Scale-dependent influence of permafrost on riverbank erosion rates

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Introduction

The rate rivers erode their banks controls the pace of migration and the impacts on neighboring communities and ecosystems. Erosion of floodplains releases sediment, carbon, and other constituents into rivers affecting the biogeochemistry of rivers and ultimately the coastal oceans into which rivers flow. Across the Arctic, rivers erode through floodplains frozen continuously for more than two years (permafrost). Before ice-bounded sediments can be eroded by flowing water they must be thawed. Using aerial photographs, satellite imagery, and direct field observations we found that permafrost slows the rate rivers erode their banks relative to rivers without permafrost. The effect of permafrost, however, varies with the size of the river and the erosion rates of large rivers are disproportionately slowed by permafrost. As a result, permafrost thaw due to climate change will likely increase erosion rates on large rivers and have limited impact on small rivers, but very little data is available for small rivers in the Arctic highlighting a key data need.

Figure 1: Images of riverbanks eroding permafrost. a) Thermal-erosion niche undercutting a bank composed of frozen sand along the Yukon River, in central AK. b) Massive failure blocks resulting from thermal erosion undercutting of banks along the Yukon River, AK (66.33º N, 147.60º W). The top of the bank is approximately 4 m above the waterline. c) Exposed ice wedge and associated bank erosion in the banks of the Yukon River, AK. d) Thermal denudation and collapse of an ice-rich bank along the Koyukuk River (65.780º N, 156.437º W). Shovel handle in center of photo for scale. e) Sediments piled up on riverbank due to river ice erosion and sediment transport on the Yukon River, AK. f) Riverbank along the Selawik River in July 2012 showing loose thawed gravels and tundra blocks from spring bank erosion protecting the bank face (66.48º N, 157.71º W).

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Global and pan-Arctic measurements of riverbank erosion rates

Using remotely sensed imagery, we analyzed bank erosion rates on 15 Arctic rivers (Figure 2b) and compared these results to a global meta-analysis of published bank erosion rates (Figure 2a). When normalized by river width, to control for river size, we find that rivers in permafrost setting have bank erosion rates that are 9 times lower than rivers without permafrost (Figure 3)

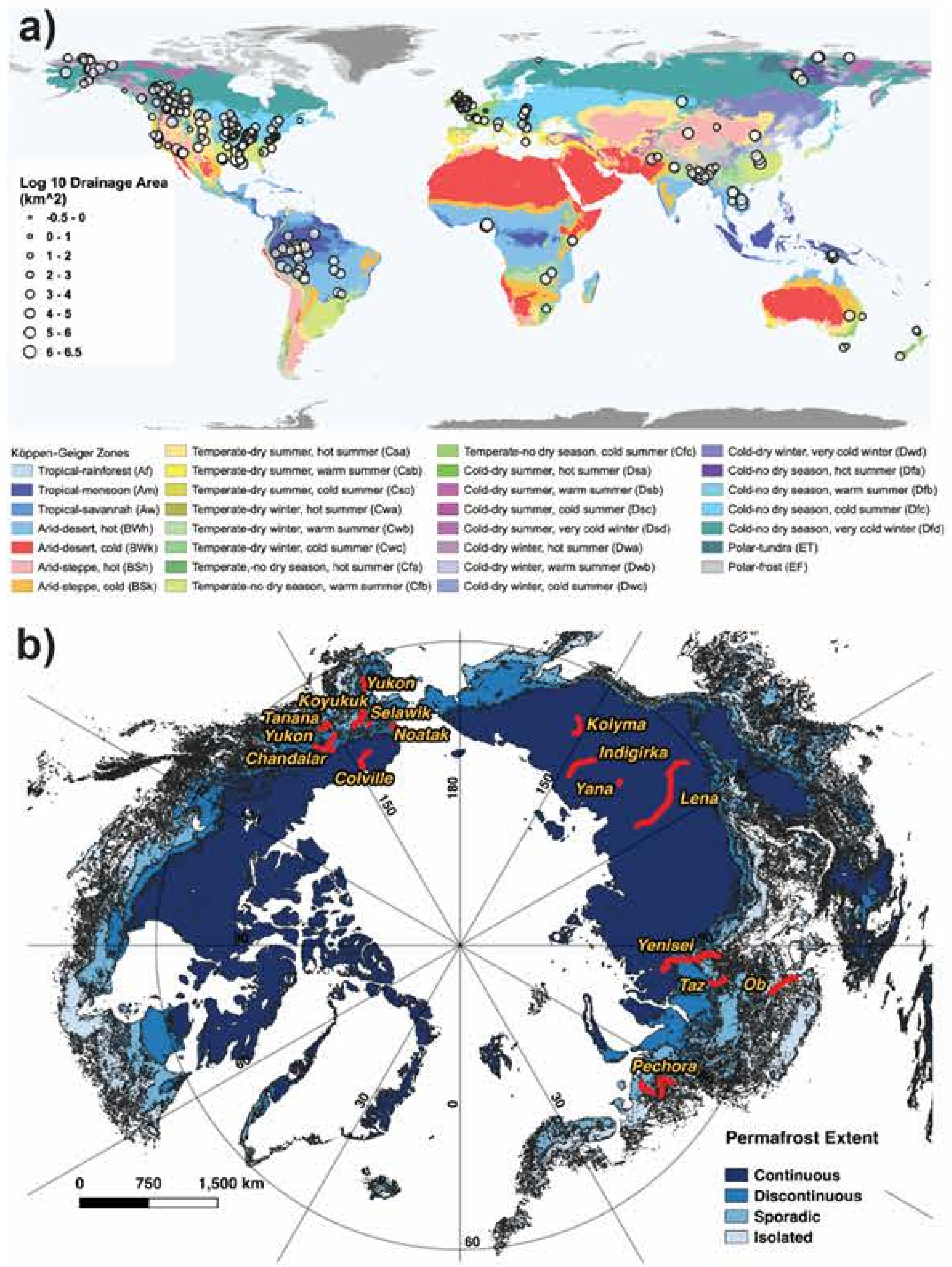

Figure 2: a) Locations of erosion rates compiled from published. Circle size is logarithmically (base 10) scaled to the upstream drainage area. The underlying map is colored by the Köppen-Geiger climate zone (Beck et al., 2018). b) Map of rivers permafrost regions analyzed and permafrost extent. Locations of rivers analyzed for bank erosion rates shown in red. The permafrost map shows zones of permafrost extent from isolated to continuous (Obu et al., 2019 version 2.0).

Schwenk, J., Zussman, T., Stachelek, J., and Rowland, J.C. (2022), rabpro: global watershed boundaries, river elevation profiles, and catchment statistics. *Journal of Open Source Software*. 7(73), p. 4237.

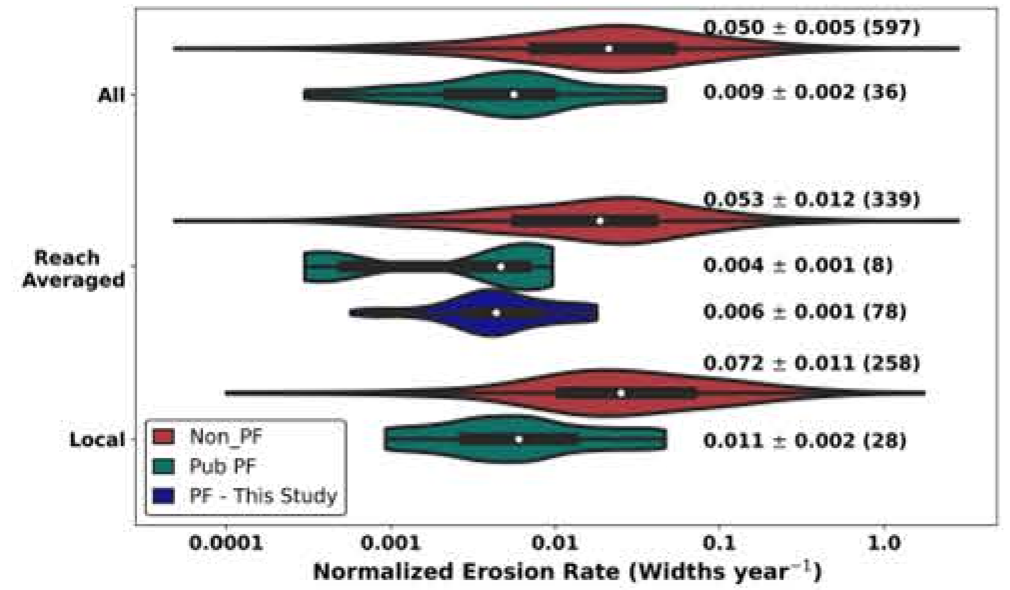

Figure 3: Comparisons of permafrost and non-permafrost riverbank erosion rates. Violin plots of width-normalized riverbank erosion rates for permafrost and non-permafrost rivers. These plots show the range and distribution of bank erosion rates from published data and our analyses. The y-axis indicates three categories: "All"-data regardless of the scale of measurement, "Reach-averaged" measurements, and "Local" measurements (point to bend-scale). The black rectangles display the interquartile range, the lines indicate the 1.5x interquartile range, white dots represent median values. The numbers report the mean, standard error, and number of observations (in parentheses).

Use of InteRFACE watershed tools to investigate drivers for bank erosion

Using data analysis tools developed with support from InteRFACE (Schwenk et al. 2022), we extracted hydrological and topographic data at each bank erosion data point to calculate stream power. Erosion rates are plotted as a function of stream power (Figure 4) we observe that the difference in bank erosion rates between permafrost and non-permafrost systems increase with the stream power (size) of the river, up to 40 x for the largest rivers analyzed.

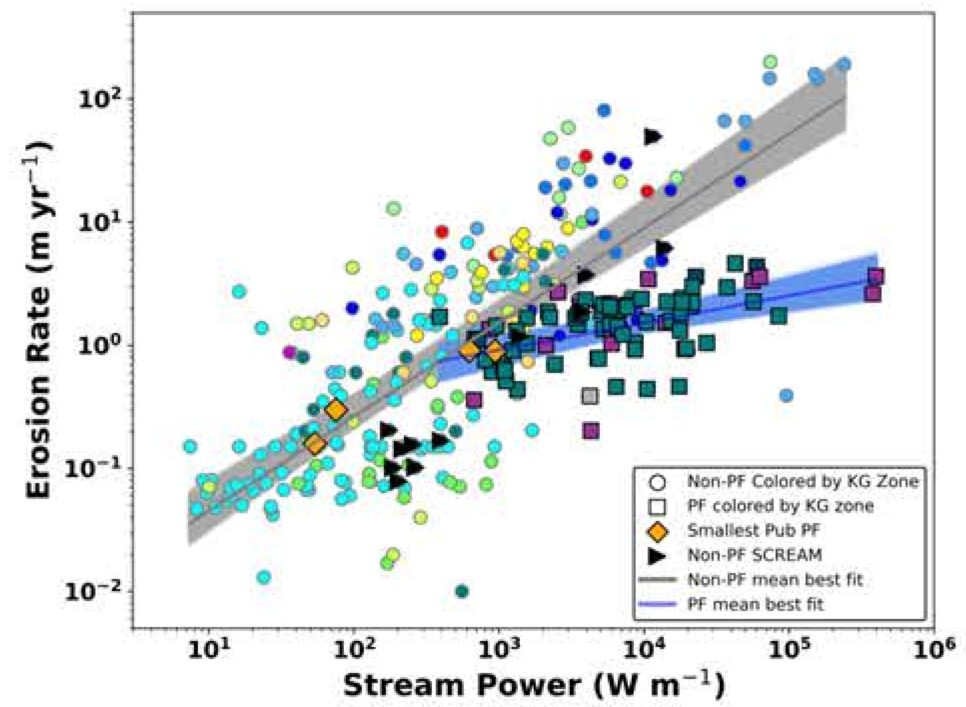

Figure 4: Reach-averaged erosion rates plotted by stream power. Circular points are data compiled from published studies and squares are permafrost rivers analyzed in this study. All points are colored by the Köppen-Geiger climate zones (Beck et al., 2018) shown in Figure3. The solid gray and blue lines show the mean best fit regressions from the 5,000 bootstrapped linear fits to the log10 transformed data. The shaded regions show all the regressions that fell within the 95th confidence intervals based on the distributions of modeled slopes. Diamond symbols show the published erosion rates of rivers with the smallest stream powers.