===== **RESEARCH TECHNIQUES** =====

Water Exchange in Small Riversheds With Severe Climatic Conditions During a Cold Period of a Year

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Abstract – Presented are the results of experimental studies into the interaction between the surface and subsurface water in 16 mountain river basins of East Sayan and Lake Baikal as carried out by the Irkutsk-based Institute of Geography during 1984–1990. The research program included regular measurements of the thickness, area and volume of the surface and underground ice along the entire length of the valleys, pressure in closed lenses of underground waters, daily measurements of water discharges and chemical composition throughout the channel network. It was found that at the end of winter about 80–90% of the area of the valleys of the rivers under study are covered by aufeis and by the seasonal subsurface ice of a different genesis. Furthermore, about half the volume of the seasonal ice corresponds to the surface ice (river ice and aufeis), and the other half to the subsurface segregated and injection ice. It was further shown that the period of formation of the main bulk of ice begins and ends earlier in the sections closer to the mouth. The "wave" of maximum intensity of ice formation gradually moves the river upstream. The ice volume is the last to form in the upstream components of the river network. At this time, the ice formation of the other area of the watershed has terminated or its main part has formed already. A cryogenic barrage phenomenon occurs, as a result of which the channel network receives subsurface water which, under normal conditions, is not drained by the river. The winter river runoff increases from 50% in the sections close to the source to 5–10% at the mouth of the river.

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FORMULATION OF THE PROBLEM

Rivers in regions with severe climatic conditions, deep seasonal freezing and with permafrost are alimented for the larger part of the year solely by subsurface water. These regions occupy more than half the territory of Russia. The water exchange between rivers and aquifers occurs under the influence of seasonal interphase transitions of moisture from the liquid phase to the solid phase and back. One of the results of such an influence is the redistribution of the annual runoff of rivers where its winter part (very low already as it is) decreases and the summer part increases.

Two mechanisms of cryogenic redistribution of the runoff may be singled out. In one of them, a part of the runoff in river channels and in subsurface aquifers alimenting them accumulates in ice formations (river ice, aufeis and ground ice of a different genesis) during a cold period. During a warm period, this moisture at the time of thawing enters back the channel network. The process of winter accumulation of a part of the runoff in the ice formations of river basins has been much studied in a large number of publications, the most thorough of which are [1–4], as well as in publications dealing with separate regions [5–7].

The second mechanism implies the emergence of additional hydraulic resistances in the case of a decrease in carrying capacity of the geofiltration environment (shallow soft sediments in river valleys and river flows as a result of their partial freezing through. This gives rise to new routes of moisture migration differing from gravity discharging in the thawed state, its discharge in places not conditioned by hydrogeological characteristics of the strata, or to closed contours which do not freeze through during the wintertime. As a result, this involves a decrease in the discharge intensity of basin storage of subsurface water and in the river discharge.

The differences between these mechanisms imply that excess pressure in deposits of a small thickness encompasses the entire aquiferous layer and produces an affluent spreading the river upstream. And the ice formation involves all water contained in the horizon, unlike the former variant. In either case, the ice of a different genesis is produced. The mechanism of its formation is thoroughly described in the national [8, 9] and foreign literature [10–12].

The difference manifests itself in hydrological consequences. In either case, these processes lead to a decrease in winter subsurface inflow into rivers and to the formation of the ice of a different genesis. In the latter case, however, the water exchange process involves subsurface water which otherwise would not be drained by the river system of a given basin. And finally, the second mechanism generates rather significant local subsurface basins of free water which enters the river at the end of winter, overlapping the beginning of the thawed runoff and increasing the flood volumes.

The above process of the pressure flow under the action of freezing was termed "cryogenic barrage" by M.L. Markov [13, 14]. The just cited references are the only (known to us) publications devoted to the phenomenon under consideration. M.L. Markov investigates the hydrological consequences of cryogenic barrage: the influence on the formation of the river runoff and the subsurface inflow into rivers. The mechanism that is responsible for the cryogenic pressure flow and its hydrological characteristics are poorly understood to date. The objective of this paper is to present the results of scientific investigations into the processes of interaction of surface and subsurface water in small river basins under the effect of cryogenic processes which, among other things, describe the mechanism of cryogenic barrage.

OBJECTS AND METHODS

During 1978–1994, Institute of Geography SB RAS was engaged in experimental research on the interaction of surface and subsurface water in 16 river basins of the central part of Eastern Sayan, two basins of the Angara region, and in three basins of the southern part of the mountains surrounding Lake Baikal. The area of these basins varies from 2 to 498 km^2, and the length of the rivers varies from 1.5 to 21 km. The program of research efforts included: measurements (once every five days) throughout the entire basin: of the thickness, area and volume of surface ice (aufeis and river ice); the thickness, area and volume of ground (segregation and injection) ice, freezing and thawing of earth materials, and characteristics of snow cover; daily measurements (several times per day, throughout the entire channel network) of water discharges and chemical composition at a different distance from the mouth, every 200–250 m, as well as pressure in subsurface aquifers throughout the entire area of the valleys, and continuous recording of the runoff from runoff sites in different landscapes (including the runoff of dissolved matter), meteorological characteristics at the center of the basin (air temperature, atmospheric precipitation, solar radiation, wind, etc.).

The thickness of the ground ice was determined according to the scheme shown in Fig. 1. Across the valley bottom, every 60–80m, section lines were established and equipped by taut ropes with fixed points. Prior to the beginning of a cold period, the height of the rope above the valley bottom H_1 was determined at these points, and rods were fixed at them. During winter surveys, at each point measurements were made of the distance from the rope to the surface of the valley bottom or aufeis H_2 and the aufeis thickness from the rods H_3.
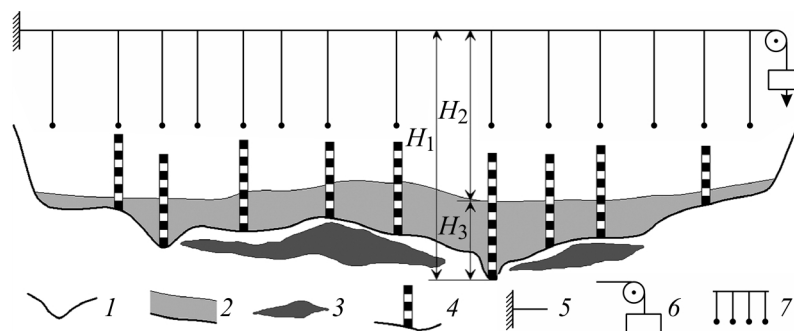

Fig. 1. Scheme for measuring characteristics of the aufeis and ground ice thickness.
1 – profile of the valley bottom; *2* – aufeis body; *3* – injection ice lenses; *4* – fixed rods; *5* – rigid fastening of the rope; *6* – pulley and counterweight; *7* – marked-off rope and plumb lines at points of measurement. For H_1–H_3, see the text.

During the ground ice formation the surface of the valley bottom is deformed and rises to a height H_1, equal to the total thickness of the segregation ice or to the thickness of the injection ice. According to the measurements listed above, the ground ice thickness is determined as the difference: $H_1 = H_1 - H_2 - H_3$.

One point of measurements encompassed, on the average, from 60 to 100 m^2 of the area of the valley. Such a density of the observation network, according to [15], ensured an average error of determining the ice characteristics across the area making up about 3–5%. The measurement of pressure in aquifers was made by using a specially developed recorder as described in [16]. The observations of the other elements of the program were made by generally accepted techniques.

FORMATION OF SEASONAL ICE OF A DIFFERENT GENESIS IN SMALL BASINS DURING THE WINTER, AND CRYOGENIC BARRAGE

In the wintertime, most small rivers of the territory under consideration freeze through, and the runoff in their channels is absent during 4–5 months. At the end of winter, about 80–90% of the area of the valleys of these rivers is covered by aufeises and seasonal ground ice of a different genesis. Their formation occurs solely by subsurface water. The volumes of water contained in this ice can ensure a winter-averaged runoff in the outlet sections from 1.8 to 3.5 L/(s·km^2) (the probable subsurface inflow into the rivers). During the low-water summer period when the subsurface water storage in small basins is much larger than in the wintertime their inflow into the rivers under consideration varies from 1.5 to 2.5L/(s·km^2) [17].

Nowadays, there are views of a weak activity of the water exchange in the upstream components of the channel network during the winter period, especially in the absence of the runoff in the river channels. However, the aforementioned increase in the winter subsurface inflow, in comparison with the summer inflow, suggests the ongoing process making it possible to extract from the subsurface aquifers the volumes of water which, in the absence of this process in the summer period, are not drained by rivers. The description of such a process for the upstream components of the channel network is given below.

As an example, the basins of the Shamanka river (Eastern Sayan) and the Shumikha river (Cisbaikalia) were used. They differ in climatic and geomorphological conditions, in the size as well as in the distribution pattern of ice volumes along the length of the river (Table 1). On the Shamanka river, the maximum of ice formation corresponds to the middle part of the basin; on the Shumikha river, it is about the same along the length of the river.

Different types of ice emerge in these drainage areas due to the runoff in depth during the winter (Table 2). The proportion of aufeis on the Shamanka river makes up 40–45%, and the proportion of the injection ice can reach 50%. With a decrease in the size of the basin (Shumikha river), the proportion of aufeis and segregation ice increases but the amount of injection ice decreases to 20–25%.

Let the volumes of surface and ground ice forming in the specified section line at an arbitrary time be expressed in terms of a per-unit basis $\psi_i = W_i/W_0$, where W_i is the volume of ice at the ith time in a given section line, and W_0 is the largest volume of ice in this section line at the end of winter. This permits us to

Table 1. Characteristic values of specific volumes of seasonal ice of a different genesis at the time of their largest development (m^3 per 1 m of the valley length) along the length of some rivers

| Characteristic	Specific volume										
	Shamanka, 1989–1990										
Distance from mouth, km	0	0.36	0.77	1.81	2.72	3.30	3.53	3.79	4.25	5.18	5.90
Aufeis	26.5	11.0	21.7	47.9	147	29.3	136	13.5	36.7	12.5	0
Injection ice	8.81	6.00	15.0	52.9	148	38.0	76.9	14.0	56.5	7.00	0
Segregation ice	2.39	4.09	3.12	8.18	19.9	6.39	10.0	2.92	11.5	2.51	0
	Shumikha, 1991–1992										
Distance from mouth, km	0	0.31	0.69	0.85	1.15	1.54	1.69	2.00	2.31	2.69	3.00
Aufeis	35.5	14.7	24.8	7.62	25.9	18.8	16.0	21.7	14.5	8.64	0
Injection ice	0	3.66	3.48	2.47	14.5	7.78	9.25	14.1	12.7	4.12	0
Segregation ice	0	4.49	8.83	1.39	13.0	10.7	11.8	17.0	12.7	5.42	0

Table 2. Volumes (W, thou m³) of different types of ice forming in separate river basins during the winter and their proportion in the total ice volume in the basin (y, %)

Basin	Year	Aufeis		Segregation ice		Injection ice		All ice types
		W	y	W	y	W	y	W
Shamanka (16.7 km²)								
all basin	1988–1989	212	40.0	48	9.1	270	50.9	530
main river		195	45.8	41	9.6	190	44.6	426
all basin	1989–1990	273	44.0	50	8.0	298	48.0	621
main river		232	47.5	37	7.6	219	44.9	488
Shumikha (4.2 km²)	1991–1992	49	57.6	17	20.0	19	22.4	85
	1992–1993	33	56.0	14	23.7	12	20.3	59

compare the intensity of ice formation in stretches with different volumes of ice, because the value of ψ_i in each section line will vary from 0 to 100%. Fig. 2 shows the variation in relative ice volumes during the winter along the length of some rivers.

The onset time of the period of the most intense formation of the complex of surface ice and ground ice (ψ_i = 20–80%) shifts, in general, on a regular basis along the length of the river from its mouth to source, starting in the beginning of winter and in its first half to the end of winter or its latter half. The period of formation of the bulk of ice begins and ends earlier in the stretches nearer to the mouth. The "wave" of the largest intensity gradually moves the river upstream. Later, ice volumes are formed in the upstream portions of the river network. At that time, ice formation in the other part of the basin stops, or its main part has formed already.
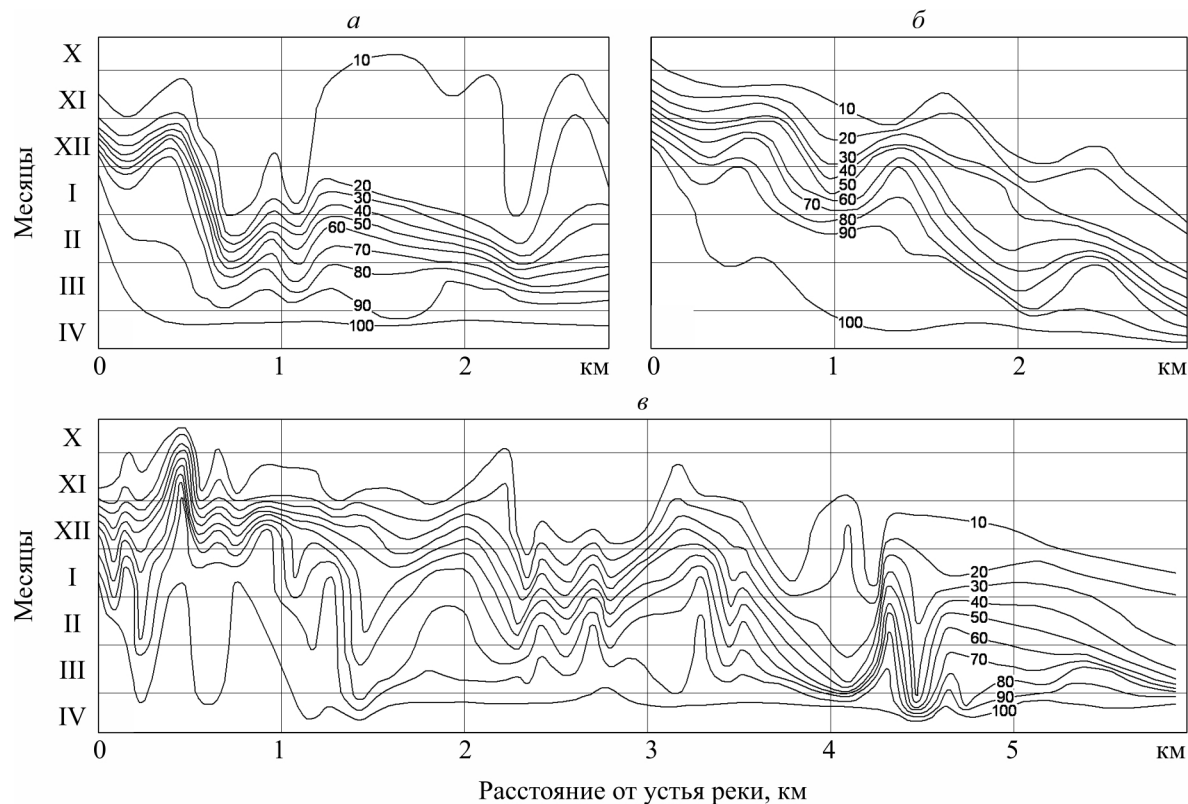
Fig. 2. Variation in relative volumes of all seasonal ice y (figures on the isolines, %) over the winter in the length of some rivers (distance from the mouth).
a – Olin brook (tributary of the Shamanka river), 1989–1990; *b* – Shumikha river, 1991–1992; *c* – Shamanka river, 1989–1990.

The above specific feature in the dynamics of development of the natural ice complex along the length of the river is observed for all basins where the investigations were made, irrespective of their size, height, aspect or geological structure.

At first glance the aforementioned regularity contradicts the views of the formation of the subsurface runoff. First and foremost the reserves of subsurface water in the upstream part of the basin must be depleted because large slopes and a high porosity of earth materials, while the capacity of aquifers is not large. The amount of water would be inadequate to ensure ice formation at the end of winter. Indeed, a fast depletion of aquifers occurs at the beginning of winter, and 30–60 days after the first frosts the channeled runoff stops. The rate of fall of the infrabed flow level is higher than the velocity of the freezing boundary so that ice formation, if any, occurs in minor volumes.

In the downstream part of the basin where the moduli of subsurface runoff are higher, the velocity of the frost boundary (front) is faster than the fall of the groundwater level. Excess water pressure is created, which leads to an intense formation of aufeis and ground ice. The frozen overlying layer is gradually growing by increasing its strength. Excess water pressure now is unable to destroy it and be realized through the aufeis formation alone. As a result, it begins to spread the river upstream [17, 18]. In the stretch under consideration, the infrabed flow freezes though, and ice formation stops. Frost pressure arises, which moves the river upstream with a changeable velocity. Its zone of wedging out determines the zone of active ice formation. In the latter half of winter, the "affluent wave" reaches the upstream components of the channel network, followed by onset of an intense ice formation.

However, the ice formation mechanism here differs from the processes in stretches nearer to the mouth. In the latter half of winter, the frost boundary now penetrates sufficiently deep into soft sediments and creates an almost rigid overlying layer of the subsurface flow, capable of resist a high excessive pressure that arrives here from the lower-lying stretches as a result of the propagation of the cryogenic "affluent wave". There are two possibilities for this water pressure to realize.

One possibility is associated with filtration of the confined flow through soft sediments of the thalweg sides (with relatively low moisture content) warmed by vegetation cover and snow. This phenomenon is only characteristic largely for the upstream sections of river valleys. It is in such sections that there most often occur aufeises descending down the slopes, the front of which reaches several hundred meters and the upper boundary is subhorizontal and is at the height of 2–10 m above the valley bottom. This height represents the height of water pressure in the alluvial flow, and it gradually rises at the end of winter. Usually, such a discharge occurs on northern slopes with a thick moss mantle preventing a deep freezing of the slopes.

One further evidence for the validity of the mechanism described above is the emergence of aufeis and injection ice in thalwegs of lateral inflows where the overland runoff exists only in the case of storm rainfall of a rare frequency. In them, ice formation begins only at the time when the "affluent wave" arrives to their mouth from the downstream stretches of the main river.

Another possibility involves the formation of thick injection ice lenses which are responsible for frost mounds, or injections of large water volumes into closed contours reaching several tens of thousands of cubic meters which do not freeze completely till the end of winter. The formation process of such volumes of free water is quite well described in [19].

Formation of the ice complex in the basin represents a unified process where the ice formation intensity in some sections depends on the cryogenic processes in the down- and upstream sections. Of course, a smooth and gradual advance of the "affluent wave" the valley upstream is an ideal case. It can only be realized in the absence of lateral inflows and homogeneous geological and morphometric conditions or their monotonic change.

In real natural conditions, water pressure moves in a jump-like manner and stopping temporarily in areas with relatively large slopes. The uneven thickness of the aquiferous complexes and the proximity of the confining layer to the day surface at the inflection points of the longitudinal profile of the valley give rise to local or intermediate base levels from which their own "affluent waves" propagate and the waves arriving from below attenuate, or their interference with local waves occurs. This process is shown in Fig. 3, illustrating a variation in increments in ice volumes for different dates during the wintertime. Saw-tooth broken lines with a large variation amplitude across time are clearly seen. Even in such conditions, however, as the river source is approached, the basin as a whole retains a general tendency for the ice formation intensity period to shift to later dates.
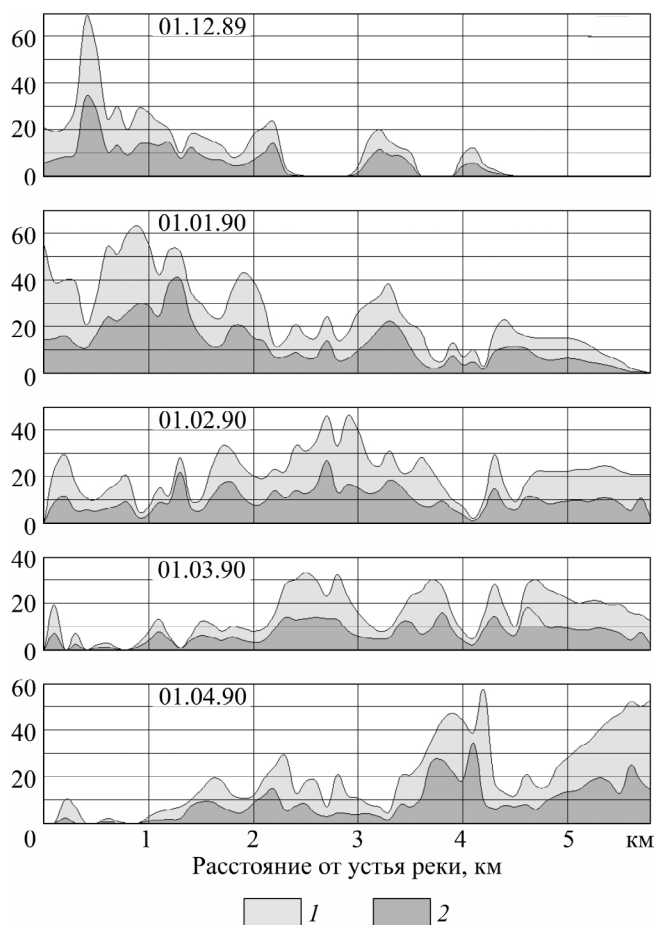
Fig. 3. Increment in relative volumes of the seasonal ice of a different genesis (y, %) for different dates along the length of the Shamanka river (distance from the mouth), 1989–1990.

1 – aufeis; *2* – ground ice (injection and segregation).

THE ROLE OF THE SEASONAL ICE AND CRYOGENIC BARRAGE IN THE RIVER RUNOFF FORMATION

In the case of the aforementioned ice formation mechanism, especially in the upstream sections of river valleys, the water exchange processes involve the waters which would never be drained if the conditions were different. Thus the subsurface alimentation of rivers in the upstream part of the basin receives additional water volumes and, in general, the subsurface alimentation somewhat exceeds the value which would be expected on the basis of the subsurface water capacity storage, the character of their depletion and the drainage capacity of the river network without taking into account the cryogenic processes.

These additional water volumes can be calculated on the basis of reconstructing the subsurface alimentation hydrograph from theoretical recession curves and,

in particular, from the widely used Boussinesq–Maillet curve which is suited to these conditions [20]:

$$Q_i = Q_0 \frac{1}{(1 + \alpha \cdot \tau)^2},$$

where Q_i is the ordinate of hydrograph at the *i*th time, Q_0 is the discharge at the beginning of the calculated period, α is the recession coefficient, τ is the duration of the interval from the beginning of the calculated period to the *i*th time.

An example of such reconstructed hydrographs at a different distance from the source is shown in Fig. 4 for a particular basin. Obviously the difference of the runoff volumes between the volumes obtained from the reconstructed hydrographs and the actual hydrographs will yield the value of an additional subsurface inflow into the rivers.

Results of the calculation show that an additional subsurface alimentation increases from mouth to source (Table 3). While in the river mouth the hydrograph inferred from the recession curve and the actual hydrograph almost coincide, in areas nearby the source the volume of subsurface alimentation is about 50% larger than its value obtained from the theoretical curve.

This lends support to the validity of the aforementioned mechanism of ice formation in the basin, the main elements of which are the "affluent wave" and an intensification of the water exchange the river upstream.

CRYOGENIC SPRING FLOODS

The phenomenon of cryogenic floods is associated with injection formations. A possible occurrence of such floods was pointed out in [14, 21]. Our research showed that not all water entering the injection contours passes into the solid phase. A part of it remains in the unfrozen state till the end of winter. On the Shamanka river, for example, the volume of unfrozen water bound in injection formations was 130 thou m³, or about 40% of the total volume of injection formations. At the end of winter, the ice formation virtually ceases. Pressure begins to increase at that time in the presence of the ongoing entry of water into the injection reservoirs. The pressure can reach 1800–2500 hPa. After that, the reservoirs open, and the water gushes out to form the runoff above the aufeises.

The outgushing water is transparent and has a saturated yellow color and a total mineralization of up to 2500 mg/dm³. Usually, the river mineralization does not exceed 150 mg/dm³ during the low-water period. Such a high mineralization is explained in
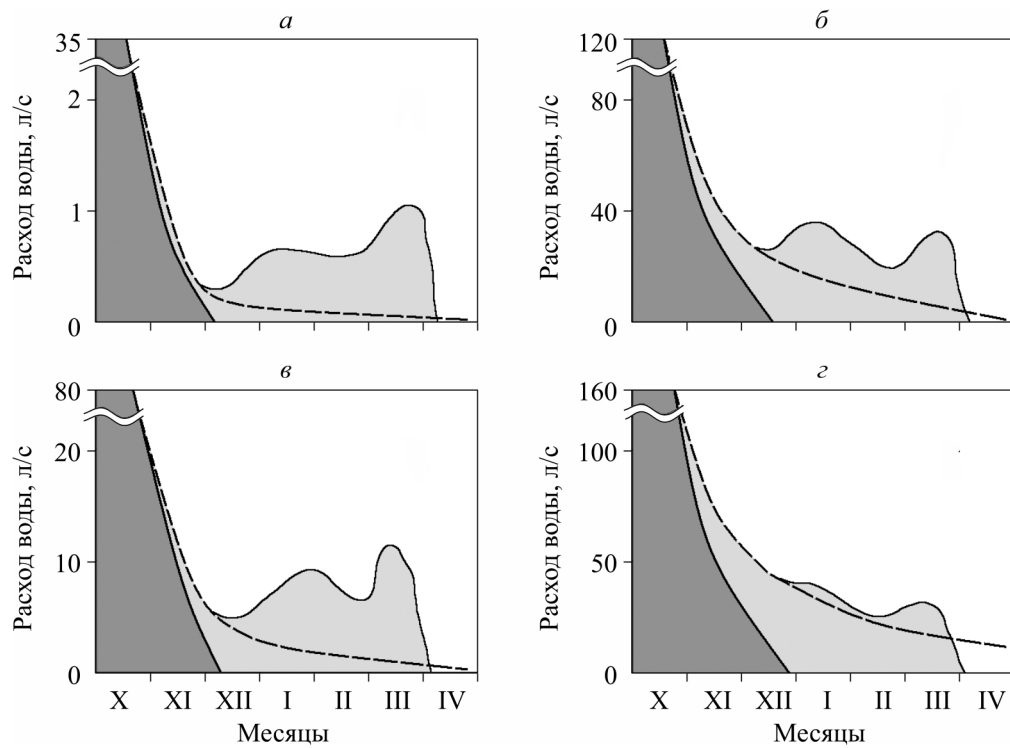
Fig. 4. Hydrographs of winter subsurface alimentation of the Shamanka river in 1989–1990 at a different distance from the mouth. Distance from the mouth, km: *a* – 4.6; *b* – 3.2; *c* – 1.6; *d* – mouth. *1* – channeled runoff; *2* – expenditures in ice formation; *3* – recession curve of basin reserves of subsurface water.

Table 3. Characteristics of separate components of winter subsurface alimentation within the Shamanka river basin at a different distance from the mouth

Distance from mouth, km	Drainage area, km²	Duration of channeled runoff, days	Recession coefficient	Modulus of flow, L/(s·km²)				Additional alimentation, %
				measured			from recession curves	
				channeled runoff	expenditures in ice formation	total		
1987–1988. Duration of the winter period – 181 days								
4.6	3.7	52	0.241	0.185	0.132	0.317	0.215	47.4
3.2	8.3	56	0.057	0.651	0.699	1.350	1.072	25.9
1.5	11.8	66	0.017	1.121	1.300	2.421	2.142	13.0
0 (mouth)	16.7	79	0.012	1.720	1.450	3.170	3.030	4.6
1988–1989. Duration of the winter period – 183 days								
4.6	3.7	66	0.139	0.352	0.110	0.462	0.318	45.3
3.2	8.3	74	0.042	0.919	0.542	1.461	1.151	26.9
1.5	11.8	78	0.023	0.938	1.082	2.020	1.760	14.8
0 (mouth)	16.7	94	0.016	1.776	1.124	2.900	2.781	4.3

terms of the theory of cryogenic metamorphization of chemical composition of the freezing waters [22].

Ice floods usually start 10–20 days before the beginning of the thawing of aufeis and snow when the injection reservoirs cease to freeze through. On the other hand, this process can also occur in the latter half of winter if pressure in the reservoirs reaches critical (destroying the frozen overlying layer) values. Such floods in such a period, spreading on the ice surface, are indicated as an unusually intense formation of aufeis. As a rule, it does not spread over significant distances.
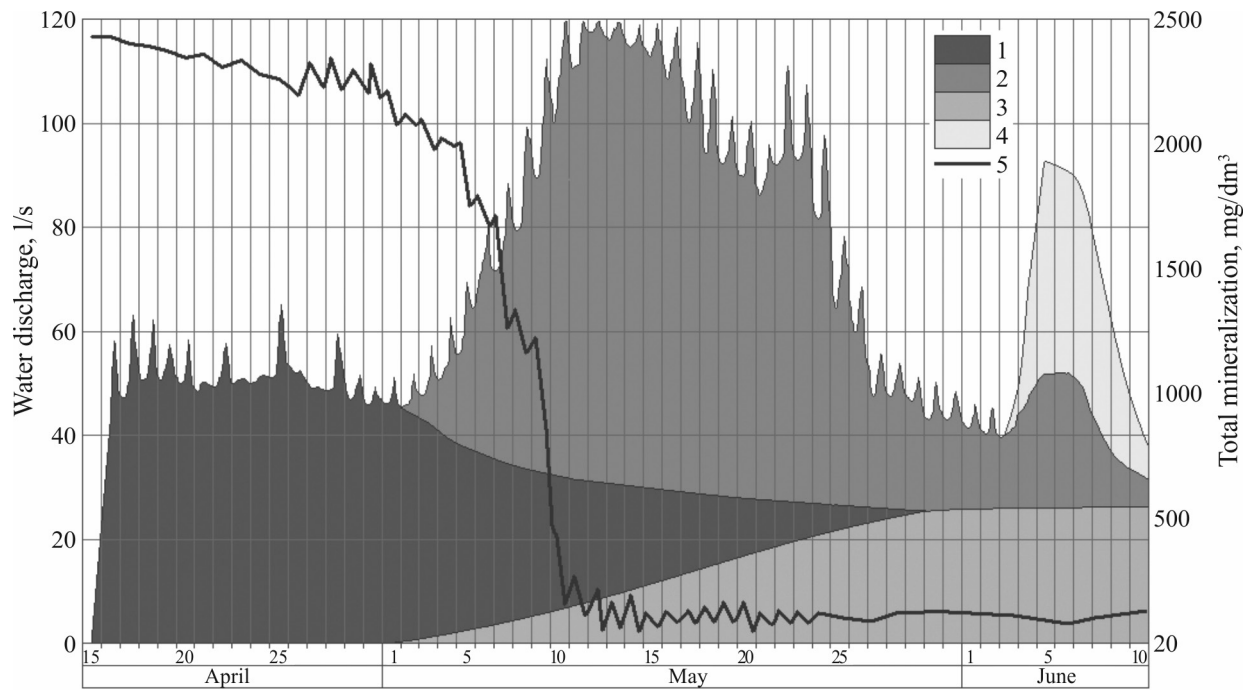
Fig. 5. Components of the Shamanka river runoff for the spring period of 1990.
River runoff: *1* – from subsurface injection reservoirs, *2* – from the thawing of aufeis, ground ice and snow, *3* – anticipated ground runoff, *4* – rainfall runoff. *5* – total mineralization.

At the end of winter, the runoff in the river starts with ice floods. The water discharges at that period are by a factor of 2–3 than the runoff of melt snow water and aufeis water starting later. However, the proportion of the volume of their runoff in the total spring runoff can vary from 35 to 50%. The hydrograph of the runoff of the waters liberated from the injection reservoirs and of the other components of the river runoff at the spring period is shown in Fig. 5.

CONCLUSIONS

A small river basin in the winter period is represented as a unified system, and the water exchange processes in each of its parts are closely interrelated. As a result of such an interrelationship and under the influence of the seasonal cryogenesis, the activity of water exchange increases, and the formation of the river runoff involves subsurface water volumes which, under different conditions, would not be drained by the water in this basin.

There remains an open question as to what the ultimate size of the basin must be in the case where the subsurface waters cease to be a unified hydraulically coupled system and where the water exchange processes in the upstream part of the basin lose their connection with such processes in stretches close to the outlet section. It is likely that the criterion for determining such a size is the fact of cessation of the infrabed runoff and through-freezing of the river, because the emergence and spread of additional water pressure is only possible provided that the front of seasonal freezing penetrates into it.

REFERENCES

1. Sokolov, B.L. and Chernaya, F.F., Assessing Annual Losses of the Winter Runoff Due to the Formation of River water Aufeis and River Ice (Exemplified by the Rivers of the North-East of the USSR), *Tr. GGI*, 1984, issue 300, pp. 50–61 [in Russian].

2. Kravchenko, V.V., The Role of Aufeis in the Formation of the Winter River Runoff and Ice Cover of the Rivers in the Western Part of BAM, *Tr. GGI*, 1986, issue 312, pp. 34–83 [in Russian].

3. Kolotaev, V.N., Water Exchange of Rivers and Basins of Subsurface Waters in Permafrost Regions, *Proc. V All-Union Hydrological Congress (October 21–24, 1986, Leningrad)*, Leningrad: Gidrometeoizdat, 1988, pp. 379–386 [in Russian].

4. Kolotaev, V.N., Change in the Interaction of the River and Subsurface Waters During a Low-Water Period Along the Length of Rivers in Conditions of Discontinuous Permafrost (Exemplified by the Central Area of the BAM Zone), *Tr. GGI*, 1988, issue 335, pp. 126–140 [in Russian].

5. Markov, M.L., Vasilenko, N.G. and Gurevich, E.V., *Aufeis of the BAM Zone: Expedition-Based Investigations*, St. Petersburg: Nesto-Istoriya, 2017 [in Russian].

6. Korotky, A.M., Korobov, V.V. and Skrylnik, G.P., Icings in the River Basins of Primorski Krai and Their Influence on Landscapes, *Geogr. Nat. Resour.*, vol. 31, issue 4, pp 377–384.

7. Tarbeeva, A.M., Krylenko, I.V. and Surkov, V.V., Icings on Small Streams Within the Protva River Basin (Kaluga Oblast) and Their Influence on Channel Processes, *Geogr. Prir. Resur.*, 2011, no. 4, pp. 75–78 [in Russian].

8. Vtyurin, B.I., *Ground Ice of the USSR*, Moscow: Nauka, 1975 [in Russian].

9. Alekseev, V.R., *Aufeis*, Novosibirsk: Nauka, 1987 [in Russian].

10. Kane, D.L., Physical Mechanics of Aufeis Growth, *Can. J. Civ. Eng.*, 1981, vol. 8, no. 2, pp. 186–195.

11. Ryan, W.L., *Cold Regions Hydrology and Hydraulics* (Technical Council on Cold Regions Engineering Monograph), R.D. Crissman, Ed., New York: ASCE, 1990.

12. Woo, M.-K., *Permafrost Hydrology*, Berlin; Heidelberg: Springer-Verlag, 2012. .

13. Markov, M.L., Dissipative Structures of the Permafrost Zone Rivers, *Geogr. Prir. Resur.*, 1991, no. 3, pp. 11–20 [in Russian].

14. Markov, M.L., The Role of Cryogenic Barrage in the Formation of the River Runoff in Permafrost Regions, *Meteorol. Gidrol.*, 1994, no. 2, pp. 98–104 [in Russian].

15. Kolotaev, V.N., Markov, M.L. and Sokolov, B.L., Assessing the Measurement Accuracy of Morphometric Characteristics of Aufeis, *Tr. GGI*, 1987, issue 314, pp. 90–114 [in Russian].

16. Chizhov, A.N. and Kravchenko, V.V., Some Issues Related to Observations of the Elements of the Winter Regime of Rivers of Eastern Siberia and the Far East, *Tr. GGI*, 1985, issue 309, pp. 66–76 [in Russian].

17. Chizhov, A.N. and Borodulin, V.V., The Role of Aufeis Phenomena in the Formation of River Ice Cover, *Tr. GGI*, 1980, issue 270, pp. 56–77 [in Russian].

18. Kravchenko, V.V., Field Investigations of the Formation Process of River Aufeis, in *Glaciological Research in Siberia*, V.V. Vorobyev, Ed., Irkutsk: IG, 1985, pp. 38–63 [in Russian].

19. Everdingen, R.O., van, Frost Blisters of the Bear Rock Spring Area Near Fort Norman, N. W. T., Arctic, 1982, vol. 35, no. 2, pp. 243–265.

20. Kravchenko, V.V. and Gizetdinov, A.M., Calculations of the Winter Runoff of the Rivers in the Permafrost Zone on the Basis of Reconstructing Its Hydrograph, *Tr. GGI*, 1991, issue 355, pp. 41–60 [in Russian].

21. Yoshikawa, K., Hinzman, L.D. and Kane, D.L., Spring and Aufeis (Icing) Hydrology in Brooks Range, Alaska, *J. Geophys. Res.*, *Biogeo.*, vol. 112, issue G4, G04S43.

22. Ivanov, A.V., *Cryogenic Metamorphization of the Chemical Composition of Natural Ice and Freezing and Melt Water*, Khabarovsk: Dal'nauka, 1998 [in Russian].