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WATER RESOURCES AND THE REGIME OF WATER BODIES

Numerical Modeling of the Behavior of a Destructive Rain Flood on a Mountain River

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Abstract—The objective of this study was to provide the most accurate presentation of the behavior of a disastrous rain flood, which had resulted in destruction of a dam, casualties, and significant material damage. The problems set were solved by methods of numerical modeling in the two-dimensional setting applying the STREAM 2D CUDA software package. To calculate the rain flood, a catchment model of the Durso River was developed on a triangular non-uniform mesh, adapted to the river channel and the main inflows. To ensure direct numerical modeling of the dam's destruction, a model was developed, which included the water area of the reservoir, the dam, composed of non-homogeneous earth material, and a downstream section of the river from the dam to the river mouth. The main results of the study were: the hydrograph of the water discharge of the rain flood, calculated by the actual precipitation data; a description of the washout of the earth dam composed of non-homogeneous materials, resulting from water spill over the dam crest, and a desctiption of the downstream spread of the breach wave.

Keywords: numerical modeling, shallow-water equations, rain flood, discharge hydrograph, earth dam, breach wave

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GENERAL INFORMATION, THE OBJECT OF THE STUDY, THE SOURCE DATA FOR MODELING

The Inundation of 2002 on the Black Sea Coast of the Krasnodar Krai

In August 2002, a disaster occurred on the Black Sea coast of the Krasnodar krai. A strong cyclone caused showers in the basins of mountain rivers. The turbulent streams, into which the rivers turned, and mud and debris flows rushed into towns and camps of the people who arrived there for holidaymaking in the mountain gorges and river valleys. A threat of the burst of alpine dams emerged. A hurricane also struck the region. People were flushed down onto the coast and into the sea together with houses, cars, and tents. Vast areas of the coast near the city of Novorossiysk were inundated. The total number of casualties was 59. The total damage was estimated at more than 1.7 billion rubles. The number of damaged dwelling houses was 4968 with 447 houses ruined, as well as 55 utility structures, 20 bridges, and 5.5 km of motor roads, 5 water intake facilities were destroyed, 19 transformer stations were switched off; serious damage was inflicted to farmland (60 hectares of vineland were destroyed) [9].

The disaster began on August 6 and continued till August 10. In the night of August 9, a hurricane passed over the valley of the Durso River and the settlement of Abrau-Durso. The water reservoir with an earth dam became overfilled, and water started flowing over the dam crest into the downstream pool with a partial destruction of the earth dam. As a result, the dam crest was washed out to the depth of 4 m practically all along the width of the dam—up to 150 m. Concrete slabs, which were used to reinforce the upstream side, saved the dam from complete destruction. The breach wave aggravated the large natural rain flood, which resulted in a complete inundation of the river's floodplain, the destruction of some buildings on the plain, complete or partial loss of vine plantations, and several casualties [3].

Photographs of the half-ruined dam are shown in Figs. 1–2.

General Information about the Object Under Study

The Durso River flows in the central part of the Abrau Peninsula. It flows from the region near the Tkachukov cleft in the area of Kryazh on the southwestern slope of Gudzak mountain, from where it flows southward along the Pinchukov ravine, until it enters the Black Sea within the boundaries of the settlement of Durso. Its length is 14 km, its catchment area is about 53.7 km^2, and its annual runoff is

Fig. 1. The view of a half-destroyed dam from the downstream side.

Fig. 2. The dam crest is washed out, but concrete slabs save it from complete destruction.

0.45 km^3 [8]. The slope gradients of the river and of the valley are 5–7 m/km, the river width in its middle reaches (in the area of the dam) is 4–5 m; near the river mouth, it is 8–10 m; and the floodplain width varies from 100 to 200 m. The floodplain of the river is either flat or has a small slope towards the river channel, primarily on one side, as the channel is close either to the left slope or to the right slope of the valley. The valley slopes are mountainous and steep (up to 40%), covered by dense forest.

In the middle reaches of the river, 7 km from its inflow into the Black Sea, there is an artificial reservoir, called the Durso Reservoir, or Lake Bam. It was put into operation in 1976, with a view to accumulating the waters of the Durso River to water the crops. The volume of the reservoir at the normal headwater level was 4.5 million m^3 (at the time of the disaster it rose to 6 million m^3), its water area is 0.4 km^2, and its length is 1.5 km [7].

The reservoir is supported by an earth dam of trapezoid cross section made of local clayey materials. The dam's length on top is 215 m, the crest width is 4 m, the greatest height is 25 m, the base level is 42 m, the crest level is 67 m, the upstream slope 1 : 2.5 is reinforced with concrete slabs 0.1-m thick, and the downstream slope 1 : 2 is covered with turf. At the left bank of the dam, there is a two-step overflow spillway, the end part of which is fixated with concrete slabs. To channel the extremely high overflows (discharges) under the dam crest, there are two pipes located under the dam crest 1 m in diameter [3].

Preparation of the Source Data for Numerical Modeling

The source data used for developing the numerical model were the following:

A digital raster map of the area, the scale 1 : 100000, obtained from an open internet source;

A digital electronic map of the area, the scale 1 : 200000;

Data of the SRTM radar topographic survey (Shuttle radar topography mission), with a spatial resolution of 90 m) for the catchment area of the Durso River, obtained from an open internet source;

Parameters of the river channel and of the floodplain (bathymetric characteristics, vegetation, etc.), specified as a result of a survey conducted in September 2002;

Parameters of the earth dam and the reservoir;

Data on precipitation from the Novorossiysk meteorological station;

High-resolution satellite images, a modern one taken in 2017 and a historical one taken in 2003.

COMPUTATION OF THE FORMATION OF THE INFLOW TO THE RESERVOIR OF THE DURSO RIVER

The Mathematical Model of Formation of the Inflow to the Reservoir

The domain for the model of rain runoff formation the was chosen in the following way. On the topographic map, the catchment of the Durso River with the total area of 53.7 km^2 was indicated from the source to the mouth. A digital terrain model (DTM) was developed on the basis of the SRTM data. In the mapping editor program, the georaster with the SRTM data was transformed into the format of a point object in the Cartesian system of coordinates *XYZ*; the object was assigned the projection system GK Pulkovo 1942 zone 7. The terrain was not exposed to additional editing and corresponded to the ordinary conditions of the Durso River without a dam and a reservoir. The computational domain and the DTM are shown in Fig. 3.

The mesh of the model was triangular and had irregular structure with the side length from 50 m along the contour of the computational domain, adapted to the channel of the Durso River and some of its tributaries, with refinement up to 25–15 m. To make the mesh, a modified version of the TRIANA software application [4] was used, the total number of the cells being 109185. The terrain data were transferred to the cell centers of the mesh by the method of harmonic (non-Sibsonian) interpolation of the DTM [5].

One boundary condition, imposed at the outlet of the model, was the water level in the Black Sea. In the same way, an internal boundary condition was specified at the dam site, on which the hydrograph of the inflow to the waterworks was determined by computation.

Modeling the Hydrograph of the Inflow to the Reservoir

Modeling the hydrograph of the inflow to the reservoir was performed on the basis of precipitation histogram provided by the Novorossiysk meteorological station, covering the period from 00:01 July 6 to 23:59 July 7, 2012 (2 days). The total amount of precipitation that fell during this period was about 315 mm. The reason for choosing this period is that the data for August 2002 were not available to the author, but there were data on precipitation for 2012, when a flood caused by a heavy rain similar to the disaster of 2002 in its destructive force struck the Black Sea coast of the Krasnodar krai. The following situation was observed in relation to the flood of 2002, according to [12]: "...the distribution of precipitation across the coastal territory was extremely uneven. The amount of precipitation recorded by meteorological stations differed considerably from that which fell in other places, for example, in Novorossiysk on August 8 and 9, when much more precipitation fell in the western part of the city, and it was much more intense than that in the eastern part, where the meteorological station is located". In addition to the showers that fell on August 8, 2002, several hurricanes formed in the open sea, which reached the shore and brought an additional amount of seawater with them, which definitely could not be recorded by any of the meteorological stations. Therefore, the histogram of 2012 was taken to be similar to that of the rain flood of 2002.

Two characteristic rises may be seen in the histogram: the first one with the maximum of 35 mm ends rather fast, within 3 hours; and the second one, with its maximum of 47.5 mm, is more prolonged and lasts for 10 hours.

The computations were made with the STREAM 2D CUDA software package [13]. In the most recent version of this software, an algorithm is implemented, described in [1] and paralleled in the NVIDIA graphic processor using the CUDA technology. The software program is meant for calculating non-stationary and non-uniform flows, to which spates and spring floods in rivers, valleys and reservoirs; dam-break waves caused by the destruction of the waterfront of the dam, etc., belong. In this study, it is first applied to modeling the rainwater flow from the catchment of a mountain river.

As an initial condition, the water level in the Black Sea equal to 0, was set in the computation domain. The precipitation level was set in accordance with the histogram taken to be uniform for the entire computation domain.

The roughness factor n was set to be the same for the slope and channel network, and from the experience of the previous studies, it was set to 0.2. In the same way, variants with $n = 0.01$ (the roughness factor of the glass surface) and $n = 1$ were considered, and the influence of the code taken on the behavior of the hydrograph was evaluated. As the computations have demonstrated, as n increases, the hydrograph flattens out, and the response of the model to the change in the precipitation histogram becomes weaker. At $n = 0.01$, the model actively responds to changes in precipitation, the times of the discharge and precipitation peaks practically coincide, and the maximum discharge of the second peak at the river mouth (655 m^3/s) exceeds the discharge at the dam site (425 m^3/s) by a factor greater than 1.5. At $n = 1$, the delay time between the discharge and precipitation peaks increases to 3–7 hours, and there is practically no difference between

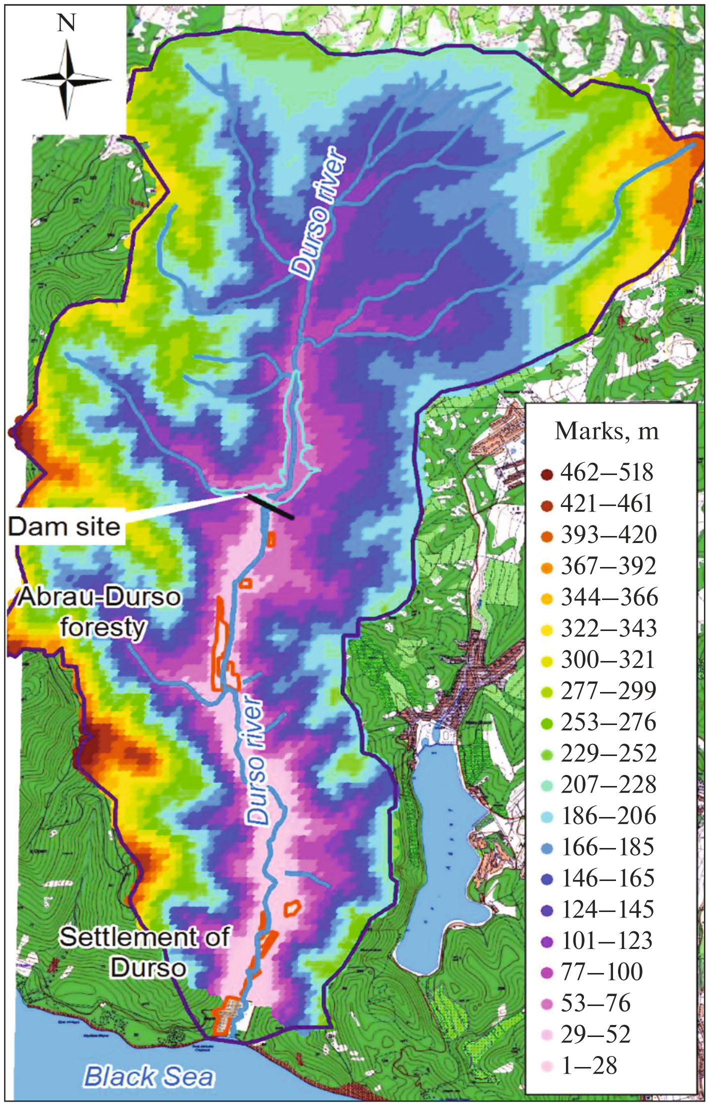

Fig. 3. The computational domain and the digital terrain model for determining the inflow to the reservoir on the Durso River.

the maximum discharges at the dam site (307 m^3/s) and at the river mouth (320 m^3/s), which seems to be unrealistic for the mountainous area with steep slopes, as the catchment area from the dam site to the river mouth site increases 1.5 times.

At $n = 0.2$, at the second peak of precipitation, the discharge of the flow at the dam site is equal to 140 and to about 150 m^3/s in the river mouth. At the second peak of precipitation, the water discharge at the dam site increased to 360 m^3/s, the maximum discharge at the river mouth was equal to 550 m^3/s. The time of maxima in the discharge hydrographs is 1.5 h behind the time of precipitation peaks at the dam site, and at the river mouth, it is 2.75 hours behind the first peak of precipitation and 1.5 hours behind the second peak of precipitation (Fig. 4).

The discharge at the dam site at the second peak of the hydrograph is 1.5 times greater than that at the first peak, and the duration of the second peak is longer than that of the first peak. We can suppose that, at the time of the first peak of precipitation, intense water saturation of the soil will be taking place, and the actual discharge of the inflow to the reservoir would be less than that obtained in the computation, i.e., there would be no overflow over the dam crest and no destruction of the dam. At the second, more prolonged, peak, a discharge (close to the value obtained in the model) will form at which the reservoir will be overfilled, water will flow over the dam crest, and the dam will be destroyed. Therefore, in modeling the destruction of the dam, it was decided to use only the second peak of the precipitation histogram. This means, the time of the beginning of the computation was shifted from the initial histogram by 15 hours, and

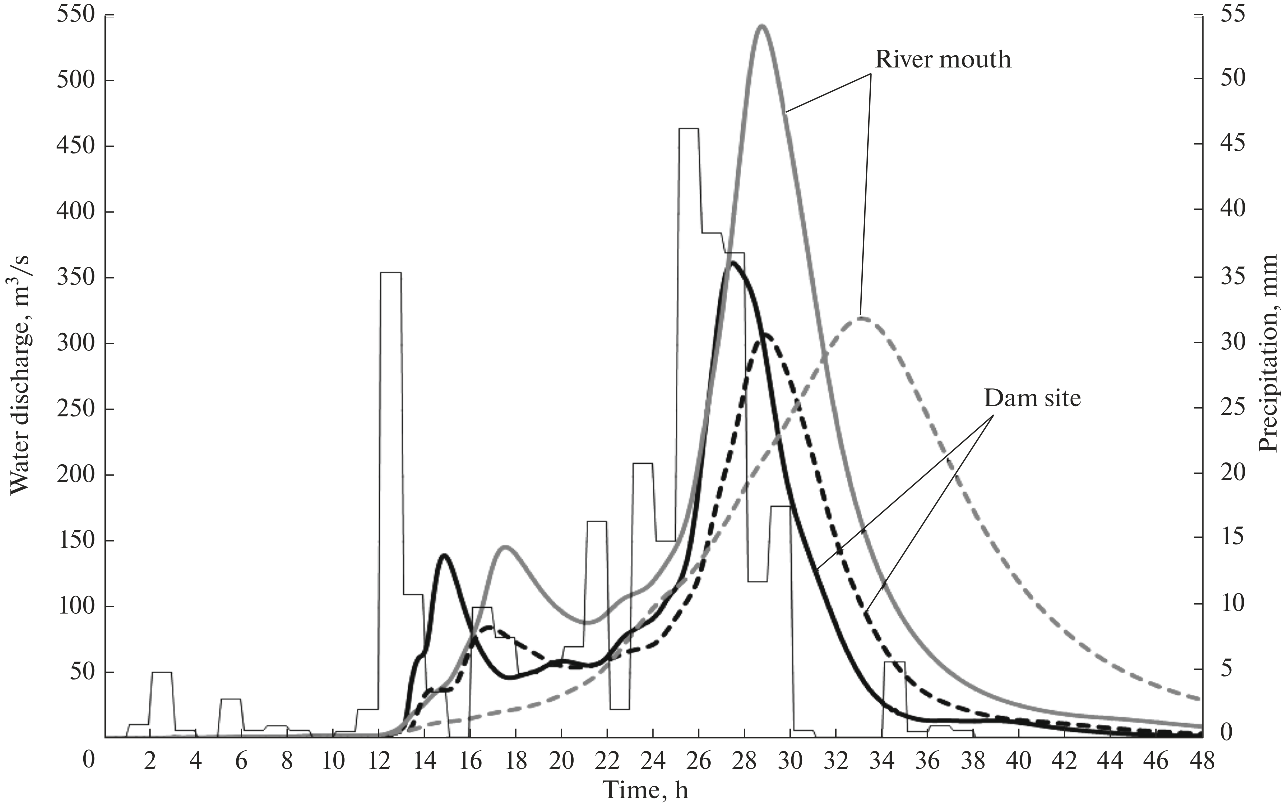

Fig. 4. The calculated hydrographs at the dam site and at the mouth of the Durso River with the roughness factor (solid lines) $n = 0.2$ and (dashed lines) $n = 1$.

the duration of the calculation time became 33 hours with the total precipitation of 250 mm.

The rain flood runoff was calculated with the use of the model of the KW-GIUH (kinematic-wave geomorphological instantaneous unit hydrograph) [10, 11], in which the flow time was evaluated by the kinematic wave equation. The parameters of the geomorphological structure of the river basin were prepared using the standard ArcGIS tools on the basis of the DTM of SRTM with the resolution of 90 m. The threshold value of the catchment area for forming the first-order water flow was taken to be 0.5 km^2, as it ensured closer matching between the calculated river network and the watercourses on the maps of the scale 1 : 100000. The computation was carried out with an increment of an hour in time in accordance with the time step of precipitation.

The comparison of the hydrographs of rain flood, calculated by the STREAM 2D CUDA and KW-GIUH software packages, showed good reproducibility of the results. In the models, identical sets of the initial data and the constitutive parameters were used: the topography of the water catchment, the precipitation histogram, the roughness factors of the slopes and river channel network ($n = 0.2$), the widths of the river channel and the floodplain. The comparison of the results is shown in Fig. 5. The reproducibility of the hydrographs in terms of the moments of peaks and the values of water discharges is best at the dam site. At the river mouth, the first peak in the STREAM 2D CUDA model was behind the KW-GIUH model by approximately 2 hours; however, the discharge values were similar. At the second peak, the time difference was insignificant, the difference between the values of peak discharges was about 25 m^3/s, or less than 5%. A comparison with the well-known and well-tested flow model KW-GIUH showed that the STREAM 2D CUDA model can be used to solve similar problems.

COMPUTATION OF THE BREACH WAVE FOR AN EARTH DAM

Mathematical Model of the Breach Wave for an Earth Dam

The total length of the model domain for the breach wave was about 10.6 km, including 1.6 km of the reservoir, 7.8 km of the Durso River from the dam site to the mouth, and 0.8 km of the Black Sea. The external boundary of the model domain was drawn on the horizontal profile of 80-m elevation.

The DTM was based on topographic maps of the scales 1 : 200000 and 1 : 100000, as well as on high-resolution satellite images. The DTM was made in the

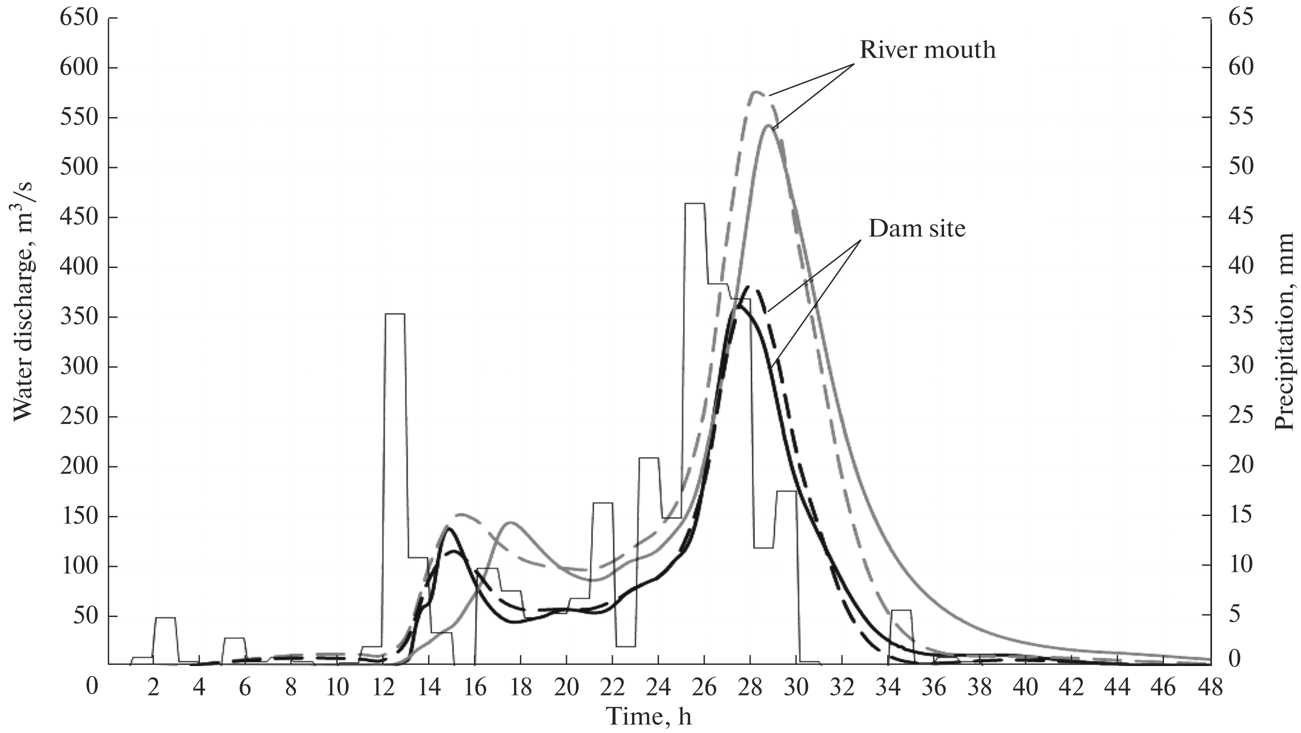

Fig. 5. Comparison of hydrographs. The solid lines are for computation by STREAM 2D CUDA, and the dashed lines, by KW-GIUH software program.

GIS editor in the projection system GK Pulkovo 1942 zone 7. A satellite image was used to determine the dam site and the contours of the shore spillway; the structure of the earth dam was reproduced according to the available description. The bathymetry of the reservoir was described by the characteristic shapes of the terrain from a topographic map, and then, using the software, the volume of water was calculated for the specified level and compared with the design value of 4.5 million m^3 at the normal water level of 62 m and 6 million m^3 at the level of 67 m. The channel contour of the downstream segment of the Durso River was formed as follows. The river contour was digitized by a raster map at scale M 1 : 100000; then, the contour was used to perform linear interpolation between the known altitudes taken from the map, thus, the river slope was taken into account in the computation. Finally, using the Delaunay triangulation method, a single DTM surface of the computational domain was generated.

The hybrid triangular–quadrangular computational mesh of the model, which had an irregular structure, was developed in accordance with the technology described above. The quadrangular mesh was used on the dam, primarily, on the crest and a part of the downstream side, as well as on the shore spillway. The size of the cells of the quadrangular mesh was 2 × 4 m and 3 × 4 m. The remaining part of the model domain was covered by a triangular mesh with side lengths from 5–15 m along the channel of the Durso River and up to 25–50 m on the floodplain. As a result, a computational mesh was developed, containing 78085 cells. Fragments of the triangulated surface of the terrain area and the computational mesh are shown in Fig. 6.

The terrain data were transferred to the centers of the cells of the model mesh by the method of projection from the triangulated surface of the DTM.

In the developed model of the breach wave, 7 computational units were set: two at the input to the model—the inflows into the reservoir (the main one and the lateral one); one at the output from the model—the Black Sea; and four internal boundaries for recording the parameters of the breach wave—the top of the spillway, the passage site, the settlement of Durso, and the mouth of the Durso River.

Modeling the Breach Wave of the Earth Dam

The computation was carried out using the STREAM 2D CUDA software package [13]. The numerical algorithm implemented in it was described in detail in [1]. As the initial conditions, the level of the reservoir on the upstream side was set equal to the normal water level of 62 m, and the Black Sea level was set equal to 0 m. At the input boundaries of the model, the water discharge hydrograph was specified, obtained by modeling the inflow to the reservoir on the basis of the

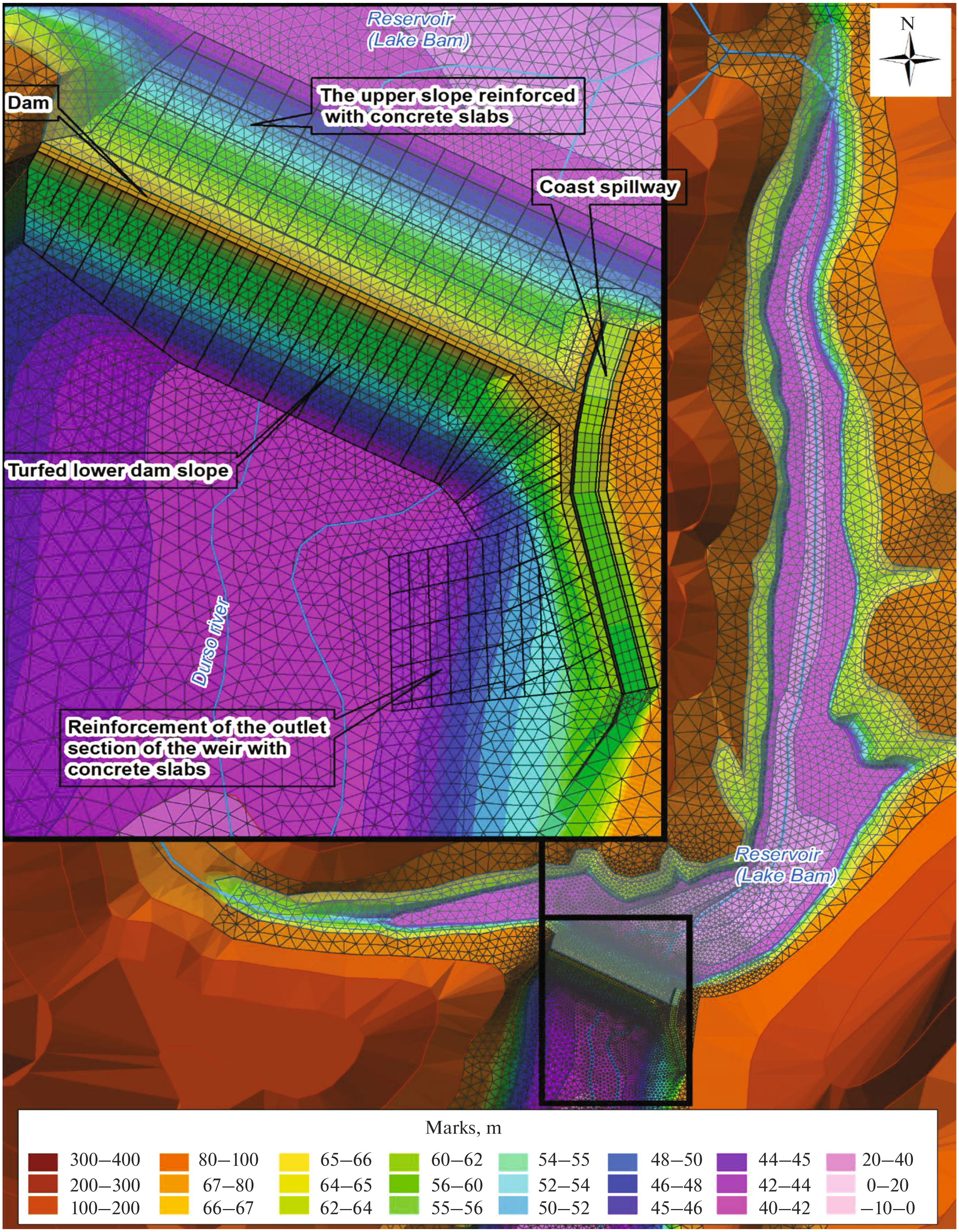

Fig. 6. Fragments of the triangulated surface of the terrain and of the computational mesh for modeling the breach wave of the earth dam.

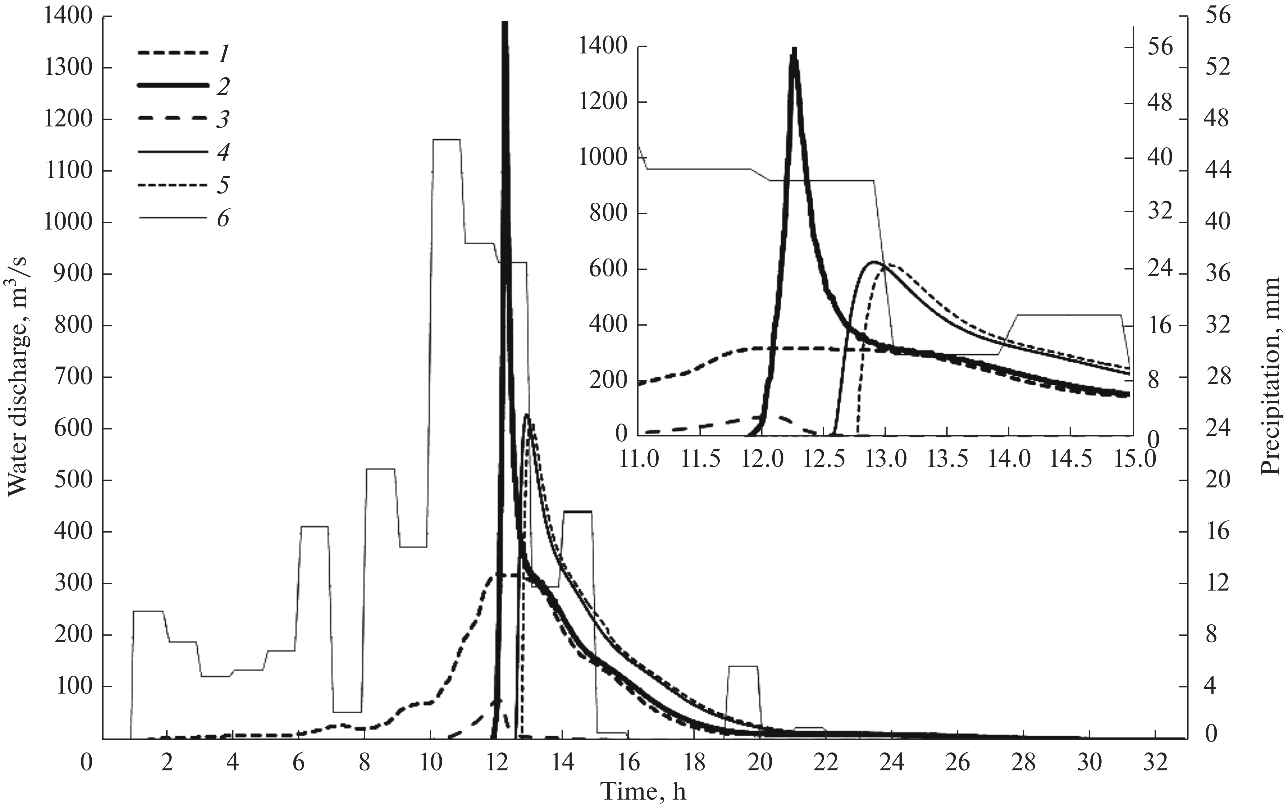

Fig. 7. Hydrographs at the breach of the earth dam. (*1*) Total inflow to the reservoir, (*2*) passage site, (*3*) spillway, (*4*) site of the settlement of Durso, (*5*) the mouth of the Durso River, (*6*) precipitation histogram.

precipitation histogram. The total discharge of the inflow was distributed between the main channel and the side inflow in the proportion of 70 : 30%.

The earth dam is composed of the material that is inhomogeneous in its composition (clay and pebbles). Therefore, two fractions of the dam material were specified in the proportion of 50 : 50%. The parameters of the first fraction were taken to be as follows: d50 = 4 mm, d90 = 6 mm, cohesion C = 5 t/m^2. The parameters for the second fraction were as follows: d50 = 100 mm, d90 = 150 mm, cohesion C = 0 t/m^2. For both fractions, the tangent of the natural slope under water and on land was taken to be 2. The Manning roughness factor in the reservoir, on the dam crest, and on the dam slopes was set the same $n = 0.03$, and in the floodplain on the downstream side, $n = 0.06$.

At the output boundary of the model, the time-constant level of the Black Sea was set at 0 m. The process was simulated within a time interval of 33 hours.

After the start of dam destruction, the maximum outflow discharge at the breach was 1395 m^3/c (Fig. 7), with the depth of the water flowing over the dam crest being 2 × 2.5 m, i.e., 1/10 of the dam's height (Fig. 8).

We had made similar calculations for a flow over an earth dam for many waterworks (see, for example, [6]); however, the present study is the first dealing with a dam consisting of nonhomogeneous material using the algorithm described in [2].

To evaluate the error of the hydrodynamic model in calculating the spill over a dam crest, we simulated the flow over a triangular weir (a Kramp weir) (Fig. 9). The results of the tests conducted in a hydraulic precision flume using high-tech laser equipment are described in detail in [14]. The computations were made on a rather rough mesh (Fig. 9). The calculated and measured water levels were compared for the upstream pool, on the weir crest, and in the downstream pool in a wide range of variations of the water discharge and the flow depths (Fig. 10). It can be seen that, at the depth of the water layer spill of about 1/10 of the dam height, the relative error of the water levels is 2% in the downstream pool, less than 0.5% on the dam crest, and 1.5% in the downstream pool near the dam base. Thus, the spill depth and the flow rate are calculated with a high degree of accuracy for the entire cross section of the dam, which is a necessary condition for verifiable calculation of the washout value.

Table 1 contains the values of water discharges at different sites. Contemporaneous examination of this table and the diagram in Fig. 7 provides understanding of the transformation of water discharge along the length of the river section under study. For example, at

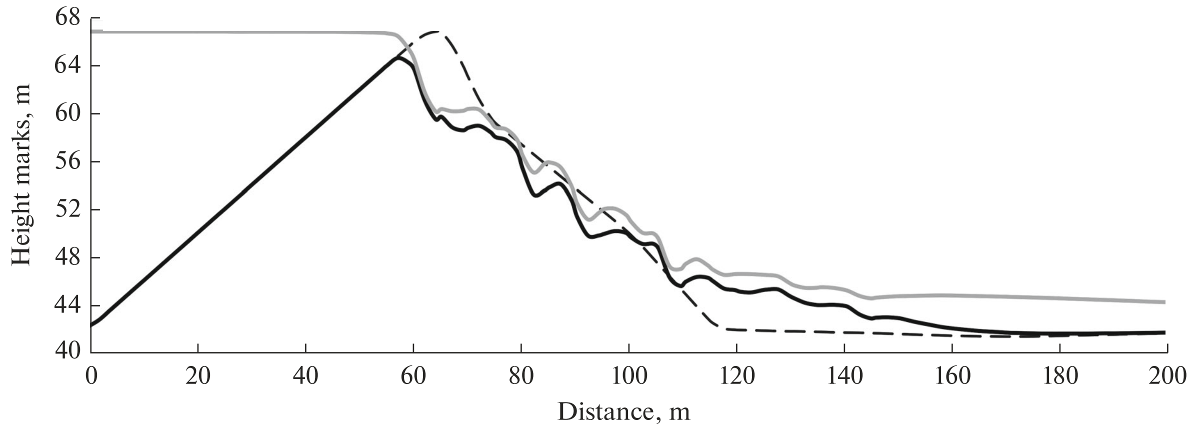

Fig. 8. Cross-section along the central axis of the earth dam at the moment of the maximum discharge at the passage site. The black dashed line is the initial dam profile, the black and gray solid lines are the bottom surface and the water level at the moment of discharge maximum, respectively.

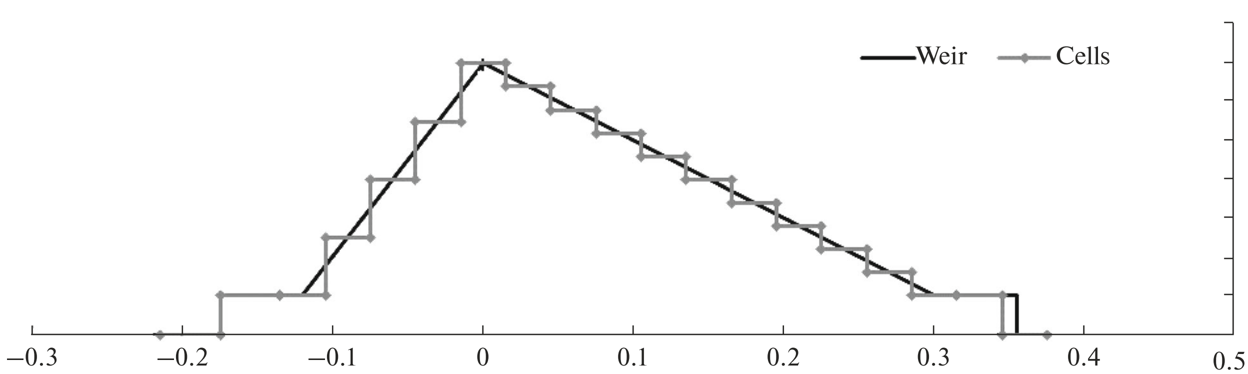

Fig. 9. Approximation of the model of the Kramp weir with a mesh, with cells 3 × 3 cm.

the maximum discharge through the breach (1395 m^3/s), the discharge of the inflow into the reservoir and the discharge through the spillway will have already passed their peaks. On the other hand, at the maximum discharge in the settlement of Durso, the discharge through the breach will be already almost half that in the Durso River and close to the total inflow rate into the reservoir. The discharge at the final site (the Black Sea) will reach its maximum 1.10 hours after the beginning of dam destruction, and its value will be 2.2 times less than the maximum water discharge in the breach.

The front of the breach wave will cover the distance between the dam site and the Black Sea coast within 0.87 hours, and the wave crest will reach the coast within 1.12 hours from the start of destruction. The maximum rise of the water level in the Durso River will be recorded near the settlement of Durso—more than 9 m from the river channel bottom (Table 2). The water levels in the lower pool will drop 6–7.5 hours after the beginning of the accident; at that time, there will be practically no rain. Calculations show that, after the destruction of the dam, the entire floodplain of the Durso River will be inundated, and areas near the river in the settlement of Durso will be 1 to 5 m under water; the houses located near the river channel will be destroyed.

The process of destruction of the dam is shown in Fig. 11 for the cross section through the central axis of the dam. In the diagram, one can see the formation of steps and a kind of terraces, which can be seen in the photographs of the destroyed dam (Figs. 1–2), suggesting similarity of model results to the natural process.

Shown in Fig. 12 are schemes of deposition of fractions of the dam's soil (in a planar view) in percentage of the total mass. Fine fractions of the cohesive clayey soil (fraction 1) were most intensely transported from the dam body, and after destruction of the dam, they account for about 60–70% of the total sediments in the alluvial cone below the dam, while the coarse fraction (fraction 2), accounts for 30–40% of the alluvial cone and 60–90% of the destroyed dam's mass.

Given below is the chronology of the events reproduced in the model:

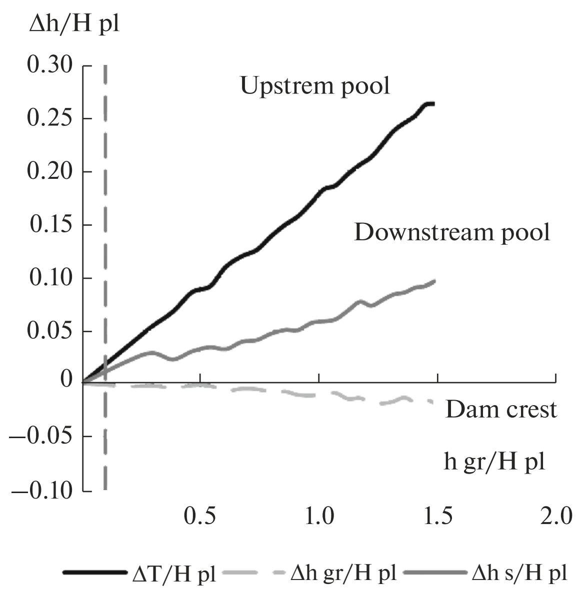

Fig. 10. The difference between the computed and measured depths at different points of the Kramp weir depending on the water depth on the crest, normalized by the dam height.

(1) **Time 0 hours.** The beginning of the rain, the normal water level in the reservoir is 62 m;

(2) **Time 9.8 hours.** Water level in the reservoir reaches the mark of 64 m, water starts discharging through near-shore spillway, the total inflow discharge 73 m^3/s;

(3) **Time 11.93 hours.** Water level in the reservoir reaches the mark of the dam crest (67 m), and water starts spilling over the dam crest, the total discharge of inflow into the reservoir is 320 m^3/s; 73 m^3/s is discharged through the spillway. This is the moment of the beginning of the dam's destruction;

(4) **Time 12.26 hours.** Water discharge through the breach reaches its maximal value of 1395 m^3/s at the total inflow of 321 m^3/s; the lower slope is being intensely washed out, the dam crest collapses, the water level in the reservoir slowly goes down, to reach 66.7 m. A breach wave is formed, which rushes into the downstream pool; by that time, it has already passed the structures in the Abrau-Durso forestry;

(5) **Time 12.58 hours, 0.65 hours after the beginning of dam destruction.** The wave front reaches the settlement of Durso, water discharge through the breach goes down to 506 m^3/s, with the total inflow of 320 m^3/s; the rate of dam washout decreases slightly; the water level in the upper pool is 65 m;

(6) **Time 12.93 hours, 1 hour after the beginning of dam destruction.** At the site of the settlement of Durso, the water rise is maximum, with 341 m^3/s flowing through the breach; the total inflow is 313 m^3/s, the water level in the upstream pool is 64.7 m (Fig. 13).

(7) **Time 14.93 hours, 3 hours after the beginning of accident.** The rate of dam washout has decreased significantly, minor redistribution of the soil from the dam body is taking place. The water level in the downstream pool abates. Water discharge through the breach is 161 m^3/s, the total inflow is 151 m^3/s, the water level in the upstream pool is 64.3 m;

(8) **Time 23 hours, 11 hours from the beginning of dam destruction.** The end of the rain, the total inflow has

Table 1. Water discharges at the sites of the area under computation

Time from the beginning of the computation, hours	Time from the beginning of the destruction, hours	Water discharge at the sites, m^3/s				
		inflow to reservoir	passage site	spillway	settlement of Durso	seashore
11.93	0.00	320.78	15.92	73.33	20	9
12.08	0.15	322.28	221.59	79.14	29	17
12.13	0.20	322.36	440.36	77.51	45	25
12.26	0.33	321.12	1395.31	54.23	60	40
12.92	0.99	314.82	342.85	7.23	631.17	546.46
13.03	1.10	311.07	328.61	6.71	605.09	622.33

Table 2. Flow times of the front and peak of the breach wave

Sites	Flow time, hours		Height of the water level rise in the Durso River
	of the breach wave front	of the breach wave peak	
Abrau-Durso forestry	0.25	0.48	5.51
Settlement of Durso	0.65	1.00	9.07
Seashore	0.87	1.12	1.32

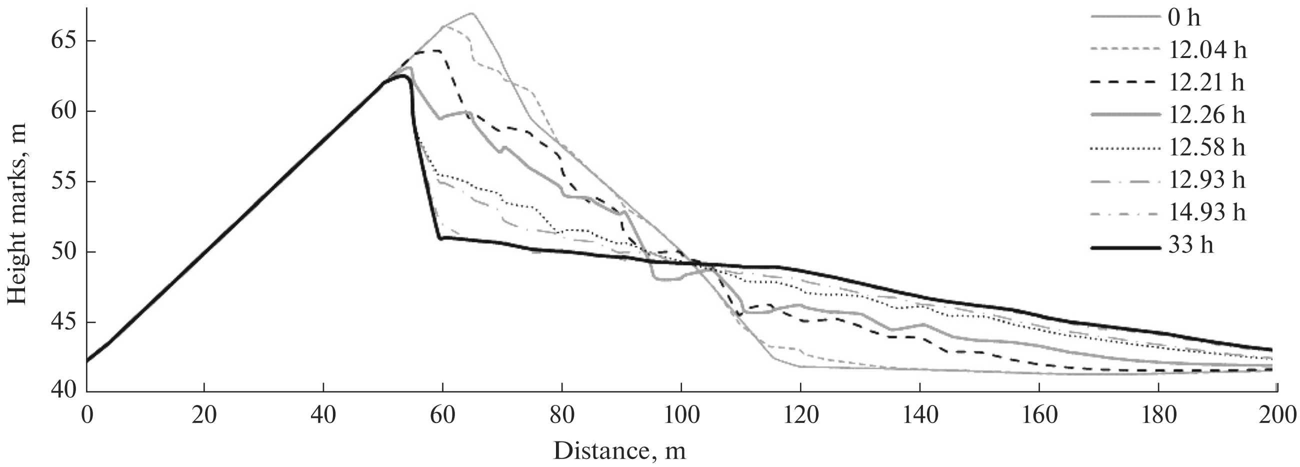

Fig. 11. Destruction of the earth dam, river bottom profiles at different moments.

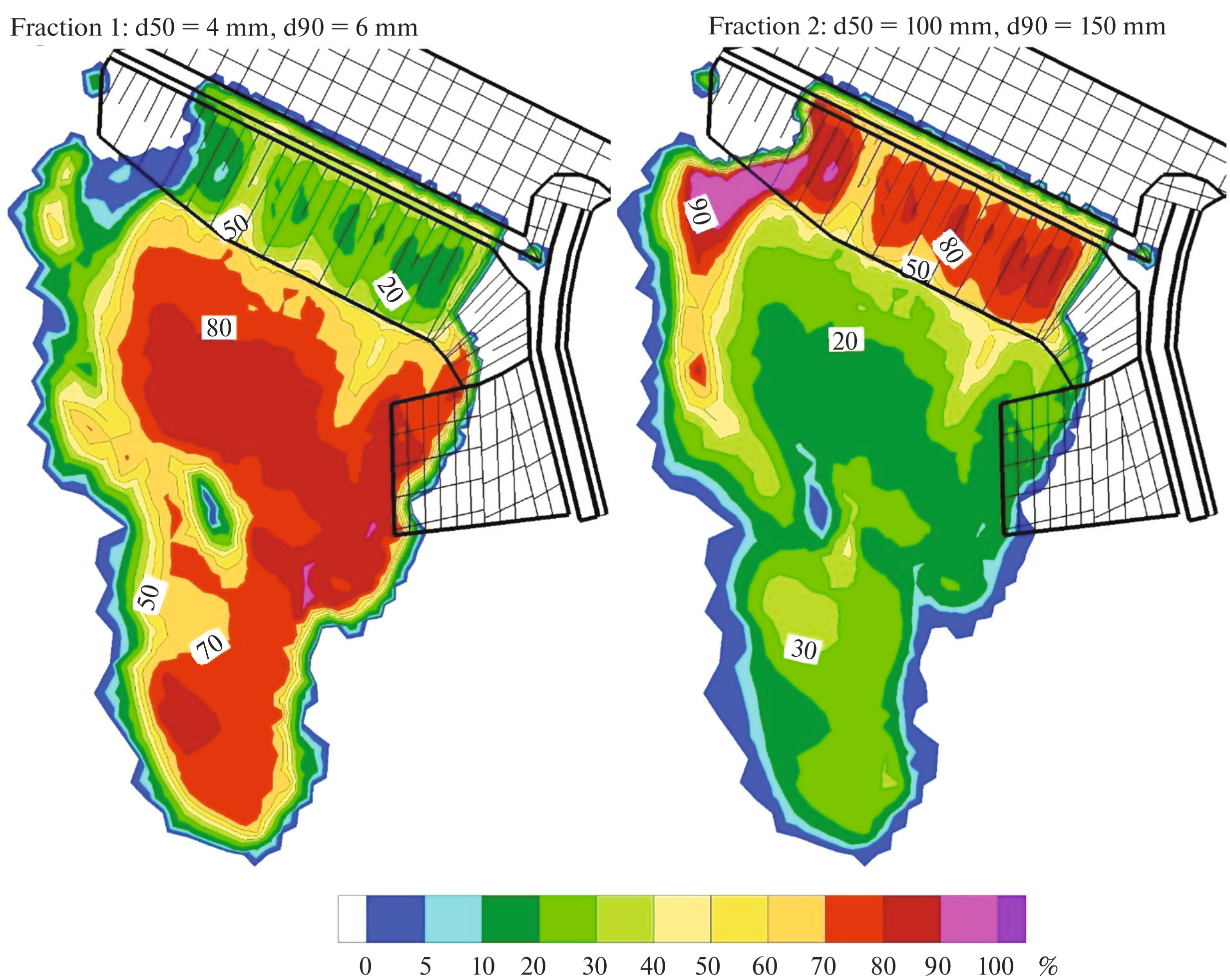

Fig. 12. Sediments of fractions of the earth of the dam body (in a planar view) in percent after destruction.

decreased to 13 m^3/s, the spill discharge is 13.6 m^3/s, the water level in the reservoir is 63.8 m, water has practically returned to the river channel in the downstream pool;

(9) **Time 33 hours, 21 hours from the beginning of dam destruction.** The end of computation. The rates of inflow and the spill through the breach are close to

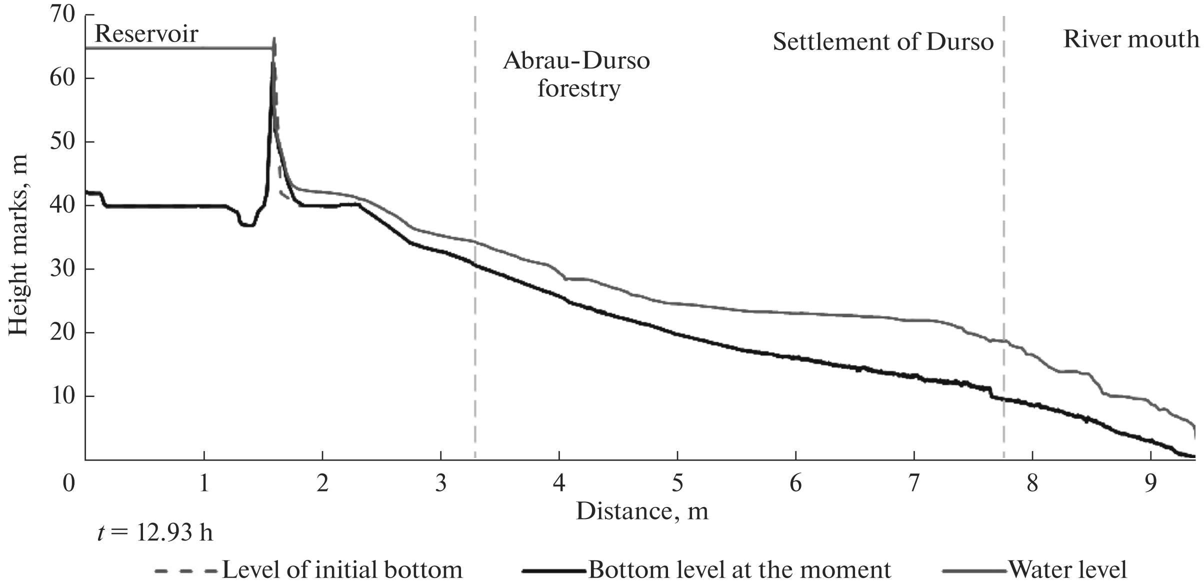

Fig. 13. The elevation–distance curve of the channel of the Durso River at the moment of maximum water rise near the settlement of Durso.

zero, the water level in the upstream pool is 63.6 m, there is no inundation in the downstream pool.

CONCLUSIONS

Numerical modeling has been used to simulate the passage of a rain flood along a mountain river, which caused overfilling of a reservoir, the destruction of a dam and the formation of a breach wave in the downstream pool. A characteristic feature of the model is that all components of this complex dynamic process, including the formation of the runoff hydrograph, spill over dam crest with its subsequent partial destruction, and the propagation of the breach wave along the river valley, have been calculated using the same STREAM 2D CUDA software package, based on numerical solution of two-dimensional Saint-Venant equations and equations of alluvial transport using an original algorithm. In addition, calculations of the rain flood hydrograph and the washout rate of an earth dam, made of inhomogeneous material, have been made in such formulation for the first time.

Comparison of the runoff hydrographs calculated with the STREAM 2D CUDA model and with the well-tested KW-GIUH model with the same initial data (the topography of the area, the precipitation histogram) and equal parameters of the models (the roughness factors, the river channel width) has shown similar results, thus suggesting that the STREAM 2D CUDA software can be used to calculate the rainfall runoff for the catchments of small mountain rivers. The advantages of such approach are the simplicity of the simulation object description and the small number of model parameters (only the roughness factor of the underlying surface, distributed, if necessary, over the catchment area is to be specified).

The results of direct numerical modeling of the collapse of an earth dam, which has an inhomogeneous structure, because of water spill over its crest were found to be qualitatively and quantitatively similar in terms of a number of parameters (the character of dam washout, the depth of inundation by the breach wave in the downstream pool) to the values obtained in the natural observations, thus demonstrating that the developed methodological approach and the physical and mathematical models and software packages can be used to predict the impact of floods in mountain rivers on waterworks and residential areas.

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