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Sediment flow at the river mouths of the permafrost zone

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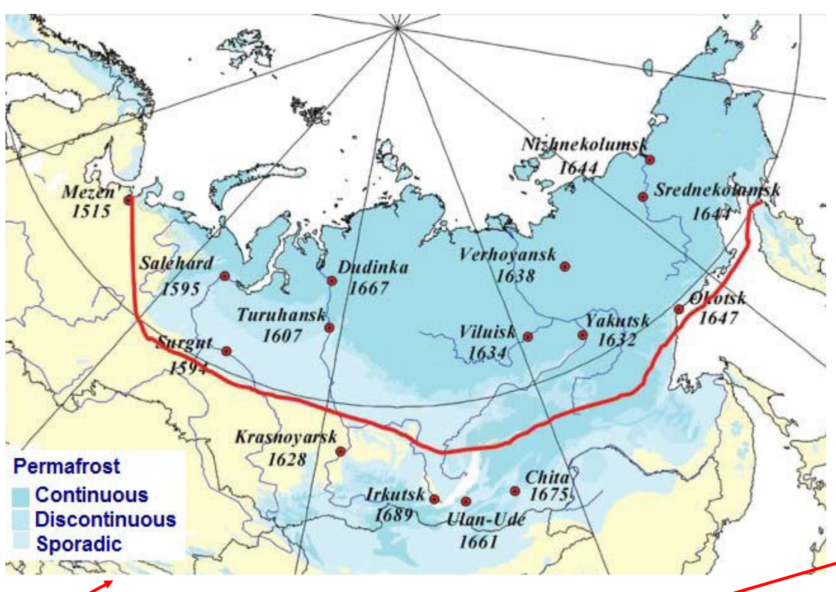
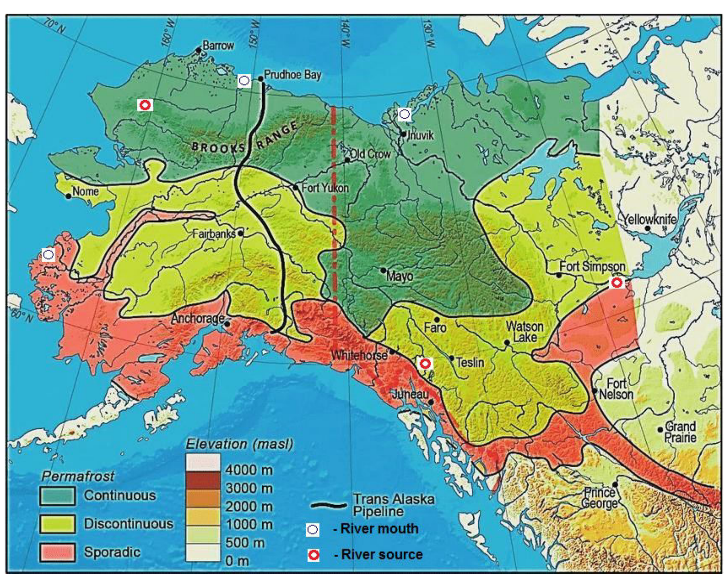
1. Distribution of permafrost grounds in the Northern Hemisphere ~ 24% :

http://www.nytimes.com/interactive/2011/12/17/science/earth/1217-permafrost.html



www.greenpeace.ru



http://www.scar.ac.cn/fulltext/2016/6/20160601.htm

Under consideration are 11 Rivers in Russia: Pechora (Barents Sea), Ob, Pur, Taz, Yenisei, (Kara Sea), Khatanga, Olenyek, Lena, Yana (Laptev Sea), Indigirka, Kolyma (East-Siberian Sea); and 3 Rivers in Nothern America: Mackenzie (Beaufort Sea, Canada), Colville and Yukon (Alaska, USA).

Permafrost can be present in soil, sediment, or rock and is defined by ground that is cryotic (<0°C) for at least two consecutive years. An increase of air temperature causes melting of permafrost grounds following by subsidence of ground, solifluction and thermal denudation. In the permafrost zone icy base of landscapes is the stabilizing factor during the natural evolution and it becomes an aggravating factor promoting destruction of natural landscapes under man-caused loading. Thaw of grounds in the river mouths would provoke a change of the factors determining their hydrological regime: ice melting and sea-level change, abrasion of banks at coastal zone of Arctic Seas, coastal flood, etc. Forecasts of possible thaw of permafrost due to increase of air temperature are as contradictory as the scenarios of climate changes. Climate changes in the areas of the upper reaches of the rivers also influence the regime of river mouths as they cause changes of ice thickness, ice phenomena duration, water and sediment flows.

2. Characteristic features of the rivers in the permafrost zone:

- Formation of frozen grounds at the mouth and near shore zone due to interaction of cold salt water with sediments washed out by fresh water;
- Small water discharge ***W*** during winter low water;
- Comparatively small sediment discharge W_s and erosion processes;
- The freeze-up begins in the river mouths with formation of supercooled anchor ice, ice jams and autumn frazil ice drift (Yenisei);
- Spring movement of ice is accompanied by strong ice jams (Pechora, Ob, Yenisei, Lena) with the water level increasing up to 20 m and flooding out low-lying lands (Yana, Lena). The duration of ice phenomena in the river mouths varies from 220 days at Pechora to 265 days at Indigirka;

3. Water and sediment flow of the river mouths in cryosphere

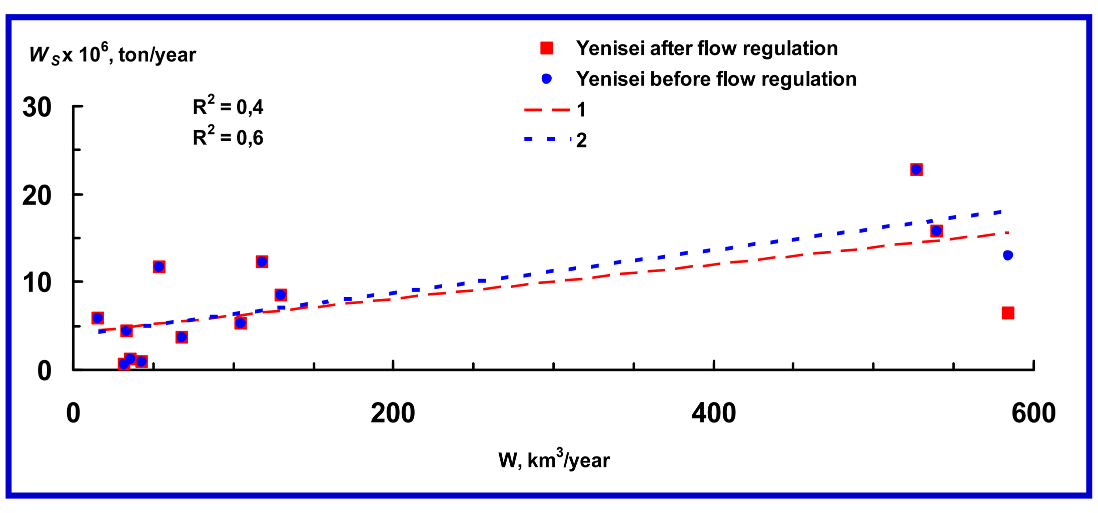
Table 1. Watershed area *F*, annual runoff W_w and sediment W_s flow of the rivers under consideration.

River	$F \cdot 10^3$, km²	W, km³/year	W_s 10^6 tons/year
Pechora	322	130	8.5
Ob	2990	402	13.0
Pur	112	32.3	0.6
Taz	150	43.4	0.9
Yenisei	2580	597	4.9
Khatanga	364	105	5.2
Olenyek	219	36.1	1.2
Lena	2490	528	22.7
Yana	238	31.9	4.2
Indigirka	360	54.0	11.9
Kolyma	647	118	12.3
Mackenzie	1800	350	130
Colville	53	15.8	5.8
Yukon	855	205	80

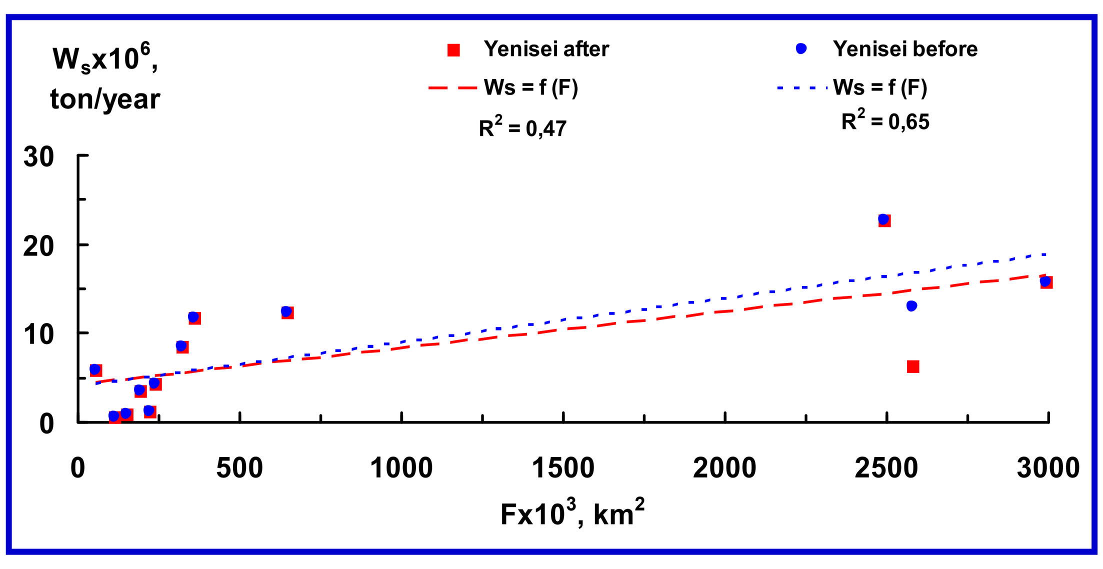
4. Sediment flow

Sediment flow W_S mainly depends on several characteristics of a river: watershed area, mean water flow, anthropogenic river flow regulation and geological structure of the river valley. Dependencies $W_S = f(W)$ and $W_S = f(F)$ for a whole number of rivers from the Table 1 do not yield significant correlation coefficient because of large values of W_S for Mackenzie and Yukon Rivers, comparable with W_S of the Rivers Danube and Nile.

Dependencies $Ws = f(W)$, $Ws = f(F)$ for all rivers excepting Mackenzie and Yukon



For the free-flow Yenisei river before the startup of Krasnoyarskaya power station at 1972 linear dependencies $Ws = f(W)$, $Ws = f(F)$ have $R^2 > 0.5$.



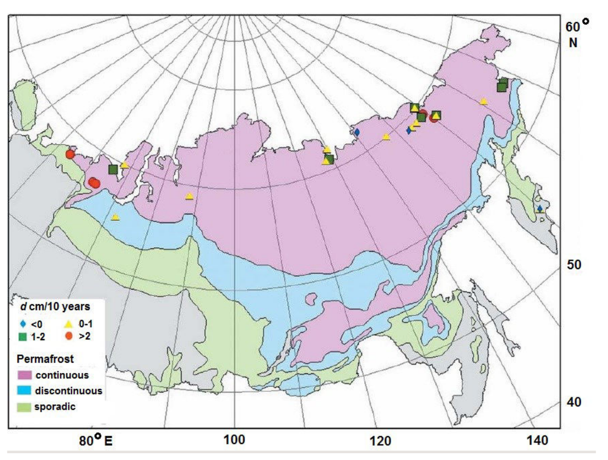
5. Climate change impact on the rivers in permafrost zone and possible reasons of large sediment flow of the Mackenzie and Yukon Rivers

Condition of frozen grounds can be described by:

1. **Temperature of the surface T_g;**
- **Depth of occurrence of frozen grounds, *D*;**
- **Active layer thickness, *d*;**
- **Ice content in the frozen ground, %.**

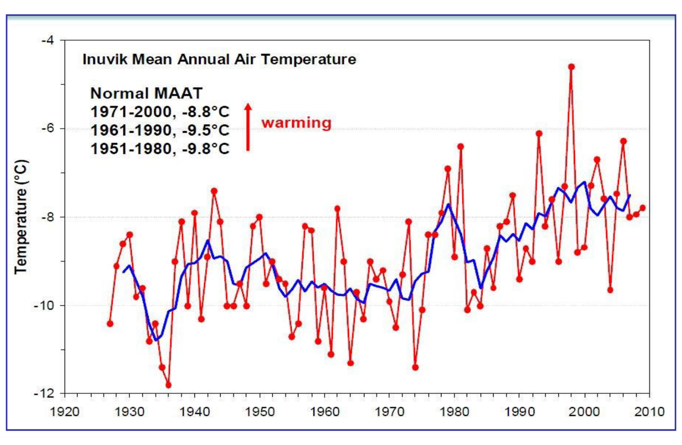
RUSSIA

The increase of mean year air temperature T_a could influence the variations of the long-term discharges of the rivers flowing into the Arctic Ocean [Dolgopolova, 2010]. During the period 2001 – 2005 climate warming in the North of Russia is estimated on average as very low – about +0.1°C which occurs mainly in the cold season. The increase of T_a at the Arctic coastal on the average amounts 0.03°C/year, with the minimum at the river mouths of Pechora and Lena 0.02°C/year, and maximum at the mouths of the Rivers Ob and Yenisei 0.05°C/year. However, T_a of the arctic region at the mouths of the rivers Ob and Yenisei during 1990 – 2005 even decreased.
Monitoring data of frozen ground in most of regions in Russia show increase of *d* and T_g during the period 1999 – 2008 [Greenpeace, 2010] (map). In the European part of Russia depth of talics increased, new talics in continuous permafrost zone appeared. The boundary of permafrost zone in the European part of Russia during 1970 – 2005 moved to the North in Pechora flat for ~30 – 40 km, and for 80 km at the plains near the Polar Ural. At the same time, at the Arctic coast of eastern Siberia and Far East, *d* decreased in the lower reaches of the Rivers Yana, Indigirka and Kamchatka (map) [Methods, 2012]. However, comparison of the maps of permafrost distribution for last 20 years shows that all river mouths in Russia, which are under study (Table 1), are located in continuous permafrost.



CANADA and ALASKA

In Canada permafrost boundary migrates in a wide range in accordance with the fluctuations of T_a. At the climate warming 6–9 thousands years ago the south permafrost boundary was located considerably northward of its current position. At the valley of Mackenzie River permafrost boundary moved with the variation of T_a from Fort Norman at the South (~ 64.5°N) to the Inuvik (~ 68.2°N) in the North [Smith, Burgess, 1999, Smith, 2011] (map). The transient decrease of T_a beginning from 1940 (figure) about 2ºC caused movement of the permafrost boundary to the South till 67.3°N. Climate at the coastal of Beaufort Sea (island Richards) change rapidly: from 1970 till 2008 increase of T_a amounted to 2.5°C [Burn, Kokelj, 2009]. At the Mackenzie River mouth $D = 100 \div 700$ m. At the region of Mackenzie River mouth during 1970 – 2008 increase of T_g varies in the range 1.5÷2.5ºC, and *d* increased by 8 cm. During 2005 – 2009 the time period of active layer freezing in alluvial lowlands became twice as long as in drier hills [Morse, Burn, Kokelj, 2012]. The circumpolar Arctic is warming faster than the global average and, specifically, permafrost supported peatlands of the Taiga Plains have been shown to be "severely" sensitive to climate change [Coleman et al, 2015]. Permafrost is maintained beneath these peat plateaus as a result of the thermal properties of peat. Accumulation of ice beneath these peat plateaus leads to the elevation of these areas above the surrounding landscape, sustaining drier and colder soil conditions. Investigations in the upstream of Mackenzie River (50 km south of Fort Simpson) within the sporadic discontinuous permafrost zone showed that 38% of permafrost in a 1 km² study area disappeared between 1947 and 2008, and was accompanied by land subsidence and flooding of peat plateaus. Permafrost thawing is a result of stable trend of T_a registered at the Hay Station (figure).
Continuous permafrost on the North Slope of Alaska has warmed by 2–4ºC over the last century [Alaska's Thawing Permafrost]. To the South of the River Yukon the increase of frozen grounds temperature at the depth 20 m varied in the range 0.3 ÷ 1ºC during the period 1983 – 2003 [Wilson, 2015]. Near the Ruby River (map - middle stream of the Yukon) mean velocity of thawing of relic permafrost ground before 2000 was ~ 0.04 m/year, and after that it increased till 0.09 m/year. New monitoring data of frozen ground in North America showed increase of T_g in mountain regions of the head and middle stream of Yukon to be larger than that was forecasted with the help of climatic stations [Coleman et al, 2015].



CONCLUSIONS

1. Increase of active layer thickness and thawing of frozen grounds promoting degradation of permafrost right up to its disappearance resulted in catchment surface ground and drainage peat bogs, swamps and lakes.

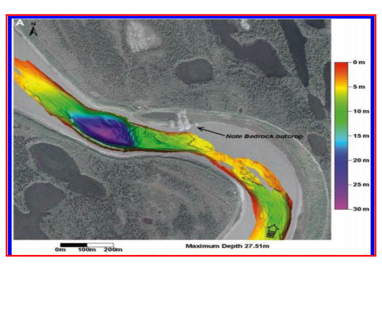
Drying of thermocarst lakes were observed at Old Crow Flats in the valley of Yukon and in Siberia.

2. Thawing and degradation of permafrost at the head of Mackenzie and Yukon Rivers, which leads to migration of the permafrost boundary in accordance with change of the mean annual air temperature, resulted in formation of easily washout soils. Migration of the permafrost boundary plays a considerable role in formation of sediment runoff of the Yukon and Mackenzie.

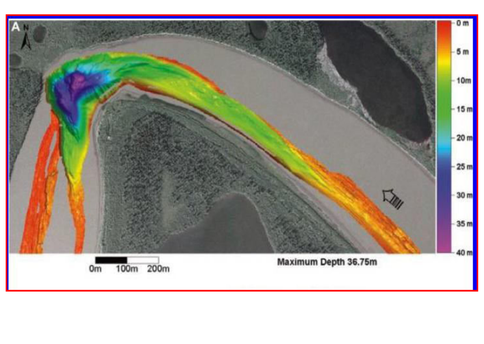
Deep score holes (~30 m) observed in the channels of the Mackenzie River delta [Beltaos, 2011] (pictures) could be considered as a confirmation of this conclusion. Thermokarst was proposed one of possible origins of such score holes at the mouths of Lena and Mackenzie [Dolgopolova, Isupova, 2014]. At the Mackenzie delta the effect could be intensified due to permafrost boundary migration and formation of easily washout grounds.
At the valley of the River Colville frozen grounds are in stable condition with $T_g = -2 \div -10$ºC, and it's sediment flow $W_S = 5.8 \cdot 10^6$ ton/year is in good correspondence with other rivers of the cryosphere.

[Beltaos et al., 2011]
Air photos of the East Channel in the vicinity of Inuvik

***H*=27.5 m**



***H*=36.8 m**



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