Supplementary Materials for

Nested, Reach-Scale Fluvial Sediment Budgets Quantify Watershed Sediment Transport Pathways

Pizzuto, J.E. *, **Cribb, K., Kelly, A.**

*Corresponding author: pizzuto@udel.edu

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Table of Contents:

Supplementary Text

Methods

Supplementary Methods Text S1. A threshold local relief to discriminate between confined and unconfined river banks of the White Clay Creek.

Confined and unconfined banks were identified in the field at McCarthy's (2018) sites 4, 6, 11, and 12 (Figures S2 – S5, S13). Banks were classified as confined by the presence of bedrock exposures, cemented colluvium, or anthropogenic structures such as railroad or highway embankments, typically armored by riprap, retaining walls, or boulders.

To develop a local relief threshold to discriminate between confined and unconfined banks, points were placed at 2meter intervals along the mapped bank lines in ARCGIS. A variable window, W, surrounding each bank point was then defined based on the maximum channel length upstream of each point, L:

$$W = 5.5\ m,\ 0 < L \leq 5000\ m$$
$$W = 10.5\ m,\ 5000 < L \leq 9505\ m \qquad (S1)$$
$$W = 15\ m,\ L > 9505\ m$$

The search window was scaled by L (a proxy for channel size) to avoid sampling elevations on both sides of smaller channels. Then, the relief associated with each bank point, R, was evaluated using the search window, W.

To determine if a threshold value of R, denoted R_{th} could correctly discriminate between confined and unconfined reaches, threshold values were varied from 0.5 m to 10.5 m at intervals of 0.1m. For each trial value of R_{th}, the numbers of predicted confined and unconfined banks were compared to the observed numbers obtained from field mapping. The best results, obtained using a value of R_{th} of 3.4 m, correctly classified 82% of banks as either confined or unconfined (Figure S6). Figure S7 compares confined and unconfined banks obtained using the relief threshold of 3.4 m with banks classified by field observations.

The relief threshold value of 3.4 m was modified before applying it to the entire drainage basin, because the data set used to create it mostly included larger channels, and this resulted in biased estimates when applied to smaller channels (i.e., the threshold of 3.4 m resulted in underestimating the number of confined banks in smaller channels). To obtain better predictions regardless less of channel size, the threshold was scaled by bankfull depth D_{bf} and the threshold of 3.4 was modified to 1.7 by dividing by the average bankfull depth of the calibration data set (~2 m). Thus, the final criterion for identifying confined banks is:

$$\frac{R}{D_{bf}} > 1.7 \qquad (S2)$$

Bankfull depth is obtained from a regression equation relating bankfull depth to L for the White Clay Creek (Figure S8).

Supplementary Methods Text S2. Field data for developing an empirical relationship for erosion of unconfined streambanks.

Field measurements of annual bank retreat and related variables were assembled to create an empirical relationship to predict bank retreat rates throughout the White Clay Creek watershed (Table S4). Data were obtained from previous studies of the White Clay Creek (McCarthy, 2018, also reported by Bodek et al., 2021) and selected studies of nearby watersheds (Allmendinger et al. 2005; Pizzuto and Meckelnburg, 1989).

Previous studies only provide information at locations with active bank erosion, but many of the White Clay Creek's banks appear to be stable (based on criteria of Pfankuch (1975), for example). To enhance the ability of an empirical relationship to account for sites with negligible erosion, data were included from 14 locations in the White Clay Creek with stable banks.

In addition to measurements of bank retreat rate, explanatory variables were also included. These included measurements of bankfull channel width, channel centerline curvature, and canopy cover (in %). Bankfull channel width was available from previous studies or, (for new data from the White Clay Creek), estimated based on nearby measurements reported by McCarthy (2018). For the White Clay Creek, centerline points were created in ARCGIS between all the 2-m bank points (described in Text S1), and curvature was computed using methods of Blankaert and DeVriend (2010) and McMillan and Hu (2016). Curvatures for sites of Allmendinger et el. (2005) and Pizzuto and Meckelnburg (1989) were estimated from maps included in the original publications. Canopy cover was estimated using the 30-m resolution NLCD 2016 Tree_Canopy L48_20190831 (CONUS) data set, described by Yang et al. (2018).

Supplementary Methods Text S3 An empirical equation to predict the annual retreat of unconfined streambanks

Measured linear bank erosion rates, BE_L, were correlated using non-linear regression with bankfull channel width, W_{BF}, channel curvature C, and % canopy cover F:

$$BE_L = \frac{W_{bf} C}{(0.004137 + 0.006519 F^{0.3})} \qquad (S3)$$

Equation (S3) provides linear bank retreat rates in units of cm/yr. W_{bf} and C have complementary units of L and 1/L (here meters are used to represent L), so the units of BE_L are implicitly carried by the two numerical coefficients in the denominator (i.e., each coefficient must have units of year/cm). Equation (S3) has an adjusted r^2 of 0.57 and an RMSE of 7.312 cm/yr. The mean observed erosion rate is 9.1 cm/yr, so scaling the RMSE by the mean yields a fractional mean error estimate of 0.80, or 80%. The 95% confidence intervals for the coefficients 0.004137 and 0.006519 are (0.002969 - 0.005305) and (0.004387 – 0.008652). The exponent 0.3 on F is imposed, rather than determined by the non-linear regression. Plotting observed and predicted erosion rates suggests that equation (S3) tends to underestimate relatively higher erosion rates, i.e., those between 25 and 40 cm/yr (Figure S9).

Supplementary Methods Text S4 Estimating mass bank erosion rates throughout the White Clay Creek watershed

To estimate mass bank erosion rates throughout the White Clay Creek mapped channel network, the 2-m spaced bank lines and channel centerlines were extended throughout. Curvature was computed for channel centerline points as describe above in Text S.2. Bankfull width was estimated using a relationship between width and maximum channel length upstream (documented in Figure S10). These data were used to compute linear bank erosion rates from equation (S3). Linear bank erosion rates were converted to mass units by multiplying by the 2-m point spacing, the local bank height (estimated from the relationship illustrated in Figure S11, and the depth-averaged bulk density of 1.3 +/- 0.09 g/cm3 obtained from the data of Figure S12 and Table S6.

Supplementary Methods Text S5 Methods to compute annual floodplain sedimentation in valley reaches

Table S7 lists 15 steps for computing annual floodplain sedimentation in each of the 140 valley reaches of the White Clay Creek. These steps are explained in this section.

Text S5.1 Field data to define floodplain sedimentation rates

Published and unpublished data are used to estimate annual floodplain sedimentation rates. Floodplain sedimentation rates for the White Clay Creek from analyses of fallout radionuclides ^{137}Cs and ^{210}Pb are presented by Pizzuto et al. (2022) and Marquard (2015). Pizzuto et al. (2022) also present data obtained using dendrochronology. Readers are directed to these publications for a discussion of field, laboratory, and analytical methods used to estimate overbank sedimentation rates. Sampling locations are denoted using identifiers proposed by McCarthy (2018) in Pizzuto et al. (2022); these locations are illustrated in Figure S13.

Floodplain sedimentation rates on the White Clay Creek vary from 0 to 1.1 cm/yr (Table S8) with a mean of 0.40 cm/yr and a standard deviation of 0.33 cm/yr. Rates are not correlated with vegetation parameters such as canopy cover, and they are also uncorrelated with valley slope. Lacking any clear reason to proceed otherwise, the mean value of 0.40 cm/yr was used to represent rates of overbank sedimentation throughout the White Clay Creek watershed. This value is assumed to represent a maximum rate of sedimentation adjacent to the channel, and is corrected for decreasing sedimentation rates with distance from the channel as described in Text S5.2.

Sedimentation rates measured by dendrochronology at Sites 6, 12, and 14, not previously published, are presented in Tables S10 – S12.

Text S5.2 Correcting floodplain sedimentation rate for the “levee” effect.

Most of the sedimentation rates reported in Table S8 were obtained on natural levees adjacent to the channel of the White Clay Creek, and these may not accurately represent spatially averaged sedimentation rates across the entire floodplain. Natural levees are very common along the White Clay Creek, as they are in the neighboring valley of Brandywine Creek (Pizzuto, 1987). The floodplain sedimentation rates in Table S8 are not correlated with distance from the channel, but these represent samples from different locations, and factors unique to each location could confound the expected correlation.

Results of Pizzuto (1987) were used to correct the average sedimentation rate of 0.40 cm/yr for decreasing sedimentation rates with increasing distance across the floodplain. Pizzuto (1987) obtained the following result to represent the decrease in sedimentation rate with increasing distance from the channel, y, across the floodplain:

$$L_f = \frac{\sinh(Gn)e^{-G}}{\cosh(G)} + e^{-Gn} \qquad (S4)$$

where L_f is a relative dimensionless sedimentation rate (L_f is 1 at the channel and decreases with increasing distance), n is the relative distance y/W_f across the floodplain (W_f is the width of the floodplain), and G is a parameter representing suspended sediment and flow properties.

Integrating (S4) across the floodplain (i.e., from n = 0 to n = 1) determines the ratio V_f/V_L, which is the ratio of the volume of sediment actually deposited across the floodplain per unit downvalley distance per year (V_f) to the volume of sediment that would be deposited if the sedimentation rate across the floodplain were uniform and equal to the rate at the edge of the channel (V_L):

$$\frac{V_f}{V_L} = \int_0^1 L_f\,dn = \frac{1}{G}\left(1 - \frac{e^{-G}}{\cosh(G)}\right) \qquad (S5)$$

Pizzuto (1987) obtained an average value of G for the Brandywine Creek of 1.10 (std. deviation 1.05), which yields a value of V_f/V_L of 0.7.

These results were used in the following way to compute overbank sedimentation along the White Clay Creek. First, the constant overbank sedimentation rate of 0.4 cm/yr was multiplied by the area of the active floodplain in a valley reach, and this result was then multiplied by a constant value of 0.7 to correct for decreasing rates of sedimentation with increasing distance across the floodplain.

Text S5.3 Determining the area of floodplain sedimentation in a valley reach

The area of floodplain sedimentation in each of the 140 valley reaches was determined following several steps. First, a characteristic return period was designated for flows that inundate the active floodplain of the White Clay Creek (Table S7, step 3). Second, a representative cross-section was selected in each valley reach (Table S7, Step 5) and extracted from the DEM (Table S7, step 5). The slope of the valley was determined by the slope of the channel within the valley reach, divided by the sinuosity to remove the effect of channel planform curvature (Table S7, step 6). Then the water surface elevation of the characteristic overbank discharge at the cross-section was determined using a 1-D hydrodynamic model (Table S7, step 9). The portion of the cross-section representing the inundated active floodplain was determined (Table S7, step 10). The water surface was then assumed to be planar and sloping downvalley (Table S7, step 11). A 0.3-m square grid was created within the valley reach in ARCGIS, and the elevations associated with each grid point was determined from the DEM (Table S7, step 12). The elevations of these grid points were compared to those of the water surface to determine which points were inundated by the characteristic flood discharge, and the inundated area determined (Table S7, step 13). The area was corrected by removing points within the channel and points outside the area of the active floodplain to determine the area of overbank sedimentation (Table S7, step 14).

A characteristic return period of overbank sedimentation was determined by identifying threshold discharges required to inundate sites where floodplain sedimentation rates were measured. To accomplish this, regional relationships were created between drainage basin area and discharges with return periods of 1.5, 2, 2.33, 5, and 10 years. Drainage areas and annual peak discharge data were downloaded for the following U.S. Geological Survey stream gaging stations in Pennsylvania, and Delaware: White Clay Creek near Strickersville, PA (#01478245); E. Branch White Clay Creek at Avondale,PA (01478120); Red Clay Creek near Kennett Square, PA (#01479820); Red Clay Creek at Wooddale, DE (#01480000); W. Branch Brandywine Creek at Modena, PA (#01480617); W. Branch Brandywine Creek at Coatesville, PA (#01480500); W. Branch Brandywine Creek near Honey Brook, PA (#01480300); East Branch Big Elk Creek at Forestville, PA (#01494850); and E. Branch White Clay Creek Tributary near London Grove, PA (#01478100). Discharges at each station with varying return periods were computed using the USGS software PeakFQ (Flynn et al, 2006), and empirical relationships in the form of power functions were determined between flood discharges of fixed return period and drainage basin area (Figure S14).

The water surface elevations for discharges required to inundate sites where floodplain sedimentation was measured in the White Clay Creek was computed using the 1-D hydrodynamic model of Pizzuto (2012). The model was calibrated using the rating curve for the gaging station White Clay Creek near Strickersville, which resulted in Manning's n values of 0.033 for the channel and 0.07 for the floodplain; these were used for all hydrodynamic computations in the White Clay Creek watershed. Cross-sections were extracted for each sampling site, and slopes were determined from the channel centerline at each site. Pizzuto's hydrodynamic model was used to determine the discharge whose water surface elevation reached each sampling site.

To determine the return period of the discharge inundating each sampling site, the drainage basin area for the sampling sites was determined using the relationship between upstream channel length and drainage basin area (Figure S1). Then, the recurrence interval of this discharge was estimated using the previously described relationships between channel area and discharge recurrence interval established using PeakFQ (Figure S14). The results of this analysis indicate that 4 sites were inundated by the 5-year flood, two were inundated by the 10-year flood, and the two remaining sites were only inundated by discharges greater than the 10-year flood. Based on these results, the 10-year flood was selected to determine the area of active sedimentation for computing overbank deposition rates for the 140 valley reaches.

Text S5.4 Computing overbank sedimentation in the 140 valley reaches

In each valley reach, a representative cross-section was identified and extracted from the DEM. The slope of the valley was determined from the slope of the channel, adjusted for sinuosity. The 10-year flood was estimated from the upstream channel length and its associated drainage basin area (Figures S1 and S14), and the 1-D hydrodynamic model provided the elevation of the 10-year water surface at the cross-section. From these results, the fraction of the inundated length associated with the active floodplain was estimated (as illustrated in Figure S15). Then, the downstream sloping plane of the 10-year water surface was merged with elevations from the DEM and the grid of valley elevations to identify inundated points. This determined the total area inundated by the 10-year flood, which was then corrected by removing areas within the channel and areas outside the active floodplain. This area was then multiplied by the sedimentation rate (corrected for the "levee effect", Text S5.2) and the floodplain bulk density (Text S4) to determine the mass of sediment deposited on the floodplain per year in the valley reach.

Supplementary Methods Text S6 Assessing uncertainty

Text S6.1 Uncertainty in headwater input fluxes and watershed output fluxes

Uncertainty in the headwater input flux at gaging station East Branch White Clay Creek tributary near Avondale is reported by Williamson (2015), who reported an annual flux of 361 +/- 77 Mg/yr, values that indicate a fractional uncertainty of 0.21. This constant fractional uncertainty was used to assess uncertainty in all headwater input fluxes, appropriate scaled for drainage basin area following standard rules of error propagation. This approach neglects local variations in headwater sediment production and storage caused by spatial variability in land use, topography, vegetation, and the distribution of landforms in headwater reaches. As a result, the 21% uncertainty estimate of Williamson represents a minimum value.

Uncertainty in the watershed output fluxes are assessed by the standard deviation of the annual sediment flux measured at the gaging station White Clay Creek near Strickersville, PA. The mean and standard deviation of the annual fluxes at this gaging station are 25300 and 16000 Mg/yr, for a fractional uncertainty of 0.63. This assessment of uncertainty only reflects annual variability and does not account for measurement error, so it represents a minimum estimate of uncertainty in the outlet sediment flux from the White Clay Creek watershed.

Text S6.2 Uncertainty in quantifying annual bank erosion rates

Uncertainty in quantifying bank erosion rates includes errors in identifying unconfined banks, errors associated with estimating bank erosion at each 2-m unconfined bank point, and the accumulated error created by summing bank erosion over all unconfined 2-m bank points throughout a channel reach. Errors also arise from our assumption that all sediment eroded from banks can be transported in suspension, but we do not have a method for quantifying this.

Bank erosion ER_m (with units of mass per year) is estimated for a 2-m bank segment “m” as the product of the bank height, an estimate of the linear bank retreat rate, and the bulk density. The fractional error of the bank erosion estimate for bank segment “m”, $f\_ER_{err\_m}$, has three components, one for errors in bank height, another for errors in estimating the linear erosion rate, and a third error for estimating bulk density. These must be summed in quadrature:

$$f\_ER_{err_m} = \sqrt{\left(\frac{Bh_{err}}{\overline{Bh}}\right)^2 + \left(\frac{ER_{err}}{\overline{ER}}\right)^2 + \left(\frac{Bd_{err}}{\overline{Bd}}\right)^2} \qquad (S6)$$

where Bh is the bank height, ER is the linear erosion rate, Bd is the bulk density, “err” refers to a typical error estimate, and the overbar represents the mean estimated value. Since bank height and the linear erosion rates are estimated from regression equations, errors in Bh and ER are defined as the standard error of the estimate provided from the regression analysis. The error in bulk density is the standard deviation of the field measurements. Mean values for all three parameters are arithmetic averages obtained from the field measurements. For the White Clay Creek, specific values of these parameters are Bh_{err} = 0.41 m, $\overline{Bh}$ = 1.41 m, ER_{err} = 7.3 m/yr, $\overline{ER}$ = 9.1 cm/yr, Bd_{err} = 0.09 g/cm^3, $\overline{Bd}$ = 1.3 g/cm^3, which collecting define a value of $f\_ER_{err_i}$ of 0.85 for the error associated with a single estimate of the mass of sediment supplied to the channel per year through the erosion of each 2-m bank sediment.

To obtain the total bank erosion rate estimate for a valley reach, bank erosion rate estimates ER_m for all 2-m bank segments "m" are summed. The error associated with the summed total will have two components, one associated with errors in classifying bank segments as confined or unconfined, and the other associated with errors in estimating erosion for the unconfined bank segments.

Assume that M unconfined eroding banks are identified within a valley reach. The error associated with misclassifying banks is denoted as M_{err}. This error could result in either underestimating or overestimating the number of eroding banks, so that the likely true range of M would lie within the interval M +/- $M_{err}/2$.

The sum of the errors associated with estimates of erosion rate for the individual 2-m segments can be obtained by simply adding error estimates for each bank segment in quadrature:

$$ER_{ER\_err\_tot} = \left(\sum_{m=1}^{M}\left(f\_ER_{err\_m}ER_m\right)^2\right)^{1/2} = f\_ER_{err_m}\left(\sum_{m=1}^{M}(ER_m)^2\right)^{\frac{1}{2}} \qquad (S7)$$

where $ER_{ER\_err\_tot}$ is the total error associated with the summed estimates of bank erosion and ER_m is the erosion rate estimate for 2-m bank segment m.

Errors associated with misclassifying banks as confined have two components. One represents errors resulting from summing the incorrect number of eroding banks, while the other results from summing the incorrect number of errors in equation (2) above. These errors can be approximately estimated by randomly selected M_{err} bank segments within the reach, and summing erosion and error estimates for each in quadrature:

$$ER_{c\_err\_tot} = \left(\sum_{m=1}^{M_{err}}(ER_m)^2\right)^{1/2} + \left(\sum_{m=1}^{M_{err}}\left(f\_ER_{err\_m}ER_m\right)^2\right)^{1/2} \qquad (S8)$$

where $ER_{c\_err\_tot}$ denotes the total error associated with misclassifying confinement in a valley reach.

The total error in estimating bank erosion in channel reach i, $ER_{err\_tot\_cr\_i}$, is then the sum of equations (S7) and (S8):

$$ER_{err\_tot\_cr\_i} = ER_{ER\_err\_tot} + ER_{c\text{-}err\_tot} \qquad (S9)$$

Given that 18% of banks are assumed to be misclassified (i.e., Merr = 0.18M) and that $f\_ER_{err\_i}$ = 0.85, equations (S7) – (S9) can be reduced to:

$$ER_{err\_tot\_cr\_i} = 0.85\left[\sum_{m=1}^{M} ER_m^2\right]^{1/2} + \left[\sum_{i=1}^{0.18M} ER_m^2\right]^{1/2} + 0.85\left[\sum_{m=1}^{0.18M} ER_m^2\right]^{1/2} \qquad (S10)$$

The total bank erosion error for the watershed-wide sediment budget, ER_{err_tot} is obtained by summing the errors for all N_{cr} channel reaches in quadrature:

$$ER_{ER\_tot} = \left(\sum_{i=1}^{N_{vr}} \left(ER_{err\_tot\_cr_i} \right)^2 \right)^{1/2} \qquad (S11)$$

Text S6.3 Uncertainty in quantifying annual floodplain deposition

Uncertainty in quantifying annual floodplain deposition in valley reaches is assessed from the mean and standard deviation of measured vertical accretion rates in the White Clay Creek watershed, which are 0.40 and 0.33 cm/yr, values that yield a fractional uncertainty of 0.83. This approach neglects substantial uncertainty in assessing the area of floodplain sedimentation in each valley reach, which cannot be rigorously evaluated. As a result, the value of 0.83 should be considered a substantial underestimate of the true uncertainty in floodplain deposition.

For assessing uncertainty in floodplain deposition for the watershed-wide sediment budget, floodplain deposition uncertainty values for all the individual valley reaches are summed in quadrature.

<u>Other Supplemental Text S7 – Notation List</u>

Units are given as mass (M), length (L), and time (T). Specific units are provided where variables are limited to a single set of units.

Bd – Bulk density (g/cm^3)

BE – Bank erosion rate (Mg/yr)

BE_L – Linear bank retreat rate (cm/yr)

Bh – Bank height (m)

C – Channel curvature (1/m)

D_{bf} – Bankfull channel depth (m)

$ER_{c\_err\_tot}$ - Total bank erosion error associated with misclassifying confinement in a channel reach (Mg/yr).

$ER_{ER\_err\_tot}$ - Total error associated with the summed estimates of bank erosion in a channel reach (Mg/yr).

ER_{err_tot} – Bank erosion error summed over all 140 (N) channel reaches (Mg/yr)

$ER_{err\_tot\_cr\_i}$ – Total error associated with bank erosion estimates in channel reach I (unlike the variable above, this one includes errors in misclassifying banks)(Mg/yr)

ER_m – Mass bank erosion rate for 2-m bank segment "m" (Mg/yr)

$f\_ER_{err_m}$ – Fractional error in mass erosion rate for bank segment "m"

F – Canopy cover (%)

FD – Floodplain deposition (Mg/yr)

FS – Fraction of the sediment entering a reach that is stored on its floodplain

G – Levee deposition parameter in equation (S4)

HI – Sediment flux supplied by headwater tributaries (Mg/yr)

i – Valley/channel reach control volume identifier

L – Maximum length of channels upstream of a location (L)

L_f – Fractional overbank deposition (1 at the channel, and < 1 elsewhere)

M – Number of unconfined (eroding) 2-m bank segments in a channel reach

n – y/W_f

N_i – Number of reaches traversed between reach i and the basin outlet

N_{cr} – Total number of channel reaches in the network (140 for the White Clay Creek)

OD – Overbank deposition (Mg/yr)

P_i – Sequence of channel reaches from a source reach i_0 to the watershed outlet

P_{rob} – Probability of a particle reaching the outlet of a watershed within 1 year

Q_s – Sediment flux (Mg/yr)

R – Relief within a bank point search window (m)

R_{th} – Threshold relief for discriminating between confined and unconfined banks (m)

V_f – Volume of floodplain deposition per unit channel length (L^3/L)

V_L – Value of V_f at the channel's banks (L^3/L)

W – Search window around a bank point (m)

W_{bf} – Bankfull depth (m)

W_f – Floodplain width (L)

y – Distance across the floodplain from the channel (L)

Xs_i – A specified flux of sediment leaving reach i per year (Mg/yr) subscripts not identified above:

$_{err}$ – Error associated with a particular variable (with the same units as the variable)
$_{j}$ – Index indicating number of channel reaches traversed along a network path from control volume i to the basin outlet downstream

$_{m}$ – Bank segment index

$_{out}$ – Value of a variable leaving a control volume

$_{t}$ – Value of a variable summed over all control volumes (i.e., all values of i)

$_{tot}$ – Total bank erosion error summed over all M 2-meter eroding banks.

$\overline{}$ - An overbar indicates the mean value of a variable

Supplementary Figures

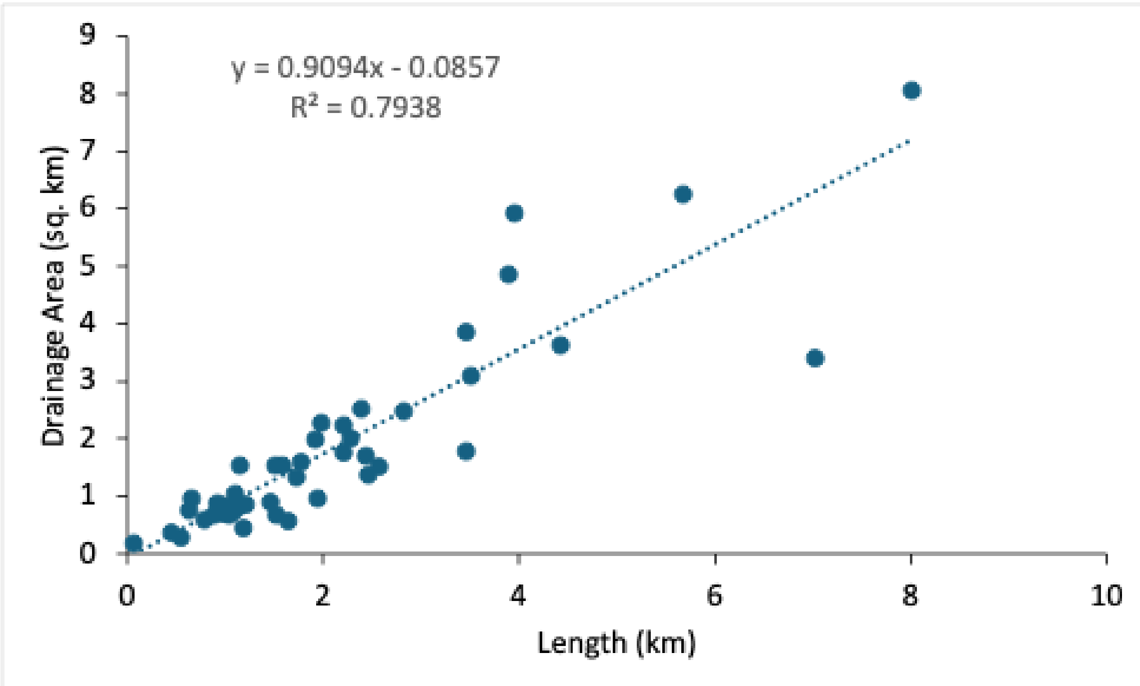

Figure S1.
Correlation between channel length and drainage basin area for selected White Clay Creek stream channels.

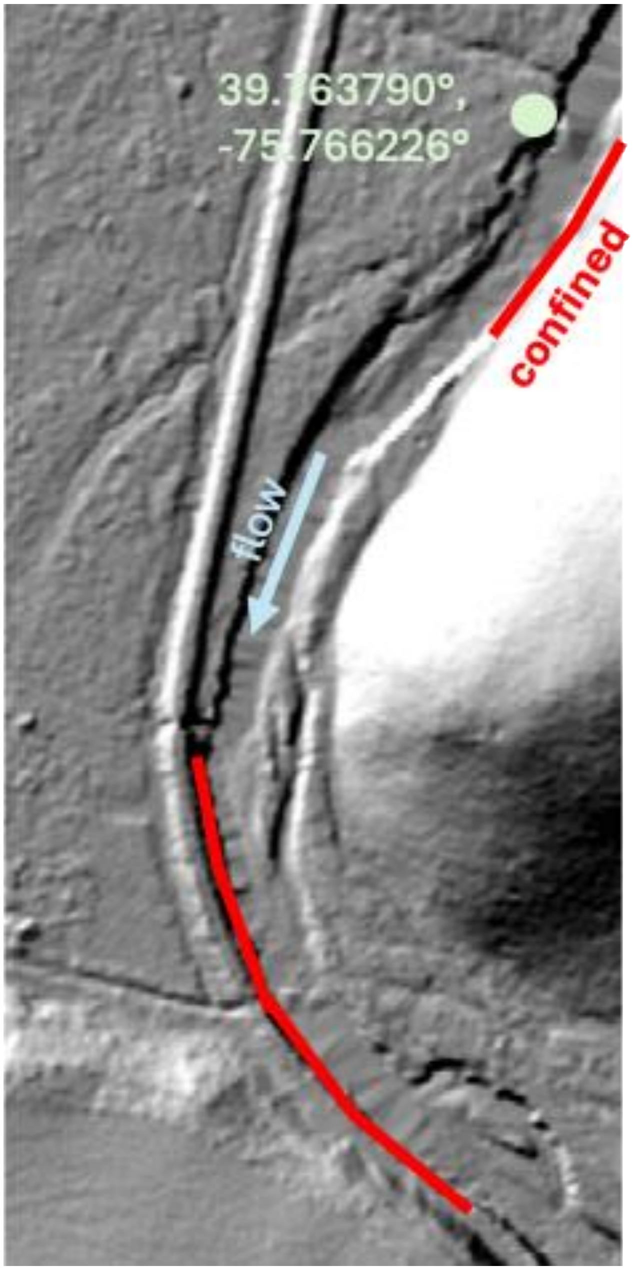

Figure S2
Observed confined reaches, McCarthy's (2018) site 4. See Figure S13 for map of sites.

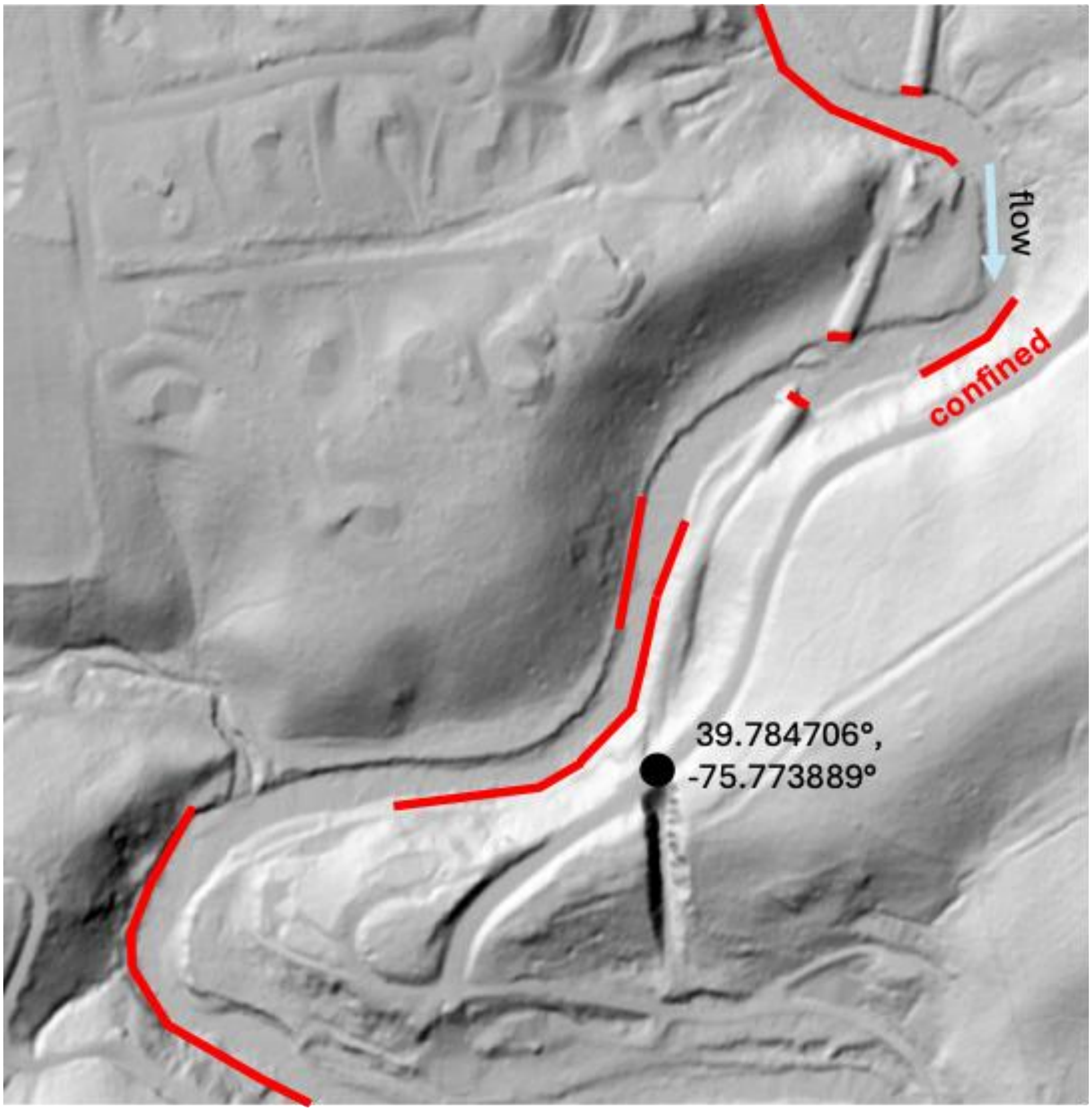

Figure S3
Observed confined reaches, McCarthy's (2018) site 6. See Figure S13 for map of sites.

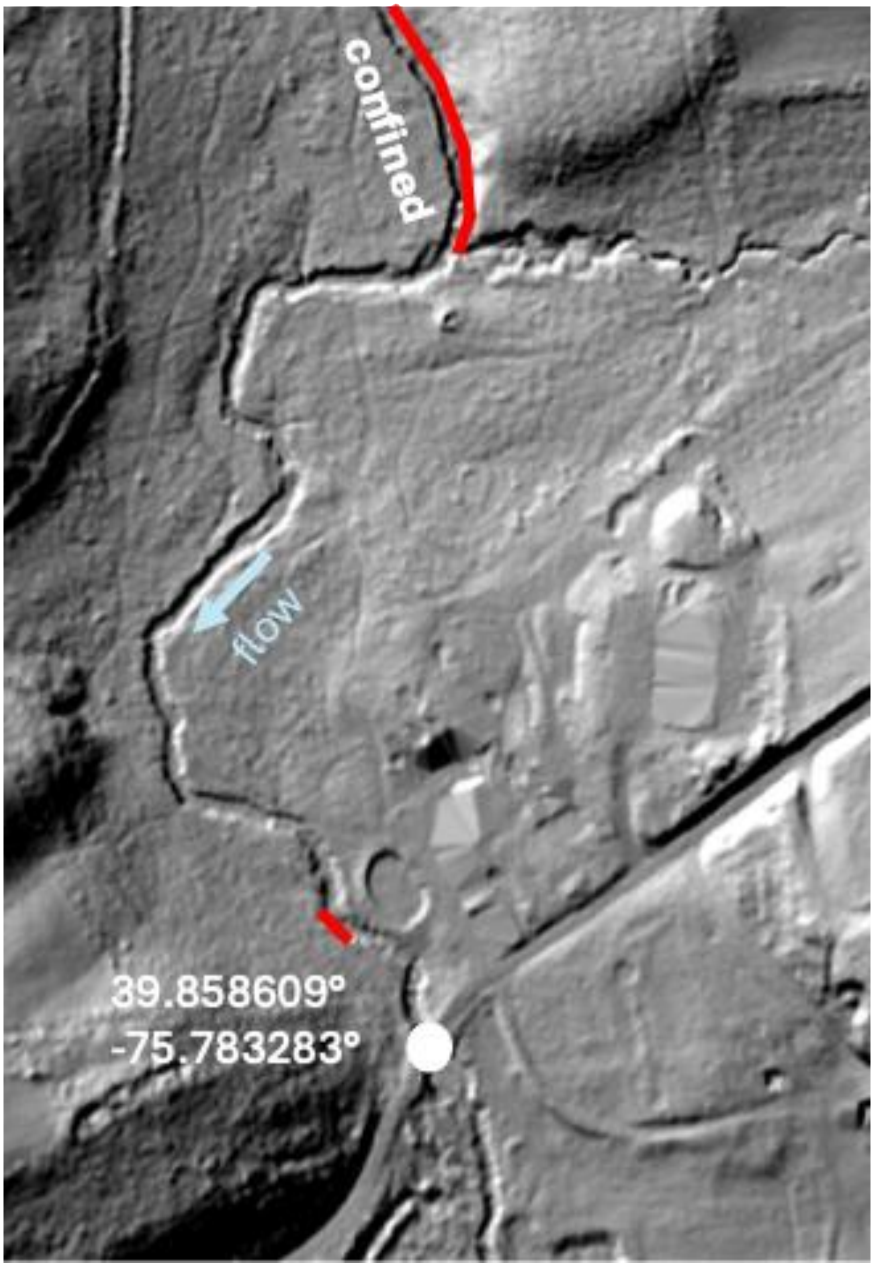

Figure S4
Observed confined reaches, McCarthy's (2018) site 11. See Figure S13 for map of sites.

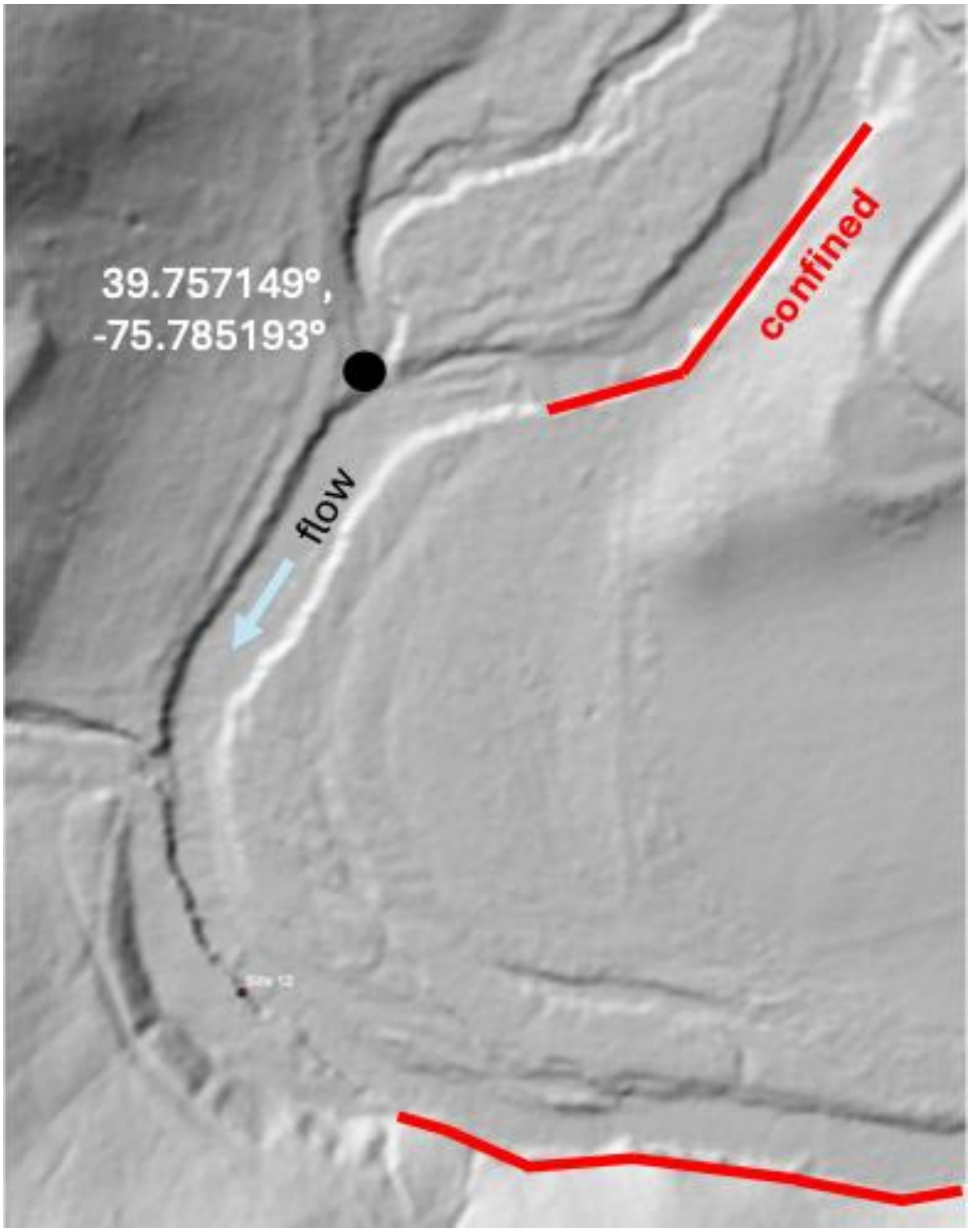

Figure S5
Observed confined reaches, McCarthy's (2018) site 12. See Figure S13 for map of sites.

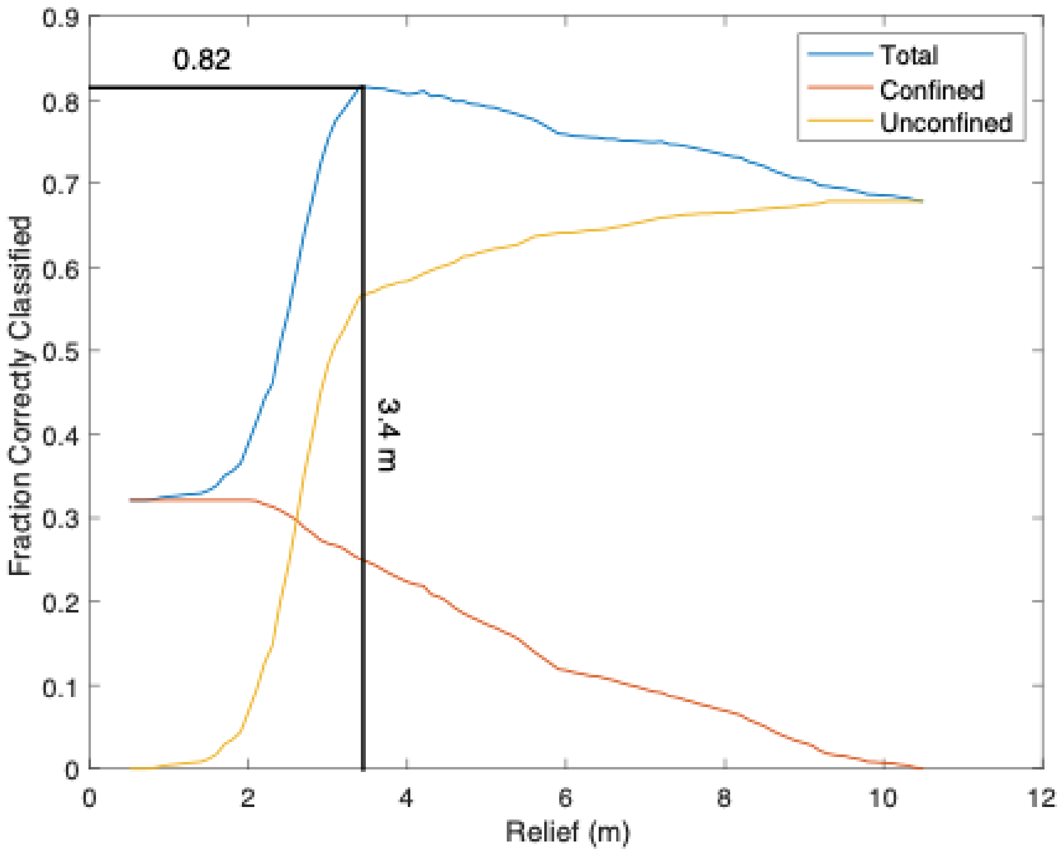

Figure S6
Relationship between relief in the neighborhood of all bank points and the fraction of bank points correctly classified as confined and unconfined. A relief value of 3.4 m provides the best result, with 82% bank correctly classified as confined or unconfined.

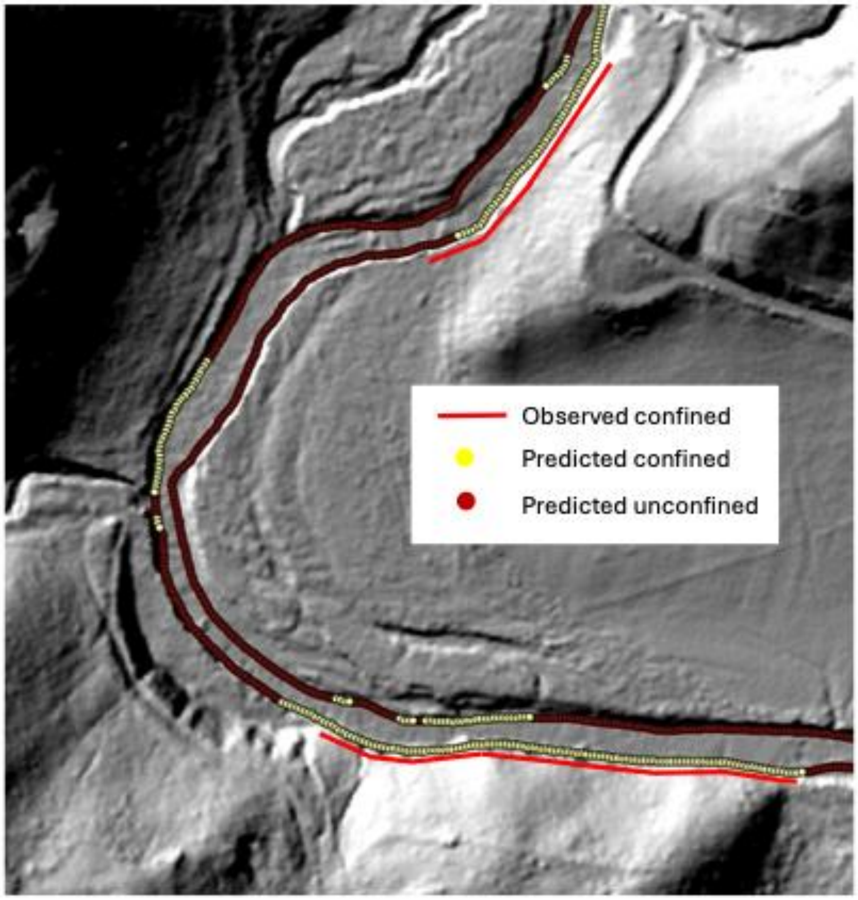

Figure S7
Comparison of observed confined and unconfined banks with confined and unconfined banks predicted using a relief threshold of 3.4 m at McCarthy's (2018) site 12 (see Figure S5 for latitude and longitude, Figure S13 for locations of sites). All banks without the solid red line ("Observed confined") were mapped as unconfined in the field.

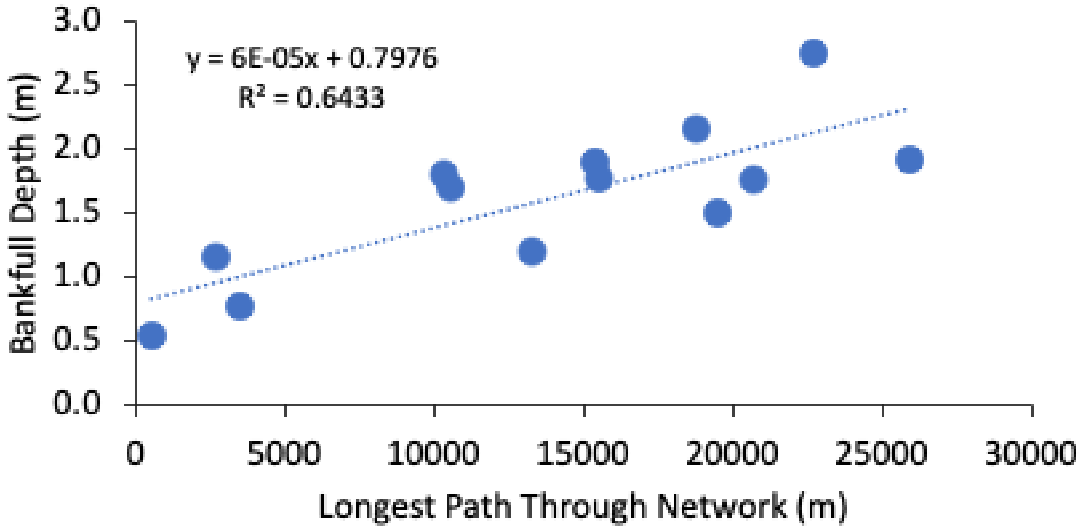

Figure S8

Bankfull depth as a function of the longest path upstream for the White Clay Creek.

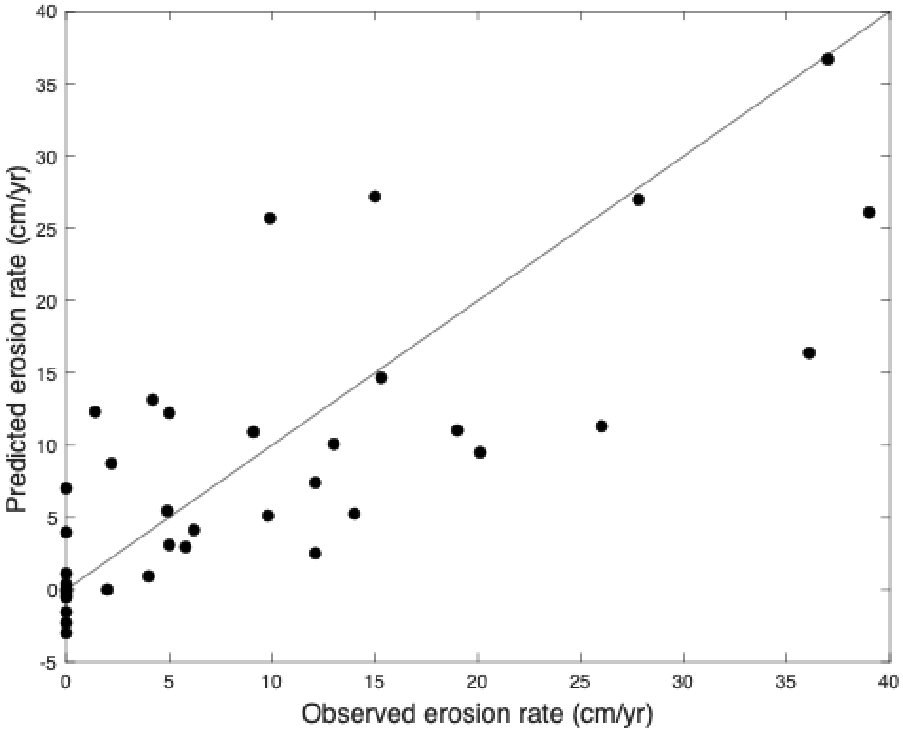

Figure S9
Correlation between the observed erosion rate and the erosion rate predicted using equation (S3).

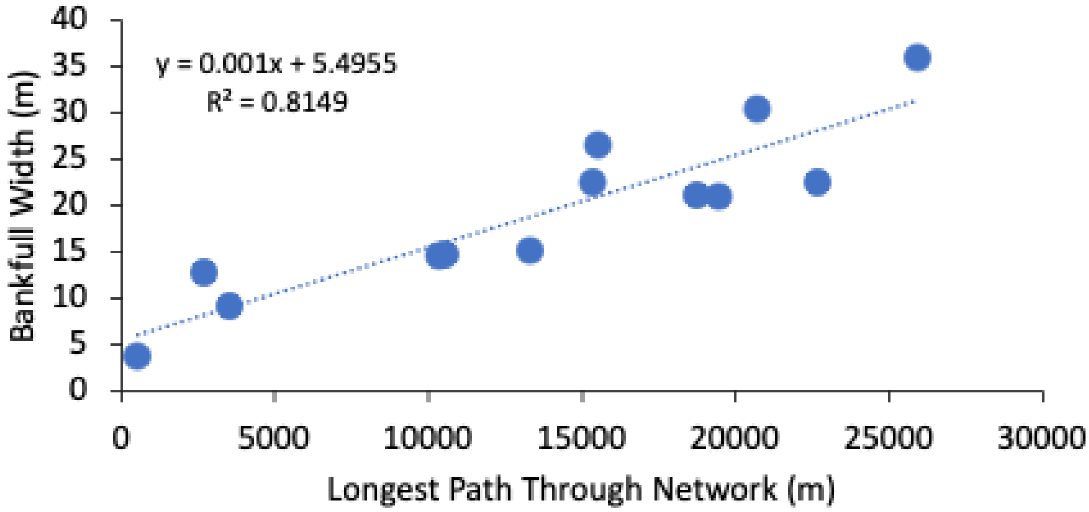

Figure S10
Bankfull width as a function of the longest path upstream for the White Clay Creek.

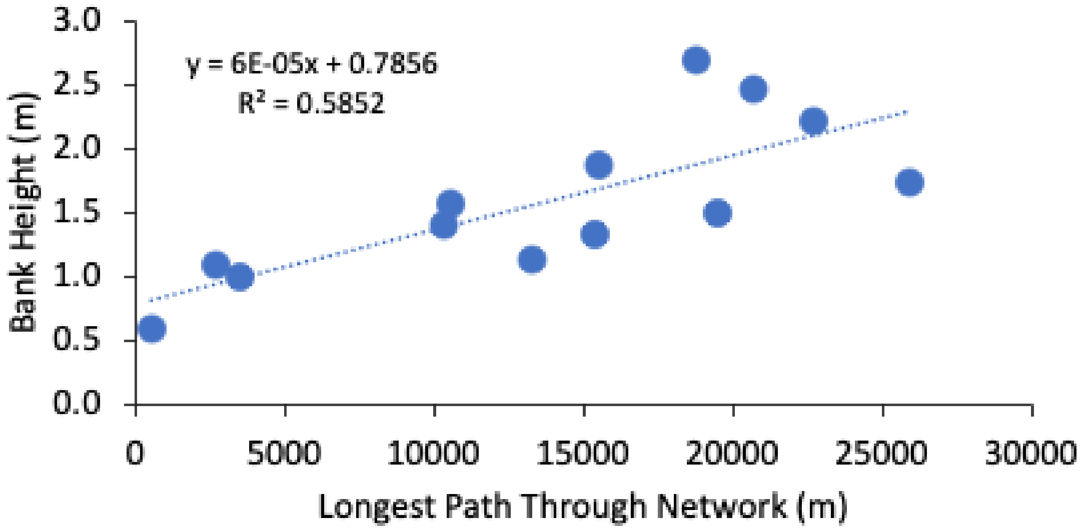

Figure S11
Bank height as a function of the longest path upstream for the White Clay Creek.

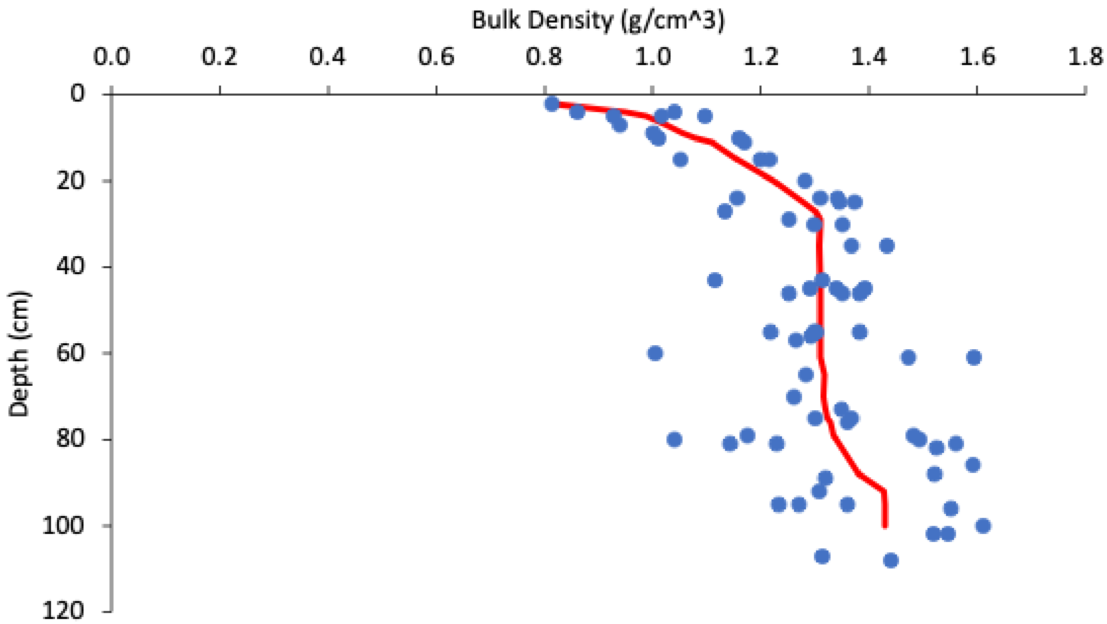

Figure S12

Bulk density as a function of depth. Data represent samples from sites of McCarthy (2018) and Pizzuto et al. (2022). Red line is a smoothed running mean.

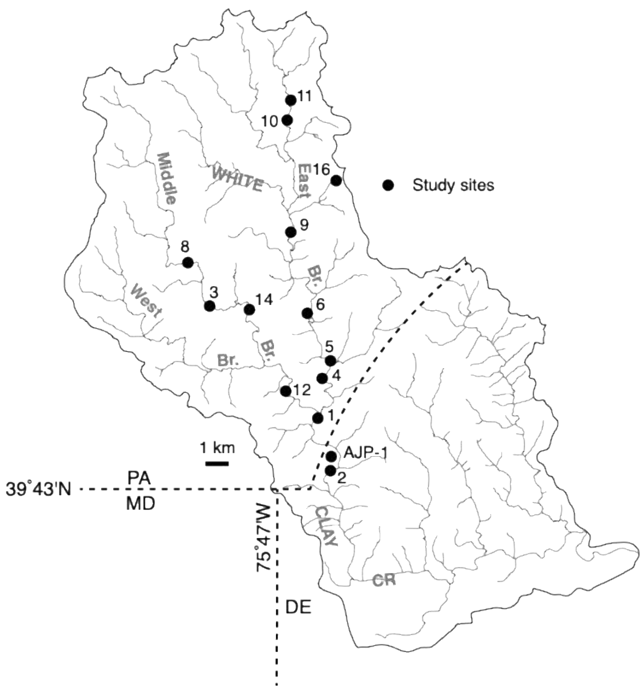

Figure S13
Map of White Clay Creek watershed showing locations of McCarthy's sites and an additional site (AJP-1) where floodplain sedimentation rates were measured.

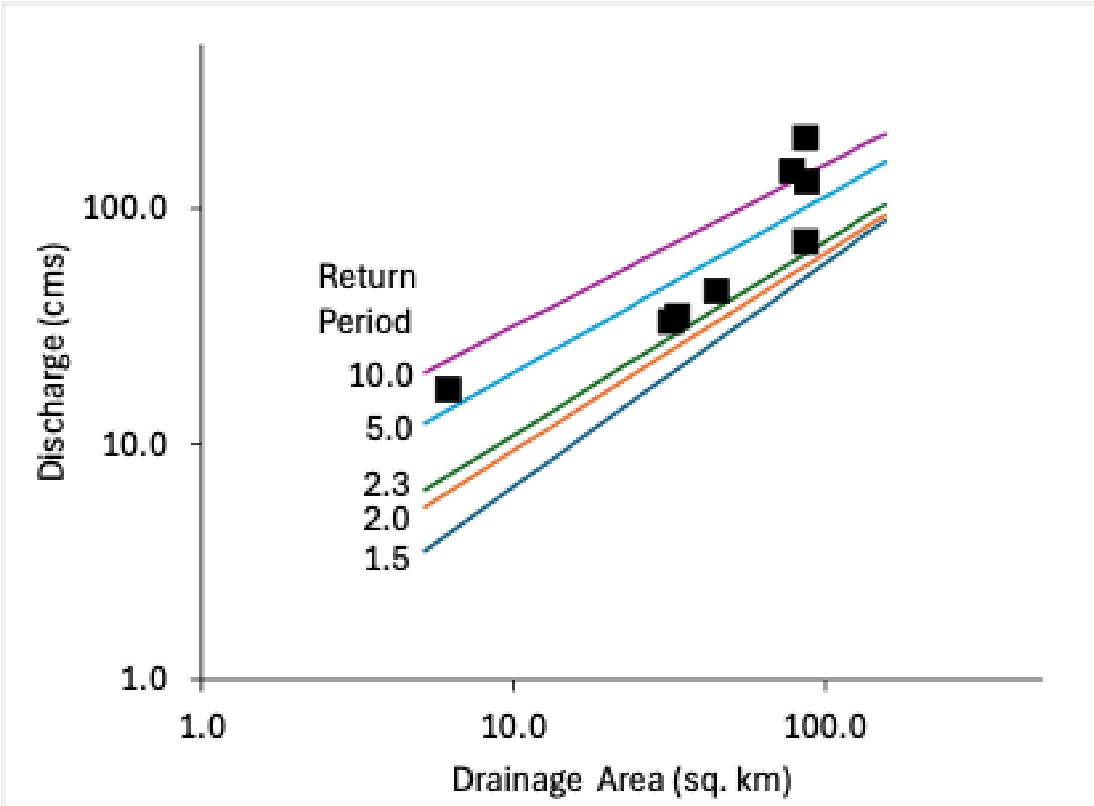

Figure S14
Relationships between discharges with specified return periods and drainage basin area for the White Clay Creek and selected nearby watersheds. Symbols indicate discharges required to inundate sampling sites where floodplain sedimentation rates were measured.

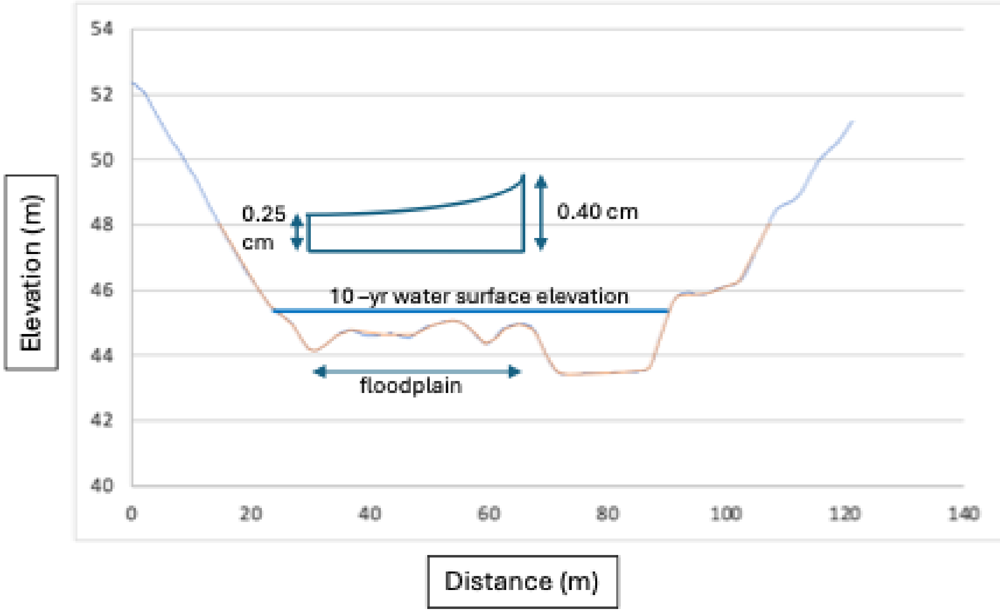

Figure S15

Valley cross-section of reach B2_2, showing the elevation of the 10-yr water surface, the annual accumulation of sediment on the floodplain (corrected for decreasing sedimentation with distance from the channel), and the active floodplain. The length of the active floodplain represents 84% of the length of the valley outside the confines of the channel inundated by the 10-year flood.

Supplementary Tables

Table S1. Steps to map channel banks and determine annual mass erosion rates at 2-meter intervals along White Clay Creek streambanks.

Step #	Task	Data source or method
1	Map streambanks by hand using GIS	DEM and associated hillshade (USGS NED Program 3DEP-3D Elevation Program), 2008 aerial imagery (PAMAP, Pennsylvania State Plane South, datum NAD83)
2	Create points at 2 m intervals along banks	ARCGIS
3	Identify unconfined banks based on local relief threshold	DEM, ARCGIS,confinement threshold defined by analyzing field data
4	Database of decadal-averaged linear bank erosion rates	Previous and current studies of White Clay Creek (McCarthy, 2018) and nearby streams (Pizzuto and Meckelnburg, 1987; Allmendinger et al., 2005)
5	Compute channel centerline	ARCGIS
6	Determine channel centerline curvature	Blankaert and DeVriend (2010)
7	Canopy cover at each bank point	NLCD 2016 Tree_Canopy L48_20190831 (CONUS), Yang et al. (2018)
8	Compute linear bank retreat rate	Empirical correlation with curvature, canopy cover
9	Determine bank height	Empirical correlation with upstream channel length
10	Convert linear rate to volumetric rate	Multiply by bank height and 2 m point spacing
11	Convert volume rate to mass rate	Multiply by bulk density

Table S2. Lengths and associated drainage basin areas for selected White Clay Creek stream channels.

Channel Length (km)	Drainage Basin Area (km^2)	Channel Length (km)	Drainage Basin Area (km^2)	Channel Length (km)	Drainage Basin Area (km^2)
3.5	3.09	0.78	0.6	0.54	0.28
2.28	2	3.89	4.85	2.46	1.37
1.97	2.28	1.1	1.05	3.46	1.79
1.18	0.45	1.12	0.79	2.82	2.48
3.46	3.85	0.06	0.19	2.43	1.71
0.45	0.36	0.92	0.87	1.91	1.98
3.95	5.93	2.2	2.23	8	8.06
5.67	6.26	1.07	0.73	1.04	0.67
0.65	0.96	0.99	0.83	2.2	1.77
1.14	1.53	0.98	0.7	1.58	1.54
0.63	0.76	7.02	3.41	1.5	1.53
2.38	2.52	0.88	0.68	1.72	1.34
4.42	3.63	2.57	1.51	1.77	1.59
1.21	0.85	1.64	0.57	1.46	0.91
		1.52	0.67	1.94	0.96

Table S3. Annual suspended sediment flux computed at the USGS stream gaging station White Clay Creek near Strickersville (USGS #01478245) 2012 – 2024.

Water Year	Mg/yr
2012	15142
2013	36731
2014	52718
2015	11085
2016	21650
2017	5381
2018	34300
2019	28337
2020	40692
2021	36400
2022	3409
2023	5154
2024	37712
Mean	25300
Median	28300
Std Dev	16000
CV	0.63
Max	52700
Min	3400

Table S4. Data used to develop an empirical relationship for annual linear bank retreat of unconfined streambanks.

Source	Stream	Site Identifier or Latitude, Longitude	Curvature (1/m)[1]	Bankfull Width (m)[2]	Canopy Cover (%)	Erosion Rate (cm/yr)	Erosion Rate (% width/year)
McCarthy (2018)	White Clay Creek	1	0.00476	22.47	56	6.2	0.3
McCarthy (2018)	White Clay Creek	2	0.01091	36.03	41	36.1	1.0
McCarthy (2018)	White Clay Creek	3	0.01526	15.19	44	20.1	1.3
McCarthy (2018)	White Clay Creek	4	0.00370	21.03	60	5.8	0.3
McCarthy (2018)	White Clay Creek	5	0.01045	21.06	28	13.0	0.6
McCarthy (2018)	White Clay Creek	6	0.00545	26.49	61	4.9	0.2
McCarthy (2018)	White Clay Creek	8	0.01899	14.71	51	19.0	1.3
McCarthy (2018)	White Clay Creek	9	0.00906	14.57	55	9.8	0.7
McCarthy (2018)	White Clay Creek	10us	0.05828	9.09	22	9.9	1.1
McCarthy (2018)	White Clay Creek	10mid	0.01697	9.09	23	12.1	1.3
McCarthy (2018)	White Clay Creek	10ds	0.03038	9.09	15	15.3	1.7
McCarthy (2018)	White Clay Creek	11us	0.01753	12.75	53	2.2	0.2
McCarthy (2018)	White Clay Creek	11mid	0.02505	12.75	56	1.4	0.1
McCarthy (2018)	White Clay Creek	11ds	0.02426	12.75	38	4.2	0.3
McCarthy (2018)	White Clay Creek	12	0.00913	30.43	52	9.1	0.3
McCarthy (2018)	White Clay Creek	14	0.00298	22.45	62	12.1	0.5
McCarthy (2018)	White Clay Creek	16	0.14477	3.80	21	27.8	7.3
This study	White Clay Creek	39.7475, -75.7708333	-6.20E-04	23.00	53	0.0	0.0
This study	White Clay Creek	39.74652, -75.771344	-1.90E-04	23.00	55	0.0	0.0
This study	White Clay Creek	39.743872, -75.772256	-2.60E-03	23.00	58	0.0	0.0
This study	White Clay Creek	39.743342, -75.771846	6.20E-03	30.00	61	0.0	0.0
This study	White Clay Creek	39.738209, -75.768079	2.20E-05	30.00	63	0.0	0.0
This study	White Clay Creek	39.737460, -75.763725	-3.60E-04	30.00	56	0.0	0.0
This study	White Clay Creek	39.732487, -75.759751	-2.60E-03	30.00	57	0.0	0.0
This study	White Clay Creek	39.756808, -75.785290	9.70E-04	30.00	57	0.0	0.0
This study	White Clay Creek	39.755239, -75.784014	-6.30E-05	30.00	40	0.0	0.0
This study	White Clay Creek	39.81456, -75.782557	6.80E-04	15.00	52	0.0	0.0
This study	White Clay Creek	39.761921, -75.767476	1.00E-04	21.00	57	0.0	0.0
This study	White Clay Creek	39.861042, -75.784154	-4.50E-03	9.00	58	0.0	0.0
This study	White Clay Creek	39.860747, -75.783909	-0.0869	9.00	60	0.0	0.0

This study	White Clay Creek	39.855451, -75.783870	0.00628	13.00	22	0.0	0.0
Allmendinger et al. (2005)	Beaver Run	Non-forested	0.018	6.00	0	39.0	6.5
Allmendinger et al. (2005)	Cobbs Creek	Non-forested	0.046	3.30	0	37.0	11.2
Allmendinger et al. (2005)	Rocky Run	Non-forested	0.025	4.50	0	15.0	3.3
Allmendinger et al. (2005)	Towamencin Creek	Non-forested	0.053	4.70	21	5.0	1.1
Allmendinger et al. (2005)	Beaver Run	Forested	0.021	7.40	94	14.0	1.9
Allmendinger et al. (2005)	Cobbs Creek	Forested	0.016	5.20	65	5.0	1.0
Allmendinger et al. (2005)	Towamencin Creek	Forested	0	6.90	90	2.0	0.3
Pizzuto & Meckelnburg (1989)	Brandywine Creek	Sites 1-3 (averaged)	0.00062	42.00	78	4.0	0.1
Pizzuto & Meckelnburg (1989)	Brandywine Creek	Sites 4-9 (averaged)	0.0066	42.00	45	26.0	0.6

[1] - positive curvature indicates erosion of the outside bank of a bend

[2] - bankfull widths for "this study" are averages of McCarthy's (2018) data obtained upstream and downstream of each location

Table S5. Bankfull channel geometry and related variables for McCarthy's (2018) study sites of the White Clay Creek. Site locations are illustrated in Figure S13.

Site #	Drainage Area (km^2)	Furthest Upstream Distance (m)	Bank Height (m)	Bankfull channel width (m)
1	153.114	22684	2.22	22.47
2	164.480	25920	1.74	36.03
3	27.879	13288	1.14	15.19
4	82.700	19464	1.50	21.03
5	72.260	18752	2.70	21.06
6	67.294	15506	1.88	26.49
8	21.998	10540	1.58	14.71
9	50.497	10328	1.40	14.57
10	7.445	3518	1.00	9.09
11	7.012	2702	1.09	12.75
12	64.163	20694	2.47	30.43
14	32.144	15374	1.34	22.45
16	NA	540	0.59	3.80

Table S6. Sediment bulk density and sampling depth below ambient ground surface. Data are from McCarthy (2018) and Pizzuto et al. (2022).

Depth (cm)	Bulk Density (g/cm^3)	Depth (cm)	Bulk Density (g/cm^3)	Depth (cm)	Bulk Density (g/cm^3)
2	0.81	30	1.3	75	1.37
4	0.86	30	1.35	75	1.3
4	1.04	35	1.37	76	1.36
5	1.1	35	1.43	79	1.18
5	0.93	43	1.12	79	1.48
5	1.02	43	1.31	80	1.04
7	0.94	45	1.39	80	1.49
9	1	45	1.34	81	1.14
10	1.16	45	1.29	81	1.23
10	1.01	46	1.35	81	1.56
11	1.17	46	1.25	82	1.52
15	1.05	46	1.38	86	1.59
15	1.2	55	1.3	88	1.52
15	1.22	55	1.22	89	1.32
20	1.28	55	1.3	92	1.31
24	1.16	55	1.38	95	1.23
20	1.28	56	1.29	95	1.36
24	1.16	57	1.27	95	1.27
24	1.34	60	1	96	1.55
24	1.31	61	1.59	100	1.61
25	1.37	61	1.47	102	1.52
25	1.34	65	1.28	102	1.55
27	1.13	70	1.26	107	1.31
29	1.25	73	1.35	108	1.44

Table S7. Steps to determine annual floodplain sedimentation in the 140 valley reaches of the White Clay Creek (see Supplementary Methods Text S5 for explanation).

Step #	Task	Data source/comments
1	Determine average floodplain sedimentation rate and uncertainty from field data	Published analyses of fallout radionuclides and published and unpublished rates from dendrochronology
2	Correct sedimentation rate to account for "levee effect" of decreasing sedimentation away from the channel	Pizzuto (1987), field data
3	Determine recurrence interval of flow inundating field sites used to determine overbank sedimentation	1-D hydraulic model of Pizzuto (2012), calibrated at USGS gaging station near Strickersville, gaging station data from nearby watersheds
4	Identify relatively straight valley reach, 200-1000 m in length	DEM, hillshade in ARCGIS
5	Select representative cross-section in each valley reach	DEM, hillshade in ARCGIS
6	Determine slope of valley reach	Centerline channel slope/channel sinuosity
7	Determine maximum channel length upstream of cross-section	Channel bank mapping
8	10-year flood @ cross-section	empirical function of upstream channel length
9	Water surface elevation of 10-yr flood at cross-section	Pizzuto (2012) 1-D hydraulic model
10	Determine portion of inundated area consisting of active floodplain	Cross-section morphology
11	Determine equation of 10-yr water surface plane within reach	steps 3 and 6
12	Create 0.3 m grid of points within valley reach, and their elevations	ARCGIS
13	Identify area submerged by 10-yr flood	steps 6 and 9
14	Remove area within channel and outside active floodplain	GIS and channel bank mapping
15	Multiply corrected inundated area by deposition rate corrected for "levee effect" and bulk density	Bulk density from field data (Table S6)

Table S8. Floodplain sedimentation rates for the sites illustrated in Figure S13. "Floodplain" indicates that multiple samples were obtained across a floodplain.

Site ID - Pizzuto (2022), Pizzuto et al. (2023), & McCarthy (2018)	Geomorphic Setting	Sedimentation Rate (cm/yr)	Method	Sed Rate - Uncertainty (cm/yr)	Sed Rate + Uncertainty (cm/yr)	Valley Slope	Publication with location and other information
1	Levee	0.75	137Cs, 210Pb	0.41	1.1	0	Pizzuto et al., 2022, Table 1
1	Levee	1.1	Tree root dendrochronology	0	2.2	0	Pizzuto et al., 2022, Figure 9, Table 5
2	Backswamp	0.32	137Cs, 210Pb	0.29	0.34	0	Pizzuto et al., 2022, Table 1
AJP1	Levee	0.75	137Cs, 210Pb	0.3	1.2	0	Pizzuto et al., 2022, Table 1
6	Floodplain	0.11	Tree root dendrochronology	0	0.35	0.01	This study
8	Levee	0.25	137Cs, 210Pb	0	0.5	0	Pizzuto et al., 2022, Table 1
9	Levee	0.25	137Cs, 210Pb	0	0.5	0	Pizzuto et al., 2022, Table 1
12	Floodplain	0.22	Tree root dendrochronology	0	0.44	0	This study
14	Floodplain	0	Tree root dendrochronology	0	0	0.01	This study
10	Floodplain	0.11	137Cs	0.03	0.18	0.01	Marquard (2015), Fig. 5.19
11	Floodplain	0.49	137Cs	0.30	0.68	0.01	Marquard (2015), Table 5.3
mean (cm/yr)		0.40					
std dev (cm/yr)		0.34					

Table S9. Fraction of the bank height comprised of legacy sediment and related data for several of McCarthy's (2018) sites. From data of Pizzuto et al. (2022, 2023), Marquard (2015), and McCarthy (2018).

Site	Post-Settlement Thickness (cm)	Depth to 1950 (cm)	Legacy sediment thickness (cm)	Bank Height (cm)	Fraction of Bank Height Legacy Sediment
1	118	51	67	222	0.30
12	110	15	95	247	0.38
8	100	13	87	158	0.55
9	110	17	93	140	0.66
11ds	152	33	119	247	0.48
6	75	15	60	188	0.32
				mean	0.45
				median	0.43
				std dev	0.14

Table S10. Floodplain sedimentation rates determined using dendrochronology at site 6 (see Figure S13 for location).

Tree ID	Latitude	Longitude	Breast Height Diameter (cm)	Tree Family	Sed. Depth Root 1 (cm)	Sed. Depth Root 2 (cm)	Sed. Depth Root 3 (cm)	Mean	Std. Dev. (cm)	Tree Age (yrs)	Average Sedimentation Rate (cm/yr)	Uncertainty
T6-1	39.78707135	75.77202366	55	Tulip poplar	15.0	24.0	9.0	16.0	7.5	117	0.14	0.06
T6-2	39.78712613	75.77198623	N/A	Beech	0.0	0.0	0.0	0.0	0.0	N/A	0.00	0.00
T6-3	39.78709123	75.77206966	22	Basket Oak	16.0	4.0	12.0	10.7	6.1	71	0.15	0.09
T6-4	39.7870738	75.77215698	11	Mockernut Hickory	9.0	15.0	10.0	11.3	3.2	12	0.94	0.27
T6-5	39.78701803	75.77203657	N/A	Beech	0.0	0.0	0.0	0.0	0.0	N/A	0.00	0.00
T6-6	39.78691368	75.77196544	34	Tulip poplar	0.0	6.0	10.0	5.3	5.0	70	0.08	N/A
T6-7	39.7869539	75.77217414	N/A	Beech	0.0	0.0	0.0	0.0	0.0	N/A	0.00	0.00
T6-8	39.78681872	75.77216841	N/A	Beech	0.0	0.0	0.0	0.0	0.0	N/A	0.00	0.00
T6-9	39.78688593	75.77220953	N/A	Beech	0.0	0.0	0.0	0.0	0.0	N/A	0.00	0.00
T6-10	39.7868654	75.77229374	10	Mockernut Hickory	12.0	12.0	6.0	10.0	3.5	73	0.14	0.05
T6-11	39.7867981	75.77228562	26	Beech	0.0	2.0	3.0	1.7	1.5	65	0.03	0.02
T6-12	39.78684958	75.77235799	N/A	Beech	0.0	0.0	0.0	0.0	0.0	N/A	0.00	0.00
T6-13	39.7869974	75.77242784	N/A	Basket Oak	0.0	0.0	0.0	0.0	0.0	N/A	0.00	0.00
T6-14	39.78685357	75.77245804	68	Tulip poplar	17.0	15.0	16.0	16.0	1.0	91	0.18	0.01
T6-15	39.78679633	75.77244311	N/A	Beech	0.0	0.0	0.0	0.0	0.0	N/A	0.00	0.00
									mean sed rate (cm/yr)		0.11	

median sed rate (cm/yr)	0.00
std dev (cm/yr)	0.24

Table S11. Floodplain sedimentation rates determined using dendrochronology at site 12 (see Figure S13 for location).

Tree ID	Latitude	Longitude	Breast Height Diameter (cm)	Tree Family	Sed. Depth Root 1 (cm)	Sed. Depth Root 2 (cm)	Sed. Depth Root 3 (cm)	Mean	Std. Dev. (cm)	Tree Age (yrs)	Average Sedimentation Rate (cm/yr)	Uncertainty
T12-1	39.75685493	75.78513569	56	Mockernut Hickory	50	56	N/A	53	3	270	0.20	0.01
T12-2	39.75677459	75.78520672	38	Mockernut Hickory	60	85	N/A	72.5	12.5	209	0.35	0.06
T12-3	39.75677459	75.78520672	42	Mockernut Hickory	48	38	N/A	43	5	119	0.36	0.04
T12-4	39.75665439	75.78510857	86	Beach [No Sed.]	N/A	N/A	N/A	0	N/A	N/A	0.00	N/A
T12-5	39.7566078	75.7817469	23	Tulip Poplar	22	21	19	21	2	43	0.48	0.04
T12-6	39.7566559	75.78509925	57	Beach [No Sed.]	N/A	N/A	N/A	0	N/A	N/A	0.00	N/A
T12-7	39.75648359	75.78520655	24	Mockernut Hickory	17.5	16.5	11.5	15	3	113	0.13	0.03
T12-8	39.75648359	75.78520655	26	Mockernut Hickory	39	45		42	3	101	0.42	0.03
T12-9	39.75648359	75.78520655	67	Black Walnut	36	31	24	30	6	87	0.35	0.07
T12-10	39.75648359	75.78520655	44	Beach	0	0	2	1	1	118	0.01	0.01
T12-11	39.75637161	75.78544194	38	Mockernut Hickory	14	12	10	12	2	70	0.17	0.03
T12-12	39.75627358	75.78542735	29	Tulip Poplar	22	21		21.5	1	25	0.86	0.02

T12-13	39.7561577	75.78538667	20	Mockernut Hickory	16	14	19	16	3	52	0.31	0.05
T12-14	39.75589513	75.78516509	33	Mockernut Hickory	31	15	15	20	9	115	0.18	0.08
T12-15	39.75576182	75.78490757	19	Beach	8	7	9	8	1	49	0.16	0.02
T12-16	39.7556925	75.78508561	36	Beach [No Sed.]	N/A	N/A	N/A	0	N/A	N/A	0.00	N/A
T12-17	39.7555921	75.78493753	9	Beach	0	5	1	2	3	75	0.03	0.04
T12-18	39.7555921	75.78493753	60	Beach [No Sed.]	N/A	N/A	N/A	0	N/A	N/A	0.00	N/A
T12-19	39.75551974	75.78496205	32	Silver Maple	16	10		13	3	114	0.11	0.03
									mean sed rate (cm/yr)			0.22
									median sed rate (cm/yr)			0.17
									std dev (cm/yr)			0.22

Table S12. Floodplain sedimentation rates determined using dendrochronology at site 14 (see Figure S13 for location).

Tree ID	Latitude	Longitude	Breast Height Diameter (cm)	Tree Family	Sed. Depth over Roots (cm)	Tree Age (yrs)	Average Sedimentation Rate (cm/yr)
T14-1	39.78649312	75.80290412	19	Beech	0.0	N/A	0.00
T14-2	39.78643459	75.80297226	20	Beech	0.0	N/A	0.00
T14-3	39.78665541	75.80303288	51	Maple?	0.0	N/A	0.00
T14-4	39.78673652	75.80296031	33	Red Maple	0.0	N/A	0.00
T14-5	39.78687669	75.80308631	44	Beech	0.0	N/A	0.00
T14-6	39.78687779	75.80322112	30	Oak?	0.0	N/A	0.00
T14-7	39.78692551	75.80326051	35	Red Maple	0.0	N/A	0.00
T14-8	39.78717157	75.80317204	55	Tulip poplar	0.0	N/A	0.00
T14-9	39.78708798	75.80316061	23	Beech	0.0	N/A	0.00
T14-10	39.78700724	75.80316403	56	Red Maple	0.0	N/A	0.00
T14-11	39.78734712	75.80316697	24	Red Maple	0.0	N/A	0.00
T14-12	39.78744216	75.80312428	37	Red Maple	0.0	N/A	0.00
T14-13	39.7875854	75.80288083	13	Red Maple	0.0	N/A	0.00
T14-14	39.7860642	75.80301844	21	Sugar Maple	0.0	N/A	0.00
					mean sed rate (cm/yr)		0.00

Supplementary Data Set S1

Location data, sediment budget components, and uncertainty for all 140 channel sediment budget reaches of the White Clay Creek. The actual file name is: WCC_channel_reach_location_&_sediment_budget_database.csv. See Data and Code Availability Statement for details.

References not cited in the main manuscript

Flynn, K.M., Kirby, W.H., and Hummel, P.R. User's manual for program PeakFQ annual flood-frequency analysis using Bulletin 17B guidelines. U.S. Geological Survey, Techniques and Methods