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Impact of stream power gradients on storage of sediment and carbon on channel margins and floodplains

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ABSTRACT

Spatial complexity impacts the resilience of river ecosystems by mediating processes that control the sources and sinks of sediment and organic material. Using four independent geochemical tracers and three morphometric indices, we show that downstream spatial gradients in stream power (Ω) predict storage of material in the channels and margins and/or floodplains. A field test in a 48 km² watershed demonstrates that reaches with downstream decreases in Ω coincide with wider floodplains and elevated inventories of ^{137}Cs, ^{210}Pb$_{ex}$ (ex—excess), and organic matter in locations of the ~3 to 20 yr floodplain. In contrast, reaches with downstream increases in Ω coincide with narrower floodplains and decreased inventories of ^{137}Cs, ^{210}Pb$_{ex}$, and organic matter. The occurrence of in-channel bedrock exposures and the activity of short-lived ^{7}Be in within-channel sediments also correlate with downstream Ω gradients, demonstrating a link, over both short and long time scales, between within-channel processes and floodplain-forming processes. The combined geochemical and physical characteristics demonstrate the importance of downstream gradients in sediment transport, characterized by downstream changes in stream power rather than at-a-point stream power, in determining spatial complexity in carbon and sediment storage at intermediate scales (10^2 to 10^3 m) in river systems.

INTRODUCTION

Spatial complexity in rivers has implications for river management and restoration through its impact on habitat, attenuation of downstream fluxes, and ecosystem resilience (Wohl, 2016; Cienciala et al., 2020; Reid et al., 2021). Channel complexity at fine scales (10^0–10^2 m) is known to result in variations in sediment and carbon storage, commonly at channel margins (Pizzuto, 2014), and to provide mosaics of diverse habitat patches (Pickett and White, 1985; Carbonneau et al., 2012). At watershed scales, $\geq 10^4$ m, the classic view depicting headwaters as sediment source areas, mid-watershed regions as transport reaches, and the lower reaches as depositional areas (Schumm, 1977) leads to broadly predictable changes in ecological communities (Vannote et al., 1980).

In contrast to variations at fine and watershed scales, variations in sediment storage at intermediate scales (10^2–10^4 m) have received less attention. Variations in sediment storage at intermediate scale are of interest because they control the sequestration and release of organic carbon, nutrients, and contaminants in riverine environments (Shanley et al., 2008; Wohl et al., 2012; Sutfin et al., 2021). Field observations suggest that understanding spatial variations in sediment and carbon storage in channel margins and floodplains over distances longer than 10^2 m requires consideration of both channel processes and broader geologic controls (Cienciala et al., 2020; Sutfin et al., 2021).

Seminal work by Exner (1920, 1925) showed that vertical sedimentation or erosion on river beds is controlled by changes in sediment flux (Q_s), specifically the downstream gradient in Q_s. Montgomery and Buffington (1997) expanded on this conceptual framing in noting that differences in the ratio of sediment transport capacity to supply allowed for reaches to be classified into source, transport, and response segments. Expanding beyond the channel, Sutfin and Wohl (2019) found that valley confinement is a significant predictor of sediment residence time. Recent work expanded on Exner's analyses to include lateral dimensions (Paola and Voller, 2005; Gartner et al., 2015a), whereby reaches with downstream-increasing Q_s are prone to erosion while reaches with downstream-decreasing Q_s are prone to deposition. Field studies have tested these predictions over intermediate spatial scales (10^2–10^3 m) and short time scales (a single day to a single year), finding that modeled gradients in sediment flux successfully predict bed erosion or deposition after a dam removal (Gartner et al., 2015b) and lateral erosion or deposition in large floods (Gartner et al., 2015a; Sholtes et al., 2018). However, it remains unclear whether moderate flows (annual peak flow recurrence intervals on the order of $\sim 10^1$ yr or less) in undisturbed systems play a predictable role in carbon and sediment storage over longer time scales.

We used multiple lines of geochemical and geomorphic evidence to evaluate whether downstream gradients in Q_s predict downstream variations in storage of material at channel margins and floodplains in a system subject to only moderate flood events over the last several decades. Sediment flux Q_s is known to scale with stream power (Bagnold, 1977), Ω, defined as $\Omega = QS\rho g$, where Q, S, ρ, and g are discharge, slope, density of water, and gravity, respectively. Because Q_s is difficult to measure while Ω is easily derived from digital elevation models (DEMs) (e.g., Gartner et al., 2015a), we used Ω calculated using the 2 yr discharge as a proxy for Q_s. We used the 2 yr flood to capture the influence of more frequent flooding and the resultant floodplain disturbance rather than those of major floods. Specifically, we tested the two-part hypothesis that (1) if a reach exhibits downstream-increasing Ω (hereafter symbolized as Ω↗), then the reach is erosional and induces minimal storage of sediment and carbon on channel margins and floodplains, and (2) if a reach exhibits downstream-decreasing Ω (Ω↘), then the reach is depositional and generates enhanced storage of sediment and carbon on

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channel margins and floodplains. Using a 14 km stream as a natural laboratory, we chose seven sites with nearly equal stream power: three with Ω↗ and four with Ω↘. We used variations in inventories of radionuclides $^{210}Pb_{ex}$ (ex—excess) and ^{137}Cs and of organic matter to determine whether channel-margin and floodplain soil profiles exhibit erosion or aggradation over decadal to century time scales, and channel sediment ^{7}Be activity to examine in-stream erosion and deposition over month to annual time scales. Floodplain morphology and soil depth and locations of bedrock channels were examined to further explore correspondence between short- and long-term channel and floodplain processes.

SITE DESCRIPTION

Mink Brook (western New Hampshire, USA) extends 14 km in a forested watershed (48 km²) with a temperate climate and ~1 m/yr of precipitation evenly distributed throughout the year (Fig. 1). The basin has 520 m of relief and is underlain by interstratified metavolcanics and metasediments covered in glacial till and outwash as much as a few meters thick. The bankfull stream width and depth are typically 7–10 m and ~0.5 m, respectively, and the stream bed and banks are dominantly comprised of silt- to boulder-size particles with occasional bedrock outcrops <~30 m in length. Median bed grain size is typically 1–2 cm and rarely as large as 5–10 cm. Over the past half century, peak flows generally have not exceeded the ~20 yr recurrence interval (RI) flood, except one event in 2006 CE with an ~40 + yr RI (U.S. Geological Survey gage 01141800; annual peak discharges are given in the Supplemental Material[1]). Downstream changes in bedrock resistance give rise to reaches with Ω↗ and reaches with Ω↘. Typical channel slopes are 1% to 2% on Ω↘ reaches and 2% to 3% on Ω↗ reaches. Near-channel valley slopes along transects perpendicular to the channel mirror the trend in stream power. Additional site details are provided in the Supplemental Material.

GEOCHEMICAL SIGNATURES OF SEDIMENT AND CARBON STORAGE AND REMOVAL

Within floodplain soil profiles, three geochemical signatures ($^{210}Pb_{ex}$, ^{137}Cs, and organic matter) show evidence of erosion, deposition, or stability as follows. Within stable soil profiles, the net balance between atmospheric deposition of the fallout radionuclides $^{210}Pb_{ex}$ (22.3 yr half-life) and ^{137}Cs (30.2 yr half-life) and their decay is represented by inventories of 5400 ± 500 Bq/m² for $^{10}Pb_{ex}$ and 1500 ± 400 Bq/m² for ^{137}Cs (Landis et al., 2016). If net erosion occurs, sediment tagged with $^{210}Pb_{ex}$ and ^{137}Cs is removed from the soil profile and the inventory decreases. If net deposition occurs, sediment tagged with $^{210}Pb_{ex}$ and ^{137}Cs is added to the soil profile, and the inventory increases. ^{137}Cs is potentially mobile within a soil profile (Landis et al., 2016), but we assume that this does not impact the total ^{137}Cs inventory. For organic matter, relatively high inventories suggest accumulation and storage of organic matter and carbon. Relatively low inventories suggest removal and reduced storage.

Soil profiles were sampled along transects at increasing flood RI elevations, equivalent to increasing distance and height from the channel (Fig. 1C) A detailed description of sampling methods is provided in the Supplemental Material. Consistent with previous work (Renshaw et al., 2014), all inventories generally peaked around the 3–5 yr RI elevation (Fig. 2). Soil profiles below ~3 yr RI elevation show no consistent pattern between Ω↗ and Ω↘ sites. They have a range of inventories that indicate rapid sediment turnover. Above the ~3 yr RI elevation, sites with Ω↗ exhibit low inventories,

[1]Supplemental Material. Additional information on sites and methods. Please visit https://doi.org/10.1130/GEOL.S.21191095 to access the supplemental material, and contact editing@geosociety.org with any questions.

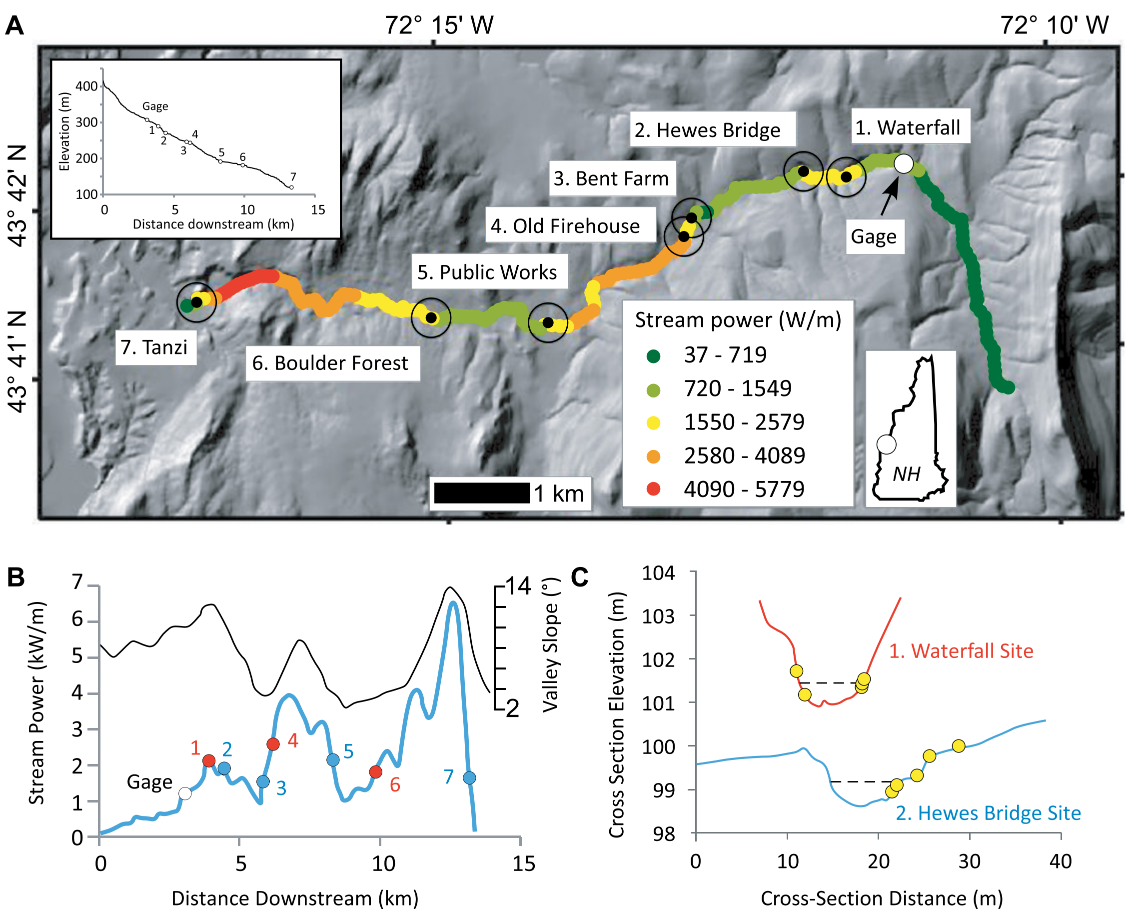

Figure 1. (A) Mink Brook (New Hampshire [NH], USA) location map with sample sites (black circles) and stream power along the river course. Inset shows downstream distance from headwaters of the topographic profiles; numbers indicate site numbers. (B) Stream power along Mink Brook with sample sites in reaches with downstream-increasing stream power (Ω↗) (red dots) and reaches with downstream-decreasing stream power (Ω↘) (blue dots). Bent Farm site (site 3) is in a short Ω↘ reach obscured by the marker. Thin black line shows the average valley slope (perpendicular to channel) within 50 m of either side of the channel. (C) Representative cross sections from a Ω↗ reach (red line) and Ω↘ reach (blue line) with soil profile locations (yellow dots) and 2 yr flood recurrence elevation (dashed black line).

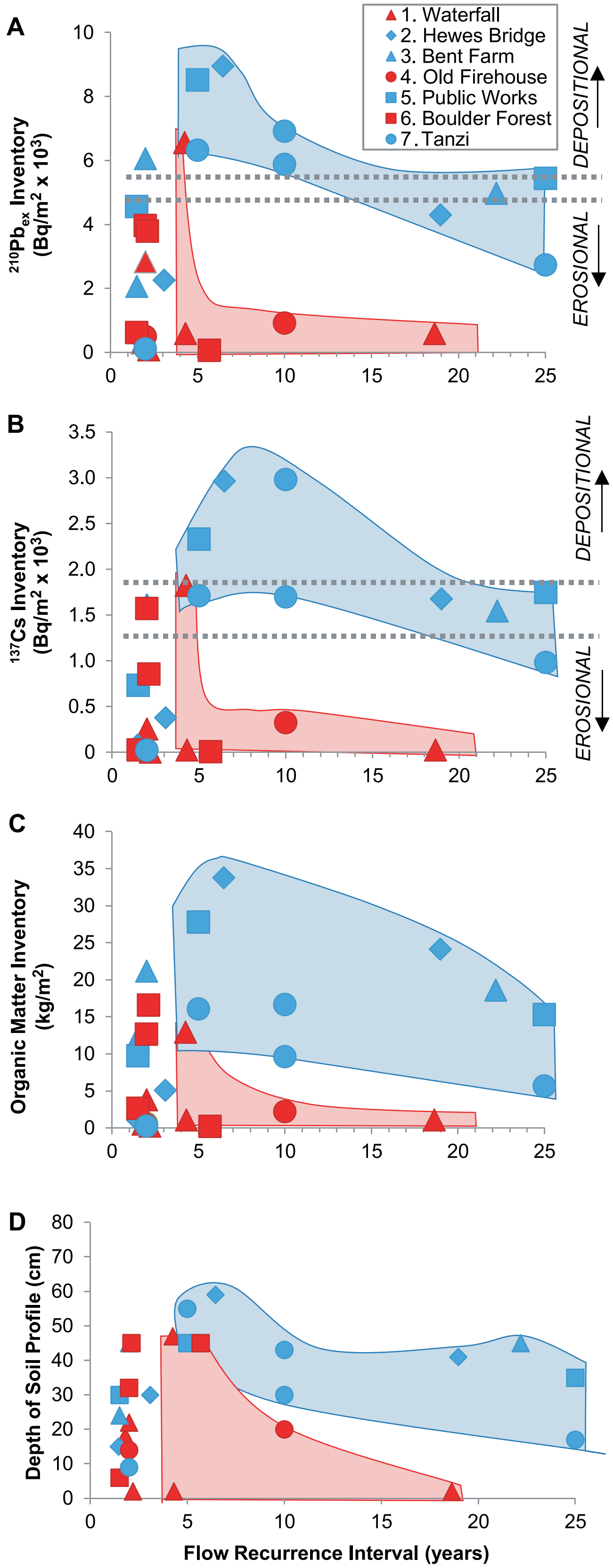

Figure 2. Inventories of $^{210}Pb_{ex}$ (ex—excess) (A), ^{137}Cs (B), and organic matter (C) in soil profiles and the depth of soil profiles (D). Increasing flood recurrence interval is similar to increasing distance and elevation from the channel, with shaded domains for >~3 yr recurrence interval flood locations in reaches with downstream-increasing stream power (Ω↗) (red shading) and reaches with downstream-decreasing stream power (Ω↘) (blue shading).

consistent with erosional environments, while sites with Ω↘ show high inventories consistent with depositional or steady-state soil profiles.

In-stream sediment ^{7}Be activity measured annually from 2009 to 2013 similarly indicates erosion in Ω↗ reaches and deposition in Ω↘ reaches. The short-lived fallout radionuclide ^{7}Be (54 d half-life) is delivered to the landscape via wet deposition. In-stream sediment ranges in activity from 0 to 20 Bq/kg in this region (Gartner et al., 2012; Kaste et al., 2014), with higher activities associated with the accumulation of fine-grained organic sediment (Landis et al., 2012b). The pattern of ^{7}Be activity is broadly the inverse of stream power (Fig. 3B). From 0 to 4 km and 6 to 7 km distance downstream from the headwaters, stream power is increasing (Ω↗) while ^{7}Be decreases, suggesting that these are erosional reaches, while from 4 to 6 km and 7 to 8 km, ^{7}Be increases as stream power decreases (Ω↘), showing these are depositional reaches. For unknown reasons, the site at ~10 km is inconsistent with this pattern, having lower-than-expected ^{7}Be activity.

GEOMORPHIC SIGNATURES OF STORAGE AND REMOVAL

Consistent with the geochemical data, three geomorphic metrics also support the hypothesis that Ω↗ reaches are erosional and Ω↘ reaches depositional (site cross sections and photographs are given in the Supplemental Material). First, in the region of ~3–25 yr RI elevations (Fig. 2D), soil profiles are thinner in Ω↗ reaches, indicative of erosion, compared to Ω↘ reaches where thicker profiles suggest accumulation and storage of alluvium and colluvium at channel margins.

Second, cross-section morphology differs between Ω↗ and Ω↘ reaches. The Ω↗ reaches typically exhibit narrower floodplains with steep-sided banks that blend to steep hillslopes. In some locations, such as at the waterfall site, cross sections lack clear expression of a bankfull shelf (Fig. 1C). In contrast, Ω↘ reaches show wider floodplains and clear expressions of a bankfull shelf, such as at Hewes Bridge site. Despite the differences in the near-channel environment, bankfull width does not differ between adjacent paired sites with differing stream power gradients (paired *t*-test $p = 0.58$, $n = 6$).

Third, the variations in floodplain morphology are consistent with the pattern of channel bedrock exposures. The occurrence of bedrock versus alluvial channel beds did not correlate with high versus low Ω, but bedrock channels occurred only in Ω↗ reaches (Fig. 3A).

In sum, the geochemical and geomorphic data indicate linkages between along-channel (downstream) and across-channel (lateral) processes, as well as correspondence over annual to century and longer time scales. Based on their half-lives, ^{7}Be indicates in-stream erosional or depositional processes over monthly to biannual time scales, and $^{210}Pb_{ex}$ and ^{137}Cs indicate floodplain erosional or depositional over decadal time scales. The time scale for organics is decades to centuries, and bedrock exposures are expressions of channel processes acting over even longer time scales.

DISCUSSION

Geology exerts a first-order control on the lateral connectivity of channel-floodplain

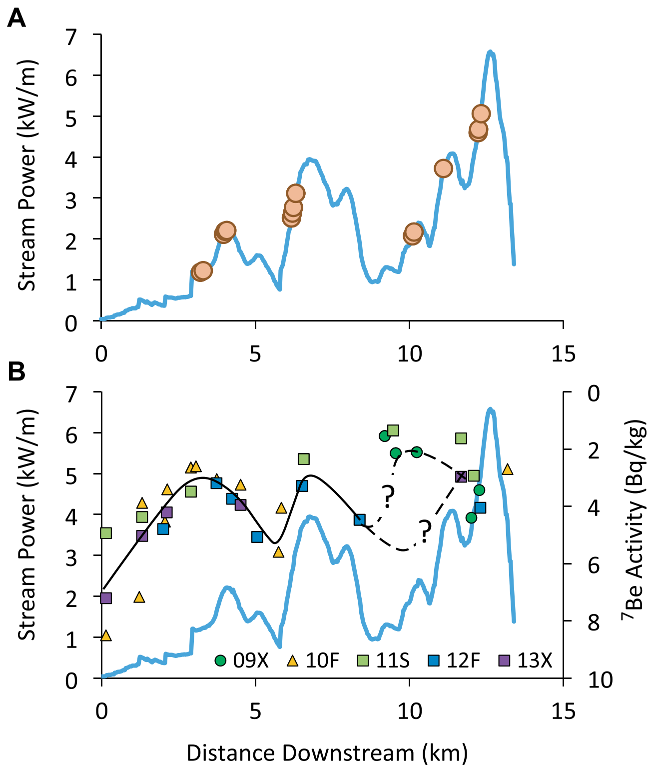

Figure 3. Bedrock channel locations and ^{7}Be activity relative to stream power gradients (blue line) relative to downstream distance from headwaters. (A) Locations of bedrock channels (circles). (B) ^{7}Be activity in channel bed sediment, 2009–2013 CE; note inverted axis. Thin black line shows patterns of ^{7}Be activity and is dashed to show trend with and without including data from site at downstream distance of ~10 km. Legend indicates sampling year and season, i.e., spring (S), summer (X), or fall (F).

exchanges through its control on valley width and slope, similar to its conditioning of erosional or depositional patterns during large floods (Wolman and Eiler, 1958; Grant and Swanson, 1995). Our results highlight that Ω mapped from widely available DEMs can identify reaches that are prone to deposit material within the channel and at channel margins. It is unclear whether the material stored in floodplains in Ω↘ reaches is derived from the channel, as was observed during extreme floods (Gartner et al., 2015a). This material could also be derived from adjacent hillslopes. Other lines of evidence support a channel source, at least for channel margins, with increased ^{7}Be activity in depositional reaches and other studies showing contaminants sourced from upstream in channel-margin deposits (Skalak and Pizzuto, 2010). In either case, the margins of Ω↘ reaches are locations where the downstream transport of material is impeded, and these areas can be viewed as sinks along river corridors. Similarly, it is also unclear whether the reduced storage of material in Ω↗ reaches is due to high flood waters that strip sediment or due to accelerated downslope hillslope processes that deliver material efficiently to channels. Nevertheless, the margins of Ω↗ reaches are source locations along river corridors.

Stream power gradients identify storage areas both longitudinally along the stream and also laterally from the channel. The geochemical data indicate that maximum storage is approximately at the 3 to 5 yr RI flood elevation in the Ω↘ reaches. This is consistent with previous research showing elevated $^{210}Pb_{ex}$ inventories at similar flood elevations (Renshaw et al., 2014) and concentrated deposits of organic material near the high-water mark of moderate flow events (Landis et al., 2012a). We surmise that these lateral locations flood frequently enough to accumulate sediment and low-density organic matter more so than higher elevations relative to the channel. The peak inventories at the 3–5 yr RI flood elevations also may be enhanced by the attenuation of available material at greater distances from the source of the material in the channel (Pizzuto, 1987).

Importantly, these data also indicate locations that are not long-term storage areas, specifically the locations above the 3 yr RI flood elevation in Ω↗ reaches and areas within and immediately adjacent to the channel in both Ω↘ and Ω↗ reaches. Material from these source locations is likely to be transported downstream to the higher flood elevations of Ω↘ reaches or to receiving waters. This is consistent with radiocarbon dating of channel-margin deposits in the South River (Virginia, USA) that indicate an average turnover time of 1.75 yr (Skalak and Pizzuto, 2010).

A growing body of research points to the importance of downstream gradients in stream power and sediment transport in characterizing variable characteristics and processes between reaches, rather than using only the at-a-point magnitudes of sediment transport (Graf, 1983; Hancock and Anderson, 2002; Bizzi and Lerner, 2015; Gartner et al., 2015a, 2015b; Lea and Legleiter, 2016; Sholtes et al., 2018; Lininger et al., 2021; Sutfin et al., 2021). Our study builds on previous work by showing that extreme floods and other rare events are not required to establish or maintain source and sink areas along river corridors. No major floods have occurred in the Mink Brook watershed over the past ~50 yr, which is the time frame that ^{210}Pb, ^{137}Cs, and ^{7}Be data demonstrate erosion in Ω↗ reaches and deposition in Ω↘ reaches. That said, the carbon storage and bedrock exposure show that stream power gradient also correlates with erosional and depositional processes acting over long time scales at the reach scale.

These findings have river management implications; e.g., in predicting the downstream attenuation of pollutant fluxes due to deposition on floodplains. Stream power gradient analyses can also inform river restoration activities by providing a physical rationale for the distribution of diverse habitat patches that provide ecosystem resilience, for the construction of floodplains in certain locations, or for allowing bank erosion to be left untreated in other locations.

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