Earth-Science Reviews 228 (2022) 103996

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Defrosting northern catchments: Fluvial effects of permafrost degradation

Nikita Tananaev [a,b,*], Eliisa Lotsari [c]

[a] Melnikov Permafrost Institute, Siberian Branch, Russian Academy of Sciences, 36 Merzlotnaya Str., Yakutsk 677010, Russia
[b] North-Eastern Federal University, 46 Kulakovskogo Str., Yakutsk 677004, Russia
[c] Water and Environmental Engineering, Department of Built Environment, Aalto University, PL 15200, Tietotie 1B, FI-00076 Aalto, Finland

ARTICLE INFO

Keywords:
Climate change
Arctic
Permafrost degradation
Fluvial processes
Fluvial landforms
Permafrost hydrology
Linear thermokarst
Hillslope water tracks

ABSTRACT

This paper discusses the potential response of fluvial processes and landforms to the projected permafrost degradation and related hydrological change. Fluvial system structure is presented in the first section of the paper along with permafrost controls over its functioning, which vary across fluvial system compartments. The distinction is drawn between primarily fluvial landforms that are expected to adjust to future hydrology with less permafrost constraints, and primarily cryogenic landforms evolving in line with permafrost disturbances. The influence of permafrost on fluvial action varies across compartments: on hillslopes, permafrost mostly controls the occurrence of surface runoff, in river valleys and channels, sediment erodibility, while thermal interaction is essential for growing thermo-erosional gullies. Observed and projected changes in permafrost and hydrology are outlined, and their relevance for cryo-fluvial evolution of fluvial systems is reviewed. Based on these projections, future changes in fluvial action in each compartment are discussed. On hillslopes, where permafrost exerts important controls on hillslope hydrology, fluvial activity of overland flow is expected to decrease following the active layer deepening and decreased overland flow duration. In erosional networks, controlled by thermal interaction between runoff and permafrost terrain, higher water temperature is expected to increase the occurrence and rates of thermo-erosional gully development. In river valleys and channels, where permafrost controls the erodibility of bed and bank material, the expected fluvial feedbacks vary across scales and stream orders, and include changes in seasonality of channel deformations, increased retreat rates in lower river banks and decreased, in higher banks, along with floodplain subsidence, and minor potential for complete destabilization of existing channel patterns. Future collateral effects of fluvial change include alterations of terrestrial biogeochemical cycles and societal impact that must be accounted for in climate change adaptation and mitigation strategies.

1. Introduction

Ongoing climate change has diverse effects on global ecosystems that are more pronounced in high latitudes because of the Arctic amplification (Serreze and Barry, 2011; Box et al., 2019). Higher air and surface temperatures and precipitation drive permafrost degradation and alter water cycle globally (Rowland et al., 2011; Streletsky et al., 2015; Krogh and Pomeroy, 2018; Oliva and Fritz, 2018). Together, these factors affect land surface evolution in cold environments, though the geomorphological response to climate change yields uncertainties related to differing sensitivity of landscapes (Harrison et al., 2019; Allaart et al., 2021). Permafrost imposes a strong 'zonal' effect on geomorphic activity, as a particular ecosystem type where a set of specific interactions is directly related to the frozen state of the ground (Berthling and Etzelmüller, 2011; French, 2017).

Cold environments host numerous geomorphic processes related to flowing water, including soil and gully erosion, river channel evolution and floodplain development. These processes, as well as associated landforms, are collectively termed 'fluvial' in the literature (Leopold et al., 1995; Chorley, 2019; Chalov, 2021). Permafrost is an important factor of fluvial activity in cold environments (Goudie, 2006). Permafrost shapes hydrological processes that physically drive fluvial activity (Woo, 2012, 2019; Tananaev et al., 2020), and affects surface water interaction with the groundwater domain (Shepelev, 2009; Fotiev, 2013; Walvoord et al., 2012; Walvoord and Kurylyk, 2016; Ma et al., 2021). Permafrost also directly influences fluvial activity by controlling the shape of fluvial networks (McNamara et al., 1999), development of alluvial channels (Zaitsev and Tananaev, 2008; McNamara and Kane,

* Corresponding author at: Melnikov Permafrost Institute, Siberian Branch, Russian Academy of Sciences, 36 Merzlotnaya Str., Yakutsk 677010, Russia.
E-mail addresses: TananaevNI@mpi.ysn.ru (N. Tananaev), eliisa.s.lotsari@aalto.fi (E. Lotsari).

https://doi.org/10.1016/j.earscirev.2022.103996
Received 18 June 2021; Received in revised form 11 March 2022; Accepted 14 March 2022
Available online 17 March 2022

2009; Crawford and Stanley, 2014), bank erosion (Scott, 1978; Walker et al., 1987; Tananaev, 2016; Chassiot et al., 2020), island and floodplain dynamics (Crampton, 1979; Lininger and Wohl, 2019; Gautier et al., 2021). Permafrost acts as an independent landscape-shaping agent through frost weathering (Matsuoka and Murton, 2008; Hall and Thorn, 2010) and periglacial, or cryogenic processes (Kizyakov and Leibman, 2016; French, 2017; Lafrenière and Lamoureux, 2019). This complexity led Sukhodrovsky (1979) to a claim that in permafrost, fluvial action is de facto a cryo-fluvial interaction. Permafrost, hydrology and turbulent flow forcing together shape resulting landforms, exerting joint control over fluvial processes across multiple scales.

An inherent complexity of this cryo-fluvial interaction impedes a holistic vision of potential fluvial responses to climate change and permafrost degradation. Recent reviews on the subject are scarce. Past climate impacts on fluvial records during the Pleistocene and Holocene were a focus of a large-scale review by Macklin et al. (2012), neither considering the role of permafrost and periglacial processes in shaping fluvial action, nor assessing the future climate situation. Climate forcing of fluvial system evolution was a central topic in (Vandenberghe, 2003, 2008), yet again, with strong focus in paleoreconstructions. Potential effects of climate change on fluvial geomorphology were reviewed by Goudie (2006), mostly focusing on the predicted hydrological change and only briefly discussing their geomorphological consequences in permafrost settings. Geomorphological sensitivity and the impact of global warming on geomorphological systems were evoked in a synopsis by Knight and Harrison (2012), exclusively centered on paraglacial environments. Dixon (2013) overviewed the totality of periglacial processes and their response to global change, though the description of fluvial response is brief and superficial because of highly condensed narration. Lafrenière and Lamoureux (2019) put an emphasis on the effect of direct permafrost disturbance, either thermal or physical, on solute and particulate matter fluxes, yet minor attention is given to the evolution of fluvial landforms. Fluvial bank erosion processes and landforms in cold environments were reviewed by Chassiot et al. (2020), exposing the potential climate change outcomes for frozen river banks that are one important part of fluvial systems.

The motivation for this review stems from major shortcomings of previous research of the subject, (1) the lack of holistic, system approach to the description of fluvial forms and processes in permafrost, and (2) limited attention given to the potential future climate feedbacks for such systems. The minor role of geomorphology in the projections of climate change scenarios and outcomes (Lane, 2013) was another motivation for our enquiry. Recent suggestion to reorient geomorphology toward landscape science (Slaymaker et al., 2021) reinvents its utility in the current climate agenda in the human geography domain. We believe that fluvial geomorphology, jointly with hydrology and geocryology, can still be relevant to the field of global change in the context of natural sciences. Therefore, we put an effort to bridge these gaps, by framing the assessment of future climate and, particularly, permafrost degradation effects into an integrated permafrost fluvial system framework. This holistic approach allows a first in-depth description of cryo-fluvial interactions across multiple spatial and temporal scales and their evolution under future climate.

This paper reports and discusses the potential effects of permafrost loss on fluvial systems in cold environments, mostly in the Northern Hemisphere. We aim at: (1) identifying hydrological changes relevant to fluvial processes at a scale range from plot to catchment, originating from permafrost degradation; (2) exploring valley- and reach-scale interactions of permafrost, hydrology and fluvial processes, responsible for driving future change in fluvial systems related to permafrost degradation. Chapter 2 provides the theoretical framework for this review, explains the fluvial system structure and permafrost controls over their functioning. Chapter 3 summarizes existing evidence, both observed and projected, of permafrost degradation and hydrological change relevant for the transformation of fluvial systems,. Chapter 4 reviews the potential fluvial effects of permafrost degradation across fluvial system compartments. Subsequent expected outcomes for biogeochemical cycles and societies are discussed in Chapter 5. Future research needs and perspectives are highlighted in Chapter 6, followed by general conclusions.

2. Permafrost fluvial systems

2.1. Fluvial system structure

Potential environmental effects of permafrost degradation are expected to be scale-dependent (Nitzbon et al., 2021). Permafrost controls over fluvial action also vary across the range of spatial and temporal scales. System approach is needed to provide integrity and holistic vision of projected evolution of fluvial forms and processes (Piégay, 2016). Our narration is built upon the fluvial system concept initially developed for non-permafrost regions (Alekseevskiy et al., 2008; Chalov, 2021). This system is hierarchical: it incorporates four compartments interconnected by water and sediment fluxes, transpiercing the system as a conveyor belt (Ferguson, 1981). Each compartment hosts a unique association of water runoff type, dominant fluvial process and landform assemblage (Chalov, 2021). In the *hillslope compartment*, diffuse overland flow over the hillslope surface controls sheet erosion and accumulation in hollows, converges to linear rills and accumulates colluvial aprons and hilltoe deposits at toeslopes (Miller and Juilleret, 2020). In the *erosional network compartment*, overland flow reaches critical thickness and converges to intermittent first-order gully streams that carve incipient channels and develop alluvial fans and cones (Patton and Schumm, 1979; Valentin et al., 2005; Ventra and Clarke, 2018). In the *river valley compartment*, internal forcing, i.e., structure of turbulent flow, acts along with external forcing, i.e., water runoff and sediment supply from adjacent hillslopes, tributaries and river banks, or human impact, that has to be integrated into the fluvial regime (Brierley and Fryirs, 2016). River valley is a major resulting fluvial form, but within the valley limits, an hierarchy of floodplain levels and bedforms develops as a function of hydrological regime, structure of turbulent flow and overall river style (Gioia and Bombardelli, 2002; Richards et al., 2002; Brierley and Fryirs, 2005). The *coastal compartment* is a marginal low-energy depositional environment, where rivers construct complex deltaic floodplains and channel networks, and mouth bars at the seaward margin. Strong marine influence places deltas and coastal areas outside fluvial domain in strict sense (Orton and Reading, 1993; Polonsky, 1996), so only limited attention is given here to this subject.

2.2. Permafrost controls in fluvial systems

Permafrost interferes with fluvial action by influencing its two major interacting agents: water cycling through watersheds, and ground surface, including catchment surface, channels and banks, and by extension, any contact surface where fluvial action may occur. Besides, the frozen state of sediments invokes heat exchange between running water and underlying sediments as a driving force of thermal erosion (Scott, 1978; Dupeyrat et al., 2011). Hydrological effects of permafrost include: (1) occurrence of a migrating frozen aquiclude, controlling water table depth and saturated layer thickness; (2) water migration in the soil matrix driven by phase transitions in the active layer; (3) transient water storage in both surface and subsurface compartments, redistributing water runoff over different timescales (Tananaev et al., 2020). Over the catchment surface, and in channels, frost weathering produces fine-grained cryoeluvium and shattered coarse alluvium subject to rapid downstream attrition (Shumilov, 1986; Konishchev and Rogov, 1993; Attal and Lavé, 2009; Weckwerth and Pisarska-Jamroży, 2015). Permafrost disturbance resulting from cryogenic processes influences fluvial action via: (1) pre-conditioning hillslopes for erosion through protective vegetation mat removal and open soil exposure (Aalto et al., 2021); (2) direct sediment supply to streams through mass movement (Kokelj et al., 2013; Lafrenière and Lamoureux, 2019); (3) creating quasi-linear landforms further reoccupied by running water and conveying water and sediment fluxes (Bowden et al., 2008; Godin et al., 2014; Morgenstern et al., 2021). Fluvial fluxes in disturbed permafrost terrain are significantly higher, and remain so during several years after disturbance has occurred (Lafrenière and Lamoureux, 2019; Beel et al., 2020).

Permafrost introduces ablation component into the particle detachment process during fluvial erosion on hillslopes, in alluvial channels and river banks (Scott, 1978; Poznanin, 1995; Lawson, 1983; Randriamazaoro et al., 2007; Dupeyrat et al., 2011). In alluvial channels, permafrost significantly limits vertical (channel) erosion. It is also generally believed to promote lateral (bank) erosion, especially in higher banks and in ice-rich permafrost (Tananaev, 2013; Kanevskiy et al., 2016; Stettner et al., 2018; Fuchs et al., 2020; Chalov, 2021), though direct comparison of frozen vs non-frozen bank retreat rates is complicated (Gatto, 1984), and concurring opinions exist in regional studies and modeling efforts (Payne et al., 2018; Lauzon et al., 2019).

Relative importance of permafrost controls over agents of fluvial action varies across fluvial system compartments (Fig. 1). In the *hillslope compartment*, fluvial processes develop mostly within the active layer or over non-frozen hillslope surfaces, hence thermal interaction has minor importance. During spring snowmelt period, when hillslope surface is frozen, heat flux associated with overland flow is insufficient for any significant thermal erosion to occur. On the intact interfluve hillslopes, where most of the snow is removed through blowing snow redistribution, snowmelt runoff is insufficient to produce significant overland flow, as Kokelj and Lewkowicz (1998) demonstrate for the Ellesmere Island, Canadian Arctic, and Sukhodrovsky (1979), for central Yakutia near Yakutsk. Rapidly thawing topsoil, which is usually organic material, effectively accommodates meltwater and conveys it downslope. Vegetation prevents snow removal and allows higher surface runoff from vegetated hillslopes, but thicker root systems inhibit erosion.

Rainfall erosion occurs in non-frozen/thawed material even in Arctic and Subarctic environments, and results in mechanical washout. Organic topsoil is highly permeable which prevents Hortonian flow, hence saturation excess runoff is dominant and its occurrence is controlled by the active layer volume. Permafrost impact on surface runoff is crucial, as its probability of occurrence is related to the position of the cryogenic aquiclude (Woo and Steer, 1983, 1986; Bogaart et al., 2003). Besides, persistence of ephemeral ice lenses and wedges in the active layer long into the thaw season locally impedes suprapermafrost groundwater transport (Burt and Williams, 1976; Kjelstrup et al., 2021).

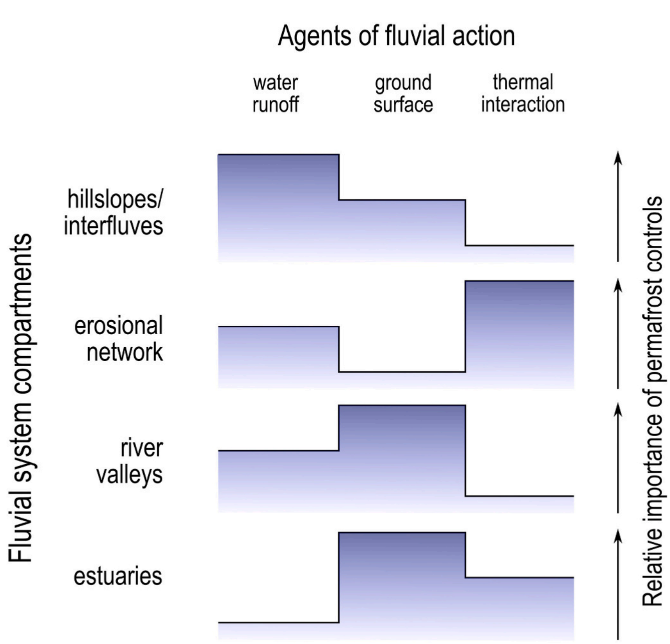

Fig. 1. Relative importance of permafrost controls over process agents in different compartments of permafrost fluvial systems

In the *erosional network compartment*, thermal interaction controls the development of both thermo-erosional gullies (Poznanin, 1995; Sidorchuk and Sidorchuk, 1998) and linear thermokarst features in ice wedge polygonal network, or thermokarst pseudo-gullies (Godin et al., 2014). Hydrology represents second important factor, since sufficient amount of water needs to be conveyed through gully thalwegs in order to induce both mechanical and thermal erosion.

In *river valley compartment*, permafrost affects sediment erodibility and directly controls river bank erosion, bed mobility and floodplain evolution. Stream hydrology generally controls magnitude and frequency of fluvial response (Wolman and Miller, 1960), which is adjusted by the presence of permafrost within the valley bottom. River flow also connects to permafrost-affected catchments through water and sediment fluxes from the first-order streams, and to valley slopes via cryogenic mass wasting processes (Lipovsky and Huscroft, 2007; Kokelj et al., 2013).

In *deltas and coastal areas*, a low energy environment, purely hydrological effects are inhibited by antecedent conditions, marine influence, and ice cover (Piliouras and Rowland, 2020; Piliouras et al., 2021). Permafrost-affected bed forms exert control over channel planform, while fluvial thermal erosion is active in river banks (Fuchs et al., 2020; Juhls et al., 2021). Deposited material is subsequently subject to seasonal and perennial freezing, increasing channel stability (Lauzon et al., 2019).

2.3. Cryo-fluvial landform development

In permafrost fluvial systems, landform development is driven by cryo-fluvial interaction (Fig. 1), each landform evolving under a distinct set of hydrological, sedimentary and cryological controls (Sukhodrovsky, 1979). Relative importance of these controls varies across fluvial system compartments, along with stream power, total heat flux, and landform dimensions. Cryo-fluvial landforms can be regarded, by major shaping agent, as either: (1) primarily fluvial, that are initiated through fluvial action, constrained by permafrost, and evolve through both mechanical and thermal erosion; (2) primarily cryogenic, where permafrost disturbance creates depressed landforms reoccupied and transformed by water runoff; (Fig. 2). In primarily cryogenic landforms, linear scale of permafrost disturbance needs to fit the continuum of fluvial forms to allow their reoccupation by the flow, otherwise fluvial activity would be inhibited by insufficient runoff, stream power, and heat flux.

On *hillslopes*, rills created by rainfall runoff are primarily fluvial landforms, but they are scarce on undisturbed hillslopes. Where they occur, their evolution is mostly unaffected by frozen ground, unless the hillslope surface has been pre-conditioned by cryogenic processes. Primarily cryogenic landforms include local thermokarst and thermal denudation features (Jones et al., 2013): retrogressive thaw slumps (Fig. 3a; Burn and Lewkowicz, 1990; Costard et al., 2021), active layer detachment slides (Fig. 3b; Lamoureux and Lafrenière, 2008; Gubarkov et al., 2014), and small-scale linear thermokarst in ice-rich deposits (Fig. 3c; Bowden et al., 2008), These forms enhance fluvial erosion, exposing mineral soil to rainfall erosion. Occasionally, these disturbances may create linear forms suitable for flow accumulation, i.e., through tunnel thermokarst, but subsequent edge material slumping is shown to be effective in smoothening such forms and inhibiting fluvial erosion (Bowden et al., 2008). We suggest that solifluction may also participate in suppressing fluvial activity in linear forms through supplying edge material to thalwegs, isolating runoff from ice-rich permafrost and thus limiting thermal erosion.

In *erosional network compartment*, primarily cryogenic landforms include thermokarst pseudo-gullies, or gullies over active thermokarst (Fig. 4a; Godin and Fortier, 2010). These features are widely termed

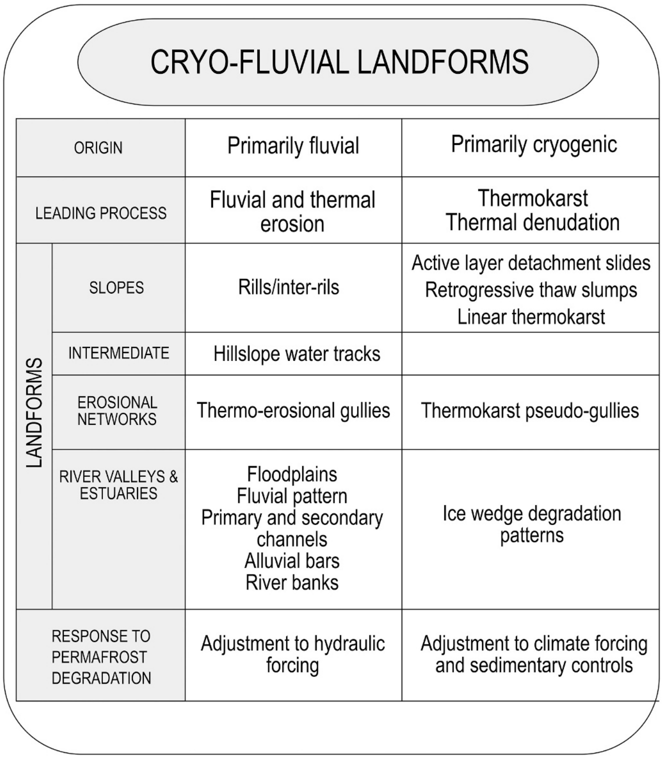

Fig. 2. Cryo-fluvial landforms in permafrost fluvial systems

'thermo-erosion gullies', but according to published descriptions, only their headwalls develop through thermal erosion, while the degrading ice wedges in a polygonal network, inherited by this quasi-linear feature, mainly lose ice volume through typical thermokarst process (Godin, 2016; Veillette, 2019; Morgenstern et al., 2021). Original thermo-erosional gullies in fine sediments are unrelated to ice-wedge degradation and evolve through thermal interaction and mechanical erosion, making them primarily fluvial landforms (Fig. 4b; Poznanin, 1995). Existing models suggest that the gullying potential is defined by contributing area, slope and surface runoff depth duration (Sidorchuk, 2020).

Hillslope water tracks, or dells, are iconic features of periglacial landscapes (Fig. 5). 'Water track' is a generic name for a large variety of actual landforms representing preferential flow alignment in the subsurface compartment (Trochim et al., 2016a, 2016b). Their origin and functions are still poorly understood and debated.

In Canadian High Arctic, they are argued to result from coarse material sorting and fine material outwash (Paquette et al., 2017, 2018). In the Antarctic McMurdo Dry Valleys, they are believed to evolve as a subsurface drainage network owing to high permeability of host material and active layer depression in the water track zone (Ball and Levy, 2015; Linhardt et al., 2019). In Chukotka, Northeast Russia, each water track type supposedly has its distinct controlling process, either fluvial erosion or thermokarst (Tarbeeva et al., 2021). In Alaska, they are considered as rudimentary fluvial network constrained by permafrost (McNamara et al., 1999; Evans et al., 2020). Among others, active layer topography (Curasi et al., 2016), linear thermokarst (Katasonova, 1963), selective thawing of ice wedges on hillslopes (Embleton and King, 1975), zoological erosion (Hall, 1987), are named responsible for water track initiation and development.

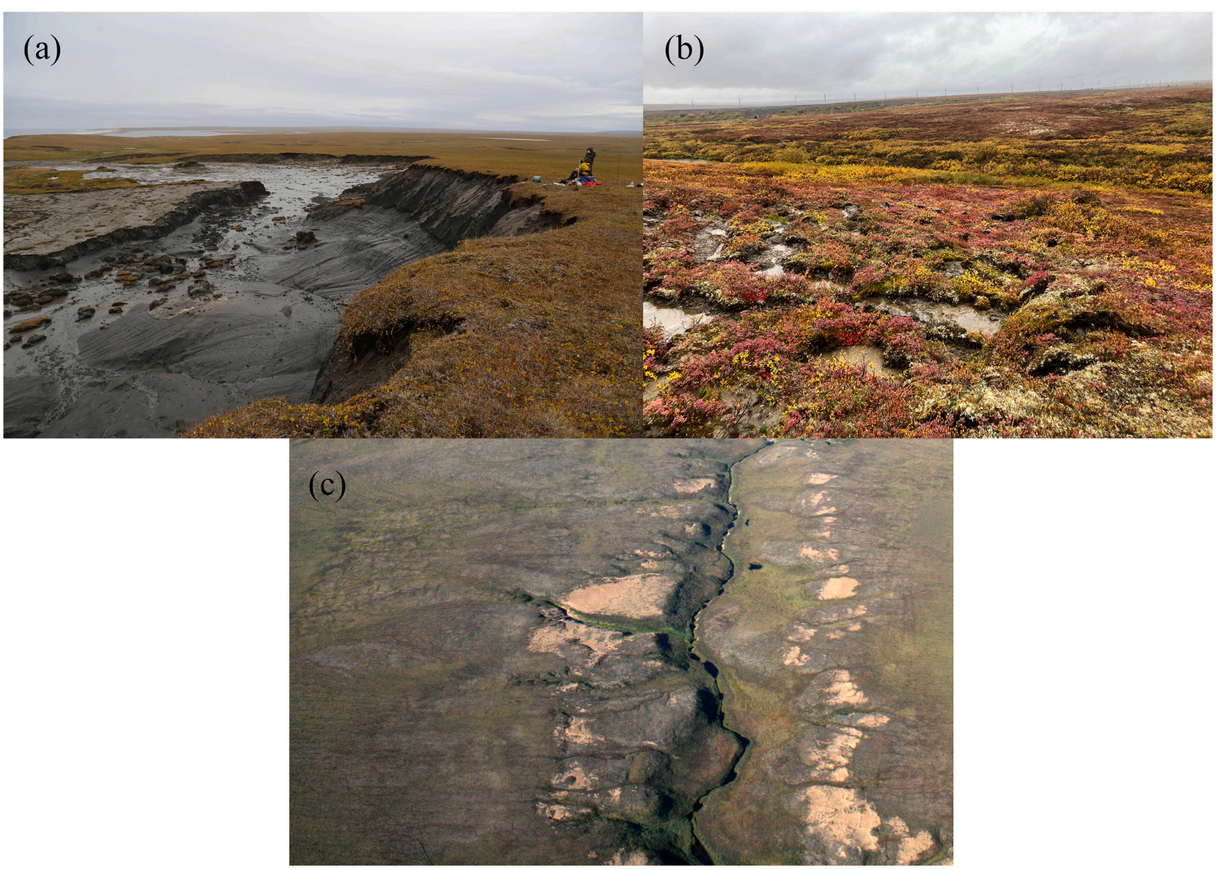

Fig. 3. Permafrost disturbance features in Arctic landscapes: (a) retrogressive thaw slump near Amderma, north European Russia; (b) active layer detachment slide near Vorkuta, north European Russia (camera looking downslope); (c) minor linear thermokarst forms converging to an incised beaded river valley, Anabar lowlands, north Eastern Siberia. Photos: (a), N. Belova; (b), (c), N. Tananaev.

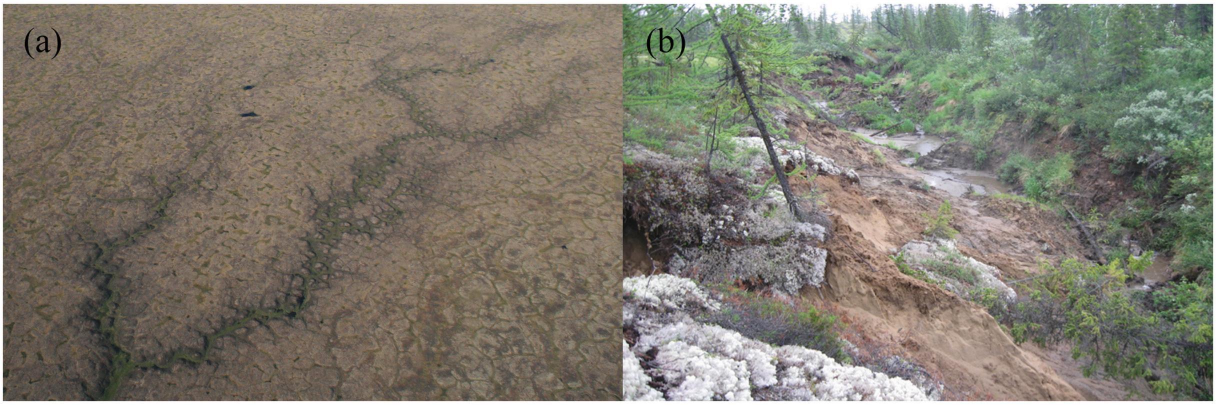

Fig. 4. Gullies in Arctic landscapes: (a) dry thermokarst pseudo-gully, polygonal tundra, Anabar lowlands, north Eastern Siberia, aerial image from a helicopter; (b) rapidly incising thermo-erosional gully, north Western Siberia. Photos: N. Tananaev.

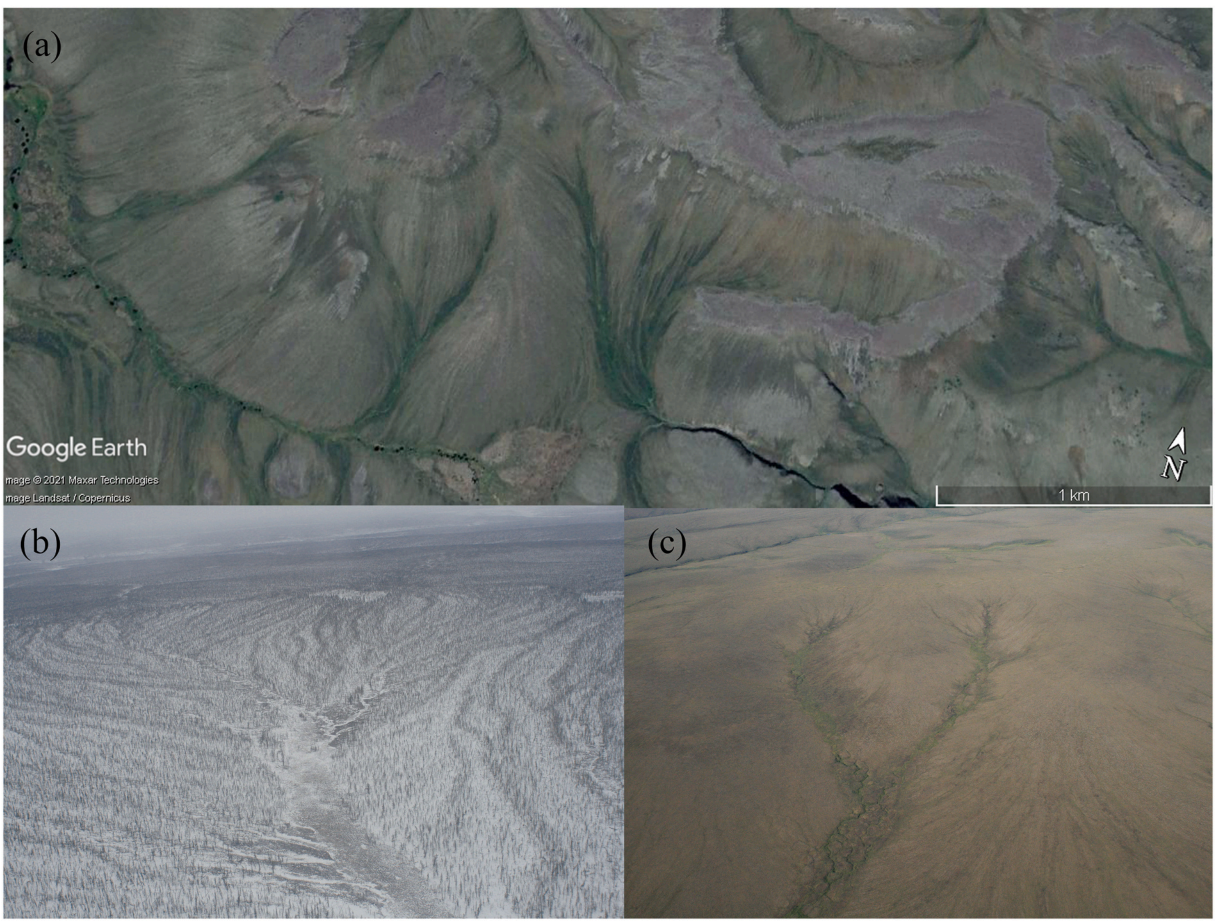

Fig. 5. Hillslope water tracks in Anabar lowlands, north Eastern Siberia: (a) dense hair-like water track network; (b) water tracks visible under snow cover, (c) water track network converging to high-order thermokarst valleys over polygonal tundra. Satellite image: Google Earth, acquisition date 8 August 2013. Photos: N. Tananaev.

One potential mechanism, proposed here, relies on data and discussion from (Schramm et al., 2007). In spring, hillslopes are frozen and remain intact. Throughout summer, saturated zone boundary consistently remains below the ground surface owing to high evapotranspiration and active layer deepening. During rainfall events, surface runoff is also limited by the transmissivity feedback effect in potential gully thalwegs (Kendall et al., 1999; Bishop et al., 2011). Toward late autumn, seasonal rains and declining plant transpiration saturate the soil profile, but this is the period of the deepest active layer that has to be fully wetted to initiate excess saturation runoff. Ultimately, overland flow occurrence and erodibility are reduced in all seasons, and gully erosion is inhibited. Resulting drainage network supposedly resembles a fully developed fluvial network in fractal dimensions, but its incision is inhibited by permafrost and related effects (McNamara et al., 1999).

This lack of understanding prevents us from claiming hillslope water tracks either cryogenic or fluvial. Based on literature review and own data, we count them as boundary fluvial landforms at the interface between hillslope and erosional network compartments.

In *river valleys* and *estuaries*, fluvial impact overrides permafrost effects and most landforms are primarily fluvial. However, streams are connected to their permafrost-affected catchments through water and sediment fluxes, and locally, to the valley slopes where cryogenic processes are active. Retrogressive thaw slumps and active layer detachment slides sustain prolonged increase in sediment transport, and can dam minor rivers affecting their channel pattern in such sections (Lipovsky and Huscroft, 2007; Lamoureux and Lafrenière, 2008; Kokelj et al., 2013).

Fluvial thermal erosion in river banks often leads to development and collapse of impressive thermo-erosional niches (Fig. 6; Lawson, 1983; Walker and Hudson, 2003). Higher potential of texture ice ablation corresponds to the ‘effective’ water stage controlled by local hydrological regime, while bank height, vertical floodplain structure and lithology of floodplain deposits represent geomorphic controls (Tananaev, 2016). During spring freshet, fluvial thermal erosion mostly occurs in high floodplain banks, and only sporadically – in medium floodplain, subject to seasonal thawing early in the season and protected by overhanging vegetation mats (cf. Lininger and Wohl, 2019). In the middle Lena River, central Yakutia, high river banks representing older floodplains show higher retreat rates, up to 70 m per year locally, compared to an average rate between 7.5 and 8.5 m (Chistyakov, 1952; Tananaev, 2016). During summer floods, intense seasonal thawing from sidewall heating is observed in most bank segments. Bank erosion is mechanical at the onset of summer floods, and only continues as thermal erosion at the later stages of floods, mostly in high floodplain banks.

Future evolution of under changing climate and permafrost loss is expected to relate to the origin of landforms (Fig. 2). Currently, permafrost is restricting the evolution of primarily fluvial features, while the evolution of primarily cryogenic landforms is inherently related to permafrost disturbance (McNamara et al., 1999; Tananaev, 2013; Sidorchuk, 2020). Permafrost loss under warmer climate will control the development of primarily cryogenic forms, either promoting or inhibiting their development, while primarily fluvial forms will tend to adjust their shape to future hydrology with less constraints from frozen ground (see Chapter 4 for discussion).

3. Defrosting northern catchments: observed and projected changes

3.1. Permafrost degradation

Permafrost degradation is driven by an increase in heat flux penetrating soils, and higher ground temperatures (Biskaborn et al., 2019), though temperature increase at zero annual amplitude depth, from 10 to 15 m, is not instructive in evaluating hydrological or fluvial change. Lafrenière and Lamoureux (2019) consider permafrost degradation as either thermal or physical perturbation of the ground surface, and this paper coins their approach. Thermal disturbance can relate to permafrost extent reduction, higher permafrost discontinuity, increased active layer volume and better hydrological connectivity in permafrost-affected catchments (Connon et al., 2014; Tananaev et al., 2021). Physical disturbance connotes to visible outcomes, such as mass wasting or higher erosion rates (Lafrenière and Lamoureux, 2019).

3.1.1. Permafrost extent

Historical permafrost extent dynamics shows its high sensitivity to even temporary air temperature increase, e.g., during the previous ‘warm Arctic’ period, in 1930’s and 1940’s, in all regions except Russia (Guo and Wang, 2017). Permafrost region extent have decreased by $1.6 \cdot 10^6$ km^2 from 1969 to 2018 (Li et al., 2022) and permafrost area, by roughly $1.25 \cdot 10^6$ km^2 from 1901 to 2010 (Guo and Wang, 2017). Consistent with projected warming, models suggest further widespread reduction of both permafrost region and area extent. Globally, modeled permafrost area drops by 35±15% by 2100 under RCP8.5 scenario (Yokohata et al., 2020), or from 36.1% under RCP4.5 to 37.6% under RCP8.5 even earlier, by 2046 (Wang et al., 2019), averaged from multiple CMIP5 climate models. The most significant permafrost loss is predicted in northern Mongolia, southern and western Siberia. Locally, it is expected to shrink by 64% on the Qinghai-Tibet Plateau, China (Lu et al., 2017), by 76% on the Seward Peninsula, Alaska, USA (Debolskiy et al., 2020), under same RCP8.5 scenario by the year 2100.

3.1.2. Active layer thickness

Active layer thickness refers generally to the maximum seasonal thawing depth, but in warmer climate, increased thermal degradation may promote shift to non-merging permafrost, where seasonally frozen layer is detached from the top of permafrost by residual thaw layers, or taliks (Linnel and Kaplar, 1966; Yershov, 1998; Shur and Jorgenson, 2007). Modeled active layer thickness has increased by about 0.2 m from 1901 to 2010, global average (Guo and Wang, 2017), and is expected to increase further.Different active layer types, identified by Bonnaventure and Lamoureux (2013): bedrock, debris, mineral, organic and submerged, would respond differently to changing climate and disturbances. The frozen soil volume in the upper 2 m of soil profile is expected to decrease by 10 to 40% with 1°C of global mean ground surface temperature increase (Burke et al., 2020). On the Alaska North Slope, by 2100, the seasonally thawed layer thickness will increase by 0.25 to 1.0 m. In the Interior Alaska the seasonal thawing will change to seasonal freezing with residual thaw layers between 1.25 and 2.00 m depth. Farther south, reduction in seasonally freezing layer thickness is expected to vary from 0.5 to 2.0 m (Streletsky et al., 2012).

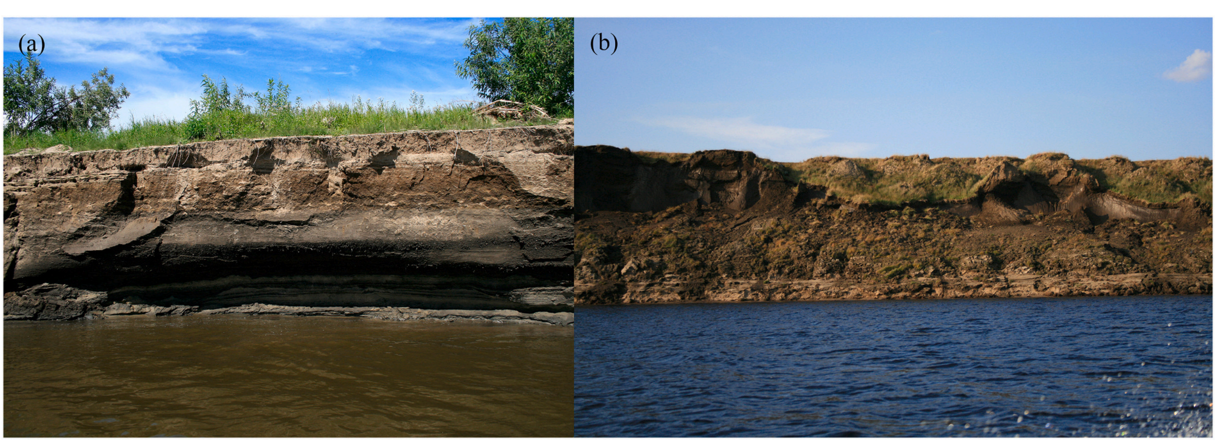

Fig. 6. Fluvial thermal erosion: (a) thermo-erosional niche in sandy deposits of a medium floodplain bank, middle Lena River, central Yakutia; (b) thermal erosion in banks containing ice wedges, lower Anabar River, north Eastern Siberia. Photos: N. Tananaev.

Landscape vulnerability to residual talik development varies with snow and organic layer thickness, and is affected by forest fires, shrub expansion and excess water accumulation at the top of permafrost (Walvoord et al., 2019; Lebedeva et al., 2019; O'Neill et al., 2020). Hydrological importance of residual thaw layers relates to their capacity to convey water during winter months, ensuring hydrological connectivity when hydrological processes at the catchment surface are inhibited (Lamontagne-Hallé et al., 2018; Tananaev et al., 2020).

3.1.3. Physical disturbance

Permafrost physical disturbance involves mass movement and vertical subsidence with visible surface disruption; in cold environments, it is abundant but highly localized, and leads to significant alteration of fluvial fluxes (Lafrenière and Lamoureux, 2019; Nitze et al., 2018). Thermokarst development is already widespread in cold ice-rich permafrost because of top-down-thaw following above-average summer warmth (Farquharson et al., 2019). Recent increase in retrogressive thaw slumping was reported in the Mackenzie Delta region (Lantz and Kokelj, 2008), in North-West Alaska (Balser et al., 2014), and Banks Island, Canadian Arctic Archipelago (Lewkowicz and Way, 2019), driven by higher summer temperatures and earlier snowmelt. Extremely large 'mega-slump' activity in the North-Western territories, Canada, is unrelated to higher summer air temperatures, but is accelerated by increased rainfall (Kokelj et al., 2015). Modeled slump initiation rates in ice-rich permafrost increase by an order of magnitude, over 10 000 cases per decade, after 2075 under moderate RCP4.5 scenario (Lewkowicz and Way, 2019). Active layer detachment slides are also expected to occur more frequently, triggered by forest fires in discontinuous permafrost, and anticyclonic conditions with high temperatures in continuous permafrost (Lewkowicz and Harris, 2005). However, in the long-term, increase in trigger frequency is not expected to increase detachment rate (Lewkowicz, 1990).

Permafrost disappearance will lead to lower terrain susceptibility to mass wasting, and land stabilization, once the ground subsidence due to ice thawing is over (Blais-Stevens et al., 2015). In ice-rich permafrost with tens of meters of tabular or wedge ice, it is not expected to happen in the nearest future, hence this system will evolve through a series of quasi-stable transitional states until a new equilibrium is reached, i.e., until permafrost completely melts away.

3.2. Hydrological change

Cold regions hydrology is expected to change under future climate, but the effect of permafrost degradation is hard to discern from other drivers, acting simultaneously in the catchments (Connon et al., 2014). Melting of ice-rich permafrost is one direct water input from thawing permafrost. Permafrost area reduction enhances hydrological connectivity, but can also impact rates and trajectories of water cycling through affected catchments, and this influence is not straightforward. Cumulatively, altered water fluxes from permafrost hillslopes and catchments influence river runoff and fluvial activity in river valleys. A simple 'space-for-time' approach is still used in hydrological predictions for the large Russian Arctic rivers, though it has limited, if any, applicability for the large-scale complex systems.

3.2.1. Ground ice melt

Global importance of direct ground ice meltwater release is probably insignificant, though may highly depend on the ground ice content and local conditions (Walvoord and Kurylyk, 2016). Active thermokarst on ice-rich permafrost supplied from 7.8 mm yr^{-1} up to 38 mm yr^{-1} to a lake in central Yakutia disconnected from the fluvial network (Fedorov et al., 2014). In high-altitude Qinghai-Tibet Plateau, highest estimated input is 5.6 mm yr^{-1} for a catchment in discontinuous permafrost with 86% permafrost coverage (Ma et al., 2019). Higher values, from 7.5 to 8.6 mm yr^{-1}, are reported for ice-rich discontinuous permafrost of Northwest Territories, Canada (Connon et al., 2014).

3.2.2. Hydrological connectivity

Permafrost extent decrease implies enhanced hydrological connectivity to groundwater through a system of interconnected taliks, or thaw layers – vertical, lateral or both (Streletsky et al., 2015). Hydrological connectivity can be understood as either connection between various surface compartments through the subsurface (Stieglitz et al., 2003; O'Connor et al., 2019; Tananaev et al., 2021), or connection to deeper groundwater sources through taliks (Lamontagne-Hallé et al., 2018). Potential effects of permafrost loss are diverse, and include: increasing winter base flow through gradual release of water retained in thaw zones, notably residual taliks; increasing annual runoff owing to increasing occurrence of vertical taliks allowing higher upward water migration and discharge from deeper intra- or subpermafrost groundwater; decreasing annual runoff following a decrease in excess hydraulic head, previously maintained by confining effect of permafrost.

Residual thaw layers increase hydrologic connectivity, most notably during winter and spring, showing stronger winter runoff correlation with autumn precipitation, and distinct isotopic signature of the heavily evaporated sources in base flow (Streletsky et al., 2015). This may partly be an inherited effect of increased subsurface travel times, caused by active layer deepening and longer percolation toward the top of permafrost (Frampton and Destouni, 2015). Under RCP8.5 scenario, annual groundwater discharge from permafrost hillslopes is expected to significantly increase by 2100. Relative increase owing to higher groundwater recharge reaches 95% in high-latitude hillslopes, and 229% on warmer high-elevation hillslopes, though this high relative increase is not expected to equate with high discharge magnitude because of the 'low base effect' (Evans and Ge, 2017). Recent simulations suggest that groundwater discharge increase through newly developed residual thaw layers is expected to be most pronounced in spring and autumn (Walvoord et al., 2019).

3.2.3. Groundwater icings

Groundwater icings in permafrost are sentinels of significant deep groundwater discharge to river valleys (Kane et al., 2003). Therefore, observed change in icing distribution and parameters would be indicative of altered hydrological connectivity with deeper groundwater flux. In Arctic Alaska, ephemeral icings are disappearing earlier in melt season, and persisting icings cover less area at peak thaw (Pavelsky and Zarnetske, 2017). In North-Eastern Russia, the area of largest icings has dropped more than twice from late 1950s to mid-2010s (Makarieva et al., 2019). In the warmer future with milder winters, fewer icings may develop in subarctic Canada ecoregions underlain by permafrost (Morse and Wolfe, 2015).

3.2.4. Total water storage

Total water storage in permafrost catchments is expected to increase with deeper active layer and persistent residual taliks, leading to higher winter baseflow. This effect depends heavily on local soil lithology and summer precipitation. Peats and sandy soils with low water holding capacity and high hydraulic conductivity will show lower increase in storage, but only slight delay in groundwater delivery to base flow. Clays and silts have higher water holding capacity, but upon percolation, this water is locked at the base of the active layer and contributes less to total runoff (Koch et al., 2013). Therefore, singled out, deeper active layer is not necessarily an important driver of hydrologic change.

GRACE satellite observations reveal the upward trend in terrestrial water storage in discontinuous permafrost domain (Velicogna et al., 2012). In continuous permafrost, downward trend is observed owing to increased evapotranspiration (Suzuki et al., 2016), or ground ice loss that exceeds soil moisture gains (Rawlins et al., 2020). Recession curve analysis was widely used in the two past decades to evaluate the hydrological consequences of permafrost degradation in terms of water storage increase (Sjöberg et al., 2013; Watson et al., 2013; Hinzman et al., 2020; Yi et al., 2021). Brutsaert and Hiyama (2012) used this method to backtrack the active layer deepening through recession curve analysis, and came up with consistent estimate between 0.3 and 1.0 cm yr^{-1} for the upper Lena River basin and its major tributaries.

3.2.5. Winter flows and ice

Winter hydrology has geographically variable impact and importance in shaping geomorphic action. In discontinuous and sporadic permafrost, winter ice-covered flow is sufficient to produce flow velocity and shear stress above the bed material transport threshold (Lotsari et al., 2020). In continuous permafrost, flow cessation is common during winter even in large rivers, hence no geomorphic action is observed. However, exposed river channels are subject to seasonal freezing of alluvium which may persist to become sub-channel permafrost. Bedfast ice occurrence promotes seasonal freezing of channel alluvium and increased channel stability. (Tananaev, 2013; Juhls et al., 2021). River ice is also an important factor in fluvial dynamics (Chassiot et al., 2020).

Deeper active layer and longer subsurface travel times cumulatively lead to observed increases in winter runoff. Minimum daily flow is increasing in the Lena River basin (Tananaev et al., 2016), in the medium-sized Yana and Indigirka River catchments (Makarieva et al., 2019), in northern Sweden (Sjöberg et al., 2013), Canadian Northwest Territories (St. Jacques and Sauchyn, 2009). In northern Alaska, cold season discharge has been increasing along with increasing fraction of subsurface runoff in total runoff and deeper active layer (Rawlins et al., 2020). In the source region of the Yangtze and Yellow Rivers, however, winter runoff was found to significantly decrease in only one of the 10 studied catchments that was underlain by continuous permafrost (Wang et al., 2017). Observations show a decrease in ice thickness on five largest Russian Arctic rivers (Shiklomanov and Lammers, 2014), reproduced also for terrestrial Arctic rivers with modeling (Park et al., 2016). The decrease in ice cover thickness increases water transport capacity of river channels and allows better hydrological connectivity with groundwater runoff (Gurevich, 2009).

3.2.6. Maximum flows

Maximum flows in permafrost rivers, as elsewhere, are responsible for major geomorphic action, though constrained by the presence of permafrost in river banks and channel beds. The observed change in maximum flows is inconsistent across the northern catchments. In North America, a decreasing trend in maximum daily flow was found in the Mackenzie River (Yang et al., 2015), and in northern Yukon, maximum flows were also decreasing in discontinuous permafrost as greater meltwater runoff is expected to enter groundwater owing to permafrost loss (Janowicz, 2011). In high alpine catchment in Austrian Alps, modeled permafrost disappearance has led to flood peak reduction by 7 to 17% because of unconstrained water percolation (Rogger et al., 2017).

In Northern Eurasia, the observed trends were found to be insignificant in six largest Russian Arctic basins (Shiklomanov et al., 2007). In the Lena River basin, only nine of the 105 gauging stations showed significant long-term trends, of them three negative and six positive (Tananaev et al., 2016). In North-Eastern Russia, no significant changes in maximum flow were found on 22 gauging stations in the Yana and Indigirka River basins (Makarieva et al., 2019).

4. Fluvial action in the future climate

4.1. Interfluves and hillslope compartment

Fluvial processes at the hillslope scale are driven by snowmelt and rainfall erosion, and their future evolution will be driven by climate forcing and permafrost disturbance (Fig. 7).On undisturbed hillslopes, significant changes to snowmelt erosion from thermal permafrost degradation are not expected. Rainfall erosivity will be affected by higher evapotranspiration, lower saturated zone boundary and major soil drying in the upper 20 cm of the profile, caused by deeper active layer or complete permafrost thaw by year 2299 (Andresen et al., 2020). Rainfall intensity is expected to increase across the Arctic (Kusunoki et al., 2015), along with probability of extreme precipitation events (Liu et al., 2021).,

On disturbed hillslopes, this trend will coincide with surface preconditioning by physical permafrost disturbance (Lafrenière and Lamoureux, 2019). Retrogressive thaw slumps and active layer detachment slides expose unprotected sediments to thawing and removal. In ice-rich permafrost and over the Ice Complex terrain, ice melt supplies a reasonable runoff during the thawing season and promote fluvial erosion in absence of the protective root mat and negligible plant transpiration (Rudy et al., 2017). Higher evaporation from topsoil in the future climate can offset this effect.

Physical disturbance acts in the hillslope compartment but its influence can transfix the fluvial system and promote fluvial adjustment downstream from disturbance zone, especially where fluvial pathways are short (Kokelj et al., 2020). Frozen soil blocks and thawed material overload rivers with sediments and transform their channel pattern both upstream and downstream from disturbance (Shur et al., 2021). Increased sediment supply to streams under stable hydrology exceeds their transport capacity and leads to widespread floodplain aggradation, as reflected in the alluvial record of medium rivers of the North Slope, Alaska (Mann et al., 2010). Ecological effect can also propagate upstream from disturbances (Pringle, 1997).

In high altitude permafrost with bedrock active layer, frost weathering increases particulate fluxes from hillslopes. Frost weathering intensity increases with number of freeze-thaw cycles and in presence of persistent snow patches promoting nivation (Thorn and Hall, 2002; Anderson et al., 2013; Deprez et al., 2020). Milder climates are projected

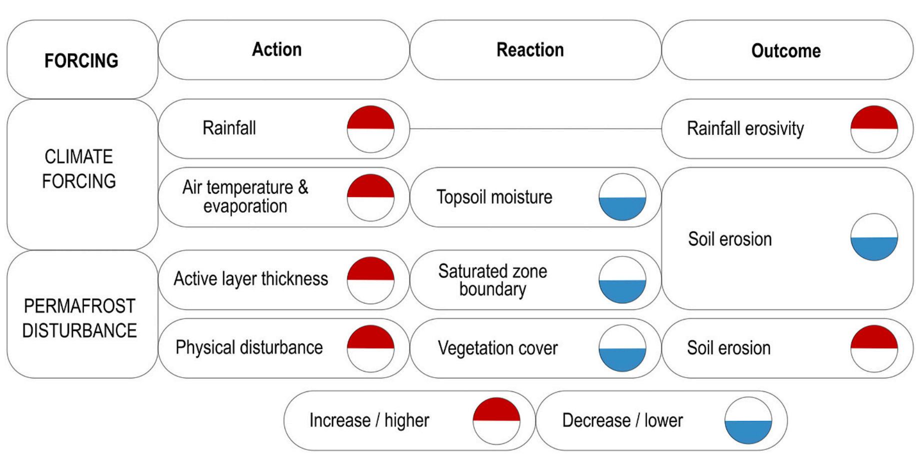

Fig. 7. Potential outcomes of climate change and permafrost degradation on soil erosion on hillslopes in cold environments

to see a decrease in annual freeze-thaw transitions, and colder climates, an increase is expected, followed by intensified frost weathering and associated, respectively, with higher particulate and chemical fluxes (Henry, 2008; Peng et al., 2016).

Primarily fluvial landforms, i.e., rills, are expected to evolve with changes in precipitation and evapotranspiration, and adjust to drier topsoil, that will reduce their activity and lead to a *future decrease in soil erosion* on both disturbed and undisturbed hillslopes. Physical degradation features are primarily cryogenic, their future initiation rate will be controlled by direct permafrost thaw, trends in air temperature and precipitation, forest fires and other feedbacks. Particulate fluxes will *increase along shorter fluvial pathways* with higher initiation rates projected for the late 21st century, and *remain stable along distant connections*.

4.2. Gullies and erosional network compartment

Permafrost constrains the initiation and evolution of erosional networks, though exact mechanism is still poorly understood (McNamara et al., 1999). Tipping point in thermo-erosional gully evolution is the inception of an ephemeral stream with direct contact between running water and frozen ground, and this point is rarely met under common Arctic tundra conditions.

Thermo-erosional gullies are widely observed in regions with non-cohesive sandy frozen soils with low ice content, e.g., north Western Siberia, where surficial deposits are highly susceptible to 'regular' fluvial erosion (Poznanin, 1995). Total heat flux of ephemeral streams and resulting conductive heat transfer to the underlying permafrost are sufficient to initiate and maintain a linear erosional feature. Hillslope steepness and contributing area will remain time-invariant, while above-critical surface runoff depth duration will decrease because of drier topsoil and longer subsurface transfer through deepening active layer. However, raising air and surface temperatures, higher precipitation and warmer rain water, and increased potential particle detachment rate due to thermal impact suggest an overall *increase in linear thermal erosion activity* in future climate (Sidorchuk, 2020).

Physical disturbance creates primarily cryogenic landforms which evolve through active thermokarst, but also accommodate streams promoting their thermal decay. The relative role of thermokarst appears to be most important in loess and organic soils, less important in colluvial soils and insignificant in aeolian deposits (Godin, 2016). In Alaska, it results in overall polygonal landscape wetting as the number of wet troughs is increasing (Liljedahl et al., 2016; Jorgenson et al., 2018). Currently, thermokarst plays an important role in development of pseudo-gullies in polygonal tundra with abundant ice wedges, as described in (Godin and Fortier, 2010, 2012; Godin et al., 2014; Veillette, 2019; Morgenstern et al., 2021). A conceptual model of ice wedge degradation developed by Kanevskiy et al. (2017) suggests high potential of post-disturbance terrain stabilization. Thermokarst lake development and their subsequent drainage are most probable terrain evolution scenario, so *no change in fluvial activity of thermokarst pseudo-gullies* is expected in the future.

In central Yakutia, ice wedge degradation creates 'bubbling' terrain with round-shaped polygons, locally known as 'byllar', and mostly dry inter-polygonal troughs (Fig. 8). Byllars are mostly associated with disturbed and abandoned terrain, i.e., arable lands or airfields (Saito et al., 2018), but are also widespread on the south- and south-west facing slopes of thermokarst lake valleys (alas), where their initiation is promoted by insolation (Séjourné et al., 2015). In otherwise smooth relief of central Yakutia, these forms convey water downslope, they can host minor ephemeral streams and produce alluvial fans at toeslope. Both over flat terrain and on slopes, byllars are expected to increase in occurrence over time, but only on slopes this may presumably *promote fluvial action and lateral material transfer*, with increased hilltoe deposition. However, most affected slopes in alas valleys are disconnected from fluvial networks, and this effect will not propagate across the fluvial system.

Tunnel thermo-erosion described in the High Arctic by Bowden et al. (2008) and Docherty et al. (2017) attracts particular attention in the scope of climate change. In fine deposits with high ice content, tunnel thermo-erosion is related to ice volume loss owing to deeper active layer along the subsurface preferential flow path, de facto, linear thermokarst (Bowden et al., 2008). In river valleys, such tunnels can be attributed to preferential filtration through coarse-grained floodplain material (Docherty et al., 2017; Ushakov and Ukhov, 2020). In both cases, higher water temperature under future climate is expected to promote tunnel thermo-erosion, other factors held equal. Important consequences include *increase in sediment, major element and dissolved organic carbon fluxes*. Interestingly, warmer water on hillslopes, intensified heat exchange with surrounding soils and moisture transfer in deeper horizons are argued to reduce water temperature in headwater channels of permafrost-free catchments and thus, in permafrost-free future (Sjöberg et al., 2021), though we can argue that 'space for time' approach is not necessarily accurate in cold environments.

4.3. Hillslope water tracks

Water tracks are rarely developing as erosional features, though fine material deposition was observed in some water track thalwegs in Chukotka underlain by highly erodible volcanic deposits (Tarbeeva et al., 2021). In High Arctic environment, the eluviation of fines from the sorted coarse material stripes may emulate erosional environment (Paquette et al., 2017).

The active layer deepening and increased precipitation will highly

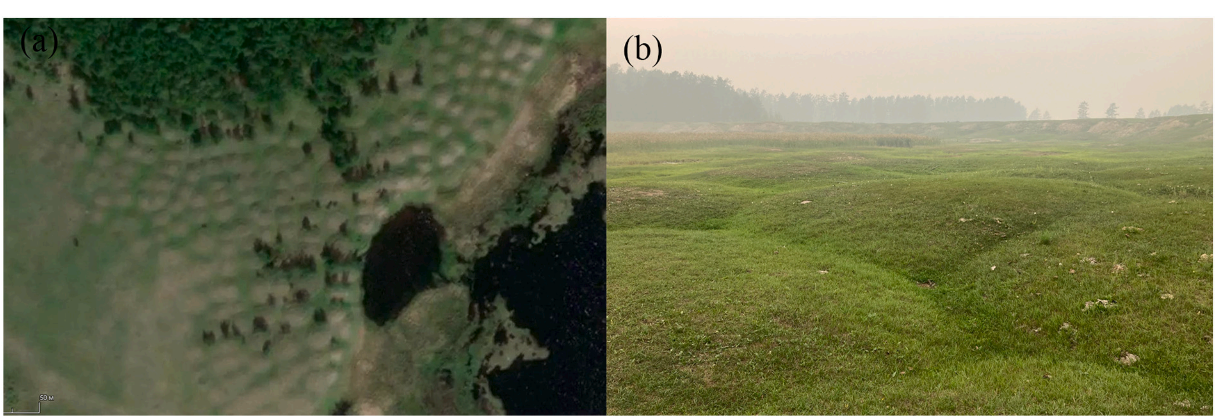

Fig. 8. Byllars, widespread thermokarst landforms of central Yakutia produced by ice wedge degradation: (a) byllars over alas valley slope; (b) byllars at the flat drained lake bottom. Satellite image: Google Earth, acquisition time: August 2020. Photo: N. Tananaev.

likely have a set of diverse consequences for water tracks. Shrub expansion toward water track thalwegs will result in higher snow retention capacity, warmer permafrost and talik development, increased soil moisture content and higher rates of organic accumulation (Hastings et al., 1989), but also higher plant transpiration. Hydrologic connectivity, already high in presence of water tracks, will be further enhanced (Evans et al., 2020). Higher heat content and total heat flux might not necessarily produce rapid thermal erosion and incision, but instead promote lateral water track expansion, increase in width, merging and avulsion of subsurface flow paths on low-energy organic hillslopes (Trochim et al., 2016a). On the other hand, longer subsurface flowpaths increase runoff duration in water track thalwegs and thermal loading on underlying permafrost, promoting thermokarst and thaw subsidence.

Water tracks are primarily fluvial features; however, under changing climate, it is unclear which drivers would dominate in their evolution. One potential future trajectory is sparce water track network where individual landforms are wider and deeper incised in their downstream sections, and develop better inter-track connections through the subsurface (Tananaev et al., 2021). North European Russia is one model region in discontinuous permafrost, showcasing this trajectory. The alternative is rapid water track development into a full-scale erosional network after the constraints imposed by permafrost are lifted. Surficial geology might ultimately control future evolution of hillslope water tracks in warmer climate. Coarse highly permeable moraine deposits, ice-rich permafrost and bedrock will suppress incision and promote lateral expansion, while active incision might occur in loose sediments.

4.4. River valleys

In river valleys, permafrost underlies floodplains, and is exposed in the riverbed and in river banks, thus only the sub-channel talik zone remains non-frozen. Catchment-scale permafrost disturbance connects to rivers through increased particulate fluxes, and their impact is more expressed in smaller streams with shorter fluvial pathways. Since most landforms in river valleys are primarily fluvial, their evolution in future climate will adjust to future hydrology with lifted permafrost constraints.

4.4.1. Floodplain development

Contemporary (Holocene) floodplains are depositional environments, and floodplain permafrost is aggrading even under current climate. Overbank deposits are subject to syngenetic 'bottom-up' freezing, so that long-term annual average permafrost aggradation at the active layer base equals the thickness of freshly deposited floodplain alluvium (Shur and Jorgenson, 1998). Under meandering channels, permafrost recovery rates during the refreezing of sub-riverine talik are as high as 1.0 m yr^{-1} during the first decade, and declined to values between 0.4 and 0.6 m yr^{-1} with frozen layer thickening (Crampton, 1979; Stephani et al., 2020). In discontinuous permafrost, floodplain was freezing during low runoff periods with less snow cover and heat insulation during the last millennium (Payette and Delwaide, 2000). Upon freezing, floodplain surface experiences additional uplift proportional to water/ice content in freshly frozen material. This process increases floodplain height and prevents its inundation. Floodplain consolidation progresses, followed by flow cessation in secondary branches during off-peak flows and development of fluvial pattern typical for incised channels in non-permafrost environments (Tananaev, 2018).

Floodplain permafrost thawing induces overall terrain subsidence, with increased inundation probability and duration, and higher fluvial activity in secondary channels. Hydrological change alone can directly lead to floodplain permafrost loss. Longer inundation can cause the active layer deepening by more than 1 m in homogenous sand and gravel deposits (Zheng et al., 2019). Large periglacial anabranching rivers react rapidly to changing climate and hydrology, including an increase in the number of major islands and a decrease in island area (Gautier et al., 2021). Subsiding floodplain is a sediment sink with growing storage capacity.

In migrating alluvial channels, reduced permafrost aggradation rate is expected in the future, which can potentially lead to longer period of non-frozen point bar development at inner meander banks, leading to higher erosion rate at the outer banks. Increased overbank deposition will increase transport capacity downstream the aggrading floodplain section, generally leading to increased riverbed and bank erosion (Alekseevskiy et al., 2008). In smaller rivers with shorter fluvial pathways, increased sediment fluxes from physical permafrost disturbance will promote floodplain aggradation (Mann et al., 2010). This effect will be damped in larger catchments with high storage capacity, as was previously shown for the impact of human activities (Trimble, 2012). Future changes in river hydrology are expected to alter the effective discharge values, both above and below the bankfull line, which are responsible for the development of floodplain levels and bank and bed topography, respectively (Tananaev, 2016; Lininger and Wohl, 2019).

4.4.2. Riverbed (channel) erosion

In permafrost regions, river bed material is subject to seasonal freezing, especially in alluvial river channels with fine-grained alluvium. Repeated seasonal freezing and incomplete thawing owing to thermal offset effect produce perennially frozen cores over the sub-riverine taliks in large alluvial bars and under secondary channels (Tananaev, 2013). Relict permafrost may persist at depths down to 30 m below the average annual water stage in point bars adjacent to floodplains (Stogniy, 2003). Field evidence is inconclusive on the extent of contemporary sub-riverine permafrost and controlling factors (Tolstov, 1966; Zernov, 1987; Arcone et al., 1998; Zaitsev and Tananaev, 2008).

Frozen riverbed surface area is related to channel pattern and cold period hydrology. In braided and anabranching rivers, over 70% of channel area below bankfull stage is subject to seasonal freezing and, possibly, permafrost core development, while under 50% in meandering rivers, and from 25 to 30% in relatively straight channels (Tananaev, 2013). Seasonal freezing occurs annually in exposed channel sections, and where bedfast ice is present.

Winter runoff increase associated with permafrost degradation, along with a decrease in ice cover thickness, would greatly reduce the channel area exposed to seasonal freezing. Even without significant change in maximum daily flows, lesser areal extent of seasonal freezing will lead to higher sediment availability during spring freshet. This change may be accompanied by an increase in heat flux during open water period, as already observed in the Lena River outlet (Tananaev et al., 2019) and modeled for the Pan-Arctic domain (Park et al., 2017). Loss of sub-channel permafrost and reduced extent of seasonal freezing would promote bedform mobility and *increase total bed material load*. A minor *decrease in maximum bed scouring depth* during spring freshet can be expected, since riverbed erosion will become less spatially constrained by frozen alluvium and less confined to deeper channel sections.

Ice cover in northern rivers increases near-bed velocity and shear stress at the expense of surface velocity, which is limited by high roughness and flow resistance of the ice cover bottom (Fig. 10; Ettema and Daly, 2004; Knack and Shen, 2015; Lotsari et al., 2017, 2019). Excess hydraulic head driven by 'piston effect' from ice growth can also increase bed shear stress, thus promoting sediment movement under water discharges under critical values for open channels (Turcotte et al., 2011). A projected increase in winter discharge will be counter-balanced by a decrease in ice thickness, but only partially, thus leading to *increased sediment fluxes under the ice cover*.

Ice processes affect channel morphology (Turcotte et al., 2011, and references therein), most notably through ice jams and associated bed deformations. Numerous evidences from the repeated bathymetric surveys, performed by Tananaev in early 2000s on the middle Lena River (unpublished), show that ice jams are responsible for massive sediment deposition close to the ice lock, and flow redistribution via the secondary branches with limited local scouring, as described by Kellerhals and Church (1980). Thinner ice cover is likely to result in *reduced ice jam occurrence* and associated fluvial change (Beltaos and Bonsal, 2021).

Seasonal patterns of bed topography evolution are expected to change in largest permafrost rivers with fine-grained alluvium, i.e., all major rivers of Northern Eurasia in their lower reaches. In permafrost-affected rivers, river bed erosion during spring freshet is only confined to non-frozen areas, including deepest submerged sections of large longitudinal and transverse bars and pools between bars, so these sections are generally over-deepened at high runoff, and heavily siltated under low-flow conditions. Permafrost loss will invert this seasonal pattern: deposition will occur on transverse bars during spring freshet, and erosion, during low flow periods, which is a regular pattern for non-permafrost rivers (Chalov, 2021). In the future, this might affect navigability of the largest Russian Arctic alluvial rivers and induce additional maintenance costs.

4.4.3. Fluvial thermal erosion

Thermal erosion of river banks is jointly controlled by fluvial activity, thermal interaction and cryogenic processes, and anticipated change owing to permafrost degradation is hard to decrypt (Fig. 9). Among other factors, stream size, relative bank height and presence of permafrost in banks have highest importance.

In permafrost rivers, higher erosion rates are observed in higher banks where thermal erosion prevails over mechanical washout (Tananaev, 2016; Gautier et al., 2021). Floodplain subsidence, as shown in Section 4.4.1, controls relative bank height along with maximum daily flow (hydrological control) and active permafrost disturbance (cryogenic controls).

Thermo-erosional niches are incepted around water stage with higher probability of occurrence (duration) during warm period, in direct analogy with effective discharge (Tananaev, 2016). Maximum daily flow in Arctic rivers is either stable or slightly decreasing, but no direct evidence exists whether these trends affect frequency distribution of daily water stage and discharge. The projected water temperature increase in northern rivers, by 1.4 to 2.1°C for 2071-2100 compared to 1971-2000 (Van Vliet et al., 2013), can effectively promote ice ablation and *increase bank erosion rates*, but this may be mostly relevant for higher banks. Polygonal floodplains will be particularly vulnerable to bank erosion in future climate, with exposed wedge ice in bluffs subject to preferential melt and subsequent collapse of the whole inter-wedge

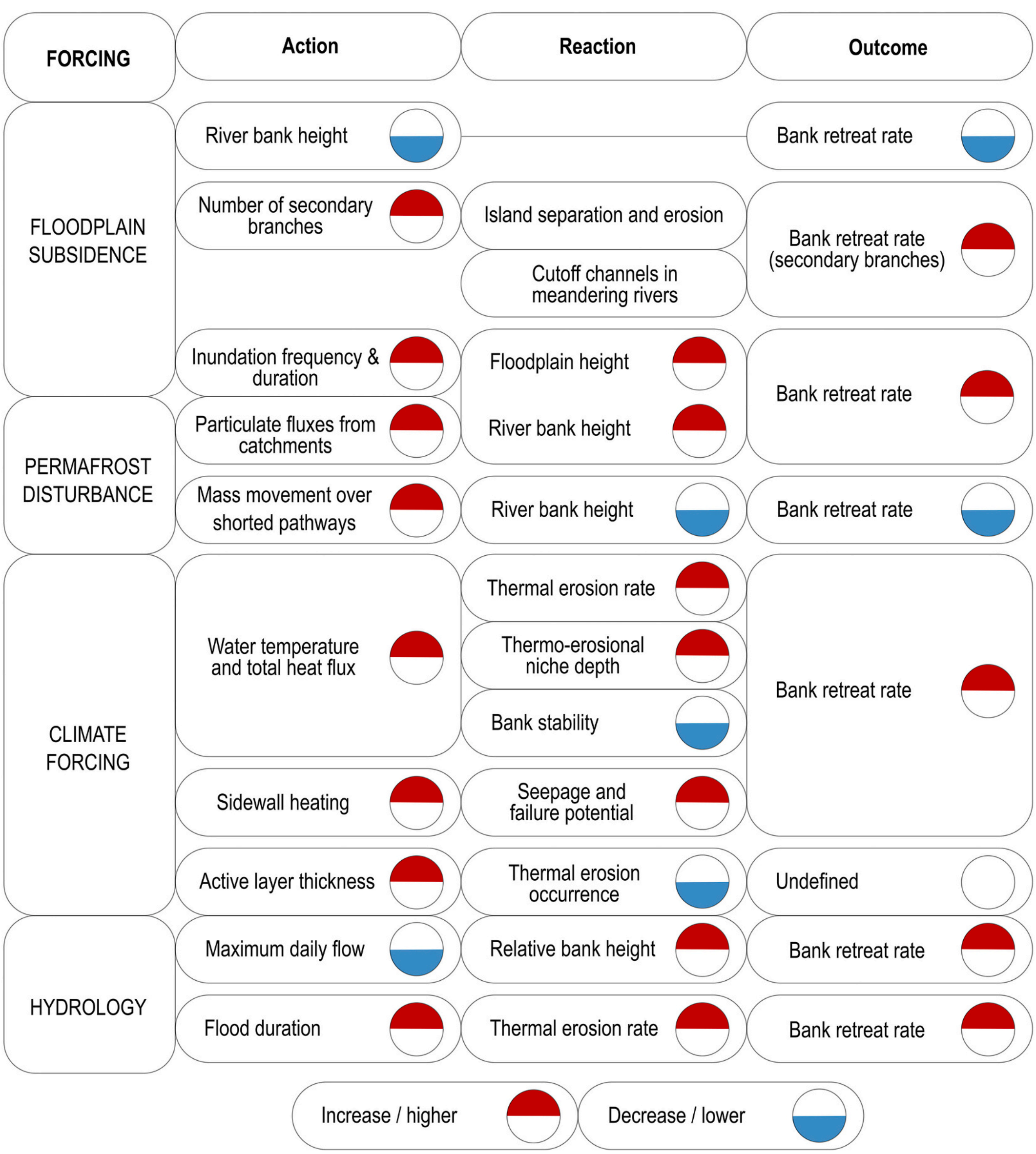

Fig. 9. Potential outcomes of climate change and permafrost degradation on fluvial thermal erosion of cold climate riverbanks

polygon material, creating a scalloped bank typical for the region.

Cryogenic processes independently in shaping river banks (Fig. 10), through mass wasting and massive ground ice melt (Stettner et al., 2018). Mass wasting processes, i.e., thermal denudation, can reduce bank height and, hence, decrease the bank retreat rate, providing yet another example of cryo-fluvial interaction. Observations show a 60% decline in sediment release from an ice-rich bank section from 2011 to 2019, resulting from bank retreat rate decrease from 8.7-10 m/yr to 4.5-5.8 m/yr at the bank top, and from 4.7-7.5 to 1.3-1.7 m at its base in one well-studied meander bend of the Itkillik River, northern Alaska. Bluff section in the studied reach was smoothed to lower bluff height by thermal denudation, and later stabilized by vegetation (Shur et al., 2021).

Groundwater seepage is an important mechanism of bank erosion and retreat (Fox et al., 2007). In subarctic rivers with sporadic permafrost in their valleys and temporarily freezing banks, this mechanism was proved to be effective during the open-water period, and clayey bank segments were shown to be most affected (Lotsari et al., 2020). In permafrost-affected rivers, this mechanism currently has limited competence in eroding banks because groundwater availability is limited, and water volume in the soil matrix is insufficient to create substantial negative pore pressure. With increased sidewall heating, deeper seasonal thaw in bank material and higher seepage potential, this factor will grow in importance in the warmer future.

Position of an eroded bank segment in relation to the flow, or angle of attack, is important. Similar to non-permafrost areas, retreat rate is highest at meander apex zones and along the downstream outer banks. In large alluvial Lena River channel, island heads are eroded faster in the changing climate because of increasing heat content of the spring meltwater peak (Costard et al., 2014). This effect, as we suggest here, is temporary and niche, and only observed in largest alluvial rivers. It corresponds to a lag period between rapid increase in water temperature and subsequent increase in suspended sediment supply and bed mobility due to permafrost loss. After this lag period, rapid sediment accumulation upstream from island heads owing to backwater effect may lead to merging of these head bars with existing islands, and retrogressive (upstream) island movement, which is typical for depositional conditions in river channels.

4.4.4. Channel pattern & hydraulic geometry

Stream hydraulic geometry of periglacial rivers is expected to reflect permafrost controls over channel adjustment, yet they are substantially understudied. Previous studies report disproportionally wide channels and valleys in permafrost, explained by active solifluction over the slopes of minor tundra valleys (Molchanov, 1972). Unconventional hydraulic geometry relationships were obtained for upper Yukon River catchments, and attributed to permafrost controls over channel depth to width ratio (Crawford and Stanley, 2014). A two-stage channel adjustment process was described, where in headwater streams, higher runoff was associated with channel deepening and not widening, while in high order river sections, vice versa, widening without significant deepening was observed.

One possible explanation, in line with the preceding discussion, is that first order streams in the headwaters were developing rather through thermal erosion, while farther downstream, less thermal interaction and permafrost-constrained incision, along with increased sediment supply from the incising headwaters, have led to channel widening. Permafrost loss is expected to invert this two-stage adjustment pattern, through less constrained lateral channel shifts, but also decreased sediment supply in the headwaters, and subsequent incision in the downstream sections, but this conclusion is highly uncertain. However, in streams with larger drainage areas, over 300 km^2, channel depth again increased more rapidly than width (McNamara and Kane, 2009). This threshold behavior is explained by the presence of bedfast ice, which limits channel scour in smaller streams (Priesnitz and Schunke, 2002), but leaves significant portions of the river bed exposed to fluvial erosion in larger streams. In this scope, higher water temperatures and decreased ice thickness are expected to act jointly in promoting vertical deformations in larger channels. As noted by McNamara and Kane (2009), datasets containing hydraulic geometry data for permafrost regions are scarce, and present analysis is incomplete.

None of the major channel patterns is uniquely typical for cold

Fig. 10. Non-fluvial river bank retreat processes: collapse of a 30m high river bank section related to massive ground ice melt, Maly Anuy River, Western Chukotka, Russia. Photo: N. Tananaev.

climate conditions (Huisink et al., 2002), though in certain periglacial and paraglacial environments, braided rivers prevail (Pin'kovskiy, 1965; Mikhaylov, 2011; French, 2017), Unconstrained braiding in permafrost rivers can be promoted by higher width-to-depth ratio and widespread freezing of channel alluvium. Other controls over the development of braided/anabranching channels, i.e., bed material load in relation to stream transport capacity, bank strength and riparian vegetation, might be not less important (Huisink et al., 2002; Candel et al., 2021; Chalov, 2021). Channel pattern and area exposed to bed material freezing are closely related, see Section 4.4.2. In this regard, seasonal and perennial freezing of bed material assures channel pattern stability even where the channel itself is relatively unstable, with active bed deformations and bank erosion (Tananaev, 2013). Increasing air temperatures and higher riverine heat fluxes are expected to increase bed material load, and potentially *drive pattern shift from meandering to braided*. Inversely, a substantial decrease in maximum flows or effective discharge may lead to a gradual transition from braided channel to meandering with secondary branches (Alabyan and Chalov, 1998).

Higher bank retreat rates in braided rivers, see Section 4.4.3, are expected to further increase width-to-depth ratio, promote in-channel accumulation and reoccupation of bedforms by vegetation, and ultimately drive their transition to anastomosing channel. In single-thread channels with cohesionless floodplains, we expect gradual transition toward pseudomeandering pattern (Visconti et al., 2010), more pronounced in smaller rivers with higher discharge variability. These processes will also be relevant for icing glades where icing fields are expected to experience significant decrease in both ice extent and duration.

Numerous geomorphological models relate contemporary channel patterns to various hydrologic metrics, but their efficiency in predicting future change is debated (Anisimov et al., 2008). The application of classical 'slope-discharge' relations, adjusted for grain size, to a set of 12 North-European river sections, partially affected by permafrost, have shown that only four sections are projected to experience fluvial pattern shift from a single-thread, either straight or meandering, to a multi-thread braided channel, under projected annual runoff increase by 10% to 20% (Anisimov et al., 2008). Expected sediment flux increase along with higher discharge may produce additional fluvial effects, though this question is substantially understudied (Chalov and Ermakova, 2011).

Changes in ice regime may affect the geomorphic effectiveness of bankfull stage in permafrost rivers (McNamara and Kane, 2009). Otherwise, hydrological change, shift from nival to pluvial regime (Beel et al., 2020), would significantly affect frequency distribution of daily and maximum discharges, change effective discharge and lead to the adaptation of hydraulic geometry to new hydrological conditions.

River icings, widespread in northern catchments, are independent geomorphic agents, transforming the river valley bottom. Icing glade is a typical anabranching channel pattern with underdeveloped floodplain and quasi-absence of woody vegetation (Ensom et al., 2020). Icing response to projected climate change is still debated, but recent observations support further decline in icing occurrence and extent (Pavelsky and Zarnetske, 2017; Crites et al., 2020). Reduced icing extent and accumulated ice layer thickness might lead to partial revegetation of icing glades, increased braidplain stability, siltation and abandonment of the former secondary channels, and their transformation to low floodplain.

4.5. Estuarine compartment

River deltas and estuaries are interfaces between the riverine and the marine environments, dominated by ice and permafrost which provide increased stability to deltaic channels. Low-gradient deltaic environments are dominated by thermal interaction between river water and surrounding alluvial deposits. Future change associated with higher air and water temperatures, permafrost degradation and reduction in ice thickness, will lead to higher channel mobility, less overbank deposition and increased rates of delta shoreline propagation (Piliouras et al., 2021).

Larger amplitudes in water stage during ice-free period are expected, since marine ice retreat and later sea refreezing might increase the probability of windblown backwater conditions and related water stage fluctuations (Isaev et al., 2019). This may lead to intensified thermal bank abrasion and coastal erosion during summer storm events (Cunliffe et al., 2019; Lim et al., 2020), putting at risk numerous communities along the Arctic Ocean coast.

5. Projected effects of fluvial change

5.1. Fluvial change and biogeochemical cycles

Cryo-fluvial interaction exposes substantial stock of organic material currently stored in permafrost (Van Huissteden, 2020). Permafrost physical disturbance displaces organic material downslope, and removes protective vegetation mat from frozen deposits, promoting localized permafrost degradation. At interfluves, local thermokarst depressions are expected to increase in size and subside owing to an increased ground ice loss with higher temperatures, abruptly increasing permafrost carbon emissions and associated radiative forcing (Walter Anthony et al., 2016). Accounting for thermokarst effects increases modeled carbon release from thawing permafrost up to 12 times under RCP8.5 by 2100 (Nitzbon et al., 2020). In minor river valleys, fluvial thermal erosion supplies eroded bank material directly to the streams, and exposes massive ground ice which is also an important and vulnerable stock of organic carbon, though still insufficiently quantified (Fritz et al., 2015).

The effects of permafrost degradation on DOC fluxes are variable and non-uniform across the northern environment (Frey and McClelland, 2009). Increase in active layer thickness in mineral soils leads to higher DOM adsorption on soil particles, decreasing DOM export, especially where higher DOM fluxes were associated with shallow subsurface runoff through the organic layer. In organic soils, and in regions with abundant peatlands, deeper summer thawing and potential residual thaw layer development increase hydrological connectivity through the active layer, and lead to an increase in DOM export (Frey and McClelland, 2009; Walvoord et al., 2019; Tananaev et al., 2021). Physical permafrost disturbance is also reported either to increase or decrease the downstream DOC concentrations (Abbott et al., 2015; Lafrenière and Lamoureux, 2019).

Dissolved organic carbon (DOC) in largest Arctic rivers is modern (Raymond et al., 2007). This is in part related to the dominance of fresh leachate DOC in Arctic streams, and in part, affected by active preferential microbial degradation of old, but highly labile permafrost DOC (Mann et al., 2015). Signals of the DOC aging were recently observed in the northern Mackenzie River (Schwab et al., 2020), potentially reflecting changes in subsurface throughflow, occurrence of mass-wasting processes or tapping the transient layer DOC sources. Particulate organic carbon (POC) is generally older than DOC, since particulate material is supplied by floodplains and adjacent hillslopes, and collapsing peatlands (McClelland et al., 2016; Wild et al., 2019). Increased occurrence of physical permafrost disturbance, including thaw slumps and detachment slides, may lead to increased POC supply, but this POC was recently shown to be predominantly recalcitrant (Keskitalo et al., 2021). Northern rivers are also shown to be major pathways of mercury transport to the Arctic Ocean (Sonke et al., 2018).

5.2. Fluvial changes, ecosystems and societies

Northern societies rely heavily on permafrost environments, rivers and associated landforms, and numerous ecosystem services they provide, which are now endangered (Miner et al., 2021). Extensive tundra areas and forested hillslopes across permafrost regions are traditionally used for reindeer herding, and fluvial disturbance related to climate change may reduce pasture capacity and foraging sustainability (Istomin and Habeck, 2016). Industrial development in reindeer herding regions, in its turn, leads to wide appearance of off-road tracks, which are known to promote linear thermal erosion and subsequent gullying (Kumpula et al., 2011; Kevan et al., 1995). A comparable loss of Arctic tundra biodiversity may come from prolonged tundra flooding associated with projected shift to pluvial regime, as was observed recently in the lower Indigirka River, North-Eastern Russia (Beel et al., 2020; Tei et al., 2020).

Soil erosion and sediment dynamics affect global water security globally (Owens, 2020). Northern communities rely heavily on water supply from rivers and lakes, since deeper permafrost groundwaters are unavailable or lack drinking water quality, i.e., are saline. Higher suspended sediment concentration associated with permafrost loss, either through increased soil loss to hillslope and gully erosion, or active river channel and bank erosion, increases pressure on water supply facilities. This increase in suspended sediment concentration is not confined to a certain season or water regime phase.

Permafrost loss may lead to an increase in bed material fluxes. In the Lena River main channel, 120 km upstream from Yakutsk, in-channel permafrost degradation caused by a period of increased water runoff have increased large bedform migration rate, which resulted in the sub-channel water intake blockage by bedload and disruptions in water supply to several communities (Tananaev, 2007). Here, higher bed mobility will lead to an increase in maintenance costs of sub-channel water intake facilities.

Fluvial thermal erosion is expected to intensify in the coming decades, an effect from raising water temperature and heat flux, putting at risk rural communities along permafrost rivers. In North-Eastern Russia, numerous communities have already reported damage from thermal bank erosion in two previous decades. A system of protective spur dikes was constructed between 2005 and 2007 in Zyryanka, middle Kolyma River, after a spectacular property loss during 2003 spring freshet, resulting from frozen bank failure. Similar dikes already protect communities on the middle Lena River, and on Viluy River, western Yakutia, and some settlements are currently at risk

In large periglacial rivers, navigable passages in longitudinal and transverse bars are naturally eroded, even over-deepened, during spring freshets, and are subject to sediment deposition under low-flow (Tananaev, 2013; Chalov, 2012), in contrary to non-permafrost rivers. Permafrost loss and an increase in sediment mobility are expected to revert this evolution sequence, with channel bar deposition in spring and erosion during low-flow. During spring freshet, this will have a negligible effect on river transportation, since water stage is high and not limiting the navigable passage. However, under low-flow conditions, erosion in natural navigable passages will be retarded by higher bed mobility, and disruptions in riverine navigation are expected to become more frequent in the nearest future. Overall channel instability will lead to increased waterways maintenance costs and higher probability of navigating staff errors, leading to ship blockage in shallow waters.

6. Future research perspectives

6.1. Permafrost hydrology

Permafrost hydrology concerns water migration in both surface and subsurface compartments driven by gravity and phase-state change. Hydrological research is not falling by default into permafrost hydrology domain if conducted in permafrost-affected region, but only if cryo-hydrological interaction is directly concerned (Tananaev et al., 2020). This approach requires the development of methodologies and research protocols proper to permafrost hydrology, and interpretation of instrumental observations.

Active layer hosts abundant elementary forms of ground ice, which are poorly quantified. In geocryology, these ice features are regarded as ephemeral as they never survive the summer season, conceding to the active layer development. Their influence on hillslope hydrology is disproportionate to the amount of attention drawn. Horizontal segregation ice lenses lower the rate of thawing front propagation in the early summer because of the high latent heat of fusion of the pure ice, limit infiltration rate and capacity, and locally promote saturation excess overland flow. Vertical elementary ice wedges, or vein ice, are probably less common in the active layer, but their presence can impede subsurface drainage through local damming effect.

Residual thaw layers are emerging features, growing in abundance with the progression of permafrost degradation. Their hydrological role was recently discussed in several review papers and modeling studies (Lamontagne-Hallé et al., 2018; Walvoord et al., 2019; O'Neill et al., 2020). Field data are needed to explain their origin, quantify excess hydraulic head during the freezing season, evaluate average residence time and their role in maintaining hydrological connectivity in river basins losing permafrost.

River icings capture and store a significant amount of winter runoff otherwise available as base flow. A recent review of Ensom et al. (2020) provides a brief statement on icing research objectives, and concludes on the region-specific response of icings to future climate change. However, only limited field observations on icing volume and its evolution throughout both accumulation and meltdown seasons exist, and field procedures yield significant uncertainties (Gagarin et al., 2020). Icing connection to groundwater sources is long assumed and described qualitatively, but lacks detailed quantification.

6.2. Permafrost and fluvial geomorphology

Advancing future research in fluvial geomorphology in periglacial environments require the clear distinction between geomorphic processes, driven purely by climate and hydrology, i.e., controlled by precipitation, evapotranspiration and runoff, and processes, occurring in direct contact with frozen ground. Even fluvial thermal erosion is only observed during limited time in the open-channel season (Tananaev, 2016), otherwise performing as a regular mechanical erosion of non-frozen bank deposits. It is important to distinguish between cases where permafrost has either direct or indirect influence on fluvial activity, or no influence at all.

Water tracks represent important subsurface drainage pathways in permafrost regions, their place in hydrological system is well established, but the trajectories of their future development rest unconstrained. Hillslope erosional features are projected to produce one-third of carbon losses associated with abrupt permafrost thaw by year 2300 (Turetsky et al., 2020), and water tracks may play significant role in these losses – or not. Whether water tracks will develop as thermo-erosional features which belong to natural fluvial networks constrained by permafrost, and scorch the thawing tundra to erosional badlands after the constraint is removed, or other processes from permafrost, hydrology or biology domain will interfere and promote slow thermal permafrost disturbance under water tracks?

Permafrost distribution under large river channels is currently understudied, and the field material from largest rivers is particularly lacking. In minor channels, the temporal evolution of permafrost table was studied in detail, and showed only a minor interaction of water flow with permafrost during open water period (Brosten et al., 2009). Bed evolution in such streams is not directly controlled by permafrost. Inversely, on larger alluvial rivers with highly developed bed topography, seasonally and perennially frozen alluvium is frequently exposed to streamflow (Scott, 1978; Wankiewicz, 1984; Tananaev, 2013).

Recurrent freeze-thaw cycles of surficial sediments leads to their frost weathering and sequential fining. This process is documented in literature for surficial deposits, but is less understood for alluvial material within bankfull limits, subject to intermittent submergence, fluvial transport, redeposition and exposure to low negative temperatures. Existing field evidence, as mentioned earlier, is scarce and incomplete (Shumilov, 1986), but suggests intense frost shattering and substantially finer fractions in exposed alluvial material. Cold regions are projected to experience more freeze-thaw cycles and intensified frost weathering of surficial alluvial deposits.

Future projections of river channel response to climate change need both hydrological and geomorphological input data, and the complexity of this input is defined by the spatial and temporal resolution of a particular forecasting or modeling effort (Lotsari et al., 2015). From hydrological perspective, relevant data include bankfull discharge return intervals for both ice and ice-free regimes, and effective (channel-forming) discharge values and distributions. Our review has shown that, while effective discharge is a useful metrics defining river valley style and channel pattern, we are lacking knowledge on its actual values, return intervals and distributions. Previously published data, e.g., (Berkovich et al., 1990), are outdated and need revision because of recently observed hydrological trends in the Arctic domain. Re-evaluation of effective discharge values, comparative analysis with historical data and hydrological modeling using future climate scenarios might allow more accurate predictions of fluvial change in permafrost-affected regions, including floodplain development and channel pattern evolution.

Cryo-fluvial interaction appears to be a useful concept helping to decrypt the relative roles of its components in shaping fluvial landforms across permafrost catchments. The field of geomorphology was once divided between land-shaping agents, and this was 'first geomorphology', where fluvial, aeolian or glacial geomorphology have their origin. Climatic geomorphology stems from the idea of climate as an overarching land-shaping agent, and periglacial geomorphology was long seen as its derivative. 'Second geomorphology' was geomorphology of land-shaping processes, i.e., creating bonds with periglacial processes and permafrost (Summerfield, 2005; Church, 2017). In permafrost domain, as we discuss in this review, landforms are developing in interaction between shaping agents, processes from different domains; such interaction varies across spatial scales and physiographical contexts. Systematic analysis of the interactions between different 'geomorphologies' (cf. Marks et al., 2006; Ostercamp et al., 2012; Liu and Coulthard, 2015; Beach et al., 2019) is important for the evolution toward the geomorphology of interactions.

7. Conclusions

Permafrost is exerting control on fluvial action through interference with major agents of fluvial processes. This interference is scale-dependent, and is reviewed in the present paper using the fluvial system framework. Relative importance of permafrost-related effects is differentiated by compartments. Future evolutionary trajectories of fluvial landforms upon permafrost loss, as we suggest here, are related to a dominant process shaping these landforms under cryo-fluvial interaction. This research considers them as either primarily fluvial or primarily cryogenic. Under warmer climate without permafrost, the former will tend to adjust their shape to future hydrology with less or no constraints from frozen ground, while the latter will respond to direct permafrost loss and physical terrain disturbance, i.e., thermokarst and thermal denudation. Complete permafrost thawing will bring the ecosystems to a new stable state, but the time scale of this future stability is still unconstrained.

Deeper active layer, or complete permafrost disappearance, are expected to reduce fluvial activity and soil erosion on both undisturbed and disturbed hillslopes through topsoil drying, lower surface flow potential and less overland flow with above-critical runoff depth. Increasing water temperature and higher total heat content of streams will lead to intensified ice ablation and thermal erosion in valley thalwegs, promoting thermo-erosional gullying and linear thermokarst development in soils susceptible to fluvial erosion. Physical disturbance will intensify rapidly following permafrost thawing, but end with terrain stabilization after a threshold permafrost loss, though in ice-rich permafrost, it can take substantial time. Catchment particulate fluxes will increase along shorter fluvial pathways with higher initiation rates projected for the late 21st century, and remain stable along distant connections. Future evolution of hillslope water tracks attracts particular attention, as defreezing northern catchments might lead to rapid thermal erosion over their thalwegs ending with cryo-fluvial badland.

In river valleys and estuaries permafrost loss will lift constraints imposed on primarily fluvial landforms, and they will gradually adjust to future hydrology which is expected to change in the following decades. Small rivers with shorter fluvial pathways will be put in disequilibrium state by increasing sediment fluxes, while in large rivers with high storage capacity this signal will be damped. Permafrost loss in floodplains will reduce bank retreat rates, and in river banks, retreat rates will increase in lower banks and decrease, in higher banks. This effect will concur with higher water temperatures during flood events, and more rainfall floods on rivers with nival regime. Channel erosion patterns will change with less seasonal and perennial freezing of bed material and higher fluvial fluxes even in ice-covered channels.

Funding

This paper was prepared under the Academy of Finland Mobility Grant to N.T. [grant number 333218], during his stay at the University of Eastern Finland in Joensuu, Finland. The research is part of the state-supported project awarded to Melnikov Permafrost Institute, SB RAS [project number AAAA-A20-120111690008-9], and partially funded by RFBR [grant number 21-55-75004].

Declaration of Competing Interest

The authors have no competing interests to declare.

References

Aalto, J., Niittynen, P., Riihimäki, H., Luoto, M., 2021. Cryogenic land surface processes shape vegetation biomass patterns in northern European tundra. Commun. Earth Environ. 2, 222. https://doi.org/10.1038/s43247-021-00292-7.

Abbott, B.W., Jones, J.B., Godsey, S.E., Larouche, J.R., Bowden, W.B., 2015. Patterns and persistence of hydrologic carbon and nutrient export from collapsing upland permafrost. Biogeoscience 12 (12), 3725–3740. https://doi.org/10.5194/bg-12-3725-2015.

Alabyan, A.M., Chalov, R.S., 1998. Types of river channel patterns and their natural controls. Earth Surf. Process. Landf. 23, 467–474. https://doi.org/10.1002/(SICI)1096-9837(199805)23:5%3C467::AID-ESP861%3E3.0.CO;2-T.

Alekseevskiy, N.I., Berkovich, K.M., Chalov, R.S., 2008. Erosion, sediment transportation and accumulation in rivers. Int. J. Sed. Res. 23, 93–105. https://doi.org/10.1016/S1001-6279(08)60009-8.

Allaart, L., Schomaker, A., Håkansson, L.M., Farnsworth, W.R., Brynjólfsson, S., Grumstad, A., Kjellman, S.E., 2021. Geomorphology and surficial geology of the Femmilsjøen area, northern Spitsbergen. Geomorphology 382, 107693. https://doi.org/10.1016/j.geomorph.2021.107693.

Anderson, R.S., Anderson, S.P., Tucker, G.E., 2013. Rock damage and regolith transport by frost: an example of climate modulation of the geomorphology of the critical zone. Earth Surf. Process. Landf. 38, 299–316. https://doi.org/10.1002/esp.3330.

Andresen, C.G., Lawrence, D.M., Wilson, C.J., McGuire, D.M., Koven, C., Schaefer, K., Jafarov, E., Peng, S., Chen, X., Gouttevin, I., Burke, E., Chadburn, S., Ji, D., Chen, G., Hayes, D., Zhang, W., 2020. Soil moisture and hydrology projections of the permafrost region – a model intercomparison. Cryosphere 14, 445–459. https://doi.org/10.5194/tc-14-445-2020.

Anisimov, O.A., Vandenberghe, J., Lobanov, V., Kondratiev, A., 2008. Predicting changes in alluvial channel patterns in North-European Russia under conditions of global warming. Geomorphology 98, 262–274. https://doi.org/10.1016/j.geomorph.2006.12.029.

Arcone, S.A., Chacho, E.F., Delaney, A.J., 1998. Seasonal structure of taliks beneath the Arctic streams determined with ground-penetrating radar. In: Seventh International Conference on Permafrost (Proceedings). Collection Nordicana 55, pp. 16–24.

Attal, M., Lavé, J., 2009. Pebble abrasion during fluvial transport: Experimental results and implications for the evolution of the sediment load along rivers. J. Geophys. Res. Earth Surf. 114, F04023 https://doi.org/10.1029/2009JF001328.

Ball, B.A., Levy, J., 2015. The role of water tracks in altering biotic and abiotic soil properties and processes in a polar desert in Antarctica. J. Geophys. Res. Biogeosci. 120, 270–279. https://doi.org/10.1002/2014JG002856.

Balser, A.W., Jones, J.B., Gens, R., 2014. Timing of retrogressive thaw slump initiation in the Noatak Basin, northwest Alaska, USA. J. Geophys. Res. Earth Surf. 119, 1106–1120. https://doi.org/10.1002/2013JF002889.

Beach, T., Luzzadder-Beach, S., Cordova, C., 2019. Human impacts on geomorphic systems and the legacy of Karl W. Butzer. Geomorphology 331, 1–3. https://doi.org/10.1016/j.geomorph.2018.12.027.

Beel, C.R., Lamoureux, S.F., Orwin, J.F., Pope, M.A., Lafrenière, M.J., Scott, N.A., 2020. Differential impact of thermal and physical permafrost disturbances on High Arctic dissolved and particulate fluvial fluxes. Sci. Rep. 10, 11836. https://doi.org/10.1038/s41598-020-68824-3.

Beltaos, S., Bonsal, B., 2021. Climate change impacts on Peace River ice thickness and implications to ice-jam flooding of Peace-Athabasca Delta, Canada. Cold Regions Sci. Technol. 186, 103279. https://doi.org/10.1016/j.coldregions.2021.103279.

Berkovich, K.M., Kalinin, A.M., Sidorchuk, A.Y., Chalov, R.S., Chernov, A.V., 1990. Razrabotka edinoy skhemy rayonirovaniya territorii SSSR po rusloformiruyuschey deyatel'nosti rek (Development of a unified scheme of territorial division of the USSR by the channel-forming activity of rivers). Bull. Moscow State Univ. Geogr. (2), 17–27 (in Russian).

Berthling, I., Etzelmüller, B., 2011. The concept of cryo-conditioning in landscape evolution. Quat. Res. 75, 378–384. https://doi.org/10.1016/j.yqres.2010.12.011.

Bishop, K., Seibert, J., Nyberg, L., Rodhe, A., 2011. Water storage in a till catchment. II. Implications of transmissivity feedback for flow paths and turnover times. Hydrol. Process. 25, 3950–3959. https://doi.org/10.1002/hyp.8355.

Biskaborn, B.K., Smith, S.L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D.A., Schoeneich, P., Romanovsky, V.E., Lewkowicz, A.G., Abramov, A., Allard, M., Boike, J., Cable, W.L., Christiansen, H.H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckmann, J.-P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A.B.K., Sergeev, D., Seybold, K., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M., Lantuit, H., 2019. Permafrost is warming at a global scale. Nat. Commun. 10, 264. https://doi.org/10.1038/s41467-018-08240-4.

Blais-Stevens, A., Kremer, M., Bonnaventure, P.P., Smith, S.L., Lipovsky, P., Lewkowicz, A.G., 2015. Active layer detachment slides and retrogressive thaw slumps susceptibility mapping for current and future permafrost distribution, Yukon Alaska Highway Corridor. In: Lollino, G., Manconi, A., Clague, J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and Territory, 1. Springer, Cham., pp. 449–453. https://doi.org/10.1007/978-3-319-09300-0_86

Bogaart, P.W., Tucker, G.E., de Vries, J.J., 2003. Channel network morphology and sediment dynamics under alternating periglacial and temperate regimes: a numerical simulation study. Geomorphology 54 (3-4), 257–277. https://doi.org/10.1016/S0169-555X(02)00360-4.

Bonnaventure, P.P., Lamoureux, S.F., 2013. The active layer: a conceptual review of monitoring, modelling techniques and changes in a warming climate. Progr. Phys. Geogr. 37 (3), 352–376. https://doi.org/10.1177/2F0309133313478314.

Bowden, W.B., Gooseff, M.N., Balser, A., Green, A., Peterson, B.J., Bradford, J., 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: potential impacts on headwater stream ecosystems. J. Geophys. Res. 113, G02026 https://doi.org/10.1029/2007JG000470.

Box, J.E., Colgan, W.T., Christensen, T.R., Schmidt, N.M., Lund, M., Parmentier, F.-J.W., Brown, R., Bhatt, U.S., Euskirchen, E.S., Romanovsky, V.E., Walsh, J.E., Overland, J. E., Wang, M., Corell, R.W., Meier, W.N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., Skovgård Olsen, M., 2019. Key indicators of Arctic climate change: 1971–2017. Environ. Res. Lett. 14 (4), 045010 https://doi.org/10.1088/1748-9326/aafc1b.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Wiley-Blackwell, Oxford, UK (416 pp.).

Brierley, G.J., Fryirs, K.A., 2016. The use of evolutionary trajectories to guide 'moving targets' in the management of river futures. River Res. Appl. 32 (5), 823–835. https://doi.org/10.1002/rra.2930.

Brosten, T.R., Bradford, J.H., McNamara, J.P., Gooseff, M.N., Zarnetske, J.P., Bowden, W.B., Johnston, M.E., 2009. Estimating 3D variation in active-layer thickness beneath arctic streams using ground-penetrating radar. J. Hydrol. 373, 479–486. https://doi.org/10.1016/j.jhydrol.2009.05.011.

Brutsaert, W., Hiyama, T., 2012. The determination of permafrost thawing trends from long-term streamflow measurements with an application in eastern Siberia. J. Geophys. Res. 117, D22110 https://doi.org/10.1029/2012JD018344.

Burke, E.J., Zhang, Y., Krinner, G., 2020. Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change. Cryosphere 14 (9), 3155–3174. https://doi.org/10.5194/tc-14-3155-2020.

Burn, C.R., Lewkowicz, A.G., 1990. Retrogressive thaw slumps. Can. Geogr. 34 (3), 273–276. https://doi.org/10.1111/j.1541-0064.1990.tb01092.x.

Burt, T.P., Williams, P.J., 1976. Hydraulic conductivity in frozen soils. Earth Surf. Proc. 1, 349–360. https://doi.org/10.1002/esp.3290010404.

Candel, J., Kleinhans, M., Makaske, B., Wallinga, J., 2021. Predicting river channel pattern based on stream power, bed material and bank strength. Prog. Phys. Geogr. 45 (2), 253–278. https://doi.org/10.1177/0309133320948831.

Chalov, R.S., 2012. Seasonal deformation regime of rifts in lowland rivers. Water Res. 39, 82–89. https://doi.org/10.1134/S0097807811060029.

Chalov, R.S., 2021. Fluvial processes: theory and applications. In: Drivers and Conditions of River Channel Character and Change, 1. Springer (578 pp.).

Chalov, S., Ermakova, G., 2011. Fluvial response to climate change: a case study of northern Russian rivers. In: Cold Region Hydrology in a Changing Climate, 346. IAHS Publ, pp. 111–119.

Chassiot, L., Lajeunesse, P., Bernier, J.-F., 2020. Riverbank erosion in cold environments: review and outlook. Earth-Sci. Rev. 207, 103231. https://doi.org/10.1016/j.earscirev.2020.103231.

Chistyakov, G.E., 1952. Ruslovye processy na r. Lene pod g. Yakutskom. Issledovaniya vechnoy merzloty v Yakutskoy Respublike, Vol. 3. Soviet Academy of Sciences Publ, Moscow, pp. 15–20 (in Russian).

Chorley, R.J. (Ed.), 2019. Introduction to Fluvial Geomorphology. Routledge (232 pp.).

Church, M., 2017. Reconstructing periglacial geomorphology: the contribution of J. Ross Mackay. Permafr. Periglac. Process. 28 (3), 517–522. https://doi.org/10.1002/ppp.1867.

Connon, R.F., Quinton, W.L., Craig, J.R., Hayashi, M., 2014. Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada. Hydrol. Process. 28 (14), 4163–4178. https://doi.org/10.1002/hyp.10206.

Costard, F., Gautier, E., Fedorov, A., Konstantinov, P., Dupeyrat, L., 2014. An assessment of the erosion potential of the fluvial thermal process during ice breakups of the Lena River (Siberia). Permafr. Periglac. Process. 25, 162–171. https://doi.org/10.1002/ppp.1812.

Costard, F., Dupeyrat, L., Séjourné, A., Bouchard, F., Fedorov, A., Saint-Bézar, B., 2021. Retrogressive thaw slumps on ice-rich permafrost under degradation: results from a large-scale laboratory simulation. Geophys. Res. Lett. 48 (1), e2020GL091070 https://doi.org/10.1029/2020GL091070.

Crampton, C.B., 1979. Changes in permafrost distribution produced by a migrating river meander in the Northern Yukon, Canada. Arctic 32 (2), 148–151.

Crawford, J.T., Stanley, E.H., 2014. Distinct fluvial patterns of a headwater stream network underlain by discontinuous permafrost. Arct. Antarct. Alp. Res. 46 (2), 344–354. https://doi.org/10.1657/1938-4246-46.2.344.

Crites, H., Kokelj, S.V., Lacelle, D., 2020. Icings and groundwater conditions in permafrost catchments of northwestern Canada. Sci. Rep. 10, 3283. https://doi.org/10.1038/s41598-020-60322-w.

Cunliffe, A.M., Tanski, G., Radoslavljevic, B., Palmer, W.F., Sachs, T., Lantuit, H., Kerby, J.T., Myers-Smith, I.H., 2019. Rapid retreat of permafrost coastline observed with aerial drone photogrammetry. Cryosphere 13, 1513–1528. https://doi.org/10.5194/tc-13-1513-2019.

Curasi, S.R., Loranty, M.M., Natali, S.M., 2016. Water track distribution and effects on carbon dioxide flux in an eastern Siberian upland tundra landscape. Environ. Res. Lett. 11, 045002 https://doi.org/10.1088/1748-9326/11/4/045002.

Debolskiy, M.V., Nicolsky, D.J., Hock, R., Romanovsky, V.E., 2020. Modeling present and future permafrost distribution at the Seward Peninsula, Alaska. J. Geophys. Res. Earth Surf. 125, e2019JF005355 https://doi.org/10.1029/2019JF005355.

Deprez, M., De Kock, T., De Schutter, G., Cnudde, V., 2020. A review on freeze-thaw action and weathering of rocks. Earth Sci. Rev. 203, 103143. https://doi.org/10.1016/j.earscirev.2020.103143.

Dixon, J., 2013. Response of periglacial geomorphic processes to global change. Treat. Geomorphol. 13, 176–189. https://doi.org/10.1016/B978-0-12-374739-6.00351-1.

Docherty, C.L., Hannah, D.M., Riis, T., Rosenhøj Leth, T., Milner, A.M., 2017. Large thermo-erosional tunnel for a river in northeast Greenland. Polar Sci. 14, 83–87. https://doi.org/10.1016/j.polar.2017.08.001.

Dupeyrat, L., Costard, F., Randriamazaoro, R., Gailhardis, E., Gautier, E., Fedorov, A., 2011. Effects of ice content on the thermal erosion of permafrost: Implications for fluvial and coastal erosion. Permafr. Periglac. Process. 22, 179–187. https://doi.org/10.1002/ppp.722.

Embleton, C., King, C.A.M., 1975. Glacial and periglacial geomorphology. In: Periglacial Geomorphology, 2. Edward Arnold, London (203 pp.).

Ensom, T., Makarieva, O., Morse, P., Kane, D., Alekseev, V., Marsh, P., 2020. The distribution and dynamics of aufeis in permafrost regions. Permafr. Periglac. Process. 31 (3), 383–395. https://doi.org/10.1002/ppp.2051.

Ettema, R., Daly, S.F., 2004. Sediment transport under ice. In: ERDC/CRREL Report TR-04-20, 54 pp. http://hdl.handle.net/11681/5380.

Evans, S.G., Ge, S., 2017. Contrasting hydrogeologic responses to warming in permafrost and seasonally frozen ground hillslopes. Geophys. Res. Lett. 44 (4), 1803–1813. https://doi.org/10.1002/2016GL072009.

Evans, S.G., Godsey, S.E., Rushlow, C.E., Voss, C., 2020. Water tracks enhance water flow above permafrost in upland Arctic Alaska hillslopes. J. Geophys. Res. Earth Surf. 125 (2), e2019JF005256 https://doi.org/10.1029/2019JF005256.

Farquharson, L.M., Romanovsky, V.E., Cable, W.L., Walker, D.A., Kokelj, S.V., Nicolsky, D., 2019. Climate change drives widespread and rapid thermokarst development in very cold permafrost in the Canadian High Arctic. Geophys. Res. Lett. 46, 6681–6689. https://doi.org/10.1029/2019GL082187.

Fedorov, A.N., Gavriliev, P.P., Konstantinov, P.Y., Hiyama, T., Iijima, Y., Iwahana, G., 2014. Estimating the water balance of a thermokarst lake in the middle of the Lena River basin, eastern Siberia. Ecohydrology 7, 188–196. https://doi.org/10.1002/eco.1378.

Ferguson, R.I., 1981. Channel forms and channel changes. In: Lewin, J. (Ed.), British Rivers. Allen and Unwin, London, pp. 90–125.

Fotiev, S.M., 2013. Underground waters of cryogenic areas of Russia (classification). In: Earth's Cryosphere XVII, 2, pp. 41–59 (in Russian).

Fox, G.A., Wilson, G.V., Simon, A., Langendoen, E.J., Akay, O., Fuchs, J.W., 2007. Measuring streambank erosion due to ground water seepage: correlation to bank pore water pressure, precipitation and stream stage. Earth Surf. Process. Landf. 32 (10), 1558–1573. https://doi.org/10.1002/esp.1490.

Frampton, A., Destouni, G., 2015. Impact of degrading permafrost on subsurface solute transport pathways and travel times. Water Resour. Res. 51, 7680–7701. https://doi.org/10.1002/2014WR016689.

French, H.M., 2017. The Periglacial Environment, 4th Ed. Wiley-Balckwell. (544 pp.).

Frey, K.E., McClelland, J.W., 2009. Impacts of permafrost degradation on arctic river biogeochemistry. Hydrol. Process. 23, 169–182. https://doi.org/10.1002/hyp.7196.

Fritz, M., Opel, T., Tanski, G., Herzschuh, U., Meyer, H., Eulenburg, A., Lantuit, H., 2015. Dissolved organic carbon (DOC) in Arctic ground ice. Cryosphere 9, 737–752. https://doi.org/10.5194/tc-9-737-2015.

Fuchs, M., Nitze, I., Strauss, J., Günther, F., Wetterich, S., Kizyakov, A., Fritz, M., Opel, T., Grigoriev, M.N., Maksimov, G.T., Grosse, G., 2020. Rapid fluvio-thermal erosion of a Yedoma permafrost cliff in the Lena River delta. Front. Earth Sci. 8, 336. https://doi.org/10.3389/feart.2020.00336.

Gagarin, L., Wu, Q., Melnikov, A., Volgusheva, N., Tananaev, N., Jin, H., Zhang, Z., Zhizhin, V., 2020. Morphometric analysis of groundwater icings: intercomparison of estimation techniques. Remote Sens. 12, 692. https://doi.org/10.3390/rs12040692.

Gatto, L.W., 1984. Tanana River monitoring and research program. Relationships among bank recession, vegetation, soil, sediments and permafrost on the Tanana River near Fairbanks, Alaska. CRREL Special Report. Hanover, New Hampshire USA 53, 84–121. https://hdl.handle.net/11681/11997.

Gautier, E., Dépret, T., Cavero, J., Costard, F., Virmoux, C., Fedorov, A., Konstantinov, P., Jammet, M., Brunstein, D., 2021. Fifty-year dynamics of the Lena River islands (Russia): spatio-temporal pattern of large periglacial anabranching river and influence of climate change. Sci. Total Environ. 783, 147020. https://doi.org/10.1016/j.scitotenv.2021.147020.

Gioia, G., Bombardelli, F.A., 2002. Scaling and similarity in rough channel flows. Phys. Rev. Lett. 88 (1), 014501 https://doi.org/10.1103/PhysRevLett.88.014501.

Godin, E., Fortier, D., 2010. Geomorphology of thermo-erosion gullies – case study from Bylot Island, Nunavut, Canada. In: Proc. 6th Can. Permafrost Conf, pp. 1540–1547.

Godin, E., Fortier, D., 2012. Geomorphology of a thermo-erosion gully, Bylot Island, Nunavut, Canada. Can. J. Earth Sci. 49, 979–986. https://doi.org/10.1139/e2012-015.

Godin, E., Fortier, D., Coulombe, S., 2014. Effects of thermo-erosion gullying on hydrologic flow networks, discharge and soil loss. Environ. Res. Lett. 9, 105010. https://doi.org/10.1088/1748-9326/9/10/105010.

Godin, E., 2016. Le processus de thermo-érosion du pergélisol dans la zone de pergélisol continu. Ph.D. Thesis, Université de Montréal, 221 p. (in French). http://hdl.handle.net/1866/15863.

Goudie, A.S., 2006. Global warming and fluvial geomorphology. Geomorphology 79, 384–394. https://doi.org/10.1016/j.geomorph.2006.06.023.

Gubarkov, A., Leibman, M., Andreeva, M., 2014. Cryogenic landslides in paragenetic complexes of slope and channel processes in the Central Yamal Peninsula. In: Shan, W., et al. (Eds.), Landslides in Cold Regions in the Context of Climate Change, 2014. Springer Intern. Publ, Switzerland, pp. 291–308. https://doi.org/10.1007/978-3-319-00867-7_21.

Guo, D., Wang, H., 2017. Simulated historical (1901-2010) changes in the permafrost extent and active layer thickness in the Northern Hemisphere. J. Geophys. Res. Atmos. 122, 12285–12295. https://doi.org/10.1002/2017JD027691.

Gurevich, E., 2009. Influence of air temperature on the river runoff in winter (the Aldan River catchment case study). Russ. Meteorol. Hydrol. 34 (9), 628–633. https://doi.org/10.3103/S1068373909090088.

Hall, K., 1987. Zoological erosion in permafrost environments: a possible origin of dells? Polar Geogr. 21 (1), 1–9. https://doi.org/10.1080/10889379709377613.

Hall, K., Thorn, C., 2010. The historical legacy of spatial scales in freeze–thaw weathering: misrepresentation and resulting misdirection. Geomorphology 130, 83–90. https://doi.org/10.1016/j.geomorph.2010.10.003.

Harrison, S., Mighall, T., Stainforth, D.A., Allen, P., Macklin, M., Anderson, E., Knight, J., Mauquoy, D., Passmore, D., Rea, B., Spagnolo, M., Shannon, S., 2019. Clim. Chang. 156, 69–86. https://doi.org/10.1007/s10584-019-02520-8.

Hastings, S.J., Luchessa, S.A., Oechel, W.C., Tenhunen, J.D., 1989. Standing biomass and production in water drainagesof the foothills of the Philip Smith Mountains, Alaska. Holarct. Ecol. 12, 304–311. https://doi.org/10.1111/j.1600-0587.1989.tb00850.x.

Henry, H.A.L., 2008. Climate change and soil freezing dynamics: historical trends and projected changes. Clim. Chang. 87, 421–434. https://doi.org/10.1007/s10584-007-9322-8.

Hinzman, A.M., Sjöberg, Y., Lyon, S.W., Ploum, S.W., van der Velde, Y., 2020. Increasing non-linearity of the storage-discharge relationship in sub-Arctic catchments. Hydrol. Process. 34 (19), 3894–3909. https://doi.org/10.1002/hyp.13860.

Huisink, M., de Moor, J.J.W., Kasse, C., Virtanen, T., 2002. Factors influencing periglacial fluvial morphology in the Northern European tundra and taiga. Earth Surf. Process. Landf. 27, 1223–1235. https://doi.org/10.1002/esp.422.

Isaev, V.S., Koshurnikov, A.V., Pogorelov, A., Amangurov, R.M., Podchasov, O., Sergeev, D.O., Buldovich, S.N., Aleksyutina, D.M., Grishakina, E.A., Kioka, A., 2019. Cliff retreat of permafrost coast in south-west Baydaratskaya Bay, Kara Sea, during 2005–2016. Permafr. Periglac. Process. 30 (1), 35–47. https://doi.org/10.1002/ppp.1993.

Istomin, K.V., Habeck, J.O., 2016. Permafrost and indigenous land use in the northern Urals: Komi and Nenets reindeer husbandry. Polar Sci. 10 (3), 278–287. https://doi.org/10.1016/j.polar.2016.07.002.

Janowicz, J.R., 2011. Streamflow responses and trends between permafrost and glacierized regimes in northwestern Canada. In: Cold Region Hydrology in a Changing Climate, 347. IAHS Publ, pp. 9–14.

Jones, B.M., Amundson, C.L., Koch, J.C., Grosse, G., 2013. Thermokarst and thaw-related landscape dynamics – an annotated bibliography with an emphasis on potential effects on habitat and wildlife. In: USGS Open-file Report 2013-1161. Reston, VA, USA.. https://doi.org/10.3133/ofr20131161

Jorgenson, J.C., Jorgenson, M.T., Boldenow, M.L., Orndahl, K.M., 2018. Landscape change detected over a half century in the Arctic National Wildlife Refuge using high-resolution aerial imagery. Remote Sens. 10 (8), 1305. https://doi.org/10.3390/rs10081305.

Juhls, B., Antonova, S., Angelopoulos, M., Bobrov, N., Grigoriev, M., Langer, M., Maksimov, G., Miesner, F., Overduin, P.P., 2021. Serpentine (floating) ice channels and their interaction with riverbed permafrost in the Lena River Delta, Russia. Front. Earth Sci. 9, 548. https://doi.org/10.3389/feart.2021.689941.

Kane, D.L., Yoshikawa, K., McNamara, J.P., 2003. Regional groundwater flow in an area mapped as continuous permafrost, NE Alaska (USA). Hydrogeol. J. 21, 41–52. https://doi.org/10.1007/s10040-012-0937-0.

Kanevskiy, M., Shur, Y., Strauss, J., Jorgenson, T., Fortier, D., Stephani, E., Vasiliev, A., 2016. Patterns and rates of riverbank erosion involving ice-rich permafrost (yedoma) in northern Alaska. Geomorphology 253, 370–384. https://doi.org/10.1016/j.geomorph.2015.10.023.

Kanevskiy, M., Shur, Y., Jorgenson, T., Brown, D.R.N., Moskalenko, N., Brown, J., Walker, D.A., Raynolds, M.K., Buchhorn, M., 2017. Degradation and stabilization of ice wedges: implications for assessing risk of thermokarst in northern Alaska. Geomorphology 297, 20–42. https://doi.org/10.1016/j.geomorph.2017.09.001.

Katasonova, E.G., 1963. Rol' termokarsta v razvitii delley (The role of thermokarst in dell dynamics). In: Usloviya i osobennosti razvitiya merzlykh tolsch v Sibiri i na Severo-Vostoke (Conditions and raticularities of permafrost dynamics in Siberia and North-East). Academy of Sciences, USSR, Moscow, pp. 91–100 (in Russian).

Kellerhals, R., Church, M., 1980. Comment on 'Effects of channel enlargement by river ice processes on bankfull discharge in Alberta, Canada' by D. G. Smith. Water Resourc. Res. 16 (6), 1131–1134. https://doi.org/10.1029/WR016i006p01131.

Kendall, K.A., Shanley, J.B., McDonnell, J.B., 1999. A hydrometric and geochemical approach to test the transmissivity feedback hypothesis during snowmelt. J. Hydrol. 219, 188–205. https://doi.org/10.1016/S0022-1694(99)00059-1.

Keskitalo, K.H., Bröder, L., Shakil, S., Zolkos, S., Tank, S.E., van Dongen, B.E., Tesi, T., Haghipour, N., Eglinton, T.I., Kokelj, S.V., Vonk, J.E., 2021. Downstream evolution of particulate organic matter composition from permafrost thaw slumps. Front. Earth Sci. 9 https://doi.org/10.3389/feart.2021.642675.

Kevan, P.G., Forbes, B.C., Kevan, S.M., Behan-Pelletier, V., 1995. Vehicle tracks on High Arctic tundra: their effects on the soil, vegetation and soil arthropods. J. Appl. Ecol. 32 (3), 655–667. https://doi.org/10.2307/2404660.

Kizyakov, A.I., Leibman, M.A., 2016. Cryogenic relief-formation processes: a review of 2010-2015 publications. In: Earth's Cryosphere XX, 4, pp. 40–52.

Kjelstrup, S., Ghoreishian Amiri, S.A., Loranger, B., Gao, H., Grimstad, G., 2021. Transport coefficients and pressure conditions for growth of ice lens in frozen soil. Acta Geotech. 16, 2231–2239. https://doi.org/10.1007/s11440-021-01158-0.

Knack, I., Shen, H.-T., 2015. Sediment transport in ice-covered channels. Int. J. Sed. Res. 30 (1), 63–67. https://doi.org/10.1016/S1001-6279(15)60006-3.

Knight, J., Harrison, S., 2012. Evaluating the impacts of global warming on geomorphological systems. Ambio 41 (2), 206–210. https://doi.org/10.1007/s13280-011-0178-9.

Koch, J.C., Ewing, S.A., Striegl, R., McKnight, D.M., 2013. Rapid runoff via shallow throughflow and deeper preferential flow in a boreal catchment underlain by frozen silt (Alaska, USA). Hydrogeol. J. 21, 93–106. https://doi.org/10.1007/s10040-012-0934-3.

Kokelj, S.V., Lewkowicz, A.G., 1998. Long-term influence of active-layer detachment sliding on permafrost slope hydrology, Hot Weather Creek, Ellesmere Island, Canada. In: Proc. 7th Intern. Conf. on Permafrost. Yellowknife, Canada, 1998, pp. 583–589.

Kokelj, S.V., Lacelle, D., Lantz, T.C., Tunnicliffe, J., Malone, L., Clark, I.D., Chin, K.S., 2013. Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. J. Geophys. Res. Earth Surf. 118, 681–692. https://doi.org/10.1002/jgrf.20063.

Kokelj, S.V., Tunnicliffe, J., Lacelle, D., Lantz, T.S., Chin, K.S., Fraser, R., 2015. Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. Glob. Planet. Chang. 129, 56–68. https://doi.org/10.1016/j.gloplacha.2015.02.008.

Kokelj, S.V., Kokoszka, J., van der Sluijs, J., Rudy, A.C.A., Tunnicliffe, J., Shakil, S., Tank, S., Zolkos, S., 2020. Permafrost thaw couples slopes with downstream systems and effects propagate through Arctic drainage networks. In: The Cryosphere Preprint. https://doi.org/10.5194/tc-2020-218.

Konishchev, V.N., Rogov, V.V., 1993. Investigations of cryogenic weathering in Europe and Northern Asia. Permafr. Periglac. Process. 4 (1), 49–64. https://doi.org/10.1002/ppp.3430040105.

Krogh, S.A., Pomeroy, J.W., 2018. Recent changes to the hydrological cycle of an Arctic basin at the tundra–taiga transition. Hydrol. Earth Syst. Sci. 22, 3993–4014. https://doi.org/10.5194/hess-22-3993-2018.

Kumpula, T., Pajunen, A., Kaarlejärvi, E., Forbes, B.C., Stammler, F., 2011. Land use and land cover change in Arctic Russia: ecological and social implications of industrial development. Glob. Environ. Chang. 21, 550–562. https://doi.org/10.1016/j.gloenvcha.2010.12.010.

Kusunoki, S., Mizuta, R., Hosaka, M., 2015. Future changes in precipitation intensity over the Arctic projected by a global atmospheric model with a 60-km grid size. Polar Sci. 9 (3), 277–292. https://10.1016/j.polar.2015.08.001.

Lafrenière, M.J., Lamoureux, S.F., 2019. Effects of changing permafrost conditions on hydrological processes and fluvial fluxes. Earth-Sci. Rev. 191, 212–223. https://doi.org/10.1016/j.earscirev.2019.02.018.

Lamontagne-Hallé, P., McKenzie, J.M., Kurylyk, B.L., Zipper, S.C., 2018. Changing groundwater discharge dynamics in permafrost regions. Environ. Res. Lett. 13, 084017 https://doi.org/10.1088/1748-9326/aad404.

Lamoureux, S.F., Lafrenière, M.J., 2008. Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada. Arct. Antarct. Alp. Res. 41, 59–68. https://doi.org/10.1657/1523-0430-41.1.59.

Lane, S.N., 2013. 21st century climate change: where has all the geomorphology gone? Earth Surf. Process. Land. 38, 106–110. https://doi.org/10.1002/esp.3362.

Lantz, T.C., Kokelj, S.V., 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. Geophys. Res. Lett. 35 (6), L06502 https://doi.org/10.1029/2007GL032433.

Lauzon, R., Piliouras, A., Rowland, J.C., 2019. Ice and permafrost effects on delta morphology and channel dynamics. Geophys. Res. Lett. 46, 6574–6582. https://doi.org/10.1029/2019GL082792.

Lawson, D.E., 1983. Erosion of perennially frozen streambanks. In: CRREL Report 83-29. Hanover, New Hampshire, USA (26 pp.).

Lebedeva, L.S., Bazhin, K.I., Khristoforov, I.I., Abramov, A.A., Pavlova, N.A., Efremov, V. S., Ogonerov, V.V., Tarbeeva, A.M., Fedorov, M.P., Nesterova, N.V., Makarieva, O. M., 2019. Suprapermafrost subaerial taliks, central Yakutia, Shestakovka River basin. In: Earth's Cryosphere XXIII, 1, pp. 35–44. https://doi.org/10.21782/EC2541-9994-2019-1(35-44).

Leopold, L.B., Wolman, M.G., Miller, J.P., 1995. Fluvial processes in geomorphology. Dover Publ., Mineola, NY, USA, p. 544.

Lewkowicz, A.G., 1990. Morphology, frequency and magnitude of active-layer detachment slides, Fosheim Peninsula, Ellesmere Island, N.W.T. In: Proceedings of the Fifth Canadian Permafrost Conference. Québec City Université Laval, pp. 111–118.

Lewkowicz, A.G., Harris, C., 2005. Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, Northern Canada. Permafr. Periglac. Process. 16, 115–130. https://doi.org/10.1002/ppp.522.

Lewkowicz, A.G., Way, R.G., 2019. Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. Nat. Commun. 10, 1329. https://doi.org/10.1038/s41467-019-09314-7.

Li, G., Zhang, M., Pei, W., Melnikov, A., Khristoforov, I., Li, R., Yu, F., 2022. Changes in permafrost extent and active layer thickness in the Northern Hemisphere from 1969 to 2018. Sci. Tot. Environ. 804, 150182. https://doi.org/10.1016/j.scitotenv.2021.150182.

Liljedahl, A., Boike, J., Daanen, R.P., Fedorov, A., Frost, G.V., Grosse, G., Hinzman, L.D., Iijima, Y., Jorgenson, J.C., Matveyeva, N., Necsoiu, M., Raynolds, M.K., Romanovsky, V.E., Schulla, J., Tape, K.D., Walker, D.A., Wilson, C.J., Yabuki, H., Zona, D., 2016. Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. Nat. Geosci. 9, 312–318. https://doi.org/10.1038/ngeo2674.

Lim, M., Whalen, D., Mann, P.J., Fraser, P., Berry, H.B., Irish, C., Cockney, K., Woodward, J., 2020. Effective monitoring of permafrost coast erosion: Wide-scale storm impacts on outer islands in the Mackenzie Delta area. Front. Earth Sci. 8, 454. https://doi.org/10.3389/feart.2020.561322.

Linhardt, T., Levy, J., Thomas, C.K., 2019. Water tracks intensify surface energy and mass exchange in the Antarctic McMurdo Dry Valleys. Cryosphere 13, 2203–2219. https://doi.org/10.5194/tc-13-2203-2019.

Lininger, K.B., Wohl, E., 2019. Floodplain dynamics in North American permafrost regions under a warming climate and implications for organic carbon stocks: a review and synthesis. Earth-Sci. Rev. 193, 24–44. https://doi.org/10.1016/j.earscirev.2019.02.024.

Linnel, K.A., Kaplar, C.W., 1966. Description and classification of frozen soils. In: CRREL Technical Report 150, Hanover, NH, USA (12 pp.).

Lipovsky, P., Huscroft, C., 2007. A reconnaissance inventory of permafrost-related landslides in the Pelly River watershed, central Yukon. In: Emond, D.S., Lewis, L.L., Weston, L.H. (Eds.), Yukon Exploration and Geology 2006. Yukon Geological Survey, pp. 181–195.

Liu, B., Coulthard, T.J., 2015. Mapping the interactions between rivers and sand dunes: Implications for fluvial and aeolian geomorphology. Geomorphology 231, 246–257. https://doi.org/10.1016/j.geomorph.2014.12.011.

Liu, J., Wu, D., Xu, X., Ji, M., Chen, Q., Wang, X., 2021. Projection of extreme precipitation induced by Arctic amplification over the Northern Hemisphere. Environ. Res. Lett. 16, 074012 https://doi.org/10.1088/1748-9326/ac0acc.

Lotsari, E., Thorndycraft, V., Alho, P., 2015. Prospects and challenges of simulating river channel response to future climate change. Prog. Phys. Geogr. 39 (4), 483–513. https://doi.org/10.1177/0309133315578944.

Lotsari, E., Kasvi, E., Kämäri, M., Alho, P., 2017. The effects of ice cover on flow characteristics in a subarctic meandering river. Earth Surf. Process. Landf. 42, 1195–1212. https://doi.org/10.1002/esp.4089.

Lotsari, E., Tarsa, T., Kämäri, M., Alho, P., Kasvi, E., 2019. Spatial variation of flow characteristics in a subarctic meandering river in ice-covered and open-channel conditions: 2D hydrodynamic modelling approach. Earth Surf. Process. Landf. 44, 1509–1529. https://doi.org/10.1002/esp.4589.

Lotsari, E., Dietze, M., Kämäri, M., Alho, P., Kasvi, E., 2020. Macro-turbulent flow and its impacts on sediment transport potential of a Subarctic river during ice-covered and open-channel conditions. Water 12 (7), 1874. https://doi.org/10.3390/w12071874.

Lu, Q., Zhao, D., Wu, S., 2017. Simulated responses of permafrost distribution to climate change on the Qinghai–Tibet Plateau. Sci. Rep. 7, 3845. https://doi.org/10.1038/s41598-017-04140-7.

Ma, Q., Jin, H.-J., Bense, V.F., Luo, D.-L., Marchenko, S.S., Harris, S.A., Lan, Y.-C., 2019. Impacts of degrading permafrost on streamflow in the source area of Yellow River on the Qinghai-Tibet Plateau, China. Adv. Clim. Change Res. 10, 225–239. https://doi.org/10.1016/j.accre.2020.02.001.

Ma, R., Sun, Z., Chiang, Q., Ge, M., Pan, Z., 2021. Control of the interactions between stream and groundwater by permafrost and seasonal frost in an alpine catchment, Northeastern Tibet Plateau, China. J. Geophys. Res. Atm. 126 (5), e2020JD033689 https://doi.org/10.1029/2020JD033689.

Macklin, M.G., Lewin, J., Woodward, J.C., 2012. The fluvial record of climate change. Phil. Trans. R. Soc. A 370, 2143–2172. https://doi.org/10.1098/rsta.2011.0608.

Makarieva, O., Nesterova, N., Post, D.A., Sherstyukov, A., Lebedeva, L., 2019. Warming temperatures are impacting the hydrometeorological regime of Russian rivers in the zone of continuous permafrost. Cryosphere 13, 1635–1659. https://doi.org/10.5194/tc-13-1635-2019.

Mann, D.H., Groves, P., Reanier, R.E., Kunz, M.L., 2010. Floodplains, permafrost, cottonwood trees, and peat: what happened the last time climate warmed suddenly in arctic Alaska? Quat. Sci. Rev. 29 (27-28), 3812–3830. https://doi.org/10.1016/j.quascirev.2010.09.002.

Mann, P.J., Eglinton, T.I., McIntyre, C.P., Zimov, N., Davydova, A., Vonk, J.E., Holmes, R.M., Spencer, R.G.M., 2015. Utilization of ancient permafrost carbon in headwaters of Arctic fluvial networks. Nat. Commun. 6, 7856. https://doi.org/10.1038/ncomms8856.

Marks, J.C., Parnell, R., Carter, C., Dinger, E.C., Haden, G.A., 2006. Interactions between geomorphology and ecosystem processes in travertine streams: implications for decommissioning a dam on Fossil Creek, Arizona. Geomorphology 77, 299–307. https://doi.org/10.1016/j.geomorph.2006.01.008.

Matsuoka, N., Murton, J., 2008. Frost weathering: recent advances and future directions. Permafr. Periglac. Process. 19 (2), 195–210. https://doi.org/10.1002/ppp.620.

McClelland, J.W., Holmes, R.M., Peterson, B.J., Raymond, P.A., Striegl, R.G., Zhulidov, A.V., Zimov, S.A., Tank, S.E., Spencer, R.G.M., Staples, R., Gurtovaya, T. Y., Griffin, C.G., 2016. Particulate organic carbon and nitrogen export from major Arctic rivers. Glob. Biogeochem. Cycles 30 (5), 629–643. https://doi.org/10.1002/2015GB005351.

McNamara, J.P., Kane, D.L., 2009. The impact of a shrinking cryosphere on the form of arctic alluvial channels. Hydrol. Process. 23, 159–168. https://doi.org/10.1002/hyp.7199.

McNamara, J.P., Kane, D.L., Hinzman, L.D., 1999. An analysis of an arctic channel network using a digital elevation model. Geomorphology 29, 339–353.

Mikhaylov, V.M., 2011. Morfodinamika rusel rek gornykh stran i litologiya korennykh porod (River channel patterns in mountainous countries and bedrock lithology). Geomorfologiya 2011 (4), 11–21. https://doi.org/10.15356/0435-4281-2011-4-11-21 (In Russian).

Miller, B.A., Juilleret, J., 2020. The colluvium and alluvium problem: Historical review and current state of definitions. Earth-Sci. Rev. 209, 103316. https://doi.org/10.1016/j.earscirev.2020.103316.

Miner, K.R., D'Andrilli, J., Mackelprang, R., Edwards, A., Malaska, M.J., Waldrop, M.P., Miller, C.E., 2021. Emergent biogeochemical risks from Arctic permafrost degradation. Nat. Clim. Chang. 11, 809–819. https://doi.org/10.1038/s41558-021-01162-y.

Molchanov, A.K., 1972. Issledovaniya zavisimosti morfometricheskikh kharakteristik rusla ot opredelyayuschikh faktorov (Study of the Relation of Channel Morphometry Features on Governing Factors). Ph.D. Abstract. Moscow State University, Moscow, USSR (22 pp. (in Russian)).

Morgenstern, A., Overduin, P.P., Günther, F., Stettner, S., Ramage, J., Schirrmeister, L., Grigoriev, M.N., Grosse, G., 2021. Thermo-erosional valleys in Siberian ice-rich permafrost. Permafr. Periglac. Process. 32, 59–75. https://doi.org/10.1002/ppp.2087.

Morse, P.D., Wolfe, S.A., 2015. Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada. J. Geophys. Res. Earth Surf. 120, 1670–1686. https://doi.org/10.1002/2015JF003534.

Nitzbon, J., Westermann, S., Langer, M., Martin, L.C.P., Strauss, J., Laboor, S., Boike, J., 2020. Fast response of cold ice-rich permafrost in northeast Siberia to a warming climate. Nat. Commun. 11, 2201. https://doi.org/10.1038/s41467-020-15725-8.

Nitzbon, J., Langer, M., Martin, L.C.P., Westermann, S., Schneider von Deimling, T., Boike, J., 2021. Effects of multi-scale heterogeneity on the simulated evolution of ice-rich permafrost lowlands under a warming climate. Cryosphere 15, 1399–1422. https://doi.org/10.5194/tc-15-1399-2021.

Nitze, I., Grosse, G., Jones, B.M., Romanovsky, V., Boike, J., 2018. Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. Nat. Commun. 9, 5423. https://doi.org/10.1038/s41467-018-07663-3.

O'Connor, M.T., Bayani Cardenas, M., Neilson, B.T., Nicholaides, K.D., Kling, G.W., 2019. Active layer groundwater flow: the interrelated effects of stratigraphy, thaw, and topography. Water Resourc. Res. 55 (8), 6555–6576. https://doi.org/10.1029/2018WR024636.

O'Neill, H.B., Roy-Leveillee, P., Lebedeva, L., Ling, F., 2020. Recent advances (2010–2019) in the study of taliks. Permafr. Periglac. Process. 31 (3), 346–357. https://doi.org/10.1002/ppp.2050.

Oliva, M., Fritz, M., 2018. Permafrost degradation on a warmer Earth: challenges and perspectives. Curr. Opin. Environ. Sci. Health 5, 14–18. https://doi.org/10.1016/j.coesh.2018.03.007.

Orton, G.J., Reading, H.G., 1993. Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. Sedimentology 40 (3), 475–512. https://doi.org/10.1111/j.1365-3091.1993.tb01347.x.

Ostercamp, W.R., Hupp, C.R., Stoffel, M., 2012. The interactions between vegetation and erosion: new directions for research at the interface of ecology and geomorphology. Earth Surf. Process. Landf. 37 (1), 23–36. https://doi.org/10.1002/esp.2173.

Owens, P.N., 2020. Soil erosion and sediment dynamics in the Anthropocene: a review of human impacts during a period of rapid global environmental change. J. Soils Sediments 20, 4115–4143. https://doi.org/10.1007/s11368-020-02815-9.

Paquette, M., Fortier, D., Vincent, W.F., 2017. Water tracks in the High Arctic: a hydrological network dominated by rapid subsurface flow through patterned ground. Arct. Sci. 3 (2), 334–353. https://doi.org/10.1139/as-2016-0014.

Paquette, M., Fortier, D., Vincent, W.F., 2018. Hillslope water tracks in the High Arctic: seasonal flow dynamics with changing water sources in preferential flow paths. Hydrol. Process. 32 (8), 1077–1089. https://doi.org/10.1002/hyp.11483.

Park, H., Yoshikawa, Y., Oshima, K., Kim, Y., Ngo-Duc, T., Kimball, J.S., Yang, D., 2016. Quantification of warming climate-induced changes in terrestrial Arctic river ice thickness and phenology. J. Clim. 29 (5), 1733–1754. https://doi.org/10.1175/JCLI-D-15-0569.1.

Park, H., Yoshikawa, Y., Yang, D., Oshima, K., 2017. Warming water in Arctic terrestrial rivers under climate change. J. Hydrometeorol. 18 (7), 1983–1995. https://doi.org/10.1175/JHM-D-16-0260.1.
Patton, P.C., Schumm, S.A., 1979. Gully erosion, Northwestern Colorado: a threshold phenomenon. Geology 3 (2), 88–90. https://doi.org/10.1130/0091-7613(1975)3<88:GENCAT>2.0.CO;2.
Pavelsky, T.M., Zarnetske, J.P., 2017. Rapid decline in river icings detected in Arctic Alaska: implications for the changing hydrologic cycle and river ecosystems. Geophys. Res. Lett. 44 (7), 3228–3235. https://doi.org/10.1002/2016GL072397.
Payette, S., Delwaide, A., 2000. Recent permafrost dynamics in a Subarctic floodplain associated with changing water levels, Québec, Canada. Arct. Antarct. Alp. Res. 32 (3), 316–323. https://doi.org/10.2307/1552530.
Payne, C., Panda, S., Prakash, A., 2018. Remote sensing of river erosion on the Colville River, North Slope Alaska. Remote Sens. 10 (3), 397. https://doi.org/10.3390/rs10030397.
Peng, X., Frauenfeld, O.W., Cao, B., Wang, K., Wang, H., Su, H., Huang, Z., Yue, D., Zhang, T., 2016. Response of changes in seasonal soil freeze/thaw state to climate change from 1950 to 2010 across China. J. Geophys. Res. Earth Surf. 121 (11), 1984–2000. https://doi.org/10.1002/2016JF003876.
Piégay, H., 2016. System approaches in fluvial geomorphology. In: Condolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology. https://doi.org/10.1002/9781118648551.ch5.
Piliouras, S., Rowland, J.C., 2020. Arctic river delta morphologic variability and implications for riverine fluxes to the coast. J. Geophys. Res. Earth Surf. 125 (1), e2019JF005250 https://doi.org/10.1029/2019JF005250.
Piliouras, A., Lauzon, R., Rowland, J.C., 2021. Unraveling the combined effects of ice and permafrost on Arctic delta morphodynamics. J. Geophys. Res. Earth Sci. 126 (4), e2020JF005706 https://doi.org/10.1029/2020JF005706.
Pin'kovskiy, S.I., 1965. Tipy rechnykh rusel Severo-Vostoka SSSR i poluostrova Kamchatki (Channel patterns of rivers in North-Eastern USSR and Kamchatka Peninsula). In: Trudy GGI (State Hydrological Institute Proceedings), 120, pp. 77–117 (in Russian).
Polonsky, V.F., 1996. Physicostatistical approach to river delta hydrology. J. Hydraul. Eng. 122 (6), 333–340. https://doi.org/10.1061/(ASCE)0733-9429(1996)122:6(333).
Poznanin, V.L., 1995. Priroda ovrazhnoy termoerozii (The Nature of Gully Thermal Erosion). Dr. Hab. Thesis Abstract. Moscow State University, Moscow (33 pp. (in Russian)).
Priesnitz, K., Schunke, E., 2002. The fluvial morphodynamics of two small permafrost drainage basins, Richardson Mountains, Northwestern Canada. Permafr. Periglac. Process. 13, 207–217. https://doi.org/10.1002/ppp.424.
Pringle, C.M., 1997. Exploring how disturbance is transmitted upstream: going against the flow. J. North Am. Bentholog. Soc. 16 (2), 425–438. https://doi.org/10.2307/1468028.
Randriamazaoro, R., Dupeyrat, L., Costard, F., Carey-Gailhardis, E., 2007. Fluvial thermal erosion: heat balance integral method. Earth Surf. Proc. Landf. 32, 1828–1840. https://doi.org/10.1002/esp.1489.
Rawlins, M.A., Cai, L., Stuefer, S., Nicolsky, D., 2020. Changing characteristics of runoff and freshwater export from watersheds draining northern Alaska. Cryosphere 13, 3337–3352. https://doi.org/10.5194/tc-13-3337-2019.
Raymond, P.A., McClelland, J.W., Holmes, R.M., Zhulidov, A.V., Mull, K., Peterson, B.J., Striegl, R.G., Aiken, G.R., Gurtovaya, T.Y., 2007. Flux and age of dissolved organic carbon exported to the Arctic Ocean: a carbon isotopic study of the five largest arctic rivers. Glob. Biogeochem. Cycles 21 (4), GB4011. https://doi.org/10.1029/2007GB002934.
Richards, K., Brasington, J., Hughes, F., 2002. Geomorphic dynamics of floodplains: ecological implications and a potential modelling strategy. Freshw. Biol. 47, 559–579. https://doi.org/10.1046/j.1365-2427.2002.00920.x.
Rogger, M., Chirico, G.B., Hausmann, H., Krainer, K., Brückl, E., Stadler, P., Blöchl, G., 2017. Impact of mountain permafrost on flow path and runoff response in a high alpine catchment. Water Resour. Res. 53 (2), 1288–1308. https://doi.org/10.1002/2016WR019341.
Rowland, J.C., Jones, C.E., Altmann, G., Bryan, R., Crosby, B.T., Hinzman, L.D., Kane, D. L., Lawrence, D.M., Mancio, A., Marsh, P., McNamara, J.P., Romanovsky, V.E., Toniolo, H., Travis, B.J., Trochim, E., Wilson, C.J., Geernaert, G.L., 2011. Arctic landscapes in transition: responses to thawing permafrost. Eos 91, 229–236. https://doi.org/10.1029/2010EO260001.
Rudy, A.C.A., Lamoureux, S.F., Kokelj, S.V., Smith, I.R., England, J.H., 2017. Accelerating thermokarst transforms ice-cored terrain triggering a downstream cascade to the ocean. Geophys. Res. Lett. 44 (21), 11080–11087. https://doi.org/10.1002/2017GL074912.
Saito, H., Iijima, Y., Basharin, N.I., Fedorov, A.N., Kunitsky, V.V., 2018. Thermokarst development detected from high-definition topographic data in central Yakutia. Remote Sens. 10, 1579. https://doi.org/10.3390/rs10101579.
Schramm, I., Boike, J., Bolton, W.R., Hinzman, L.D., 2007. Application of TopoFlow, a spatially distributed hydrological model, to the Imnavait Creek watershed, Alaska. J. Geophys. Res. Biogeosci. 112, G04S46 https://doi.org/10.1029/2006JG000326.
Schwab, M.S., Hilton, R.G., Raymond, P.A., Haghipour, N., Amos, E., Tank, S.E., Holmes, R.M., Tipper, E.T., Eglinton, T.I., 2020. An abrupt aging of dissolved organic carbon in large Arctic rivers. Geophys. Res. Lett. 47 (23), e2020GL088823 https://doi.org/10.1029/2020GL088823.
Scott, K.M., 1978. Effects of permafrost on stream channel behavior in Arctic Alaska. In: USGS Prof. Paper 1068. US Government Printing Office, Washington DC. https://doi.org/10.3133/pp1068, 19 pp.
Séjourné, A., Costard, F., Fedorov, A., Gargani, J., Skorve, J., Massé, M., Mège, D., 2015. Evolution of the banks of thermokarst lakes in Central Yakutia (Central Siberia) due to retrogressive thaw slump activity controlled by insolation. Geomorphology 241, 31–40. https://doi.org/10.1016/j.geomorph.2015.03.033.
Serreze, M.C., Barry, R.G., 2011. Processes and impacts of Arctic amplification. Glob. Planet. Chang. 77 (1-2), 85–96. https://doi.org/10.1016/j.gloplacha.2011.03.004.
Shepelev, V.V., 2009. Suprapermafrost waters of the cryolithosphere and their classification. Geogr. Nat. Resour. 30 (2), 151–155. https://doi.org/10.1016/j.gnr.2009.06.011.
Shiklomanov, A.I., Lammers, R.B., 2014. River ice responses to a warming Arctic – recent evidence from Russian rivers. Environ. Res. Lett. 9, 035008 https://doi.org/10.1088/1748-9326/9/3/035008.
Shiklomanov, A.I., Lammers, R.B., Rawlins, M.A., Smith, L.C., Pavelsky, T.M., 2007. Temporal and spatial variations in maximum river discharge from a new Russian data set. J. Geophys. Res. 112, G04S53. https://doi.org/10.1029/2006JG000352.
Shumilov, Yu., 1986. Kontinentalny litogenez i rossypeobrazovanie v kriolitozone (Continental Lithogenesis and Placer Formation in Permafrost) (Nauka, Novosibirsk, 176 pp. (in Russian)).
Shur, Y.L., Jorgenson, M.T., 1998. Cryostructure development on the floodplain of the Colville river delta, Northern Alaska. In: Seventh International Conference on Permafrost (Proceedings). Collection Nordicana 55, pp. 993–999.
Shur, Y.L., Jorgenson, M.T., 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafr. Periglac. Process. 18, 7–19. https://doi.org/10.1002/ppp.582.
Shur, Y.L., Jones, B.M., Kanevskiy, M., Jorgenson, T., Ward Jones, M.K., Fortier, D., Stephani, E., Vasiliev, A., 2021. Fluvio-thermal erosion and thermal denudation in the yedoma region of northern Alaska: revisiting the Itkillik River exposure. Permafr. Periglac. Process. 32 (2), 277–298. https://doi.org/10.1002/ppp.2105.
Sidorchuk, A., 2020. The potential of gully erosion on the Yamal Peninsula, West Siberia. Sustainability 12 (1), 260. https://doi.org/10.3390/su12010260.
Sidorchuk, A., Sidorchuk, A., 1998. Model for estimating gully erosion. In: Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes, 249. IAHS Publ, pp. 333–343.
Sjöberg, Y., Frampton, A., Lyon, S.W., 2013. Using streamflow characteristics to explore permafrost thawing in northern Swedish catchments. Hydrogeol. J. 21, 121–131. https://doi.org/10.1007/s10040-012-0932-5.
Sjöberg, Y., Jan, A., Painter, S.L., Coon, E.T., Carey, M.P., O'Donnell, J.A., Koch, J.C., 2021. Permafrost promotes shallow groundwater flow and warmer headwater streams. Water Resour. Res. 57, e2020WR027463 https://doi.org/10.1029/2020WR027463.
Slaymaker, O., Spencer, T., Embleton-Hamann, C., 2021. Recasting geomorphology as a landscape science. Geomorphology 384, 107723. https://doi.org/10.1016/j.geomorph.2021.107723.
Sonke, J., Teisserenc, R., Heimbürger, L.-E., Petrova, M., Marusczak, N., Le Dantec, T., Chupakov, A., Li, C., Thackray, C., Sunderland, E., Tananaev, N., Pokrovsky, O., 2018. Eurasian river spring flood observations support net Arctic Ocean mercury export to the atmosphere and Atlantic Ocean. Proc. Natl. Acad. Sci. 115 (50), E11586–E11594. https://doi.org/10.1073/pnas.1811957115.
St. Jacques, J.-M., Sauchyn, D.J., 2009. Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. Geophys. Res. Lett. 36, L01401 https://doi.org/10.1029/2008GL035822.
Stephani, E., Drage, J., Miller, D., Jones, B.M., Kanevskiy, M., 2020. Taliks, cryopegs, and permafrost dynamics related to channel migration, Colville River Delta. Alaska. Permafr. Periglac. Process. 31 (2), 239–254. https://doi.org/10.1002/ppp.2046.
Stettner, S., Beamish, A.L., Bartsch, A., Heim, B., Grosse, G., Roth, A., Lantuit, H., 2018. Monitoring inter- and intra-seasonal dynamics of rapidly degrading ice-rich permafrost riverbanks in the Lena Delta with TerraSAR-X time series. Remote Sens. 10 (1), 51. https://doi.org/10.3390/rs10010051.
Stieglitz, M., Shaman, J., McNamara, J.P., Engel, V., Shanley, J.B., Kling, G.W., 2003. An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport. Glob. Biogeochem. Cycl. 17 (4), 1105. https://doi.org/10.1029/2003GB002041.
Stogniy, V.V., 2003. Impulsnaya induktivnaya elektrorazvedka talikov kriolitozony tsentralnoy Yakutii (Transient Electromagnetic Prospecting of Taliks in Permafrost of Central Yakutia). Akademiya Publ, Yakutsk, 124 pp. (in Russian).
Streletsky, D.A., Shiklomanov, N.I., Nelson, F.E., 2012. Spatial variability of permafrost active-layer thickness under contemporary and projected climate in Northern Alaska. Polar Geogr. 35 (2), 95–116. https://doi.org/10.1080/1088937X.2012.680204.
Streletsky, D.A., Tananaev, N.I., Opel, T., Shiklomanov, N.I., Nyland, K., Streletskaya, I. D., Tokarev, I., Shiklomanov, A.I., 2015. Permafrost hydrology in changing climatic conditions: seasonal variability of stable isotope composition in rivers in discontinuous permafrost. Environ. Res. Lett. 10, 095003 https://doi.org/10.1088/1748-9326/10/9/095003.
Sukhodrovsky, V.E., 1979. Kriogennoye relyefoobrazovaniye v kriolitozone (Exogenous Morphogenesis in Permafrost) (Nauka, Moscow, 280 pp. (in Russian)).
Summerfield, M.A., 2005. A tale of two scales, or the two geomorphologies. Trans. Inst. Br. Geogr. 30, 402–415.
Suzuki, K., Matsuo, K., Hiyama, T., 2016. Satellite gravimetry-based analysis of terrestrial water storage and its relationship with run-off from the Lena River in eastern Siberia. Int. J. Remote Sens. 37 (10), 2198–2210. https://doi.org/10.1080/01431161.2016.1165890.
Tananaev, N.I., 2007. Stok nanosov i ruslovye protsessy na rekakh kriolitozony (*Sediment runoff and fluvial processes in rivers of permafrost zone*), Ph.D. Thesis Abstract, Moscow State University, Moscow, 26 pp. (in Russian).
Tananaev, N., 2013. Hydrological and geocryological controls on fluvial activity of rivers in cold environments. In: Cold and Mountain Region Hydrological Systems Under

Climate Change: Towards Improved Projections, 360. IAHS Publ, pp. 161–167. https://doi.org/10.13140/RG.2.1.1096.0407.
Tananaev, N., 2016. Hydrological and sedimentary controls over fluvial thermal erosion, the Lena River, central Yakutia. Geomorphology 253, 524–533. https://doi.org/10.1016/j.geomorph.2015.11.009.
Tananaev, N., 2018. The contemporary dynamics of the longitudinal profile of the middle Lena River. In: Izvestiya Rossiiskoi Akademii Nauk. Seriya Geograficheskaya, 5, pp. 46–54. https://doi.org/10.1134/S258755661805014X (in Russian).
Tananaev, N., Makarieva, O., Lebedeva, L., 2016. Trends in annual and extreme flows in the Lena River basin, Northern Eurasia. Geophys. Res. Lett. 43 (12), 10764–10772. https://doi.org/10.1002/2016GL070796.
Tananaev, N., Georgiadi, A., Fofonova, V., 2019. Revising contemporary heat flux estimates for the Lena River, Northern Eurasia. Hydrol. Res. 50 (5), 1440–1452. https://doi.org/10.2166/nh.2019.062.
Tananaev, N., Teisserenc, R., Debolsky, M., 2020. Permafrost hydrology research domain: process-based adjustment. Hydrology 7 (1), 6. https://doi.org/10.3390/hydrology7010006.
Tananaev, N., Isaev, V., Sergeev, D., Kotov, P., Komarov, O., 2021. Hydrological connectivity in a permafrost tundra landscape near Vorkuta, North-European Arctic Russia. Hydrology 8, 106. https://doi.org/10.3390/hydrology8030106.
Tarbeeva, A., Tregubov, O., Lebedeva, L., 2021. Patterns of the slope drainage network of the permafrost in the area of Anadyr. Geomorfologiya 2021 (1), 109–120. https://doi.org/10.31857/S0435428121010132 (in Russian).
Tei, S., Morozumi, T., Nagai, S., Takano, S., Sugimoto, A., Shingubara, R., Fan, R., Fedorov, A., Gavrilyeva, T., Tananaev, N., Maximov, T., 2020. An extreme flood caused by a heavy snowfall over the Indigirka River basin in Northeastern Siberia. Hydrol. Process. 34 (3), 522–537. https://doi.org/10.1002/hyp.13601.
Thorn, C.E., Hall, K., 2002. Nivation and cryoplanation: the case for scrutiny and integration. Prog. Phys. Geogr. 26 (4), 533–550. https://doi.org/10.1191/0309133302pp351ra.
Tolstov, A.N., 1966. O nalichii merzlykh porod pod ruslami rek v Severnoy Yakutii (On the presence of frozen ground under river channels in Northern Yakutia). In: Materialy VIII Mezhduvedomstvennogo soveschaniya po merzlotovedeniyu (geokriologii) (Materials of the VIIIth Inter-Departmental Conference on Permafrost Research (Geocryology)). Yakutian Book Publishing, Yakutsk, pp. 135–142 (in Russian).
Trimble, S.W., 2012. Historical sources and watershed evolution. Philos. Trans.R. Soc. A 370, 2075–2092. https://doi.org/10.1098/rsta.2011.0606.
Trochim, E.D., Jorgenson, M.T., Prakash, A., Kane, D.L., 2016a. Geomorphic and biophysical factors affecting water tracks in northern Alaska. Earth Space Sci. 3, 123–141. https://doi.org/10.1002/2015EA000111.
Trochim, E.D., Prakash, A., Kane, D.L., Romanovsky, V.E., 2016b. Remote sensing of water tracks. Earth Space Sci. 3, 106–122. https://doi.org/10.1002/2015EA000112.
Turcotte, B., Morse, B., Bergeron, N.E., Roy, A.G., 2011. Sediment transport in ice-affected rivers. J. Hydrol. 409 (1-2), 561–577. https://doi.org/10.1016/j.jhydrol.2011.08.009.
Turetsky, M.R., Abbott, B.W., Jones, M.C., Walter Anthony, K., Olefeldt, D., Schuur, E.A.G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D.M., Gibson, C., Sannel, B.K., McGuire, A.D., 2020. Carbon release through abrupt permafrost thaw. Nat. Geosci. 13, 138–143. https://doi.org/10.1038/s41561-019-0526-0.
Ushakov, M.V., Ukhov, N.V., 2020. Modern changes in the thermal regime of mountain rivers in the permafrost zone (A case study for the Upper Kolyma). Russ. Meteorol. Hydrol. 45, 858–863. https://doi.org/10.3103/S1068373920120067.
Valentin, C., Poesen, J., Li, Y., 2005. Gully erosion: impacts, factors and control. Catena 63, 132–153. https://doi.org/10.1016/j.catena.2005.06.001.
Van Huissteden, J., 2020. Thawing Permafrost. Permafrost Carbon in the Warming Arctic. Springer, Switzerland. https://doi.org/10.1007/978-3-030-31379-1, 508 pp.
Van Vliet, M.T.H., Franssen, W.P.H., Yearsley, J.R., Ludwig, F., Haddeland, I., Lettenmaier, D.P., Kabat, P., 2013. Global river discharge and water temperature under climate change. Glob. Environ. Chang. 23 (2), 450–464. https://doi.org/10.1016/j.gloenvcha.2012.11.002.
Vandenberghe, J., 2003. Climate forcing of fluvial system development: an evolution of ideas. Quat. Sci. Rev. 22, 2053–2060. https://doi.org/10.1016/S0277-3791(03)00213-0.
Vandenberghe, J., 2008. The fluvial cycle at cold-warm-cold transitions in lowland regions: a refinement of theory. Geomorphology 98, 275–284. https://doi.org/10.1016/j.geomorph.2006.12.030.
Veillette, A., 2019. Stabilisation du paysage périglaciaire suite à un épisode de ravinement par thermo-érosion : implication pour la structure et la stabilité thermique du pergélisol de surface. M.Sc. Thesis. Université de Montréal, 91 pp. http://hdl.handle.net/1866/22507.
Velicogna, I., Tong, J., Zhang, T., Kimball, J.C., 2012. Increasing subsurface water storage in discontinuous permafrost areas of the Lena River basin, Eurasia, detected from GRACE. Geophys. Res. Lett. 39, L09403 https://doi.org/10.1029/2012GL051623.
Ventra, D., Clarke, L.E., 2018. Geology and geomorphology of alluvial and fluvial fans: current progress and research perspectives. Geol. Soc. Lond. Spec. Publ. 440, 1–21. https://doi.org/10.1144/SP440.16.
Visconti, F., Camporeale, C., Ridolfi, L., 2010. Role of discharge variability on pseudomeandering channel morphodynamics: results from laboratory experiments. J. Geophys. Res. Earth Surf. 115, F04042 https://doi.org/10.1029/2010JF001742.
Walker, H.J., Hudson, P.F., 2003. Hydrologic and geomorphic processes in the Colville River delta, Alaska. Geomorphology 56, 291–303. https://doi.org/10.1016/S0169-555X(03)00157-0.
Walker, H.J., Arnborg, L., Peippo, J., 1987. Riverbank erosion in the Colville Delta, Alaska. Phys. Geogr. 69 (1), 61–70. https://doi.org/10.1080/04353676.1987.11880197.
Walter Anthony, K., Schneider von Deimling, T., Nitze, I., Frolking, S., Emond, A., Daanen, R., Anthony, P., Lindgren, P., Jones, B., Grosse, G., 2016. 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes. Nat. Commun. 9, 3262. https://doi.org/10.1038/s41467-018-05738-9.
Walvoord, M.A., Kurylyk, B.L., 2016. Hydrologic impacts of thawing permafrost – a review. Vadose Zone J. 15 (6), 1–20. https://doi.org/10.2136/vzj2016.01.0010.
Walvoord, M.A., Voss, C.I., Wellman, T.P., 2012. Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: example from Yukon Flats Basin, Alaska, United States. Wat. Resourc. Res. 48, W07524 https://doi.org/10.1029/2011WR011595.
Walvoord, M.A., Voss, C.I., Ebel, B.A., Minsley, B.J., 2019. Development of perennial thaw zones in boreal hillslopes enhances potential mobilization of permafrost carbon. Environ. Res Lett. 14 (1), 015003 https://doi.org/10.1088/1748-9326/aaf0cc.
Wang, X., Chen, R., Yang, Y., 2017. Effects of permafrost degradation on the hydrological regime in the source regions of the Yangtze and Yellow Rivers, China. Water 9, 897. https://doi.org/10.3390/w9110897.
Wang, C., Wang, Z., Kong, Y., Zhang, F., Yang, K., Zhang, T., 2019. Most of the Northern Hemisphere permafrost remains under climate change. Sci. Rep. 9, 3295. https://doi.org/10.1038/s41598-019-39942-4.
Wankiewicz, A., 1984. Hydrothermal processes beneath Arctic river channels. Wat. Resourc. Res. 20 (10), 1417–1426. https://doi.org/10.1029/WR020i010p01417.
Watson, V., Kooi, H., Bense, V.F., 2013. Potential controls on cold-season river flow behavior in subarctic river basins of Siberia. J. Hydrol. 489, 201–226. https://doi.org/10.1016/j.jhydrol.2013.03.011.
Weckwerth, P., Pisarska-Jamroży, M., 2015. Periglacial and fluvial factors controlling the sedimentation of Pleistocene breccia in NW Poland. Geogr. Ann. Ser. A 97 (2), 415–430. https://doi.org/10.1111/geoa.12082.
Wild, B., Andersson, A., Bröder, L., Vonk, J., Hugelius, G., McClelland, J.W., Song, W., Raymond, P.A., Gustaffson, Ö., 2019. Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing permafrost. PNAS 116 (21), 10280–10285. https://doi.org/10.1073/pnas.1811797116.
Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. J. Geol. 68 (1), 54–74. https://doi.org/10.1086/626637.
Woo, M.-K., 2012. Permafrost Hydrology. Springer Verlag (575 pp.).
Woo, M.-K., 2019. Cryohydrology in Canada: a brief history. Hydrol. Process. 33, 3407–3411. https://doi.org/10.1002/hyp.13581.
Woo, M.-K., Steer, P., 1983. Slope hydrology as influenced by thawing of the active layer, resolute, N.W.T. Can. J. Earth Sci. 20 (6), 978–986. https://doi.org/10.1139/e83-087.
Woo, M.-K., Steer, P., 1986. Runoff regime of slopes in continuous permafrost areas. Can. Wat. Res. J. 11 (1), 58–68. https://doi.org/10.4296/cwrj1101058.
Yang, D., Shi, X., Marsh, P., 2015. Variability and extreme of Mackenzie River daily discharge during 1973–2011. Quat. Int. 380–381, 159–168. https://doi.org/10.1016/j.quaint.2014.09.023.
Yershov, E.D., 1998. In: Williams, P.J. (Ed.), General Geocryology. Cambridge University Press (608 pp.).
Yi, W., Feng, Y., Liang, S., Kuang, X., Yan, D., Wan, L., 2021. Increasing annual streamflow and groundwater storage in response to climate warming in the Yangtze River source region. Environ. Res. Lett. 16, 084011 https://doi.org/10.1088/1748-9326/ac0f27.
Yokohata, T., Saito, K., Takata, K., Nitta, T., Satoh, Y., Hajima, T., Sueyoshi, T., Iwahana, G., 2020. Model improvement and future projection of permafrost processes in a global land surface model. Progr. Earth Planet. Sci. 7, 69. https://doi.org/10.1186/s40645-020-00380-w.
Zaitsev, A.A., Tananaev, N.I., 2008. Multiannual dynamics of the Lena River mouth near the "Yakut Robbery" and the ground freezing impact. Geomorphologiya 1, 25–35. https://doi.org/10.15356/0435-4281-2008-1-25-35 (in Russian).
Zernov, A.V., 1987. Osobennosti uluchsheniya i podderzhaniya sudokhodnykh usloviy na rekakh severa Zapadnoy Sibiri (na primere rek Nadym, Pur i Sob') (Regional Features of Enhancement and Maintenance of Navigable Waterways on Rivers of North Western Siberia (Nadym, Pur and Sob' Rivers as Examples)). Ph.D. Thesis Abstract. Leningrad Institute of Water Transportation Studies, Leningrad (25 pp. (in Russian)).
Zheng, L., Overeem, I., Wang, K., Clow, G.D., 2019. Changing Arctic river dynamics cause localized permafrost thaw. J. Geophys. Res. Earth Surf. 124, 2324–2344. https://doi.org/10.1029/2019JF005060.