THERMAL REGIME OF NORTHERN RIVERS AND ITS RELATION TO THE DEVELOPMENT OF TALIKS

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ABSTRACT

Flood-plain taliks occupy vast areas, many times wider than rivers. In spite of century-long history of research, their existence was not thermophysically substantiated. On the other hand, conventional models of river thermal regime in application to northern watercourses often result in sharp discrepancies with reality.

Both problems are due to previously unaccounted for two-way water exchange between river and adjacent permeable massif accompanied by heat transfer. Incorporating this process into the general model of river thermal regime, simple analytic solutions are deduced which easily eliminate contradictions intrinsic to the previous ones. Lateral heat exchange with surrounding grounds decreases water temperature and thus relatively cool river water is indicative (all other factors being equal) of more intensive heating of the adjacent flood-plain massif and extensiveness of the thawed zone. Very high alluvium permeability promoting this process is due to the existence of preferential pathways for water movement - a phenomenon known in many branches of Earth sciences.

Field research conducted on the Kolyma River and on the watercourse of forth order Kontaktovy Creek fully confirmed developing concepts and made it possible to obtain the first evaluations of water and heat exchange characteristics. It seems evident, that wide spreading of flood-plain taliks in the mountainous areas of the North-eastern Russia suggests an equally wide occurrence of lateral water and heat exchange in river valleys.

INTRODUCTION

Investigations of taliks in river valleys constitute one of the traditional and profound problems of geocryology. In northern regions economical activities are concentrated in river valleys. They are and will be in the future subjected to the greatest anthropogenic pressure. Especially important in this connection are flood-plain taliks with azonal ecosystems developing on them. They stand out with the most contrast in the Northeastern Russia where typical vegetation of the flat interfluves is sparse suppressed larch (such landscapes are often called a specific name 'tundra-forests'), while on the flood-plain taliks multitied mixed forests flourish. According to the evaluations made in the Institute of Biological Problems of the North, Magadan, river valleys occupying 7 percent of the region's territory yield about half of its yearly wood growth (A.V.Andreyev, personal communication, 1983). Undoubtedly, this amount is provided mainly by flood-plain taliks.

In spite of age-long investigations, the formation of flood-plain taliks has not been consistently considered from the thermophysical point of view. But without clear understanding of mechanisms and processes sustaining those vast ground massives in the thawed state, reliable geocryological and ecological prognosis in river valleys is hardly possible.

THEORY

For geocryologists, it seems evident that floodplain taliks owe their existence to rivers. But this notion comes into conflict with conventional models of river thermal regime. Up to the most recent works, the amount of heat transfer from rivers into surrounding grounds is believed to be a minor quantity. It is not even calculated, but specified in tables, with maximum value as small as 27 W/m^2. (e.g.Donchenko, 1987). Being distributed over the whole talik's surface (which can be by order and more greater than that of the river), it yields a negligibly small heat influx. It is as if flood-plain taliks existed independently from rivers, and in the latter heat exchange was confined essentially to water surface.

However, on close examination certain doubts arise in the all-inclusive adequacy of conventional models for river temperature regime. Sometimes they lead to curious contradictions. For example, in the Kolyma River, the highest summer temperatures are observed at the polar city Srednekolymsk. Near Seymchan, almost 5 degrees of latitude to the south, the river is cooler by 1.5 - 2^0 C, though the climate there is the warmest over the whole river basin. At that, flood-plain taliks are absent in the first of those places but well developed in the latter one - as well as in the valleys of many other, still more cold rivers. Notably, only near the Arctic coast does the Kolyma River cool to the same temperatures as in the Seymchan vicinity.

Such examples are numerous. But most revealing are the heat balance estimates made for the watershed of IV order Kontaktovy Creek. Using conventional schemes, they resulted in very large unconformities indicative of some unaccounted for heat flux with peculiar properties. In spite of all assumptions aiming consistently at underestimating its absolute value, it averaged at sunny noon about - 500 W/m^2, being invariably positive before dawn. Simple logical reasoning incontrovertibly points at the adjacent permeable massif as the only 'reservoir' capable of receiving from river the great amounts of heat and then partly returning it. And hence, the only possible mechanism of heat transfer is lateral water exchange (Mikhailov, 1993).

This process is due to a combination of geological and geomorphological factors which cause the directions of river channel and groundwater flow to diverge (one of the obvious examples is shortcutting by the latter of river bends). As a result, inseepage of water into the alluvium and backward exseepage into the river channel may simultaneously take place in each cross-section, and each elementary volume of water can repeatedly migrate back and forth from channel flow to underground one. At high permeability of alluvial deposits this mass exchange reaches high intensity and leads to significant heat exchange between a river and adjacent flood-plain massif.

Regarding daily values of heat balance of the river surface, an absorbed short-wave radiation is its major positive component. It undergoes little changes over vast areas and averages in the North-eastern Russia during the summer about 200 W/m^2. To give away large amounts of energy by latent and sensible heat transfer and long-wave emissivity, water should be sufficiently warmer than air, while for most of the rivers, the relation is opposite. Another matter is lateral heat transfer operating at comparatively low temperatures. And the more energy goes with it, the lower the river temperature becomes and the lesser the heat flux into air, so that the latter often changes its sign and becomes an income part of heat balance. In other words, relatively cool river water is indicative (all other conditions being equal) of more intensive heating of the adjacent grounds. This is a clue to the contradiction with the Kolyma River. Due to the absence of flood-plain talik in the vicinity of Srednekolymsk, the river there has an opportunity for heating to higher temperature than in southern latitudes with a warmer climate. The closest interrelation between thermal regimes of rivers and flood-plain massives becomes obvious.

The extended scheme of heat exchange leads to the more general model of river thermal regime. For the river site within which the discharges of ex- and inseepage related to the unit water surface area (ω^+ and ω^- correspondingly) remain constant, analytic steady state solutions are easily derived. In the partial case of equilibrium water exchange ($\omega^+ = \omega^-$) they are readily correlated with the conventional formulae having a similar form:

$$T = T_0 + (T_e - T_0)\,[1 - \exp(-Kx / CVh)] \tag{1}$$

$$T_e = q_0 / K \tag{2}$$

$$K = K' + C\omega^+ k_T \tag{3}$$

where T_0 is river temperature in the initial cross-section; T_e - equilibrium temperature (at zero heat exchange of a river with its surroundings); C - volumetric heat capacity of water; V and h - mean values of correspondingly river velocity and depth; x - distance; q_0 - resultant heat exchange at zero water temperature; K' - combined surface heat exchange coefficient; k_T - mean coefficient of heat transfer from seeping water to the ground.

The sole difference here is that previously in (1) and (2) the coefficient K' was used instead of K (e.g., Gosink, 1986), though resulting from this, both equilibrium temperature and the rate of actual temperature's approach to it may change greatly.

Formulae (1) and (2) contain now the quantity ω^+ which is strongly dependent upon the groundwater flow velocity and therefore upon valley inclination. But to the latter the river velocity is also closely related. Implicit connection between river temperature and its hydrological characteristics also becomes obvious.

Construction of this model required introducing three new quantities. Of those, the water exchange characteristics in small rivers can be easily determined with a slightly modified tracer method sometimes used for stream discharge measurements (e.g., Karasyov and Shumkov, 1985). Obviously, at well developed water exchange this method in its direct purpose gives somewhat distorted results due to partial replacement of tracer containing river water with tracer free exseeping one. This effect may be put to use for our purposes. Solution to differential equation of tracer balance leads to the expression:

$$\frac{\omega^{+}}{\omega} = ln\frac{\Omega}{\Omega_t} : ln\frac{\Omega_0}{\Omega} + 1 \tag{4}$$

or, in the case of equilibrium water exchange,

$$\omega^{+} = \omega^{-} = \frac{\Omega_0 ln(\Omega_t / \Omega)}{Bx} \tag{4,a}$$

where ω is the resultant of water exchange; Ω_0, Ω and Ω_t - river discharges: accordingly in the initial and closing cross-sections and calculated with the tracer method; B - mean river width. Estimating ω on the basis of routine hydrometric measurements, we obtain all characteristics of water exchange.

Independent determination of the heat transfer coefficient is also theoretically possible, but it requires a knowledge of too many quantities of different natures (among them, three-dimensional field of ground water velocities and heat exchange conditions on the flood-plain surface). Such an approach can hardly yield an acceptable accuracy. Another way is solving a reverse task basing on detailed heat balance measurements and regarding k_T in (1)-(3) as an unknown quantity. This approach, though cumbersome and essentially limited, seems the only feasible one for the time being.

CASE STUDIES

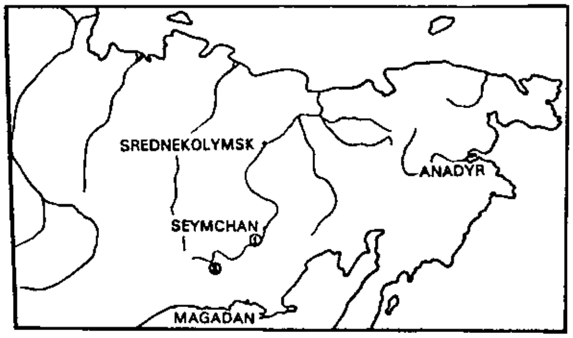

Fig. 1. Map of locations of the experimental sites
1 - Kolyma site; 2 - Kontaktovy site.

Field research was conducted on two sites in the Kolyma River basin (fig. 1). The first of them is located on the river itself in its middle reaches (fig. 2), another one - on the watercourse of IV order Kontaktovy Creek (fig. 3). Both lie within the area of continuous permafrost (mainly 100 to 200 m thick) and are placed on the surfaces of flood-plain taliks approximately by order wider than corresponding watercourses. Another common feature of both sites is coarse grained alluvial grounds underlying them.

In the Kontaktovy site, about 500 m in length, three different portions are clearly distinguished (fig. 4). In the upper one, the talik's cross-section strongly decreases downstream, so that at its end, stream discharges are the largest over the whole creek. Further downstream, the talik widens and rates of flow diminish: smoothly in the middle portion and more sharply in the lower one. The existence of a two-way water exchange there is most clearly demonstrated by the water isotherms at the profile No.21 testifying to the exseepage of ground water with different temperature.

Numerical values of water exchange characteristics determined with the above described method (see the table) also confirm the two-way nature of this process in two lower portions while in the upper one, only a forcing out of water from underground flow into the river channel takes place. Notably, in the middle portion, superficially detectable effects of water exchange are virtually absent, though the values of ω^{+} and ω^{-} are as large as accordingly 1.5 x 10^{5} and 7.5×10^{-5} m/s.

In this portion comprehensive heat balance measurements were conducted. During the low water period in July, heat transfer from stream channel to talik in the day time was up to 2000 Wt per sq. meter of water surface and at nights averaged almost 700 W/m^2. So large values are due to the general water loss to talik in this site. Heat transfer coefficient in the second half of July approximated 0.08 gradually decreasing with time - probably owing to the warming of the creek valley grounds.

Table. Water exchange characteristics in the different portions of Kontaktovy Creek, mid-August 1993

Portion	Stream discharge, l/s			Water exchange characteristics $\times 10^{-5}$, m/s		
	inlet cross-section	outlet cross-section				
		with standard technique	with tracer technique	ω^+	ω^-	ω
upper	101	128	128	5.9	0	5.9
middle	130	86	144	1.5	7.5	-6.0
lower	86	44	205	6.1	10.8	-4.7

Fig. 2. Aerial view of the Kolyma River valley in the vicinity of experimental site (in the frame).

On large rivers the execution of equally complete observations is very difficult - mainly because application of the tracer method in its traditional form would require too large amounts of salt. At present time, it is only possible to demonstrate indirectly the existence of prerequisites for water exchange. It can be done by means of estimating the effective hydraulic conductivity of alluvium based on the well known Boussinesq's equation tying together spatial and temporal changes in ground water levels.

Measurements were made on a dense observation network (approximately 4 boreholes per sq.km) in the Kolyma site located inside the river bend with a radius about 1.5 km (fig. 5). The isolines of ground water levels in opposite phases of rapid rise and decline show that ground water moves straight along the general valley inclination, enduring little if any influence from the river bend. Estimations of the alluvium's effective permeability yielded values between 200 and 300 m/h. Reference data for grounds of similar granulation do not exceed 20 m/h. The cause of this drastic disagreement may be only that the water movement in our case occurres mainly along the preferential pathways - a phenomenon well known in different branches of Earth sciences (Aravin and Nosova, 1969; Ormsbee and Khan, 1989 and others). Apparently, these pathways contain only skeleton particles with little or no filling material.

The most spectacular evidence for this during our research in Kolyma River valley was the finding of large ephemeral larvae in the borehole located 400 m from the nearest river bank. It occurred less than two months after the borehole was made, so the larvae could not penetrate it any other way than with groundwater flow; this also gives an insight into the minimal size of apertures along the preferential pathways.

Our results testify that the conditions for the intensive water exchange can be present in the valleys of large rivers. Though accurate estimates of accompanying heat transfer are as yet impossible, a very conservative evaluation made for the Kolyma site vicinity amounts (over three summer months) to 150 MJ per sq.meter of talik's surface. According to A.V. Pavlov (1984), the heating of the grounds from the soil surface in two typical forest landscapes in Central Yakutiya is 60 and 80 MJ/m^2 over five warm months.

The importance for the flood-plains of heat exchange with rivers is clear from the comparison of these magnitudes. In all probability, the wide spreading of flood-plain taliks in the North-eastern Russia suggests an equally wide occurrence of lateral water and heat exchange in river valleys.

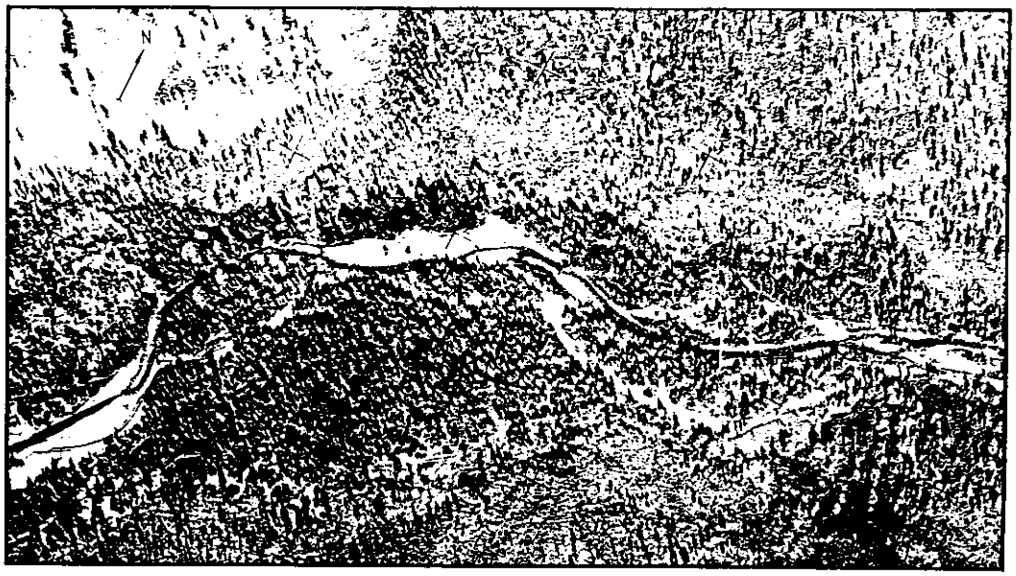

Fig. 3. Aerial view of the Kontaktovy Creek experimental site.

CONCLUSION

In the valleys of rivers in mountainous areas, the conditions often build up for sustaining the pathways with heightened water conductance in alluvial deposits. Through these preferential pathways, an intensive water exchange develops between rivers and ground waters of their flood-plains. It entails a powerful and strongly varying with time (subjected to diurnal and seasonal changes) heat exchange between rivers and flood-plain massives. In the permafrost area it causes the existence of vast thawed zones - flood-plain taliks.

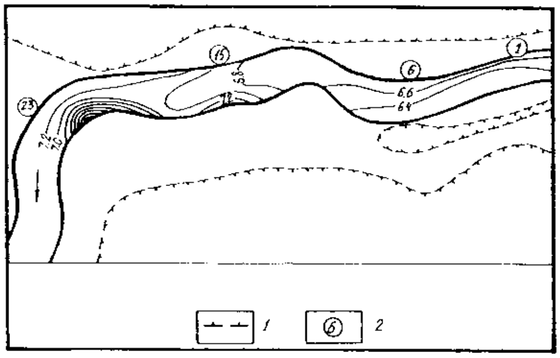

Fig. 4. Isolines of water temperature (centigrades) in the Kontaktovy Creek at solar noon, 17.07.1993 (stream width exaggerated 10 times).
1 - lateral borders of talik; 2 - numbers of profiles.

With well developed heat exchange, conventional models of river thermal regime should be replaced by more general and complex ones. First of all, this concerns the prognoses of temperature conditions and ice phenomena downstream from river dams. Some principal corrections can already be made on the basis of the results obtained.

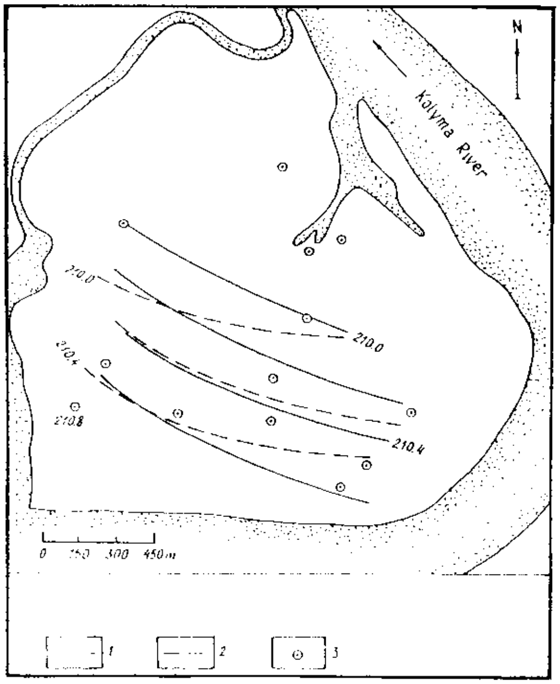

Fig. 5. Isolines of ground water levels (msl) in the Kolyma experimental site
1 - at 2 a.m. 9.06.1992 (decline); 2 - at 10 a.m. 10.06.1992 (rise); 3 - boreholes.

But the problem as a whole is far more complicated. That the flood-plain taliks existence depends upon maintanance of preferential pathways for water movement, makes them potentially sensitive to changes not only of river temperature, but of hydrological regime as well. Elucidation of corresponding criteria requires systematic and complex research. Only thus can a solid basis be made for geocryo-logical and ecological prognosis in river valleys.

ACKNOWLEDGMENTS

This study was conducted in the course of preparing my Candidate of Sc. dissertation. I feel deep gratitude to my advisor Dr. G.Z.Perlshtein. I am also indebted to my colleague T.V.Bantsekina for her help during the field research and data processing.

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