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Hydrological and geocryological controls on fluvial activity of rivers in cold environments

NIKITA I. TANANAEV
P. I. Mel'nikov Permafrost Institute, 36 Merzlotnaya Str., Yakutsk 677010, Russia
nikita.tananaev@gmail.com

Abstract Permafrost affects the major interactions between the streamflow and the fluvial forms in a cold environment. Alluvial bedforms are subject to frozen ground formation, and 35–75% of the bed surface is affected, depending on channel pattern. Bed mobility is restricted as permafrost is limiting the movement of most mobile dunes, and ice-cored alluvial bars are persistent channel pattern features. Fluvial thermal erosion is driven by stream power, and is more effective in eroding higher riverbanks. Under climate change conditions, increased sediment supply to the streams is assumed to be the major fluvial feedback, and related channel adjustment processes might be considered.
Key words alluvial channels; bank erosion; bed morphology; channel pattern; climate change; permafrost

INTRODUCTION

Observed climate change of the last decades already promotes changes in the thermal state of permafrost and its consequent widespread degradation (Romanovsky *et al*., 2010; Jafarov *et al*., 2012). Along with the recent water cycle intensification in circum-Arctic regions and higher water delivery to the drainage networks of the region (Stocker & Raible, 2005; Déry *et al*., 2009), this puts the hydrological systems in permafrost regions under substantial pressure. The nature and geomorphic patterns of fluvial response to climate shift, however, is still poorly understood and thus require intimate attention (Goudie, 2006; McNamara & Kane, 2009).

The nature of geocryological controls on fluvial activity in periglacial environments is better understood when expressed in terms of a *cryo-conditioning* approach (Berthling & Etzelmüller, 2011). Permafrost, as a key feature of periglacial landscapes, influences the geomorphic action by exerting control both on the processes and on forms. In relation to fluvial systems, permafrost should be taken into account as affecting, yet not totally defining, streamflow and sediment regimes, hence linked to the in-channel flow dynamics, fluvial erosion, transport and deposition, and alluvial morphology.

Water cycle and balance, streamflow and sediment regimes are major focuses of permafrost hydrology, intensively developing its scope and methodology (Woo *et al*., 2008). The close relationship of bank erosion processes to geocryological features of the floodplain is relatively well studied, the major effects being attributed to polygonal ice-wedge structures and thermal interactions between the bank slope and the channel flow (Scott, 1978; Costard *et al*., 2003). The presence of frozen grounds within the channel boundaries is much less acknowledged, since the taliks are believed to dominate the channel floor – a view undermined by recent drilling and ground penetrating radar studies (Delaney *et al*., 1990; Tananaev, 2012). Fluvial activity of rivers in cold environments is therefore highly affected by permafrost presence within most of the geomorphic units within the river valley floor.

The main scope of this paper is to review the hydrological and geocryological controls on the fluvial activity, mostly related to the fluvial regime of the large alluvial Lena River, Central Yakutia, Russia. The potential frozen ground presence in the channel floor is evaluated, based on hydrological data and channel bed topography. The influence of frozen ground on bed morphology is estimated using a dune hierarchy approach (Alekseevskiy, 2004) in terms of dune mobility restriction. Bank erosion rates are linked to the streamflow regime and floodplain structure. Finally, development of a braided channel pattern of the middle Lena River section is considered as a result of complex overlapping impacts, and potential climate change consequences are anticipated.

STUDY AREA

General considerations throughout this paper are applicable to the majority of alluvial rivers in permafrost environments. However, most of the implications here are made concerning the 230-km long middle Lena River section from Yakutsk to the Lena-Aldan confluence (Fig. 1). This part of the river valley is the most inhabited part of Sakha (Yakutia) Republic, the world's largest administrative district.

Fig. 1 Landsat 7 ETM+ (2011) image of the Lena River section; north is to the right, and flow direction is from left to right.

Climate of the region is strongly continental; MAAT is –10.2°C, and averages for January and July are –42.6°C and +18.7°C, respectively. Mean annual precipitation is 254 mm, of which about 30% falls as snow. At Yakutsk, the Lena River drains about 900 000 km^2 of its total 2.49×10^6 km^2 basin. Mean annual discharge for the section is 7140 $m^3 s^{-1}$, with spring peak discharges reaching 55 000 $m^3 s^{-1}$ and winter flow not exceeding 1500 $m^3 s^{-1}$. Valley and channel planform of the river section reflect the transition from the elevated plains of the Lena Plateau to the subsiding Central-Yakutian Lowlands. Valley floor width varies around 15–20 km and narrows locally to 4–5 km, restricted by 120 m high Jurassic sandstone terraces. Braiding belt width is 7–10 km, and the channel itself is 1.5 to 4 km wide at bankfull discharge. The average annual sediment load estimate is 12.54 Mt, with 8.99 Mt being transported in suspension and 3.55 Mt as bedload.

FROZEN GROUND IN ALLUVIAL CHANNELS

Permafrost was present in floodplain deposits of periglacial alluvial rivers since at least the early Holocene, when their valley fill and floor topography were developed to a state, close to their contemporary character. Since that time, frozen ground is in most cases formed syngenetically following the floodplain aggradation, and is exposed by the streams undercutting their banks. Channel floor permafrost is a much less persistent feature, mostly due to the intensive heat exchange with the streamflow. It owes its existence to either of two closely related processes:

(a) Lateral movement of the channel, leading to the exposure of older frozen floodplain layers at the channel floor, briefly described for a meandering river section by Crampton (1979).

(b) Permafrost core formation in the alluvial bars, initially a hydroclimatic phenomenon but frequently linked with sediment production at the eroded convex bank and its redeposition near the concave bank further downstream (in the case of a meandering river) or at multiple side bars and central bars (in non-meandering rivers).

While bank permafrost exposure to flow is largely a derivative of flow dynamics, frozen core formation is a thermal process. It is driven by channel surface exposure to heat exchange with the atmosphere during long-lasting winters either due to streamflow conditions (extremely low water level) or ice formation, lacking the insulation features of snow. In terms of affected channel surface areas S (m^2) this can be written as an illustrative equation:

$$S_{fr} = S_d + S_w + S_{ice} \tag{1}$$

where S_{fr} is the total riverbed area affected by frozen alluvium formation; S_d is the "dry" channel area (which is above the water level at the first day of ice formation); S_w is the channel area, exposed during water level decline; S_{ice} is the channel area directly contacting the ice bottom (see Fig. 1 for graphical reference).

This equation (1) formulation *sensu stricto* is applicable only to the 2-D picture, rather than a full 3-D frozen ground distribution on the channel floor, and hence reflects only the spatial allocation of frost penetration areas. The major ambiguities in the position of the frozen layer bottom result from the lack of information on moisture content of the alluvial bar and on the conductive heat fluxes at the flow–bed boundary. As a first approximation for frozen layer thickness *FL* (m), a simple heat transfer-based (Stefan-Kudryavtsev) equation can be used:

$$FL = \sqrt{\frac{2\lambda \cdot \Omega}{Q_p}} \tag{2}$$

where λ is the thermal conductivity of alluvial material ($kJ \cdot m^{-1} \cdot h^{-1} \cdot K^{-1}$); Ω is the sum of negative degree-hours ($K \cdot h$); Q_p is latent heat loss due to phase transitions ($kJ \cdot m^{-3}$). Active layer thickness *AL* (m) estimated by the same equation (2) with respect to the shorter summer and to the difference in thermal conductivity of frozen and unfrozen alluvium, will normally give $AL < FL$, the inequality, which itself is a major prerequisite for the existence of frozen ground in alluvial bars. For the climatic conditions of Central Yakutia and silty sands of the Lena River channel alluvium, $FL = 3.08$ m and $AL = 2.73$ m, hence there is a 0.35 m residual, responsible for the permafrost core inception and development.

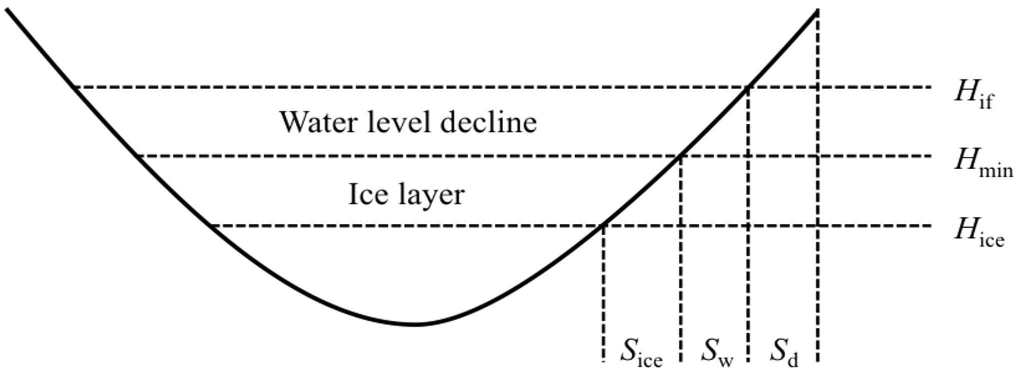

Fig. 2 The definition of areas, affected by permafrost formation (equation (1)), and their respective height positions; see text for label descriptions.

In order to apply equation (1) to channel bed topography, the former should be reinterpreted in terms of height positions *H* (m), corresponding to respective surface areas *S*. Characteristic *H* values include: H_{if}, water level at the first day of ice formation; H_{min}, winter lowest water level; H_{ice}, bottom of the ice layer, all in m a.m.s.l. on account of the river slope (see Fig. 2). These data are easily obtainable from the yearly hydrological datasheets to be applied to the relevant bathymetric survey results. Some channel portions will obviously be covered by ice during level decline, which leads to overlapping of the respective areas. The main assumption made here to avoid such overlap is that level decline is quite rapid, while maximum ice thickness is reached no earlier than mid-April. The height position approach allows the use of probabilistic models in estimating the permafrost formation potential under various hydrological conditions (especially hydrological extremes, such as extremely thick ice or low winter water levels).

BED MORPHOLOGY AND FROZEN GROUND

Low-gradient alluvial channels normally transport their bedload in dune form, the parameters of the latter (height, length, movement rate) being linked with the internal turbulent spectrum of the flow. Alluvial dunes not only are a dominant form of bed load transport, but also are major elements of bed topography. Alekseevskiy (2004) showed that fully developed dune hierarchy in channels with sand and silt alluvium includes 5 overlapping dune types (named *A* to *E*, where *A* is the largest), each having its own characteristic height and movement rate. For Lena River at Yakutsk, heights and movement rates, calculated using the Alekseevskiy (2004) technique, are given in Table 1.

Table 1 Dune parameters for Lena River at Yakutsk.

Dune type	*A*	*B*	*C*	*D*	*E*
h (m)	11.08	5.23	2.64	1.31	0.56
C (m d^{-1})	0.61	0.40	26.75	3.05	3.05

h, full dune height, including its own height and total height of the smaller dunes; *C*, dune movement rate.

In order to address potential bed mobility restrictions imposed by permafrost formation, the height position of the channel freezing lower boundary, H_{ice}, should be overlapped with the bed topography structure. Hence, full dune heights h should be converted to respective height positions and compared to H_{ice}. Calculations of the latter for the various values of lowest water level and ice thickness, taken from respective empirical probability distributions, give the relative values of about 2.6 to 4.2 m below the top of the smallest (and, thus, uppermost) *E*-type dunes. Therefore, frozen ground is formed at the surface of topmost *C*, *D* and *E* types.

The most important point to notice is that freezing affects the most mobile *C*-type dunes, restricting their mobility during at least some part of the spring freshet. This fact leads us to a suggestion that above-mentioned bedload fluxes for this river section, calculated using the technique of Alekseevskiy (2004), are overestimated. Restricted dune mobility is in its turn leading to the development of highly stable ice-cored sidebars, which define the persisting meandering patterns in an otherwise braided channel (Fig. 3). These forms, which are numerous throughout the whole studied section, have much in common with "pseudomeandering" forms, described by Hickin (1972), notably wide and shallow "outer channel" with underdeveloped chute cutoffs. Pseudo-meanders are regarded as typical for subcritical flow, which is clearly not the case for the studied Lena River section, but their development can be promoted either by high discharge variability (see Visconti *et al*., 2010) or by frozen alluvium core. The latter also increase the material volume by 10% (at full saturation) due to ice presence, thus increasing the elevation of the sidebars, reducing the timing of bar inundation and promoting vegetation development. Chute channels are mainly developed due to ice jams that frequently occur in the deep and narrow areas of the meander apex.

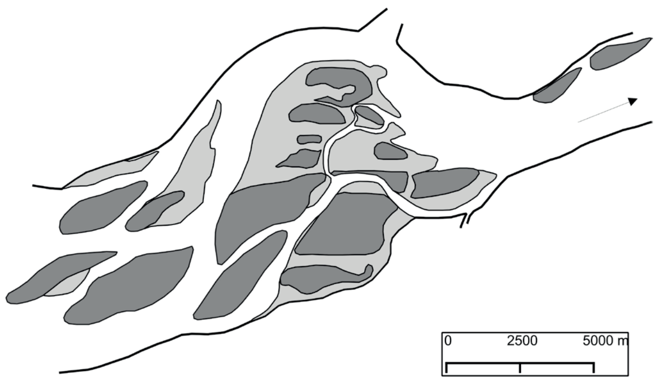

Fig. 3 Large At-Aryta (Horse-Island) "pseudomeander", 60 km downstream from Yakutsk. Islands and vegetated sand dunes are dark grey, sands are light grey; north is to the right.

FLUVIAL THERMAL EROSION

Fluvial thermal erosion is a complex process including bank material thaw and its further removal by the streamflow, often accompanied by thermo-erosional niching and subsequent block failure of the bank section. The process itself develops in discrete steps rather than in a continuous manner, so purely heat transfer-based model outputs, like that reviewed by Costard *et al*. (2007) should be regarded with caution. Heat transfer itself is no more than a prerequisite for niche formation, and it is influenced by both the excess shear stresses at the bank–flow boundary, bank lithology and gravitational forcing, and no holistic quantitative model exists to date to describe the complexity of the whole sequence of fluvial thermal erosion events.

Our long-term (2002–2011) observations on the middle Lena River section near Yakutsk show that the thermo-erosional niche inception point corresponds well with water levels, associated with channel-forming discharges; the result, complying with conclusions of (Nanson & Hickin, 1986). The latter occur well below bankfull level and are related to the peaks on the flow kinetic energy graph. For the Lena River near Yakutsk, this graph has three distinct extremes around 24 000, 16 600 and 7700 m^3 s^{-1}, of which the first two discharges are responsible for intensive fluvial thermal erosion. Their competence in thermal erosion is unevenly distributed between three distinct floodplain levels, developed within the valley bottom (see Table 2).

Table 2 Lena River floodplain levels and retreat rates

Floodplain levels	h (m)	R (m year^{-1})	Q (m^3 s^{-1})	Dominant process
High	7–9	7–20	24 000	Thermal erosion, mass movement
Middle	4–6	5–8	16 000	Fluvial erosion
Low	2–3	1–3	16 000	Thermal erosion

h, floodplain level height above the mean summer low-flow level; *R*, bank retreat rate; *Q*, channel-forming discharge.

At 24 000 m^3 s^{-1}, only high floodplain banks are subject to active thermal erosion. For the middle floodplain level, this discharge is responsible for development of small niches in the top 0.5–0.7 m of the bank section; low floodplain level is inundated at this discharge. At 16 000 m^3 s^{-1}, thermo-erosional niching occurs at the low floodplain banks, while for the higher banks it is only active in removal of the material from the base of the bank slope. Hence, bank retreat rates are increasing with increase in bank height, which is uncommon for the non-periglacial rivers.

CHANNEL PATTERN AND FROZEN GROUND

River planform development in permafrost areas generally follows the regularities observed under moderate climate conditions, but is affected by frozen ground development and related bedform stability. Channel pattern can be described in terms of flow concentration and, as such, it regulates the potential for permafrost formation via the availability of exposed channel surface areas (see Fig. 2). For straight channels, the latter is just a narrow stripe along the floodplain or the valley wall, which is highly affected by heat exchange with the streamflow and probably becomes extinct during early summer. In meandering channels, frozen ground is formed in sidebars attached to concave banks of the meander bends, while in braided channels ice cores are potentially developing within the majority of the large alluvial bars.

Quantitative analysis of channel area distribution can be carried out using the height position approach in any GIS software, if relevant hydrological data and bed topography from bathymetric surveys are available. Frozen areas inferred from GIS calculations for distinct channel patterns of the studied Lena River section are given in Table 3. Under average hydrological conditions, permafrost occupies significant areas (about 74%) only in braided channels, while in meandering and straight sections at least half of the channel area is not subject to frozen ground formation.

Winter low water level is the major prerequisite for the latter in braided and meandering sections, while in straight sections water level and ice thickness are of equal importance.

Table 3 Channel patterns and permafrost-affected areas for the middle Lena River section.

Channel pattern	$S_d + S_w$ (%)	S_{ice} (%)	Below H_{ice} (%)
Braided	58.5	15.4	26.1
Meandering	32.9	12.1	55.0
Straight	18.3	17.8	63.9

As a result, the channel morphology and dynamics of the middle Lena River are geocryologically controlled. Bank retreat due to thermal erosion supplies the streamflow with large volumes of freshly eroded material. Annual sediment supply due to bank retreat was estimated using Landsat imagery (NASA, 1972–2011) for the 150-km Lena River section above Yakutsk. It equals about 5 to 6.5 Mt, an amount that exceeds annual bedload volumes and is comparable with the annual suspended load of the river. During spring freshet and summer rain-induced flow peaks this material is accumulated on the floodplain and numerous alluvial bars.

Restricted bed mobility during nival freshet leads to intensification of bank erosion due to high excess shear stresses and transport capacity of the flow, further increasing both width-to-depth ratio and flow de-concentration, and enhancing braided pattern stability. Large ice-cored sidebars are formed adjacent to the floodplain or large island massifs, inducing the development of meandering sections with a distinct "pseudomeandering" outlook within an otherwise braided channel. Frequent ice jams cause both backwater and jam break-up floods, leading to the development of chute cut-offs and numerous side channels within the lower floodplain levels. The channel pattern and overall aggradational environment of the middle Lena River are thus highly sustainable and promoted by permafrost, underlying both the streambed and the valley floor.

CONCLUSIONS

Fluvial systems in cold environments function in a *cryo-conditioning* state. High discharge variability confines the geomorphic activity of streams to a short period of spring freshet and a limited number of summer rain-induced floods. Limited slope and gully erosion, though not emphasized in the scope of this paper, leads to intensification of fluvial processes within the river valleys. Here, at the lowest part of the valley, permafrost affects alluvial morphology, bank erosion and floodplain aggradation, adding complexity to the fluvial system dynamics.

Observed environmental changes are expected to produce a significant feedback from cold region hydrological systems. Major drivers of fluvial response to climate change include:

(a) Increase in water supply to the high latitudes with the intensifying water cycle. Mean annual discharge of the six largest Russian rivers has already increased by 10% from 1936 to 2008 and is further increasing. Winter runoff almost doubled in some regions, including northeastern Russia (Shiklomanov & Lammers, 2009).

(b) Increase in global permafrost temperatures by 0.5–3.0ºC over the last 30 years, along with active layer depth increase (Romanovsky *et al*., 2010).

Hydrological and geocryological changes are expected to produce a number of responses in fluvial systems of the cryosphere, but in our view the most significant is the increase in sediment fluxes, conveyed by the rivers both in suspension and as bedload. Indeed, runoff increase should lead to the corresponding nonlinear increase in transport capacity and suspended load, as reflected by the rating curve approach. Furthermore, higher winter runoff along with air and ground warming, thinner ice and higher heat fluxes, should increase the competency of flow in transporting bedload. Bed mobility will increase significantly if the most mobile dunes stay free of permafrost influence throughout the winter and are readily moved during spring freshet. Fluvial thermal erosion is expected to be more effective, but that may not be the case where bank retreat is linked with ice-cored sidebars and "pseudomeandering" patterns. Higher water runoff and sediment fluxes are competent at shifting the stream equilibrium conditions that may result in subsequent channel pattern adjustment. However, any general suggestions on this point should be made with caution and an individual approach to each river section might be implemented.

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