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## **ICE-DAMMED LAKE OUTBURST FLOODS IN THE ALTAI MOUNTAINS, SIBERIA – A REVIEW WITH LINKS FOR FURTHER READINGS**

*This review focuses on selected attempts to reconstruct the ice-dammed lake outburst flood in the valley-bottom of the Chuja River, the main tributary of the Katun River, which is the major source of discharge to the Ob River, while several previous publications present general reviews based on the state of knowledge available at the time of publication. Other studies focus on special aspects, for example, Parnachov and Carling et al. on the geology of giant bars, Carling on the gravel dunes, Reuter et al., on the age of the outburst floods, or Borodavko and Carling et al. on the ice-dammed lake itself. Recent investigations will provide more detailed information regarding the age of the floods. In the review papers mentioned above, the majority of dated flood-related features indicate ages between 40 and ~17 ka. Some of the dates are based on luminescence methods, for which methodological problems make older applications doubtful (Carling, personal comm.).*

*The different attempts to estimate flow conditions of the Pleistocene outburst floods in Altai Mountains result in data for flow velocity and discharge of the flood's peak and unspecified stages of the waning flood. Based on the conservative estimate of the peak discharge to be about  $10\,000\,000\text{ m}^3\text{s}^{-1}$  and assuming that the entire lake basin, with a volume of  $607\text{ km}^3$ , drained during the outburst a hydrograph can be generated. The hydrograph indicates a flood that did not last for more than 2–3 days. The duration of the flood was determined by the integral curve based on the limitations of the drained volume (= integral) and the peak discharge. Advanced modelling of unsteady two-dimensional flow confirms this magnitude. From a negligible baseflow, an abrupt rise of the hydrograph represents the outburst flood wave, which reached peak discharge values almost immediately. It should be noted that the hypothetical hydrograph does not consider ponding effects along the flood's pathway. Consequently, a tendency towards underestimation of the duration of the flood is inherent.*

*Compared with the earlier estimates of the peak discharge of the outburst flood the new calculations give a slightly higher discharge magnitude. Considering the fact that the present study is based on larger number of palaeostage indicators and also includes the calculation of the discharge downstream of the former ice-dam, the new estimations appear reliable and contain several elements of conservative assessment.*

**Key words:** ice-dammed lake; outburst flood

### **Area of investigation and evidence of floods**

The headwaters of the river Ob, which form the centre of this study, have their origin close to the border to Mongolia in the Altai-Mountains, located in

southwestern Siberia (fig. 1). During the Pleistocene, several mountain glaciers reached the valley-bottom of the Chuja River, the main tributary of the Katun River, which is the major source of discharge to the Ob River. Near the village of Aktash, the extended glaciers blocked the course of the river Chuja and formed an ice-dammed lake, which attained a volume of  $607 \text{ km}^3$ . The water surface of the lake reached a maximum altitude of 2 100 m which is indicated by strandlines and ice-rafted debris in the intra-mountainous basins of the Kuray and Chuja.

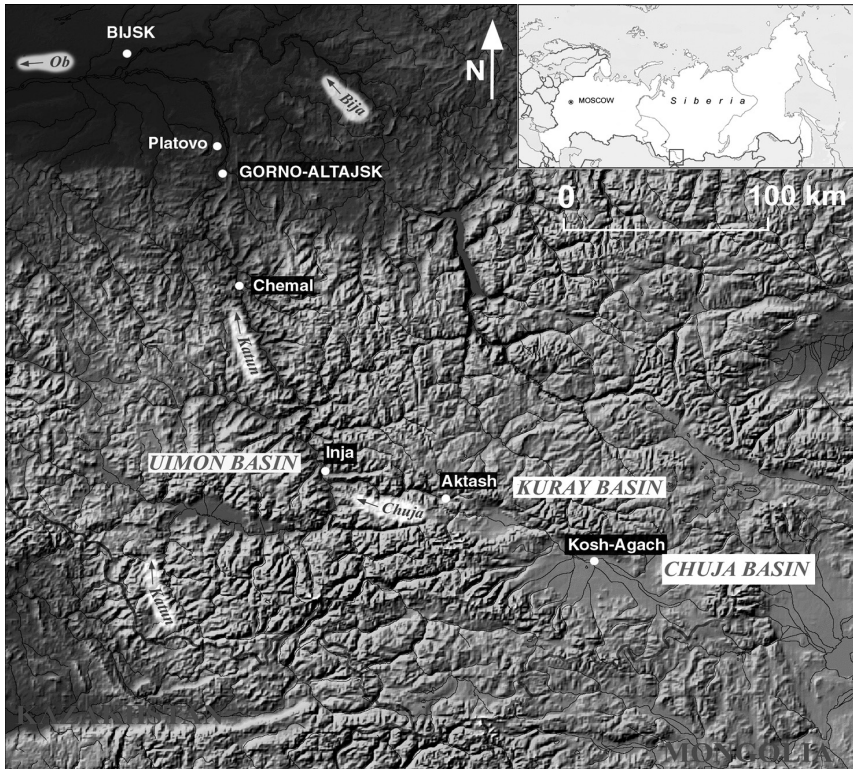


Fig. 1

At the time of ice-dam failure, giant floods passed through the valleys of the Chuja and Katun Rivers. The collapse was probably caused by overtopping and rapid incision into the glaciers. The flow transported gravel in suspension [1, 2] deposited this gravel in the form of giant bars at local valley expansions and tributary mouths along the flood route [3] (fig. 2).

At the mouths of some tributaries along the flood route the giant bars blocked valleys and generated secondary lakes, which lasted over different periods of time. These lakes are indicated by lacustrine deposits, such as at Injushka in a tributary valley to the Katun Valley at Inja, where lacustrine sediments are interbedded with suspension gravel indicating repeated outburst floods from the ice-dammed

lake upstream. Other flood-related features are gravel dunes and deposits of erratic boulders. In combination with exposures of characteristic suspension gravels at the current bedrock valley-bottom, the surfaces of the giant bars reveal depths of flow of up to 400 m in Chuja Valley, close to the downstream extent of the ice-dam. In the wider valley of Katun River, the depth of flow reached about 250 m. At several locations, drawdown levels along the slopes of the giant bars indicate phases of temporary stable water surface levels during the waning flow (fig. 3).

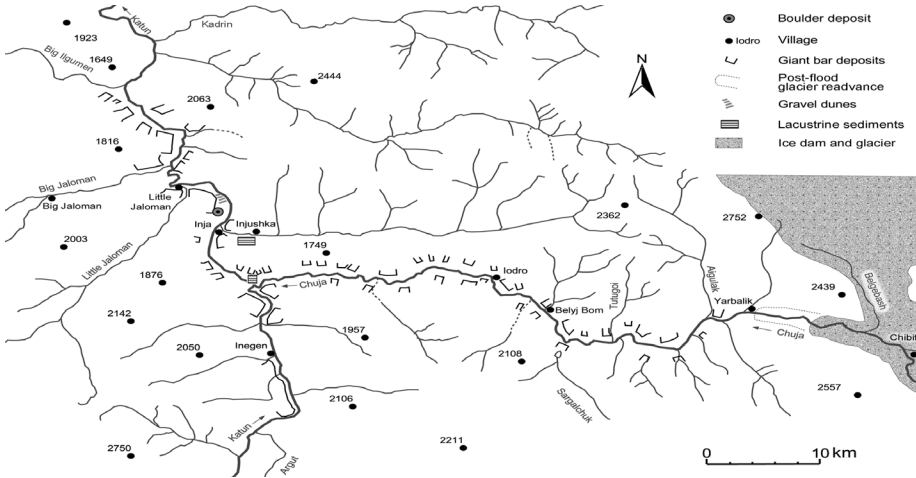


Fig. 2

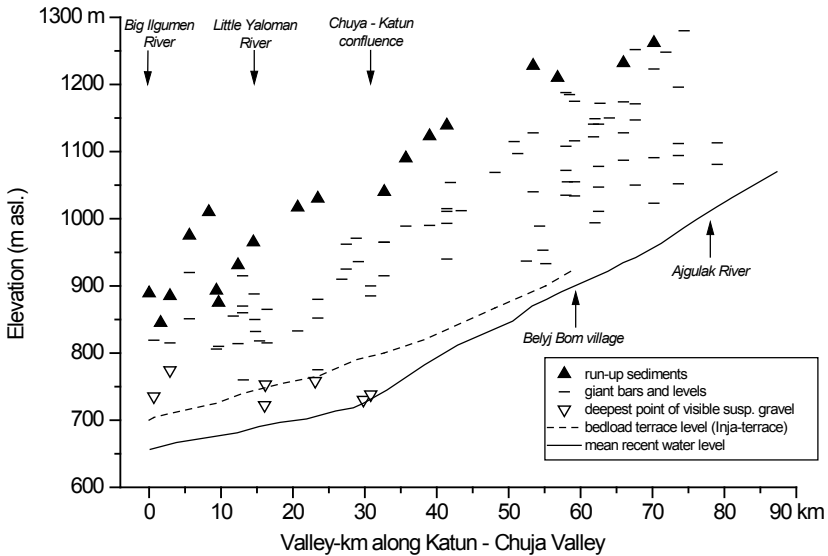


Fig. 3. Longitudinal profile along Katun and Chuja River downstream of the former ice-dam with locations and elevations of giant bars and related levels

Run-up sediments are deposited in front of local valley obstructions, as a thin layer of suspension gravel on more or less steep bedrock surfaces and can be used to estimate local flow velocity. They indicated a rising water surface level when flow velocity abruptly decreased at the valley obstruction caused by energy conservation [4].

This review focuses on selected attempts to reconstruct the ice-dammed lake outburst flood, while several previous publications present general reviews based on the state of knowledge available at the time of publication [2, 4–8]. Other studies focus on special aspects, for example, Parnachov [1] and Carling et al. [3] on the geology of giant bars, Carling [9–10] on the gravel dunes Reuter et al. [11], on the age of the outburst floods, or Borodavko [12] and Carling et al. [13] on the ice-dammed lake itself. Recent investigations will provide more detailed information regarding the age of the floods. In the review papers mentioned above, the majority of dated flood-related features indicate ages between 40 and ~17 ka. Some of the dates are based on luminescence methods, for which methodological problems make older applications doubtful (Carling, personal comm.).

### **Different methods of reconstruction**

Previous estimations of the discharge of the outburst floods were carried out by different researchers. Butvilovski [6 and written comm.] applied a number of different empirical equations to estimate the mean velocity of the flow, based on geometrical parameters of the valleys and basins. Discharges were calculated for cross-sectional areas consisting of the entire basins resulting in estimated peak discharges of up to  $50\,000\,000\text{ m}^3\text{s}^{-1}$ . Baker et al. [5] applied the water-level calculation software HEC-2 to estimate the discharge based on the elevation of flood-related features. In this approach the assumed discharge values are iteratively optimised until the model calculation of the water-level matches the altitude of the water-level indicators in the field. They chose a location within the extension of the former ice-dam and estimated a peak discharge of  $18\,000\,000\text{ m}^3\text{s}^{-1}$  based on a hydraulic jump located in the modelled reach of the valley. Carling [9] investigated the hydraulic implications of the gravel dunes in Kuray Basin, which was inundated by the ice-dammed lake. He found a discharge of the magnitude of  $750\,000\text{ m}^3\text{s}^{-1}$  for the volume of flow passing over the dunefield which value does not represent the outflow from the Kuray Basin, following the ice-dam failure. This estimated discharge could not be related to peak discharge of the outburst flood downstream of the ice-dam as the dune field is located upstream of the valley blockage. Contrary to Butvilovski [6 and written comm.], Carling's attempted to estimate the local discharge of an unspecified stage associated with the decreasing flood in the Kuray Basin appears more plausible. Based on my own investigations of flood-related features along the Chuja and Katun Valleys, seven independent attempts to gain information about the discharge of the outburst floods were made. The main findings of the study are presented in this paper. Additional details are discussed elsewhere [4].

### Conveyance – slope method

Based on the continuity equation and the empirical formula for the estimation of the mean flow velocity in channels by Manning, the discharge  $Q$  of the outburst flood can be expressed as  $Q = A n^{-1} R^{2/3} S^{1/2}$  where  $A$  is the cross-section area,  $n$  is the roughness coefficient,  $R$  is the hydraulic radius and  $S$  is the slope of the energy line [14]. Data for the geometric parameters were obtained by surveys of the giant bars along the flood's pathway. The location and the elevations were derived by using GPS as well as calibrated altimeter measurements, or were obtained from 1:50 000 topographic maps (the cross-section area and the hydraulic radius). It is assumed that the slope  $S$  of the energy line is, more or less, similar to the slope of the water surface along the direction of the flow (indicated by the slope between the giant bar surfaces along the valleys). The roughness coefficient  $n$  was also estimated on the basis of earlier studies. Previous studies on floods of comparable magnitude, such as the drainage of Pleistocene Lake Bonneville [15, 16] and the outburst flood of Lake Missoula [17, 18], the most representative values for the roughness coefficient were determined in the range of  $0,04 < n < 0,07$ . Hence, for the calculation of the outburst floods in the Altai Mountains, the upper and the limits were considered as extremes.

Six locations of the highest bar surfaces along the Chuja and Katun Valley were selected to estimate peak discharge of the outburst flood. The elevation of the water-level indicated by the giant bars, the slope between the bar surfaces, and the recent slope of the rivers are shown in fig. 4. Considering the unknown slope of the flood flow water surface, the surfaces of the giant bars and the current mean river water-level are taken as the slope parameter  $S$ . Based on the investigations of hydraulic conditions of the flow in steep gradient river flow [19], it is assumed that the subcritical flow conditions are dominant along the outburst flood flow. For the Pleistocene Lake Missoula and Lake Bonneville Floods also, subcritical flow conditions were found to be predominant [16; 17. P. 14]. Therefore, locations and hydraulic parameters associated with flows with  $Fr > 1$  (table 1) were excluded from further analysis.

Considering these assumptions, a peak discharge was estimated to be in the range of  $10\,000\,000\text{ m}^3\text{s}^{-1}$  to  $14\,000\,000\text{ m}^3\text{s}^{-1}$ .

### Run-up sediments indicating velocity head of flow

Run-up sediments form a relatively thin layer of suspension gravel deposited in front of local valley obstructions and are the uppermost deposits related to the outburst flood (fig. 3, fig. 5). They could be considered an indicator of locally elevated water surfaces, due to the physical law of energy conservation. Based on the energy equation after Bernoulli, the total energy  $H$  is constant along the channel [14, 20]. As pressure energy is not of relevant for free surface flow, the energy equation can be expressed as

Table 1

Estimated flow velocities and discharges for selected locations derived by conveyance – slope estimations

Location valley-km	Cross-section data: altitude of water-level depth of flow y cross- section area A hydraulic radius R	Slope S	Roughness coefficient n	Velocity of flow v, m/s	Froude number Fr	Discharge Q, m <sup>3</sup> /s
DejJugem km 74.4	1280 m y = 294 m A = 297 000 m <sup>2</sup> R = 166 m	S = 0,006	n = 0,04 n = 0,07	v = 58 v = 33	Fr = 1,08 Fr = 0,61	Q = 17,2×10 <sup>6</sup> Q = 9,8×10 <sup>6</sup>
Tutugoj km 67.6	1252 m y = 310 m A = 216 000 m <sup>2</sup> R = 162 m	S = 0,006	n = 0,04 n = 0,07	v = 58 v = 33	Fr = 1,05 Fr = 0,60	Q = 12,5×10 <sup>6</sup> Q = 7,1×10 <sup>6</sup>
Sirnakh km 57.95	1188 m y = 294 m A = 358 000 m <sup>2</sup> R = 173 m	S = 0,006	n = 0,04 n = 0,07	v = 60 v = 34	Fr = 1,12 Fr = 0,63	Q = 21,5×10 <sup>6</sup> Q = 12,1×10 <sup>6</sup>
Bar in lower Chuja Valley km 49.1	1140 m y = 293 m A = 241 000 m <sup>2</sup> R = 155 m	S = 0,006	n = 0,04 n = 0,07	v = 56 v = 32	Fr = 1,04 Fr = 0,60	Q = 13,5×10 <sup>6</sup> Q = 7,7×10 <sup>6</sup>
Bar at river confluence km 29.8	1020 m y = 296 m A = 273 000 m <sup>2</sup> R = 174 m	S = 0,0043 S = 0,0022	n = 0,04 n = 0,07 n = 0,04 n = 0,07	v = 51 v = 29 v = 37 v = 21	Fr = 0,95 Fr = 0,54 Fr = 0,69 Fr = 0,39	Q = 13,9×10 <sup>6</sup> Q = 7,9×10 <sup>6</sup> Q = 10,1×10 <sup>6</sup> Q = 5,7×10 <sup>6</sup>
Te-Mojn km 5.6	920 m y = 252 m A = 287 000 m <sup>2</sup> R = 159 m	S = 0,0043 S = 0,0022	n = 0,04 n = 0,07 n = 0,04 n = 0,07	v = 48 v = 27 v = 34 v = 20	Fr = 0,97 Fr = 0,54 Fr = 0,68 Fr = 0,40	Q = 13,8×10 <sup>6</sup> Q = 7,7×10 <sup>6</sup> Q = 9,8×10 <sup>6</sup> Q = 5,7×10 <sup>6</sup>



$$H = (y + z) + (v^2 / 2 g),$$

where,  $(y + z)$  is the potential energy,  $y$  is the depth of flow,  $z$  is the elevation above datum,  $(v^2/2 g)$  is the kinetic energy,  $v$  is the velocity of flow, and  $g$  is the acceleration due to gravity.

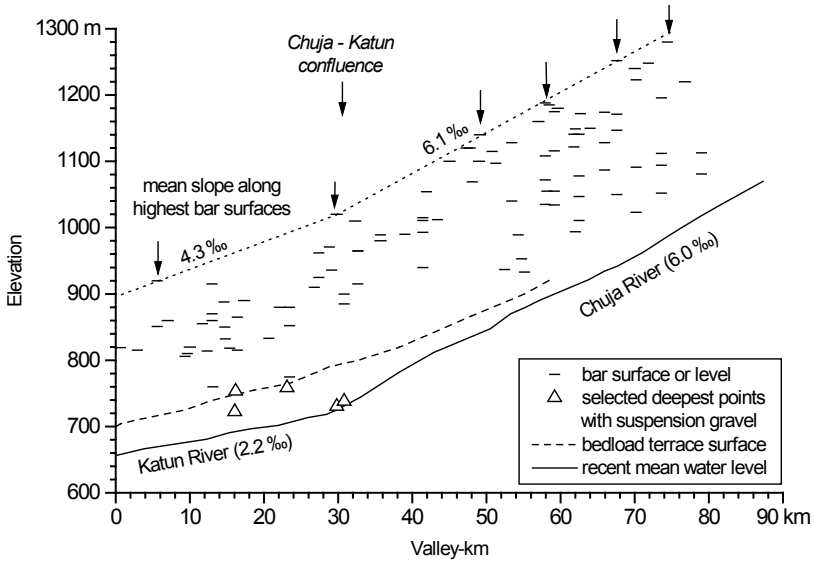


Fig. 4. Giant bar surfaces and terrace levels along Chuja and Katun valley



Fig. 5

While total energy  $H$ , elevation above datum  $z$  and acceleration of gravity  $g$  remain constant, an abrupt decreased in the flow velocity leads to an increased depth of flow, hence, the water-level rises on the upstream side of an obstruction.

This phenomenon can be observed, for instance, at bridge piers where the elevated water surface on the upstream side of the obstruction occurs and it is used to measure the flow velocity by velocity-head rods [21, 22]. The deposited suspension load indicates the risen water surface level in front of the obstruction, hence provides evidence of the energy head of the peak discharge of the flood. Due to non-uniform distribution of velocity within the open channel flow, an energy coefficient  $\alpha$  is introduced to calculate the change in height of the water-level from the total loss of kinetic energy [14]. Except in the case of uniform flow, the energy coefficient  $\alpha$  is always greater than unity and increases with the steepness of the channel. The equation for the mean velocity head  $v_h$  in a channel can be written as

$$v_h = \alpha (v^2 / 2g).$$

Depending on the amount of irregularities in channels, the values of  $\alpha$  vary between 1 and 2, rarely exceeding 4,70 [23]. Available literature indicates that the average value is about 1,3. However, experience shows that the effect of an increased velocity head  $v_h$  by  $\alpha$  is small compared with other uncertainties. Hence, the energy coefficient is frequently considered to be equal to unity, as the data are sparse and are found to be inconsistent [14, 24, 25].

Assuming that the run-up sediments and uppermost giant bar surfaces located nearby, were generated during the same stage of the flood, flow velocity  $v$  can be determined by taking velocity  $v_h$  as the difference in elevations of the run-up sediments and the giant bar surfaces and assuming  $\alpha = 1,3$ .

While the elevated water-level upstream of obstructions is indicated by suspension gravel being deposited in the uppermost position, the depth of the flow above the giant bar surfaces is unknown. The maximum value for velocity head  $v_h$  is given by the assumption that the undisturbed water-level of the flood was identical to that of the giant bar's surfaces. Therefore, calculated flow velocity also reaches maximum values. To check the sensitivity of this parameter, an undisturbed water-level half way between the giant bar and the related run-up sediments is considered.

For several locations along the Chuja and Katun Valley (fig. 3), velocities of the flow can be estimated on the basis of the relation between run-up sediments and related giant bar surfaces nearby. It is important to note, that the run-up sediments are deposited only during the peak discharge due the elevated water-level on the upstream side of local obstructions, but also during lower stages of the decreasing flood. Figure 6 shows values of local velocity heads  $v_h$  for different locations at two elevations considered for the undisturbed water-levels. A maximum value of  $v_h = 137$  m is indicated by field data.

Figure 7 shows the calculated mean flow velocities based on the velocity heads given in Figure 6 and an assumed value of the energy coefficient  $\alpha = 1,3$ . Velocity heads would decrease for higher water-levels, hence the undisturbed flow velocity would also decrease. Flow velocities estimated from both water-levels are within the expected range considering the magnitude of the flood as estimated previously by uniform flow calculations (table 1). For  $v_{h \max}$  flow velocities vary between 24 and 45 ms<sup>-1</sup>, for the higher water-level with  $v_{h \text{ assumed}}$  17 ms<sup>-1</sup> <  $v$  < 32 ms<sup>-1</sup> are calculated.



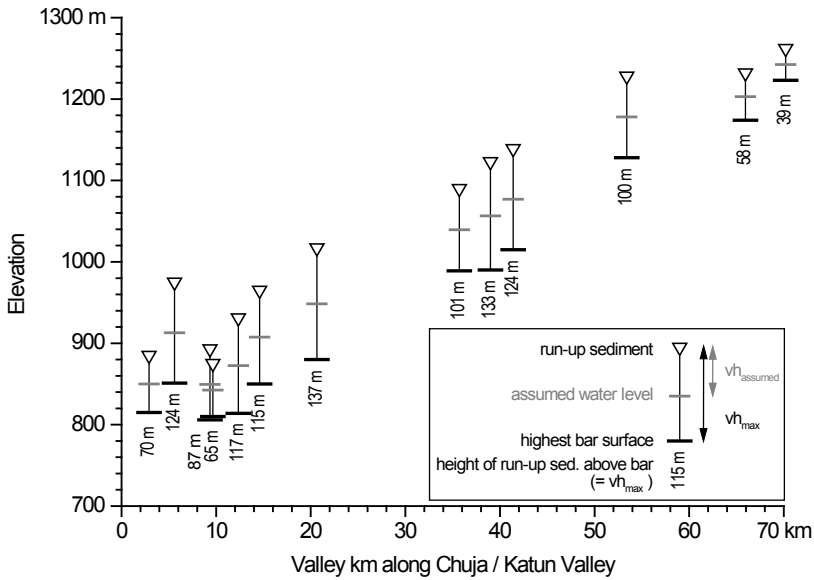


Fig. 6. Locations of run-up sediments and related bar surfaces indicated velocity heads along Chuja and Katun valley (The maximum possible velocity head  $v_{h_{max}}$  is limited by the difference in elevation of the run-up sediments and the bar surfaces. Its value is given in the figure. The velocity head  $v_h$  assumed for the assumed water level above the bar's surfaces is half of this value)

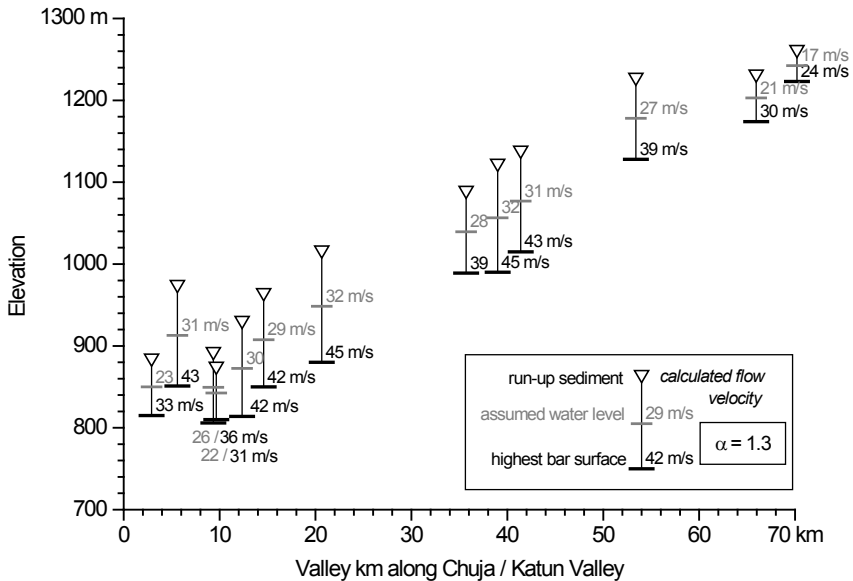


Fig. 7. Estimated mean undisturbed flow velocities derived from velocity heads indicated by run-up sediments for two local water levels along Chuja and Katun valley

These current conditions of higher kinetic energy (= higher flow velocity) can be expressed by Froude number ( $Fr$ ). For lower water-levels,  $Fr$  was found to be in the range of 0.48 and 1.17, whereas for the higher water-level the number was determined as  $0,32 < Fr < 0,69$ . The broad bedload terrace filling the valley-bottom is assumed to be deposited up to the current thickness later during the recession limb of the flood and also during the Holocene. Hence, the depth of flow used to calculate Froude number reaches from the current river channels (bedrock) up to the water-level of the flood stage, forming the run-up sediments.

To obtain subcritical conditions of flow, the energy coefficient  $\alpha$  must be modified up to a value of 1,8. This gave Froude numbers between 0,40 and 0,99 for the lower water-level, and between 0,28 and 0,58 for the higher one. For this value of the energy coefficient, flow velocities vary between 21 and 39  $\text{ms}^{-1}$  for the lower and between 15 and 27  $\text{ms}^{-1}$  for the higher water surface. None of these values appear critical as all the data are within the expected magnitude. This sensitivity analysis reveals that, considering the scale of the flood, the calculated flow velocities and Froude numbers are less sensitive to modifications of the energy coefficient  $\alpha$ . Hence, the value for  $\alpha$  is not a critical in the estimation of large-magnitude floods. Nevertheless, supercritical conditions of flow might have occurred at locations of valley obstructions.

The calculation of discharge  $Q$  based on the continuity equation  $Q = v \cdot A$ , for estimating the flow velocities  $v$  is occasionally a difficult task, because of the problems related with the calculation of the cross-section area  $A$ . As some of the run-up sediments are located at prominent valley obstructions and extended into ineffective areas of flow, the incident cross-section area cannot be determined. Similar problems occur at other locations, where the run-up sediments are deposited within the mouth of tributaries, and where flow separation phenomena must have occurred. Here too, related cross-section areas cannot be accurately estimated.

The calculated discharges (table 2) are within the expected range for peak discharge of the outburst flood. The relatively small difference between discharges of higher and of lower water-level elevations is remarkable. The lower water-level with reduced cross-section area is compensated by higher flow velocities to reach the height of the run-up sediments from a lower water surface elevation. Only occasionally, the flow velocity increases by an amount that results in a higher discharge for the lower water surface elevation. This effect might be enhanced by steep valley-slopes, which result into lower decrease of cross-section area at a decreased water-level than for valley sections with gentle slopes. On the other hand, the differences are in many cases within the range of accuracy. Therefore, the need for assuming the height of the water surface seems to be less crucial for the estimation of discharge.

The method to estimate flow velocities for discharges from investigated data of the velocity head appears to be a valid approach to determine the magnitude of the flood. This is due to the fact that the results are within the expected range of

the peak flood associated with the giant bars and run-up sediments, to give a peak discharge of about  $10\,000\,000\text{ m}^3\text{s}^{-1}$ . The assumed parameters of energy coefficient  $\alpha$  and the surface of the undisturbed water-level appear to be less critical in the estimation of the discharge. Occasionally, depending on the local topography with extended areas of ineffective flow in tributary valleys, the determination of the related cross-section area is complicated and precludes the accurate calculation of discharge from the estimated velocity of flow. Due to the nature of the obstructions – such as the ridges at tributary confluences causing the water-level to rise – the valley cross-sections show a significant modification in width which varies the cross-sectional area of flow for a given water surface elevation by several hundred percent.

Table 2

**Discharges calculated by velocity heads for selected run-up sediment locations**

Location valley-km	vh (assumed) : altitude of water-level flow velocity $v$ cross-section area $A$ discharge $Q$	vh (max) : altitude of water-level flow velocity $v$ cross-section area $A$ discharge $Q$
Kezek-Dzhala km 9,35	850 m $v = 26\text{ m/s}$ $A = 222\,000\text{ m}^2$ $Q = 5,8 \times 10^6\text{ m}^3/\text{s}$	806 m $v = 36\text{ m/s}$ $A = 133\,000\text{ m}^2$ $Q = 4,7 \times 10^6\text{ m}^3/\text{s}$
Anijakh km 9,65	843 m $v = 22\text{ m/s}$ $A = 205\,000\text{ m}^2$ $Q = 4,5 \times 10^6\text{ m}^3/\text{s}$	810 m $v = 31\text{ m/s}$ $A = 139\,000\text{ m}^2$ $Q = 4,3 \times 10^6\text{ m}^3/\text{s}$
Little Jaloman Village km 14,6	908 m $v = 29\text{ m/s}$ $A = 306\,000\text{ m}^2$ $Q = 8,9 \times 10^6\text{ m}^3/\text{s}$	850 m $v = 42\text{ m/s}$ $A = 215\,000\text{ m}^2$ $Q = 9,0 \times 10^6\text{ m}^3/\text{s}$
Giant bar between Inja and Little Jaloman Village km 20,65	949 m $v = 32\text{ m/s}$ $A = 384\,000\text{ m}^2$ $Q = 12,3 \times 10^6\text{ m}^3/\text{s}$	880 m $v = 45\text{ m/s}$ $A = 225\,000\text{ m}^2$ $Q = 10,1 \times 10^6\text{ m}^3/\text{s}$
Lower Chuja Valley km 35,7	1040 m $v = 28\text{ m/s}$ $A = 362\,000\text{ m}^2$ $Q = 10,1 \times 10^6\text{ m}^3/\text{s}$	989 m $v = 39\text{ m/s}$ $A = 256\,000\text{ m}^2$ $Q = 10,0 \times 10^6\text{ m}^3/\text{s}$
Lower Yalbak-Tash km 39	1057 m $v = 32\text{ m/s}$ $A = 300\,000\text{ m}^2$ $Q = 9,6 \times 10^6\text{ m}^3/\text{s}$	990 m $v = 45\text{ m/s}$ $A = 186\,000\text{ m}^2$ $Q = 8,4 \times 10^6\text{ m}^3/\text{s}$
Upper Yalbak-Tash km 41,4	1077 m $v = 31\text{ m/s}$ $A = 342\,000\text{ m}^2$ $Q = 10,6 \times 10^6\text{ m}^3/\text{s}$	1015 m $v = 43\text{ m/s}$ $A = 240\,000\text{ m}^2$ $Q = 10,3 \times 10^6\text{ m}^3/\text{s}$

The roughness of the surface of the valley-slopes might lead to an underestimation of the kinetic energy of the flow. Parts of the energy necessary to raise the

water-level at local obstructions might be dissipated to overcome the roughness of the obstruction's surface. This effect, in turn, might lead to deposition of the suspension load at lower elevation, implying that the extent of the rise in the water surface is determined by the surface roughness, which cannot be easily quantified. Validation of the method is desirable to estimate it accurately. Wilm and Storey [21] found 10% errors in the flow velocity estimated on the basis of velocity-head rod method. However, this value was derived for flows of much lower magnitude and partly from controlled flume experiments.

### **Regression drained lake volume-peak discharge**

A well-established method to estimate the peak discharge of modern ice-dammed lake outburst floods is the empirical regression of the drained volume of water and the peak discharge. Even though there is no physical relationship between these parameters and significant differences are expected occur along the floods' pathway due to valley topography and slope and retention effects, the relationships work remarkably well. Several attempts have been made to derive regression equations, in spite of the criticism related to the selection of the events, differences in outflow mechanism and the triggering mechanism of the outbursts. The plots given in figure 7 show that the regression lines obtained by various workers are comparable.

The application of such relationships for large-scale events is limited. Only Clague and Mathews [26] considered estimations of peak discharge of the outburst flood from the Pleistocene ice-dammed Lake Missoula. Therefore, a new regression was derived for large-scale events. An arbitrarily threshold drained volume of  $1 \text{ km}^3$  ( $= 10^9 \text{ m}^3$ ) was chosen to identify large-scale events and separate them from the smaller events. Eighteen instances of ice-dammed lake outburst floods from Pleistocene and modern times were taken from the literature to derive the relationship. The instances are listed in Table 3. Note that well-known examples that were either not exclusively related to ice-dams and those that were related to some kind of uncertainties, were not considered. For a drained volume  $V$  given in  $\text{km}^3$  a regression equation of  $Q = 6\,645\, V^{0.98}$  was determined,  $Q$  is given in  $\text{m}^3\text{s}^{-1}$  and  $r^2 = 0.93$ .

Assuming that the entire volume of the ice-dammed lake in the Kuray and Chuja Basin, with a volume of  $607 \text{ km}^3$  (for a lake level at 2100 m), was drained during the outburst flood, the estimated peak discharge is  $3\,500\,000 \text{ m}^3\text{s}^{-1}$ .

A comparison of this estimate with the earlier estimates indicates that regression equation underestimates the peak discharge. A closer examination of the examples given in table 3, reveals that Lake Missoula Flood is the only outburst flood with an estimated drained volumes of more than  $100 \text{ km}^3$ . Even after taking into account the fact that it is incorrect to include two different values for the estimated peak discharge from Lake Missoula (based on different estimation attempts) and that the complex topography of the flood's pathway have a profound ponding

effect, the amount of data to develop a regression equation is insufficient. Hence, it could be concluded that such an estimate of the peak discharge is not reliable.

Table 3

**Large ice-dammed lake outburst floods in historic and pre-historic times**

Location	Date	Lake volume, km <sup>3</sup>	Peak discharge, m <sup>3</sup> /s	Reference
Missoula, Montana USA	Pleistocene	2,184	17 000 000	O'Connor and Baker (1992)
Missoula, Montana USA	Pleistocene	2,184	10 000 000	Baker and Costa (1987)
Nedre Glåmsjø, Norway	Pleistocene	99	170 000	Berthling and Sollid (1999)
Lake Alsek, Canada	Holocene	30	470 000	after Clarke from Clague and Evans (1994)
Kjölur, Iceland	9500 BP	25	200 000	Tómasson (2002)
Hubbart Glacier, Alaska USA	1986	5,3	104 500	Mayo (1987), Seitz et al. (1986), Mayo (1989)
Lake Alsek, Canada	ca. 1850	4,7	30 000	after Clarke from Clague and Evans (1994)
Lake Elk, Canada	Pleistocene	4	20 000	Clague (1973)
Lake George, Alaska USA	1958	2,2	10 160	after US Geological Survey from Fahnestock and Bradley (1973)
Lake George, Alaska USA	1961	1,73	10 050	after US Geological Survey from Fahnestock and Bradley (1973)
Graenalon, Iceland	1935	1,5	5 800	Thorarinsson (1939)
Graenalon, Iceland	1939	1,5	5 000	Thorarinsson (1939)
Lake Batal, Himalaya	Pleistocene	1,496	24 000	Coxon et al. (1996)
Lake George, Alaska USA	1960	1,48	9 280	after US Geological Survey from Fahnestock and Bradley (1973)
Van Cleve Lake, Alaska USA	1992	1,4	4 500	after Brabets from Walder and Costa (1996)
Chong Kumdan (Shyo), India	1929	1,35	22 650	after Gunn or Mason et al. From Hewitt (1982)
Lake George, Alaska USA	1959	1,11	6 310	after US Geological Survey from Fahnestock and Bradley (1973)
Lake George, Alaska USA	1965	1,11	6 680	after US Geological Survey from Fahnestock and Bradley (1973)

### Further attempts

Additional attempts to estimate discharge related to the outburst floods in Altai Mountains are applied. Due to the limitation of the space, only a short review of the attempts and related problems is given.

The water-level calculation software **HEC-RAS** (Hydrologic Engineering Center of the US Army Corps of Engineers – River Analysis System) [27, 28, <http://www.hec.usace.army.mil/software/hecras/> – 27<sup>th</sup> Sept. 2011] is applied to

estimate discharge based on the palaeostage, represented by giant bars' surfaces [29]. The software package allows calculations of discharge and water surface level for one-dimensional steady and unsteady flow under sub- and supercritical conditions. Energy losses are evaluated by friction (Manning equation) and contraction or expansion by coefficients multiplied by the change in velocity head. The momentum equation is applied in situations where the water surface profile is rapidly varied, including mixed flow regime calculations with hydraulic jumps, hydraulics of bridges and profiles at river confluences.

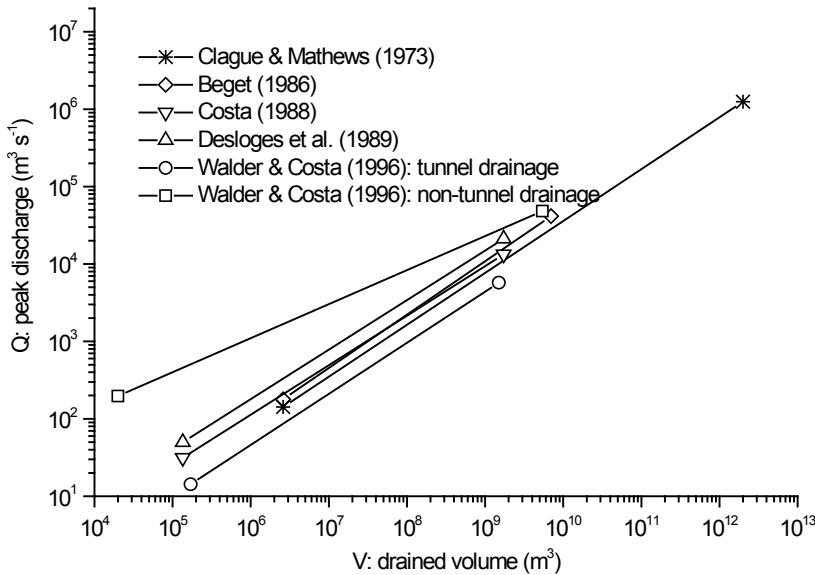


Fig. 8. Selected published relations of drained ice-dammed lake volume  $V$  and peak discharge  $Q$

To accomplish the presumption of gradually varied flow between the 244 cross-sections derived from detailed topographic maps, the modelled reaches of the valleys must be relatively homogenous. Hence, three units were separated and modelled independently, because obvious changes in valley characteristics require this: the broad and less steep Katun Valley up to the confluence with the Chuja River (km 0–30; 2,2‰), the straight and relatively steeper lower part of the Chuja Valley (km 30–44; 6,0‰) and the winding upper part of the Chuja Valley (km 44–85; 6,0‰). The area of the confluence itself is left out for modelling as the conditions of flow change abruptly in this section. Considering, the available literature the following loss coefficients of roughness, contraction and expansion were chosen:  $n = 0,04$ ,  $c = 0,2$  and  $e = 0,4$ . Regarding run-up sediments as indicator of maximum water-level and giant bar surfaces as minimum elevations, peak discharge for sub-critical flow conditions can be estimated as between  $8 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  and  $12 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  for all sub-reaches. Depth of flow varies between 280 and 400 m,



with mean flow velocity of  $9\text{--}37\text{ ms}^{-1}$ . Froude numbers of  $0,20\text{--}0,85$  confirm sub-critical flow conditions along the entire valley.

In the meantime, improvements of the HEC-RAS software allow unsteady flow simulations which were not possible due to numerical instabilities with previous versions. Rudoy and Zemtsov [30] modelled the unsteady outburst flood principally, but the modelled flood levels do not reach the palaeostage indicators like the giant bar surfaces and peak discharge is less than found by other approaches. Carling et al. [31] used alternative software to model the outburst flood as unsteady, one- and two-dimensional flow and found peak discharges confirming previous magnitudes.

Between the villages of Inja and Little Jaloman in the Katun Valley (fig. 2), **boulders**, which were obviously transported by the flood are deposited. The mean diameter of the five largest boulders is  $11,3\text{ m}$ , while the largest one has a diameter of  $13,5\text{ m}$ . To interpret the competence of the flow indicated by the dimension of the boulders, is an apparent attempt but limited by the dimension of the transported boulders. As described previously, for example, by Baker [32], transport of boulders with diameters of more than about  $2\text{--}3\text{ m}$  is related to macroturbulence effects, which create an uplift force due to modification of the current system around the boulder. Due to the magnitude of the related flow conditions, hydraulic interpretation of this effect of non-linearity is not well understood [33] and theory-based attempts are not available.

In spite of these problems, a rough estimation of the flow conditions required to transport these large boulders, based on relationship derived for smaller dimension boulder deposits available in the literature, result in flow velocities of about  $20\text{ ms}^{-1}$  with related discharges of  $3\,000\,000\text{ m}^3\text{s}^{-1}$ . As these values could be overestimations, due to the macroturbulence effects mentioned above, the transport of the boulders may not be necessarily related to the peak discharge of the outburst flood. Even the magnitude of the required discharge is significantly smaller than peak discharge estimated by other attempts. Hence, the transport of the boulder occurred at an unspecified stage associated with falling flood stage.

Fluvial gravel dunes are formed as bedform features at the previous lake bottom and along the flood's pathway down to the opening of the Katun Valley towards the western Siberian Plain, where traces of the event fade out. As mentioned above, the sedimentology of several gravel dune fields is subject of detailed investigations by Carling [9, 10], who also carried out hydraulic interpretations, which result in estimated flow velocities of  $1,5\text{--}8\text{ ms}^{-1}$  and related discharges of  $20\,000\text{--}750\,000\text{ m}^3\text{s}^{-1}$  over the span of the dune fields. The largest gravel dunes were found at the eastern margin of the Chuja Basin with heights up to  $23\text{ m}$  and wavelengths up to  $320\text{ m}$ .

Based on a) empirical relationships for the geometry of fluvial dunes; b) the depth of flow in combination with estimations of the flow competence indicated by the gravel sizes of the investigated dunes, the estimation of flow conditions forming the residual dune structures can be made. Depending up on the different sizes of the

dunes, mean flow velocities of  $4,8\text{--}10\text{ ms}^{-1}$  and discharges in the range of  $10\,000\text{--}1\,340\,000\text{ m}^3\text{s}^{-1}$  were determined. As gravel-dunes grow during the rising stage of a flood and decrease at the end, the residual dimensions cannot be related to the peak discharge but again to an unspecified stage at the termination of the outflow.

Similar problems are encountered in case of the obstacle marks, found in different sizes at the boulder field between Inja and Little Jaloman, and around a bedrock hill near the village of Chagan-Uzun at the eastern margin of the Chuja Basin. As scour holes refill during the decreasing flood [34], they are dynamic features like gravel-dunes.

The boulder between Inja and Little Jaloman is about 10,8 m wide with a length of 13,8 m and a maximum height of 3,1 m above the surrounding surface. The scour hole is filled by loess deposits blown in after the outburst floods, but can easily be separated from the gravel-paved surface around by changes in the vegetation cover. The width of the depression is 24,3 m with a maximum observed depth of 2,3 m. The scour hole around the bedrock hill near Chagan-Uzun has a measured depth of 8,1 m. Length along the direction of flow is 91,5 m and the width is nearly 400 m, while the hill itself is 50 m high. The maximum elevation of the deposits on leeward side of the hill is about 4 m above the area, while its counterpart at the boulder reaches the height is 0,5 m.

Calculations of scour hole dimensions and dynamics are a classical engineering task as bridges and oil platforms, for example, are in potential danger to fail by scour around the piers. Unfortunately experiences gained by related investigations cannot be transferred, as the current pattern is different, because piers engineering structures are not usually submerged by the flow. Similarly, the results from flume experiments are not applicable directly, because earlier investigations derived mainly qualitative results, while current studies are mainly carried out on a fluid mechanical base in flumes under well-defined environmental conditions.

Finally, the estimations of flow conditions based on the characteristics of the obstacle marks are based on minimum values of the depth of flow derived from the scour hole dimensions and flow velocity assessments related to the flow competence indicated by grain sizes of sediments at the outer scour hole walls. The scour hole around the boulder near Inja seems to be finally formed by a current with a velocity of  $1,4\text{ ms}^{-1}$  at a discharge of about  $800\text{ m}^3\text{s}^{-1}$ . The larger depression around the bedrock hill contains evidence of a flow of about  $11\,500\text{ m}^3\text{s}^{-1}$  with flow velocity of approximately  $1,7\text{ ms}^{-1}$ . Obviously, these discharges represent the very final stage of the flood, and had previously reduced the scour holes dimension by refilling with transported sediments.

## Results

The different attempts to estimate flow conditions of the Pleistocene outburst floods in Altai Mountains result in data for flow velocity and discharge of the flood's peak and unspecified stages of the waning flood. Based on the conservative

estimate of the peak discharge to be about  $10\,000\,000\text{ m}^3\text{s}^{-1}$  and assuming that the entire lake basin, with a volume of  $607\text{ km}^3$ , drained during the outburst a hydrograph can be generated. The hydrograph indicates a flood that did not last for more than 2–3 days (fig. 9). The duration of the flood was determined by the integral curve based on the limitations of the drained volume (= integral) and the peak discharge. Advanced modelling of unsteady two-dimensional flow confirms this magnitude. From a negligible baseflow, an abrupt rise of the hydrograph represents the outburst flood wave, which reached peak discharge values almost immediately. It should be noted that the hypothetical hydrograph does not consider ponding effects along the flood's pathway. Consequently, a tendency towards underestimation of the duration of the flood is inherent.

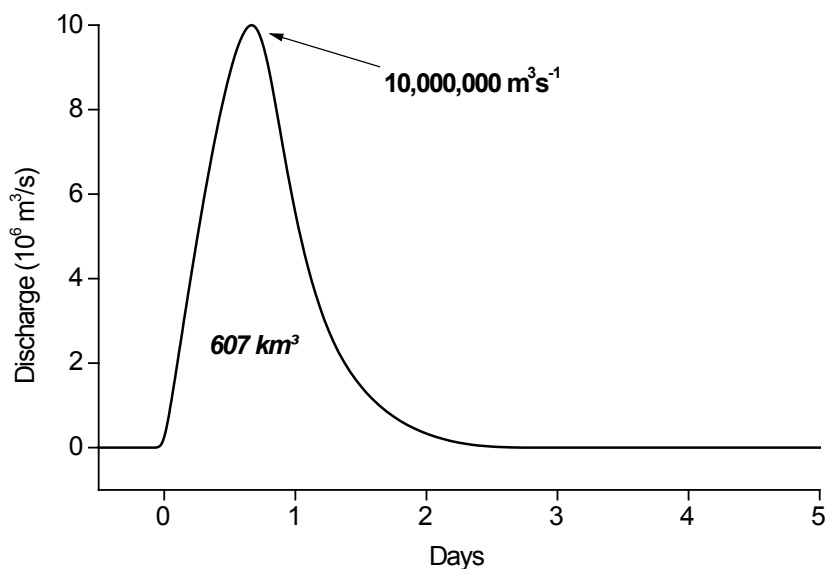


Fig. 9. Theoretical hydrograph of the ice-dammed lake outburst flood based on peak discharge and drained volume

Compared with the earlier estimates of the peak discharge of the outburst flood [5] the new calculations give a slightly higher discharge magnitude. Considering the fact that the present study is based on larger number of palaeostage indicators and also includes the calculation of the discharge downstream of the former ice-dam, the new estimations appear reliable and contain several elements of conservative assessment.

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## ПРОРЫВНЫЕ ПАВОДКИ ИЗ ЛЕДОВО-ПОДПРУДНЫХ ОЗЕР ГОРНОГО АЛТАЯ (СИБИРЬ)

В период плейстоцена несколько горных ледников выдвигались в долину р. Чуя, притока Катуня. В месте, где теперь расположен пос. Акташ, ледники блокировали сток Чуя и формировали подпруженное льдом озеро, объем которого достигал 607 км<sup>3</sup>. Водная поверхность в озере, располагавшемся в Чуйской и Курайской межгорных котловинах, достигала максимальной отметки в 2100 м. При быстром разрушении ледовой плотины по долинам Чуя и Катуня проходили гигантские паводки. Вероятно, дамба разрушалась в результате перелива воды через нее и быстрого врезания потока в ледовое тело плотины. Поток переносил во взвешенном состоянии гравий и отлагал его, формируя гигантские бары в местах расширения долин и устьях притоков. В устьях притоков по пути движения паводков гигантские бары блокировали их долины, образуя вторичные озера, которые обнаруживаются по озерным отложениям, переслаивающимся с гравием, что говорит о том, что паводки образовывались неоднократно. Отметки поверхности гигантских баров соответствуют глубине потока в долине Чуя сразу ниже ледовой плотины, достигавшей 400 м. Имеются и другие многочисленные свидетельства неоднократного прохождения гигантских паводков по долинам Чуя и Катуня.

Предшествующие исследователи сосредоточивались только на отдельных аспектах проблемы, например С.В. Парначев и П. Карлинг и др. – на геологии гигантских баров, П. Карлинг – на гравийных дюнах, А. Райтер и др. – на возрасте прорывных паводков, П.С. Бородавко и П. Карлинг и др. – на самом ледово-подпрудном озере. Новые публикации дадут более детальную информацию, касающуюся времени прохождения паводков. Согласно отмеченным выше публикациям, большинство датированных следов паводков свидетельствует о времени их прохождения между 40 и 17 тыс. лет назад.

В представленном обзоре делается попытка реконструировать размеры паводка, формирующегося при прорыве ледово-подпрудного озера.

Для получения информации о расходах воды при прохождении прорывных паводков использованы семь независимых методов: 1) метод «пропускная способность долины – уклон», когда уклон потока определялся по высоте поверхности наиболее высоких баров; 2) по высотным отметкам материала, отложенного на бортах долины в результате заплесков потока, которые позволяют оценить его скоростной напор, а следовательно, и скорость; 3) по регрессионным зависимостям максимальных расходов воды от объема воды в опорожняющемся озере; 4) моделирование потока в программе HEC-RAS Гидрологического инженерного центра Корпуса гражданских инженеров Армии США, позволяющего оценить расходы потока, соответствующие определенной его кривой свободной поверхности при установившемся и неустановившемся движении воды; моделирование осуществлялось также с помощью двумерной модели течения; 5) по размерам



валунов, явно принесенных и отложенных потоком (пять валунов, отложенных между селами Иня и Малый Яломан в долине Катунь, имеют средний диаметр 11,3 м при максимальном 13,5 м); 6) по размерам флювиальных гравийных дюн, образующих поля в Курайской котловине и в долине Катунь ниже по течению и, вероятно, сформировавшихся на завершающей стадии опорожнения озера; 7) по размерам котловин вымывания образовавшихся у местных препятствий по пути движения паводка, так же, по-видимому, образовавшихся на завершающей стадии паводка.

В результате были получены данные о расходах и скоростях течения воды, соответствующие времени прохождения пика паводка и разным этапам его нисходящей фазы. Максимальный расход воды оценивается примерно в  $10 \text{ млн м}^3 \text{ с}^{-1}$ , а общая продолжительность паводка – не более 2–3 сут. Настоящее исследование опирается на большее количество индикаторов уровней палеопотоков и включает расчет расходов воды ниже по течению от разрушившейся ледовой плотины, новые оценки выглядят достаточно надежными.

Данная работа проведена на основе совместных исследований с Полом Карлингом (Школа географии Университета Саутгемптона, Саутгемптон, Великобритания) и Павлом Бородавко (геолого-географический факультет Томского государственного университета, Томск, Россия).

**Ключевые слова:** ледово-подпрудное озеро; прорывной паводок.

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