time the debris flow did not move as a continuous flow but formed in discrete portions with intervals of some calm.

Table 1

Part of initiation zone	Average slope	Vol. of soil 1000 m^3
Upper erosion-landslide part (I)	30°	4.3
Upper erosion part (II)	17°40'	8.7
Middle part (III)	23°	7.0
Lower erosion-landslide part (IV)	19°	30.0
Lower erosion part (V)	13°40'	50.0
Entire initiation zone	17°10'	106.0

Let us evaluate the mean discharge of the debris flow over the entire period of its movement. For the location at the mouth of the initiation zone

$$\bar{Q}_d = \frac{W_{soil} + W_{water}}{\tau}$$

When τ = 3 h and when Q_{water} = 1 m^3/s $\bar{Q}_d$ - 10 m^3/s; for τ = 2 h $\bar{Q}_d$ = 18.4 m^3/s.

These figures show the lower limit of $\bar{Q}_d$ for a given interval of time because within this interval, as noted above, the flow occurred in separate portions with periods of calm between them. Naturally, comparisons of the discharge of the debris flow with that of the water stream flowing into the initiation zone convince us that at least the greater part of the debris flow was formed by the landslide and not by the gradual saturation of the flowing water with solid material.

According to previous investigations the density of moraine soils in natural stratification amounts to 2260 kg/m^3 with a moisture content of 1.86%, and the density of absolutely dry soil is 2220 kg/m^3, then the porosity of such soil with a density of rock material of 2700 kg/m^3 will come to 18%. Consequently, each cubic meter of completely water-logged soil could contain 180 liters of water, and its density in this case amounted to: 2220 kg/m^3 + 180 kg/m^3 = 2400 kg/m^3. Taking into account that the flow could undergo some degree of aeration and that part of the water could flow out as a result of the dilution of the soil, one can reckon with confidence that the density of the debris-flow mass (not the advance and residual floods) amounted to more than 2000 kg/m^3.

Many investigators of debris flows have noted that very often a debris flow is preceded and terminated by a large alluvium-transporting water flood of short duration, and this was also noted by the authors during the debris flow of 11 June. Formation of the advance alluvium-transporting water flood is evidently due to the partial release of free water during the dilution of the water-saturated soil. In addition, the velocity of the main debris-flow mass is somewhat greater than the velocity of the advance flood (otherwise it would rapidly spread out), and hence the debris-flow mass acts as a bulldozer pushing the

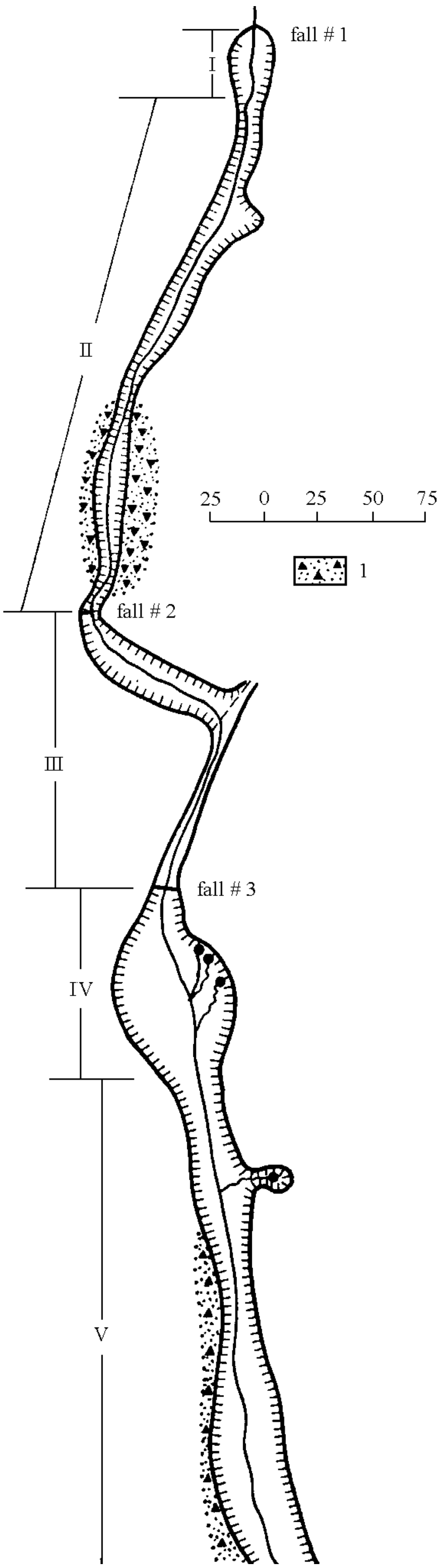


Fig. 1. Plan view of the initiation zone*1* - debris-flow deposits.

water surge before it. The residual flood forms from liquid component partially flowing out of the body of the stopped debris flow and from normal water runoff.

Views on many of the observed phenomena are the subject of considerable discussion among debris-flow investigators. The authors' observations of the flow under discussion make it possible to fairly confidently come to conclusions about some aspects of the formation and movement of debris flows.

1. Under certain geological, geomorphological and hydrometeorological conditions debris flows can occur as a result of the shearing, structural breakup and dilution of water-logged soils, that is, a landslide transforms into a debris flow. In this case there does not have to be an abrupt increase in the discharges of the water flow in the thalweg.

2. The action of the water flow on rocks beneath the channel bed causing part of the ground mass to slide may be divided into two successive phases:

   a) saturation of all or a significant part of the soil pores by water (a comparatively slow and long process);

   b) dynamic action on the soil causing the breakup of its structure and its dilution, resulting in the landslide process.

3. The formation of new initiation zones as a result of the sliding of a portion of moraine soil is altogether feasible and does not require a large quantity of water in the channel (that is, in a volume commensurate with the quantity of soil carried away).

4. The formation of debris flows is also possible in soils containing clay-silt particles within 1% of the weight of the entire solid component.

5. The density of the debris-flow mass of the debris flow formed in this case is close to the density of the debris flow-forming soil and, as a rule, exceeds 2000 kg/m^3.

6. Advance and residual floods can form when part of the water component is set free upon the dilution of the soil, when liquid mud runs off from the body of the stopped flow and when, under certain conditions, the velocity of the debris flow is greater than that of the water flow.

Determining the age of debris-flow deposits in the Chemolgan river basin by the dendrochronological method*

R. I. Belogrivtseva

Old debris-flow deposits of varied age have been well-preserved to the present day in the transition channel of the main Chemolgan initiation zone in the form of several terraces of varied height. To give a more complete picture of the morphological interrelationships of the terraces a composite schematic geomorphological cross section of the transition section is presented in Fig. 1*b*. Turkestan juniper (Juniperus Turkestanica) densely covering the surface of the debris-flow terraces served as the subject for analysis. The field material was collected in August 1972.

The age of the debris-flow terraces was determined by relating scarrings on the juniper trunks to their annual rings and by the age of the oldest species [2, 3, 5, 8, 11, 12]. In all 146 cuts from 13 trees were analyzed. On various cuts a different number of annual rings after the same scarring was observed. This is owing to the different growing conditions of the buried part of the tree and that on the surface. Moreover, in juniper as in other trees it is sometimes found that several rings form in the course of a year [4, 7]. A reduction of or forming of annual rings over less than the entire circumference of the trunk most often occurs under unfavorable growth conditions [1, 6]. This was very clearly manifest in cuts from tree No 2, buried under debris-flow deposits to a depth of 1.1 m. A branch of this tree with scarring had 51 rings in cuts taken above the earth's surface and 46, below. At the same time the thickness of the annual rings decreased significantly. For the reasons described above the accuracy with which the dates of debris-flow events were determined varied within ± 1-3 years.

The age of trees taken for analysis varied from 30 to 268 years (Table 1, Fig. 1*a*).

Most trees were exposed more than once to the effects of debris flows. As reliable dates of debris-flow events we took dates verified by analysis of several trees and cuts.

The oldest debris flow fixed by our investigations dates from 1746 (Table 2). Debris-flow deposits of approximately the same age are recorded in Chertovoye Canyon on the basis of data from lichenometry. The reliability of this date is confirmed by trees No 7 and 8 which grew in the deposits of this debris flow in the course of 10 years after it occurred (Table 1, Fig. 1). Observed here is a buried soil-vegetative layer ranging in thickness from 10–17 to 19–21 cm. In thickness and color this layer is identical to one on the nearby slope, whereas the debris-flow deposits are covered by a lighter-colored soil-vegetative layer 3–10 cm in thickness (Fig. 1*b*). In addition, according to the account of shepherd Dzhayakatay Sopakov, his grandfather in 1902, in connection with a debris flow that had just occurred along the Aksay River, told about flooding which had taken place at the Uzun-Kargaly River 160 years previously. In his words, floods had passed at that time along all rivers of the northern slope of the Zailiysky Alatau. Among the local inhabitants of the town of Talgar legends have been preserved of a debris flow that they attribute to the middle of the XVIII century [9].

In 1970 the Department of Debris Flows of KazNIGMI [Kazakh Institute of Hydrometerorological Research] jointly with the Problem Laboratory of Snow Avalanches and Debris Flows of Moscow State University established by the lichenometric method that simultaneously with the debris-flow events in the Chemolgan River in 1834, 1858, 1864, 1872 and 1878 debris flows occurred in the basins of the Malaya Almatinka and Bol'shaya Almatinka. The debris flows of 1887, 1902, 1921, 1931, 1941 and 1947 were recorded and verified by lichenometry in the basins of the Malaya Almatinka, Aksay, Issyk and Talgar

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 53–59.

Rivers [9, 10]. The remaining debris flows (Table 2) apparently were small. The coincidence of debris flows in several river basins of the Zailiysky Alatau indirectly points to their cloudburst genesis.

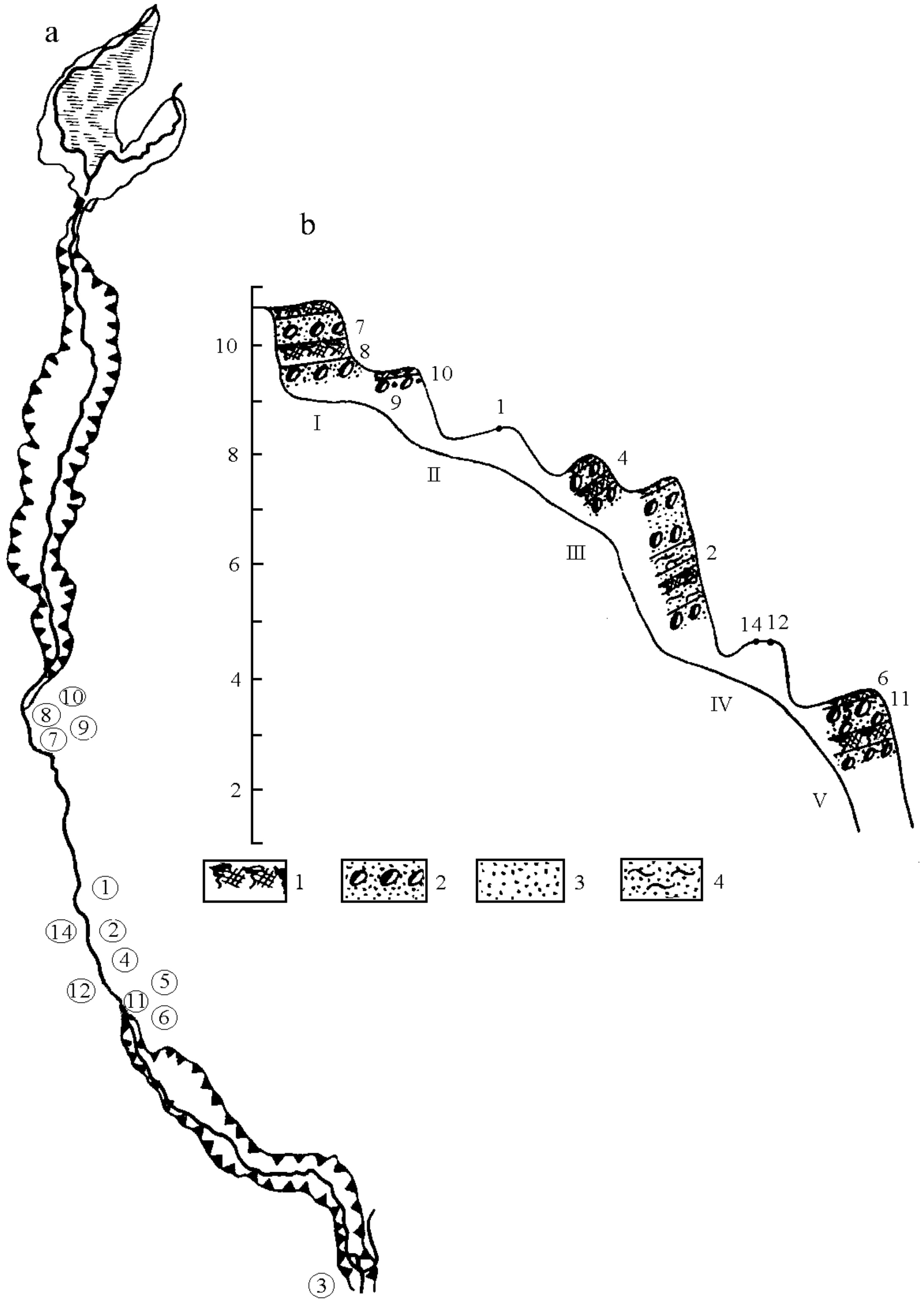


Fig. 1. Diagram of places where dendrochronological material was collected in the upper reaches of the Chemolgan River in 1972 (*a*) and a composite schematic lithological-geomorphological cross section of debris-flow terraces in a section of the transition channel of the Chemologan River (*b*): *I-V* - numbers of the debris-flow terraces; *1* - turf cover; *2* - boulders with sand; *3* - sand; *4* - clayey sand.

Table 1

Tree No	Tree age, years	Tree No	Tree age, years
1	268	8	217
2	132	9	121
4	76	10	60
5	44	11	30
6	33	12	36
7	190–220	14	251

Table 2

Sequence No	Quantity		Year of debris-flow occurrence	Length of period between debris flows, years
	Trees with scarring, number	Annual rings after scarrings, years		
1	1	226±3	1746±3	–
2	3	167±3	1805±3	59
3	5	138±3	1834±3	29
4	4	114±3	1858±3	24
5	3	108+1	1864±1	6
6	3	100-2	1872±2	8
7	3	94±3	1878±3	6
8	4	85±2	1887±2	9
9	3	76-1	1896+1	9
10	4	70±3	1902±3	6
11	6	51-3	1921+3	19
12	5	41±3	1931±3	10
13	3	31±3	1941±3	10
14	3	25-2	1947+2	6

Moreover, the fact that there was very little glacier development in the Chemolgan River basin practically rules out the formation here of glacial debris flows.

Deposits of the debris flows of 1805, 1834, 1858, 1864, 1872, 1878 and 1896 in the Chemolgan River basin were not found; only scarrings on trees that had existed in those times were preserved (Table 2).

However, debris-flow mass was found on the grown-over scarring dating the debris flow of 1872 inside the trunk of tree No 2 (Fig. 2).

Of the 14 debris flows the largest were those of 1746, 1872 and 1921, as indicated by the character of the scarrings on the tree trunks and the hypsometric location of the debris-flow terraces (Fig. 1). The largest debris flow was in 1921. Trees with scarrings datable to 1921 are located at the highest elevations, and the debris-flow deposits are superimposed on all previous ones. For example, at the outlet of the initiation zone deposits of the 1921 debris flow partially cover the deposits of the 1746 debris flow, covering trees No 8, 9 and 10 to a depth of 10–40 cm (Fig. 1*b*), and in the transition zone deposits of the 1921 debris flow cover the deposits of the 1746 debris flow to a depth of 1.1 m. The debris-flow deposits of 1921 are separate from an underlying 5–6 cm-thick humus layer, and on their surface the thickness of the latter measures 1–3 cm (1.7 cm on average). Consequently, the accumulation rate of of the humus layer under these climatic conditions amounts to 17 mm: 51 years = 0.33 mm/year. Then a 5–6 cm-thick layer can accumulate in 160–180 years. Consequently, the underlying debris-flow

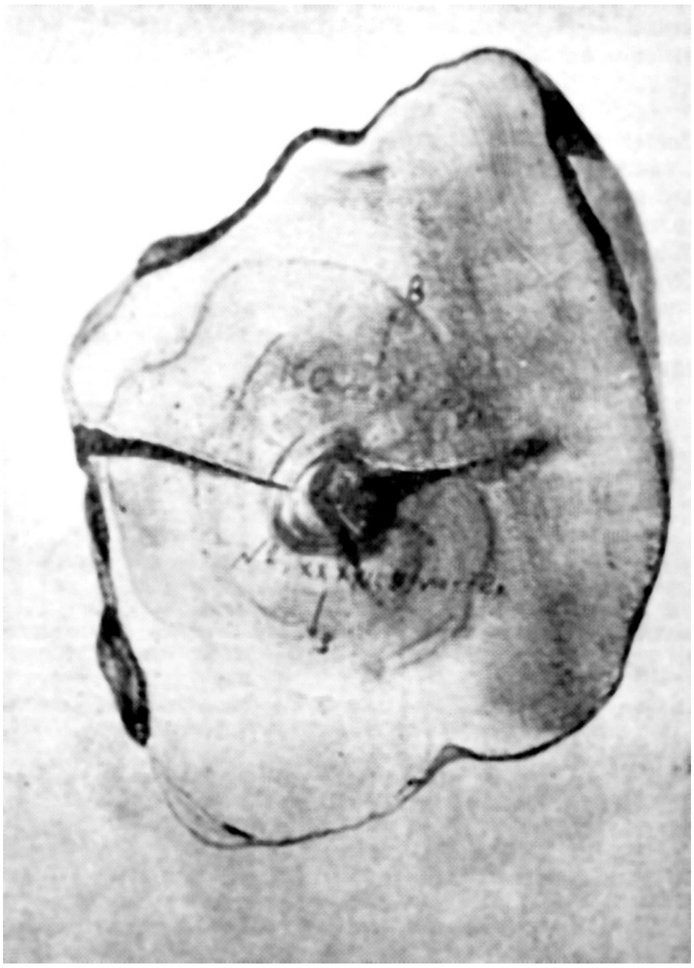


Fig. 2. Sawing from tree No 2. Seen inside is the 1872 scarring with intergrown sand. Wood from the scarring side had begun to decay.

deposits could have formed in 1740–1760. This fact indirectly verifies the date of the 1746 debris-flow event.

Thus, the maximum period between debris flow events over the last 230 years comes to 59 years and the minimum, 6 years. Debris-flow activity in the Chemolgan River basin accelerated substantialy beginning in 1858. This may be explained simply by the lack of more reliable data on debris-flow events in the XVIII-XIX centuries. The traces of the earlier debris flows could have been obliterated by larger debris flows of the later period.

If one examines the series of debris flows from 1858 and later, one may note that debris flows of varied magnitude formed every 6–9 years in the Chemolgan basin. It is also possible that debris flows occurred in the interval between 1902 and 1921, because in 1911 there was an enormous earthquake which must have been accompanied by debris flows.

The attenuation of debris-flow activity over the last 27-30 years can be explained by the "aging" of the initiation zone, the decrease in longitudinal slopes, and change in climatic conditions toward a decrease in the frequency of precipitation, in its intensity and in the magnitude of the precipitation layer per 1 rainfall, etc.

REFERENCES

1. Bitvinskas, T. T. On some questions concerning synchronization (verification) in dendroclimatochronological investigations and on the principles of classifying and selecting dendrochronological material. In the collection of papers: *Dendroclimatochronology and Radiocarbon Dating (Proceedings of the Second All-Union Conference on Dendrochronology and Dendroclimatology).* Kaunas (1972) pp 148–158.
2. Gorchakovskiy, P. L., Shiyatov, S. G. Phytoindicators of snow cover and snow avalanches in high-mountain regions. *Ekologiya* (1971) No 1 pp 22–35.
3. Gorchakovskiy, P. L., Shiyatov, S. G. Photoindicators of the dynamics of mountain glaciers and the ecological regimes of territory adjacent to glaciers. *Ecologiya* (1971) No 6 pp 19–27.
4. Gurskiy, A. V., Kanevskaya, I. B., Ostapovich, L. F. Principal results of the introduction of plants in the Pamir Botanical Garden. I Wild beds of Juniper trees. *Proceedings of the Academy of Sciences of the Tadzhik SSR* (1953) Vol XVI pp 68–78.
5. Lekhatinov, A. A. The dendrological method of establishing the time and periodicity of debris-flow events *Moscow University News, Geographical Series* (1967) No 2 pp 140–142.
6. Lobzhanidze, E. D. The effect of ecological conditions on the formation of annual tree rings. *Proceedings of the All-Union Meeting – Scientific Conference on Problems of Dendrochronology and Dendroclimatology.* Vilnyus (1968) pp 94–97.
7. Lobzhanidze, E. D. The effect of climatic factors on the formation of false annual tree rings in the Transcaucasus. In the collection: *Dendrochronology and radiocarbon dating (Proceedings of the Second All-Union Conference on Dendrochronology and Dendroclimatology).* Kaunas (1972) pp 62–65.
8. Perov, V. F. *Experience with the Use of the Dendrochronological Method of Analyzing Debris flows in the Khibini. Phytoindicator Methods in Glaciology.* Moscow: Publisher MSU (1971) pp 42–49.
9. Svyatskiy, D. O. On debris flows in the Malaya and Bol'shaya Almatinka Rivers in connection with the water-bearing regime of these rivers. *Papers of the Kazakhstan Directorate of the Unified Hydrometeorological Service* (1935-1936) Vol I pp 57–80.
10. *Debris flows in the USSR and Measures to Defend Against Them.* Moscow: Nauka pp 269–272.
11. Turmanina, V.I. Tree indicators of slope processes. *Priroda* (1968) No 6 pp 83–85.
12. Turmanina, V. I. Use of some morphological-anatomical features of trees for indicating slope processes. In the book: *Theoretical Problems of Phytoindication.* Leningrad Nauka (1971) pp 151–154.

The third experiment on the artificial replication of a debris flow*

R. V. Khonin, V. A. Keremkulov and V. P. Mochalov

For the purpose of further refining the methodology of computing debris flows staff of the Department of Debris Flows of KazNIGMI [Kazakh Institute for Hydrometeorological Research] in 1975 conducted a third experiment on the artificial replication of a high-density debris flow. The following tasks were formulated for conducting the experiment: optimize the techniques and equipment for determining debris-flow density by contactless means (magnetometric, radar, inclinometric) and the rate of motion of characteristic elements of the debris-flow body (the"head" and individual waves) by seismic means; measure the rate of motion of the wave front (the "head") of the debris flow; determine the technical requirements for stereophoto apparatus intended for analyzing the dynamic characteristics of debris flows and perform trial photography; develop rational techniques for protecting against debris flows. The process by which debris flows form and move was recorded by six motion-picture cameras with 35-mm negative color film set up at various locations in the site.

Preparation of the debris-flow site included the following: geodetic surveying, preparing the dam outlet works and filling the reservoir to ensure a release with a peak discharge of up to 30 m^3/s, setting up contactless debris-flow measuring apparatus, and organizing observation points.

The 1975 experiment was begun on 19 August at 12:55 when the level of the reservoir reached 366 cm, corresponding to a volume of stored water of 60 thousand m^3. In the course of two releases the reservoir level fell by 43 cm, corresponding to a dump of 15.03 thousand m^3 of water. The duration of the releases with account taken of the time intervals between them amounted to 62 min 45 s. Each release with water outlets fully open lasted 5 min. More than 2.5 min were required to fully open the three gates. During the second release water was dumped through two outlets.

The lowering of the water level in the reservoir was observed by depth gages at two points–in the portal part of the dam outlet works and at the damping sink of the water-level recorder "Valday" No 2. Water level readings were taken from these gages every minute.

A hydrograph of the releases was computed on the basis of observational data on the water level in the reservoir with the aid of hydraulic formulae making it possible to define the output capacity of the spillway openings, and also on the basis of the reduction in reservoir level and a curve of water volumes as a function of level.

The peak discharge of the first release in 1975, computed from the hydraulic formulae on runoff of water through the spillway, was 27.5 m^3/s and the second release, 15.2 m^3/s. The change in water level and the hydrograph of releases are shown in Fig. 1.

The principal characteristics of the debris flow were measured at the "control cross section" measuring site located in the torrent channel at the boundary with the lower gully at a distance of 1.6 km from the dam. In the section of this site the channel exposes bedrock that creates a fairly stable profile of the site. The slight deformation of the latter is associated with the fracturing of intrusive rock which promotes their corrosion during the movement of the debris flow. Height of the debris-flow measurement site above sea level was 2493 m, and the slope on the preceding 100-meter section was 0.20. The angle of incidence of the radar beam measuring the level and surface velocity of the debris flow was 36°30. Set up in the vicinity of the site in addition to a two-frequency Doppler meter were a seismic flowmeter with four seismic receivers dispersed at various points and devices for contactless measurement of debris-flow density. In order to determine the flow geometry in the vicinity of the

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1977) No. 2, pp 57–63.

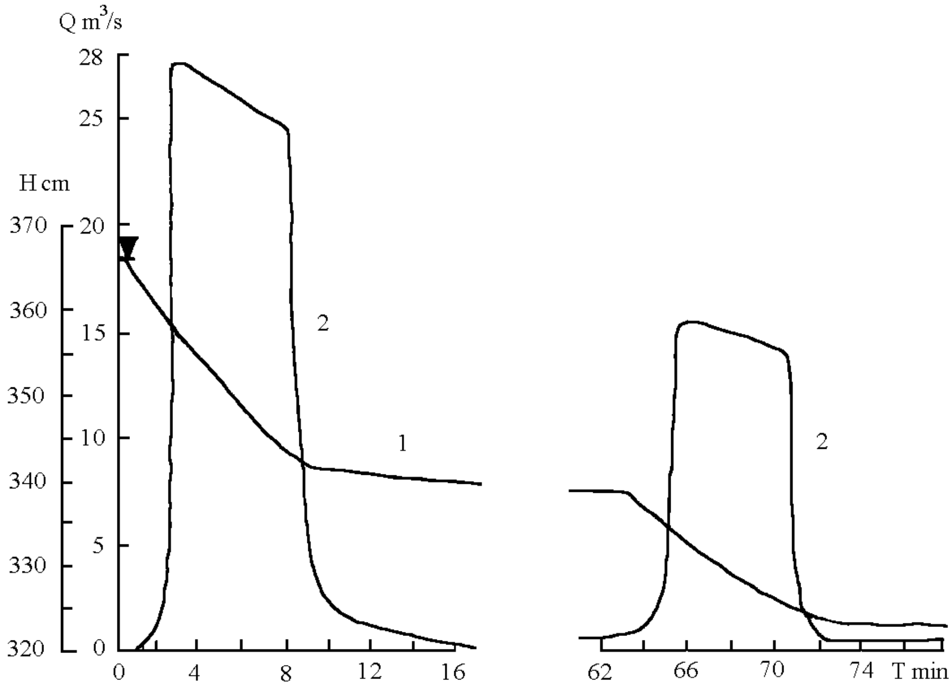


Fig. 1. Change in water level (*1*) and hydrograph of water releases from the reservoir (*2*).

measurement site, at places with outcroppings of bedrock we took levels of five cross-sectional profiles associated with the longitudinal profile.

As in the second experiment, the discharge of the debris flow was measured by converting the seismic signals created by the debris flow during its movement into electrical signals, registering them on a multichannel recorder and then interpreting them. The peak discharge attained during the first release was 430 m^3/s and during the second release, 320 m^3/s. The considerable magnitude of the peak discharge of the debris flow induced by the second water release (the magnitude of the latter was almost two times less than the first release) may be attributed to the rupturing of the structural bonds in the soil of the potential debris-flow mass (PDFM) of the initiation zone as a result of vibration occurring during the formation of the first debris flow. Peak debris-flow depth during the first release, as determined from the recording of change in level by the Doppler meter, amounted to 6.5 m and during the second release, 5.5 m.

In the 1975 experiment the density of the debris flow was measured by three means: magnetometric, radar and inclinometric. Fig. 2 gives the results of density measurements (kg/m^3) by magnetometric means. This same figure gives a hydrograph of the debris flow. The plot shows relative time, and the time at which the water outlets in the dam are opened is taken for the start of computation.

The methodology for measuring the density of the debris flow and interpretation of data are thoroughly described in [2]. The velocity of discontinuities in the body of the debris flow is measured by comparative analysis of data from seismic observations at the locations of seismic receivers No 2 and 4 and at sites separated from each other by a distance of 174 m. In spite of some deformation of the debris-flow body taking place during its movement down the stabilized channel, the results of seismic observations make it possible to identify a number of the most characteristic discontinuities (the "heads" and individual waves) of the debris flow. If one knows the distance between the sites and the time at which the debris-flow waves arrive at them, one can determine their velocity. The results of this analysis are given in Table 1.

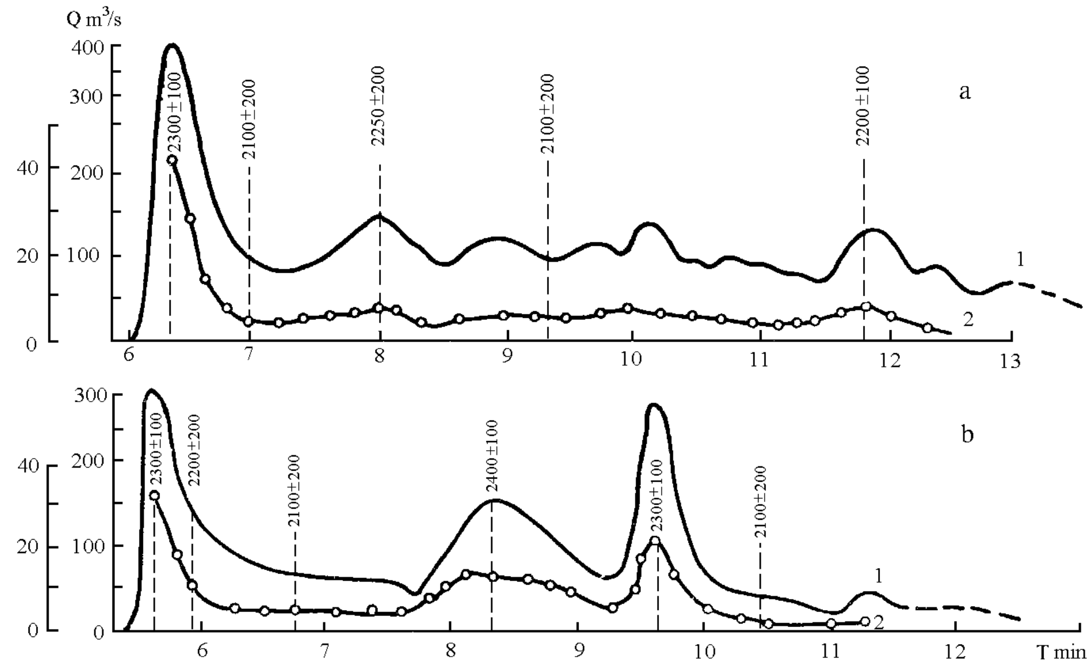


Fig. 2. Hydrograph of debris flow (*1*), change in magnetic field intensity with time (gamma) (*2*):
a - first discharge, *b* - second discharge.

In the torrent gully the velocity of the frontal part of the debris flow (the "head") was measured from two observation points; the measurements of the observers were duplicated by motion-picture filming. The time of movement of the debris-flow head between individual points (tagged boulders) with a known distance between them was determined by the number of photo frames counted automatically in a frame projector. The data of the observers proved to be inadequately precise because it was difficult to determine the moment at which the flow touched a tagged boulder and aspect distortions had a substantial effect on the conditions of observation. The diameter of the marked boulders on average measured 3–5 m. Table 2 presents the principal data used in computation of the velocity of the wave front.

Table 1
Computation of the velocity of debris-flow waves

Characteristic maximums	Time of wave's run from upper to lower site	Velocity of wave, m/s	Flow level at "control cross section" site, m
"Head" of flow	17.7	9.8	6.5
1st wave	27.2	6.4	2.5
2nd wave	27.6	6.3	2.5
3rd wave	28.7	6.1	2.6
"Head" of wave in second release	21.7	8.0	5.5

The mean velocity of the debris-flow head during the first release in a section 612 m long was 5.3 m/s. In some sections the velocity of the head fell to 2.9 m/s and rose to 10.0 m/s. These fluctuations in the velocity of the leading wave of the debris flow were not associated with changes in the longitudinal slope of the PDFM of the gully (Table 2). Most likely they were caused by the morphological features of the

PDFM structure and of the secondary gully enclosed in it that was formed by debris flows during the experiments of 1972–1973. They probably had an effect on the velocity of the debris-flow head through the intensity of the erosion-shear process and in some sections through changes in the physio-mechanical properties of the debris flow-forming soils.

Table 2
Computation of the velocity of the "head" of the debris flow during the first release

Serial No	Distance between marked points, m	Slope of section between points	Velocity of debris-flow "head," m/s
1	0.0	–	–
2	34.4	18°10'	4.9
3	25.0	19 20	4.5
4	25.6	17 45	4.1
5	36.8	14 20	5.2
6	25.8	17 00	3.9
7	39.0	20 30	4.8
8	51.0	17 50	4.6
9	45.0	13 45	6.4
10	56.0	17 20	5.3
11	35.2	17 20	2.9
12	87.0	14 40	10.0
13	44.0	18 25	7.6
14	107.0	13 00	5.2

The flow head slowed down significantly between the 5th and 6th points evidently because the flow split into two arms enveloping a kind of island composed of large boulders. A still greater deceleration of the front of the debris flow was observed between the 10th and 11th points, where the flow was enriched substantially by solid material. An increase in the quantity of boulders in the flow at this place was very visible in the motion-picture frames.

The mean velocity of the wave front of the debris flow which formed during the second release in a 490 m-long section between the surviving 5th and 14th points measured 4.5 m/s. The other marked boulders were swept away by the first debris flow. The head of the second debris flow was less steep and high and differed from the first by its smaller quantity of course debris. Within 2.5 min after the head passed a wave was observed in the second debris flow that was highly enriched with boulders. This wave was also recorded at the debris-flow measuring site (Fig. 2).

The velocity of the debris flow front was measured from a helicopter. The distance was computed from a topographic map, and time of movement was measured by stopwatch. The mean velocity of the debris-flow front in the channel below the measurement site (slopes of the order of 5–6°) in a section 4.8 km long was 4.0 m/s. Over the entire section under observation (23.3 km) with gradually diminishing slopes the mean velocity was on the order of 2.3 m/s.

The volumes of soil displaced by the debris flow as estimated with the aid of instruments are shown in Fig. 3.

As may be seen from plots characterizing the areas of the washouts and deposits in individual sections of the initiation zone and torrent channel, and of the integral rise (or decrease) in the volume of loose debris set in motion by the debris flow, in the 1975 experiment the maximum volume of soil passed through 72

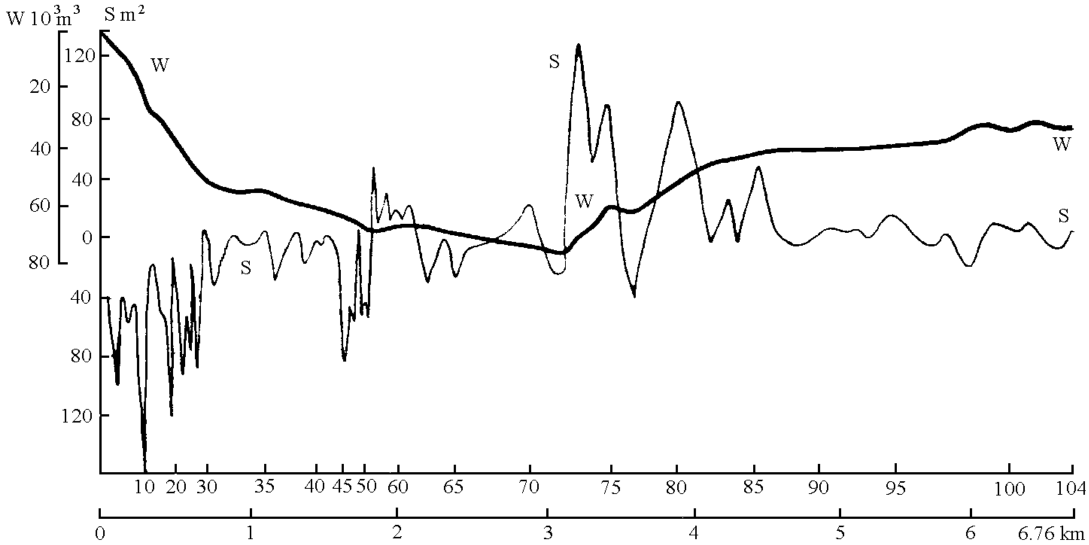


Fig. 3. Plot of areas of washout and deposits (*S*) and an integral curve of volumes of removed (*W*) solid material (loose).

cross-sectional profiles and equaled 79.8 thousand m^3. Through the "control cross section" measurement site passed 60.4 thousand m^3 of soil.

In 1975 as in the previous experiments considerable fluctuations were recorded in the movement of the PDFM of the main torrent gully (Fig. 3). The volume of entrained loose rock debris in the lower gully was greater than during the previous artificially triggered debris flows. In the lower part of this gully was a deposit of 3.2 thousand m^3, which was 6 times less than in the previous years. The latter can be attributed to an almost 4-fold increase in the peak discharge of the debris flow, although its total volume was less because the release times were shortened. Below the 68th cross-sectional profile the rise in debris flow volume was negligible and in the vicinity of the 72nd cross section its volume began to decrease. The short releases, despite the greater discharges, spread out more rapidly. The latter is a positive factor in the conduct of the experiments, for it makes them safe for economic facilities located 25 km below the experimental site.

An analysis of the traces of the artificially triggered debris flows showed that they are identical to the traces of naturally formed debris flows [1]. Visual observations and motion-picture film of the moment at which the debris-flow mass is deposited and geodetic surveys before and after the debris flow have not validated the fairly commonly held view regarding the formation and breaching of obstructions. The deposits accumulate fairly slowly and are not breached; they are only set in motion by the debris flow. When the debris-flow mass stops, from it flows suspended material consisting of fine earth, gravel and fine pebble, substantially inhibiting large boulders from being set in motion because the slopes of the channel where such an "obstruction" occurs are usually 2–3 times smaller than the longitudinal slopes of the torrent gully. Investigation of the transformation of the debris flow in the channel of the Chemolgan site considerably facilitated the "deciphering" of the traces of the debris flows in the Malaya Almatinka (1973) and Kumbelsu (1975).

At the present time when debris-flow measurement apparatus is only being developed, breadboard models of instruments are being tested and theoretical models of high-density debris flows are being developed for the first time, it is practically impossible to obtain sufficiently reliable characteristics of naturally formed mudflows and debris flows. Hence, we can reliably measure the principal parameters only of artificially triggered debris flows passing through preprepared measurement sites.

REFERENCES

1. Vardugin, V. N. The granulometric composition of loose debris in initiation zones (in this collection).
2. Stepanova, T. S. Some techniques for contactless measurement of the density of debris flows (in this collection).

Results of an experiment on the artificial replication of a debris flow in the Chemolgan river basin in 1976*

T. S. Stepanova, R. V. Khonin, N. I. Krzhechkovskaya and A. Kh. Khaydarov

This paper represents a summary of the results obtained during the experiment, including, however, some elements of an incomplete analysis of these results.

The program for the experiment on the artificial replication of a debris flow at the Chemolgan site in 1976 sought to do the following: further refine the methodology and techniques for determining debris-flow density by the magnetometric method, test breadboard models of debris-flow hazard warning devices, measure flow characteristics, verify the potential of high-speed motion picture filming, and further improve stereophotographic equipment and the methodology of deciphering stereo photos with the aim of defining the geometric characteristics of the flows and surface roughness.

Preparation for the experiment included work on restoring the dam gates and filling the reservoir, marking off cross sections, and selecting and equipping the debris-flow measuring site. By the beginning of the experiment the reservoir was filled to a level of 188 cm, which corresponds to a volume of stored water of 13.2 thousand m^3 (from a plot of reservoir volume as a function of level [7]). Contactless measuring apparatus was set up in a new monitoring site located 170 m above the old one. Marked off and their levels taken were six cross-sectional profiles, the third one of which was used as a new debris-flow measuring site. Within the marked-off cross sections the channel runs in a fairly straight line in bedrock, with a 0.14 grade on the bottom of the above-lying section. Here above the section to be measured the transducers of quantum magnetometers were suspended on cables, and Doppler devices for measuring the level and velocity of the debris flow were set up along with a high-speed 35-millimeter movie camera and a specially designed and fabricated stereo-photo camera (both looking down on the flow). As before, seismic apparatus was employed for measuring the debris-flow discharge, and its transducers were set out on the bank of the valley. Made ready in the field laboratory were quantum magnetometers (main and reserve) for recording in plot and digital form the magnetic field anomaly, amplifiers and recorders of the seismic receivers, debris-flow hazard warning device, recorders, power supply units and other auxiliary apparatus.

The debris-flow experiment of 1976 was distinguished by the small discharge of the water release (Fig. 1) and, accordingly, also of the debris flow: $Q_{w.max} = 5\frac{m^3}{s}, Q_{d,max} = 45\ m^3/s$.
The results of measuring the debris flow characteristics are illustrated with the aid of plots (Figs. 2-5). Depicted in Fig. 2 are curves of the discharge: solid line—computed from data on level and velocity and broken line—the curve of the discharge as recorded by seismic instrumentation. It is of interest to note that while the debris-flow hydrographs roughly coincide in the initial section (up to 120 sec) they are subsequently observed to sharply diverge. This situation is attributed to the fact that when the discharge of the debris flow decreased the debris-flow mass partially halted in the area of the monitoring cross section, causing a change in the level of the channel bottom. The plots show relative time with the time of arrival of the debris-flow head at cross section 2 taken as the start of the count.

A recording of the variation in level and velocity is presented in Fig. 3, from which one sees that the maximum values for level and surface velocity were: H_{max}= 1.5 m, V_{max} = 4.5 m/s.

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1978) No. 3, pp 86–92.

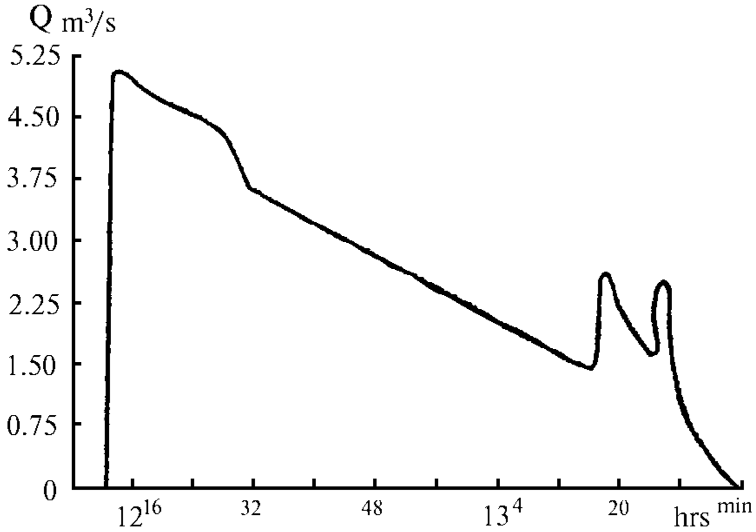


Fig. 1. Hydrograph of release of water from the reservoir in 1976.

As we know [7], data on density using the magnetometric measuring technique are obtained by interpreting the anomaly in the magnetic field *Z* (Fig. 4). Values for the geometric characteristics are found by deciphering stereophotos of the flow. The mean value for the magnetic susceptibility of the potential debris-flow mass $\bar{\chi}_T$ is determined statistically on the basis of massive measurements of the magnitude of χ in samples of rock in the debris-flow initiation zone ($\bar{\chi}_T$= 600 units). The obtained values for the density of the debris-flow mass are shown as dots in Fig. 4.

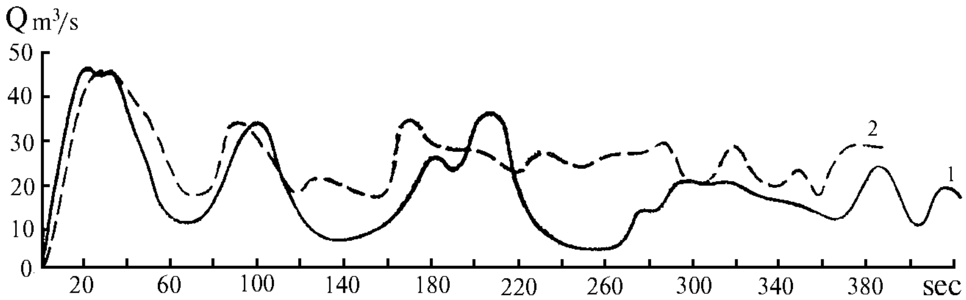


Fig. 2. Debris-flow hydrograph observed at the monitoring site:
1 - computed, *2* – measured.

From the data presented one sees that the density of the debris flow, in spite of the small scale of the debris-flow process, was distinguished by its fairly high values (γ_d= 2000–2400 kg/m^3). By comparing similar data from previous experiments (1972, 1973, 1975), one can note how stable the density characteristic is for one type of debris flow, which justifies its use as a classification criterion [4].

The experiment again verified that in initiation zones of the gully type debris flows form as a result of discharges of water entering the initiation zone above the critical, and that for the Chemolgan torrent gully the latter is 3–5 m^3/s when the rocks in the PDFM have a natural moisture content.

Fig. 5 presents a plot of areas of washout and deposits according to data from levels taken of cross-sectional profiles and an integral curve of volumes of washout and deposits.

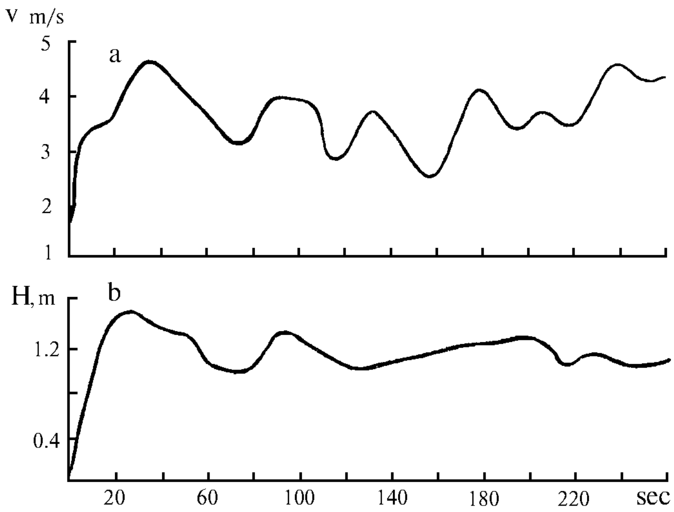


Fig. 3. Plot of the variation in debris-flow level (*b*) and surface velocity (*a*) measured at the monitoring cross section.

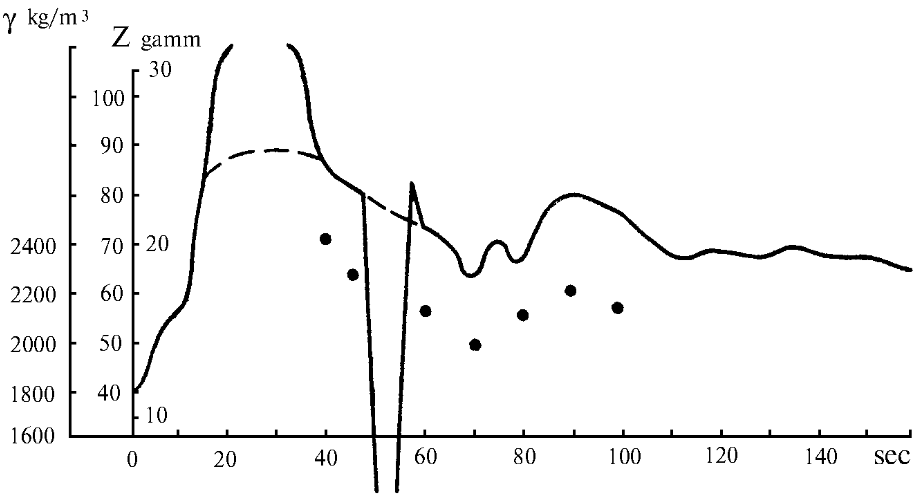


Fig. 4. Magnetic field anomaly induced by the debris flow, and values for density (shown as dots) obtained by interpretation.

After completion of the experiment and levels of the cross-sectional profiles were again taken, the locations of which are shown in [7], it was found that the volume of debris mass formed in the upper part of the PDFM of the torrent gully until cross-sectional profile 15 was almost the same as that which had traveled beyond the boundaries of the initiation zone below profile 33 (12.5 and 12.7 thousand m^3, respectively). There was a general increase in the volume of debris flow in the torrent channel until cross-sectional profile 28, where the volume of transported loose rock debris attained 15.2 thousand m^3. Below this profile occurred a substantial deposition of debris-flow mass (2.5 thousand m^3).

A minimal volume of debris flow passed through cross-sectional profile 54—8.3 thousand m^3, after which a significant increase in debris-flow mass was observed (Table 1).

Unlike in the previous experiments, in the region of a bend in the lower gully (cross sections 57–62) loose rock debris was intensively entrained by the debris flow (Fig. 5). Thus, 15.0 thousand m^3 of debris-flow mass passed through cross-sectional profile 63. Below cross section 64 the intensity with which loose rock debris was mobilized diminished somewhat. In the section between profiles 65 and 67 debris flow deposits predominated. Beginning with cross section 69 the entrainment of loose rock debris into the flow was observed everywhere. Though cross section 84 passed 34.4 thousand m^3 of debris-flow mass. In the sections between cross-sectional profiles 84–87 and 88–91 debris-flow deposits predominated. Below profile 91 there was mainly washout of loose-detrital material. Through the last, profile 104, passed 38.3 thousand m^3 of debris-flow mass, which was deposited beyond the boundaries of the experimental site.

The artificially triggered debris flow of 1976 differed considerably from the debris flows of previous years [2, 6]. While the greater debris flows of 1972–1973 and particularly 1975 for the most part increased their volume in the torrent gully, the debris flow of 1976 carried off only 33.2% of its volume from the initiation zone. Only 21.4% of the total volume of the debris flow moving in the area of profile 104 passed through cross-sectional profile 54.

As has already been stated, the range of problems to be solved by the experiment was not confined to measuring the characteristics of the debris flow. An important aspect of the program was the testing of breadboard models of measuring instrumentation. The use of the quantum magnetometer (in comparison with the proton device in 1975) made it possible to lower the sensitivity threshold and raise the accuracy of anomalous magnetic field measurements, which is particularly important when observing a small debris flow and when the value for the mean magnetic susceptibility of the PDFM is low. The results of tests of the seismic system for warning of debris-flow hazard are set forth in [3]. The potential of high-speed motion picture filming was the subject of [1]. As far as stereophotography is concerned, it still needs some dedicated research.

Table 1

Integral sum of volumes of washout and deposits

No of cross-sec. profile	Distance from dam to cross-sectional profile, km	Volume of earth passing through site of cross section, 1000 m^3	% of total volume of solid component of debris flow
15	0.41	12.5	32.6
32	0.80	12.7	33.2
40	1.46	11.0	28.7
47	1.70	10.8	28.2
54	1.86	8.3	21.7
57	1.93	9.1	23.8
63	2.21	15.0	39.2
65	2.41	14.8	38.6
68	2.71	15.0	39.2
84	4.20	34.4	89.8
87	4.61	34.0	88.8
88	4.71	34.5	90.1
91	5.01	34.3	89.6
104	6.77	38.3	100.0

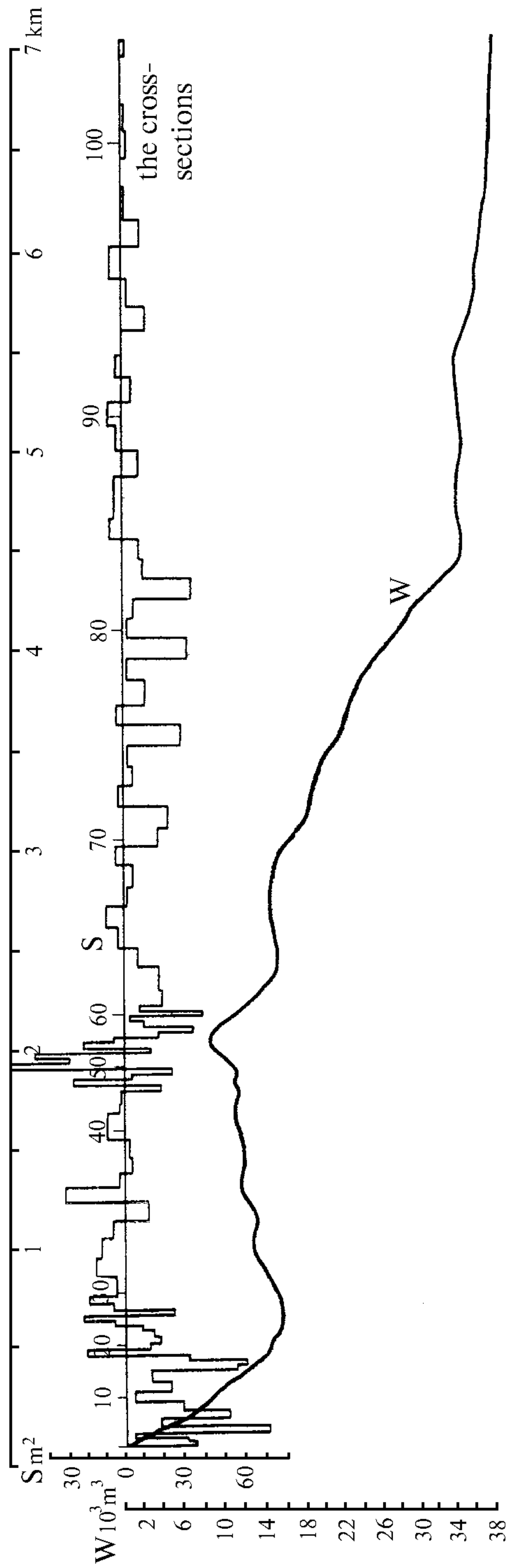


Fig. 5. Plot of areas *S* and an integral curve of volumes *W* of washout and sediment deposits.

REFERENCES

1. Gavrishina, L. N., Stepanova, T. S. Use of motion picture filming for studying the kinematics of debris flows. *Debris Flows* (1978) No 3 pp 96–101.
2. Zems, A. E., Khonin, R. V., Laptev, V. I. The solid/liquid balance in the debris flows of 1972–1973 in the Chemolgan River Basin. *Debris Flows* (1976) No 1 pp 35–43.
3. Kovalenko, P. I., Krasyukov, V. A., Novikov, M. Ya., Stepanov, B. S. Results of tests of a seismic system for warning of debris-flow hazard. *Debris Flows* (1978) No 3 pp 92–96.
4. *Handbook for the Study of Debris Flows.* Leningrad: Gidrometeoizdat (1976) 144 pp.
5. Stepanov, T. S. Some techniques for contactless measuring of debris-flow density. *Debris Flows* (1977) No 2 pp 67–78.
6. Khonin, R. V., Keremkulov, V. A., Mochalov, V. P. The third experiment on the artificial replication of a debris flow. *Debris Flows* (1977) No 2 pp 57–64.
7. Khonin, R. V., Mochalov, V. P., Zems, A. E. The experimental site in the Chemolgan River Basin and the history of its founding. *Debris Flows* (1976) No 1 pp 7–25.

Results of tests of a seismic system for warning of debris-flow hazard*

P. I. Kovalenko[1], V. A. Krasyukov[1], M. Ya. Novikov[1], and B. S. Stepanov[2]

[1]*Kazakh Geophysical Instruments Plant,* [2]*Kazakh Institute for Hydrometeorological Research*

The objective of tests of a transducer complex for warning of debris-flow hazard conducted in 1976 by the Special Design Bureau of the Kazakh Geophysical Instruments Plant was to determine the actual characteristics of the developed systems, define the signal-to-noise (interference) ratio and resolve issues associated with the optimal placement of the transducers.

The tests were conducted jointly with the Department of Debris Flows of the Kazakh Institute for Hydrometeorological Research at the Chemolgan experimental site during the artificial replication of a debris flow on 8 September 1976. It should be noted that thanks to the Chemolgan site with its unique capabilities it became feasible to test this apparatus under conditions maximally approximating reality.

The apparatus was set up in the area of a monitoring site equipped with contactless meters of debris-flow level, velocity and density and movie and photo cameras, which made it possible to objectively evaluate the operation of the warning system [1].

A simplified block diagram of the seismic warning system is presented in Fig. 1. The system incorporates seismic receivers 1 and 1'; band filters 2, 2'; amplifiers 3, 3'; detectors 4, 4'; filters of lower frequencies 5, 5'; comparator 6; control unit 7; light alarm 8 and multichannel recorder 9.

The seismic signals after being converted and amplified are fed to comparator 6 and recorder 9 (channels 1 and 2). When the system is activated by a debris-flow event, the control unit turns on the light alarm and commutates the signal with filter 5' on channel 3 of the recorder. Oscillograms of the converted seismic signals are presented in Fig. 2. One can readily see that the signal being generated by seismic receiver 1 considerably exceeds the signal of seismic receiver 1'; it should be noted here that the amplification coefficient of amplifier 3' exceeds the amplification coefficient of amplifier 3 by a factor of 3.

The surge-like character of the movement of the debris-flow mass, clearly displayed on the oscillogram (Fig. 2), makes it possible, through correlation with the recordings of other seismic receivers located higher and lower along the flow relative to the seismic receivers of the warning system, to compute the velocity of the surges with no more than 10% error.

During the tests considerable attention was given to elucidating the relation between signals generated by the debris flow and signals caused by other phenomena.

With the aim of obtaining diverse data during the conduct of the debris-flow experiment seven seismic transducers were set up on one leg of the channel (Fig. 3).

Transducers SP-3, SP-2 and SP-1 were for determining the velocity and discharge of the debris flow. Transducers SP-2 and SP-4 were part of the warning system while the remaining transducers were for analyzing the character of the distribution of the seismic waves being generated by the debris flow.

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1978) No. 3, pp 92–96.

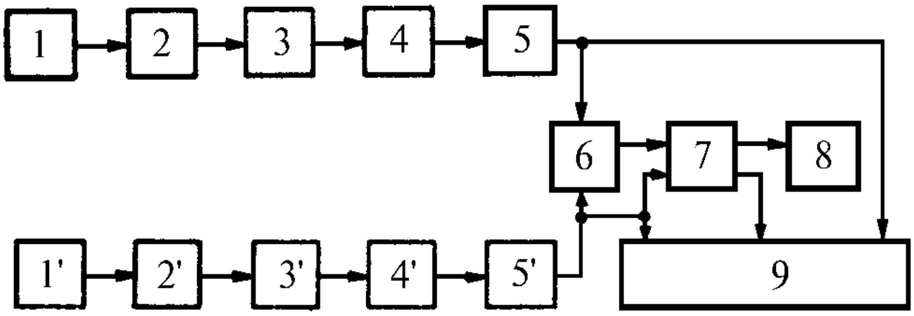


Fig. 1. Block diagram of seismic system for warning of debris-flow hazard.

Transducers SP-1, SP-2, SP-3 and SP-4 were installed in 0.3 x 0.3 x 0.35 m concrete wells in outcroppings of bedrock, and SP-6 and SP-7, in wells with the same dimensions in the sedimentary mantle covering the bedrock.

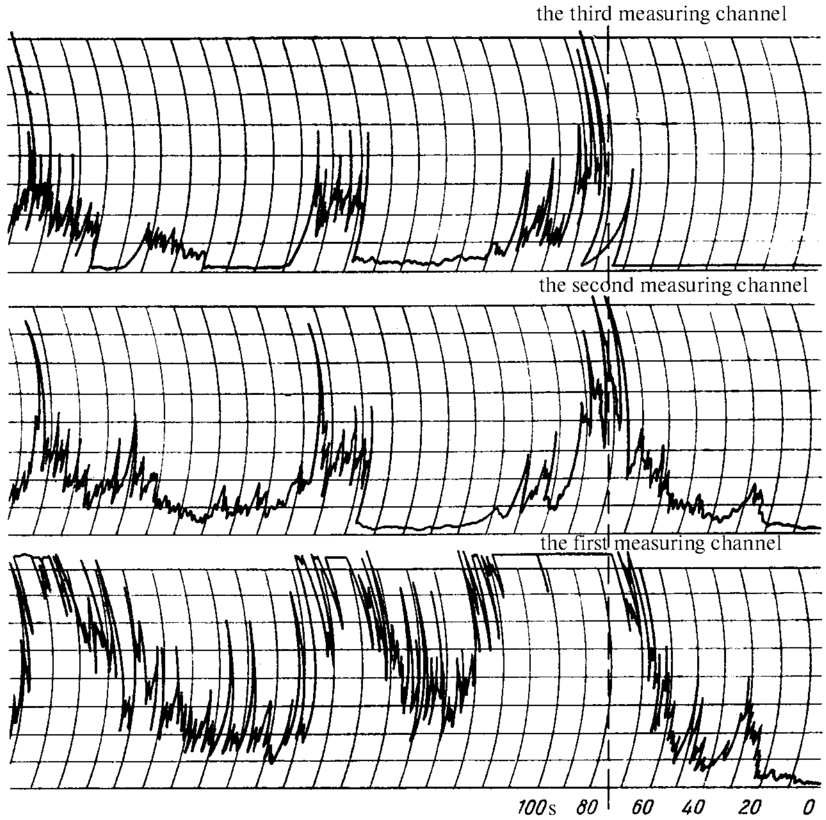


Fig. 2. Oscillograms of seismic signals produced by the debris flow.

As a result of the experiments it was found that the movement of a debris flow with a discharge of 45–50 m^3/s and density of 2300–2400 kg/m^3 generates seismic waves whose amplitude exceeds by a factor of 20–30 the amplitude of waves produced as a result of impacts on the bedrock by a sledge hammer weighing about 5 kg and by a factor of 4–5 by the impact of a rock weighing 25 kg (the impacts were produced in the torrent channel at a distance of about 20 m from the seismic receivers). A decrease in the distance between seismic receiver 1 and the place of noise generation causes a decline in the signal-noise ratio; however, if this distance is not less than 5 m, the seismic signals produced by very vigorous movements of animals and humans are an order of magnitude less than the signals generated under the described conditions by the debris flow.

The results obtained allow us to reach a number of conclusions.

The warning system being developed can be highly protected against interference when the seismic transducers incorporated in it are separated by a relatively short distance (tens of meters).

The seismic transducers of the system must be placed to the extent possible in identical geological conditions, preferably in outcroppings of bedrock.

The distance from the seismic receiver (Fig. 1) to the torrent channel must be of the same order of magnitude as the distance between seismic receivers 1 and 1'.

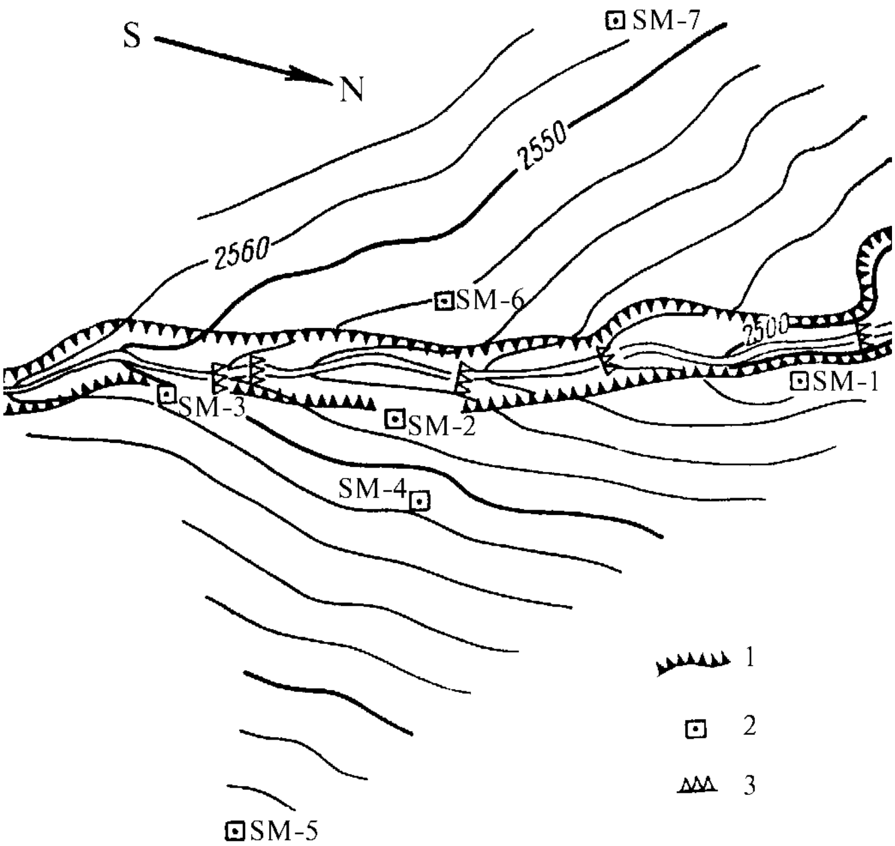


Fig. 3. Placement of seismic transducers of the warning system in the 1976 experiment: 1 - escarpment, 2 - seismic transducer, 3 - waterfall.

Accuracy in estimating the mean velocity of the debris flow by performing a correlation analysis of signals from the seismic transducers placed along the channel decreases markedly when there is both a short distance between them (the degree of averaging is low and velocity is close to instantaneous) and a large distance. The optimal distance, it seems evident, should be considered one that exceeds by a factor of 10–20 the length of a pronounced discontinuity in the debris flow (the head or surge), that is, approximately 50–100 m.

For the warning system to function reliably the following features of the seismic signals from transducers 1 and 1' must be taken into account:

a) signal spectral composition (selection of a portion of the spectrum);

b) absolute signal level (selection of a threshold for activating circuits);

c) correlation of the signal levels of transducers 1 and 1', selection of a relation between the transmission coefficients of amplifiers 3 and 3' (Fig. 1).

The experiment verified previously expressed assumptions, that the following should be considered optimal:

a) transmission band of filters 2 and 2' – 20–100 Hz;

b) input threshold for activating the system—1-10 mV (depending on the morphometry of the channel, the presence of initiation zones and other factors allowing one to predict the minimal discharge of the debris flow in a given channel, and also depending on the degree to which the seismic waves attenuate in the space between the channel and seismic transducer 1).

The experiment verified that the warning system also can be used for estimating debris-flow discharges through analysis of the seismograms.

The area in which the seismic transducers are set up must be protected from animals (cattle, wild animals) by some kind of fencing with a radius of $R \geq 5$ m. Moreover, the system can be activated by false seismic signals only when they are deliberately generated in the immediate vicinity of the seismic receiver, but a simple analysis of the signals at the control panel will allow one to suppress transmission of a hazard signal over the warning net.

REFERENCES

1. Stepanova, T. S., Khonin, R. V., Krzhechkovskaya, N. I., Khaydarov, A. Kh. Results of an experiment on the artificial replication of a debris flow in the Chemolgan River Basin in 1976. *Debris Flows* (1978) No 3 pp 86–92.

Chemolgan-78*

T. L. Kirenskaya, T. S. Stepanova & F. G. Balabayev

On 9 September 1978 a fifth experiment on the artificial replication of debris flows was conducted at the Chemolgan site. The purpose of the experiment was to investigate the mechanisms by which debris flows of high density form as a result of the interaction of water flow with loose detrital material (potential debris-flow mass) in the initiation zone (gully), validate debris-flow measuring apparatus, and perform production tests of a seismic debris-flow hazard warning system.

As always, before conducting the experiment we pooled and analyzed our accumulated knowledge of debris-flow phenomena, identified certain disparities between existing concepts and the objective properties of debris flows, advanced working hypotheses, planned the experiment and conducted preparatory work at the site.

As we have already pointed out, the subject of our investigation under the conditions of the Chemolgan basin was the natural erosion-shearing processes (and not their models, the creation of which would require satisfying similitude criteria) occurring in a torrent gully (the type of initiation zone commonly found in the Zailiysky Alatau as well as in other mountain systems of the country) when floods from an artificially created reservoir enter it. The experiment on the artificial replication of debris flows included recording the preplanned characteristics of the water release, measuring the parameters of the forming debris flow, and analyzing the traces left by it.

At the present time an analysis of existing theoretical insights into debris-flow processes as well as of information obtained in the artificial replication of debris flows at the experimental site and an investigation of the debris-flow traces formed in analogous initiation zones of the Zailiysky Alatau where natural outbursts of morainic lakes occurred (Malaya Almatinka, 1973; Sredny Talgar, 1974, 1975; Kumbel, 1977) show that the principal characteristics of the debris flows are dependent on the characteristics of the water flood which caused them, the morphometric characteristics of the initiation zones and the physio-mechanical properties of the PDFM.

In order to bring to light the role of these factors in the debris-flow formation process, various characteristics of water floods (peak discharge, volume, hydrograph form, etc.) are set in the programs for the artificial debris-flow experiments. But the range of variation in these parameters unfortunately is not wide enough and widening it to extreme values (which may open up new aspects of the debris flow process) involves the need to appropriately fit out the field site (build sedimentation basins and additional capacity in the reservoir at the expense of the above-lying morainic lake, rebuild the dam outlet works, and so on).

It remains beyond the scope of this research to elucidate the dependence of debris-flow characteristics on the morphometric characteristics of the initiation zone and the properties of the PDFM, this attributed primarily to difficulties in formulating similitude experiments and the lack of developed similitude criteria. But when experimental theory becomes further developed and observational and measuring techniques more refined, it may be possible to vary the length of the initiation zone, for example, by introducing into it flows of increased turbidity and varying the porosity, moisture content and granulometric composition of the loose rock debris of the PDFM. The task of the Chemolgan experiments is not confined to elucidating the functional relations between individual parameters of the process under study. The new information helps us to understand the nature of debris-flow processes, gain essential insights into them, uncover new relations and linkages extending beyond the scope of the initial data, and enables us to form new ideas for defining the further course of scientific research in this field. The Chemolgan experiments

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1980) No. 5, pp 64–71.

already have produced a number of unexpected results that diverge from existing theories, and they have stimulated the advancement of new scientifically valid hypotheses.

For conducting the 9 September 1978 experiment a number of preparatory efforts were undertaken in accordance with its formulated objectives, including the building of a partitioning dike in the reservoir to provide for an increase in the peak discharge of the release through a decrease in its volume, renovating the dam outlet works, equipping previously existing observation sites and organizing new ones.

The monitoring site located in the region of cross-sectional profile 37 (as in the 1976 experiment) was outfitted with the following debris-flow measuring instruments: a Doppler meter for measuring debris-flow surface velocity and level, a seismograph for determining the discharge of the debris flow, a quantum magnetometer for measuring the density of the debris-flow mass, seismic transducers and monitoring and signaling apparatus of a debris-flow hazard warning system, and photo- and movie cameras.

Besides the monitoring site, an additional point for observing flow behavior was marked off between cross-sectional profiles 65 and 66 of the debris-flow channel. Because of the lack of a second set of contactless instruments, measurements here were taken using older, traditional methods: measuring flow level by theodolite, determining flow velocity by floats and measuring density of the debris flow by collecting samples.

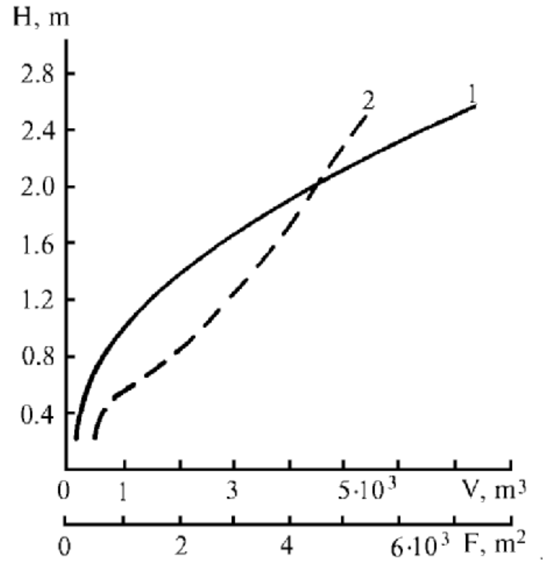


Fig. 1 Reservoir volume *1* and surface area *2* as a function of level.

The 9 September 1978 experiment was begun at 13:17 h with the water level in the reservoir at 175 cm, corresponding to a volume of 7500 m^3 (Fig. 1) which provided for a peak release discharge of 9.25 m^3/s. A hydrograph of the water release is presented in Fig. 2.

The results of level measurements *H* recorded on the diagrammatic tape of the level gage and evaluated along with the analysis of photofilm taken at the monitoring site with an exposure time of 10 s are presented in Fig. 3. Shown in Figs. 4 and 5 are the flow front and moment of peak rise in debris-flow level (H_{max} = 2.7 m). Absolute error in measuring level with values of $H \geq 1.5$ m was ±0.1 m, and with $H < 1.5$, ±0.15 m. Error in measuring level with Doppler radar was due to the small scale of recording, and error in the photographic data, to inaccuracies in determining the boundaries of the flow in the photo because of bends on the flow surface and perturbations along the banks (see Fig. 5).

The results of measuring surface velocity are presented in Fig. 6. Peak velocity was 5.4 m/s. Apart from these data there were two points for measuring the mean velocity of the frontal part of the flow in sections 65 and 69 m in length above and below the monitoring site. The first value (m/s) was obtained using a stopwatch:

$$\tilde{v}_1 = 65 \,/\, 15.1 = 4.3;$$

the second value using the seismogram of the warning transducers:

$$\tilde{v}_2 = 69 \,/\, 16 = 4.32$$

These data allow one to find the coefficient for converting surface velocity measured by the Doppler device to mean flow velocity:

$$k_v = \bar{v} \,/\, v_{sur} = 4.3 \,/\, 5.4 = 0.8.$$

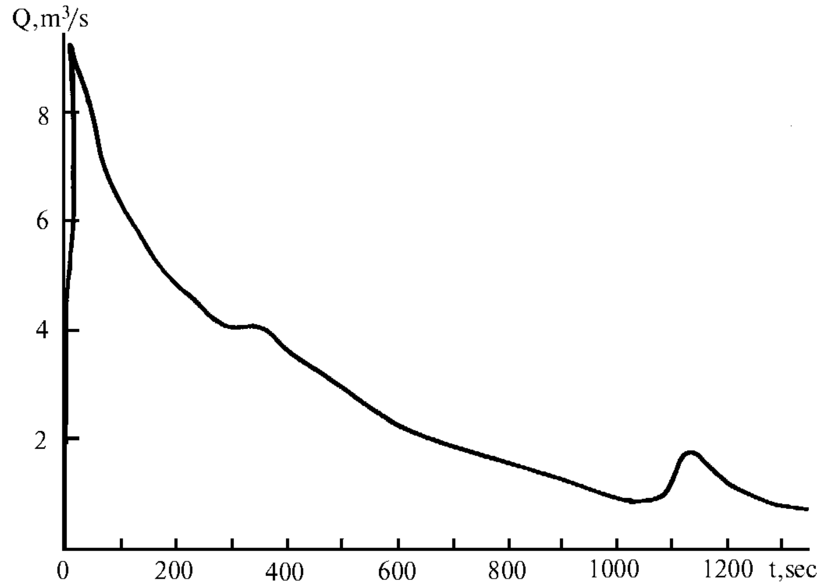


Fig. 2. Hydrograph of release from reservoir.

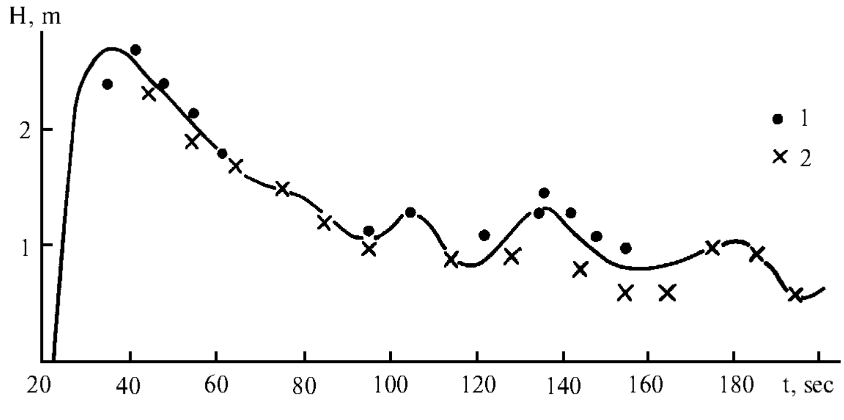


Fig. 3. Variation in debris-flow level. 1 - level gage data, 2 photo-film data.

From the production tests of the warning system conducted during the experiment three seismograms were obtained for the hydrograph of the debris flow (Fig. 7). The seismic flow meter and the first transducer of the warning system set up at the monitoring site recorded identical seismograms. The peak discharge of the debris flow was 130 m^3/s.

Fig. 4. The debris-flow front.

By analyzing the shape of the debris-flow hydrograph one can note that the debris flow of 1978 had a well-formed first surge (head) and a moderately pronounced second surge with an interval between them of approximately 2 min and a relation of their discharges

$$Q_{1\,surge} \;/\; Q_{2\,surge} = 130 \;/\; 40 = 3.25$$

The situation noted is obviously attributable to the sharply falling hydrograph of the release of water from the reservoir.

The photo frames in Figs. 4 and 5 allow us to evaluate the slope of the frontal edge of the debris flow. But because the exposure time proved relatively long for these purposes, only a minimal estimate of the slope could be obtained (it is 7 °). The surface velocity values recorded by the Doppler device at the moment when the level increased were corrected for this value.

Fig. 8 presents the results of determinations of debris-flow mass density and magnetic field strength. The measured values of the change modulus in the complete vector of the magnetic field strength ΔT are converted to the vertical component of the strength of an anomalous field z_c (Fig. 8*b*, curve *1*). A technique for interpreting z_c described in [3] proposes the computation and construction of a calibration curve $z_{cal} = f(H)$ (Fig. 9).

We were able to interpret the value of z_c only to the 75th second, because an increase in error in the measuring of level to 13% when its value decreases to 1.5 m leads to 20% error in determining z_{cal}, which makes it practically impossible to further interpret the magnitude of z_c. It follows from this that permissible error in measuring level must exceed ±5%. Then error in determining debris-flow density is ±7.5% (maximal bound).

The system for warning of debris-flow hazard using seismic transducers which was designed by the Special Design Bureau of the Experimental Geophysical Instruments Plant with technical assistance provided by the Department of Debris Flows of the Kazakh Institute for Hydrometeorological Research

Fig. 5. Debris flow at the moment of peak level.

(pursuant to an order by Kazglavselezashchita [Kazakh Main Directorate for Protection against Debris Flows]) passed production tests in the Chemolgan experiment. The physical phenomena lying at the base of the warning concept, a functional block diagram of the device, an optimal scheme for placing the seismic receivers, and other issues are set forth in [1, 2].

When the debris flow passed through the monitoring site, the first seismic receiver gave the signal "debris flow," which converted the entire system from a watch mode to an operating mode, and at the controller's station an audio alarm signal and the tape drives of recorders were switched on. Each seismic receiver had its own recording channel, and all data coming from the site of the events were recorded during the entire debris-flow process. Also proving itself was the design of a functional unit for protection against noise, which permitted the entire system to operate normally during a high level of noise (from a helicopter constantly patrolling above the channel, large numbers of people, etc.).

Thus, all parameters of the system come up to tolerances and norms, and as a result we have a reliable, mobile and modern device that can be used as a transducer in an automated data retrieval complex for acquiring debris-flow and hydrologic characteristics.
The value for density relates to the moment of time immediately after passage of the debris-flow head, and it is recomputed taking into account the full granulometric composition of the debris-flow mass.

The results of geodesic measurements of the initiation zone and channel after the debris flow are presented as a plot of washouts and deposits and a curve of volumes of removed material (Fig. 10). In all 11 thousand m^3 of solid material was removed from the initiation zone, of which 82% falls in the leg before the 20th cross section. The volume of debris flow increased until the 50th cross section, after which there was substantial deposition of debris-flow mass in the region of the lower channel, which was caused by the slight slope of this leg.

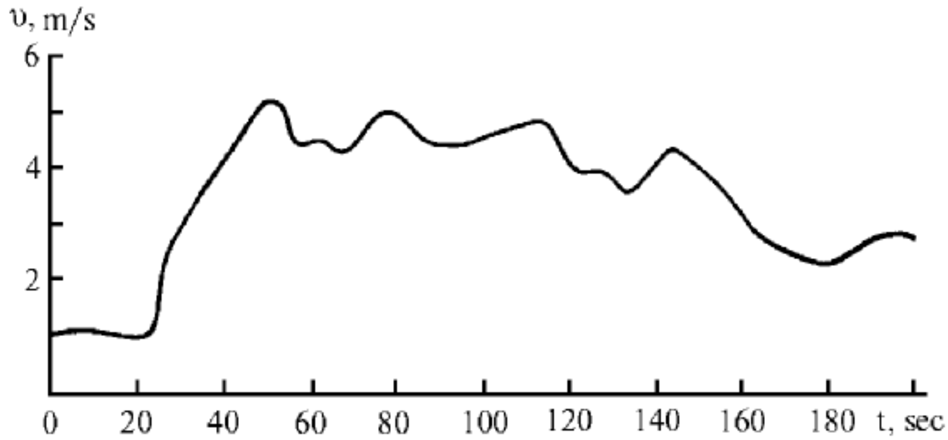


Fig. 6. Variation in debris-flow surface velocity.

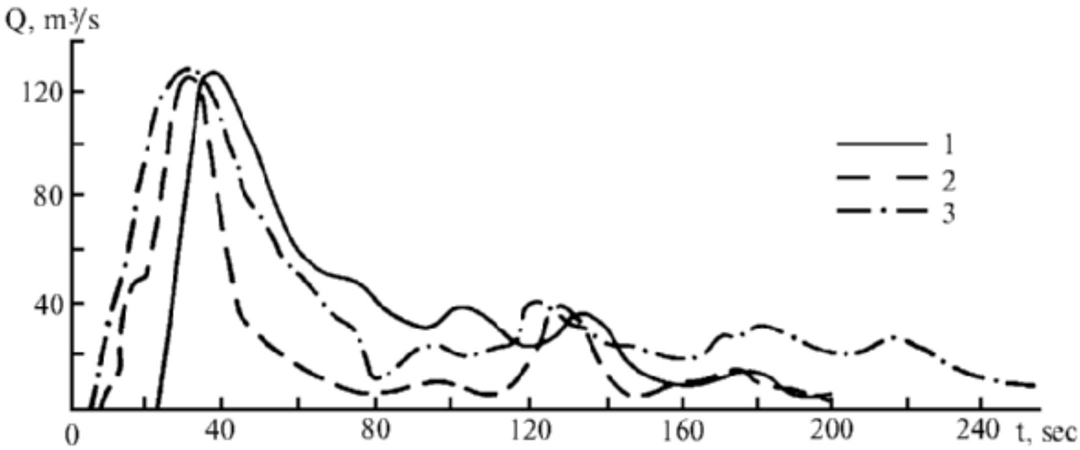


Fig. 7. Hydrograph of debris flow
1 - according to seismic flow meter data, *2* - according to data from the debris-flow hazard warning device. *3* - computed from measured values for level and velocity.

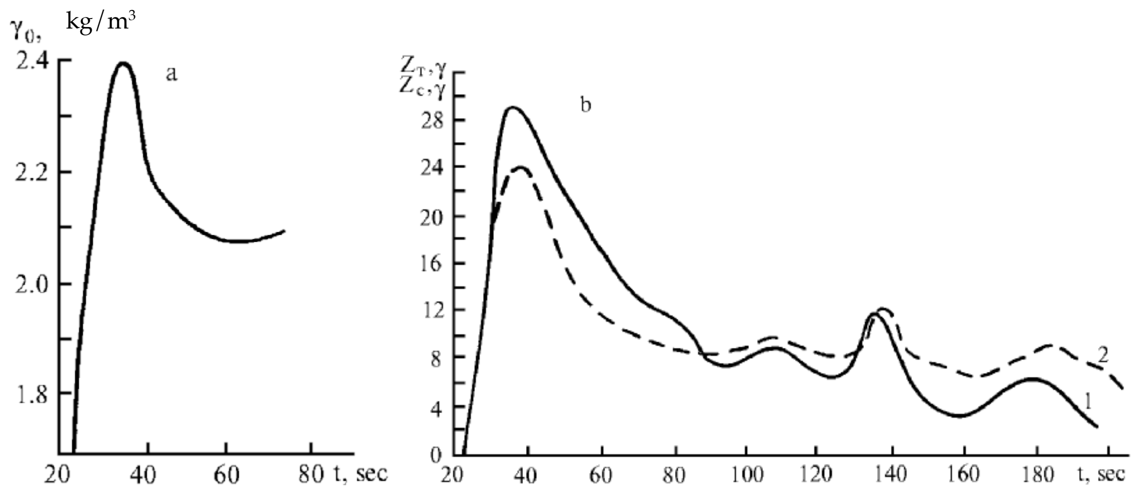


Fig. 8. Variation in debris-flow density (*a*) and magnetic field strength (*b*)
1 - computed data, *2* - measured data.

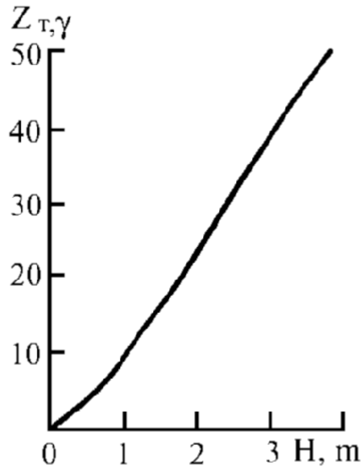


Fig. 9. Calibration curve.

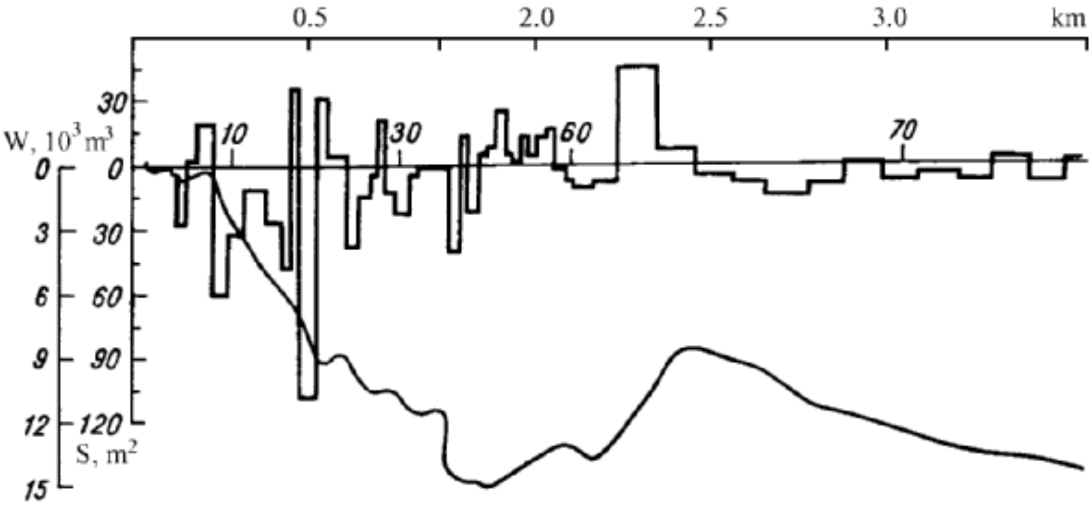


Fig. 10. Plot of areas of washouts and deposits.

REFERENCES

1. Kovalenko, P. I., Krasyukov, V. A., Novikov, M. Ya., Stepanov, B. S. Results of testing a seismic system for warning of debris-flow hazard. *Debris Flows* (1978) No 3 pp 92–96.
2. Krasyukov, V. A. The principal design and functional features of the transducers of a debris-flow hazard warning system. *Debris Flows* (1977) No 2 pp 64–66.
3. Stepanov, T. S. Some techniques for contactless measurement of debris-flow density. *Debris Flows* (1977) No 2 pp 67–78.

Results of the experiment "Chemolgan-91"*

V. P. Mochalov, A. K. Kim & A. Kh. Khaydarov

On 12 August 1991 an experiment on the artificial replication of a debris flow was conducted at the Chemolgan site on the initiative of Kazselezashchita within the framework of the Soviet-Chinese-Japanese Symposium on Hazardous Natural Phenomena.

Staff of KazNIGMI [Kazakh Institute for Hydrometeorological Research] participated in the experiment. Its purpose was to determine the characteristics of a formed debris flow and its subsequent transformation as it moves downslope until egressing from the mountains, and to test a seismic device for warning of debris-flow hazard. As in previous years, the experiment consisted of releasing a specified amount of water into the torrent gully, the evolution of the debris-flow process thereafter being practically the same as a natural one.

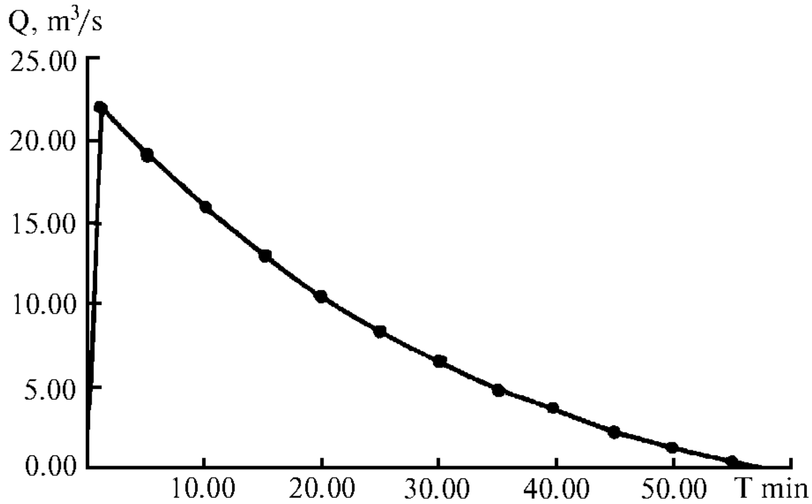


Fig. 1. Hydrograph of debris flow-forming flood.

Water was released into the Chemolgan torrent gully from the reservoir in which 28 thousand m^3 water had been stored by the start of the experiment. Unlike experiments previously performed by KazNIGMI, water was dumped through two water discharge openings which used to be covered by vertical metal panels. During the period when the reservoir was being filled, the panels were raised, and the openings were covered by wooden gates supported from the downstream wall.

The wooden gates were blown out by micro-explosives to ensure the synchronous release of water from both openings. The discharge of the release attained its peak value within the first minute. An attempt to lower the metal gates and thereby cut off the release of water into the initiation zone at the requisite moment was not successful. Thus, the debris-flow process lasted about an hour, practically until the reservoir was completely drawn down. As in previous years, a hydrograph of the release of water from the reservoir was computed in two ways:

1) by bathymetric curve taking into account the rate at which the reservoir was drawn down;

2) by hydraulic formulae for flow through the spillways (dimension of openings 1.95 x 1.95 m^2).

---

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1992) No. 12, pp 101–109.

Fig. 2. The "head" of the debris flow.

Observations of the reservoir's drawdown were accomplished by depth gages set up in the upstream wall at a distance of 35 m from the dam. As the reservoir drew down the next depth gage was set up in such a manner that 3-5 parallel readings could be taken by two neighboring gages.

After the last tacheometric survey there were no notable changes in the reservoir basin, and hence a previously constructed bathygraphic curve [2] was employed for computing the hydrograph. The hydrograph of the release (Fig. 1) was derived with account taken of the bathygraphic curve and observational data on the rate of the reservoir's drawdown, with differences between the magnitude of the discharges and the values of discharges computed by hydraulic formulae not exceeding 5-7 %. The following are the characteristics of the water release: volume - 28 thousand m^3, peak discharge of water - 22 m^3/s, duration - 60 min.

With the purpose of studying the characteristics of the debris flow and their subsequent transformation down the channel, level, velocity, discharge and density were measured at the control site ("Chemolgan-76" [1]) and at the "Camp" site (7.7 km below the control site).

The debris flow, accompanied by clouds of wet spray and roaring, was recorded as reaching the control site at 13:07 (Fig. 2).

Change in the debris-flow level was recorded with the aid of a simple instrument that is both completely safe and sufficiently accurate. The instrument for contactless measurement of flow level consists of a sighting device (1) (Fig. 3) on which a vertical gage with millimeter markings is fastened and an aiming frame (2) with a horizontal cross hair. The sighting device may be secured in any position relative to the horizontal axis, and the aiming frame moves along a guide. The entire instrument is assembled on the base of a theodolite stand and is freely aligned in the requisite direction. When operated against light the sighting device is brightened by a mirror (3). The following procedures are employed in preparation for the measurements:

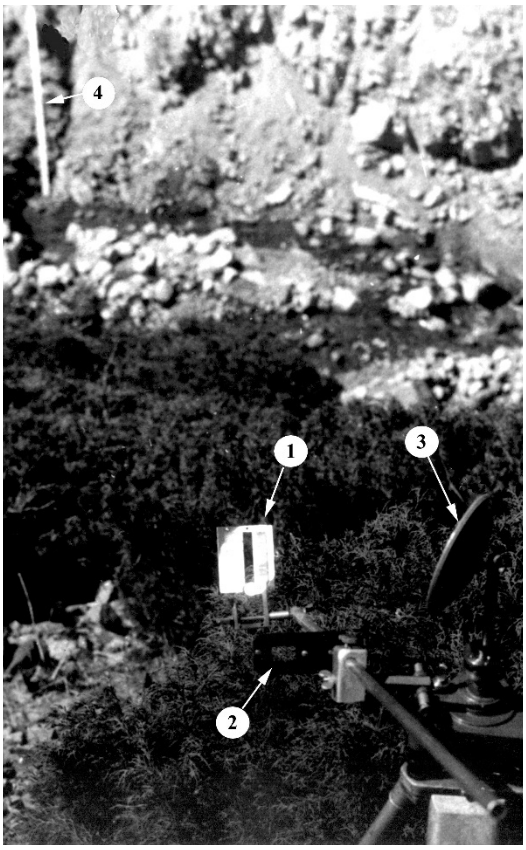


Fig. 3. Instrumentation for contactless measurement of debris-flow level.

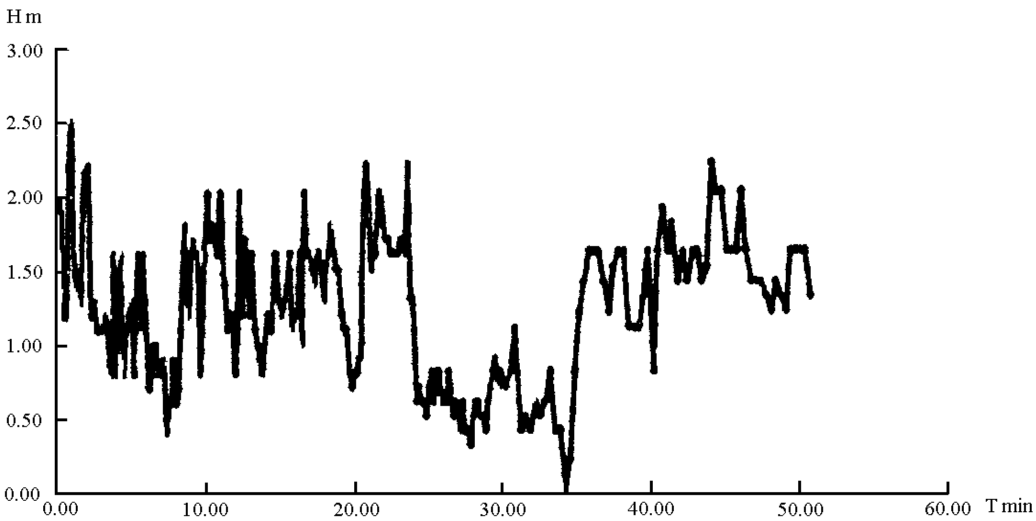


Fig. 4. Variation in debris-flow level at the control site.

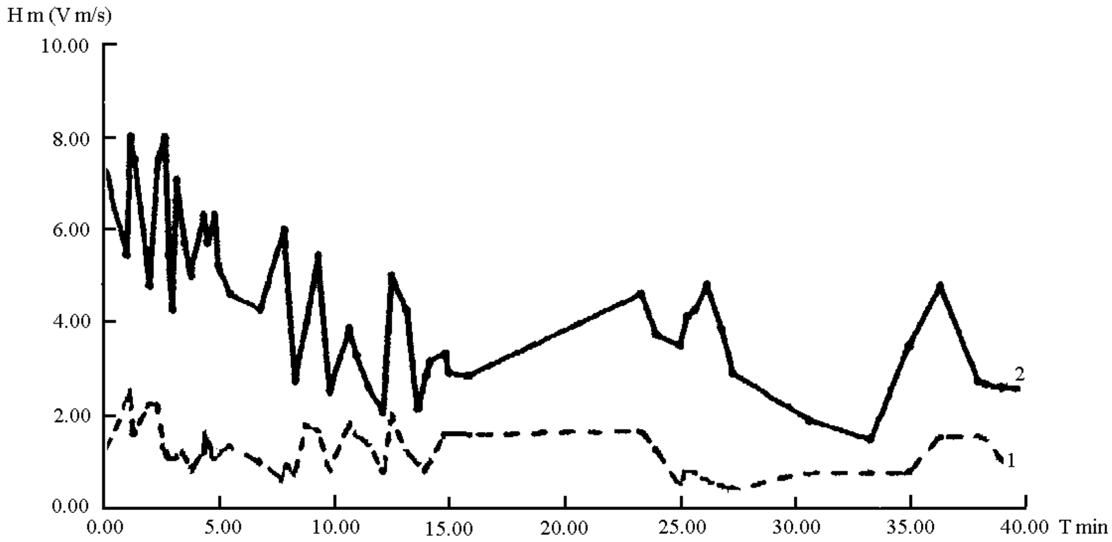


Fig. 5. An integrated plot of changes in debris-flow level (1) and velocity (2) at the control site.

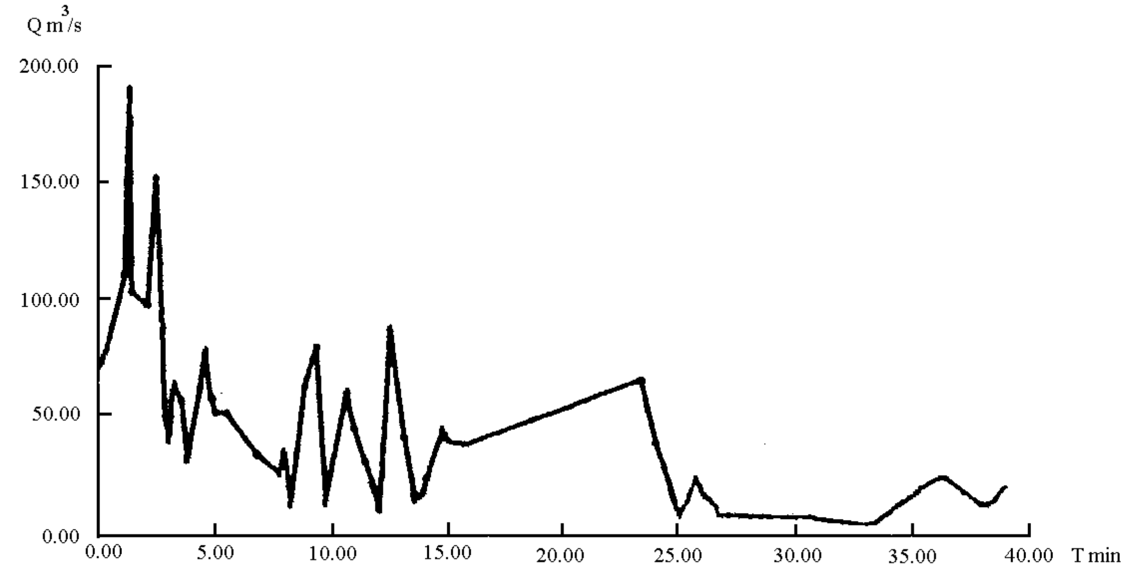


Fig. 6. Hydrograph of the debris flow at the control site computed by area and velocity.

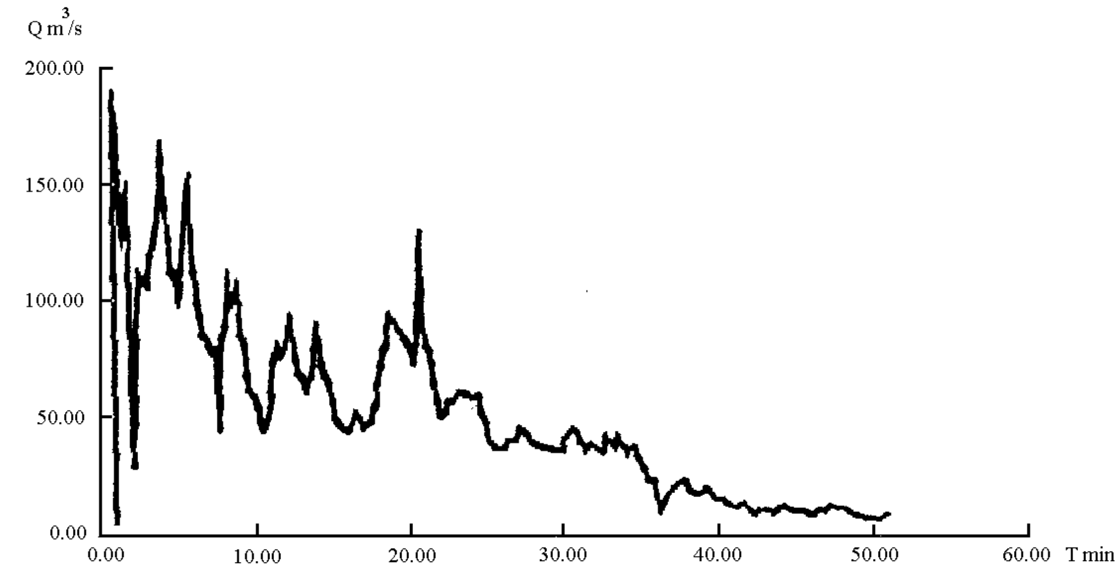


Fig. 7. Hydrograph of the debris flow at the control site (by seismic flowmeter).

Fig. 8. One of the surges observed in the debris-flow formation process.

1. Select a suitable section of the channel with a steep non-erodable bank on which to perform the sighting.

2. A tacheometric or level survey of the cross-sectional profile of the channel at the measurement site.

3. Temporarily set up a level or other kind of surveying rod (4) for calibrating the instrument.

4. Set up the sighting device parallel to the rod and select the scale of the survey. For this one shifts the aiming frame while watching the lower and upper ends of the rod on the bar of the sighting device. (For example, the aiming frame is set so that a three-meter rod takes up 60 mm on the sighting bar. Thus, the value of a scale division of 1 mm on the bar is 5 cm.)

Fig. 9. The debris flow at peak level.

The measurements consist of taking readings of the flow level at the edge of the bank over specified time intervals. To determine the true values the readings taken of flow level are multiplied by the sine of the angle of inclination of the calibrating rod. Variation in the level of the debris flow with time is shown in Fig. 4.

Velocity was measured by the float method. Rocks moving on the surface layer of the debris flow served as the floats. An integrated plot of changes in level and velocity is given in Fig. 5. The peak mean velocity of the debris flow was 8 m/s.

Discharges of the debris flow were computed by the "area-velocity" method (Fig. 6) and from readings of the seismic flowmeter (Fig. 7). A comparison of the derived plots shows that during the entire process of debris-flow formation 20 particularly pronounced surges occurred, one of which was recorded on film and is shown in Fig. 8; the peak level (H = 2.5 m) of the debris flow was attained in the very first minute, the discharge then measuring 190 m^3/s (Fig. 9); debris-flow volume measured around 155 thousand m^3.

The arrival of the debris flow at the "Camp" site was recorded at 13:59. Plots of the change in debris-flow characteristics with time are presented in Figs. 10 and 11 and make it possible to judge the transformation of these characteristics along the channel.

With the purpose of checking out the debris-flow warning apparatus a field unit of the seismic debris-flow hazard warning device was set up on the left bank of the river at a site located 60 m below the control site and a receiver unit was set up at the "Camp" site. When the debris flow descended information was transmitted via an ultra-shortwave radio set. Data were recorded automatically on a digital printer. The readings of one of the sensors located 100 m below the control site characterize the hydrograph of the debris flow (Fig. 12).

It should be noted that in all plots the time of arrival of the debris flow at a site (any one) is taken as zero on the time scale.

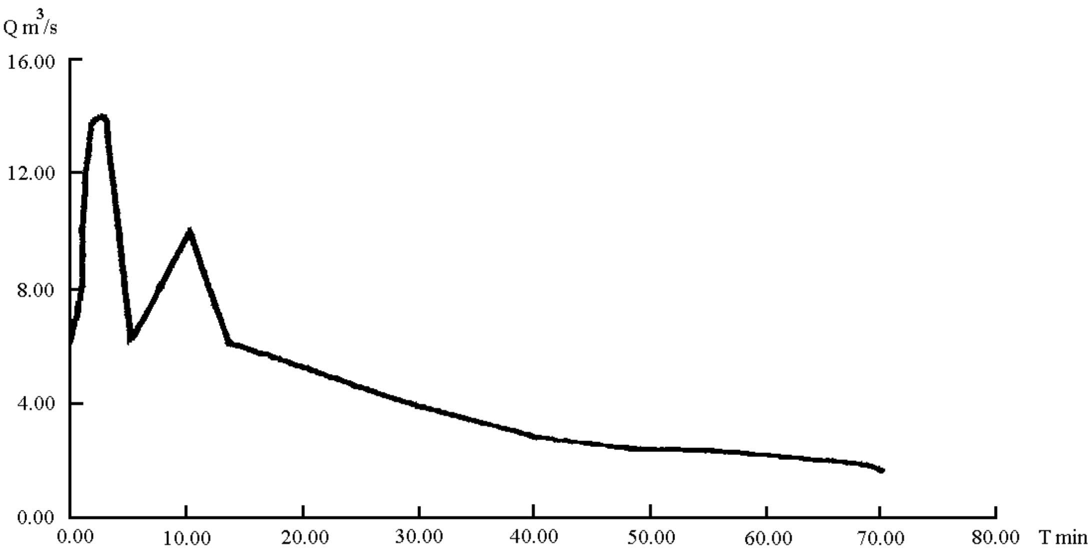


Fig. 10. Hydrograph of debris flow at the "Camp" site.

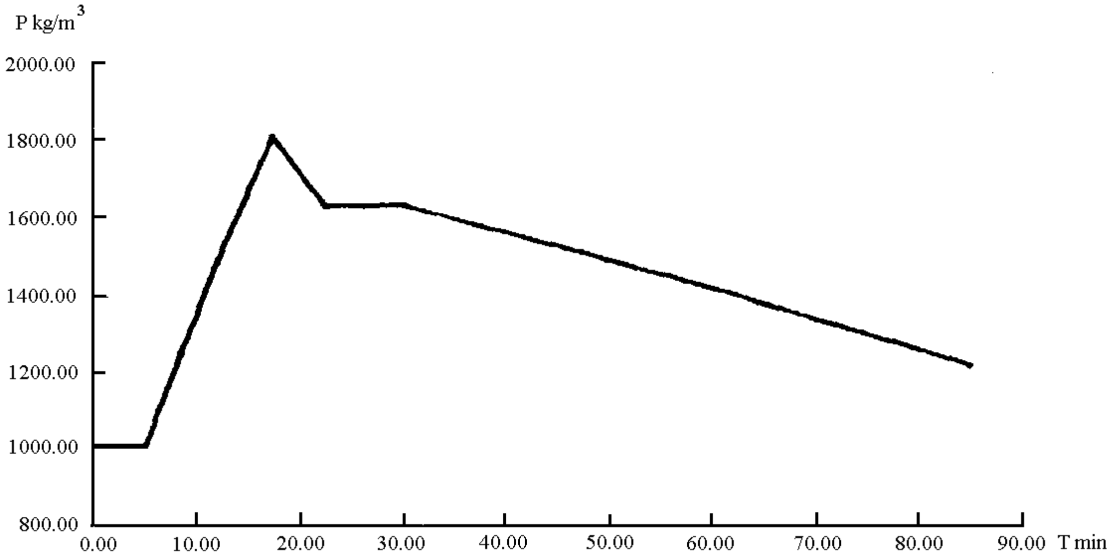


Fig. 11. Variation in debris-flow density at the "Camp" site.

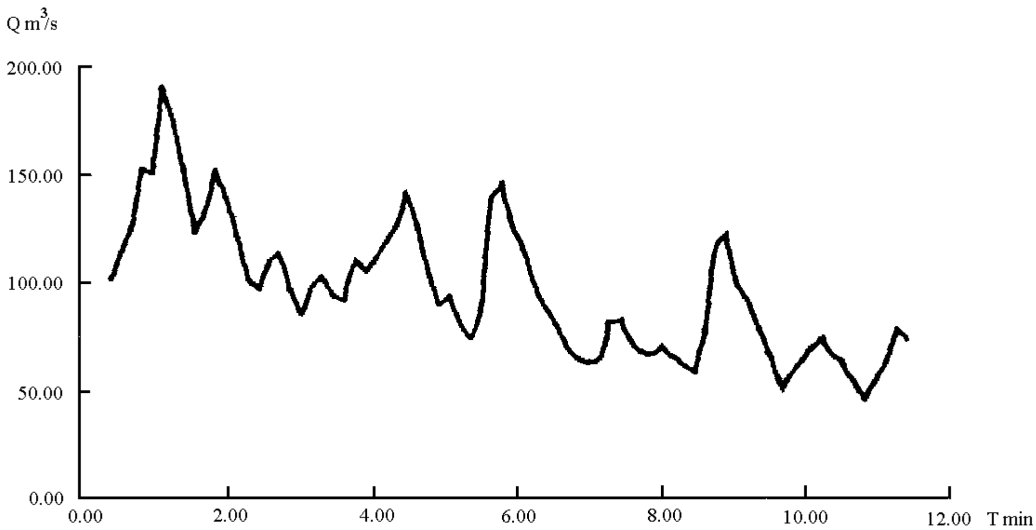


Fig. 12. Hydrograph of the debris flow at a location 100 m below the control site (from the seismic warning data).

REFERENCES

1. Stepanova, T. S. et al. Results of experiments on the artificial replication of debris flows in the Chemolgan River basin. Stepanova, T. S., Khonin, R. V., Krzhechkovskaya, N. I., Khaydarov, A. Kh. *Debfis Flows* (1978) Col. Pap. No 3 pp 86–92.
2. Khonin, R. V., Mochalov, V. P., Zems, A. E. The experimental site in the Chemolgan River basin and the history of its founding. *Debris Flows* (1976) Col. Pap. No 1 pp 7–25.

Post-debris flow phenomena in the Chemolgan riverbed, 12–22 September 1991*

Ye. I. Svetlakov

On 12 September 1991 an experiment on the artificial replication of a debris flow was conducted in the upper reaches of the Chemolgan River. When the debris flow exited from the initiation zone and merged with the Levy Chemolgan River, the debris-flow mass partially disintegrated. The considerable decrease in slope in this section enhanced the disintegration. As a result of this disintegration the course fractions settled, and the fine particles that may have been suspended by the flow resulting from the merging of the debris flow with the waters of the Levy Chemolgan were carried away.

On the following day at the channel location 1.5 km below the place where the rivers merged one could observe a moving sand-gravel mass (shown in the figure) having the following geometric dimensions: length 3300–3500 m, width 4–5 m, depth 0.1–0.2 m; the granulometric composition of the mass is presented in the table.

The velocity of the mass front was estimated to be 2.5–3 cm/s, that is, 2.2–2.6 km/day, and the discharge of the entrained alluvium was 23–27 kg/s.

By accurately determining the velocity of the sand mass it was possible to compute the time of its arrival at the irrigation systems of the Dzhandosovo collective farm, thanks to which it was possible to prevent sand from choking up the hydraulic works and running onto the fields.

In essence, after the termination of the debris-flow processes the forming of channels begins anew, that is, the position of the channels in plan view, their depth, etc. can change. This is owing to the constant removal from the debris-flow deposits of particles which the water flow can transport in any state.

On a steep slope sand is transported as a result of intensive mixing caused by turbulence and the interaction of the flow with the roughness elements of the channel. In sections of the channel with slight slopes characterized by calmer flow the sand settles and is then transported by saltation and rolling. When the sand settles in the head part of the mass, all recesses in the relief of the channel's rocky floor are gradually filled in, causing a marked decrease in the roughness of the channel and in turn causing an increase in the transporting capability of the water even with minimal discharges and depths (at a flow depth of 10 cm particles of entrained alluvium up to 100 mm in diameter roll over the surface of the sand).

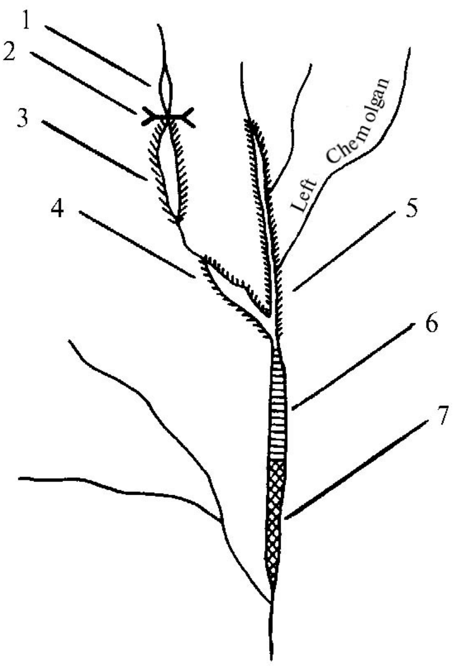
Table 1

Granulometric composition of entrained debris in the post-debris flow period in the Chemolgan River on 13 September 1991

Fraction, mm	20–10	10–5	5–2	2–1	1–0.5	0.5–0.25	0.25–0.1	0.1
Weight	131	531	1075	651	260	192	42.5	15.5
Percentage	4.5	18.3	37.1	22.4	9.0	6.6	1.5	0.6

The movement of the sand mass is similar to the movement of a caterpillar track, that is, sand in entrained and suspended state from the "tail" part of the mass moves along the body of the mass. On reaching the

* Published originally in *«Debris Flows», Collected Papers, Kazakh Regional Institute for Hydrometeorological Research* (1992) No. 12, pp 110–112.



Plan view of the formation of sand mass:
1 - lake-storage basin, 2 - dam, 3 - main torrent gully, 4 - lower torrent gully, 5 - new initiation zone, 6 - deposits of the debris-flow mass - region of sand-mass feed, 7 - sand mass.

head part a large portion of particles transported by saltation settle because of a sharp increase in roughness, and they smooth out the unevenness of the rocky floor. At the same time the granulometric composition is transformed: courser particles which the flow is not capable of transporting reform the rocky floor, and the finest particles are washed out and carried away with the flow in suspended state at high velocity. Despite this, during the travel of the sand mass over tens of kilometers its geometric characteristics remained practically unchanged. The reason for this probably is as follows: as a result of the depositing of sand the water level in the channel rises, fine fractions wash away from the side (river bank) debris-flow deposits, and thus the mass is constantly replenished with sand and gravel particles and the volume of the mass changes negligibly.

Moving masses of entrained alluvium several kilometers long in the post-debris-flow period were observed during the experiments at the Chemolgan site in 1972–1978 and 1988 [2], and the barrages in the Bol’shaya Almatinka River were filled with such alluvium in 1988.

Thus, in forecasting the consequences of debris flows in order to lessen material damage we must take into account the effect of post-debris flow phenomena, as a result of which substantial (tens of thousands of cubic meters) volumes of sand masses may be brought to a zone of human economic activity.

Moreover, such sand masses can be useful. If during the movement of the mass the water flow is directed to a sedimentation basin, then, first, the entire volume of diverted water can be preserved for later use, and, secondly, the clean, washed sand remaining in the sedimentation basin is needed for construction and other economic needs.

REFERENCES

1. Mochalov, V. P., Kim, A. K., Khaydarov, A. Kh. Results of the experiment "Chemolgan-91" (in this collection of papers).
2. Stepanov, B. S., Stepanova, T. S. *The Mechanics of Debris Flows.* Moscow: Gidrometeoizdat (1991) 379 pp.

Overview on Chemolgan field experiments and analysis of erosion data*

D. Rickenmann[1], D. Weber[1] & B. Stepanov[2]

[1]Swiss Federal Research Institute WSL, Birmensdorf, Switzerland; [2]Kazakh Research Institute for Environmental Monitoring and Climate, Almaty, Kazakhstan

1. Introduction

The attempts to measure erosion due to debris flows at the Chemopgan test site likely represent the first attempts to quantify this important process. More studies were undertaken to describe the initiation condition for a debris flow forming in a channel (e.g. Takahashi 1991, Tognacca et al. 2000). In several debris-flow models it is assumed that a given flow will entrain solid material from the bed until an equilibrium condition is reached (e.g. Takahashi et al. 1992), which is similar to the use of bedload transport formulas in fluvial hydraulics. Other researchers have either empirically determined possible volume changes of debris flows (Cannon 1993) or proposed to specify a sediment yield rate which may vary along the flow path (Hungr & Evans 1997).

At the Chemolgan test site in Kazakhstan, a total of seven experiments on debris flows were carried out between 1972 and 1991. The debris flows were artificially triggered by releasing water from a reservoir situated at 2900 m a.s.l. The sudden release of water with relatively large peak discharges resulted in a strong erosion of bed and bank material in the upper reaches of the gully below the lake. The gully is situated in an ancient moraine. The rapid entrainment of solid material led to the formation of debris flow surges with a distinct granular front, as can be observed both on photographs (Fig. 1) and film documents. These experiments form a valuable data set on field debris flows, with measurements of several parameters concerning flow behavior, soil properties and erosion/deposition characteristics. The principal objective of this paper is to present the main results of the Kazakh field experiments on debris flows, and to make a rough analysis how the erosion may depend on mean flow parameters.

Fig. 1. Experimental debris flow in 1975 at Chemolgan test site (from Stepanov & Stepanova 1991).

*This is an extended version of the paper Rickenmann et al. (2003), see References

2. Experiments and main results

2.1 Field test site and experiments

The debris flow experiments were performed in the Chemolgan River basin. The test site is situated in the Zailiysky Alatau Mountains, about 50 km southwest of Almaty, the former capital of Kazakhstan. The reservoir is located at an elevation of 2900 m a.s.l. In this region, several glacial lakes were present in former times. A gate was built at the natural outlet, to artificially store water. A general description of the experimental site including the construction of the gate and its operation during the experiments is given by Khonin et al. (1976). The maximum storage volume of the lake is about 80,000 m^3. During the experiments carried out between 1972 and 1991, the released water volume varied between 3600 m^3 and 40,600 m^3.

The gully downstream of the lake forms the debris flow test reach which extends over several kilometers. The longitudinal profile of the upper part of the channel is shown in Fig. 2. Along the first 950 m, the gully is deeply incised into an ancient moraine. The steeper part of this reach has a mean gradient of about 30 %. During the experiments most erosion usually occurred in this channel reach ("erosion cut" in Fig. 2). The end of this reach is marked by the cross-section no. 33 in Fig. 2. The following 700 m long channel reach is located mainly in bedrock, with a mean gradient of about 20 %. Typically, some more solid material was entrained in this reach. At the so-called "control" cross-section no. 42 (at a horizontal distance of 1680 m below the reservoir) the most detailed measurements and calculations were usually made of the debris flow surges, such as flow depth, flow velocity, peak discharge and mixture density.

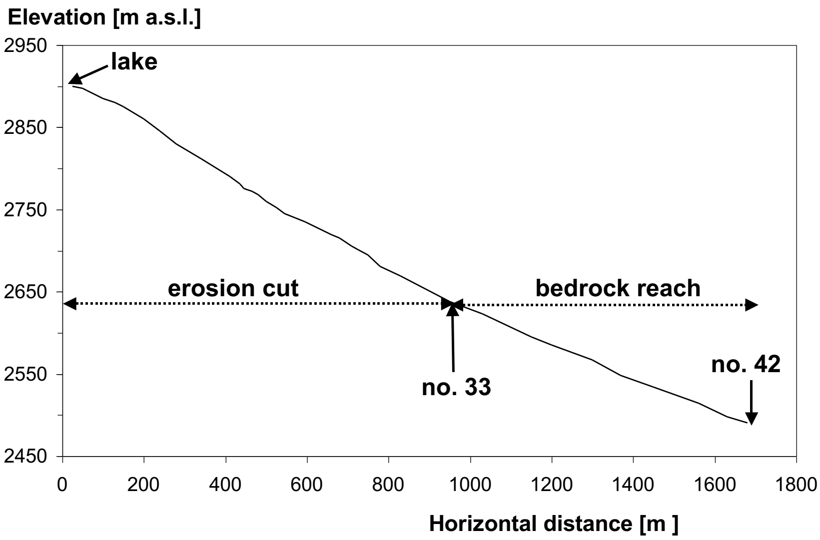


Fig. 2. Longitudinal profile of upper part of debris-flow test site at Chemolgan River.

To determine volume changes of eroded and deposited solid material, 104 cross sections (including the side slopes) were surveyed before and after each debris flow experiment, covering a total channel length of 7 kilometers downstream of the reservoir (Zems et al. 1976). At a horizontal distance of about 2 km below the reservoir there is both a sharp right turn of the debris flow path and a confluence of a major tributary. In this area typically the first substantial deposition occurred during the experiments. The channel gradient in this area is on the order of 15 %. One kilometer further downstream there are confluences of two other tributaries, and the channel gradient drops below 10 %. In this area, the larger debris flows deposited most of the solid material. Fig. 3 shows an example of the grain size distribution of material from the Chemolgan debris flow deposits. The material is composed mainly of granite and diorite particles. For comparison, material used in laboratory experiments is also included in Fig. 3 (s. also section 3.3 below).

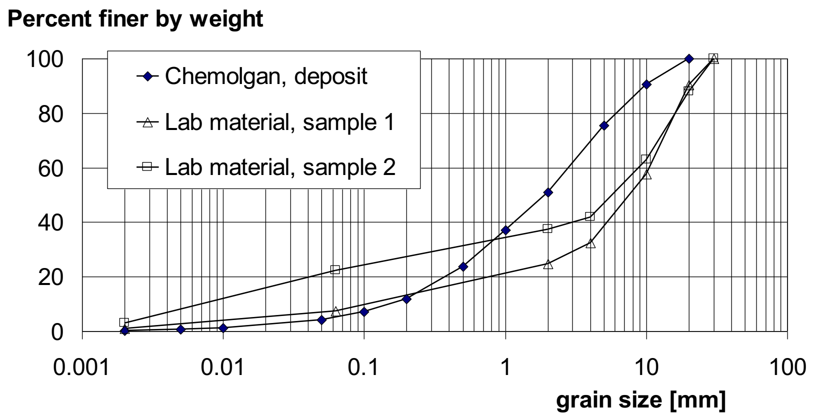


Fig. 3. Grain size distributions of material from a debris-flow deposit at the Chemolgan site and of the material used in the laboratory flume experiments.

2.2 Mean parameters and general trends

Table 1 lists the most important parameters which were recorded for the six debris-flow experiments carried out between 1972 and 1991. The water discharge out of the lake was measured with velocity meters at several locations over the outflow cross-section at the spillway at the gates of the reservoir (Khonin et al. 1976). The soil porosity was determined to be 0.181, and the relative water content (by volume) in the soil pores is given as 0.65 for the 1972 and 1973 conditions (Zems et al. 1976). Regarding the total volume of entrained solids (including pore spaces), this suggests an additional water input of almost 12 % into the debris flow mass.

In Fig. 4, a comparison is made between the eroded volume V_E down to cross-section no. 42 and the volume of the released water V_W. Assuming that all eroded solid material was entrained by the debris flow, a mean bulking factor of 3.8 is determined from Fig. 4, where the bulking factor is defined as $(V_E + V_W) / V_W$.

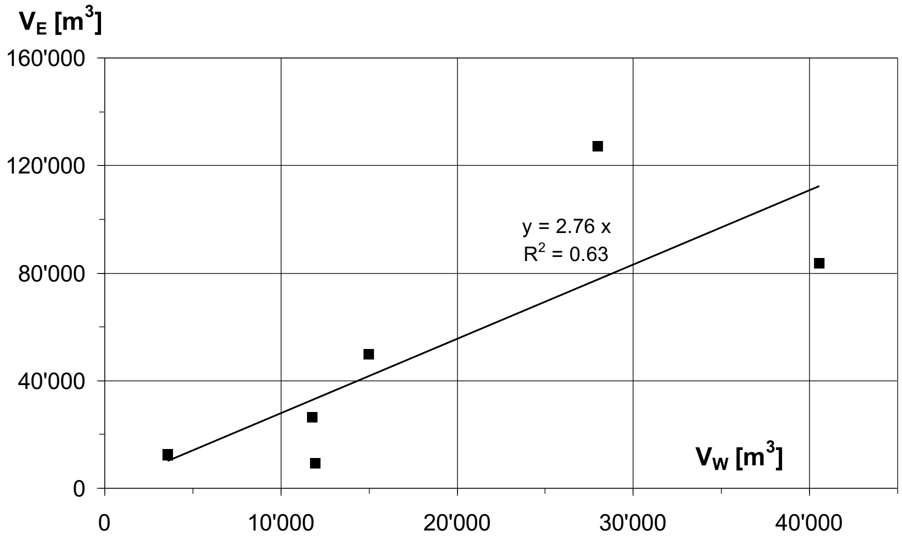


Fig. 4. Comparison of eroded soil volume V_E down to cross-section no. 42 and water volume V_W which generated the debris flows.

This corresponds to an overall mean solid volume concentration C_s of 0.74 (at cross-section no. 42), where C_s is defined as $V_E / (V_E + V_W)$. If the C_s values are determined including additionally the entrained pore water (soil moisture) (Table 1), they are smaller and vary from 0.40 to 0.73 for the individual debris flows. As is indicated in Fig. 4, larger water volumes tend to produce more erosion and form larger debris flows. The volume of eroded soil material appears to depend also to some extent on the peak water discharge,

$Q_{p,W}$. If the ratio V_E / V_W is plotted against the peak water discharge, $Q_{p,W}$, a weak trend can be observed in Fig. 5 for V_E / V_W to increase with $Q_{p,W}$.

The data of Table 1 suggests that there is a correlation between peak discharge of the generated debris flow $Q_{p,DF}$ and the triggering water flow $Q_{p,W}$. As shown in Fig. 6, on average the following relationship can be established: $Q_{p,DF} \approx 11\ Q_{p,W}$. This analysis also includes the multiple peak data of the 1973 and 1975 experiments, for which the time intervals of the peak flows of the released hydrographs match well with the intervals of the resulting debris-flow peak discharges.

The peak discharge of debris flows has been found to correlate with the event magnitude or the total mixture volume (Mizuyama et al. 1992, Rickenmann 1999). As illustrated in Fig. 7, the Chemolgan data largely show a similar trend and scatter as data from the European Alps, China, and Japan.

Table 1: Parameters of the debris-flow experiments performed at the Chemolgan field test site. The data sources of the values are as follows: 1972 + 1973 experiments (exp), Zems et al. (1976); 1975 exp, Khonin et al. (1977); 1976 exp, Stepanova et al. (1978); 1978 exp, Kirenskaya et al. (1980); 1991 exp, Mochalov et al. (1992), Khegai et al. (1992). The division of the 1973 experiments concerning erosion and mixture volumes is based on seismic recordings giving information on the change of debris-flow discharge with time (Stepanov & Stepanova 1991).

Year of experiment	**1972**	**1973**	**1973a**	**1973b**	**1975**	**1976**	**1978**	**1991**
Month/day	08/27	08/22			08/19	09/08	09/09	09/12
Lake outflow		both parts	part 1:	part 2:				
No. of waves	1	3	28 min.	210 min.	2	1	1	1
Peak water discharge, $Q_{p,W}$ [m^3/s]	16	16 / 16 / 12		2	28 / 16	5	9	22
Water volume, V_W [m^3]	11,800	40,600	15,000	25,600	15,030	12,000	3,600	28,000
Net erosion								
Erosion volume of solids (without pore space), V_E [m^3], passing no. 32	19,800	71,300			45,000	11,466	9000	
Erosion volume of solids (without pore space), V_E [m^3], passing no. 42	26,200	83,500	42,000	41,500	49,500	9000	12,300	127,000
Water volume including entrained soil moisture [m^3] (at no. 42)	15,600	52,600	20600	32,000	22,000	13,300	5400	46,000
Debris flow characteristics								
Peak debris-flow discharge, $Q_{p,DF}$[m^3/s]	100	100 / 80 / 75			430 / 320	45	130 / 40	190
Mixture volume [m^3] (at no. 42)	41,800	136,100	63,300	72,800	71,500	22,300	17,700	173,000
Mean volume concentration of solids (incl. moisture, at no. 42), C_s	0.63	0.61	0.66	0.57	0.69	0.40	0.69	0.73
Ratio of mean solid volume concentration to natural packing density of soil material, C_s/C^*	0.77	0.75	0.81	0.70	0.85	0.49	0.85	0.90

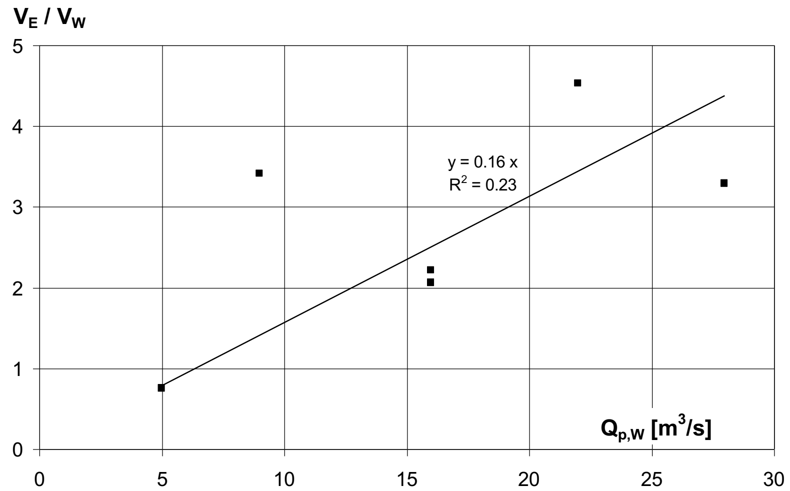


Fig. 5. Comparison of the mean ratio of eroded soil volume (V_E) to water volume (V_W) (down to cross-section no. 42) and peak water discharge ($Q_{p,W}$).

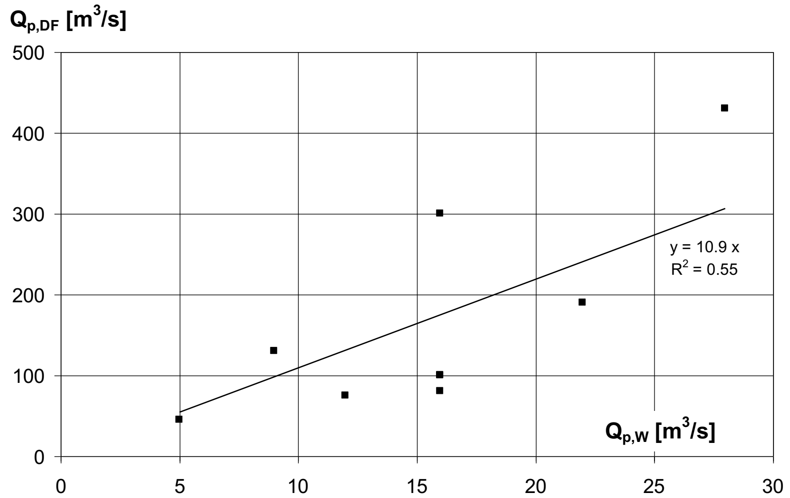


Fig. 6. Comparison of the peak debris flow discharge ($Q_{p,DF}$) and the peak water discharge ($Q_{p,W}$).

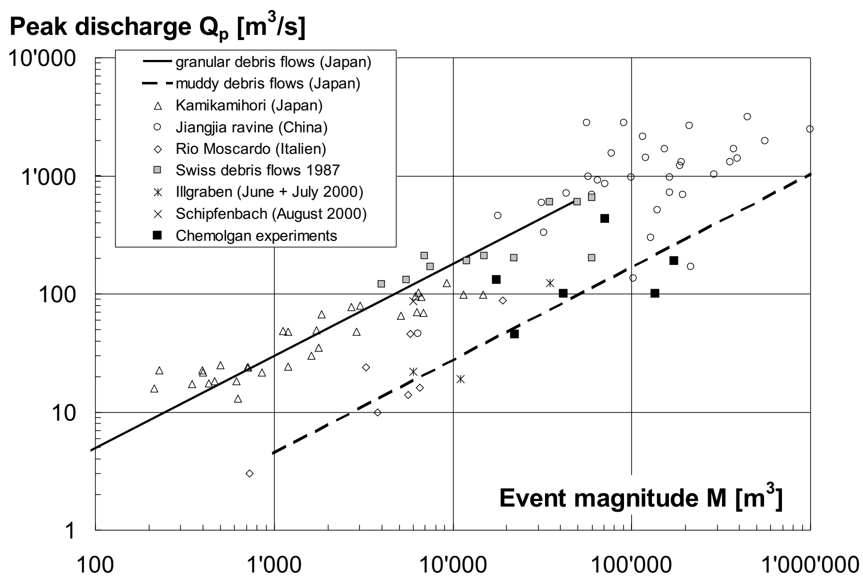


Fig. 7. Comparison of the peak debris flow discharge ($Q_{p,DF}$) and event magnitude (M). For the Chemolgan experiments, the mixture volume passing at cross-section no. 42 (values from Table 1) are used for the event magnitude.

3. Further Analysis of erosion characteristics

3.1 Experimental data for cross-sections 1 through 42

The further analysis considers single reaches for the cross-sections 1 through 42 (Fig. 1). A reach is defined here as channel segment between two adjacent cross-sections. The determination of the erosion volumes for each reach is based on diagrams of the channel cross-section profiles (elevations) which are available for the years 1972 through 1976 for the conditions before and after each experiment. We digitized the profiles and determined for each reach the net erosion or deposition volume of solid material after each experiment. The distances between the cross-sections were measured from a map, and the channel gradients for the reaches were determined together with an average elevation of the thalweg (absolute elevations given on the cross-section profiles). The corresponding data is listed in Table 2. Reach length varied from 10 m to 120 m in most cases (except for one case with missing data) and reach gradient (sin of bed slope angle θ) from 0.05 to 0.55.

Our estimates of the sediment budget (net erosion) at cross-section no. 32 and 42 are listed in Table 3. The agreement between the two independent volume estimates (Table 3 and those given in Table 1 taken from the publications in Russian) is good for the 1972 and 1973 experiments, and fair for the 1975 experiment. For the 1976 experiment, our first estimate of the net erosion passing cross sections 32 and 42 was much larger (ca. 31,000 m^3). In some cases, relatively large volume changes at a cross-section indicated large side-slope movements into the channel. Assuming that a large part of these masses were not transported during the experiment, we neglected this sediment input and made corrections for the cross-section changes in seven cases for the 1976 experiment (see also Table 2). These corrections do not affect the conclusions of our analysis since the scatter of the data is considerable in any case (as can be seen below).

Fig. 8 illustrates the evolution of the mean solid concentration, C_s, during the Chemolgan debris-flow experiments along the flow path. The C_s values represent here a mean value for each reach integrated over the duration of an experiment. In general, the flows tend to erode solid material primarily over the first 400 to 600 m of the horizontal flow length, with only minor changes in the solid content further downstream of about 800 m. The cross-section no. 32 is located at a distance of 830 m.

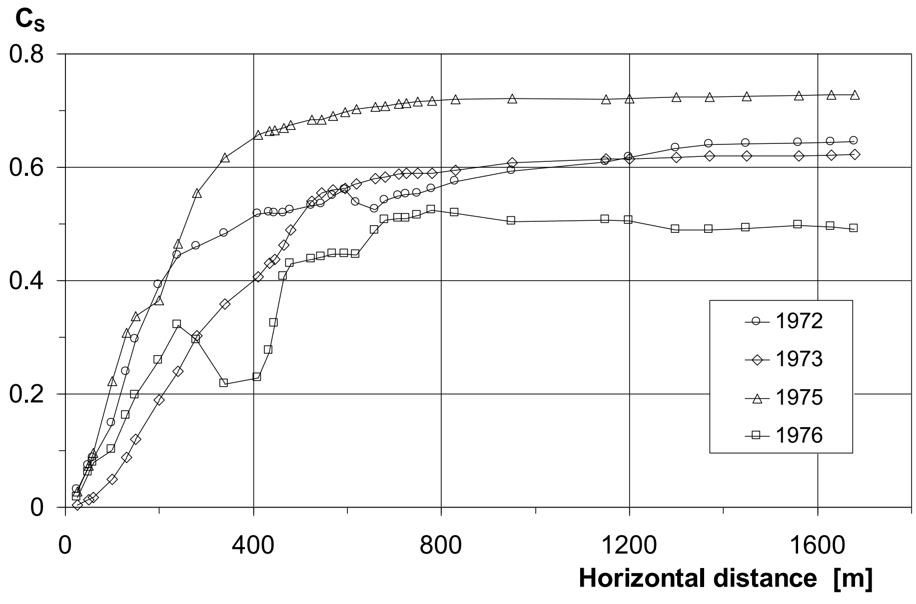


Fig. 8. Evolution of the mean solid concentration during the Chemolgan debris-flow experiments along the flow path. The bedrock reach is located at a horizontal distance from 950 m to 1680 m.

In Fig. 8, the evolution of the mean solid concentration along the flow path is different for the 1976 experiment over a distance of about 200 m to 400 m below the lake. This may indicate some uncertainty about the erosion data of the 1976 experiments (similarly as indicated by the discrepancy between our estimate and the values given in the Russian publications regarding the total erosion volume caused by this experiment).

Table 2: Channel data of cross-sections 1 through 42. The following notation is used: no = cross section number, x = horizontal distance, z = vertical elevation (thalweg), θ = bed slope angle, dL = effective distance between cross sections. For the 1976 experiment, relatively large volume changes at some cross sections indicated large side-slope movements into the channel; assuming that a large part of these masses were not transported during the experiment, we corrected the changes for seven cross-section areas (marked with an asterix) for the 1976 experiment.

					Change in cross-section area				**Change in reach volume**			
no	**x**	**z**	**sin θ**	**dL**	**1972**	**1973**	**1975**	**1976**	**1972**	**1973**	**1975**	**1976**
	[m]	[m]		[m]	[m^2]	[m^2]	[m^2]	[m^2]	[m^3]	[m^3]	[m^3]	[m^3]
0	0	2900										
1	25	2890	0.37	26.7	33.7	13.7	39.6	19.3	454	185	533	260
2	50	2884	0.23	25.7	20.5	22.4	33.1	35.3	696	465	935	702
3	60	2882	0.20	10.2	23.8	26.6	66.0	26.3	226	250	505	314
4	100	2880	0.05	40.0	35.4	58.4	110.0	-5.7	1185	1702	3523	411
5	130	2872	0.26	31.0	104.3	84.2	97.9	83.7	2168	2213	3226	1210
6	150	2866	0.29	20.8	59.7	114.1	29.8	-4.4	1711	2070	1333	828
7	200	2849	0.32	52.5	84.4	78.1	26.8	*67.0	3805	5076	1494	1654
8	240	2835	0.33	42.1	44.5	133.2	293.0	30.7	2733	4476	6775	2069
10	280	2820	0.35	42.4	4.6	174.7	149.7	-73.6	1050	6575	9457	-916
11	340	2802	0.29	62.4	44.9	55.5	193.2	*0.0	1551	7210	10741	-2304
13	410	2784	0.25	72.1	29.6	150.0	88.6	*8.0	2692	7426	10182	289
15	435	2773	0.40	27.0	-12.8	173.6	61.0	*93.0	229	4419	2042	1379
16	445	2768	0.45	11.0	-15.6	91.3	25.7	200.0	-159	1481	485	1638
17	465	2763	0.24	20.6	20.9	428.3	76.1	151.2	54	5356	1049	3621
18	480	2758	0.32	15.7	35.0	344.7	172.7	*0.0	442	6111	1967	1195
20	525	2745	0.28	46.7	0.0	291.9	-19.5	19.6	821	14909	3587	459
21	545	2741	0.20	20.4	24.1	224.5	15.9	7.6	246	5266	-37	277
22	570	2733	0.30	26.1	84.8	-59.4	168.5	17.8	1430	2167	2421	333
23	595	2728	0.20	25.5	3.5	151.1	90.5	*-23.0	1126	1169	3302	-67
24	620	2724	0.16	25.3	-190.5	95.1	76.5	18.7	-2367	3116	2113	-55
26	660	2712	0.29	41.6	136.1	79.3	26.7	*122.0	-1137	3641	2154	2937
27	680	2707	0.24	20.6	15.8	63.0	31.0	12.1	1565	1467	595	1383
28	710	2703	0.13	30.3	37.0	75.7	104.1	8.4	798	2100	2044	311
29	725	2700	0.20	15.3	-1.3	15.3	45.9	-12.3	273	696	1147	-30
30	750	2696	0.16	25.3	16.5	12.1	31.3	49.1	192	346	978	466
31	780	2676	0.55	34.3	28.7	-7.2	36.0	-3.6	815	88	1213	820
32	830	2666	0.20	51.0	35.2	86.2	10.6	-13.6	1628	2015	1188	-440
33	950	2633	0.27	124.1	3.2	24.7	-2.6	-7.6	2390	6905	497	-1321
35	1150	2588	0.22	204.8	19.8	10.5	-0.4	10.3	2366	3615	-315	277
36	1200	2578	0.20	51.0	27.8	10.9	24.9	-17.5	1214	546	623	-183
37	1300	2558	0.20	101.9	32.2	19.8	4.8	-5.6	3057	1563	1515	-1176
38	1370	2544	0.20	71.3	3.5	5.0	-2.7	4.2	1272	886	75	-51
39	1450	2530	0.17	81.2	-1.4	1.5	21.7	2.0	83	265	770	252
40	1560	2514	0.14	111.1	8.9	0.0	2.5	4.0	414	84	1346	337
41	1630	2502	0.17	71.0	1.9	20.6	7.8	-8.3	383	731	366	-153
42	1680	2492	0.20	51.0	2.1	9.4	-3.6	-3.2	102	764	105	-293

Table 3: Comparison of our estimates of net erosion volumes with values from publications in Russian given in Table 1.

Year of experiment	**1972**	**1973**	**1975**	**1976**
Erosion volume of solids (without pore space), V_E [m^3], passing cross-section no. 32 (calculated from Table 2)	19'800	75'300	61'400	15'300
Ratio to value in Table 1	1.00	1.06	1.36	1.33
Erosion volume of solids (without pore space), V_E [m^3], passing cross-section no. 42 (calculated from Table 2)	29'100	87'900	65'400	13'500
Ratio to value in Table 1	1.11	1.05	1.32	1.50

3.2 Comparison of erosion characteristics with bedload transport relations

The following general relationship has been proposed to describe bedload transport in torrents and gravel bed streams as a function of the "effective" discharge ($Q_m - Q_c$) and the channel slope S (Rickenmann 1994, 1997, 2001):

$$Q_b = a_1 (Q_m - Q_c)^{\alpha} S^{\beta} \quad (1)$$

where a_1 = an empirical constant; Q_m = mean discharge during a flood event; Q_c = critical discharge at initiation of bedload transport; and $S = \sin\theta$ = bed slope. In several bedload transport equations (Schoklitsch 1962, Smart 1984, Rickenmann 2001) the exponents in Equation 1 have the values $\alpha = 1$ and $\beta = 1.5$. Using these values, neglecting bed form roughness and considering the flow per unit channel width, Equation 1 can be written as:

$$\Phi_b = a_2\, \theta^{0.5} (\theta - \theta_c)\, Fr \quad (2)$$

where a_2 = an empirical constant; $\Phi_b = q_b/[(s\text{-}1)g d_m^3]^{0.5}$ = the dimensionless bedload transport rate, with q_b = bedload transport rate per unit channel width, $s = \rho_s/\rho$ = the ratio of solid to fluid density, g = gravitational acceleration, d_m = mean grain size; $\theta = h\,S\,/[(s\text{-}1)d_m]$ = dimensionless shear stress, with h = flow depth; θ_c = dimensionless critical shear stress at initiation of bedload transport; and $Fr = v/(gh)^{0.5}$ = Froude number equal to, with v = mean fluid velocity.

The above equations show that the bedload transport rate is basically a function of the shear stress acting on the bed, modified by the Froude number. In laboratory experiments, the agreement between measurements and predictions with the above relationships is generally the better for high flow intensities (with $Q >> Q_c$) and for conditions where no substantial bedform friction losses are present. At higher flow intensities, the exponent in Equation 1 and 3 is close to 1 whereas it may be much higher at flows close to the threshold for the initiation of bedload transport (Rickenmann 2001). From laboratory experiments on bedload transport with steep channel gradients up to 25 % it appears that an exponent $\beta = 2$ in equation (1) is more appropriate than $\beta = 1.5$ (Rickenmann 2001).
Integrating Equation 1 over the time of the flood event, we obtain:

$$V_B = a_1 (V_{W,e})^{\alpha} S^{\beta} \quad (3)$$

where V_B = bedload volume transported during the event; $V_{W,e}$ = effective volume of runoff water (with discharges higher than the threshold value Q_c). In the experiments leading to Equation 1 and 2, the moving solid material occupied more than half of the flow depth at higher bedslopes; for such conditions the distinction between bedload and suspended load is difficult to make, and the equations may be considered to represent total sediment transport rather than only bedload.

The Chemolgan data in Fig. 4 shows that the volume of entrained sediment appears to depend on the total volume of water which flowed along the test reach. For the further analysis it is assumed in analogy to Equation 3 that the observed erosion in a given reach depends essentially on a kind of integrated mean shear stress or hydraulic load of the debris-flow mixture which passed through that reach during one experiment:

$$A_e = V_e / dx = a_0 (V_m) (\rho_m/\rho_w) S^{\beta} \quad (4)$$

where A_e = erosion yield per unit channel length; V_e = volume of eroded solid material within a reach; dx = length of a reach; a_0 = an empirical constant; V_m = mixture volume (solids and water) which enters the reach from upstream; ρ_m = the density of the mixture entering; and ρ_w = density of water. The mass density is normalized because of easier comparison with results from laboratory experiments (see below). For $\beta = 1$ and assuming a constant average solid concentration and equal velocity for the flowing mixture, the expression $g\rho_m V_m S$ represents the integrated mean shear stress which acted on the channel reach during a given experiment.

The following assumptions and simplifications are made when applying 4 to the Chemolgan data: (i) The erosion is governed by similar factors as the bedload transport capacity of a water stream. (ii) All eroded solid material has been entrained into the flow during one given experiment. (iii) The mixture volume multiplied by the relative mixture density implies a heavier load acting on bed and banks for a more solid-rich mixture of a given volume. (iv) The amount of erosion is proportional to the length of the reach. (v) The threshold discharge for beginning of bedload transport at the Chemolgan test site is approximately Q_c = 2 to 3 m^3/s, and thus considerably smaller than $Q_{p,W}$ (except for the 1976 experiment) and $Q_{p,DF}$; therefore a value of $\alpha = 1$ is assumed. (vi) Differences in bed and soil properties among the reaches and in time (for different experiments) are neglected. (vii) The main erosion occurs behind the front of the debris flow where quasi-steady flow conditions can be assumed.

The further analysis includes only the cross-sections no. 1 through 32 where the erosion by the debris flows was not limited by bedrock. Using an exponent of $\beta = 1.5$, Equation 4 is applied to the Chemolgan data. In the following, the right-hand side of Equation 4 is labeled "hydraulic load". Fig. 9 shows a trend for the erosion volume to increase with increasing hydraulic load of the mixture flowing along the channel. Despite the large scatter of the data, a tenfold increase in the load implies roughly a tenfold increase in the eroded volume. This trend, however, is only evident for "higher" loads or for more "developed" flows with higher solid concentrations. The ratio of the eroded volume to the hydraulic load, $B = A_e/[V_m (\rho_m/\rho_w) S^{1.5}]$, may be considered as a kind of "erosion efficiency". This ratio is plotted in Fig. 10 against the sediment concentration of the flowing mixture. On average, the erosion efficiency does not seem to vary up to a solid concentration C_s of about 0.03 to 0.4, but it appears to decrease for higher solid concentrations of the mixture.

The same analysis presented in Fig. 5 to 6 was also made taking into account a value of Q_c = 3 m^3/s which has almost no influence on the results. The same is true if the analysis is made for $\beta = 1.0$ and for $\beta = 2.0$, which covers an approximate variation of this exponent as deduced from sediment transport studies.

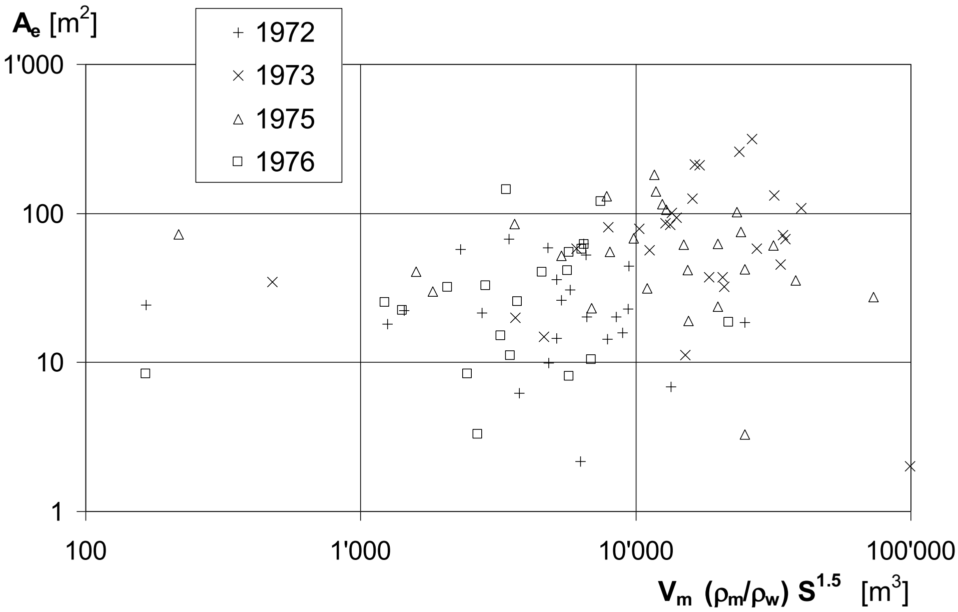


Fig. 9. Volume of eroded solid material per unit length of channel reach versus integrated "hydraulic load" of the mixture which enters the reach from upstream.

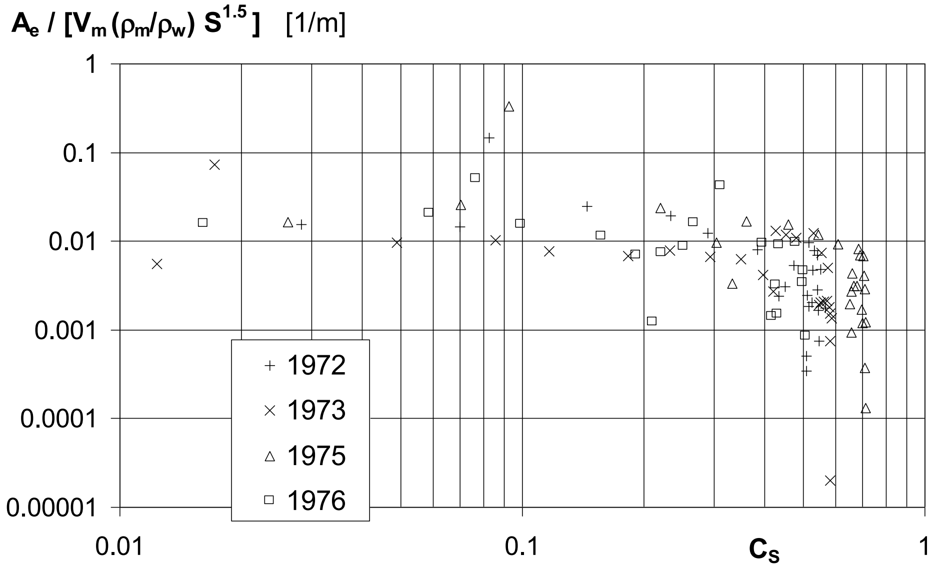


Fig. 10. The "erosion efficiency" ratio $B = A_e/[\ V_m\ (\rho_m/\rho_w)\ S^{1.5}]$ shown as a function of the solid concentration of the mixture entering the channel reach, C_s.

Neglecting Q_c in Equation (1), the analysis of sediment transport experiments in a steep laboratory flume with bedslopes up to 0.20 resulted in the following regression equation (Rickenmann 1990):

$Q_b = 6.8\ Q_m\ S^{2.1}$ (5)

Integrated over the time (duration of an experiment), and defining the mean sediment (bedload) volume concentration by $C_s = V_B / (V_B + V_W)$, with V_W = total water volume, Equation 5 can be transformed into:

$C_s / C^* = 6.8\ S^{2.1} / (6.8\ S^{2.1} + 1)$ (6)

where C^* is the maximum packing density of the bed material. Tognacca (1999) analyzed laboratory debris flows for bed slopes from 0.25 to 0.70, included bedload transport data from a steep laboratory flume with bed-slopes from 0.03 to 0.20, and derived the following regression equation:

$C_s / C^* = [\tanh(9.0\ S_e^{0.85} - 2.4) / 2.3] + 0.43$ (7)

where S_e is the energy slope which is approximated here with the bed slope of the channel ($\sin\theta$). Takahashi (1991) proposed an equation to determine the equilibrium sediment concentration in debris flows which is based on theoretical considerations and laboratory experiments. Dividing his equation 2.3.9 (Takahashi 1991) by C*, it reads in a comparable form:

$C_s / C^* = (s - 1) \tan\theta / [(\tan\phi - \tan\theta) / C^*]$ (8)

where ϕ is the angle of internal friction of the bed material, and the equation is only valid for the range C_s =< 0.9 C^*. The three equations are compared in Fig. 11 with the reach-wise data from the Chemolgan experiments. For this comparison it is assumed that $S = S_e = \tan\theta$ and that $\phi = 36°$ in equation 8. The observed solid concentration C_s represents a mean value over the duration of an experiment of all sediment and water entering each reach with a given bed-slope angle θ.

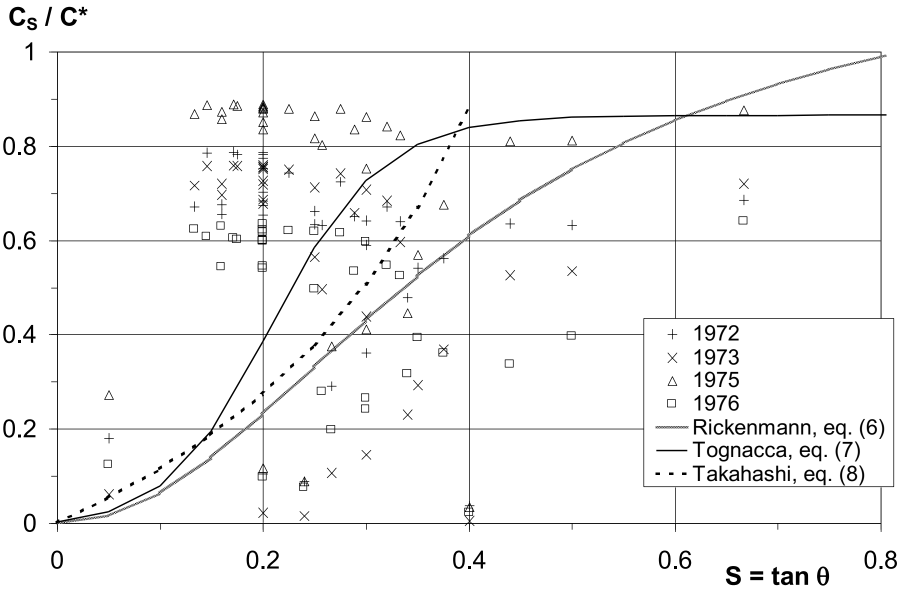


Fig. 11. Solid concentration of the mixture entering the channel reach (C_s) vs. bed-slope of the reach (tanθ), and comparison with three equations developed for bedload transport at steep slopes and debris flows.

Concerning Fig. 11 it is noted that equation 6 is applied here on slopes steeper than those pertaining to the experimental data which formed the basis for its development. The Chemolgan data points in Fig. 11 clearly display a large scatter. Interestingly they plot both above and below the three equations. Some of the scatter may possibly be attributed to rather short reaches, not promoting the development of "equilibrium" sediment transport conditions, apart from other perturbating effects (e.g., varying resistance of the bed against sediment entrainment). However, it is also pointed out that this is a very simplified representation of the reality (e.g., the data represent mean values over the duration of an experiment).

3.3 Comparison of Chemolgan data with laboratory data

In a laboratory flume, more than 140 experiments were performed to study the flow and erosion characteristics of debris flows and water surges along a steep erodible channel, covering a large range of solid concentrations of the initial mixture. The laboratory flume experiments are described in Rickenmann et al. (2003) and in more detail in Weber (2004).

Sediment material from the Swiss debris flow torrent Schipfenbach (Hürlimann et al. 2003) was used to make up the experimental bed where also bank erosion was possible. Fig. 3 shows the grain size distribution of the Schipfenbach test material, which is composed mainly of limestone, with some granite and limestone with smaller amounts of granite, shale, and gneiss. The initial volume of solids and water put into the reservoir ranged from 50 to 150 liters. The average solid volume concentration C_s of the flowing mixture was systematically varied between 0 (clear water pulses similar to dam break waves) and 0.77. The slope of the flume inclination ranged from 0.24 to 0.48. The debris flow surges had maximum flow depths between 0.10 m and 0.35 m, and the front velocities generally varied between 1 m/s and 6 m/s.

The volumes of the material eroded along the test reach were generally less than 10 % of the initial surge volume released from the starting container. The eroded material tended to be incorporated in the rear part of the surge. Statistical correlations are generally rather weak when the erosion volumes are compared with parameters characterizing the debris-flow surges. Nevertheless, a trend can be observed for erosion volumes to increase with increasing channel gradient, initial mixture volume and water content of the mixture. Using equation 4, a similar analysis was made for the laboratory experiments as for the field experiments. To allow for a direct comparison between laboratory and field experiments, a modified erosion efficiency factor B' is defined in a nondimensional way as follows:

$$B' = A_e W_o / [V_m (\rho_m/\rho_w) S^{1.5}] \quad (9)$$

where W_o = a characteristic length, here taken as a typical channel width. The factor W_o also acts to modify the effect of the hydraulic load. For otherwise equal conditions, the flowing mixture has a smaller flow depth (and shear stress) in a wider channel than in a narrower channel. The following values are used here: W_o = 0.35 m (series A) and W_o = 0.30 m (series B) for the laboratory experiments, and W_o = 8 m for the field experiments. These values represent a typical width during the main part of the flows.

The results are shown in Fig. 12 where the factor B' is plotted against solid concentration. In order to assign less weight to the fewer data points with small solid concentrations (where the field debris flows were in their initial phase), the expression $(1- C_s/C^*)$ is used here instead of C_s alone where C^* is the natural packing density of the eroded bed material. C^* = 0.85 for the laboratory material and C^* = 0.82 for the field material were used. The erosion efficiency of the series A data appears to be smaller than for the series B data. Despite the considerable scatter of the data, a similar trend can be observed as for both the field and laboratory data.

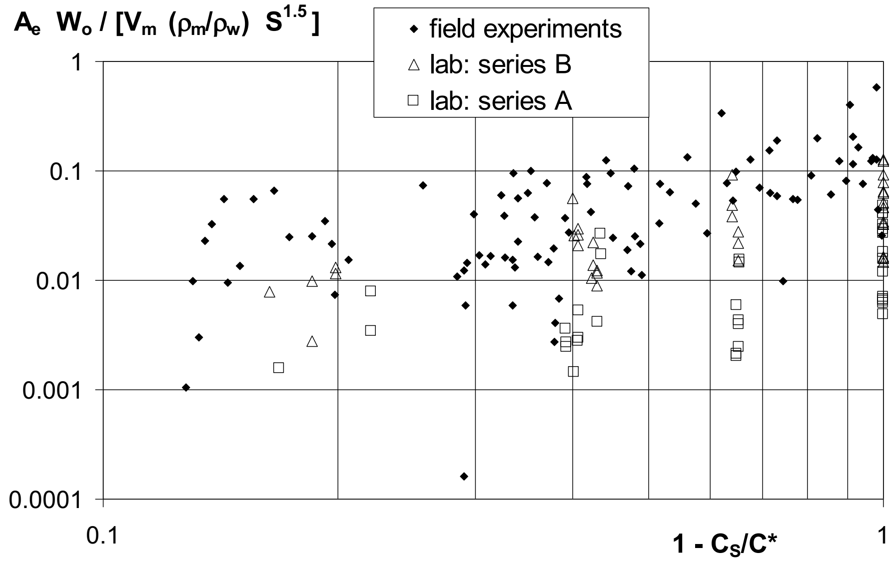


Fig. 12. The dimensionless "erosion efficiency" ratio $B' = A_e W_o / [V_m (\rho_m/\rho_w) S^{1.5}]$ shown as a function of the expression for the solid concentration of the mixture entering the channel reach, $(1- C_s/C^*)$, comparing field and laboratory data.

4. Discussion

The largest uncertainty regarding all assumptions listed in section 3.2 is probably associated with the assumption vi, described above, regarding equation 4 that the amount of erosion is proportional to the length of the reach. In reality, it may be expected that erosion resistance characteristics are quite variable in space and time. This serious restriction in the analysis may be a major factor responsible for the large scatter of the data in Fig. 5 to 7. It is noted that sediment transport loads (for example averaged over the time of a flood event) show a similar scatter for given flow conditions (Rickenmann 2001). In fact, the scatter of in bedload transport rates at given flow intensities may even be much larger, particularly close to critical conditions for beginning of motion.

In the experimental laboratory flows with an erodible bed it was observed that most erosion by debris flows takes place behind the front where the mixture was generally more fluid (Weber 2004). In these experiments, the front part mainly acted to destabilize the banks, and this material was then often entrained by the rear part of the surge. At the Chemolgan experiments, the relatively small bulking factor of about 3.8 on average indicates that majority of the eroded material was incorporated into the flow behind the main body and rear parts of the debris flows. This suggests that the local flow conditions at the front are probably not of primary importance for the erosion and entrainment of solid material, and that the use of the bed slope as an approximation of the energy slope may be justified.

According to Fig. 10 and 12 less concentrated debris-flow mixtures tend to be more erosive than those already heavily loaded with sediments. This trend is in agreement with observations in torrents or rivers, where flood waters are generally much more erosive downstream of a sediment retention structure with substantial or complete blocking of the bedload transfer.

A major restriction of the laboratory experiments was the limited volume available for the surges, as compared to typical natural debris flows. This is probably an important factor contributing to the relatively large scatter when analyzing the erosion volumes. In natural debris flows, much of the eroded material is likely to be entrained by the by the body or rear part of the surge where there is generally a higher water content. As compared to field conditions, in the laboratory flume the peak flow velocities were somewhat too high whereas the surge volumes and especially the surge durations were clearly too small (Rickenmann et al. 2003).

5. Summary and Conclusions

Several field experiments on debris were carried out at the Chemolgan test site in Kazakhstan. This field experiments represent a unique data set. The experiments allowed to study the debris-flow formation as a result of an initial water surge entraining bed and bank material along a steep channel entrenched into morainic deposits. Artificial floods triggered the formation of debris flows with resulting solid concentrations by volume of more than 0.73.

The presented analysis is based on only a few parameters, mostly representing peak values or values integrated over the surge duration. In general, the data show a considerable scatter. The measured flow parameters and the erosion characteristics were analyzed in terms of the evolution of mean values over the duration of an experiment along discrete reaches of the channel. The following conclusions can be drawn, although the data show a large variability:

1. The erosion volume tends to increase with increasing water runoff volume.
2. The peak debris-flow discharge tends to increase with increasing peak water discharge.
3. The mean erosion per unit channel length appears to depend on the hydraulic load, here defined as the product of the mixture volume entering the reach, the normalized mixture density and a bed slope factor.
4. The observed mean sediment concentration is only in very rough agreement with three semi-empirical relationships which predict increasing equilibrium sediment concentration with increasing bed slope.
5. Above a mixture solid concentration of about 0.4 (by volume), the erosion efficiency appears to decrease with increasing solid concentration of the flowing mixture. It appears that surges with a high sediment concentration tend to be less erosive than more fluid mixtures.

Similar measurements were performed in a laboratory flume. The analysis of this data shows an even larger variability of the eroded volumes but on the whole results in similar trends.
It is expected that a more accurate analysis should also consider factors characterizing in particular the resistance of the channel bed against erosion.

REFERENCES

1. Cannon, S. 1993. An empirical model for the volume-change behavior of debris flows. In H.W. Shen, S.T. Su & F. Wen (eds), *Hydraulic Engineering ´93, Proceedings ASCE Conference, San Francisco*: 1768–1773.
2. Davies, T.R.H. 1994. Dynamically similar small-scale debris flow models. *Proceedings International Workshop on Floods and Inundations Related to Large Earth Movements, Trento, Italy, IAHR*: A12.1–A12.11.

3. Hungr, O. & Evans, S.G. 1997. A dynamic model for landslides with changing mass. In Marinos, Koukis, Tsiambaos & Stournaras (eds), *Engineering Geology and Environment*: 719-724. Rotterdam: Balkema.
4. Hürlimann, M., Rickenmann, D., & Graf, C. 2003. Field and monitoring data of debris-flow events in the Swiss Alps. *Canadian Geotechnical Journal* 40: 161–175.
5. Khegai, A.Y., Popov, N.V., Plekhanov, P.A. & Keremkulov, V.A . 1992. Experiments at the Chemolgan debris-flow testing ground, Kazakhstan. *Landslide News* 6: 27–28.
6. Khonin, R.V., Keremkulov, V.A. & Mochalov, V.P. 1977. The third experiment on the artificial replication of a debris flow. In *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* 2: 57–63. (in Russian*)
7. Khonin, R.V., Mochalov, V.P. & Zems, A.E. 1976. The experimental site in the Chemolgan River basin and the history of its founding: In *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* 1: 7–25. (in Russian*)
8. Kirenskaya, T.L., Stepanova, T.S. & Balabayev, F.G. 1980. Chemolgan-78. In *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* 5: 64–71. (in Russian*)
9. Mizuyama, T., Kobashi, S. & Ou, G. 1992. Prediction of debris flow peak discharge. *Proceedings International Symposium Interpraevent, Bern, Switzerland*, Vol. 4: 99–108.
10. Mochalov, V.P., Kim, A.K. & Khaydarov, A.K. 1992. Results of the experiment "Chemolgan-91". In *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* 12: 101–109. (in Russian*)
11. Rickenmann, D. 1990. Bedload transport capacity of slurry flows at steep slopes. Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, Nr. 103, 249p.
12. Rickenmann, D. 1994. Bedload transport and discharge in the Erlenbach Stream. In P. Ergenzinger & K.H. Schmidt (eds), *Dynamics and Geomorphology of Mountain Rivers, Lecture Notes in Earth Sciences* 52: 53–66.
13. Rickenmann, D. 1997. Sediment transport in Swiss torrents. *Earth Surface Processes and Landforms* 22: 937–951.
14. Rickenmann, D. 1999. Empirical relationships for debris flows. *Natural Hazards* 19 (1): 47-77.
15. Rickenmann, D. 2001. Comparison of bed load transport in torrents and gravel bed streams. *Water Resources Research* 37 (12): 3295–3305.
16. Rickenmann, D., Weber, D., Stepanov, B. 2003. Erosion by debris flows in field and laboratory experiments. In D. Rickenmann & C.L. Chen (eds), "Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment", Proceedings 3rd International DFHM Conference, Davos, Switzerland, September 10–12, 2003: 883–894. Rotterdam: Millpress.
17. Schoklitsch, A. 1962. *Handbuch des Wasserbaus*. 3rd Edition. Vienna: Springer. (in German)
18. Smart, G.R.M. 1984. Sediment transport formula for steep channels. *Journal of Hydraulic Engineering* 110 (3): 267–276.
19. Stepanov, B.S. & Stepanova, T.S. 1991. *Mechanics of debris flows*. Moscow: Publishing house Gidrometeoizdat. (in Russian)
20. Stepanova, T.S., Khonin, R.V., Krzhechkovskaya, N.I. & Khaydarov, A.K. 1978. Results of an experiment on the artificial replication of a debris flow in the Chemolgan River basin in 1976. In *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* 3: 86–92. (in Russian*)
21. Takahashi, T. 1991. *Debris Flow*. IAHR Monograph Series. Rotterdam: Balkema.
22. Takahashi, T., Nakagawa, H., Harada, T. & Yamashiki, Y. 1992. Routing debris flows with particle segregation. *Journal of Hydraulic Engineering* 118 (11): 1490–1507.
23. Tognacca, C. 1999. Beitrag zur Untersuchung der Entstehungsmechanismen von Murgängen. *PhD Dissertation No. 13340, ETH Zürich,* Switzerland. [= Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, Nr. 164, 259p.]
24. Tognacca, C., Bezzola, G.R. & Minor, H.-E. 2000. Threshold criterion for debris-flow initiation due to channel-bed failure. In G.F. Wieczorek & N.D. Naeser (eds), *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment; Proceedings 2nd International DFHM Conference, Taipei, Taiwan, August 16–18, 2000*: 89–97. Rotterdam: Balkema.
25. Weber, D. 2004. Untersuchungen zum Fliess- und Erosionsverhalten granularer Murgänge. *PhD Dissertation No. 15321, ETH Zürich,* Switzerland.
26. Zems, A.E., Khonin, R.V. & Laptev, V.I. 1976. The solid/liquid material balance in the debris flows of 1972-1973 in the Chemolgan River basin. In *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* 1: 35–43. (in Russian*)

* The original publications in Russian indicated with an asterix are included as English translations in this volume [Rickenmann, D., Stepanov, B. & McArdell, B. (eds) 2004. Field experiments and natural debris flows in Kazakhstan. Swiss Federal Research Institute WSL, Birmensdorf, Switzerland.]

Part B: Natural Debris Flows in the Zailiysky Alatau Mountains

Debris flows in the Zailiysky Alatau Mountains and climate change

R.K. Yafyazova

National Hydrometeorological Service of Kazakhstan (Kazhydromet), Astana, Kazakhstan

In the foothills of the northern slope of the Zailiysky Alatau a narrow area formed as a result of the confluence of debris fans that close the mountain valleys (90–95 % of the volumes of the fans consists of debris-flow deposits). It is the most favorable area for human life and economic activity. At the present about two million people live in this area. Hence, the settlements and objects of economic activity are in a debris-flow hazard zone. A schematic map of the northern slope of the Zailiysky Alatau is shown in Fig. 1.

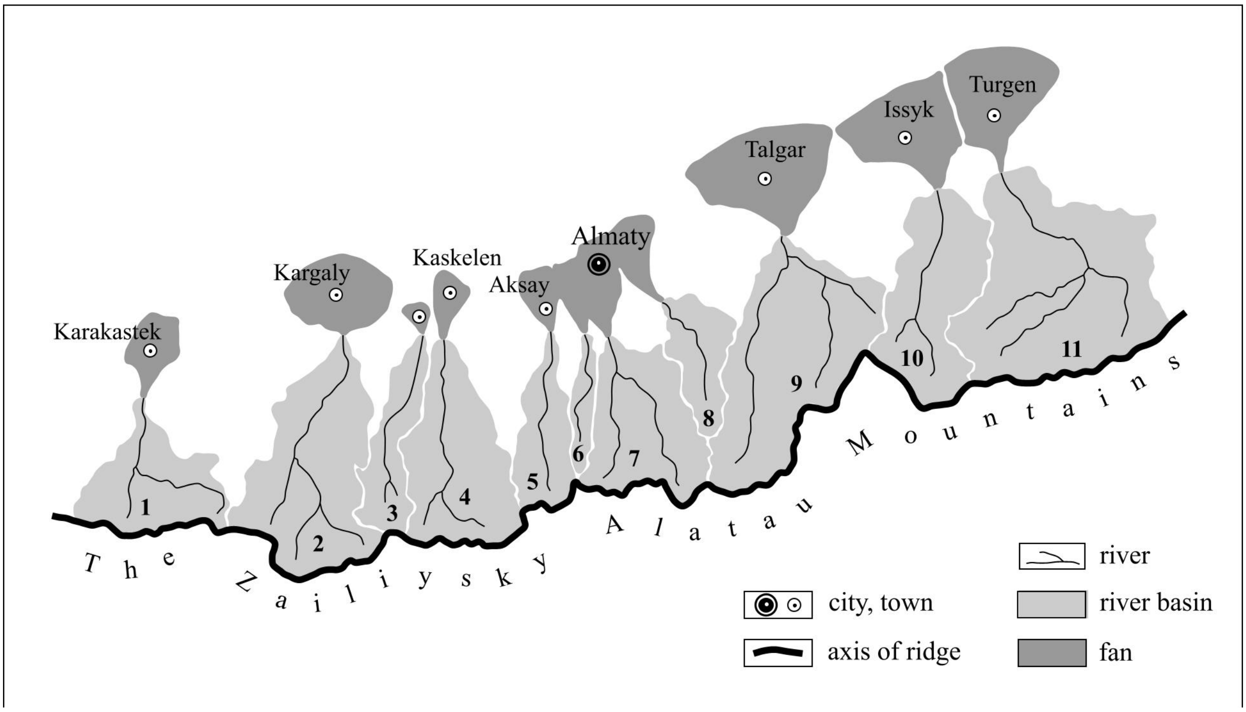


Fig. 1. The northern slope of the Zailiysky Alatau. River basins: 1 − Karakastek, 2 − Uzunkargaly, 3 − Chemolgan, 4 − Kaskelen, 5 − Aksay, 6 − Kargaly, 7 − Bol'shaya Almatinka, 8 − Malaya Almatinka, 9 − Talgar, 10 − Issyk, 11 − Turgen.

To evaluate debris-flow activity under a changing climate were used data a unique repository, which is data of the debris fans [4, 5 and 9]. A study of the relief of the mountain and foothill zones showed that around 50 % of the volumes of the fans consists of deposits the Riss-Würm interglacial period. The study of stratigraphic section of the debris fan of the Aksay River showed geochronologic and paleogeographic data encompassing the last 300–350 thousand years. The most complete data on the magnitude of glaciation and debris-flow activity are available for the period encompassing the terminal phase of the Riss glacial, Riss-Würm interglacial, Würm glacial periods, and the Holocene.

Past climate change and debris-flow activity

Debris-flow activity is characterized by the recurrence of debris flows, by the discharge and by the volume of material removed by them. These characteristics are determined by geological, geomorphological and, above all, climatic factors which form a system with deep reciprocal ties. Radical variations in climate caused debris-flow activity to change from practically zero to the peak value, which occurred in the Quaternary period. There were practically no debris flows during the Riss Ice Age, when air temperature was 9–10.5 °C below present-day values and the snow line depression on the northern slope of the

Zailiysky Alatau was 1300–1500 m. The peak of debris-flow activity in the Quaternary period occurred in the warmest period of the Riss-Würm interglacial period, when air temperature was 2–2.5 °C above present-day values.

Landscapes were radically transformed in the course of climate changes. Fig. 2A&B show the hypothetical landscapes of the Malaya Almatinka River basin corresponding to the peak of the Riss Ice Age and to at the present climate, respectively. It is easy to see that during the Riss Ice Age the nival landscape became dominant in the mountain zone, meadow landscape were replaced not only on the territory where forest landscape are present now, but also partly on the territory which is occupied by steppe landscape. Mountainous forest landscape could grow on the debris fans if moisture was sufficient. In accordance with migration of flora, fauna migrated as well.

The Riss Ice Age was characterized by much less erosion in the middle- and low-mountain zones and active accumulation of sediment in the high-mountain zone where formation of glacial deposits took place. In the low-mountain zone loess accumulated. During glacial periods as a result of decrease of air temperature a streamflow was greatly reduced. The starting places of most rainfall-caused debris flows were in an area with slight slope where soil was thin. During glacier expansion and later stabilization, the danger from glacier lakes outburst was at a minimum. Taken together all information leads to the conclusion that during glacier periods debris-flow activity was very limited.

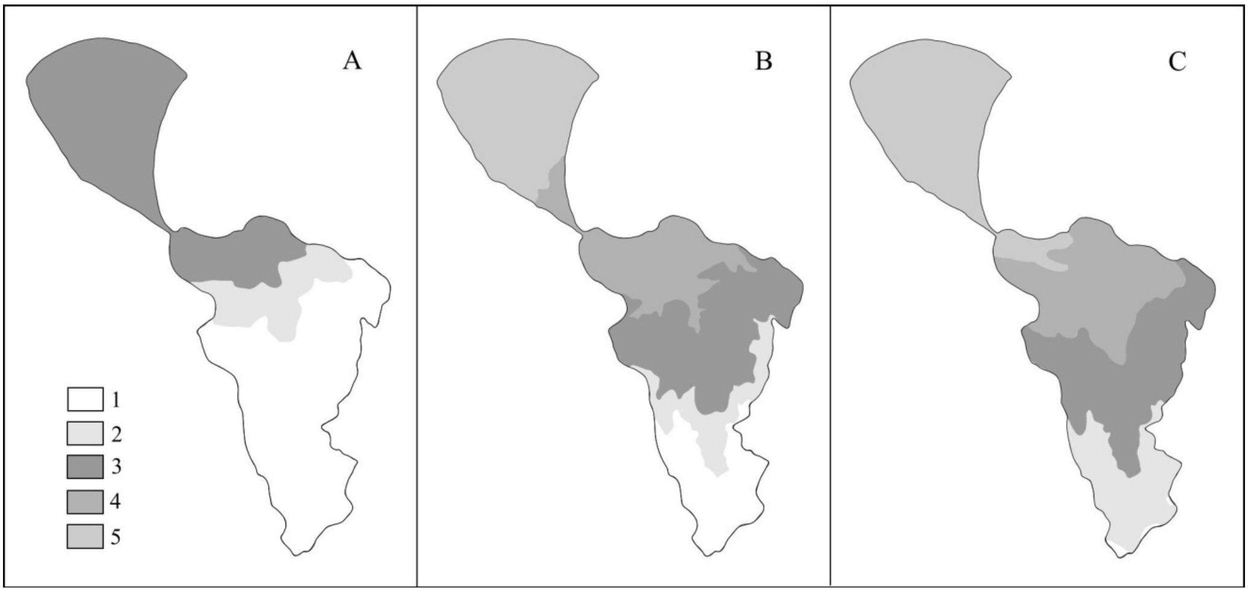


Fig. 2. The schematic map of landscapes of the Malaya Almatinka River basin. A − in the period of the Riss Ice Age; B − at the present time; C − under climate warming (the Riss-Würm interglacial period and the modern climate warming). Landscapes: 1 − nival; 2 – meadow (alpine and subalpine); 3 − forest; 4 − steppe; 5 − semi-desert.

The climate of the Riss-Würm interglacial period led to radical transformation of landscapes on the northern slope of the Zailiysky Alatau (Fig. 2C). Nival landscape occupied less than 10 % of the total area of the basin at that time. Glaciers were still present, but only on the northern slopes of the highest parts of the mountain range. Global air temperature was 2–3 °C higher than the present [2]. This led to degradation of glaciers and caused formation, evolution, and breakout of lakes of the moraine-glacial complexes. The starting places of rainfall-caused debris flows were in an area with steep slope where soil was relatively thick. During the Riss-Würm interglacial period global climate warming created favorable conditions for forming rainfall-caused debris flows, as the probability of rainfalls in the high-mountain zone considerably increased and led to increase of frequency and scale of debris-flow events. During the Riss-Würm interglacial period debris-flow activity increased so much that for relatively short time interval

[2] drift deposits of the Riss Ice Age were mostly removed by debris flows formed a major part of the debris fans on the foothill plain. At this time, the volume of debris fans located on the foothill plain increased nearly two times. These deposits have a volume between 0.5 and 7 billion m^3 [11].
During the Riss-Würm interglacial period the localities of most present-day valley glaciers were occupied by meadow landscape. The territory occupied today by meadow landscape became forest landscape. Steppe landscape occupied the territory between altitudes of 1400–2200 m a.s.l. During the interglacial period, after glaciers contracted, fauna "spread" into favorable mountain habitats. The largest part of the low-mountain zone became arid and semi-arid vegetation. Loess cover lost their protective plant cover and could not resist extensive erosion. As a result, billions of cubic meters of sediment were eroded and carried away by debris flows and filled the area between debris fans. Thus, at altitudes of 1000–2000 m a.s.l. the topography of interfluve of the Zailiysky Alatau was transformed.

The Würm Ice Age again led to changes of landscapes, though not as major as during the Riss Ice Age. According to paleoclimatic data, temperature dropped by several degrees for relatively short time interval (thousands of years) during the Würm Ice Age [3]. This drop led to vegetation changes on the northern slope of the Zailisky Alatau. However, these short intervals were insufficient for initiation of debris flows. Overall, debris-flow activity nearly stopped. A noteworthy event occurred 20–25 thousand years ago when an abrupt increase of sediment runoff took place in nearly all the river basins on the northern slope of the Zailiysky Alatau. However, the increase was of relatively short duration. It is likely that the increase was caused by a strong earthquake which led to massive slope failures, breakage of streams and formation of lakes in the basins of the Issyk and debris fans located on the foothill plain [8, 10].
Holocene climatic warming has led to contraction of glaciers in the mountain ranges. Following the climatic optimum of the Holocene, mountain landscapes stabilized to a state typical of the 20th century. Thus, it appears that debris-flow activity and volume of sediment carried out to the foothill plain during the Holocene did not exceed 1 % of the volume of sediment carried to it during the Riss-Würm interglacial period [6].

Modern climate warming and debris-flow activity

When we consider that the Minor Glacial Period ended in the middle of the 19th century and changes in debris-flow forming factors take several decades because of the gradual nature of such changes, we can see that the climate in the second half of 20th century was most favorable for debris-flow activity. Glaciers are presently retreating everywhere, and proglacial, karst and thermokarst lakes are forming on them. At the same time, runoff from the glaciers is increasing, causing the lakes to overflow and increasing the probability of their catastrophic outburst.
These conditions also may be considered favorable for the formation of rainfall-caused debris flows in the high-mountain zone. With the present position of the climatic snow line the probability of cloudburst precipitation in liquid form in the high-mountain zone rose to values at which we can expect large rainfall-caused debris flows to occur once in 25–50 years in each of the large torrent catchments.
According to the scenarios worked out for climate change, air temperature in the Zailiysky Alatau will rise 3–4 °C [1]. Such a temperature change, particularly during the summer period, will lead to radical change in the debris-flow forming factors and, accordingly, to an increase in the frequency and magnitude of debris-flow events. Moreover:

- the snow line will rise by more than 400 m, causing a sharp degradation of glaciation and consequently an increase in the number of debris-flow hazardous lakes and the probability of their outburst;
- landscape belt elevations will change, which will have an effect on the characteristics of runoff processes; as a result of the elevating of the forest line the denudation process will intensify in the elevation belt of 1600–2000 m;
- debris-flow initiation zones will be displaced to higher elevations (up to 4000 m), and consequently their areas will enlarge and their longitudinal gradients will be steeper;
- the probability of precipitation in liquid form will increase by a factor of three.

The elevation zone of 3500–4000 m and higher is characterized by high gradients of potential energy, providing the prerequisites for a rise in the number of debris-flow initiation zones in comparison with the number existing today and for an increase in the magnitude of debris-flow processes.
Future climate warming will lead to the breakup of large glaciers into relatively small ones and, consequently, to an increase in the number of debris-flow hazardous lakes. (Thus, for example, on the northern slope of the Zailiysky Alatau 57 glaciers broke up in the years from 1955 to 1990, and as the result 131 glaciers formed.) The time necessary for the forming of lakes will be reduced, which means that the frequency of lake outbursts will increase. Failure to undertake measures with respect to the formation and preventive draining of debris-flow hazardous lakes is fraught with the risk of a substantial increase in debris-flow activity during the 21st century. More details on climate change and debris-flow activity in this region are given in [12, 13].

Debris-flow hazard and strategy for protection

Study of climatic changes in Kazakhstan showed [1] that over the 20th century mean annual temperature rose at the rate of 0.1 °C every 10 years. This trend is the consequence of a prolonged natural fluctuation in climate, complicated by climatic change resulting from the intensification of the greenhouse effect caused by an increase in the concentration of greenhouse gases in the Earth's atmosphere. If the experts have judged correctly that the present concentration of carbon dioxide is the highest in the last 420 thousand years, then the warming in the coming decades will reach and even surpass that which occurred in the Riss-Würm interglacial period.
We can avoid the catastrophic consequences of warming for the economy of Kazakhstan (resulting from the intensification of debris-flow activity) only by radically revising the presently employed strategy for protection against debris-flow occurrences. A principal role in the new strategy must be given to preventive measures aimed at averting or reducing the magnitude of debris-flow events.
Under these circumstances anthropogenic control over the debris-flow processes cannot be regarded as crude interference in natural processes because in the past, as is evident from the Earth's history, periods of accumulation and removal of sediments have differed from each other for thousands and tens of thousands of years. With time for steady development work, we will be able to find optimal ways to solve problems associated with the erosion and denudation processes [7].

REFERENCES

1. Assessment of the effect of climate change and measures for adapting to it for the coastal zone of the Caspian Sea and the mountain regions of Southern and South-Eastern Kazakhstan: A summary for officials responsible for social-economic and environmental protection policy. Almaty: Kazakh Research Institute for Environmental and Climate Monitoring (2000) 51 pp.
2. Jouzel, J., Lorius, C., Petit, J.R., Barkov, N.I. & Kotlyakov, V.M. 1994. Vostok isotopic temperature record. In T.A. Boden, D.P. Kaiser, R.J. Sepanski & F.W. Stoss (eds.), *Trends’93: A Compendium of Data on Global Change*: 590–602. ORNL/CDIAC-65. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.
3. Kotlyakov, V.M. & Lorius, C. 1992. Global changes during the last glacial-interglacial cycle. *Proceedings of the Russian Academy of Sciences, Geographical series* 1: 5–22 (in Russian).
4. Stepanov, B.S. & Yafyazova, R.K. 1995. Details concerning the formation of debris fans on the northern slope of the Zailiysky Alatau Mountains. *Hydrometeorology and Ecology* 3: 18–28. (in Russian)
5. Stepanov, B.S. & Yafyazova, R.K. 1995. The role of climate in debris-flow activity on the northern slope of the Zailiysky Alatau. *Hydrometeorology and Ecology* 4: 46–59 (in Russian).
6. Stepanov, B.S. & Yafyazova, R.K. 2002. Holocene climate and activity of debris flows in the northern slope of the Zailiysky Alatau Mountains. *Hydrometeorology and Ecology* 1: 74–81 (in Russian).
7. Stepanov, B.S. & Yafyazova, R.K. 2014. *Debris flows in the Southeast Kazakhstan: Debris-flow processes and countermeasures against debris-flow hazards* (in Russian).
8. Stepanov, B.S., Khaidarov, A.Kh. & Yafyazova, R.K. 2003. Post-seismic disasters: past and potential in the Northern Tien Shan. *Problems of Destructive Earthquake Disaster Prevention; Proceedings of the second Kazakhstan-Japan Workshop, Almaty, Kazakhstan, September 23–25, 2002*: 90–96.

9. Yafyazova, R.K. 1996. Details concerning the mechanisms for the formation of debris fans of mountain rivers. *Hydrometeorology and Ecology* 2: 175–187 (in Russian).
10. Yafyazova, R.K. 2001. Phenomena of loess cover of debris cones of the Zailiysky Alatau northern slope rivers. *Hydrometeorology and Ecology* 1–2: 155–160. (in Russian)
11. Yafyazova, R.K. 2002. Debris fan volume as an indicator of debris flow activity. *Hydrometeorology and Ecology* 2: 90–99. (in Russian)
12. Yafyazova, R.K. 2003. Influence of climate change on mudflow activity on the northern slope of the Zailiysky Alatau Mountains, Kazakhstan. In D. Rickenmann & C.L. Chen (eds), *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment; Proceedings 3rd International DFHM Conference*, Davos, Switzerland, September 10–12, 2003: 199–204. Rotterdam: Millpress.
13. Yafyazova, R.K. 2007. Debris cones as a source of information on debris-flow activity. In C.L. Chen & J.J. Major (eds), *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment; Proceedings 4th International DFHN Conference*, Chengdu, China, September 10-13, 2007:87-93.

The debris flow of 15 July 1973 in the Malaya Almatinka River*

Yu. B. Vinogradov, A. E. Zems & R. V. Khonin

The authors of this paper by now have had time to become familiar with certain papers devoted to the Malaya Almatinka debris flow of 1973 [1–4]. A certain amount of haste in preparing these papers for publication is to some extent understandable, but debris-flow specialists on reading them are left with a feeling of disappointment. In addition to the clearly false information (photography erroneously taken as depicting moraine lakes at the end of the Tuyuksu glacier [2], treating the emergency situation at the Medeo dam as related to a shortage of water "for the normal irrigation of fields and orchards" [2], an erroneous quantitative evaluation of the magnitude of the initial outburst flow [3, 4], attributing the debris waves following the main debris flow to the outburst of internal glacial waters from the righthand side of the Tuyuksu glacier [1]), a distinctive feature of these papers is a too loose treatment of numerical data, in particular the quantitative characteristics of the debris flow of 1973 as well as the cloudburst-induced debris flow of 1921.

The events unfolding at the end of the day on 15 July were preceded by unusually hot weather on the northern slope of the Zailiysky Alatau. In the period from 10 to 15 July the mean daily temperature at the Mynzhilki high-mountain station (3017 m) fluctuated between 9.5 and 14.4 °C, which considerably exceeds the usual norm, while the height of the zero-degree isotherm on the morning of 13 July reached 4800 m, which is also observed here fairly rarely.

For information on certain details of the processes taking place (15 July 1973) on the moraine of the Tuyuksu glacier we are indebted to associates of the Geographic Section of the AN KazSSR [Academy of Sciences of the Kazakh SSR] P. A. Sudakov and P. A. Plekhanov. Despite the fact that as direct observers of this extreme phenomenon they did not quantitatively record many important details and sometimes recorded conflicting numbers, particularly with respect to the times of some events, it is nevertheless difficult to overrate the significance of the fact that thanks to them we have available an approximate hydrograph of the lake's draining.

During the first half of the day on 15 July P. A. Sudakov and P. A. Plekhanov recorded a surface overflow from lake 2 into lake 3, despite the fact that the water level in lake 2 was 35–40 cm short of its maximum level of 1971. The difference between the lake levels, according to a 1958 survey, measured 7.7 m. By 15:00 the overflow discharge was visually estimated as 0.2–0.3 m^3/s. It was precisely at this time that an opportunity was lost to avert the catastrophe with modest means.

At approximately 16:00 the water level in lake 3, despite the increasing flow into it, began to fall and started to rise precipitously only a few minutes before the outburst. It may be supposed that the subsidence and weakening of the dam between lakes 2 and 3 on the one hand, and fluctuations in the drainage system of lake 3 on the other, were associated with the shifting of part of the morainic mass at this location. Obviously, the latter was associated with the intensified thawing of buried ice and frozen rock as a result of the influence of the stray filtration flow of melted waters from the glacier.

At 17:54 h the failure of the dam between lakes 2 and 3 became catastrophic in character, and at the same time water rushed out of lake 3 over the external terrace of the moraine. Fig. 1 presents a hydrograph of the outburst of lake 2 constructed from the data of P. A. Sudakov and a curve of the water volume of the lake as a function of its level obtained from data in a survey of the basin of lake 2 completed by KazNIGMI [Kazakh Institute for Hydrometeorological Research].

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 60–73.

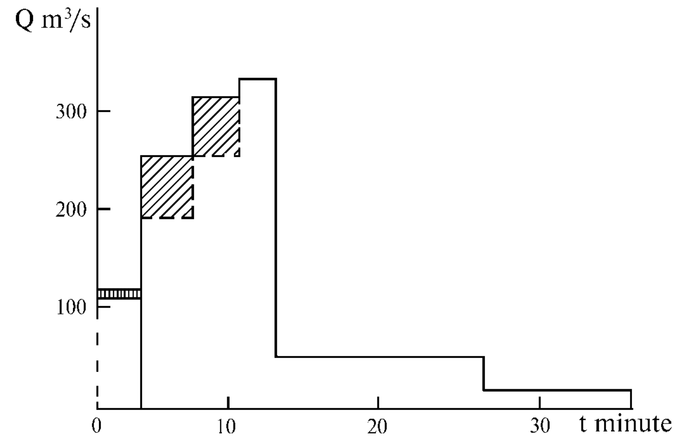


Fig. 1. Hydrograph of discharges during the outburst of lake 2.

The hydrograph indicates that the outburst opening, which was 30 meters wide in its upper part (Fig. 2), was completely formed by 18:03 h, followed immediately (around 18:04–18:05 h) by a peak outburst discharge, estimated at approximately 350 m^3/s. In 12 min the level of lake 2 fell by 3.5 m, which corresponds to an outflow volume of 162 thousand m^3. The completely lowered level measured 5.8 m (224 of 260 thousand m^3). The total volume of water discharged from the moraine was estimated as 225 thousand m^3, taking into account the small contribution of lake 3. A volume of water reckoned at 42 thousand m^3 (Fig. 3) remained in the basin of lake 2 after the outburst.

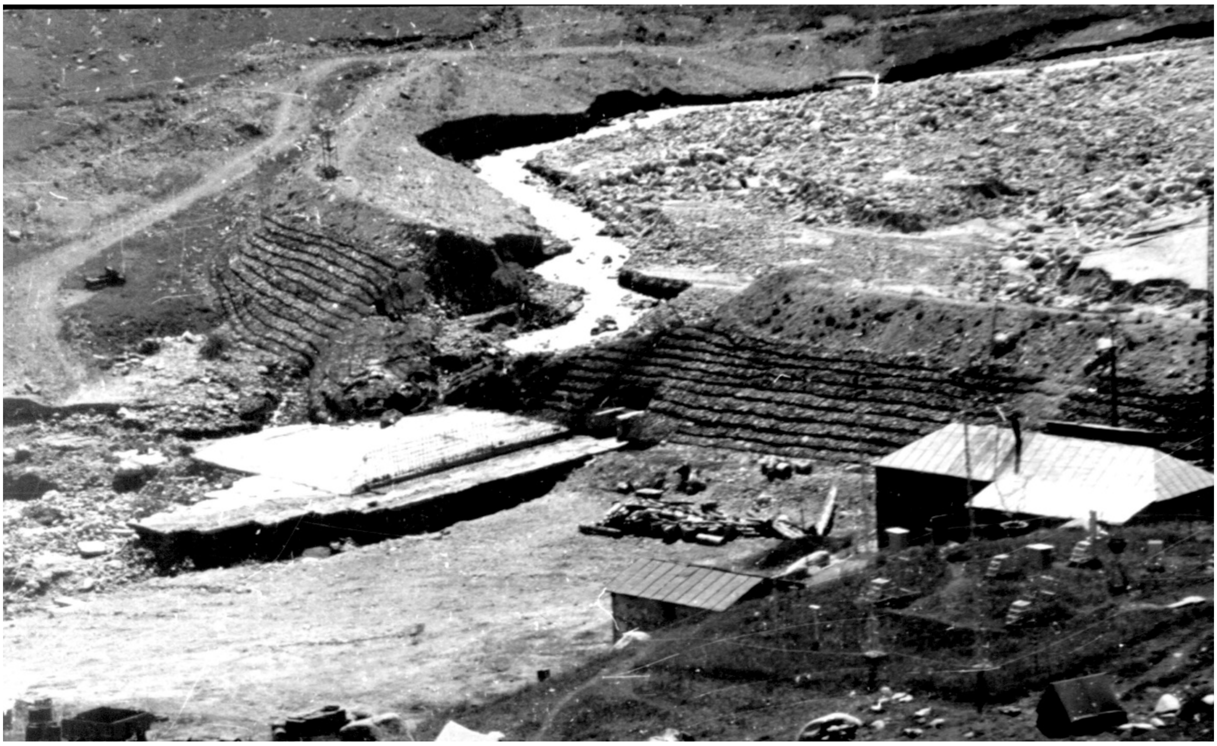


Fig. 2. Gabion dam opening after the debris flow of 15 July 1973.

Despite the steep slopes on the moraine terrace (Fig. 4) and the large magnitude of the outburst discharge, the eroding power of the water flow had only a negligible effect, which is attributed to the presence of buried ice and frozen rock under less than a meter-thick moraine. The path of the water flow over the terrace of the moraine into the Mynzhilki glacial trough is well traced in a schematic drawing and photography (Figs. 5, 6). Rock shed from the moraine was deposited in an 800 meter strip extending from the foot of the moraine frontal terrace to the gabion dam by the Mynzhilki weather station.

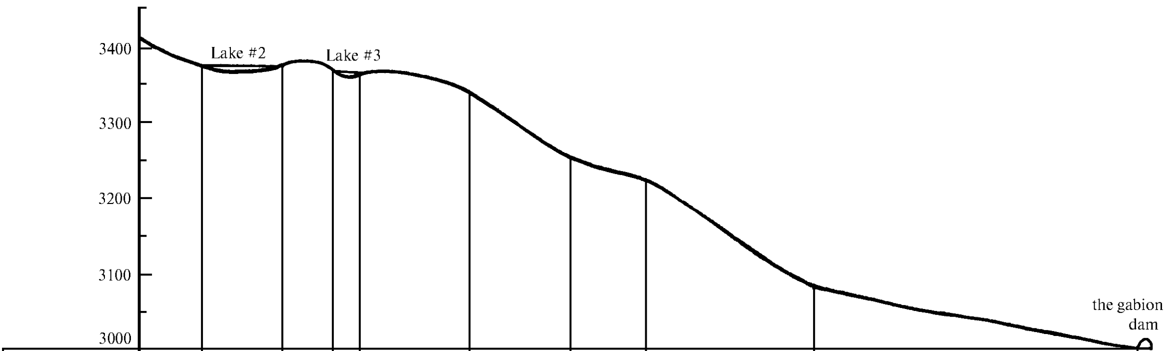
According to data from multiple levels taken by V. A. Golubovich (of the Almatinka debris-flow observation station of UGMS [Directorate of the Hydrometeorological Service] of the Kazakh SSR), the total volume of debris-flow deposits above the gabion dam is estimated at 140 thousand m^3.

The gabion dam in the Mynzhilki trough (Fig. 7), constructed in 1964–65, was intended for the retention of outburst floods similar to the flood of 7 August 1956 which produced the notorious debris flow. The dam was 6 m in height, and the capacity of the potential debris-flow or water reservoir was 32,000 m^3. The dam core was made of boulders and rubble reinforced by a metal netting of 2-millimeter wire forming a system of flat gabions. The spillway part of the dam (designed for 25 m^3/s) and its downstream wall of the dam were braced by reinforced concrete slabs.

The sediment-water flow reached the gabion dam at 17:57–17:58. It took around 2 min to fill the basin in front of the dam, after which the latter failed within a period of 2 min (Fig. 8). Deposited on the upstream wall of the dam were layers of sediments totaling 22,500 m^3 by volume.

Fig. 3. Plan view of morainic lakes 2 and 3:
1-level of lake before the outburst; 2-level of lake after the outburst.

What was the role of the gabion dam in the process of forming the debris flow? Opinions on this question are varied. S. M. Fleishman [3], for instance, proposes that the flow came to the dam "… with a mean discharge of up to 30 m^3/s." Right after the outburst the discharge attained 150–180 m^3/s. In co-authorship with I. A. Mossakovskaya and V. F. Perov [4] S. M. Fleishman replaces these figures with the more "definitive" figures of 20 and 200 m^3/s, respectively. Thus, clearly expressed here is the idea that the gabion dam had a decisive role in the forming of the catastrophic debris flow. Fleishman [3] writes that if the flow (20–30 m^3/s) "… were not impeded by anything, it would pass by noticed only by observers …", "but … the flow ran into an obstacle in the form of … the gabion dam …". This idea is based on a false premise relating to the conversion of a powerful outburst water flow with a peak discharge of around 350 m^3/s into something trifling (with discharges of no more than 20 m^3/s [4]).



Elevation, m a.s.l.	3373	3373	3365	3365	3340	3250	3230	3090	3010
Slope, tan	0.2313	0.0	0.0615	0.0	0.0893	0.3333	0.1053	0.3256	0.0941
Distance, m	160	210	130	67	280	270	190	430	850

Fig. 4. Longitudinal profile of the modern moraine of the Tuyuksu glaciers in the zone of the outburst flow from lake 2 to the Mynzhilki dam.

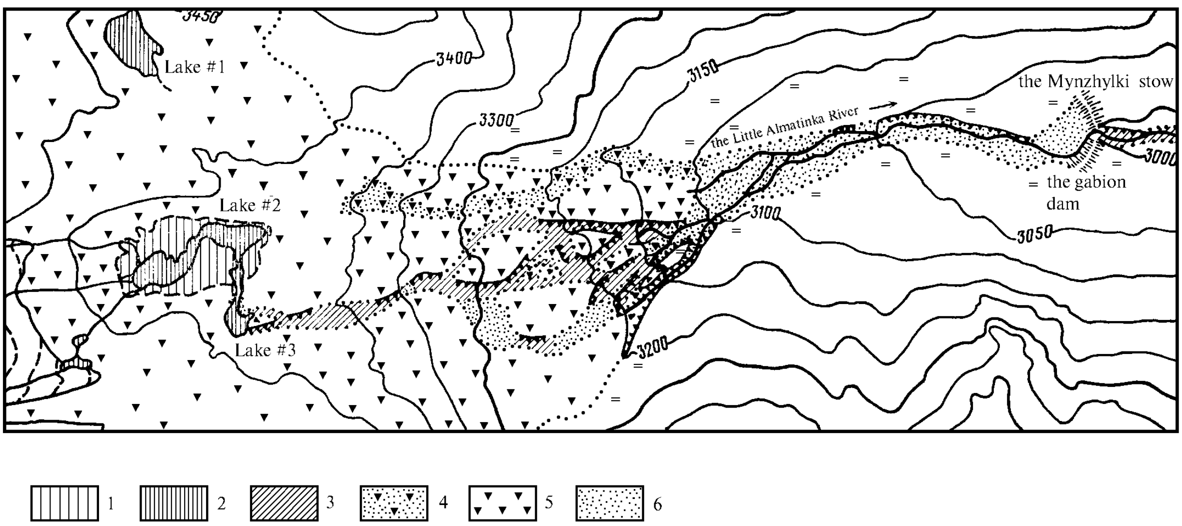


Fig. 5. Schematic drawing of the outburst flow from lake 2 to the gabion dam in the Mynzhilki trough:
1-area of lake 2 before the outburst; 2-area of lake 2 after the outburst;
3-zone of washout on the path of the outburst flood over the modern moraine; 4-the torrent gully of 1956; 5-modern moraine; 6-zone of deposits from the outburst flood.

Fig. 6. Path of the outburst flow into the Mynzhilki valley.

Fig. 7. The gabion dam after the outburst, view from the upper reach.

Fig. 8. Flow of the outburst flood through the crest of the gabion dam
(photo by V. Ya. Bosharimov).

Here we encounter something that, from our viewpoint, is literally a tragedy for debris-flow science. We have in mind the peremptory citing of numerical data without even the slightest attempt to argue them or if only to cite their source, or the means by which they were obtained. The following, for instance, is the account given of the destiny of the 20 cubic-meter flow that had reached the gabion dam [4]: "… after the outburst the debris-flow discharge increased by a factor of 8–10, having attained 200 m^3/s", "within 2–3 km the discharge doubled", "this already was a catastrophic debris flow with a discharge of more than 500 m^3/s", "below the tourist center the debris-flow discharge was 1000 m^3/s". On reading this text the reader might form the impression that its authors had at their disposal data from almost direct measurements. Not at all. Observations of the debris-flow discharges were not performed, and indeed could not be performed. Consequently, the figures given were obtained by purely speculative means, based, as is said in such instances, on intuition and experience.

Let us return to the question of the gabion dam. The volume of the temporary reservoir, in comparison with the total volume of the glacial outburst waters, was not large, clearly no more than 10% (indeed, one should take into account that at the beginning of the flood a substantial portion of the 22.5 thousand m^3 of sediments was entrained into it). Hence, one can speak of the "fatal" role of the gabion dam only as a matter of dispute. But some "compression" of the hydrograph along the axis of the time of flow in the Malaya Almatinka torrent gully undoubtedly took place. It is clear that until the peak discharge from the opening in the morainic dam of lake 2 reached the site of the gabion dam there was no discernible obstacle in the path of the water flow. The most probable transformation of the hydrograph under the influence of the gabion dam and volume of water stored in lake 3 is presented in Fig. 1.

The reconstruction of the hydrograph to take account of the temporary storing effect of the reservoir above the gabion dam was done most primitively. It was supposed that the first column of the histogram (hydrograph) corresponds to the temporarily retained volume. In reality, a water mass with a volume of

21.2 thousand m^3 arrived at the upstream wall of the dam in the first 3 min. It follows from this that during these 3 min the remaining 10.8 thousand m^3 of capacity was filled with solid material making up 64% of the total quantity of alluvium (22.5 thousand m^3 with a porosity of 0.82) that had arrived at the upstream wall, and the density of the alluvium-transporting flow came to 1240 kg/m^3 (34% saturation). The cited figures are altogether plausible. The stored volume was equally distributed between two ensuing 3-minute intervals, which conforms to the hypothesis that the dam failed steadily during the first of these intervals and that the discharge attained a magnitude corresponding to the sum of the ordinates of the 1st and 2nd columns of the histogram by a moment of time corresponding to the boundary between the 2nd and 3rd columns.

Following is the authors' view of the role of the gabion dam in the formation of the catastrophic debris flow: The very presence of the dam in the path of the water flow was a negative factor. If it were absent the leading wave of the debris flow could be lower, even though the peak discharge and volume of the debris flow would hardly undergo substantial changes. An indestructible dam in this same place could play only a positive role, although it could have a key effect on the unfolding process if the reservoir had, say, a capacity of 100 thousand m^3.

Having breached the gabion dam, the water flow rushed down along the bed of the Malaya Almatinka in a torrent gully with a slope angle more or less evenly declining from 14 to 8° as it extended downward.

The potential debris-flow mass (PDFM) of the torrent gully was composed of loose rock debris, the granulometric composition of which (with cut off at *d* = 500 mm) is presented in Fig. 9. The density of the PDFM in dry state was estimated as 2200 kg/m^3. V. N. Bardugin, from whose data the granulometric curve was constructed, having determined in 1965 the physicomathematical properties of rock in the immediate vicinity of the bed of the Malaya Almatinka, affirms that the integral curves of the granulometric composition of moraines in the immediate vicinity of lakes 2 and 3 and below the gabion dam are practically the same.

The interaction of a massive water flow with rock of the PDFM in the torrent gully led to the development of a swift eroding-shearing process, which formed a large debris flow of high density. The torrent gully, until then mostly smoothed out and even grown over with vegetation after being inactive for many years, was deepened over its entire length by 12–15 m (in places up to 40 m), and the average cross-sectional area of this new formation was estimated to be 560 m^2.

An immense landslide recess in the volume of around 150 thousand m^3 formed in the region of the debris cone of Chertov Ravine on the right side of the debris-flow canyon. This, evidently, should be attributed to the vibrational action of the passing debris flow on wetted debris-flow deposits. Such mass could by itself form a flow of low intensity, similar to that reaching the debris-flow reservoir at 21:15 h and 17:00 on the following day.

The retention of the debris flow in the Medeo reservoir allowed us to determine the volume of the debris flow with an accuracy that is usually unattainable. The initial value of this volume, 4 million m^3, was obtained on the basis of a curve of volumes of the debris-flow reservoir when it was filled to a level of 1838 m (as recorded on the morning of 16 July). This value appeared to be somewhat too high, since it included a volume of water which replenished the reservoir on the night of 15/16 July. Surveys

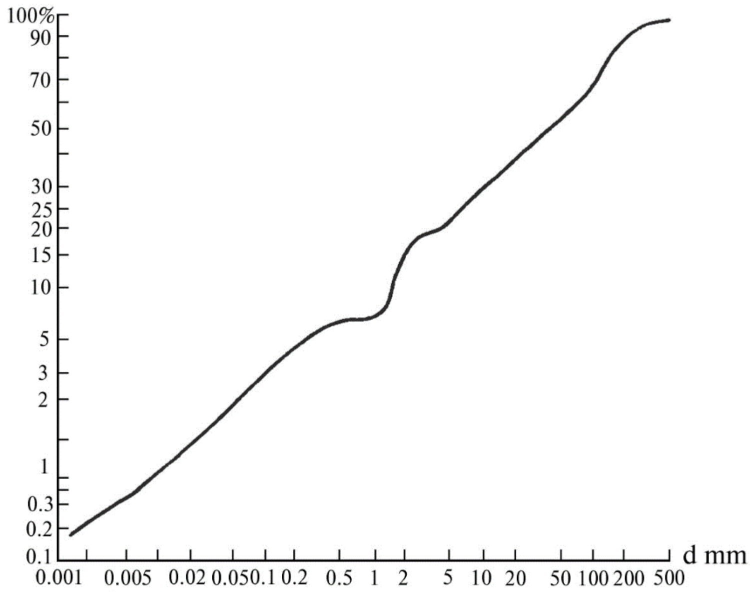


Fig. 9. Integral curve of the granulometric composition of the debris-flow forming soil of the Malaya Almatinka torrent gully.

across the surface of the reservoir done by staff of KazNIGMI and Kazgidroproekt give a more precise estimate of the debris flow volume: 3.8 million m^3.

The debris-flow reservoir became filled with boulder-gravel deposits with loamy fill that are characteristic of the debris flows of the Zailiysky Alatau. The maximum depth of the deposits was 51 m, and sandy-sludgy material dominated in the upper part of the vertical cross section (1–3 m). There was no free water above the surface of the debris-flow mass at the moment when the debris flow ended, which is confirmed by observational data of the UGMS of the KazSSR on the rise of the water level before the dam. At the moment when observations began (02:10, 16 July) the level attained an elevation of 1836.81 m, corresponding to a volume of water above the debris-flow deposits of 140 thousand m^3. The cited volume corresponds to a six-hour flow of water into the reservoir with a mean discharge of 6.5 m^3/s.

The average density of the debris-flow deposits (in dry state) based on few direct determinations but confirmed by data on the Issyk (the Zharsay debris flow of 1963) and Chemolgan events (the artificial debris flows of 1972 and 1973), was taken to equal 2200 kg/m^3. With a density of solid material in the rock of 2700 kg/m^3 the porosity of the deposits is estimated at 0.185, and the density of the debris-flow mass, that is, debris-flow deposits completely water-saturated, at 2385 kg/m^3.

Let us perform a quite simple computation of the water balance: volume of water entered from lake 2: 224 thousand m^3, volume of water entered from lake 3: 1 thousand m^3, volume of water entrapped in the bed of the Malaya Almatinka: 9 thousand m^3, volume of water entered from tributaries of the Malaya Almatinka: 9 thousand m^3, volume of ground water entered upon the deepening of the channel: 2 thousand m^3, total water volume: 245 thousand m^3, volume of solid material: 3.8 (1–0.185) = 3.1 million m^3. The water volume lacking to bring the balance to complete accord is estimated at 455 thousand m^3. This value is an estimate of the quantity of interstitial water that entered the debris flow along with loose rock debris, and corresponds to a volumetric moisture content for the latter of 11.8% (degree of water saturation of porous space 64 %), which seems realistic since most of the rock was found below the level of the ground water. The cited estimates of the volume of solid and liquid components of the debris flow lead to the following value for the average density of the debris-flow mass: γ_m= 2390 kg/m^3.

The debris flow moved along the bottom of the Malaya Almatinka valley as a massive and compact debris avalanche, marking a deep scar in its 8-kilometer path, which it traversed in 12–13 min (10–11 m/s). At bends the cross-sectional slope of the flow surface attained 15–20°. The flow was extremely turbulent with mud spray wreathing above it-a phenomenon very familiar to the authors from experiments with artificial debris flows at the Chemolgan experimental site.

Fig. 10. Frontal wave of the debris flow of 15 July 1973 entering the reservoir in the Medeo trough (photo attributed to a tourist from Moldavia).

At the Gorelnik tourist center, on impact with the open metal debris-flow control structure, which was immediately swept away, the debris avalanche literally bombarded both banks with large and small rocks flung several tens of meters. The debris-flow control structure proved incapable of withstanding the force of the flow. Its role during the debris flow may be assessed only as a negative one.

At 18:15 h a debris surge with a 15-meter wall fell with a roar and mud cloud into the debris-flow reservoir (Fig. 10). The dam at Medeo in this case performed the role of a perfect weapon. One does not want to think about the consequences of the debris flow on the below-lying valley and city.

After the first mammoth avalanche a series of debris-flow surges moved down the valley. From the character of the hydrograph of the outburst (Fig. 1) one has grounds for assuming-and this is confirmed by the above-cited experiments which provide evidence that the length of a debris-flow process of this type is equal to the period of the ingress of water into the initiation zone-that the main debris mass was discharged into the debris-flow reservoir in the course of some 10 min in total. The time of the "conclusion" of the debris flow cited by many eyewitnesses is just as undefined and unnecessary as in a hopeless attempt to find the "end" point of an exponential curve.

If we assume that 3.0 or 3.8 million m^3 of debris-flow mass actually entered the reservoir in a 10-minute interval, then the mean discharge of the flow for a segment of time turns out to be 5 thousand m^3/s, and the peak discharge (with the simplest triangular form of hydrograph) is 10 thousand m^3/s. This "bold" estimate is not contradicted by a computation based on traces of the debris flow (a site 3–3.5 km above the debris-flow reservoir) with 520–560 m^2 of cross-sectional area above the profile of the channel as it existed before the debris-flow, whereas the true area should be significantly greater as a consequence of the certain and severe deformation [editorial note: erosion] of the channel (after passage of the debris flow, the bottom at the computational sites was lowered by not less than 15 m) and the convexity of the cross-sectional profile of the debris flow. For the sake of completeness let us also point out that the level of the debris flow was taken as the boundary of the dense mud coating, whereas the traces of a solid strip of mud splashes spread much higher.

The debris flow filled the Medeo reservoir to more than half of its capacity (3.8 of 6.7 million m^3). A riverside water-receiving gallery, which was supposed to provide for the unimpeded discharge of normal runoff from the Malaya Almatinka through a bypass tunnel when the debris-flow reservoir became filled with debris mass, had not been completely constructed by that time. Because the water drainage conduits became clogged with debris-flow mass, the reservoir began to accumulate additional water, the rising level of which raised the threat of a surface overflow and failure of the dam. By 20 July the water level rose by 6 m, only 8 m short of the elevation of the top of the unfinished spillway part of the dam. By undertaking vigorous measures to pump out water from the reservoir and divert flow from the Malaya Almatinka through a bypass pipeline, the threat of a dam breach was eliminated. However, the last is more of a hydroengineering problem than a debris-flow problem.

REFERENCES

1. Kuzmin, K. K. The catastrophic debris flow of 1973 and the Medeo dam. *Gidrotekhnicheskoye stroitelstvo* (1974) No 3 pp 10–12.
2. Pokrovskiy, G. I., Chemin, A. N. A debris-flow control dam averts a catastrophe. *Priroda* (1974) No 3 pp 72–77.
3. Fleishman, S. M. Engineering lessons from the Almatinka debris flow. *Gidrotekhnika i melioratsiya* (1974) No 2 pp 19–22.
4. Fleishman, S. M., Mossakovskaya, I. A., Perov, V. F. The Almatinka debris flow of 15 July 1973. *Vest. Mosk. un-ta, ser. V, geogr*. (1974) No 2 pp 35–39.

The meteorological conditions attending the formation of the debris flow of 15 July 1973*

R. S. Golubov

Despite the fact that many papers have been devoted to the problem of forecasting glacial debris flows, we have not found a conclusive solution to this problem.

In order to identify some of the conditions under which glacial debris flows form the meteorological situations observed before the debris-flow events in the Malaya Almatinka and Issyk river basins (31 July 1944, 11 August 1944, 20 August 1951, 7 July 1956, 6 July 1958, 7 July 1963) were examined. Based on an analysis it was found that common to all events were the high altitude of the zero-degree isotherm (>4.8 km) and the high mean daily temperature of the air recorded by the Mynzhilki high-mountain weather station (>8°) over the 10-day period preceding the critical altitude of the zero-degree isotherm [1]. These characteristics were selected as predictors and used in preparing subsequent forecasts.

The need for simultaneously using two predictors (rather than merging them into one) was indicated by the results of research on the linkage between the altitude of the zero-degree isotherm and the mean daily air temperature at the Mynzhilki weather station. No clearly manifest relationship between these two characteristics was observed. This is attributed to the fact that the altitude of the zero-degree isotherm determined from sounding data characterizes the temperature distribution in free atmosphere, while the values for mean daily air temperature at the weather station reflect the influence of the bed surface.

In order to confirm the validity of the selected predictors their recurrence over a 20-year period was examined (Table 1).

From the tabulated data it follows that the number of days with critical value h_c comprised 7% of the entire set examined, while the number of days with a combination of critical values h_c and *i* comprised only 3.5%. A combination of these characteristics was noted in 11 years of the period examined. Over the 11-year period in which debris-flow events were possible according to the proposed criteria, debris flows were observed 6 times.

Based on the developed criteria a debris-flow hazard was forecast for the Zailiysky Alatau on 13 July 1973. According to data from an atmospheric sounding on 13 July 1973 (at 3 h Moscow time) it was found that h_c equaled 4.8 km. After computation of the mean daily temperature for the preceding 10-day period which came to 8.8°, a notice was issued warning of a possible

Table 1

Recurrence of critical parameters over 20 years

No of cases examined	Number				
	days with h_c	debris flows when h_c	debris flows when $h_i > h_c$	days with h_c and *i*	debris flows when h_c and *i*
1840	132	6	-	64	6

Note: h_c is a zero-degree isotherm altitude above 4.8 km, *i* is a mean daily temperature at the Mynzhilki weather station greater than 8° over the 10-day period preceding a critical altitude of the zero-degree isotherm.

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 73–74.

debris flow event in the Zailiysky Alatau. For preparing a forecast for subsequent days the expected temperatures at altitudes of 3000 m (at AT_{700}) and 5800 m (at AT_{500}) were computed. According to the computed data it was to be expected that air temperature at an altitude of 3000 m in free atmosphere would remain within the same limits for the next few days, while at an altitude of 5800 m it would rise from -6 to -4° on 14 July 1973. Taking into account that the vertical temperature gradient γ would be 0.75°/100 m, a zero-degree isotherm was to be expected at an altitude of 5.3 km. In fact, on 14 July the zero-degree isotherm was at an altitude of 5.1 km. On 15 July 1973 large debris flows were observed in the Malaya Almatinka and Sredny Talgar river basins.

REFERENCE

1. Golubov, R. S., Ryndina, V. R. Some possibilities for assessing debris-flow hazard in river basins on the northern slope of the Zailiysky Alatau. *Tr. KazNIGMI* (1968) No 29.

Some quantitative characteristics of the Zharsay debris flow of 1963 in the Issyk River*

A. E. Zems

[Editorial note: the English translation refers to a cone and/or a pile of sediment at the inlet of Lake Issyk, which we interpret as a depositional feature, e.g. a debris fan or fan-delta deposited by the interaction of the Issyk River and the Lake Issyk.] The catastrophic debris flow which formed on 7 July 1963 in the upper reaches of the Zharsay River, a lefthand tributary of the Issyk River (Zailiysky Alatau), and caused the outburst of the lake of the same name, in terms of its scale was one of the largest in the USSR. Yet this event, which served as the impetus for the development of debris-flow research in Kazakhstan, did not become the subject of sufficiently thorough study on its own. Most publications regarding it are descriptive in character and devoted mostly to the outburst of Lake Issyk and its consequences, while questions of the greatest interest concerning the causes and mechanisms of the debris flow and its quantitative characteristics are far from cleared up and are elucidated only on the level of hypothetical, often conflicting judgements.

The present paper sets forth the results of some investigations in this direction that were performed by Kazgidroproekt [Kazakh Institute for the Design of Hydrofacilities] in 1969 during the preparation of a scheme for protecting the valley of the Issyk River against debris flows. The general physio-geographical characteristics of the Issyk River basin and a description of the conditions under which the debris flow occurred are not presented here since they may be found in a number of other papers [2, 4, 7].

The most important objective of the investigations in question was to determine the volume of solid material transported by the debris flow to the cone of the Issyk River in Lake Issyk.

The initial estimates of this volume (1.5–3.0 million m^3) presented in reports of the KazNIGMI [Kazakh Institute for Hydrometeorological Research], the Institute of Geological Sciences of the AN KazSSR [Academy of Sciences of the Kazakh SSR], the Institute of Soil Science of the AN KazSSR as well as in scientific papers [4, 7] were based on visual estimates of the thickness of the layer of debris-flow deposits above Lake Issyk. In this case it was assumed that the thickness of the 1963 debris-flow deposits visible in natural cross sections (in the section where the Issyk River flows into the lake basin) could be taken as the mean value for the entire 3-kilometer section of deposits from this debris flow above the lake.

The first instrument-based determination of the volume of rock entrained and deposited by the Zharsay debris flow was carried out by B. A. Paramonov [9] with a comparison of aerial photos of 1955 and 1964–1965. According to this evaluation the volume of debris-flow deposits in Lake Issyk was 5.7 million m^3, which corresponded to the volume of rock removed from the initiation zones. A deficiency in this determination was the failure to take account of the 1958 debris flow whose volume of deposits above the lake is unknown (only the volume of material transported by this debris flow directly into the lake was estimated—0.14 million m^3).

In 1969 Kazgidroproekt estimated the deposits of the 1963 debris flow by comparing the present-day longitudinal profile of the Issyk River valley above the lake with a 1962 profile prepared by the Surveying Department of Kazgidroproekt in connection with stationary hydrologic observations conducted in the upper reaches of the Issyk River.

Shown in Fig. 1 are the merged longitudinal profiles of 1962 (1) and 1969 (2) embracing the 3-kilometer section of the Issyk River valley above Lake Issyk (the debris fan of the Issyk River in the former lake).

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No 1, pp 75–85.

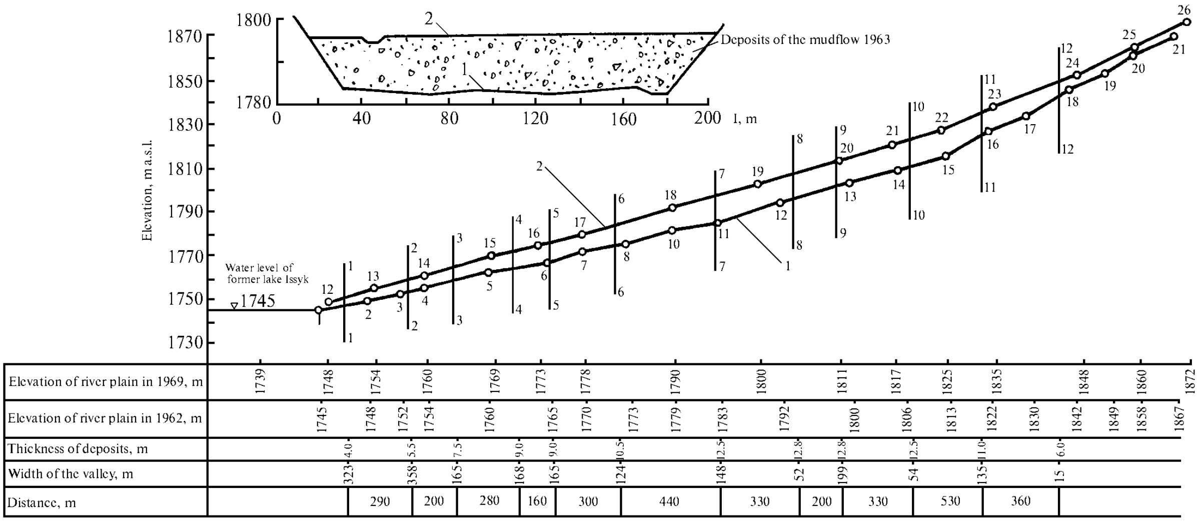


Fig. 1. Cross-sectional (cross section 7–7) and longitudinal profiles of the 3-kilometer section of the Issyk River valley above Lake Issyk.

A comparison of the profiles testifies to the fact that the thickness of the deposits from the 1963 debris flow in this section is substantially more than 1–2 m, measuring on average 5–6 m and in places 12.5 m. Computed on the basis of these data and a topographic map from the 1965 survey, the volume of deposits by the 1963 debris flow before Lake Issyk amounted to 4.3 million m^3.

A similar computation within the limits of the lake's former area of water is impracticable, however, because sufficiently accurate data are lacking on the relief of the lake bottom before 1963. Some idea of the volume of material transported directly into the lake by the debris flow of 1963 is provided by that portion of the 1963 debris-flow deposits within the lake basin which had evenly covered the underwater surface of the debris cone of the Issyk River with a 1–2 meter thick layer clearly distinguishable from the lake deposits [8]. With an area of 0.4 km^2 the volume of this portion of the debris-flow removals is 0.5–0.7 million m^3. Not taken into account in this case, however, is that portion of the debris-flow removals which reached the deep-water zone of the lake, having run off from the 30-meter front terrace where the underwater section of the cone of the Issyk River terminated. Unlike that described above, the latter portion did not preserve the structure characteristic of debris deposits (in consequence of their breakdown when fine fractions fell off and were carried away upon the outburst of the lake). After the outburst of the lake, it was covered by material which eroded from the front terrace of the fan of the Issyk River, and at the present time it is difficult to directly estimate its volume.

It is possible, however, to indirectly estimate the total volume of debris-flow material transported into the lake by estimating the volume of water displaced by the debris flow. An observer of the water-metering station of Kazgidroproekt recorded the water level in the lake (1745.53 m) at the moment at which the debris flow stopped, when the erosion of the Issyk dam which had begun from below was still only approaching the crest of the lake dam. The static increase in the water level in the lake was 168 cm, which with a mirror surface of 0.80 km^2 (according to a topographic survey of 1969) corresponds to a volume of 1.34 million m^3. To this volume should be added the water released from the lake during the period of the debris-flow movement, the release caused by an increase in the water level and wave discharges. With a gradual rise in level from 1743.85 to 1745.53 m discharges of water in the outflow from the lake should have increased from approximately 6 to 20 m^3/s, which over a 5-hour period corresponds to an additional release of 0.12 million m^3 of water. Moreover, an additional release of water from the lake occurred when large waves caused by the entry into the lake of debris-flow surges ran up against the lake dam. The magnitude of wave discharges with a wave height of up to 5.5 m and with a runoff width of 20 m could have been quite substantial (which evidently played a decisive role in eroding the Issyk dam), but the total volume of water discharge in this case, in view of the short duration of the wave discharges, hardly exceeded the magnitude of the discharge that was constant over time. Thus, the total volume of water displaced from the lake by the debris flow may be estimated at about 1.5 million m^3 (1.34+0.12+(W<0,12)), which characterizes the volume of that portion of the debris flow that reached the lake.

Hence the total volume of material transported by the Zharsay debris flow of 1963 to the area of Lake Issyk and the adjoining area of the debris cone of the Issyk River was 1.5+4.3 = 5.8 million m^3.

This estimate on the whole corroborates Paramonov's data (5.7 million m^3), although the components in the former case were somewhat different (0.7+5.0). The disparity between the components is attributed to two factors that compensate for each other: In Paramonov's computations debris-flow removals which reached the deep-water zone of the lake were not taken into account, but the deposits of the 1958 debris flow were included in the volume of deposits in the fan. The main factor causing the larger (in comparison with the previous) estimate of the volume of removals of the 1963 debris flow is the same in both works: the maximum thickness of the debris-flow deposits above the lake was not 2–5 but 12.0–12.5 m. Indirectly corroborating this figure is the fact that a pit dug to a depth of 7 m in this area in 1965 during preparation of an engineering-geological survey by the Zailiysky Party of the MG [Ministry of Geology] of the KazSSR failed to disclose a layer underlying the deposits from the 1963 debris flow.

With a volume of materials transported of 5.8 million m^3 the mean discharge of the debris flow over the 4–5-hour period of its run is 320–400 m^3/s. The peak discharge exceeded this value by many times, which is deduced from the following assessments:

a) an observer of the water-metering station of Kazgidroproekt recorded the height of the water wave (551 cm) that originated in the lake after the largest debris-flow surge entered it at 14:15. The velocity of the front of this wave with a height of 5.5 m must have been 7.4 m/s, which also characterizes the velocity of the debris-flow surge induced by it (the latter could only be higher than the velocity of the wave);

b) the width of the debris flow during the run of the large surges corresponded to the width of the valley bottom (the floodplain of the river), which is corroborated by both the testimony of witnesses [2, 3] and photos of the flow taken from the northern shore of the lake (Fig. 2);

c) the height of the largest debris-flow surge according to visual estimates [2] attained 12 m (the surges "carried Tien Shan spruces upright "). According to the data of Kazgidroproekt, on both sides of the Issyk River valley at a distance of 1–2 km above the lake, traces of the flow rise above the level of the debris-flow deposits in places up to 10 m, and next to the lake (at a distance of 150 m), to a height of 6.8 m. However, taking for computational purposes the very modest estimate of the average height of the largest surge as between 3 and 5 m, we will obtain (with a width of the river floodplain before the lake of 320 m and a velocity of 7.4 m/s) a discharge of 7–12 thousand m^3/s.

It is interesting to compare the volume of removals by the 1963 debris-flow with the average rate of accumulation of solid material in front of the Issyk dam. The latter characteristic may be estimated in the following manner. The age of the Issyk dam, according to the data of A. P. Gorbunov which were based on an estimate of the maximum thickness (and corresponding number of annual layers) of the strip sediments that had settled on the sides of the lake basin, is not less than 4 thousand years [5]. A better-known estimate, based on analysis of the overall geotectonic conditions of the region, takes the age of the lake to be close to 8 thousand years. The maximum thickness of the deposits in front of the dam, according to data from geophysical investigations and drillings by the Zailiysky Party, is around 170–200 m, which fully corresponds to the character of the contemporary longitudinal profile of the Issyk River (a terrace, clearly defined in the profile and caused by the damming of the river by the Issyk dam, also has a height of around 200 m, Fig. 3). With a backwater length of 5 km, a deposit surface area of 1.4 km^2 and a maximum deposit thickness of 200 m, the total volume of deposits accumulated behind the Issyk dam can be estimated to be approximately 80 million m^3. With the age of the lake being 4–8 thousand years, the average rate of its filling by usual solid runoff and debris flows is thus 1–2 million m^3 per 100 years, and, consequently, the removals by the Zharsay debris flow of 7 July 1963 correspond to the mean volume of the total solid runoff in the Issyk River basin above the lake for a period of 300–600 years.

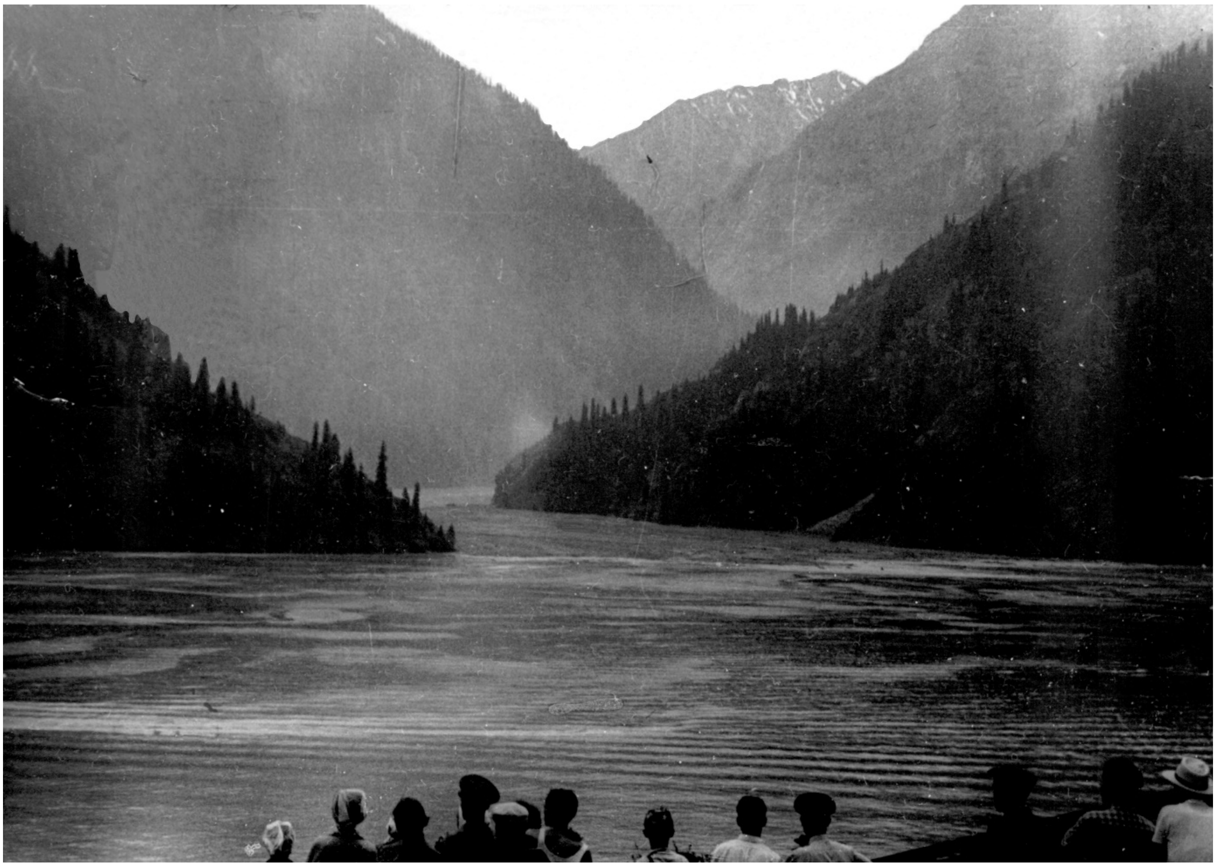


Fig. 2. The debris flow of 7 July 1963 entering Lake Issyk
(Photo by V. Amirov).

Of considerable interest is the density of the debris-flow mass-a most important indicator of the type of debris-flow event. In the investigations described the density of the Zharsay debris flow of 1963 was estimated by two methods: by comparing the volume of solid removals with the maximum possible volume of water capable of taking part in forming the debris flow under the given conditions, and by an analysis of the traces left by the debris flow on the branches of spruces that were left standing.

The first method was basically as follows. As was shown above, the volume of solid removals by the debris flow was 5.8 million m^3 (in a loose medium). In the overall judgement of the investigators, the main source of this material was large landslides in the area of the ancient Zharsay moraine at a height of 3000 m (the solid material entrained by the debris flow in the transition zone according to Paramonov's computations [9] was not more than 13–15% of the total volume). In regard to the liquid component of the debris flow, the opinions of the investigators diverge; various hypotheses are advanced as to the causes of the debris flow: the rapid draining of a morainic reservoir, a local cloudburst, and infiltration wetting.

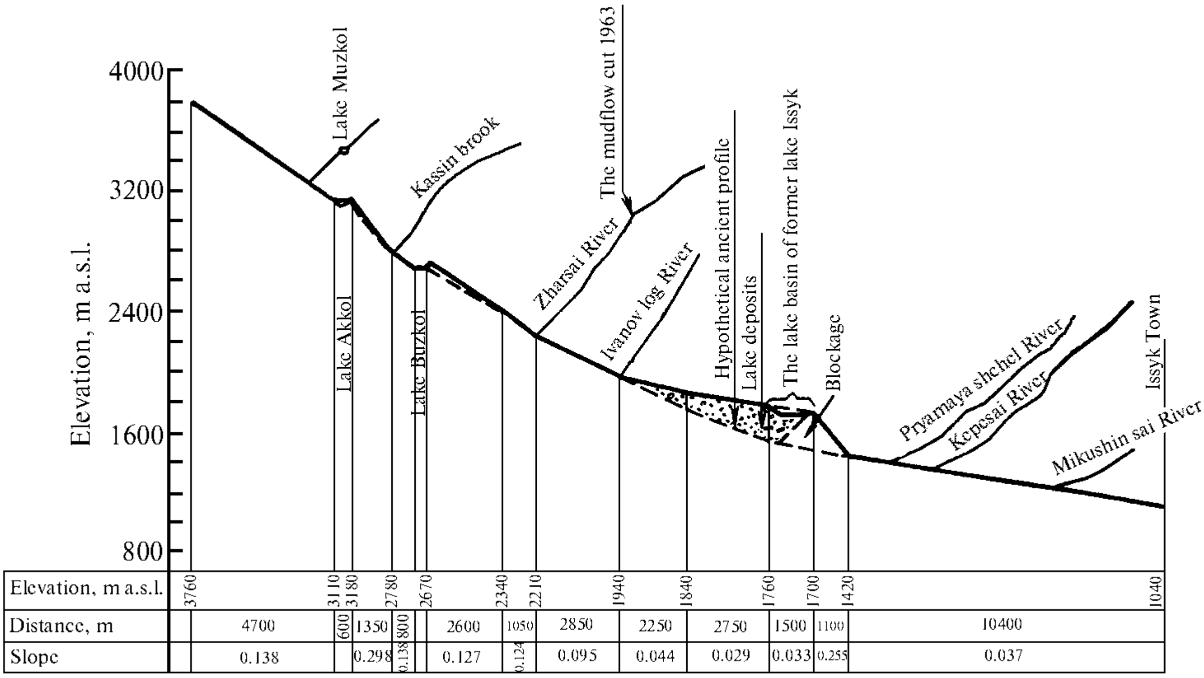


Fig. 3. Longitudinal profile of the Issyk River valley.

Without getting into a discussion of the validity of these hypotheses, we shall try to evaluate the maximum volumes of water in each case.

The volume of the thermokarst basin at the tongue of the Zharsay glacier, which in the judgement of some investigators could have filled with water at the moment when the debris flow formed and then rapidly drained, is 0.2 million m^3 [7].

A local cloudburst represents an even lesser possibility in this regard. In [6] it is pointed out that when an aerial visual survey of the Zharsay River valley was conducted on 12 July 1963, "… a section of the valley with a radius of 0.5–0.8 km below the terrace of ancient frontal moraine had the shape of an unusual initiation zone worked over by concentrated surface runoff." It is not difficult to reckon that the maximum volume of water that could enter the initiation zone in this case would not be more than 20–30 thousand m^3.

The most substantial source of wetting of the debris-flow mass could have been pore water entrained along with soil in the debris flow. Assuming a very high coefficient for the relative water saturation of soil pores (α = 0.8), we shall obtain the maximum volume of pore water $V_{pore} = \alpha \; x \; n \; x \; V_{soil}$ where V_{soil} is the volume of entrained soil taken as equal to the volume of deposits, since the densities of the debris-flow deposits and morainic soil are practically the same [1]; *n* is the porosity of the soil, equal to 0.185 (according to the data of the Zailiysky Party of the MG KazSSR). Here $V_{pore} = 0.8 \; x \; 0.185 \; x \; 5.8 = 0.86$ million m^3.

Summarizing these three estimates, we conclude that the maximum volume of water in the area where the debris flow originated was not more than 1.1 million m^3.

While moving along the channels of the Zharsay and Issyk Rivers the debris flow could have been replenished with entrained channel water and water from lateral tributaries. According to the data of the water metering station of Kazgidroproekt located 1.6 km above the lake, in the course of the ten days preceding the debris flow, discharge from the Issyk River fluctuated between 6.7–7.7 m^3/s. At 08:00 on 7 July 1963 the water level corresponded to a discharge of 7.0 m^3/s. During the 5-hour period of the debris flow such a discharge could have provided an additional 0.126 million m^3 of water. The volume of water residing in the channels of the Zharsay and Issyk Rivers in the 11-kilometer path of the debris flow is 0.029 million m^3 based on a mean (by length) discharge of 4 m^3/s and a river flow velocity of 1.5 m/s.

Hence the full volume of water in the debris flow was not more than 1.26 million m^3. There are no bases for supposing the existence of some as yet unaccounted for sources, for example, the outburst of endoglacial cavities or the outburst of temporary reservoirs caused by the hypothetical damming of the river in the period preceding the debris flow. Thus, the confinement of the initiation zones to ancient moraine rules out the possibility that endoglacial outburst waters entered them underground (according to engineering-geological data of the Zailiysky Party the ancient moraines contain no buried ice and consequently no hollow water-runoff tunnels). At the same time there were no indications that large (of the order of 100 m^3/s) discharges of surface water from the above-lying modern moraine and glacier entered the region of the initiation zones. This means that outburst waters (if an outburst took place) could enter the initiation zone only by filtration, and in this case their volume is already accounted for in the composition of the pore water.

Even less practicable is the hypothetical possibility of an outburst of a large temporary water reservoir formed by some landslide that preceded the debris flow. Under the conditions of the steep Zharsay ravine (slope-0.3) even debris piles 50–60 m in height would not create any significant reservoir, and under the conditions of the Issyk River valley a large landslide simply could not have remained unnoticed.

Summing up the foregoing, one can conclude that the Zharsay debris flow of 7 July 1963 contained no more than 1.26 million m^3 of water. With a volume of removal by the debris flow of 5.8 million m^3, porosity of 0.185 and a density of the solid material of 2700 kg/m^3, this means that the average density of the debris flow (without taking into account aeration) was not less than 2340 kg/m^3. This estimate is corroborated by data from analyzing traces of the debris flow. After the run of the debris flow the sides of the Issyk River valley above the lake were covered everywhere (to a height of 3–10 m) with a layer of dense mud 10–20 cm thick that accurately fixed the maximum level of the debris flow. Preserved to this day on the branches and trunks of spruces that escaped destruction in this zone are adhered soil masses in the form of globs of hardened mud up to 10 cm thick (Fig. 4, specimen No 10). In 1971 Kazgidroproekt acting on a proposal by Doctor of Engineering Sciences M. A. Dementyev undertook to establish experimentally under what consistency the soil mass of the 1963 debris-flow deposits could form such traces.

For solving this problem specimens of the debris-flow deposits on the spruce branches were directly used as the soil material to be tested. After being wetted and thoroughly agitated the original structure of the specimens completely disintegrated. With the addition of varied amounts of water, solutions of varied consistency were obtained from the material (Fig. 5). The volume-weight method was used to determine the density of the solutions. Then spruce branches were rapidly lowered into the solutions and after being withdrawn were photographed (Fig. 4). Obtained in this manner was a set of spruce branches with debris-flow mass of various densities adhered to them. The results of the tests, performed by M. S. Kolyada, are presented in Table 1.

A comparison of these test specimens with the traces of the 1963 debris flow (specimen No 10 in Fig. 4) leads us to conclude that only test specimen 7 with a density of 2030 kg/m^3 corresponds to the natural traces. Taking into account that the specimens of debris-flow mass examined contained no boulder-gravel fractions, which comprised about 2/3 of the content of the debris-flow deposits [1], one may presume that the average density of the mass of the 1963 debris flow (with a density of course debris of 2590 kg/m^3) was close to 2400 kg/m^3, which corresponds to the balance estimate given above (over 2340 kg/m^3). The actual density of the debris flow could have been somewhat less on account of the aeration of the flow, but the latter plays no role in estimating the sediment-water ratio.

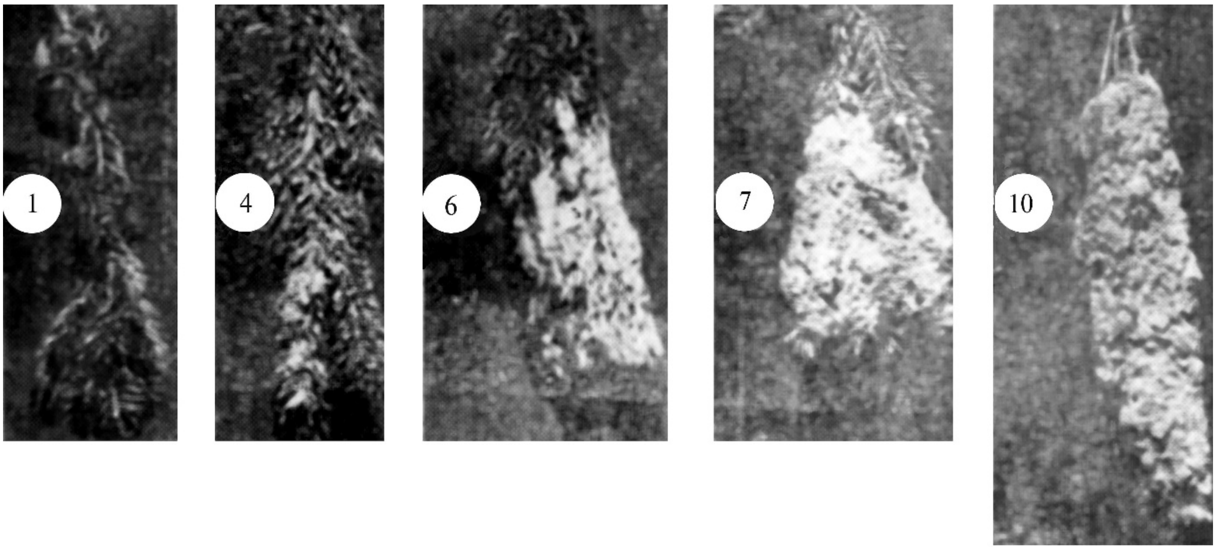


Fig. 4. Comparison of traces left from the mud mass of the 1963 debris flow with various densities ρ kg/m³

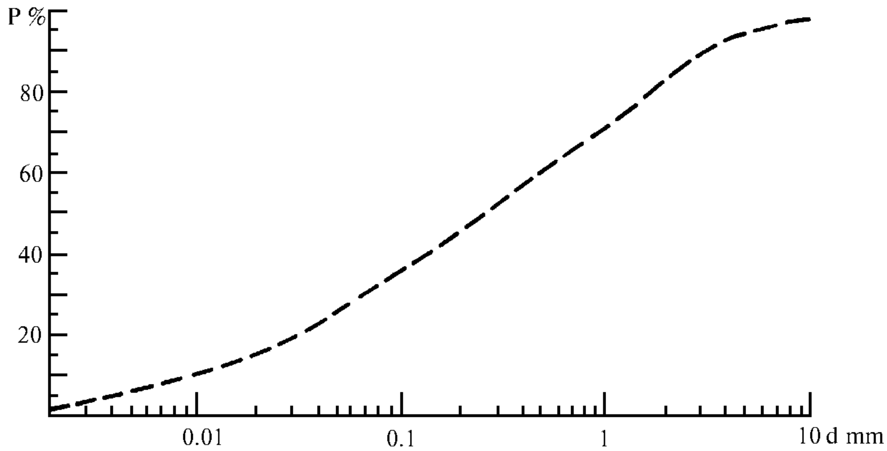


Fig. 5. Granulometric composition of deposits from the 1963 debris flow on branches of spruces left intact above Lake Issyk.

The estimate of the average density of the debris-flow mass indicates that the 1963 Zharsay debris flow should be classified among high-density debris flows and not at all among mud floods [7] or the so-called turbulent debris flows containing less than 40% sediments [2].

An analysis of the possible sources providing more water to the initiation zone shows that pore water must have played a definitive role in this process, by virtue of which the large landslides on the frontal terrace of the ancient Zharsay moraine noted by all investigators are sufficient to cause formation of the debris flow. Thus, the debris flow may be visualized as a phenomenon close in character to landslides-flows.

Table 1

No of test specimen	No of specimen in Fig. 4	Density, kg/m^3	Description of external appearance of solution of the debris-flow	Description of external appearance of branch with adhered soil
1	*1*	1900	After agitation only sand remained in a suspended state in the solution	Very little soil retained
2	-	1950	After agitation stones larger than 15–20 mm sink	Only sand retained
3	-	1960	After agitation stones α = 15–20 mm do not sink and remain in suspension, surface of solution evens out, becomes horizontal	More soil retained mainly on the ends of small twigs
4	*4*	1970	After agitation irregularities remain on surface of solution and do not smooth out for long time	Same
5	-	1980	After agitation surface is uneven. Stones α = 15–20 mm on surface do not sink	Adhered soil only around lower part of branch
6	*6*	2000	Same	Same
7	*7*	2030	Surface of solution same as in test specimen No 5	Adhered soil around entire length

In examining the probable causes of the landslide, one should take into account that under normal conditions the total volumetric moisture content of a mass of morainic soil is not high-about 6% (the degree of relative water saturation of the pores is 0.32) [1]. Its sharp increase is most probably the result of anomalous infiltration wetting which can be the consequence of both the clogging of previous filtration channels [8] and a sharp increase in the depth of the filtration flow, for instance, as a result of the underground draining of glacier reservoirs. In both cases the wetting of the steep (40–45°) slope of moraine creates sufficient preconditions for initiating the landslide. An additional external trigger (in the form of a cloudburst or an outburst surface flow) in this case may not be required.

REFERENCES

1. Vardugin, V. N. Some engineering-geological features of the debris flow- hazardous basins of the northern slope of the Zailiysky Alatau. *Tr. KazNIGMI* (1969) No 33 pp 118–122.
2. Duysenov, Ye. D. Debris flows. Alma-Ata. *Kazakhstan* (1966) pp 86–105.
3. Duysenov, Ye. D. Debris flows in the Zailiysky Alatau. Alma-Ata *Kazakhstan* (1971) p 192.
4. Kalmynkina, Ye. M., Gorbunov, A. P. The demise of a mountain lake. *Priroda* (1964) No 6 pp 81–84.
5. Kalmynkina, Ye. M., Gorbunov, A. P. The causes of the initiation and the relief-forming role of the Issyk debris flow of 7 July 1963. *Izv. AN SSSR ser. geogr.* (1967) No 4 pp 53–58.
6. Kolotilin, N. F., Bochkarev, V. P., Antonenko, E. M. et al. Engineering-geological conditions in the foothills of the Zailiysky Alatau. Alma-Ata *Nauka* (1967) pp 85–90.
7. Litovchenko, A. F. The catastrophic mud flood in the Issyk River. *Meteorologiya i gidrologiya* (1964) No 4 pp 39–42.
8. Paramonov, B. A. The causes for the formation of the catastrophic debris flow in the upper reaches of Zharsay Creek on 7 July 1963 (in this collection of papers).
9. Paramonov, B. A. Initiation of the solid phase of the debris flow in the Issyk River on 7 July 1963 (in this collection of papers).

The causes for the formation of the catastrophic debris flow of 7 July 1963 in the upper reaches of Zharsay Creek*

B.A. Paramonov

There are several views, some diametrically opposed, regarding the Issyk debris flow that formed on the frontal terrace of the Zharsay moraine in 1963. The question of the origin of the water constituent took on special importance, particularly after the volume of the debris flow's solid phase was determined.

The cause of the 1963 debris flow in the upper reaches of Zharsay Creek (a tributary of the Issyk River) was the landslide of glacial deposits on the frontal terrace of the Zharsay moraine which dates from the Upper Quaternary period. The mechanism producing the landslide of 6,000,000 m^3 and the debris flow is as follows: Increased ablation produced an increase in suffusion activity and a change in the natural hydrodynamic conditions within the underground runoff channels in the moraine. The possibility is not ruled out that, besides the ablation, the suffusion activity could have been caused by the outburst of a hidden body of water in the present-day glacial deposits where thermal karst processes are taking place. But the outburst of this body of water by itself could not have caused such an immense landslide. The activation of suffusion along the runoff channels within the glacial deposits could have led to a failure in the stability of the anticline of an underground kettle hole or channel and to its collapse in one or more sections. The collapse could have clogged the channels for the runoff of melted waters, abruptly increased the ground-water level, increased the hydrodynamic pressure and, accordingly, caused the glacial deposits to become water-logged. With a discharge of melted waters inside the glacial deposits of the order of 2.25 m^3/s over 10 days, around 2.0 million m^3 of water could have accumulated, which is sufficient for producing not only the landslide but the debris flow as well [1]. The prolonged wetting of the glacial deposits with their fine-earth fill caused an accumulation of a huge amount of water within the moraine (including the pore water in the fine-grained soil). The frontal terrace of the moraine with a height of up to 300 m and a slope of 23–25° was the least stable section of water-saturated glacial deposits, which produced a landslide of immense proportions. Also not ruled out is the possible influence of cloudbursts that were local in character. But their role could be very slight because a significant surface runoff in the water basin above the landslide would be very difficult. Most of the foots of the adjacent slopes are cones of gravitational and partially gravitational-proluvial deposits. No substantial traces of surface waterflows were noted here. And it is doubtful that the foots of slopes located above the landslide, and the surface of the moraine could produce the substantial surface runoff capable of removing the moraine terrace by erosion.

Some authors believe that there was very little precipitation in the initiation zone on 7 July [3], while others [4] think that the precipitation above the landslide could have been only in solid form. A. F. Litovchenko [5] proposes that the water constituent of the debris flow was provided by a volume of 200,000 m^3 from a drained glacial lake located near the frontal terrace. Of interest are the conclusions of a group led by V. P. Bochkarev (A. S. Bochkarev, Zh. Kospanov, E. I. Konovalov) who believe that the regime and source of Zharsay Creek are not defined by only one body of water, because the outflows of morainic waters have maintained the same regime as before the debris flow. The section of the outlet opening from the body of water (lake) in the moraine, in their judgement, does not provide for a rapid discharge of 200,000 m^3 of water. They have not noted fresh and active traces of erosion on the surface of the depression near the frontal terrace. This confirms the judgement of the authors that the surface water had a negligible role in the breakdown of the frontal terrace of the moraine. Neither the volume of water drained from the lake in the amount of 200,000 m^3 nor a short-duration cloudburst of a local character [2] could provide for the water saturation of 6,000,000 m^3 of glacial deposits before the debris flow. If there had been a discharge of 200,000 m^3 of water from the lake in the basin, it was not a decisive

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, 86–87

factor in the formation of the landslide and the debris flow, and only in the subsequent stage could it facilitate the washout of the recess formed by the landslide and have an effect on the duration of the debris flow and on its water content. Also ruled out is the possibility that huge bodies of water existed within the Upper Quaternary moraine and that they subsequently burst out.

It should be noted in conclusion that the debris flow formed on 7 July 1963 on the frontal terrace of the Zharsay moraine was glacial in origin. The large volume of liquid phase could have been provided only by melted waters from the Zharsay glacier.

REFERENCES

1. Gagoshidze, M. S. The nature of structural (debris) flows and controlling them. In the book *Controlling Mountain Soil Erosion and Debris Flows.* Tashkent (1962) pp 216–224.
2. Duysenov, Ye. D. Debris flows. Alma-Ata *Kazakhstan* (1966) 217 p.
3. Kavetskiy, S. N., Kalmynkina, Ye. M. The debris flow in the Issyk River on 7 July 1963. *Vesti. Moscow Univ., Ser. V, Geogr.* (1964) No 2 pp 77–80.
4. Kolotilin, N. F. Bochkarev, V. P., Antonenko, E. M. et al. Engineering-geological conditions of the piedmont zones of the Zailiysky Alatau. Alma-Ata *Nauka* KazSSR (1967) 139 p.
5. Litovchenko, A. F. The catastrophic debris flood of the Issyk River. *Meteorologiya i gidrologiya* (1964) No 4 pp 39–42.

Formation of the solid phase of debris flow of 7 July 1963 in the Issyk River*

B. A. Paramonov

Moscow State University

In the course of work with aerial techniques during engineering-geological investigations in the debris-flow hazardous regions of Southeast Kazakhstan, the question arose of whether it is feasible to use aerial photography for determining the zones of action of debris flows and the volumes of their solid component. For resolving this question, we chose as an example a section of the valley of the Zharsay Creek-Issyk River where a catastrophic debris flow occurred in 1963. The aim of the research was 1) to determine the zone of action of the debris flow and to identify areas where the debris flow originated and areas of transit where it was replenished with solids and fluids, deposits, and 2) to compute the volume of displaced masses of soil and their spatial distribution in the zone of action of the debris flow.

Initially aerial photos from flights of different years were examined. Using a stereophotogrammetric technique on aerial photos of 1955, 1964–1965 we determined the volume of mobilized landslide on the frontal terrace of the Zharsay moraine that had triggered the debris flow (Fig. 1, Table 1). The second stage of the work was field observations, by means of which we determined the character of the torrent gullies and their mean dimensions and also identified areas for determining the thickness of debris-flow deposits (Tables 2, 3). It should be noted that through field observations we were able to obtain data on the thickness of the deposits of the 1963 debris flow only in the "Mertvaya Polyana" section located above the Ivanov Log debris fan, and in a negligible area in the upper and lower parts of the fan before the earth dam of Lake Issyk. The thicknesses of the debris-flow deposits on the main part of the fan remained undetermined. This task was completed in subsequent laboratory work with a topographic stereometer (STD-2) in processing aerial photos from the 1955 and 1965 flights (Tables 4, 5).

The following data were obtained as a result of this work:

1) the initiation zone of the debris flow, sections in which the debris flow was replenished with solid phase and also areas of debris-flow deposits were identified and mapped (Fig. 2);

2) the volume of loose rock entrained or deposited by the debris flow was determined for each of the 5 identified sections;

3) along the valleys of Zharsay Creek and Issyk River in characteristic places sites were identified that characterized the total volume of entrained debris which passed through the given points.

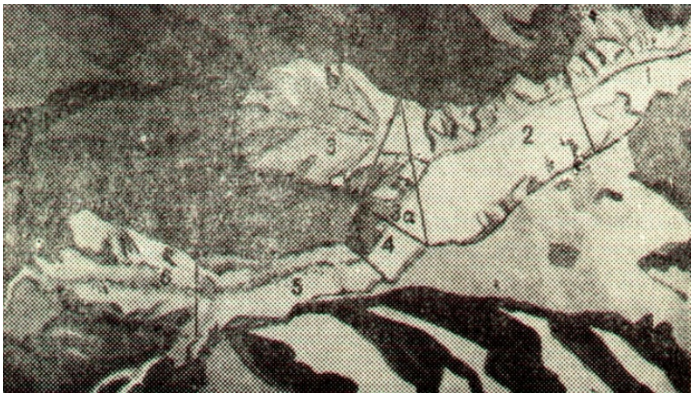


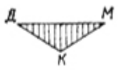
Fig. 1. Layout of monotypic sections in the debris-flow initiation zone on the frontal terrace of the Zharsay moraine.

Table 1

---

*Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1976) No. 1, pp 88–92.

Computation of the amount of glacial deposits removed from the Zharsay river basin

No section	Cross-section of monotypic sections	Year of flight	Measured cross-section elements	Average section width, m	Average section length, m	Photogrammetric measurements					Volumes of gully elements in a section, m³	Actual volume of removed of soil in a section, m³
						Edge parallax, mm	Parallax thalweg, mm	Parallax difference, mm	Average gully depth, m	Corrected, m		
1		1964 1955	△ ДМК △ АБС	120 100	260 260	4023 4570	3945 4530	078 040	62 28	61 27	901600 351000	550600
2		1964 1955 1964	△ ДМК △ АБС △ ДМБА	208 75 142	254 254 254	4070 4652 4070	3945 4628 4033	125 024 037	100 17 30	98 17 29	2430272 161925 513986	1754361
3		1964	△ ДМК	200	221	4130	4030	100	80	77	1701700	1701700
4		1964 1964 1955	△ ДМК △ БЕМ △ АБС	130 40 49	84 84 84	4125 4155 4735	4050 4125 4712	075 030 023	60 24 16	55 22 15	300300 36960 30870	296390
5		1964 1964 1955	△ ДМК △ БЕМ △ АБС	90 22 46	325 325 325	4310 4325 4873	4245 4310 4850	065 015 023	52 12 16	50 12 15	771250 42900 112125	662025
6		1964 1961 1955	△ ДМК △ БЕМ △ АБС	182 37 108	234 234 234	4465 4477 5060	4365 4465 5010	100 012 050	80 10 40	76 10 38	1618344 86580 480168	1224756
											ВСЕГО	6189832

Note: The volume of removed of soil in section 3*a* is about 150-200 thousand m³.

Table 2

Computation of loose deposits entrained by the debris flow in sections IIb and IV

Elements of gully	Section IIb as of		Section IV as of	
	1955	1965	1955	1965
Average depth, m	6	12	5	10
Average width, m	24	40	20	35
Length, m	1645	1645	1360	1360
Volume, m³	236880	789600	136000	476600
Volume of deposits entrained by the debris flow, m³	552720		340600	

Table 3

Computation of debris-flow deposits in the section "Mertvaya Polyana" (section III)

Thickness in sector, m	Area of sector, m²	Volume in sector, m³
4.0	31968	127872
5.5	35964	197802
4.5	75924	341658
3.5	19980	69930
2.0	18648	37296
1.0	21313	21313
Total:	203797	795881

Table 4

Computation of the quantity of debris-flow deposits in the cone (section IV)

Thickness in sector, m	Area of sector, m^2	Volume in sector, m^3
1.5	89093	133639
2.5	119353	298382
3.5	50430	176505
4.5	53792	242064
6.0	50430	302580
8.0	36982	295856
12.0	72283	867396
10.0	30253	302530
8.0	31939	255512
7.0	87412	611884
6.0	179867	1079202
5.0	102675	513375
4.0	104044	416176
3.0	45177	135531
2.0	28749	51498
1.0	41070	41070
Total:	1122549	5729200

Table 5

Computed thickness of debris-flow deposits in the central part of the cone according to aerial photos examined on the STD-2

No of point	Year of flight	Parallax		$P_b - P_H = \Delta P$, m	$h = \frac{H}{b}\Delta \cdot p$, m	thick-ness of deposit, m
		at upper point, mm	at lower point, mm			
1	1955	45.45	44.26	1.19	102.34	
1	1965	37.63	36.79	0.84	96.60	5.74
2	1955	44.92	44.18	0.74	63.64	
2	1965	37.32	36.88	0.44	50.60	13.04
3	1955	45.20	44.07	1.13	97.18	
3	1965	37.74	36.96	0.78	89.70	7.48
4	1955	44.90	43.83	1.07	92.02	
4	1965	38.15	31.40	0.75	86.25	5.77

It may be noted in concluding that the main mass of the solid component of the 1963 debris flow was removed from the initiation zone located on the terrace of the Zharsay moraine (6,190,000 m^3). From the mouth of Zharsay Creek to the beginning of the "Mertvaya Polyana" the debris flow entrained 550,000 m^3 of the loose rock constituent of the bed and the adjoining slopes. In the "Mertvaya Polyana" section 800,000 m^3 were deposited. From the mouth of the Ivanov Log Creek to the top of the fan the debris flow entrained 340,000 m^3. In the fan before the lake 5,000,000 m^3 were deposited, and 730,000 m^3 were carried into the lake. The difference of 550,000 m^3 between the loose rock entrained in the debris flow and that redeposited was due, evidently, to errors in determining the dimensions of the gullies and the thicknesses of the deposits. The debris-flow deposits of 1958 (140,000 m^3) were not taken into account in the computations. Based on the age of the spruces (150–200 years) that had grown on the cone before the debris flow, one can deduce that a debris flow of such large size had not occurred here for the last 200 years. The derived magnitudes of the solid phase of the 1963 debris flow must be taken into account in determining the entire volume of its debris mass, in evaluating the debris-flow hazard of the basin and in constructing debris-flow control structures.

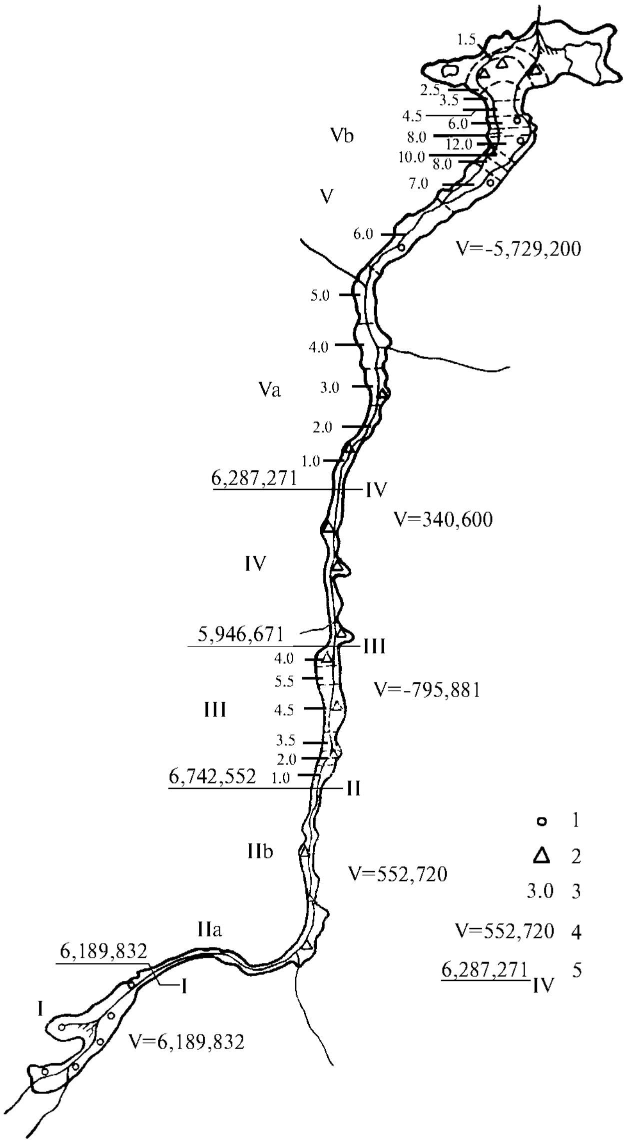


Fig. 2. Schematic of the formation of the solid phase I-V-numbers of sections, *1*-stereophotogrametric determinations of gully depths and deposit thicknesses, *2*-field determinations of gully depths and deposit thicknesses, *3*-mean thickness of debris-flow deposits in sector, *4*-volume of loose rock entrained in the debris flow (with plus sign) or deposited by it along the valley (with minus sign), *5*-location of observation site and volume of solid material transported by the debris flow through the site.

The debris flow of 19 August 1975 in the Bol'shaya Almatinka River Basin*

T. L. Kirenskaya, B. S. Stepanov & R. V. Khonin

The debris flow which occurred in the basin of the Bol'shaya Almatinka River on 19 August 1975 initiated in the upper reaches of the Kumbelsu River. The Kumbelsu is a tributary of the Bol'shaya Almatinka. Because there were no witnesses to the onset and runout of the debris flow, the characteristics of the debris flow were determined from its traces. Because the traces were surveyed by specialists of the debris-flow observation station, KazUGKS and KazNIGMI [Kazakh Institute for Hydrometeorological Research], there was no unanimous judgement as to what caused the onset of the debris flow.

The debris flow probably was initiated by the draining of the morainic lake. A ground survey conducted on 28 August 1975 showed that the water level in the lake had lowered. During the time of the survey there was no surface runoff from the lake, although it had taken place in the past. During an airborne visual survey of the moraine of the Kumbelsu glacier on 19 August the specialists saw puddles around the lake. These puddles disappeared in a few days.

The lake probably drained as the result of a 0.4–0.7 m subsidence of a substantial area of the moraine, including the lake and a section of the riverbed from the lake to the frontal terrace of the moraine. Traces of the subsidence were tracked along the entire length of the lake. Because the surface of the modern moraine subsided over a large area, the drainage of water from the lake did not cause formation of a pronounced torrent gully in the frontal terrace of the moraine. Probably contributing to this was the moderate slope of the frontal terrace of the moraine.

In the present case there was hardly any runoff of water from an endoglacial reservoir. The authors of this paper are familiar with the hypothesis of V. A. Golubovich [2] that an endomorainic reservoir had drained, but they do not agree with it.

Upon a careful survey we found no traces of an increased runoff of water (with a discharge of up to 4 m^3/s) in the eastern part of the glacier. The remains of winter snow were preserved in a small hollow which served as a channel for this waterflow. A stream with a discharge of several liters flowed over the bottom of the hollow.

Specialists of KazUGMS [Kazakh Directorate of the Hydrometeorological Service] reject the debris-flow forming role of the morainic lake because the volume of water discharged from the morainic lake is too small (150 m^3) for initiation of an erosion-shearing process. They have advanced the hypothesis that the debris flow formed as a result of the outburst of an endomorainic reservoir.

In our judgement, it is most likely that the debris flow initiated with the displacement of loose debris on the frontal terrace of the moraine. For a prolonged period the loose rock on the frontal terrace of the moraine was inundated by surface and ground water [1]. The monolithic state of the frozen soil of the moraine was broken [2]. Even a slightly increased discharge of water could induce a shearing debris-flow process. In the present case, the debris flow was caused by an increased discharge of water as a result of the draining of the lake. The draining of the lake could have become the cause of a shearing debris-flow process. The debris flow developed in the torrent gully located below the lake. The debris-flow deposits located below the torrent gully testify to the slow character of the debris-flow process and the low density of the debris-flow mass (2000 kg/m^3). Then the debris flow moved down the torrent gully (the bed of the Mynzhilki River serves as the bottom of the torrent gully), the discharge and density of the debris flow constantly increasing with a density of 2500 kg/m at the mouth of the Kumbelsu River and 2500 kg/m in the channel of the Bol'shaya Almatinka.

---

* Published originally in *«Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research* (1977) No. 2, pp 115–119.

Debris flow velocity was derived from the time of receipt of signals from a ROS [debris-flow radio-technical warning system]. These signals were recorded by specialists of KazUGMS. The distance between the ROSs was determined from a large-scale map. The locations of the ROS's and the cross-sectional profiles are shown on a schematic map of the Kumbelsu and Bol'shaya Almatinka Rivers, which were used to determine the maximum sections of the debris flow for a given site of the channel. Tables 1 and 2 show the main results of determining the velocities and discharges of debris flow in the Bol'shaya Almatinka River basin. At computing the velocities of debris flow between ROS-2 and ROS-3 (slope 0.077) in the site of the second cross sections profile (Fig. 1) according to the formulas of V.V. Golubtsov [3] and I.I. Kherkheulidze [5] obtained values of 4.2-4.4 m/s, respectively, i.e. higher than observed.

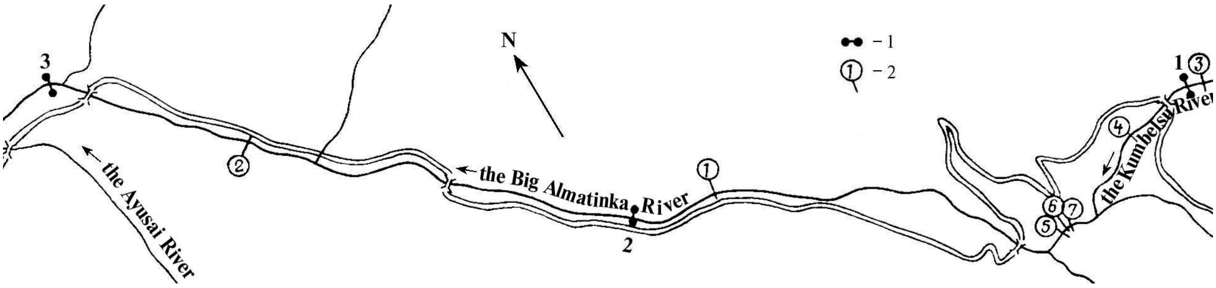


Fig. 1. Schematic drawing of the locations of ROS (2) and
cross-sectional profiles (1) in the Kumbelsu and Bol'shaya Almatinka Rivers.

Table 1

Debris flow velocity determined from the ROS signals

Observation point	Time of debris-flow passage, hours minutes	Distance between points, km	Mean slope of river in leg, tan α	Velocity of debris flow in leg, m/s
ROS-1	2 42	2.60	0.124	1.73
ROS-2	3 07	2.95	0.077	0.64
ROS-3	4 24			

Table 2

Discharge of debris-flow at the points of cross-sectional profiles, determined by the "area-velocity" method

No of cross-sectional profile	Area of cross-section, m^2	Depth of debris flow, m		Discharge of debris flow, m^3/s
		Mean	Maximum	
3	90	3.8	5.6	155
4	87	3.2	5.2	149
7	81	3.3	5.3	140
6	71	3.4	4.9	124
5	68	3.0	4.0	118
1	65	2.8	4.1	113
2	37	1.5	3.0	23

The following are indications of the low velocity of the debris flow:

a) the particularly pronounced trace of the upper boundary of the debris flow on the bank of the river (Fig. 1);

b) the absence of an aerosol mud cloud above the debris-flow surface. Vegetation located above the trace of the upper boundary of the debris flow on the riverbank is clean;

c) little skewing of the debris-flow surface at bends with debris-flow depths of 4–6 m.

Fig. 2. Traces of the debris flow in the basin of the Bol'shaya Almatinka River, 19 August 1975.

Because of the lack of reliable data on the length of the debris-flow process, we are not able to accurately estimate its volume. Nevertheless, by analyzing the deformation of the riverbed and the debris-flow deposits we can confirm that the volume of the debris flow was not more than a few tens of thousands of cubic meters.

The previously described debris-flow process significantly expanded our understanding of the possible values of the density of debris flows of the Zailiysky Alatau, and even more clearly showed the unsuitability of the existing analytical expressions for determining the velocity of debris flow. It is becoming evident that the density and granulometric composition of the solid component of the debris flow must be taken into account in computing its velocity.

REFERENCES

1. Vinogradov, Yu. B. The shearing debris-flow process and the formation of initiation zones. *Debris Flows* (1977) No 2 pp 27–39.
2. Golubovich, V. A. Some features of the onset of the debris flow in the Kumbelsu River on 19 August 1975. *Meteorologiya i gidrologiya* (1976) No 3 pp 100–101.
3. Golubtsov, V. V. Hydraulic resistance and a formula for computing the mean flow velocity of mountain rivers. *Trudy KazNIGMI* (1969) No 33 pp 30–41.
4. Stepanov, B. S. Determining the density of debris flows. *Debris Flows* (1977) No 2 pp 79–83.
5. Kherkheulidze, I. I. The flow velocities and channel characteristics of debris flows. *Trudy ZakNIGMI* (1972) No 40(46) pp 134–180.

The debris-flow events of 3–31 August 1977 in the Bol’shaya Almatinka River Basin*

V. I. Popov, B. S. Stepanov, V. P. Mochalov, R. V. Khonin, I. N. Markov, V. A. Golubovich & V. Ye. Bekarevich

UGKS of the Kazakh SSR and Kazakh Institute for Hydrometeorological Research

The basin of morainic lake No 13, located on present-day moraine at the end of the tongue of the Glacier of the Soviets in the upper reaches of the Kumbelsu River (a tributary of the Bol’shaya Almatinka), each year was filled with water during the ablation period. Water was drained from the lake by way of the surface through a lake dam (Fig. 1). In two sections the runoff channel passed through caverns of buried ice.

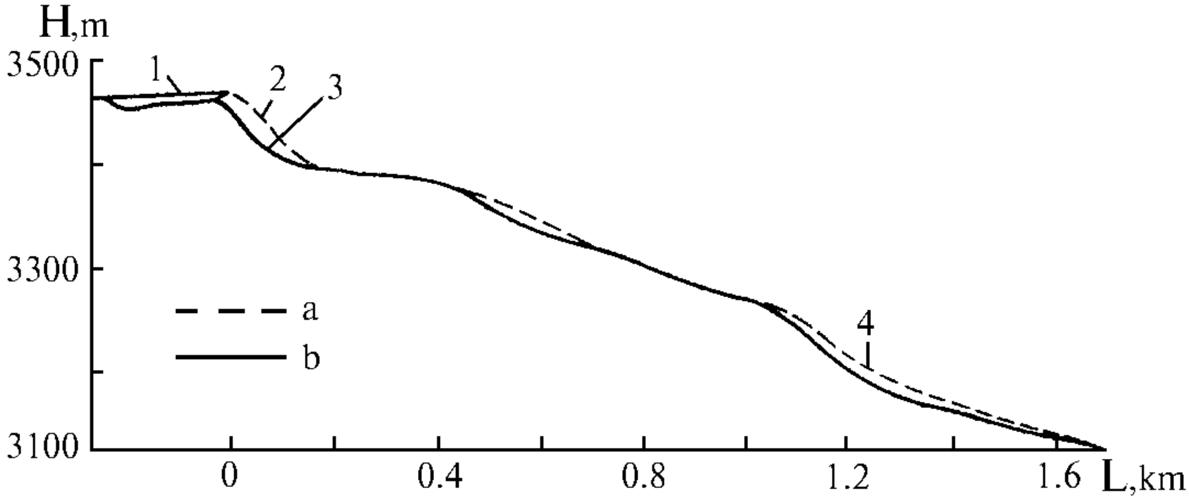


Fig. 1. Longitudinal profile of the modern moraine of the Glacier of the Soviets
a-before the debris flows of 3–31 August 1977, *b*-after the debris flows of 3–31 August 1977; *1*-lake, *2*-lake dam, *3*–opening in the body of the dam, *4*-frontal terrace.

In recent years the volume of water in the lake increased (1969: 138 thousand m^3, 1974: 220 thousand m^3). In the period 1974–1976 Kazglavselezashchita [Kazakh Main Directorate for Protection against Debris Flows] carried out a series of measures to partially drain the lake. The basic intent of the measures was to artificially lower the elevation of the overflow threshold. A temporary embankment 0.5–0.8 m in height was built on the overflow threshold, causing the capacity of the lake to increase by 10–17 thousand m^3. Then the embankment was demolished, and the resulting water flood washed away the dam. Explosive charges were set off on the dam to loosen the morainic soil. In 1975–76 lake No 13 was drained when a runoff channel from the lake formed in the frozen ground.

In early August 1977 as a result of land reclamation work and the thermal effect of normal discharges on the soil, practically no ice-cemented soil remained under the bed of the runoff channel. By 3 August a rise in the water level of 0.7 m relative to the natural overflow crest resulted in the gradual washout of the dam and then, when the water flow exceeded the critical discharge value, in a debris flow process directly on the dam, causing the lake to drain almost completely. The rapid failure of the dam was facilitated by the presence of melted and water-saturated soils in its lower part.

* Published originally in «Debris Flows», Collected Papers, Kazakh Institute for Hydrometeorological Research (1980) No. 4, pp 57–63.

As of 4 August 1977, the opening in the body of the dam had the following dimensions: maximum width 35 m, depth 25 m, length 200 m. The negative slope angle of the sides of the opening in its upper part was due to the presence of a frozen layer of soil 3–5 m thick, with the underlying soil slightly wetted and unsolidified. The state of the soil in the dam and its lack of ice lenses and filaments point to the fact that there could not have been any substantial underground flow of water from the lake. An examination of lakebed showed that there was no concentrated underground runoff through its bottom and sides.

The hypothesis that the lake dam failed relatively slowly in the initial phase fully agrees with data from observations of the debris-flow phenomena that took place on 3 August 1977. According to the data of KazUGMS [Kazakh Directorate of the Hydrometeorology Service] observer A. Ya. Shcherbinin, at 15:17 h at the frontal part of the moraine, water, ice, and morainic soil were discharged from the underground runoff channel with a noise resembling an explosion. This was because pressure in the underground runoff channel increased sharply with the increasing discharge of water. Within 19 min a similar discharge was observed 800 m higher, which was recorded by observers of KazUGMS and Kazglavselezashchita. A further increase in runoff through the dam led to its complete failure.

The shape of the opening in the dam body (Fig. 2), analysis of the progress of the debris-flow process, and the character of the soil deposits on the above-lying sections of moraine rule out the hypothesis that the lake could have drained because of the collapse of a substantial mass of earth from the frontal part of the moraine.

Fig. 2. Opening in the dam of lake No 13 (view from the downstream wall of the dam).

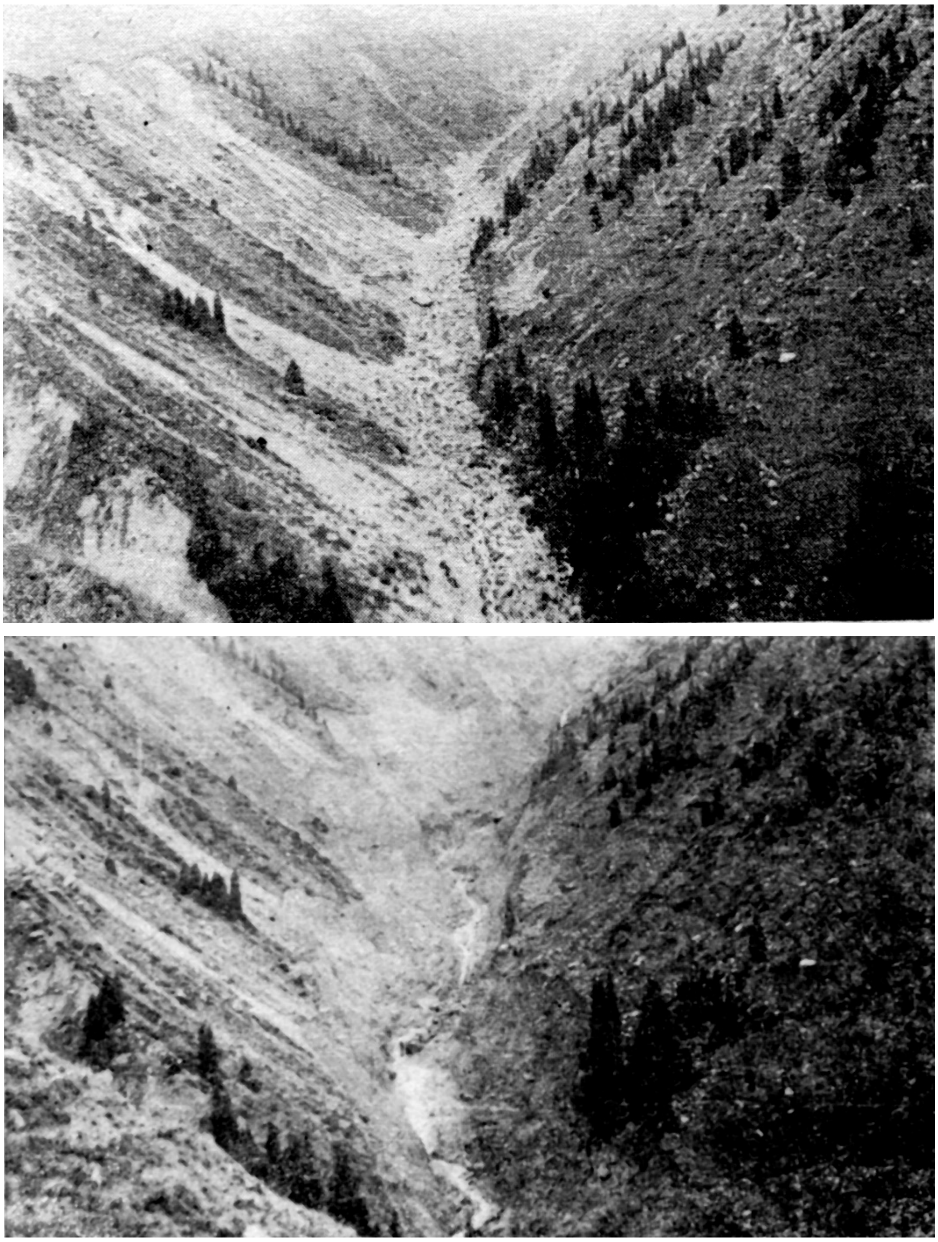


Fig. 3. The initiation zone in the basin of the Kumbel River
before the debris flows (*a*) and after the debris flows (*b*) of 3–31 August 1977.

According to the bathymetric survey completed by the Debris-flow Hydrographic Party of KazUGMS, as a result of the washout of the dam of lake No 13, 74.5 thousand m^3 of water were discharged from it in the course of 1 h 25 min, and at the same time the water level in the lake fell by 4.2 m. The mean discharge of water through the dam was 15 m^3/s, and peak discharge, more than 30 m^3/s. With account taken of the inflow of water from the glacier during the draining of the lake, water released from the mechanical wearing away of ice in the runoff channel, channel water reserves and reserves of moisture in the ground, an additional volume of water may be estimated to be approximately 16 thousand m^3. The draining of the lake was accompanied by debris flows not only at the lake dam but on all steep slopes of the modern moraine.

The torrent gully, which ranged in height above sea level from 2565 to 2920 m, is around 1.1 km long and before initiation of the debris flow had been a very deep depression (up to 100–150 m) in Upper-Quaternary glacial deposits (Fig. 3*a*). The average longitudinal slope of the torrent gully was 19°. The gully sides had an even slope ranging between 28 and 35° and were covered with turf and subalpine grass. Dendrochronologic data show that no debris flows occurred here at least during the last century. In consequence of the debris-flow events of 3–4 August 1977 the gully underwent substantial changes and was transformed into a hardly accessible canyon with steep, almost vertical sides attaining heights of 80 m (Fig. 3*b*). Numerous collapse lines formed along the left- and righthand sides of the gully. In the lower third of the gully the potential debris-flow mass (PDFM) was almost completely depleted, and outcroppings of bedrock lay exposed on the bottom. The deepening of the gully and the collapsing of its sides led to the outlet onto the bottom surface of numerous underground springs, the waters from which previously had been discharging in a stratum of morainic deposits. It is difficult to overrate the importance of underground springs in the forming of many debris-flow surges. The gully sides remained unstable right up to the end of the period of debris-flow hazard.

At 15:28 h the first debris-flow surge reached the top of the gully to mark the beginning of the debris-flow process on the ancient moraine. At 16:00 a surge considerably larger than the others entered the torrent gully. In addition to debris-flow surges (some course detrital material was deposited in a kilometer-long section of the glacial trough), surges of alluvium-water flows enriched with fine soil entered the torrent gully. There was no debris-flow activity above the torrent gully after the run of the largest surge. But on the ancient moraine these processes recommenced periodically right up to 31 August.

Debris flows caused by collapses of the gully sides occurred on 4, 5, 6, 19–20, 26, 27, 28, 30 and 31 August. Almost all consisted of a series of debris-flow surges. For example, on 3 August staff of the Alma-Ata Debris-Flow Observation Station recorded around 300 separate surges. On 6 August in the upper reaches of the torrent gully there occurred a cave-in of 150–200 m^3 of debris-flow-forming soil, which in about 20 min (a water discharge of around 0.6 m^3/s entered the initiation zone) was set in motion. At the mouth of the Kumbel River the discharge of the debris-flow surge attained 500–600 m^3/s.

At 15:45 h on 3 August a debris-flow surge, having traveled over a transition section (from the mouth of the Mynzhilki to the mouth of the Kumbel), reached the valley of the Bol'shaya Almatinka River. The forward movement of the surges occurred in 5–20 minute intervals. Each successive surge moved down the valley of the Bol'shaya Almatinka 70–100 m further in comparison with the previous surge (Fig. 4). The surges moved to the accompaniment of crashing rocks and snapping of breaking trees; at sharp turns of the channel where the debris flow interacted with outcroppings of bedrock, rocks and splashes of mud flew fan-like out of the flow, columns of mud spray rose in front of the surges, and large clumps rolled out from the debris-flow surge when it stopped or abruptly slowed down.

By 22:19 h the debris-flow formation process had subsided. The valley of the Bol'shaya Almatinka up to GES [Hydroelectric Power Station] No 2 was continuously covered with a three- to four-meter layer of dark grey debris deposits. As soon as the surges stopped, an alluvium-water flow rushed over the solidified surface of the debris deposits, eroding them and entraining fine sediment. The lake waters entrained for several hours in the debris-flow process returned to their everyday work of channel forming.

At around 03:00 h on 4 August collapses of the sides of the torrent gully sharply intensified, and an extremely large, catastrophic surge rushed down the Bol'shaya Almatinka valley with a mean velocity of 10 m/s. In the region of the mouth of the Prokhodnaya River its discharge attained 10 thousand m^3/s and then, abruptly losing power, the flow ran slowly to the "Sayran" reservoir. On subsequent days debris flows formed also because of collapses of the gully sides, but they were considerably inferior in size to the debris flow of 4 August.

Fig. 4. Movement of the head of a successive surge over the debris-flow surface.

The density of the debris flows of 3 and 4 August exceeded 2400 kg/m^3, while the debris flows on subsequent days were distinguished by their somewhat lower density and viscosity. This was due to the relation between the solid and liquid components taking part in the debris-flow formation process. On 3 August the portions of the PDFM that were entrained in the debris-flow formation process were drier than those on subsequent days, and the number of collapses on the whole tended to decrease with time. The density of the debris-flow mass of the flows was 2100–2300 kg/m^3, and their movement was turbulent in character.

One can judge the velocities of the debris-flow surges on the basis of numerous data from observations of these surges as they passed between two fixed points. These observations were conducted in several reaches of the torrent gully, at the hydro-observation post at the mouth of the Kumbel and in the Bol'shaya Almatinka valley. Data obtained by debris-flow radio-technical warning system were included for this purpose.

The velocity distribution of most debris-flow surges along the Kumbel and Bol'shaya Almatinka valleys on 3 August had the following pattern: soil set in motion in the torrent gully already had attained a velocity of up to 2–3 m/s in a 150–200 meter reach. At the exit from the torrent gully velocity rose to 5–6 m/s and towards the mouth of the Kumbel River attained 8–10 m/s and higher. In the valley of the Bol'shaya Almatinka the velocity of the surges diminished and in a section of fresh debris-flow deposits remained at about 5–6 m/s. After passing over these deposits, the debris-flow mass spread out in a 70–100 meter reach of the valley and solidified. The peak velocity of the flow of 4 August in the reach from the torrent channel to the hydro-observation post at the mouth of the Kumbel River was more than 10 m/s, and in the leg between the hydro-observation posts at the mouth of the Kumbel and the Bol'shaya Almatinka and to above the mouth of the Prokhodnaya River, around 9–10 m/s. The high velocity of this surge was due, on the one hand, to the formation in the torrent gully of an extremely large debris flow, and on the other, to the fact that the bed of the Bol'shaya Almatinka up to the GES No 2 was covered with fresh debris deposits. Below the mouth of the Prokhodnaya its velocity sharply diminished as debris-flow mass was deposited in the debris fan.

The velocity distribution of the debris-flow surges that formed after 4 August was different in character. In the torrent gully and right up to the mouth of the Kumbel River velocities of the debris-flow surges were practically in the same range as those of the debris flow of 3 August. In comparison with the debris flow of 3 August the velocities of the surges (after 4 August) down the Bol'shaya Almatinka had both higher and lower values and ranged between 3 and 7 m/s.

On their exit from the torrent gully the height of most surges changed from 1–2 to 7–8 m, and in the Bol'shaya Almatinka valley, from 1 to 6 m. The debris flow of 4 August had the greatest surge height, which reached 15 m in the Bol'shaya Almatinka valley. Even in the relatively straight sections of the channel, the movement of the debris-flow surges was accompanied by a sharp, cross-sectional skewing of the debris-flow mass by several meters.

The runout distance of the debris-flow mass was governed by the magnitude of the peak discharge and by the volume of debris-flow mass involved in the forming of the debris-flow surge at the exit from the torrent gully, by the character of the flow's motion and the degree to which the channel was covered with debris-flow deposits. Mainly debris-flow mass removed from the torrent gully in ancient moraine was deposited in the Bol’shaya Almatinka valley in the leg between GES No 1 and No 6. Previously-existing channel deposits in the Bol’shaya Almatinka valley played no part in the debris-flow process.

The peak discharges of the debris-flow surges on leaving the torrent gully varied widely from 100–150 m^3/s to 1300 m^3/s. The debris-flow surges in the Bol’shaya Almatinka valley had discharges ranging between several tens and 10 thousand m^3 per second with the highest peak discharge values belonging to the debris flow of 4 August. For the purpose of making a preliminary estimate of the total volume of the debris flows of 3–31 August staff of the Alma-Ata debris-flow observation station and the Debris-Flow Hydrographic Party of KazUGMS in September 1977 estimated the volume of material removed from the torrent gully and also took levels of previously marked cross sections in the transition channel and in the debris cone. The data obtained by the two methods were very close-2.7–2.9 million m^3. Thus, taking into account the material removed from the modern moraine, the total volume of removals over the period 3–31 August was not more than 3.0–3.2 million m^3.