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Hydrological and sedimentary controls over fluvial thermal erosion, the Lena River, central Yakutia

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A B S T R A C T

Water regime and sedimentary features of the middle Lena River reach near Yakutsk, central Yakutia, were studied to assess their control over fluvial thermal erosion. The Lena River floodplain in the studied reach has complex structure and embodies multiple levels varying in height and origin. Two key sites, corresponding to high and medium floodplain levels, were surveyed in 2008 to describe major sedimentary units and properties of bank material. Three units are present in both profiles, corresponding to topsoil, overbank (cohesive), and channel fill (noncohesive) deposits. Thermoerosional activity is mostly confined to a basal layer of frozen channel fill deposits and in general occurs within a certain water level interval. Magnitude-frequency analysis of water level data from Tabaga gauging station shows that a single interval can be deemed responsible for the initiation of thermal action and development of thermoerosional notches. This interval corresponds to the discharges between 21,000 and 31,000 $m^3 s^{-1}$, observed normally during spring meltwater peak and summer floods. Competence of fluvial thermal erosion depends on the height of floodplain level being eroded, as it acts preferentially in high floodplain banks. In medium floodplain banks, thermal erosion during spring flood is constrained by insufficient bank height, and erosion is essentially mechanical during summer flood season. Bank retreat rate is argued to be positively linked with bank height under periglacial conditions.

1. Introduction

Riverbanks are dynamic interfaces between fluvial, atmospheric, and soil domains where each medium contributes to their transformation. Stream power is a major force, exerting action on the banks, while resistive properties of bank material restrict fluvial action. Hydraulic erosion rates are controlled by stream power and shear stress values along the eroding bank (Nanson and Hickin, 1986; Darby and Thorne, 1997), position of the eroding segment within the channel section, defining flow 'angle of attack', and effectiveness of shear stress application (Shur et al., 1978; Are, 1983; Nanson and Hickin, 1986), lithology and cohesive properties of overbank sediment (Shur et al., 1978; Julian and Torres, 2006; Parker et al., 2008), bank height (Berkovich and Vlasov, 1982; Nanson and Hickin, 1986), and vegetation (Thorne, 1990; Millar, 2000). In permafrost areas, direct ice impact, solifluction, thaw slumps, detachment slides, and needle ice formation also contribute to the frozen banks' instability and collapse (Prowse and Culp, 2003; Lawler, 2006; Lipowski and Huscroft, 2007).

Fluvial thermal erosion is virtually omnipresent in periglacial environment but is best perceivable along the banks of large alluvial rivers. It is active mostly during a short spring flood period when the streams undercut their frozen banks, forming spectacular thermoerosional niches (Walker and Hudson, 2003). Inception of these niches is a juxtaposition of thermal and hydraulic action and, as such, represents the essence of fluvial thermal erosion. Observations in Arctic Alaska show that mechanical washout generally proceeds slower than thaw, except in the apexes of thermoerosional niches where these processes are assumed to be in equilibrium (Scott, 1978). Heat transfer rate controls particle detachment, thus overriding purely hydraulic impact (Shur et al., 1978; Randriamazaoro et al., 2007). Noncohesive bank material with massive cryogenic texture ('ice cement') and low ice content is more susceptible to thermal erosion than cohesive deposits or organic material having higher ice content (Scott, 1978; Gautier and Costard, 2000; Dupeyrat et al., 2011). Block slumping occurs after its flexural resistance had been exceeded either because of excessive undercutting or active layer thickening.

Preceding quantitative studies of fluvial thermal erosion concentrated on observing and prediction of the process rate given the sediment ice content and water temperature (Randriamazaoro et al., 2007; Dupeyrat et al., 2011; Debolskaya, 2014) and on field and remote observations of bank erosion (Are, 1983; Costard et al., 2003, 2007, 2014). Little notion was given to explain the factors promoting the formation of thermoerosional niches. Notably, however, floodplain sediment heterogeneity and water stage variations discourage their development. Position of the notch formed by thermal erosion is

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important, as it defines implicitly the notch depth as well as volume of slumped material and bank retreat rate (Scott, 1978).

Scott (1978) and, later, Costard et al. (2003) assumed that the thermoerosional niche development is concentrated at the base of the cohesive layers where the bank material is more susceptible to erosion. However, this observation is eventually phenomenalistic and cannot be generalized, i.e., over cases where the banks are uniform and no such boundary is present. The research rationale behind the present paper is an assumption that hydrological controls are somehow responsible for notch inception and thermoerosional niche development.

Effective (dominant, channel-forming) discharge concept is used extensively to evaluate the long-term competence of the streamflow in shaping channels and controlling their hydraulic geometry (Wolman and Miller, 1960; Alabyan and Chalov, 1998; Doyle et al., 2005; Caissie, 2006). Effective discharge is frequently associated with that at the bankfull stage, though it may be significantly lower if considering sediment transport efficiency (Benson and Thomas, 1966) or rivers in degradational mode (Hassan et al., 2014).

The application of effective discharge concept to fluvial thermal erosion in periglacial rivers has several limitations. Bankfull discharge has limited competence in affecting bank erosion insofar as this process occurs normally at discharges well below bankfull level (Wolman, 1959). Complexity of floodplain structure, consisting of multiple levels, complicates the identification of a single discharge causing overbank spill (Nanson and Croke, 1992; Gautier and Costard, 2000). Moreover, recurrent ice jams are known to disrupt a steady stage–discharge relationship during the break-up period (Prowse and Culp, 2003). Stage fluctuations up to several metres are related to variations in flow resistance and hydraulic roughness and can be caused solely by changes in ice conditions (Zaitsev et al., 2006).

This study is based on data collected during multiple field campaigns in the middle Lena River section adjacent to the city of Yakutsk, central Yakutia, between years 2002 and 2008. This river section was subject to previous regional studies in regard to channel pattern development and sedimentary features (Zaitsev and Chalov, 1989; Gautier and Costard, 2000; Costard et al., 2003; Degtyarev et al., 2007), as well as recent climate shift (Costard et al., 2007) and ice breakup and spring flood (Costard et al., 2014) as affecting the thermal erosion process. However, hydrological controls over the latter remain largely understudied; hence the present paper is aimed at partially closing this gap. The Lena River floodplain in the studied reach has complex structure and embodies multiple levels varying in height and origin: high, medium, and low inundation plains (Gautier and Costard, 2000). Performance of fluvial thermal erosion is expected to vary between these levels, and this variability in relation to water regime is the major subject of this study.

First, sedimentary features of the overbank deposits at two representative key sites, corresponding to distinct floodplain levels, are presented. Second, the 'magnitude-frequency' approach is used to evaluate the effective water stage (or, stages, if multiple) responsible for preferential inception of thermoerosional notches and niches. Finally, these results are overlapped to infer the differences in effectiveness of fluvial thermal erosion in riverbanks of various heights.

2. Study area

Field studies were carried out within the 20-km section of the middle Lena River in the vicinity of Yakutsk, central Yakutia (Fig. 1). At an upstream limit of the studied section, a 120-m-high Tabaginsky Mys terrace (an outcrop of the Jurassic (J_2) sandstones) narrows the Lena River valley from the west. Farther downstream, the main channel approaches the 30-m-high alluvial Bestyakh terrace (experiencing intense fluvial erosion during spring and summer floods) and heads toward Yakutsk after a gentle left turn. The width of the Lena River valley is between 5 and 6 km in the upper section and increases to 15–20 km farther downstream. Active channel deformations occur within 8 to 10 km of the valley width and are also limited by the Tabaginsky Mys terrace outcrop in the upstream section.

The Lena River channel pattern in the studied section is anabranching, after Lewin and Ashworth (2014). The main channel is relatively straight during floods, but its sinuosity increases with decline in water stage. During flow recession, submerged side bars are exposed and start controlling the low-flow channel pattern. A braided pattern emerges within relatively straight sections, where central bars are present. Stability of sand bars is augmented by presence of perennially frozen deposits at their base (Tananaev, 2013). Floodplain is present on both sides of the channel except the Bestyakh terrace cross section and has a well-developed network of the highly sinuous secondary branches, through which the water excess is flushed to the main channel after the flood peak. Floodplain to bankfull channel width ratio is quite low (≤3), reflecting the limited ability of the floodplain to convey flood water and to store the overbank deposits. The vertical structure of the floodplain is complex, with at least three distinct levels, as referenced by Gautier and Costard (2000). Contemporary cryogenic processes are active within the highest floodplain levels and include frost heave and polygonal ice-wedge growth.

Hydrological features of the Lena River were recently described in several papers (Yang et al., 2002; Ye et al., 2003; Berezovskaya et al., 2005; Dzhamalov et al., 2012), and specific attention was paid to the ice break period and associated ice jams (Zaitsev et al., 2006; Kilmjaninov, 2007; Costard et al., 2014). Hence, only a brief hydrological overview is given here based on data from 1938 to 2013, published by Russian Hydrometeorological Agency.

Lena River at Tabaga gauging station (GS; see Fig. 1 for gauge location reference) drains a catchment of 897,000 km^2, which contributes about 42% of total basin flow at the outlet (Ye et al., 2003); mean annual discharge equals 7270 $m^3 s^{-1}$ for the 1938–2013 period. Recent changes in streamflow include significant increase in winter discharges over the last 25 years, accompanied by a visible increase in annual-average streamflow (Fig. 2). Cumulative duration of flood events, i.e., number of days with daily discharge exceeding 25,000 $m^3 s^{-1}$, reached its maximum in 2012 (63 days), but no clear trend emerges from these data. Spring floods of the 1930s and 1940s were retarded, the fact that can give an impression of a substantial increase in flood severity to what is essentially a 'low base' effect. Peak discharges remain at about the same level as in mid-1950s and throughout the 1960s (Fig. 2).

Water regime of the Lena River is dominated by snowmelt, although heavy rains in the mountainous headwaters can produce storm events comparable to spring flood in terms of peak discharges (Fig. 3). Distinct winter low-flow period, with daily discharges below 3000 $m^3 s^{-1}$, lasts for 198 days, early November until early May, and has an average discharge of 1520 $m^3 s^{-1}$. With air temperatures frequently hitting the −50 °C mark during winter seasons, ice thickness in main channels reaches 1.32 m on average and normally exceeds 2.0 m in secondary branches. Rapid (in 10 to 15 days) discharge increase, originating from snowmelt runoff, is fed by the Lena River and its major tributaries, the Vitim and the Olekma rivers. It occurs between late April and late May, frequently accompanied by ice jams (Zaitsev et al., 2006).

Spring flood duration varies between 54 and 96 days depending on snow abundance and insolation of the mountainous headwaters in the Lena River basin. Local meltwater sources are considered to be negligible, as central Yakutia receives on average 120 mm of solid precipitation, which evaporates partially during seasonal transition to positive air temperatures. Spring peak discharge averages 36,500 $m^3 s^{-1}$ and can exceed 50,000 $m^3 s^{-1}$ during extreme flood events. Post-peak flow recession is gradual, and continues from mid-July until early November, when the river again enters the wintry dormant state. Summer low-flow periods are frequently interrupted by rain floods originating from the Vitim and Olekma basins. Rain-induced peak discharges can exceed those of the preceding spring floods.