

River icings and fluvial activity in extreme continental climate: Khangai Mountains, Mongolia

WOJCIECH FROELICH AND JANUARY SZUPIK

*Department of Geomorphology and Hydrology, Institute of Geography and Spatial Organization, Polish Academy of Sciences,
św. Jana 22, 31-018 Kraków, Poland*

In the conditions of extreme continental climate prevailing in the Khangai Mountains, icings perform an important hydrological and geomorphological function. Despite a lower water discharge, water stages are higher during the melt period than during the summer season, because the main channel is filled with ice. This causes fluvial activity on the flood plain during the melt period. Reserve channels, being deepened annually, may gradually take over the function of the main river channel. Beside shifting, avulsion is the second process through which river channels are transformed under these climatic conditions. In the mountain segment of the Tsagan-Turutuin-Gol River, intensive lateral erosion can be observed locally, caused by the growth of spring-time icings. Meltwaters are the main source of soil moisture, maintaining rich grass land on the flood plain.

En climat hypercontinental comme dans la région des monts Khangai les tarines jouent un rôle important en géomorphologie et en hydrologie. Malgré des débits plus faibles les niveaux d'eau sont plus élevés pendant la période de fonte que pendant l'été parce que le chenal principal est plein de glace. Il en résulte une activité fluviale dans la plaine alluviale pendant la période de la fonte. Les chenaux secondaires qui se creusent chaque année peuvent progressivement remplacer le chenal principal. En plus de cette instabilité, les avulsions constituent un deuxième processus par lequel les chenaux des cours d'eau sont transformés sous ces climats. Dans la partie montagneuse du cours de la rivière Tsagan-Turutuin-Gol on peut observer localement une intense érosion latérale attribuable aux élévations du niveau d'eau causées par les tarines printanières. Les eaux de fonte constituent la principale source d'humidité des riches herbages de la plaine alluviale.

Proc. 4th Can. Permafrost Conf. (1982)

Study Area

Investigations were carried out on the southern slope of the Khangai Mountains, in the basin of the Tsagan-Turutuin-Gol River (lat. 47°N, long. 100°E). The river segment under study is about 40 km long and lies between 1960 and 2100 m above sea level (Figure 1). In this segment, the catchment area increases from about 1100 to 2100 km² and the channel changes its character (Klimek *et al.* 1976). In the mountains, the channel is cut in granitic rock. A flat valley bottom, several hundred metres wide, is covered with coarse fluvioglacial gravels. Water flows down the main channel; reserve channels, situated higher, are filled with organic matter (Froehlich and Sugar 1975). At the end of the mountain segment the river channel is cut in the coarse sediments of a fluvioglacial fan and resembles a braided river for several kilometres. Downstream from the fan, in the bottom of the mountainous basin of Bayan-Nuurin-Khotnor, the river winds through sandy-silty deposits of fluvial and limnic origin (Rotnicki and Babiński 1977). The river banks show evidence of intensive thermal erosion (Klimek 1975; Froehlich *et al.* 1977).

The low-water discharge of the Tsagan-Turutuin-Gol is about 1 m³/s, and the high-water discharge may reach 100 m³/s (Froehlich *et al.* 1975). Maxi-

mum turbidity during the summer floods occurs simultaneously with the peak discharge (Froehlich and Sugar 1975). The sediment transport in the channel is derived almost exclusively from the channel itself, not from the slopes.

The granitic walls in the mountain segment show fresh scars of lateral erosion in the form of niches reaching above the water level of the summer inundation. In the Bayan-Nuurin-Khotnor basin the flood plain is cut by reserve channels that resemble cut-off meanders. They show fresh evidence of headward and lateral erosion, even though they are only occasionally filled with water during summer floods. The channel pattern resembles a braided river in one river segment and a winding channel with cut-off meanders in another. It is known from the literature (Alekseyev and Savko 1975; Hopkins *et al.* 1955) that the areas covered with icings in winter have a similar appearance. The authors have studied the Tsagan-Turutuin-Gol valley floor during the transition from winter into spring, when the icings start melting and meltwater provides most of the runoff.

Climatic Conditions for the Occurrence of Icings

In the catchment basin of the Tsagan-Turutuin-Gol icings are very common (Froehlich and Szupik

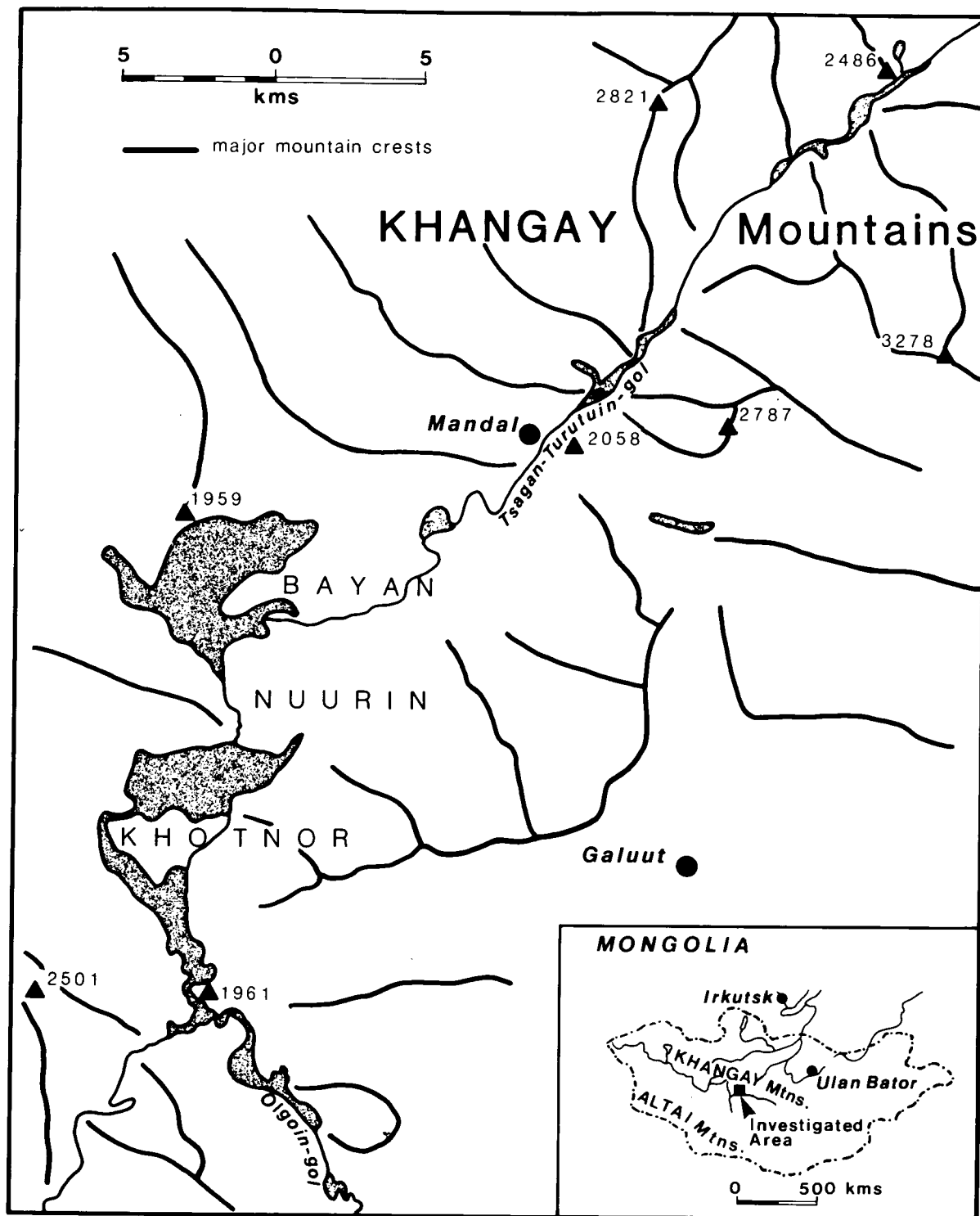


FIGURE 1. The study area. The shaded areas indicate icings within the Tsagan-Turutuin-Gol valley in April 1976.



FIGURE 2. An icing in the mountain part of the Tsagan-Turutuin-Gol valley bottom.

1977; Longid 1962). Their formation is favoured by the extreme continental climate. The temperature regime and the temporal distribution of precipitation make it possible to distinguish two seasons of quite different character: First, a short summer lasting from the beginning of June to mid-September, with 80 to 90 per cent of the annual precipitation; and secondly, a long winter lasting from October to April; the transition periods during spring and autumn are very short. In Galuut (see Figure 1) the freezing period lasts from October 2 to April 20, on the average (Gavrilova 1973). The mean temperature for July is 17°C and that for January, -29°C . In the ten-year period from 1960 to 1969, the annual average precipitation was 226.1 mm and the annual average air temperature was -5.9°C .

Permafrost occurs discontinuously. Seasonal thaw reaches depths of between 1.5 and 4.0 m, whereas seasonal frost may reach depths of between 3.3 and 5.0 m (Gravis 1974). The climatic conditions favour growth rather than degradation of permafrost. River runoff is limited to a few months (Kuznetsov 1968). During more than half the year base flow accumulates in icings.

Distribution of Icings

In the winter of 1976, icings covered an area of about 40 km^2 in the Tsagan-Turutuin-Gol valley and contained about $1.8 \times 10^7\text{ m}^3$ of water (Froehlich and Słupik 1977). That is approximately the volume of groundwater discharge and is equivalent to a discharge rate of $1.1\text{ m}^3/\text{s}$ during six months or $1.4\text{ m}^3/\text{s}$ during five months.

In the mountain segment of the valley, icings are formed downstream from large springs discharging from a subpermafrost aquifer. The icings fill the valley bottom and merge with the river ice (Figure 2). Icing blisters were observed near the spring outlets (Froehlich and Słupik 1978). The individual icings are separated by river segments frozen to the bottom during the low-water stage.

At the end of the mountain segment, the river discharge decreases for a few kilometres, as water is lost into fluvioglacial gravels. The river freezes to the bottom here during low-water stages (Figure 3). Extensive icings are found in the central part of the Bayan-Nuurin-Khotnor basin, which is filled with sandy-silty fluvial and limnic deposits (Figure 4). These are typical river icings fed by discharge of subpermafrost water. Some water flows from the tributary valleys, as evidenced by icing blisters (van Everdingen 1978), here called winter pingos (Froehlich and Słupik 1978).

The thickness of the icings varies. The maximum thickness of 4 m was observed within the main river channel. The thickness decreased with distance from the main channel and with elevation of the flood plain.

Melting of Icings

Melting of the icings begins before the end of the winter. In early April 1976, negative air temperatures were being recorded during the day. Soil surface temperatures fell to -11°C at night but they rose to above 19°C during the day (Froehlich *et al.* 1977). The absence of a snow cover favoured heating of the ground surface during sunny weather.

In the mountainous river segment, the icings around large springs were the quickest to melt; in the basin of Bayan-Nuurin-Khotnor the ice disappeared first at points where groundwater discharges into the river channel (Figure 5). In both cases, melting resulted from the thermal action of the flowing water, a phenomenon known from Siberia (e.g. Sokolov 1975) and North America (e.g. Williams and van Everdingen 1973). Flowing down the river, the water melts corridors beneath the ice (Figure 6) and brings about the collapse of the ice cover (Figure 7). This melting process lasts for several weeks and is one of two ways in which icings disappear.

The other way is through lateral melting. The thinnest portions of the icings are the quickest to disappear. They are found as a rule at the greatest distance from the main channel.

Of necessity the meltwater flows down reserve channels (Figure 8), because the main channel is still filled with ice. In this way, a relatively small volume of meltwater generates water stages that are higher than those recorded during summer floods. The discharge rate gradually increases as the melting of the icings accelerates. At the same time the water stage falls because lower and large reserve channels and finally the main channel, become ice-free and start carrying runoff.

Most of the river ice is anchored to the bottom of the channel and melts *in situ* (Figure 9). Thus, no ice movement is observed. As a result, the regression of the spring runoff is slow and the lowest discharges are recorded in autumn (Kuznetsov 1968). During spring and early summer, additional discharge is supplied by melting icings (Froehlich *et al.* 1975).

The lateral disappearance of the icings speeds up thawing of the ground in the flood plain, facilitates saturation of the soil with water, and creates favourable conditions for early growth of grass. In spring the lush green of the flood plain contrasts with the surrounding drier areas and provides rich grass land.

In the mountain segment, the first phase of melting of icings only occurs in well-insolated places. Meltwater flows over the icings, freezing in shaded places and during the night when temperatures fall. In the shade of solid-rock walls, the thickness of the ice was found to exceed 3 m (Figure 10). In this way, growth of icing may occur without discharge of groundwater. Icings formed in this way are known as spring-time icings (Romanovski 1974).

Fluvial Activity during the Melting of Icings

The development of river channels and of flood plains is asynchronous in areas where icings occur.



FIGURE 3. The channel of the Tsagan-Turutuin-Gol River, frozen at a low-water stage where it crosses a fluvio-glacial fan.



FIGURE 4. Icing covering the flood plain of the Tsagan-Turutuin-Gol valley bottom within the Bayan-Nuurin-Khotnor basin. The basin is built of sandy-silty deposits.

During high-water stages in summer, fluvial activity is concentrated in the main channel, which carries nearly the entire water flow. In the melt period, channel development occurs mainly on the flood plains. Water flows down peripheral channels while the main channel is still filled with ice. When the icings have melted, the discharge is too low to affect the morphology of the main channel.

The lateral melting of icings is linked to the flow of meltwater down the peripheral channels, often situated several hundred metres from the main channel (Figure 11). These are either undeveloped

new channels or older ones, rejuvenated during the melt period. The channels are erosional in character. Some are connected with lower channels at right angles, following the direction of outflow of meltwater (see Figures 8 and 11). As the icings melt, water covers progressively lower levels of the flood plain. The outflow of water into lower channels often involves waterfalls that may reach a height of 0.5 m. This is a zone of strong headward erosion (see Figure 11). The steps of the waterfalls, built of frozen sandy-silty material, are destroyed by a combination of thermal and mechanical erosion.



FIGURE 5. The Tsagan-Turutuin-Gol River segment within the northern part of the Bayan-Nuurin-Khotnor basin fed by discharge from a groundwater aquifer.



FIGURE 6. Melting of the icing under the influence of water flowing beneath the ice has created an ice funnel down the main channel of the Tsagan-Turutuin-Gol River.



FIGURE 7. Icing collapsed under the influence of flowing water.



FIGURE 8. The peripheral channels and the zone of small waterfalls between the higher and lower reserve channels.



FIGURE 9. The ice anchored to the channel bottom of the Tsagan-Turutuin-Gol River melts *in situ* which creates mushroom-shaped forms. The main meltwater stream flows between the river bank and the melting ice.



FIGURE 10. Spring-time icings grow in the shade of granitic river banks in the mountain segment of the Tsagan-Turutuin-Gol River. Such spring-time icings play an important role in the erosion of granitic banks.

facing river banks. Runoff is concentrated between the river bank and the ice anchored on the channel bottom (see Figure 9). Lateral erosion, both thermal and mechanical, washes out fine-grained loose material (Froehlich and Słupik 1977). The water flowing on the ice surface transports bed material even at low velocities; the material may actually glide over the ice. The material can eventually be deposited on the ice surface (Figure 12). The presence of a thin layer of deposited material accelerates the melting of the ice, while a thick layer helps to preserve the ice. As a result, blocks of buried ice melt very slowly, leaving depressions in the channel bottom. The channel profile down the Tsagan-Turutuin-Gol River, as observed in summer, is sometimes inconsistent with the distribution of water velocity. It resembles the profile charac-

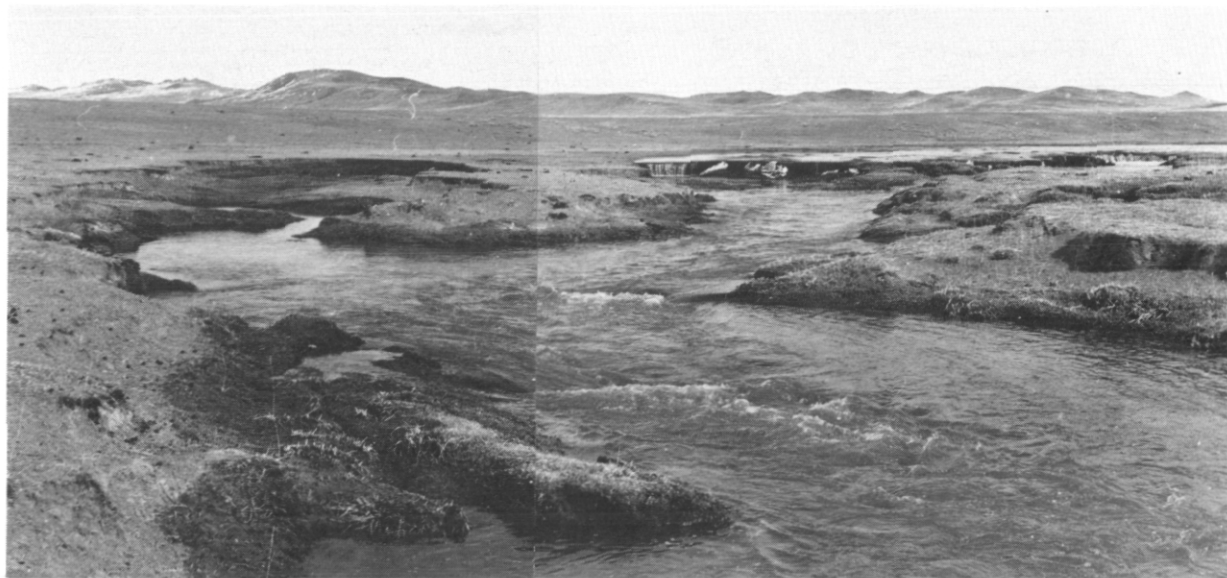


FIGURE 11. In two peripheral channels, one abandoned (left) and the other water-filled (right), the effect of headward erosion can be seen.

Silty-clayey material transported in suspension is deposited between the grass-roots or in the shallow overflow. Besides deepening of the reserve channels, aggradation of parts of the valley bottom can be observed. The meltwater runoff causes shifting and changes in the geometry of the winding river channels. The peripheral channels, deepened from year to year, may gradually become the main channel.

Besides shifting, avulsion is the second process of channel transformation under these climatic conditions. As melting progresses, the ice in the main channel begins to melt, starting from the south-



FIGURE 12. Suspended material is deposited on the ice anchored on the channel bottom.

teristic of braided streams (Brown and Péwé 1973). The process described promotes a winding course of the river.

Whereas water from melting icings is the main morphogenic agent in the Bayan-Nuurin-Khotnor basin, spring-time icings play an important role in the mountain segment of the Tsagan-Turutuín-Gol. They grow in the shade of high solid-rock banks (see Figure 10). During the diurnal freeze-thaw process, ice attacks granitic rock walls and deep niches are formed through granular disintegration and rock-fall. This process leads to widening of the valley bottom. The fresh scars of lateral erosion at 2 to 3 m above the summer flood level may surprise the casual observer in summer but they seem difficult to explain otherwise.

Conclusions

In the extreme continental climate prevailing in the Khangai Mountains, icings perform an important hydrological and geomorphological function. High-water stages during early spring result from a relatively small volume of discharge. This is caused by melting along the edges of the icings. As a result of this, the flood plain is irrigated. Additional pasture could possibly be obtained in continental climates by imitating this natural irrigation method. The *in situ* melting of icings prolongs river runoff, thus increasing water resources available during the summer.

Development of the flood plain occurs during the melting of the icings. Peripheral channels, being deepened annually, may gradually assume the function of the main channel. Besides channel shifting, avulsion is the second process through which river channels under these climatic conditions are transformed. In the mountain segments of river valleys the valley bottoms tend to be widened by lateral erosion, intensive at places, related to the growth of spring-time icings.

References

- ALEKSEYEV, V.R. AND SAVKO, N.F. 1975. Teoria nalednykh protsessov. Moskva, 204 p.
- BROWN, R.J.E. AND PÉWÉ, T.L. 1973. Distribution of permafrost in North America and its relationship to the environment; a review 1963-1973. In: North Amer. Contrib. Second Int. Conf. Permafrost, Yakutsk. Natl. Acad. Sci., Washington, D.C., pp. 453-458.
- FROELICH, W. AND SZUPIK, J. 1977. Icings in the Tsagan-Turutuín-Gol catchment basin. Bull. Acad. Pol. Sci., vol. 25, pp. 193-201.
- . 1978. Frost mounds as indicators of water transmission zones in the active layer of permafrost during the winter season (Khangay Mts., Mongolia). In: Proc. 3rd Int. Conf. Permafrost, July 1978, Edmonton, Canada, pp. 189-193.
- FROELICH, W., SZUPIK, J., AND BAASAN, T. 1977. The course of morphogenetic processes during the break of winter into spring in the Tsagan-Turutuín-Gol basin. Bull. Acad. Pol. Sci., vol. 25, pp. 173-183.
- FROELICH, W., SZUPIK, J., AND SUGAR, T. 1975. Means of alimentation of the Tsagan-Turutuín-Gol. Bull. Acad. Pol. Sci., vol. 23, pp. 171-176.
- FROELICH, W. AND SUGAR, T. 1975. Sources of rock-waste supply into the Tsagan-Turutuín-Gol channel in the light of suspension transport. Bull. Acad. Pol. Sci., vol. 23, pp. 163-170.
- GAVRILOVA, M.K. 1973. Klimaticheskie (telobalansovye) faktory formirovaniya mnogoletnemerzlykh porod v M.N.R. In: Mezhdunar. Konf. merzlotoved., Yakutsk, pp. 60-64.
- GRAVIS, G.F. 1974. Geograficheskoye rasprostraneniye i moshnost mnogoletnemerzlykh gornykh porod. In: Geokriol. Uslovia M.N.R., Moskva, pp. 30-48.
- HOPKINS, D.M., KARLSTROM, T.N.V., BLACK, R.F., WILLIAMS, J.R., PÉWÉ, T.L., FERNALD, A., AND MULLER, E. 1955. Permafrost and ground water in Alaska. U.S. Geol. Surv. Prof. Paper 264-F, pp. 113-146.
- KLIMEK, K. 1975. Thermal erosion of the Tsagan-Turutuín-River banks in the Khangai Mts. Foreland. Bull. Acad. Pol. Sci., vol. 23, pp. 185-191.
- KLIMEK, K., LOMBORINCHEN, R., STARKEL, L., AND SUGAR, T. 1976. Research problems of the First Mongolian-Polish Physical-Geographic Expedition to the Khangai Mts. in 1974. Geogr. Pol., vol. 33, pp. 107-120.
- KUZNETSOV, N.T. 1968. Vody Tsentralnoy Azii. Moskva. 272 p.
- LONGID, N. 1962. Mnogoletnemerzlye porody v Bayan-khongorskom aymake M.N.R. In: Mnogoletnemerzlye porody i sopostvuyushchie im yavleniya na territorii Yakutskoy ASSR, Moskva, pp. 107-113.
- ROMANOVSKI, N.N. 1974. Nalodzie jako zjawisko peryglacjalne. Czas. Geogr., vol. 45, pp. 473-484.
- ROTNICKI, K. AND BABIŃSKI, Z. 1977. Cryogenic relief in the Bayan-Nuurin-Khotnor Basin. Bull. Acad. Pol. Sci., vol. 25, pp. 141-148.
- SOKOLOV, B.L. 1975. Naledi i rechnoy stok. Leningrad. 190 p.
- VAN EVERDINGEN, R.O. 1978. Frost mounds at Bear Rock, near Fort Norman, Northwest Territories, 1975-1976. Can. J. Earth Sci., vol. 15, pp. 263-276.
- WILLIAMS, J.R. AND VAN EVERDINGEN, R.O. 1973. Groundwater investigations in permafrost regions of North America; a review. In: North Amer. Contrib., 2nd Int. Conf. Permafrost, Yakutsk. Natl. Acad. Sci., Washington, D.C., pp. 435-447.