GLOFCA PROJECT

«Reducing vulnerabilities of populations in the Central Asia region from glacier lake outburst floods in a changing climate»

Report on task 10:

preliminary development of a methodology for calculating the mudflow risk area on the example of the Ala-Archa river valley.

Authors: Moldobekov B.D., Erokhin S.A., Usupaev Sh.E.

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1. Introduction

Debris flows and floods generated by outbursts of mountain lakes pose a significant threat to the safety of residents of mountainous and foothill areas of the territory of the Republic. To protect against the destructive effects of these hazardous processes, it is necessary to determine the boundaries of their impact zones.

The procedure for determining flood and debris flow zones is based on an approach where the processes of outburst, debris flow formation, and debris flow and flood flow movement are considered in their close relationship as separate fragments of a single multifactorial natural phenomenon - a mountain lake outburst.

The outburst flow when moving down the gorge covers either the whole bottom of the river valley or some part of it depending on the morphology of the valley, its structure and hydrological character of the flow. Therefore, hydrological, lithological and morphological factors are taken into account to determine the boundaries of flood and debris flow zones. The factors are evaluated by the corresponding parameters: hydrological - flow rate-Q; lithological (mudflow or flood nature of the flow) - flow density ρ; morphological - width B at the bottom of the valley. To determine the parameters, longitudinal and transverse profiles of the valley are used, which reflect the morphology of its bottom and adjacent side sections. For each transverse profile, parameters characterizing the outburst flow are calculated: flow rate, height of the breakthrough flow H, width of the breakthrough flow $B_п$ (the affected area).

The magnitude of the outburst flow depends on the mechanism of the lake dam breach. Emptying of lakes is reduced to two most typical variants: 1) underground – release of water through intra-moraine and intra-glacial channels (Fig. 1); 2) surface – release of water by overflow through the crest of the dam after its subsidence or erosional destruction (Fig. 2).

2. Outburst of a lake by underground

According to the first variant, the following formula is used to determine the flow discharge of the outburst flow:

$$Q_B = \frac{\sqrt{h_c + h_к}}{A_B h_c + \beta} \quad (1)$$

Where Q_B- is the water flow discharge through underground channels; m^3/s;

h_c – excess of the level of the free water surface in the lake above the channel inlet, m. According to the most dangerous variant of emptying, the inlet opening of the drain channel is on the bottom of the lake in its deepest place.

In this case, the value of h_c is equal to the maximum depth of the lake.

$h_К$ – excess of the channel inlet over the end of the discharge section, m; often $h_К = h_Н$, where $h_Н$ – is equal to the excess of the discharge channel inlet over the outlet;

A_B – the average value of resistance Ā in the section of the pressure flow:

$$A_B = \frac{A_п \times L}{h_н} \quad (2)$$

Where Ā is the resistivity, which simultaneously takes into account both local and track losses;

n – the ratio of the actual length of the pipeline to the value of L

L- is the shortest distance between the inlet and outlet on the plan, m;

β – is the hydraulic resistance of such a section in which, at a given flow discharge $Q_в$ the pressure loss is equal to the velocity pressure in the outlet section

$$\beta = \frac{0.056}{F^2} \quad (3)$$

F – is the cross-sectional area of the underground channel in the section closing the pressure section.

For the reliability of calculations, the length of the pressure section is assumed to be equal to the length of the underground drainage channel, then F will be the cross section of its outlet (grotto).

The cross-sectional area of outburst grottoes varies over a wide range, which can be seen in specific examples:

- outburst of lake №16 in the basin of the Kaskelen river (1977)->4m^2;

- outburst of lake №17 in the basin of the Ysysk river (1980)-> 4m^2;

- outburst of lake Choktal on the southern slope of the Kungei-Alatoo ridge in the basin of the Kaskelen river (1978)- 50-60m^2;

- breakthrough of intraglacial reservoirs of the Ak-Sai glacier- 100 m^2;

- outburst of Lake Top-Karagai (northern slope of the Kyrgyz Range) (1973)- 40-50m^2;

- outburst of Lake Keydy-Kuchkach (the Sokuluk River basin) (1983)- 20-30 m^2;

- outburst of Lake Shamsi (Southern slope of the Kyrgyz Range) (1978)- 50 m^2.

From the above data it follows that the maximum allowable value of the grotto cross-sectional area does not exceed 100m^2. Otherwise, the roof of the grotto collapses.

To determine the resistivity A, we convert formulas (1) and (2) to the following form (taking $h_k = h_н$):

$$\overline{A} = \frac{I}{n \times L} \times \frac{h_c + h_н}{{Q_{max}}^2} - \frac{0.056}{F^2} \quad (4)$$

Using data on moraine-glacial lake outbursts of the northern slope of the Zailiisky Ala-Too, the average value of Ā is recommended to be 5,2 x 10 $^{-5}$ c^2/м^6.

Data on determining the discharge of possible outburst flows of emptying of some hazardous lakes are given in Table 1.

3. Surface outburst

According to the second variant, the lake outburst occurs by overflow through the crest of the dam. In this case, the outburst flow discharge is determined by the formula:

$$Q_B = K \times B' \times H^{1,5} \qquad (5)$$

Where K- is a coefficient depending on the shape of the free flow section;

B' – the width of the breach at a level equal 2/3 H;

To determine it, in addition to (5), the following formulas are used:

$$Q_B = V \times F \qquad (6)$$

Where F is the area of the breach;

$$V = 4,83 \times H^{0,5} \times i^{0,25} \qquad (7)$$

With a triangular section of the breach K=3,62 $i^{0,25}$ the slope i of the slopes and the bottom of the breach is equal to the critical one for loose clastic deposits under water (i= 35^0), then i=tg α=0,7 and K=3,31.

With a rectangular section of the breach in frozen rocks with buried ice K=4,83 $i^{0,25}$, if the slope of the bottom of the breach is critical i=0,7, then K=4,40.

With a trapezoidal section of the breach in loose clastic deposits underlain by frozen or rocky soils for a sufficiently long and powerful process of emptying the lake i = tgα =0,7.

$$K = 4,83 \times i^{0,25} \times \frac{B_B - 1,43H}{B_B - 0,95H}$$

then: (8)

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$$K = \frac{7,25 \times i^{0,25} (B_B - B_H)}{2B_B + B_H}$$

for any trapezoid; (9)

In formulas (8) and (9): i is the slope of the bottom of the breach, H is the height of the pier water horizon above the bottom of the breach, m; B_B is the width of the breach, when the crest of the dam is lower than the water level in the lake by the value H.

With a gradual rise in the water level in the lake and a surface overflow through the dam, deepening, and expansion of erosional washout with the formation of a breach, the flow discharge of the outburst flow depends on the dimension of the coarse-grained material, which makes up the flow, depends on the dimension of the coarse-grained material that makes up the dam, as well as on the speed of the outburst flow. The latter is determined by the formula:

$$V = h_{vc} \times \sqrt{2g \times \frac{(\rho_T - \rho_B)}{\rho_B} \times \sqrt{D}} \qquad (10)$$

Where h_{yc} – is the coefficient of shear stability of the stone, commonly used

equal – 0,86-0,9;

ρ_{B}, ρ_{T} – are the density of water and solid phase;

D- debris diameter;

g – free fall acceleration, g = 10 m/s^2

The outburst flow discharge is determined by formula (6): Q = V x F

V- is determined by formula (10). F is the cross-sectional area of the breakthrough washout. When it breaks through, it has a triangular cross-sectional shape, it deepens and expands under the action of gravel, the value of H (height of the backed water horizon), the flow velocity V, and the flow rate Qmax increase. The maximum speed in the breach, when the river channels are blocked, in the process of the extension of the dams from the banks, is achieved at the moment of their closing at the bottom. Up to this point, the flow rate gradually increases, after which it decreases. When a dam barrier of a mountain lake breaks, the flow rate and its flow discharge change in a similar way.

The depth of the breaching washout increases up to a certain depth H_{max}. In this case, the washout sides close in one point and at its bottom (in case of loose clastic composition, the slope of the sides is equal to their critical value under water, i.e. i = 0.7). The cross-section is triangular. Flow velocity and flow discharge are maximal. In the future, the area of the washout cross section may increase. However, H value will decrease, and flow velocity and flow discharge will drop accordingly.

Thus, to determine Q_{max}, you must first calculate the value of H_{M}. For this purpose the formula (7) is used, converted with respect to H:

$$H = \left(\frac{V}{4{,}83 \times i^{0{,}25}} \right)^2 \qquad (11)$$

The flow discharge V is determined by the above formula (10). Formula (6) includes a value F equal to F = B/2 x H.

When the steepness of the washout sides is critical, at i = 0.7, the washout width B is defined through H: B = 2.86 H. Then F = 1,43 H^2, formula (6) takes a form

$$Q = V \times 1{,}43H^2 = 6{,}91 \times H^{2{,}5} \times i^{0{,}25} \qquad (12)$$

Examples of determination of outburst flow discharge of some mountain lakes are given in Table 2.

4. Debris flow discharge determination

When a mountain lake breaks through, a powerful water flow appears in the lower part of the river valley, washing away bottom and mudflow deposits, the erosion hotspots of which are transformed into a mudflow.

To determine the mudflow flow discharge, the following formula is recommended:

$$Q_C = Q_B\left[1+\frac{C_T}{1-(1+\zeta)\times C_T}\right] \quad (13)$$

$$\zeta = \frac{\theta}{1-E}$$

Where ς is relative humidity, θ-is volumetric humidity;

E – porosity of mudflow-forming soils;

Q_B – the flow discharge of the outburst water flow before its transformation into a mudflow;

C_T – is the concentration of solid material in mudflow mixture;

Formula (13) is applicable under the condition that the flow discharge of the outburst flow exceeds the critical one for a given mudflow hotspot ($Q_B > Q_{кр}$), and the inflow of PDF(Potential Debris Flow) is not limited. For mountain lake outbursts, these conditions are met.

The value of C_T is determined by the equation:

$$tg\alpha = \frac{C_T(\rho_T-\rho_B)tg\varphi}{C_T(\rho_T-\rho_B)+\rho_B} \quad (14)$$

Conversion with respect to C_T takes the following form::

$$C_T = \frac{\rho_B\times tg\alpha}{(\rho_T-\rho_B)\times(tg\varphi-tg\alpha)} \quad (15)$$

Table 1

Determination of outburst flow discharge when draining the lake by underground

№	Lake name	Lake location	h_c m	h_k=$h_н$, m	A c^2/m^6	n	L, m	β	F, m^2	A_B c^2/c^6	Q m^3/s
1	Kaydy-Kuchkach (outburst in 1983)	River basin Sokuluk Chui region	8	94	$5{,}2x10^{-5}$	1,02	380	$5{,}6x10^{-4}$	30	$2{,}1x10^{-4}$	71
2	Kaydy-Kuchkach (possible outburst)	River basin Sokuluk Chui region	30	57	$5{,}2x10^{-5}$	1,02	430	$1{,}4x10^{-4}$	20	$4{,}0x10^{-4}$	62
3	Tez-Tor (outburst in 1953)	River basin Ala-Archa Chui region	7	85	$5{,}2x10^{-5}$	1,02	470	$2{,}5x10^{-4}$	15	$2{,}9x10^{-4}$	62
4	Tez-Tor (outburst in 1988)	The same	11	8	$5{,}2x10^{-5}$	1,02	120	$2{,}5x10^{-4}$	15	$8{,}0x10^{-4}$	54
5	Jardy-Kaindy (possible outburst)	River basin Jardy-Kaindy, Chui region	5,5	44,5	$5{,}2x10^{-5}$	1,02	275	$1{,}4x10^{-4}$	20	$3{,}3x10^{-4}$	58

6	Teke Tor (possible outburst)	River basin Tuyuk-Issykatinsky Chui region	33	2	$5{,}2x10^{-5}$	1,00	550	$1{,}4x10^{-4}$	20	$1{,}1x10^{-4}$	45
7	Suyuk Tor (possible outburst)	River basin Aksai Issyk-Kul region	10	95	$5{,}2x10^{-5}$	1,01	670	$2{,}5x10^{-4}$	15	$3{,}7x10^{-4}$	54
8	Kashka-Suu (possible outburst)	River basin Ala-Archa Chui region	8	10	$5{,}2x10^{-5}$	1,02	150	$5{,}6x10^{-4}$	10	$8x10^{-4}$	46
9	Jalpak-Tor-1 (outburst in 1969, 1976)	River basin Chirkanak Talas region	7	60	$5{,}2x10^{-5}$	1,16	100	$5{,}6x10^{-4}$	10	$1{,}0x10^{-4}$	101

Table 2

Calculations of outburst flow discharge when draining lakes by surface

№№	Lake name	Location	outburst flow parameters				Flow discharge Q m^3/s
			К	Н,м	В,м	i	
A. Dam cofferdam subsidence							
1	Zhalpak-Tor -2 (possible outburst)	Chirkanak River Basin Talas region	3,29	3	6	-	103
2	Choktal - 1 (possible outburst)	Coktal River Basin Issyk-Kul region	3,29	5	10	-	368
3	Choktal - 2 (possible outburst)	Coktal River Basin Issyk-Kul region	3,29	2	4	-	37
4	Tuyuk - 2 (possible outburst)	Ton River Basin Issyk-Kul region	3,29	4	7,6	-	201
5	Choctal - 1 (outburst in 1978)	Coktal River Basin Issyk-Kul region	3,29	1,3	5	-	24 (in the village of Choctal - 25)
Б. Erosional washout of the dam cofferdam							
1	Sokuluk (dammed lake in case of outburst of Keydy-Kuchkach lake)	Sokuluk River Basin Chui region	-	11,5	-	0,7	2262
2	Sokuluk (outburst in1983)	Sokuluk River Basin Chui region	-	4,0	-	0,29	162 (near the village of Sokuluk - 140)
3	Koltor (possible outburst)	Kegeti River Basin Chui region	-	4,0	-	0,36	170
4	Ak-Kel (possible outburst)	Min-Kush river basin Naryn region	-	10	-	0,7	1990
5	At-Joyloo (possible outburst)	Kegeti River Basin Chui region	-	2	-	0,7	36

In equations (13) and (14), the following notations are used:

$\rho_В$ and $\rho_Т$ – densities of water and solid matter of mudflow mass;

φ – angle of internal friction of PDF under water;

α is the slope angle of the PDF, on average equal to the slope angle of the valley bottom.

$C_Т$ calculation by formula (15) does not give a solution at values α exceeding $23\text{-}25^0$, since the outburst flow is maximally saturated by debris material at the debris-flow hotspots with a bottom slope of $23\text{-}25^0$ (the presence of an unlimited amount of PDF and $Q_В$ $Q_{кр}$). Debris flow density $\rho_Т$. A further increase in ρ_c even at α=25 is impossible. It follows that debris flows in mudflows hotspots of steepness more than 25^0 have a maximum possible density - ρ_{max} = 2500 kg/m^3.

$C_Т$ value is determined by the following formula:

$$C_Т = \frac{\rho_c - \rho_В}{\rho_Т - \rho_В} \tag{16}$$

When $\rho_Т$ = 2650 kg/m^3 $C_Т$ value will be 0.91.

Table 3 presents data on determining the flow discharge of debris flows in the most dangerous mudflow hotspots in northern Kyrgyzstan.

5. Determination of flood flow discharge

When the lake breaks through, the water flow rushes down the valley and, in the absence of mudflows hotspots, there is a flood flow more or less saturated with clastic material (ρ<1.1). Flood flow is also formed after decomposition of mudflow mixture in the upstream parts of the valley. Its discharge is determined by the formula:

$$Q^i_п = Q^i_в + \frac{Q^i_в \times (\rho^i_в - \rho_В)}{\rho_Т} \tag{17}$$

Q^i_n - the flow discharge in the defined section line, m^3 / s;

Q^i_n - flow discharge in the previous section line, $Q^i_В = Q^{i-1}_n$ x $(1 - C_Т^{i-1})$, m^3 / s;

$\rho^i_В$ - flow density in the defined section line, its value is determined by the formula:

$$\rho^i_В = (1 - C_Т)\ \rho_В + C_Т \rho_Т \tag{18}$$

where $\rho_Т$, $C_Т$ are density and concentration of solid matter in the flow;

$\rho_Т$, is determined by experiment, and $C_Т$ value by formula (14).

5.5. Determining outburst flow height

To determine the width (B) of the flood and debris flow zone it is necessary to know the height (depth) (H) of the outburst flow in each transverse profile – section line (Fig. 3,4). To determine the actual height H of the outburst flow is not possible due to the danger and the suddenness of the flood and debris flow process. That is why we use theoretical height of the flow - $H_р$, which will be somewhat greater than $H_д$ (actual), which increases the reliability of calculations.

$H_р$ value is calculated by formula (7), converted relative to $H_р$.

$$V = 4{,}83 \text{ x } H_p^{0{,}25} \text{ x } i^{0{,}25} \tag{19}$$

$$V = Q_n/F_p \tag{20}$$

$$H_p^{3/2} = \frac{Q_n}{4{,}83 \times i^{0{,}25} \times B} \tag{21}$$

In the formulas, H_p is the calculated height of the outburst flow, m;

V - velocity of the breakthrough flow, m/sec;

i - valley bottom slope, i =tg α - valley slope angle;

Q_n - outburst flow discharge, m^3/sec;

B - width of the valley bottom, m; the bottom is the channel, floodplain and late Holocene valley terraces;

F_p - calculated area of outburst stream cross-section (6); (for calculations we assume rectangular cross-section shape): $F_p = H_p \text{ x } B$

The product H_p x B gives the theoretically calculated cross-sectional area F_p of the outburst flow. It is assumed that the cross section of the flow is rectangular. In reality, the flow spreads along the bottom of the valley, occupying its entire cross section with area $F_д$ and height $H_д$ (see Fig. 3).

$F_д$ and $H_д$ are the actual cross-sectional area and height of the outburst flow. The shape of the section $F_д$ is usually trapezoidal. When $F_p = F_д$ is equal, the value of H_p will be greater than $H_д$.

The difference between H_p and $H_д$ creates a margin of safety for calculations, which is necessary for the reliability of determining the width and boundaries of the affected area for each transverse profile – section line.

The regime of movement of the outburst flow is turbulent, the flow discharge is unstable. Congestion in the channel, the breakthroughs of which sharply increase the height of the flow, respectively, expand the affected areas. Inequality $H_p > H_д$ fulfills the condition of calculation reliability.

Table 3

Calculation of Debris Flow Discharge at the Outlet of the Most Dangerous Debris Flows in Northern Kyrgyzstan

№	Name of the mudflow center	Location	ρ_c	$\rho_т$	tg φ	tg α	$C_т$	$Q_в$ $м^3$/сек	ε	θ	ς	Q_c m^3/s
1	Keydy-Kuchkach	River basin Sokuluk Chui region	1	2,65	0,7	0,39	0,76	62	0,3	0,07	0,1	349
2	Ashu-Tor	River basin Sokuluk Chui region	1	2,65	0,7	0,30	0,45	20	0,3	0,10	0,1	38
3	Kashka-Suu	River basin Ala-Archa Chui region	1	2,65	0,7	0,45	0,91	46	0,3	0,04	0,06	1228
4	Tez-Tor-Adygene	River basin Ala-Archa Chui region	1	2,65	0,7	0,24	0,32	61	0,3	0,10	0,14	92
5	Ak-Sai	River basin Ala-Archa Chui region	1	2,65	0,7	0,40	0,80	10	0,3	0,06	0,09	72
6	Teke-Tor	River basin Tuyuk-Issykatinsky Chui region	1	2,65	0,7	0,37	0,68	45	0,3	0,08	0,11	170
7	Chok-Tal	River basin Chok-Tal Issyk-Kul region	1	2,65	0,7	0,1	0,1	368	0,3	0,10	0,14	410
8	Suyuk Tor	River basin Ak-Sai Issyk-Kul region	1	2,65	0,7	0,22	0,28	54	0,3	0,10	0,14	76
9	Kichi-Kyzyl-Jar	River basin Chon-Aksu, Issyk-Kul region	1	2,65	0,7	1,16	0,29	10	0,3	0,10	0,14	18
10	Jalpak-Tor-1	River basin Chirkanak Talas region	1	2,65	0,7		0,27	101	0,3	0,10	0,14	169

6. Flood hazardous areas in the Ala-Archa valley

There is only one flood area in the Ala-Archa valley - the Ala-Archa River, its channel, floodplain and floodplain terraces. The flood flow zone covers not only mountain valleys, but also foothill plains, i.e. a significant part of the valley bottom. Therefore, determination of the flood affected zone boundaries is the most important task. For its fulfillment it is necessary to carry out engineering-geological survey with valley profiling, which requires specific approach and considerable expenses. Specificity of the works lies in special conditions of their performance. Firstly, they cover large areas along mountain valleys and adjacent foothill plains. Secondly, outburst streams pass through all altitude belts, from 3500-4000m to 500-1000m and through difficult to access areas (canyons, gorges) of mountain valleys. Thirdly, in order to build a cross-sectional profile of the valley it is necessary to take measurements both on the left and right banks, and this is hindered by the mountain river, which becomes very dangerous when crossing. Therefore, the work on mountain valley survey occupies a special place.

Debris flows with abnormally high flow rates repeatedly passed along the Ala-Archa riverbed. These flows reached Bishkek city, destroying road and pedestrian bridges and flooding coastal areas.

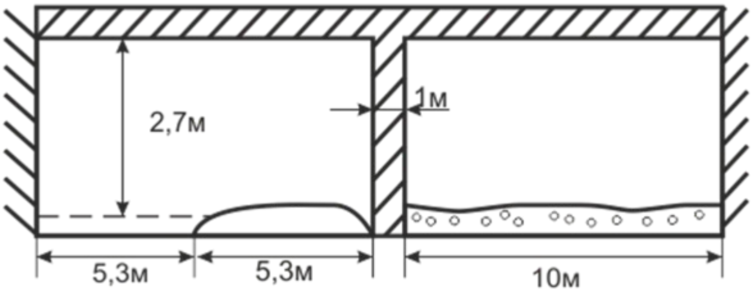
The flow, as it moves downhill through the valley, either covers the entire width of its modern bottom or a part of it, depending on the morphology of the valley section (slope, width, presence of riparian terraces), its geological structure (composition of rock layers forming the banks and bottom), and the hydrological nature of the flow (flood or debris flow). Therefore, to determine the width of the flow, and consequently the boundaries of the affected zone, it is necessary to consider the morphological, lithological, and hydrological factors contributing to the formation of the outburst flow in each specific section of the mountain valley. The role of each factor in the overall process is evaluated using corresponding parameters: morphological – width of the modern valley bottom and its slope; lithological – density of the outburst flow; hydrological – flow discharge.

The discharge of the historically maximum flood that occurred along the Ala-Archa River was 50 m^3/second (1953). However, even more powerful floods are possible. Hydrological calculations show that the discharge of such floods, with a probability of 0.1%, could reach 70 m^3/second. A probability of 0.1% is acceptable for the construction of irrigation and flood protection structures, as well as for determining the boundaries of flood-affected areas. Therefore, when defining the boundaries of flood-affected zones along the Ala-Archa River, the discharge of 70 m^3/second, representing the 0.1% exceedance probability, was used as the basis. To determine the estimated parameters, valley profiling is conducted. Transverse and longitudinal profiles are constructed along the entire length of the valley.

For the case of the Ala-Archa river valley, cross-sectional profiles were constructed

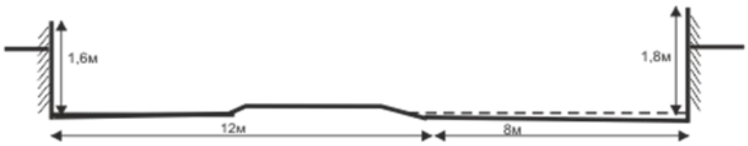
Cross-sectional profiles of the bottom of the Ala-Archa river valley in its parts (bridge on Semetei Street)

ПАА 1: Ул. Мост по ул.Семетей



ПАА2.

ПАА2-А



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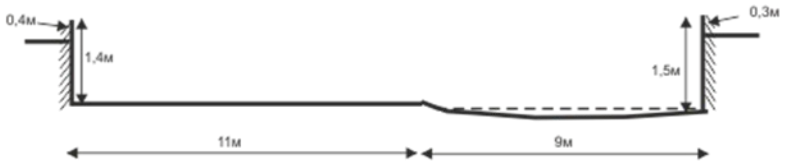

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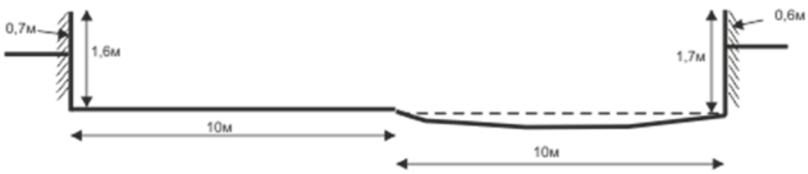

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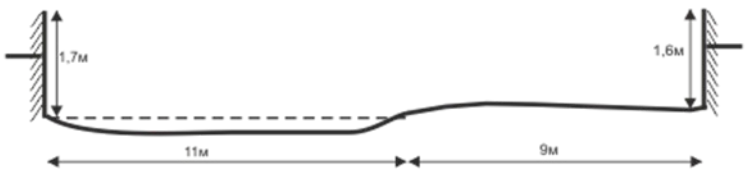

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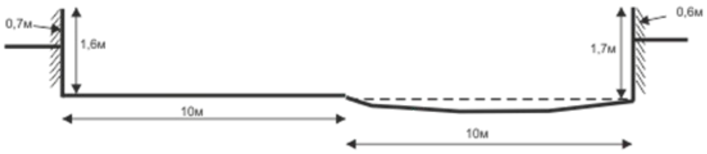

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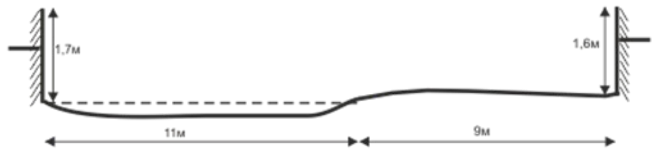

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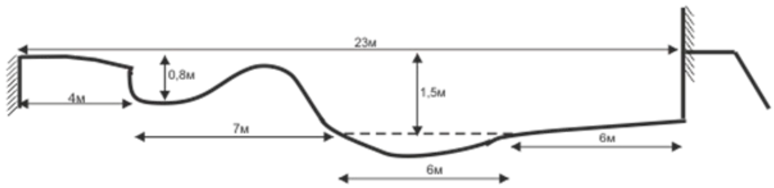

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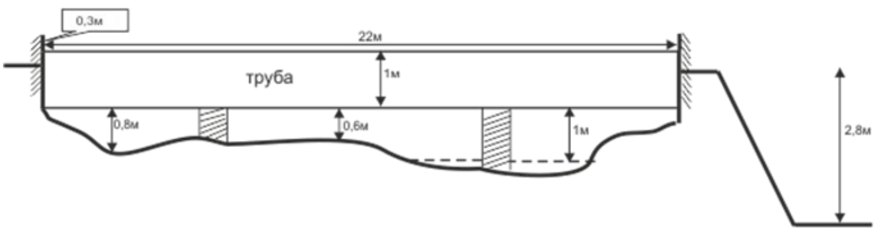

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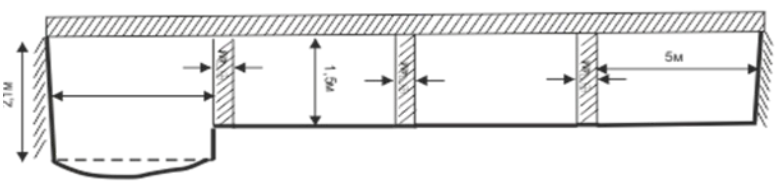

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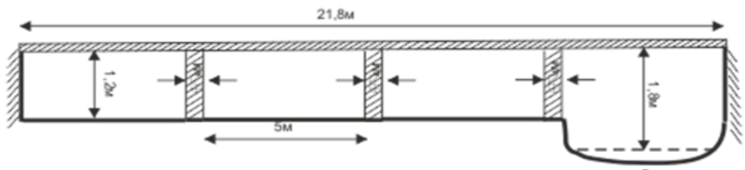
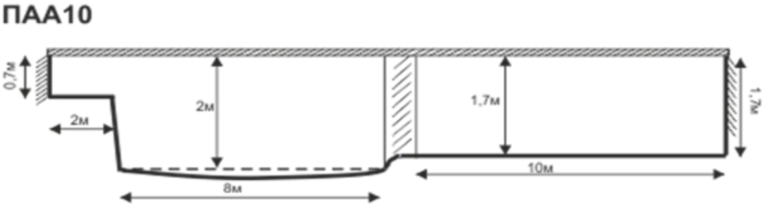


ПАА10



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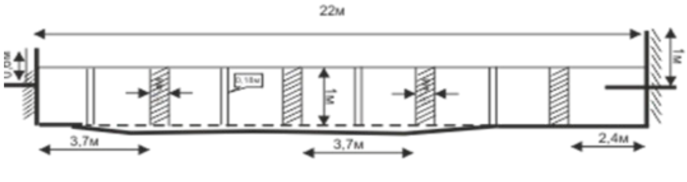
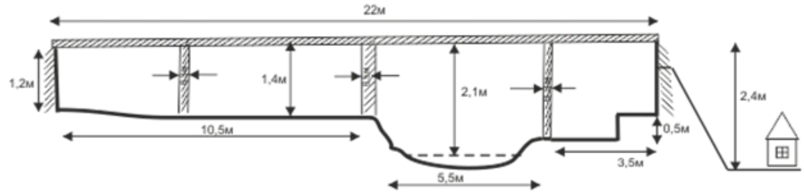


ПАА5-А



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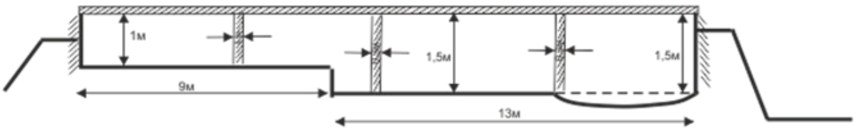
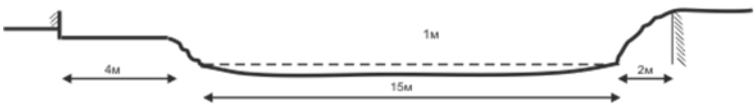
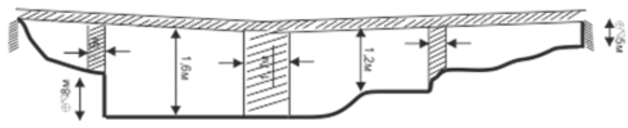


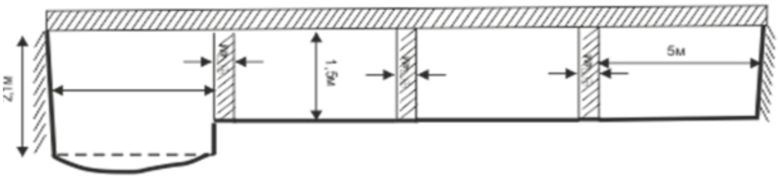
ПАА7



ПАА8



ПАА9



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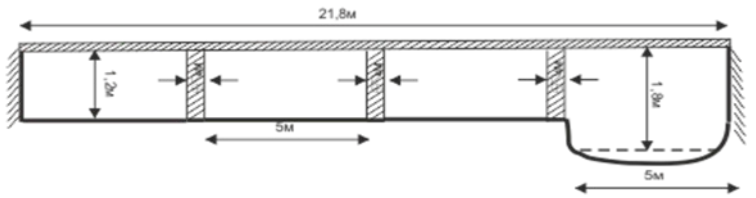
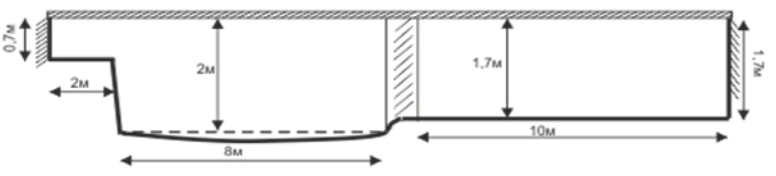


ПАА10



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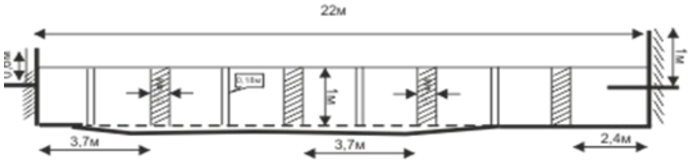
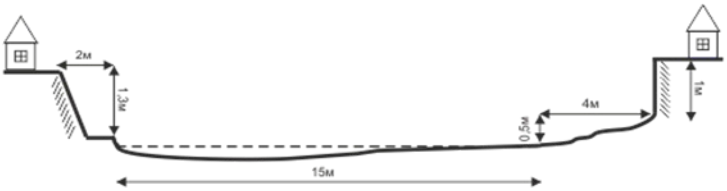
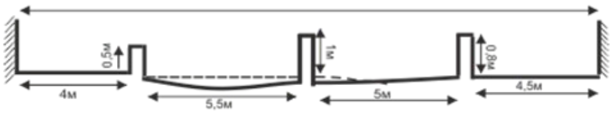


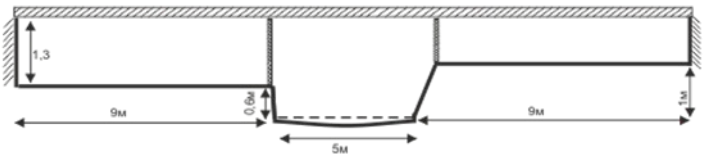
ПАА12



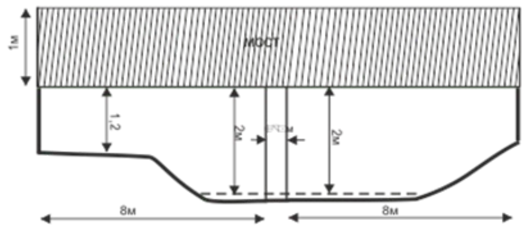
ПАА13



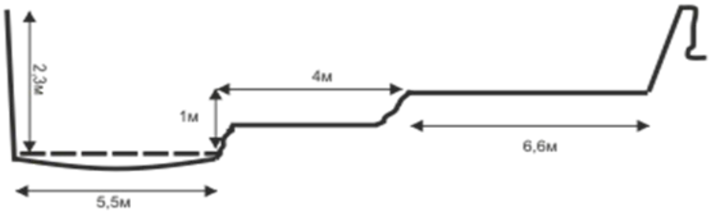
ПАА13-А



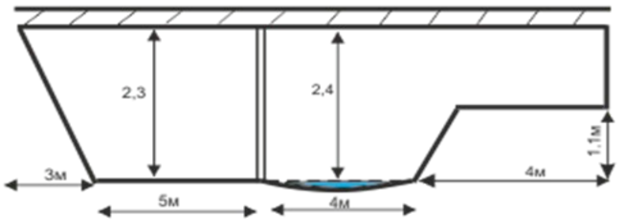
ПАА14



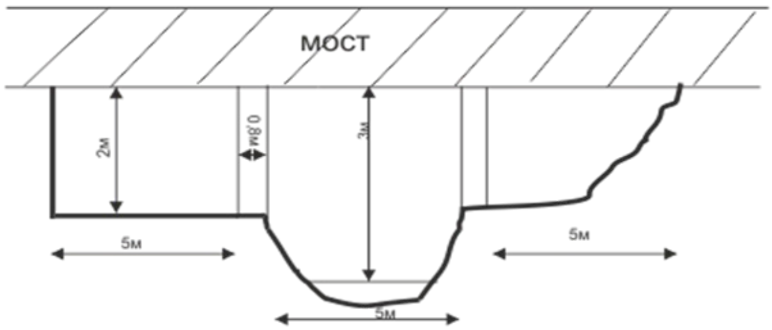
ПАА 14-А



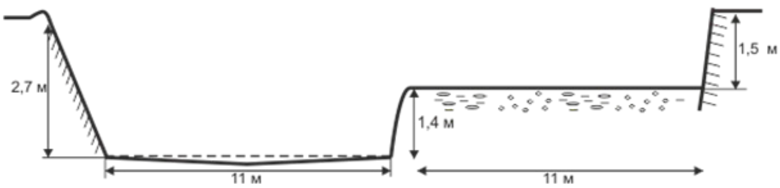
ПАА 14-Б



ПАА 14-В



ПАА15



Условные обозначения:

Железо-бетон

Речные наносы

Уровень воды (глубина не определялась)

Мост

Жилые дома

Map of the flood affected area of the site in the Ala Archa River valley.

Symbols: flood damage zone ПАА - Profile

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