A sediment budget approach to quantify sediment fluxes and organic carbon mobilisation in an Arctic catchment

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1. Introduction

Erosion of continually thickening active layers in permafrost landscapes liberates large quantities of mineral sediment and soil organic carbon (SOC) into microbially active hydrological systems. Sediment yield, commonly used to evaluate total denudation, poorly represents the overall quantity of gross erosion within the catchment due to changes in storage on hillslopes and floodplains. Given the significant SOC (1300 Pg) stores in permafrost landscapes, understanding these contemporary particulate mass balances is vital to reveal how erosion processes may impact the permafrost carbon feedback (PCF) through carbon release (Hugelius et al., 2014).

Using remote sensing and supplementary data, we quantify a contemporary (1985 to 2017) sediment budget ($I = 0 \pm \Delta S$) for the Kuparuk catchment, Alaskan North Slope. Additionally, measured gross erosion was coupled with the Northern Circumpolar Soil Carbon Database (NCSCD) to calculate the gross mobilisation of SOC.

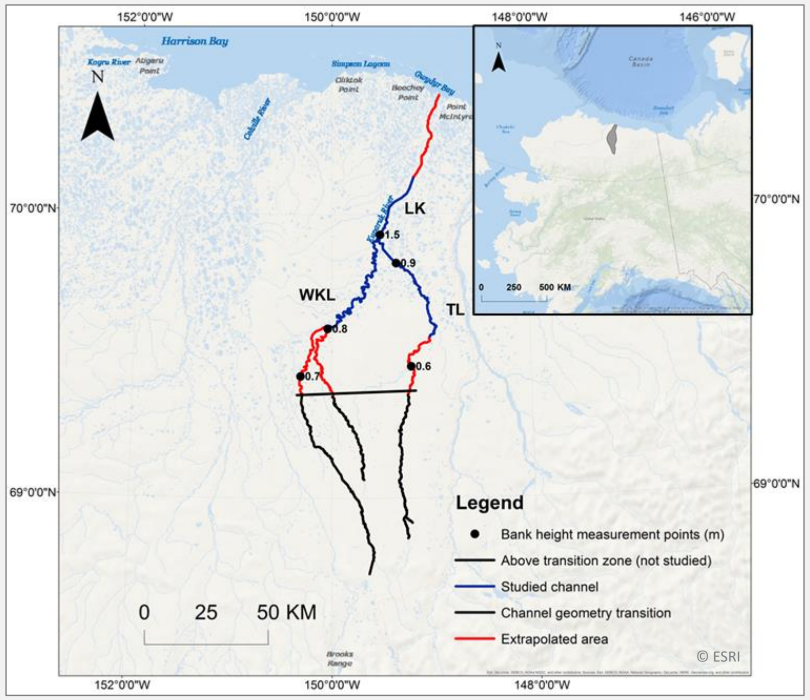


Fig.1: The 8140 km² Kuparuk catchment on the Alaskan North Slope. The extensive permafrost-underlain floodplain contains thick layers of superficial alluvial and peatland sediments

2. Methods

Using available optical satellite imagery and geospatial analysis, we quantified sediment output (USGS gauge 15896000) and the gross input of sediment through both hillslope (landslides) and alluvial bank erosion. Spatially coupling erosion with the NCSCD inventory allowed an estimation of the gross SOC mobilisation for comparison against published OC yields (McClelland et al ., 2014).

2.1 Channel bank erosion

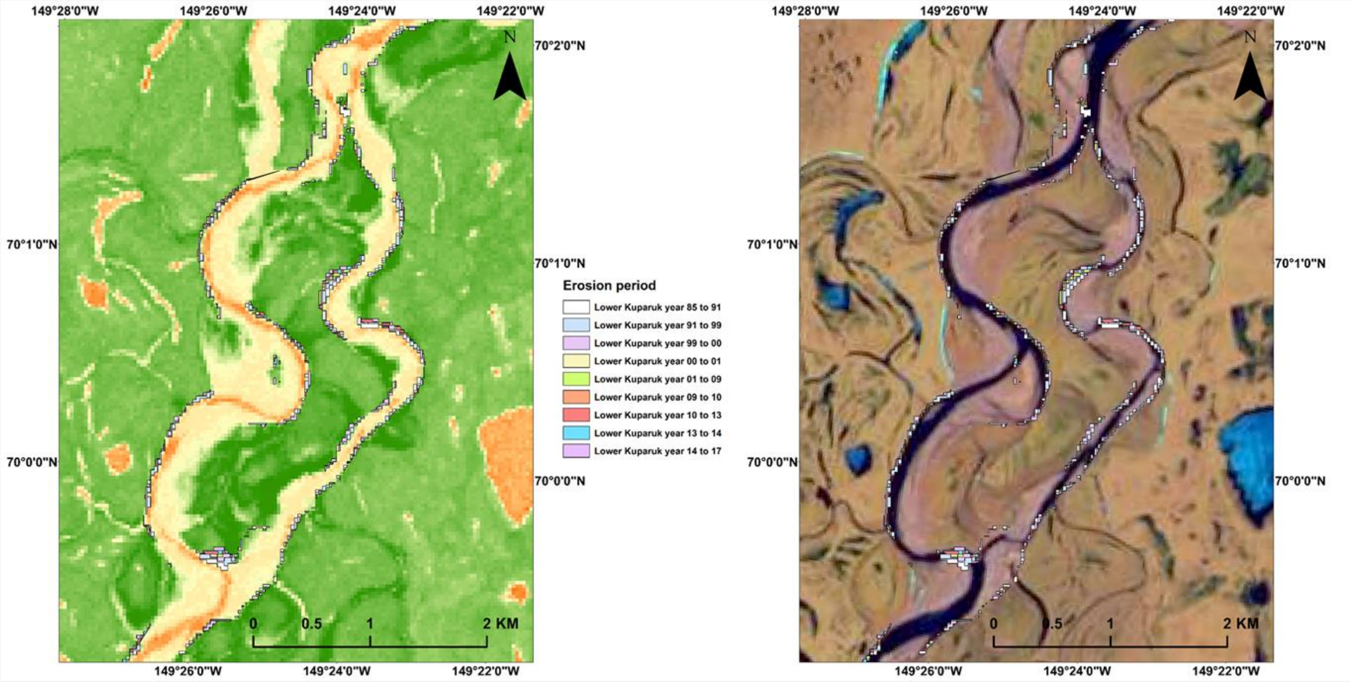


Fig.2: Chanel bank migration was quantified from Landsat imagery as the new channel area eroded on outer banks over time and manually checked for artifacts using modern Sentinel-2 imagery.

Alluvial bank erosion was vectorized from the change in the channel outer boundary extent between 1985 and 2017, distinguishable from Landsat (5, 7 & 8) level-2 surface reflectance NDVI imagery. Erosion polygons were manually checked and combined with bank height measurements made by McNamara and Kane, (2009) to obtain volumetric erosion.

2.2. Hillslope erosion

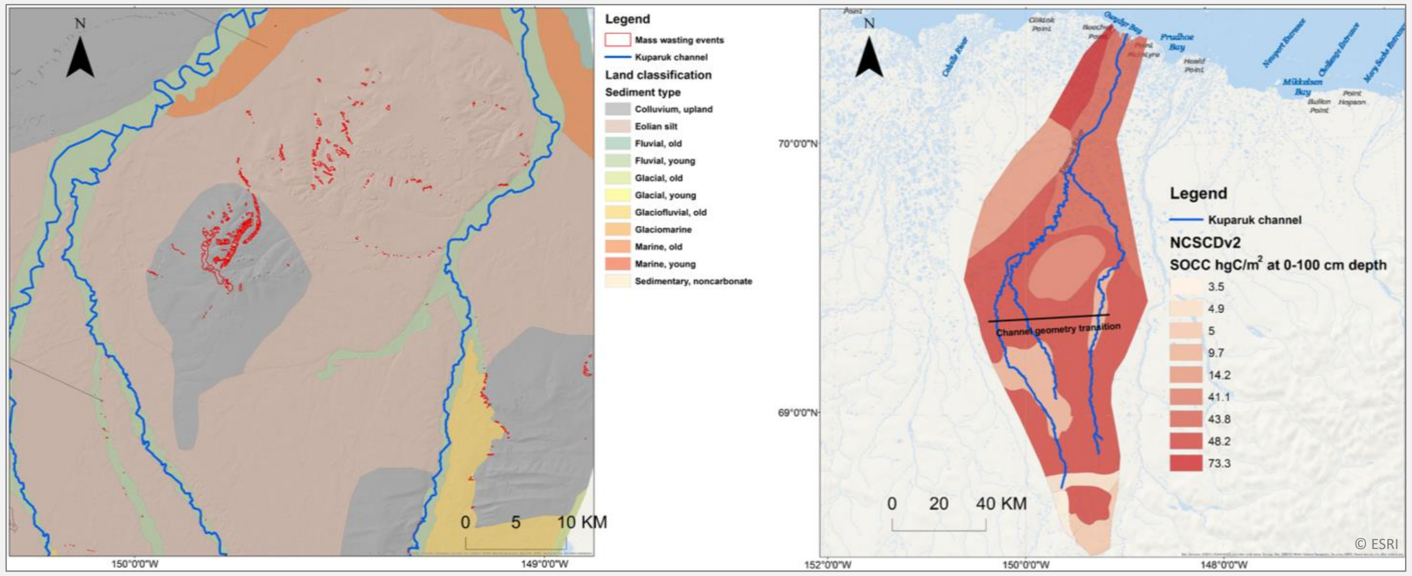


Fig.3: mapped hillslope erosion (left) with substrate information from the ORNL DAAC data portal (Muller et al., 2018), and NCSCD (Hugelius et al., 2013) SOC inventory for the Kuparuk catchment.

To estimate the total volume of hillslope erosion through active layer detachments (ALDs), thermokarst slumps (TSs) and other landslides (Debris producing slope failures: DSFs), we mapped the areal extent of mass movements using Google Earth^{TM}, multiplied by a representative measured active layer depth (0.52 m) from catchment borehole monitoring (Brown 1998).

Annual along-stream valley transport capacity from channel-connected (< 60 m) mass movements was spatially modelled via Eq. (1) from Croissant et al, (2017):

$$Qt = WK\left(\rho_w g\left(\frac{nQ_{eff}}{W}\right)^{0.6} S^{0.7} - (\rho_s - \rho_w) g \tau_c^* D_{50}\right) \quad (1)$$

Where effective discharge was calculated for both a representative 1-year spring and summer discharge within the nival hydrological regime (Fig. 4). Channel width (W) was calculated from the power law relationship derived from channel measurements by McNamara and Kane, (2009):

$$W = 1.1157x^{0.56} \quad (2)$$

2.3. Sediment yield

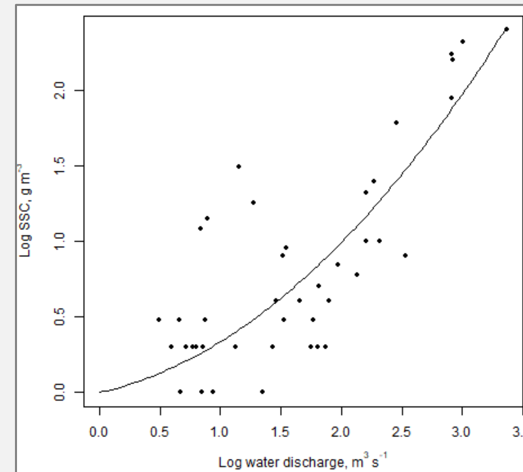
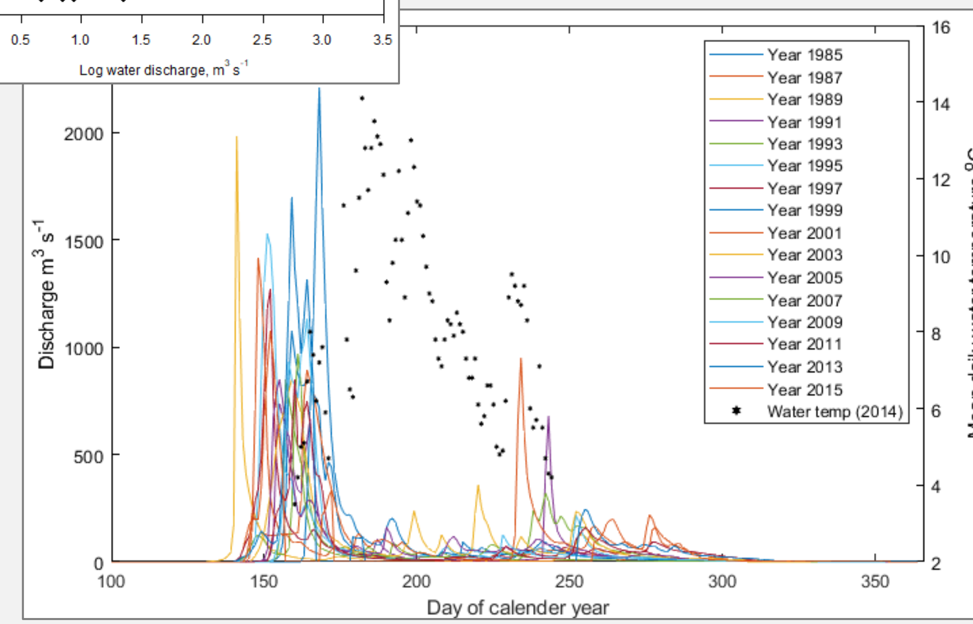


Fig.4 & 5: sediment rating curve (left) and a sample of hydrographs over the study period (below). The nival snowmelt peak dominates the discharge of water compared to pluvial events during summer.



The annual sediment yield was quantified using a second order polynomial rating curve, which achieved the best fit (R^2 = 0.65) between sampled suspended sediment and instantaneous discharge (Fig. 4).

3. Synthesis

- The quantified sediment budget for the this catchment shows only a small proportion of gross erosion is yielded from the catchment outlet (Fig. 7)**.**
- The cyclic fluxes of floodplain erosion and redeposition dominate the sediment budget, greatly exceeding sediment yield.
- Average annual sediment input through alluvial bank erosion (0.6 ± 0.12 Tg yr $^{-1}$) exceeded sediment yield (0.06 Tg yr $^{-1}$) by an order of magnitude. Channel bars and ephemeral sub-channels are major depositional sinks in offsetting gross bank erosion.

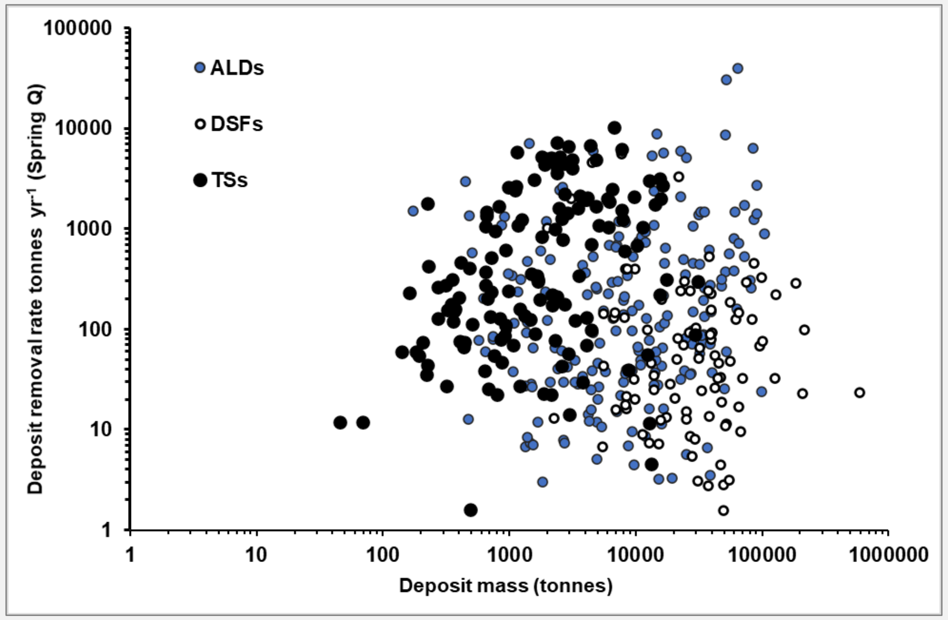


Fig.6: the relationship between hillslope erosion mass and transport capacity for different channel-connected mass wasting types.

- Hillslope mass wasting delivered a relatively large quantity of new sediment to the system with channel-connectivity (11.4 Tg) from mostly Yedoma substrates. However, an inverse relationship between transport capacity and eroded sediment mass meant the largest deposits were most transport limited (Fig. 6).
- The modelled fluvial transport capacity from hillslope erosion is the most uncertain flux due to the geomorphic inefficiency of the nival spring discharge peak when sediment remains frozen.
- The average mass of sediment transported from hillslope erosion is likely at an intermediate between the effective 1-yr summer (0.008 Tg yr $^{-1}$) and spring (0.4 Tg yr $^{-1}$) discharges, close to equilibrium with catchment sediment yield (0.06 Tg yr $^{-1}$).
- Of the 1505 ± 114 t yr $^{-1}$ particulate organic carbon (POC) from the Kuparuk (McClelland et al., 2014), gross bank erosion explained roughly 932 t yr $^{-1}$. Unknowns with respect to the masses of POC exported from transport limited mass wasting and resequestered within the floodplain represent important further research questions.

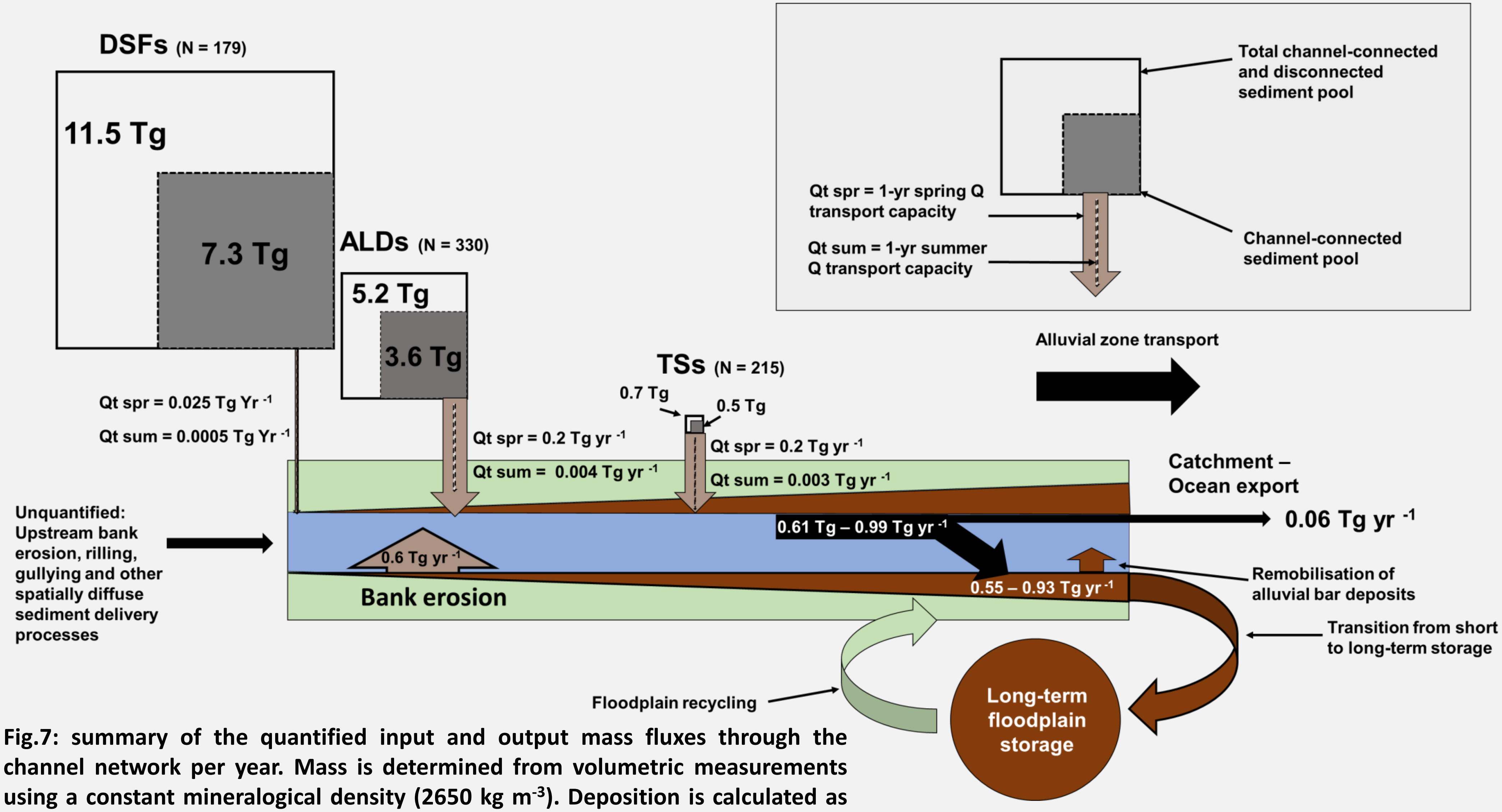


Fig.7: summary of the quantified input and output mass fluxes through the channel network per year. Mass is determined from volumetric measurements using a constant mineralogical density (2650 kg m^{-3}). Deposition is calculated as the difference between gross input and net sediment yield.

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