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Streambank and floodplain geomorphic change and contribution
to watershed material budgetsG B Noe^{1,*}, K G Hopkins², P R Claggett³, E R Schenk⁴, M J Metes⁵, L Ahmed³, T R Doody¹ and C R Hupp¹¹ U.S. Geological Survey, Florence Bascom Geoscience Center, Reston, VA, United States of America² U.S. Geological Survey, South Atlantic Water Science Center, Raleigh, NC, United States of America³ U.S. Geological Survey, Lower Mississippi Gulf Water Science Center, Annapolis, MD, United States of America⁴ City of Flagstaff, Water Services, Flagstaff, AZ, United States of America⁵ U.S. Geological Survey, Maryland-Delaware-District of Columbia Water Science Center, Baltimore, MD, United States of America

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E-mail: gnoe@usgs.gov**Keywords:** floodplains, geomorphic, contributions, watersheds, budgets, streambankSupplementary material for this article is available [online](#)

Abstract

Stream geomorphic change is highly spatially variable but critical to landform evolution, human infrastructure, habitat, and watershed pollutant transport. However, measurements and process models of streambank erosion and floodplain deposition and resulting sediment fluxes are currently insufficient to predict these rates in all perennial streams over large regions. Here we measured long-term lateral streambank and vertical floodplain change and sediment fluxes using dendrogeomorphology in streams around the U.S. Mid-Atlantic, and then statistically modeled and extrapolated these rates to all 74 133 perennial, nontidal streams in the region using watershed- and reach-scale predictors. Measured long-term rates of streambank erosion and floodplain deposition were highly spatially variable across the landscape from the mountains to the coast. Random Forest regression identified that geomorphic change and resulting fluxes of sediment and nutrients, for both streambank and floodplain, were most influenced by urban and agricultural land use and the drainage area of the upstream watershed. Modeled rates for headwater streams were net erosional whereas downstream reaches were on average net depositional, leading to regional cumulative sediment loads from streambank erosion (-5.1 Tg yr^{-1}) being nearly balanced by floodplain deposition ($+5.3 \text{ Tg yr}^{-1}$). Geomorphic changes in stream valleys had substantial influence on watershed sediment, phosphorus, carbon, and nitrogen budgets in comparison to existing predictions of upland erosion and delivery to streams and of downstream sediment loading. The unprecedented scale of these novel findings provides important insights into the balance of erosion and deposition in streams within disturbed landscapes and the importance of geomorphic change to stream water quality and carbon sequestration, and provides vital understanding for targeting management actions to restore watersheds.

1. Introduction

Erosion and deposition in stream valleys can have large influence on channel shape, processes, and sediment transport that impact local stream ecosystem health (Florsheim *et al* 2008) and watershed-scale mass balance of sediment and associated nutrients and contaminants (Trimble 1999). This balance of erosion and deposition within channel networks is fundamental to stream and river ecosystems and their

management (Wohl *et al* 2015). Fluxes of sediment and its attached nitrogen, and phosphorus, and carbon within stream valleys, particularly from streambank erosion and floodplain deposition, contribute to stream water quality within individual reaches and small watersheds (Costa 1975, Trimble 1999, Wang *et al* 2017).

The drivers and predictors of stream fluvial geomorphic change are generally understood to be watershed characteristics that influence and interact

with local reach morphology. The topography, soils, and land use, and other attributes of the upstream drainage area generate the flow and sediment supply that interact with channel-floodplain form and sediment characteristics at the local reach-scale to determine the hydraulics that can erode and deposit sediment along the stream (Fox *et al* 2016). For example, many fluvial system properties that determine stream sediment dynamics are influenced by the drainage area (Church 2002) and land use (Paul and Meyer 2001) of the upstream watershed. The erosion and deposition of stored sediment are also influenced by the shape of fluvial landforms and characteristics of sediment in the local stream reach (Wynn and Mostaghimi 2006, Fox *et al* 2016, Hopkins *et al* 2018). However, understanding of the drivers of the large spatial variability of stream geomorphic change is limited at the scale of large watersheds but would offer helpful insights into riverine sediment export patterns over very large scales (Syvitski *et al* 2005).

The cumulative impact of stream erosion and deposition on watershed processes is poorly constrained because sufficient measurements and effective tools are lacking for predicting spatial variation in geomorphic processes at all stream reaches within large watersheds or regions. Although erosion and deposition are natural processes, human alteration of landscapes has increased their rates with consequences for stream habitat and water quality (Wilkinson and McElroy 2007). Past human activities led to large amounts of soil erosion that was deposited as 'legacy' sediment currently stored in stream valleys that may undergo geomorphic reworking and elevate modern downstream sediment and nutrient loads, leading to the perception that large amounts of stream erosion and minimal floodplain deposition currently dominate the landscape (Walter and Merritts 2008). Predictions of upland erosion may not correspond to measured river sediment export in disturbed basins, suggesting other important sources or sinks of sediments exist in watersheds (Trimble 1999, Boomer *et al* 2008) such as stream geomorphic change. However, physical process models of watershed transport are currently not effective at predicting reach-scale sediment erosion and deposition for streams across large regions (Cho *et al* 2018). We present a study that combined extensive measurement with predictive statistical modeling to understand the drivers and quantities of sediment and attached nutrient loads from geomorphic change in floodplains and streambanks at the scale of large regional watersheds. These stream valley fluxes of sediment and attached nutrients were then combined with other existing models of upland erosion and of downstream loading to create watershed mass balance budgets that identify the role of streambank erosion and floodplain deposition in watershed transport processes.

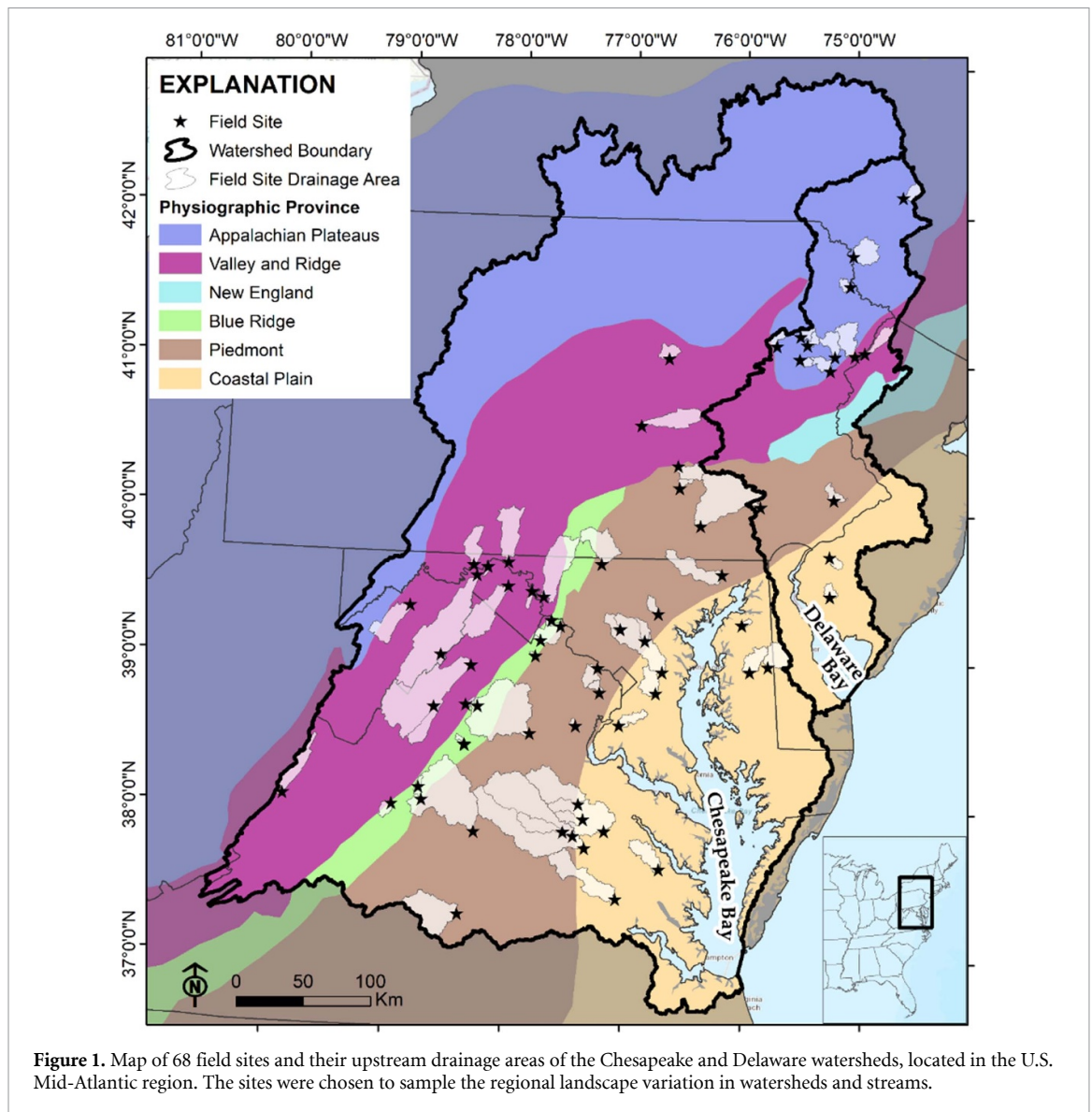
2. Methods

Sixty-eight stream and river sites were sampled to represent the landscape variability within the 185 000 km² Chesapeake Bay and Delaware River watersheds in the U.S. Mid-Atlantic (figure 1), formative watersheds in American history that now supply drinking water and economic activity to almost 40 million people (Kauffman and Collier 2018) and have a long history of watershed and stream disturbance (Costa 1975, Walter and Merritts 2008). Dendrogeomorphic measurements of long-term geomorphic change (Hupp *et al* 2016), geomorphometric surveying, and sediment characterization, were made of both streambank and floodplain throughout a representative 100 m sampling reach of each site. These measurements were used to calculate rates of vertical net change of active floodplain and of lateral net change of streambank and the resulting fluxes of mass of sediment and attached nutrients per meter of channel length per year in each site, representing mean rates over the decadal time scales of woody vegetation measurement.

Geomorphic change and flux rates were explained and extrapolated using machine-learning statistical regression models with predictors that include newly available geospatial 'big data' on watershed attributes of the upstream drainage area and local reach-scale channel and floodplain geomorphometry derived from lidar. For every mapped nontidal stream reach in the region, the statistical models predict geomorphic rates of change, and resulting fluxes of sediment, fine (<63 μ m) sediment, and attached nitrogen, phosphorus, and organic carbon, as well as fine sediment storage on the streambed. Predictions of streambank and floodplain loads for each reach were aggregated to the watershed scale and regional sediment, nitrogen, phosphorus, and carbon budgets were created using existing process model predictions of upland erosion load and delivery to streams and statistical model predictions of downstream channel loads.

2.1. Measurement

Stream and river sampling locations were stratified among major physiographic provinces of the regional watersheds and chosen to systematically sample landscape gradients in upstream geology, hydrology, land use, and drainage area (see Boomer *et al* 2008 for a description of regional physiographic provinces). Measurement reaches were chosen based on preference for the presence of a nearby stream gage where possible, landowner permission, presence of sufficient woody vegetation (see below), absence of recent major anthropogenic alteration of channel or floodplain, and absence of current intensive management of the floodplain (e.g. row crop agriculture). Notably, we did not constrain reach selection based on the presence or width of active floodplain, shape of the



channel (e.g. straight vs. meandering), nor consider the amount of legacy sediment storage or presence of historic mill dams in the stream valley. Measurement reaches were placed to avoid impacts of nearby road crossings and bridges and atypical bedrock control of channel structure that may have influenced stream gage placement.

Each stream reach was sampled once in 2013, 2014, 2015, 2017, or 2018, for Valley and Ridge, Piedmont, Coastal Plain, Appalachian Plateau (and additional sites of the first three provinces in the Delaware River watershed), and finally the Blue Ridge physiographic provinces, respectively. Although stream reaches were located within each targeted physiographic province, their upstream drainage area could incorporate multiple provinces. No extreme floods or droughts occurred during the sampling period.

Dendrogeomorphic measurements of geomorphic change encompassed the entire extent of the 100 m sampling reaches, whereas field-measured

geomorphometry and sediment physico-chemistry was measured at lateral cross-sections at the beginning and end of the reach. Each lateral cross-section included stream channel, streambank, and any active floodplain on both sides of the channel across the valley. The extent of active floodplain was measured after field delineation using visual indicators of fresh flow debris oriented perpendicular to the valley axis to indicate overbank flow, newly deposited sediment, high water marks, soil characteristics, vegetation composition, and recent stage records of nearby stream gages where available. The total width of active floodplain, height of each streambank, and width of stream channel along both cross-sections were surveyed using a total station or laser surveyor.

Surficial sediment of the alluvial floodplain and streambank was collected using a bulk density sampler (0–5 cm depth, 5 cm diameter) along the two lateral cross-sections in each reach. Floodplain sediment cores (4–8 per reach) were collected to encompass the spatial variability proportionate to

the extent of present geomorphic units, e.g. levees, fine grained and lower elevation back swamps, and toe slopes at the edge of floodplain. Streambank sediment cores (8 per reach) were collected from right and left bank and the top third and bottom third of bank, at each cross-section. Each sediment core was measured for bulk density, particle size, total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), and organic, carbonate and mineral content (See supplemental information for details available online at stacks.iop.org/ERL/17/064015/mmedia).

Geomorphic change through both floodplain vertical deposition or erosion and streambank lateral erosion were measured using dendrogeomorphology. Dendrogeomorphology measures long-term net geomorphic change integrated over the life span of woody vegetation (Hupp *et al* 2016). Floodplain net vertical change was measured as the burial (deposition) or exposure (erosion) of primary basal roots over the lifetime of trees. Floodplain change was measured using at least ten trees sampled to encompass the variability of floodplain geomorphic units throughout the reach. Species that do not produce reliable annual growth rings were not sampled but were a very small proportion of trees present among the sites (i.e. *Liquidambar styraciflua*, *Nyssa* spp., *Populus* spp., *Salix* spp., and all gymnosperms). An increment core was taken near the base of each sampled floodplain trees. The vertical distance from the existing sediment surface to the top of two primary basal roots (after excavating in the case of deposition) was measured at a distance of two trunk diameters from the tree. Because most floodplain trees had net deposition, measuring to the top of basal roots likely underestimated deposition to the fixed vertical location of root initiation near the center of the roots cross-section. Increment cores were mounted and then sanded. Total age of each floodplain tree was counted as the number of annual growth rings from the most recent ring to the biological center of the tree.

Streambank change net lateral change was measured as the horizontal erosion of the alluvial bank

over the duration of exposure of woody roots to the stream. Streambank change measurement targeted at least ten exposed and live woody roots typical of eroding streambanks throughout the reach. Exposed root sections were collected at the point most distant from the current streambank in order to maximize the integrated time period of measured geomorphic change. Root sections were air dried and then sanded. Duration of exposure of each exposed root to the stream was counted as the number of annual growth rings from the outside of the root inwards to the marker of the change from root burial to root exposure. Exposure was indicated by the oldest changes in root porosity, color, ring eccentricity, or scarring from flow debris. For a subset of sites, three individuals independently identified root exposure and estimates were averaged for each root.

The streambank dendrogeomorphology technique only measures net erosion that exposes roots, not streambank net deposition. To account for this bias when calculating reach-scale streambank erosion, measured dendrogeomorphic streambank erosion rates in a reach were corrected by multiplying by the proportion of the reach that had eroding streambank. The proportion of the reach eroding was measured by estimating the proportional area of both banks with apparent erosion while walking the channel. The floodplain and streambank dendrogeomorphic measurement approaches also do not measure vertical change of the channel (bed incision or aggradation).

In addition, 100 pebble counts were performed longitudinally as a zig-zag through the stream reach (modification of Bevenger and King (1995)). Sediment size was measured using a US SAH-97 handheld particle size analyzer with additional classification of finer material into sands or fine sediments (roughly less than 63 μm). Median streambed sediment particle size and percent streambed cover by fine sediment and sand were calculated from the pebble counts.

Flux of sediment per unit length of stream reach (Schenk *et al* 2013) was calculated as:

$$\begin{aligned} \text{Floodplain flux (kg - sediment m}^{-1}\text{ yr}^{-1}) &= \text{average dendrogeomorphic vertical change rate (m yr}^{-1}) \\ &\quad \times \text{average bulk density of floodplain sediment (g m}^{-3}) \\ &\quad \times \text{average total width of active floodplain (m)} \times 1 \text{ kg/1000 g} \\ \\ \text{Streambank flux (kg - sediment m}^{-1}\text{ yr}^{-1}) &= (-) \text{average dendrogeomorphic horizontal} \\ &\quad \text{change rate (m yr}^{-1}) \\ &\quad \times \text{average bulk density of streambank sediment (g m}^{-3}) \\ &\quad \times \text{average total height of alluvial streambank (m)} \\ &\quad \times \text{proportion of reach with eroding streambank (m m}^{-1}) \\ &\quad \times 1 \text{ kg/1000 g} \end{aligned}$$

$$\text{Net balance flux} = \text{Floodplain flux} \\ + \text{Streambank flux.}$$

Cross-sectional area change was calculated as:

$$\text{Floodplain cross-sectional area change (m}^2\text{yr}^{-1}\text{)} \\ = \text{average dendrogeomorphic vertical} \\ \text{change rate (m yr}^{-1}\text{)} \\ \times \text{average total width of active floodplain (m)}$$

$$\text{Streambank cross-sectional area change (m}^2\text{yr}^{-1}\text{)} \\ = (-) \text{average dendrogeomorphic horizontal} \\ \text{change rate (m yr}^{-1}\text{)} \\ \times \text{average total height of alluvial} \\ \text{streambank (m).}$$

Associated floodplain or streambank fluxes of fine sediment ($<63 \mu\text{m}$) and TN, TP, and TOC were calculated as the product of their average concentration in that reach and sediment flux rate. Erosion was defined as a negative flux (loss of sediment from the stream valley), and deposition as a positive flux.

2.2. Modeling

Spatial variation in the measured rates of geomorphic change, fluxes, and streambed characteristics among the 68 measurement reaches were explained by Random Forest statistical modeling using potential predictors of upstream watershed attributes and local reach-scale geomorphometry mapped to the NHDPlusV2 digital stream network (1:100 K scale; Moore and Dewald 2016). Random Forest is a machine learning approach that builds many statistical regression trees using randomization and resampling, and has the benefit of assessing nonlinear and nonparametric relationships between predictor and response variables without overfitting models (Breiman 2001). Two separate sets of Random Forest regressions were created for each of the floodplain fluxes and streambank fluxes of sediment, fine sediment, and associated C, N, and P, and for streambed particle d50, fine sediment cover, and fine plus sands sediment cover: (a) using only the attributes of the upstream drainage area to the measurement reach; and (b) using both the attributes of the upstream drainage area and the geomorphometry of the local reach (if available). Floodplain fluxes were transformed by a constant to remove negative fluxes and then $\log_{10}$.

A subset of prioritized watershed attributes was selected from an existing database of geospatial characteristics (Wieczorek *et al* 2018). Attributes were chosen for their description of geology, hydrology, soils, topography, and land use that likely influence sediment and nutrient availability and transport, and to have minimal covariation. The accumulated upstream drainage area ('ACC') values of

these 17 watershed attributes (supplementary table S1) were obtained for the NHDPlusV2 reach of each measurement reach.

The geomorphometry of reaches was estimated using a geospatial tool that processes lidar-derived digital elevation models (DEMs) to extract the dimensions and shapes of the floodplain, streambank, and stream channel (Floodplain and Channel Evaluation Toolkit, or FACET; Lamont *et al* 2019). Lidar DEMs were obtained for the Chesapeake Bay and Delaware River watersheds from the USGS National Map (<https://viewer.nationalmap.gov>) and state or local agencies and then resampled to a 3 m resolution. FACET generates a stream network from a hydrologically-conditioned DEM and then automates calculation of reach geomorphometry at a user-specified spatial resolution (every 9 m of stream channel in this study). Because FACET generates a higher resolution stream network than NHDPlusV2, the FACET stream segment with the largest Shreve magnitude within each NHDPlusV2 catchment was selected and then statistically summarized for each geomorphometric metric as the mean of the 5th to 95th percentile values (to exclude anomalous outliers) for the following attributes: streambank height, stream channel width, average streambank angle, and stream slope and sinuosity; total active floodplain width was summarized as the mean in each reach. Lidar DEMs were available for 85% and 100% of the Chesapeake Bay and Delaware River watersheds, respectively (Hopkins *et al* 2020).

For each of the fluxes and streambed characteristics, Random Forest models were built using the randomForest package of R (Breiman and Cutler 2018). Models were manually pruned to include fewer predictor variables, while retaining all metrics of land use in the upstream watershed, to identify the best model as defined by the maximum out-of-bag validation and thus predictability for unmeasured reaches. The best model was then tuned by varying *ntree* and *mtry* to achieve maximum accuracy. The resulting best model was assessed for the importance value of included predictors (a metric of each predictor's contribution to overall model accuracy) and for partial dependence plots that show the effect of each predictor on the response variable while controlling for other terms included in the model.

The best Random Forest models were then used to predict streambank and floodplain fluxes and streambed characteristics at each of the 99 664 NHDPlusV2 reaches in the Chesapeake Bay and Delaware River watersheds using the predictor variable values from the Wieczorek *et al* (2018) and FACET (Hopkins *et al* 2020) published databases. For reaches with FACET metrics available, the best Random Forest models (maximum out-of-bag validation) were chosen from among the predictor sets (a) using only the attributes of the upstream drainage area to the measurement reach, or (b) using both the

attributes of the upstream drainage area and the geomorphometry of the reach (supplementary table S1). For reaches without FACET metrics, the best model from predictor set b was chosen for extrapolation (using only upstream attributes).

The predicted load of material from geomorphic change for each reach was calculated as the product of predicted flux and stream length (NHDPlusV2 database) for floodplain and for streambank sediment, fine sediment, and TN, TP, and TOC. Flux and load predictions were censored for NHDPlusV2 reaches that were tidal, channelized, or impounded, and only predictions for the remaining 74 133 nontidal, non-modified reaches were generated. Similarly, floodplain fluxes were defined as zero for those reaches with drainage areas less than 3 km², where active floodplain deposition is unlikely (Hupp 1986, Knox 2006, Schenk *et al* 2013, Gellis *et al* 2015, Donovan *et al* 2015). Streambank fluxes were extrapolated to reaches with drainage area less than 3 km² due to the likelihood of streambank changes occurring along smaller streams.

2.3. Watershed budgeting

For each NHDPlusV2 reach, the Random Forest predictions of streambank and floodplain loads, as well as existing SPARROW model predictions of stream loads of suspended sediment, TN, and TP loads generated within the catchment (Ator 2019), were summed to calculate budgets for the combined Chesapeake Bay and Delaware River watersheds. The SPARROW models use watershed attributes to explain and predict constituent loads moving downstream. In the Chesapeake Bay watershed only, the budget also included sediment load generated from upland erosion (Revised Universal Soil Loss Equation 2: RUSLE2) and delivery of that upland sediment to the stream network (derived from an index of connectivity), and their difference defined as upland trapping (Hopkins *et al* 2018, Chesapeake Bay Program 2018). Upland erosion models were not available for the Delaware River watershed. Mass balance estimated a residual, unmeasured term for the watershed budgets:

$$\begin{aligned} &\text{Streambank load} - \text{Floodplain load} + \text{residual} \\ &= \text{Stream load.} \end{aligned}$$

Chesapeake only:

$$\begin{aligned} &\text{Upland erosion} - \text{Upland trapping} \\ &+ \text{Streambank load} - \text{Floodplain load} + \text{residual} \\ &= \text{Stream load.} \end{aligned}$$

The nitrogen, phosphorus, and organic carbon loads attached to sediment were calculated as the

product of sediment load and either measured (streambanks and floodplains) or literature values of elemental concentrations on sediment (upland sediment and carbon content of suspended sediment; see supplemental information for details).

2.4. Data availability

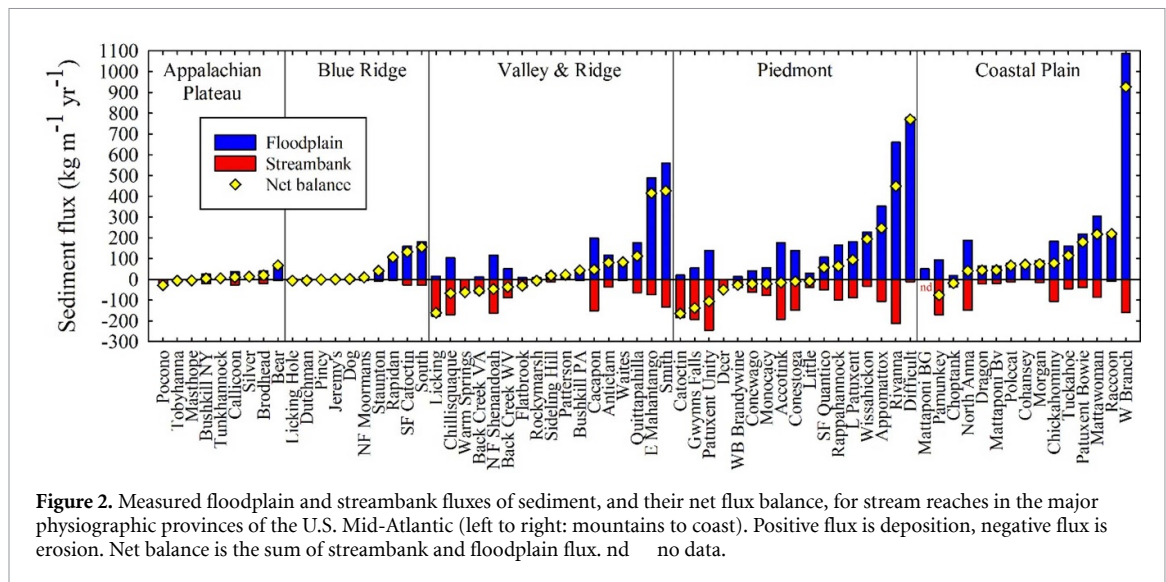
Field and laboratory measurements summarized for each measurement reach were published by Noe *et al* (2020b). Values of predictors assessed in the Random Forest models, and Random Forest predictions of streambank, floodplain, and streambed, and upland erosion and delivery to streams, for each NHDPlusV2 reach were published by Noe *et al* (2020c). Reach geomorphometry estimated by FACET were published by Hopkins *et al* (2020).

3. Results

3.1. Measurements of geomorphic change in streams

Active floodplain was present at most of the 68 U.S. Mid-Atlantic sampled stream reaches, with only three sites having less than 1 m of total lateral width of active floodplain. Dendrogeomorphic measurement indicated that regional floodplains changed vertically on average +0.26 cm yr⁻¹ (depositional) over the average 51 years of tree age (for sites with active floodplain), generating an average sediment flux of +130 kg m⁻¹ yr⁻¹ that was highly variable among sites (figure 2). The vast majority of sites with active floodplain had net vertical deposition, with only one site having vertical erosion and one site with no vertical change. Streambank was erosional over 49% of the sampling reach on average among sites. Streambank lateral erosion rates at the sampling locations with erosion and woody roots exposed within the reaches averaged -3.40 cm yr⁻¹ (erosional) across sites, integrated over the average 17 years since root exposure due to stream erosion. With correction for the percent of the reach that did not have erosional streambanks, the average rate was -1.66 cm yr⁻¹ (erosional) over the entire reach. This corrected lateral streambank erosion generated a sediment flux of -62 kg m⁻¹ yr⁻¹ that was moderately variable among sites (figure 2). The net balance (sum) of streambank and floodplain sediment fluxes in the reaches was depositional on average, +69 kg m⁻¹ yr⁻¹, with 41 net depositional sites (i.e. floodplain deposition > streambank erosion) vs. 26 net erosional sites (i.e. streambank erosion > floodplain deposition).

Measured net sediment flux balances along stream reaches (and their component streambank and floodplain fluxes) were generally small in the mountainous regions of the Appalachian Plateau and Blue Ridge, where streambanks were lower and less erosive and floodplains narrower, and larger and more spatially variable elsewhere (figure 2). Similar



to sediment, net balance fluxes of both fine sediment ($<63 \mu\text{m}$) and phosphorus attached to sediment were net depositional at 42 sites each (supplementary figure S1). In contrast, stream net balance fluxes of both organic carbon and nitrogen attached to sediment were more frequently and more strongly net depositional (46 sites each), due to higher organic content of sediment deposited on floodplains than eroded from streambanks.

3.2. Statistical modeling of stream geomorphic change

Geomorphic change and resulting fluxes were explained using Random Forests regressions with a combination of assessed predictors that included characteristics of both the entire upstream drainage area and local reach-scale geomorphometry. The best models had validation accuracy ranging from 58% for streambed fine and sand sediment cover to 10% for floodplain sediment-phosphorus flux (supplementary tables S1–S3). Average prediction accuracy was 28% for the various predictions for streambanks, 22% for floodplains, and 46% for streambeds. Although accuracy was low for some models, their predictive ability was still greater than applying averages of the geomorphic change and flux rates to unmeasured reaches. Some observations of extreme long-term floodplain deposition and streambank erosion rates were not well captured by the model predictions (figure 3); Random Forest models conservatively underpredict variability and ‘regress to the mean’ (Olson and Hawkins 2012).

Streambank lateral erosion rates and fluxes collectively were most strongly influenced by land uses (particularly the percent developed lands, pasture/hay/grassland, and wetlands), runoff, and drainage area of the entire upstream watershed, and only marginally influenced by the geomorphometry of the local stream reach (supplementary table S1). Of these

predictors, upstream drainage area and developed land use best explained streambank lateral rates of change (figure 4). Streambank sediment flux had many nonlinear thresholds to changing watershed attributes (supplementary figure S2), including a very large increase in streambank erosion (more negative flux) where developed land use exceeded 27% of the upstream watershed (figure 4). Note that these effects of individual predictors (shown in the partial plots) are independent of the other predictors included in the model.

Floodplain vertical change and fluxes also were best explained by many different upstream watershed metrics, including land use, drainage area, topography, runoff, dams, and geology, and by local reach geomorphometry (supplementary table S2, supplementary figure S3). Upstream drainage area and upstream developed land, and the width of floodplain in the local stream reach, had the most influence on rates of floodplain sediment flux. Floodplain sediment flux increased rapidly where developed land use increased to about 20% of the upstream watershed (figure 4). Like streambanks becoming more erosive, floodplains were more depositional with greater upstream contributing drainage area. Finally, sediment flux increased with active floodplain width up to a maximum rate at around 75 m total lateral width and then remained constant in wider floodplains.

Streambed percent cover by sand and fine sediment was most influenced by upstream watershed geography, and to a lesser degree by geology and land use (supplementary table S3). Streambeds were most covered by sand and fine sediment where watershed average Topographic Wetness Index was the greatest (larger drainage area upstream of flatter topography) (supplementary figure S4). Streambed sand and fine sediment cover also was greater where there was more cultivated cropland in the upstream watershed,

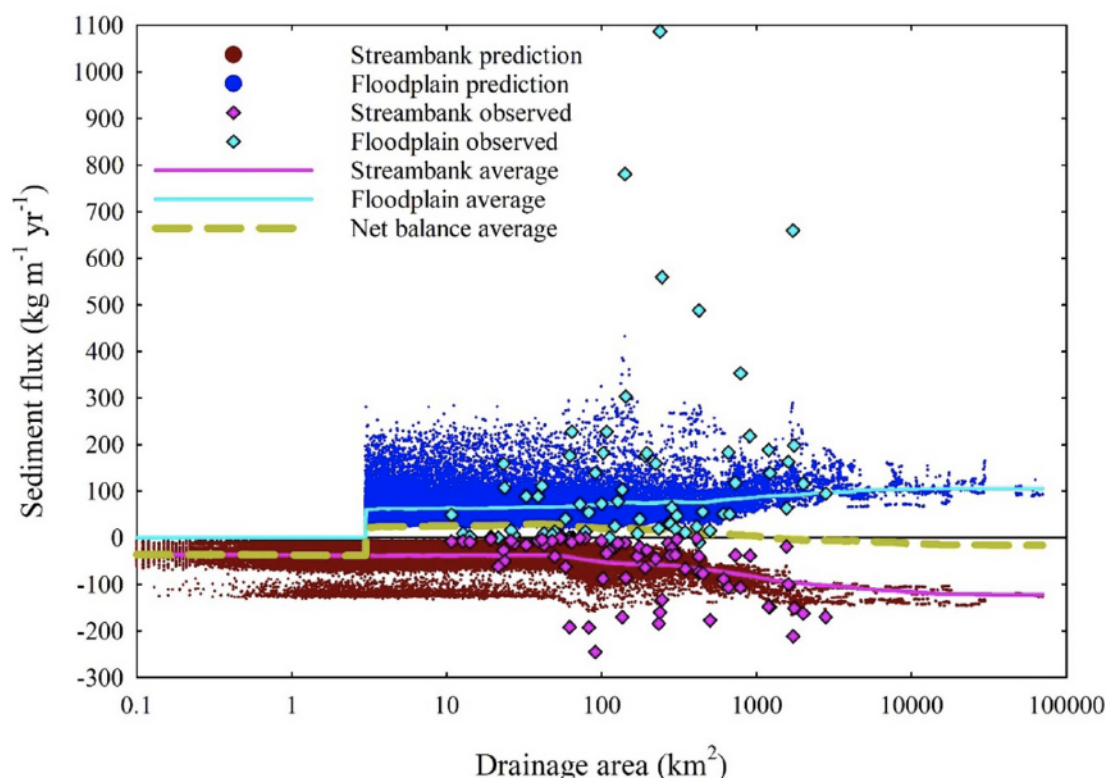


Figure 3. Distribution of measured and predicted fluxes of floodplain and streambank sediment, and their net balance, versus upstream drainage area for every NHDPlusV2 stream reach in the U.S. Mid-Atlantic that is nontidal, non-impounded, and non-channelized. Running averages of model predictions are shown. Positive flux is deposition, negative flux is erosion. X-axis is shown on a log scale.

and decreased where the ratio of floodplain width to streambank height in the local stream reach was greater.

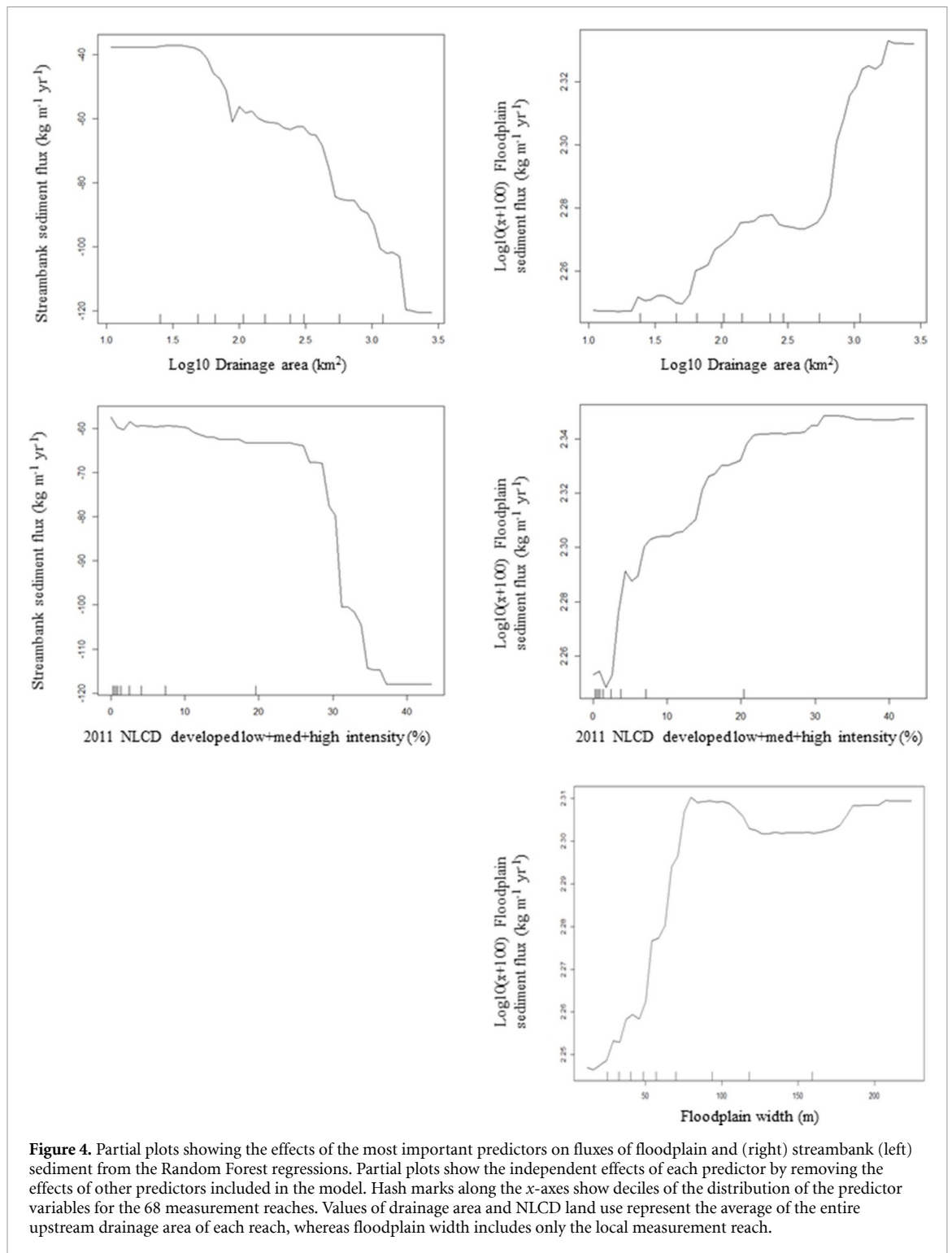
The Random Forest models were extrapolated to predict geomorphic changes at all 74 133 nontidal, non-channelized, and non-impounded NHDPlusV2 reaches in the Chesapeake Bay and Delaware River watersheds. These regional sediment fluxes averaged $+44.7 \text{ kg m}^{-1} \text{ yr}^{-1}$ for floodplain and $-44.8 \text{ kg m}^{-1} \text{ yr}^{-1}$ for streambanks (figure 3). In other words, the model predicted close to net balance of geomorphic sediment fluxes across the population of stream reaches of the U.S. Mid-Atlantic. For the subset of 26 348 reaches with less than 3 km^2 drainage area, floodplain flux was defined as a rule to be zero, but streambank flux averaged $-37.2 \text{ kg m}^{-1} \text{ yr}^{-1}$ and thus the smallest streams are net erosive. However, in the 47 785 reaches with drainage area greater than 3 km^2 , floodplain flux averaged $+69.3 \text{ kg m}^{-1} \text{ yr}^{-1}$ and streambank flux averaged $-48.9 \text{ kg m}^{-1} \text{ yr}^{-1}$ resulting in net depositional larger streams ($+20.5 \text{ kg m}^{-1} \text{ yr}^{-1}$). Minimum predicted net stream balance flux (most erosive; $-38.2 \text{ kg m}^{-1} \text{ yr}^{-1}$) occurred at drainage areas of 2 km^2 and maximum (most depositional; $+31.3 \text{ kg m}^{-1} \text{ yr}^{-1}$) occurred at 41 km^2 (figure 3). More streambank erosion occurred in reaches with more floodplain deposition ($r_s = -0.54$), indicating

that stream geomorphic change was a larger syndrome driven by watershed characteristics such as upstream land use and drainage area.

Subregions with both larger predicted streambank (more negative) and floodplain (more positive) fluxes included developed Piedmont and agricultural Valley and Ridge (figure 5). Portions of the mountainous Appalachian Plateau with mixed land use had large rates of streambank erosion but small rates of floodplain deposition. Conversely, the Coastal Plain generally had small streambank erosion and large floodplain deposition rates.

3.3. Watershed mass balance material budgets

Predictions of floodplain and streambank deposition and erosion loads were compared to existing statistical predictions of downstream suspended channel load for the entirety of the Chesapeake Bay and Delaware River watersheds (Ator 2019) and model predictions of upland erosion and delivery to streams (only available in the Chesapeake Bay watershed; Chesapeake Bay Program 2018) to create watershed material budgets. Sediment erosion sources in the Chesapeake watershed budget were determined to be 45% upland erosion delivered to the stream network, 28% streambank lateral erosion, and 27% from a budget mass balance residual term representing an unmodeled (additional) combined net erosion



source (figure 6). In the Delaware River watershed, where upland erosion model predictions were lacking, sediment erosion sources were 22% from streambanks and 78% from the budget residual term (also including upland erosion). At the scale of both the Chesapeake Bay and Delaware River watersheds, streambank erosion generated 21% of total sources of phosphorus and 6% of nitrogen sources, equivalent to 39%, 35%, and 6% of downstream channel loading of

suspended sediment, TP, and TN, respectively. Similarly, floodplain deposition was equivalent to 42%, 66%, and 12% of downstream channel load of suspended sediment, TP, and TN, respectively. Cumulative floodplain deposition load slightly exceeded streambank erosion load for the NHDPlusV2 stream network of the U.S. Mid-Atlantic. The exceedance of floodplain deposition over streambank erosion was small for sediment (floodplain load was 9% greater

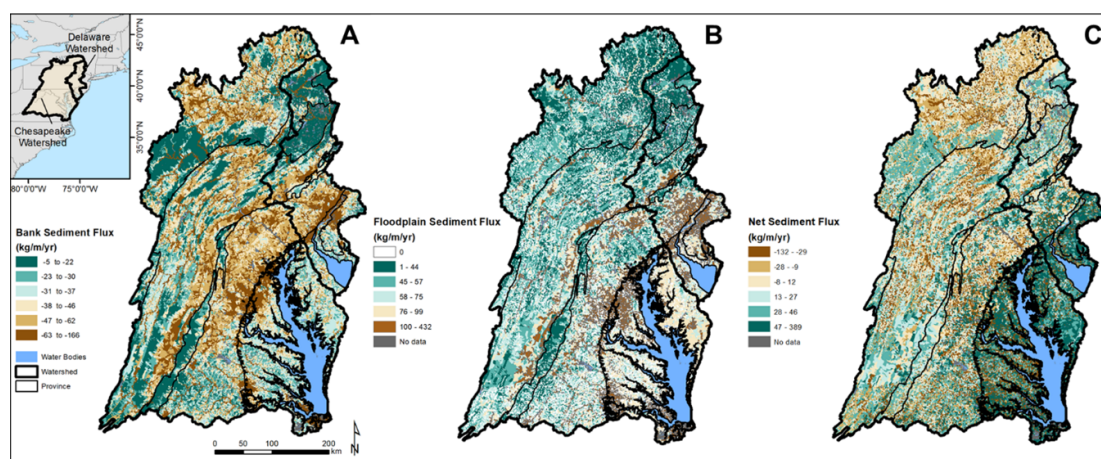


Figure 5. Maps of predicted (A) streambank, (B) floodplain, and (C) stream net sediment flux balance for each NHDPlusV2 reach in the Chesapeake Bay and Delaware River watersheds. Positive flux is deposition, negative flux is erosion.

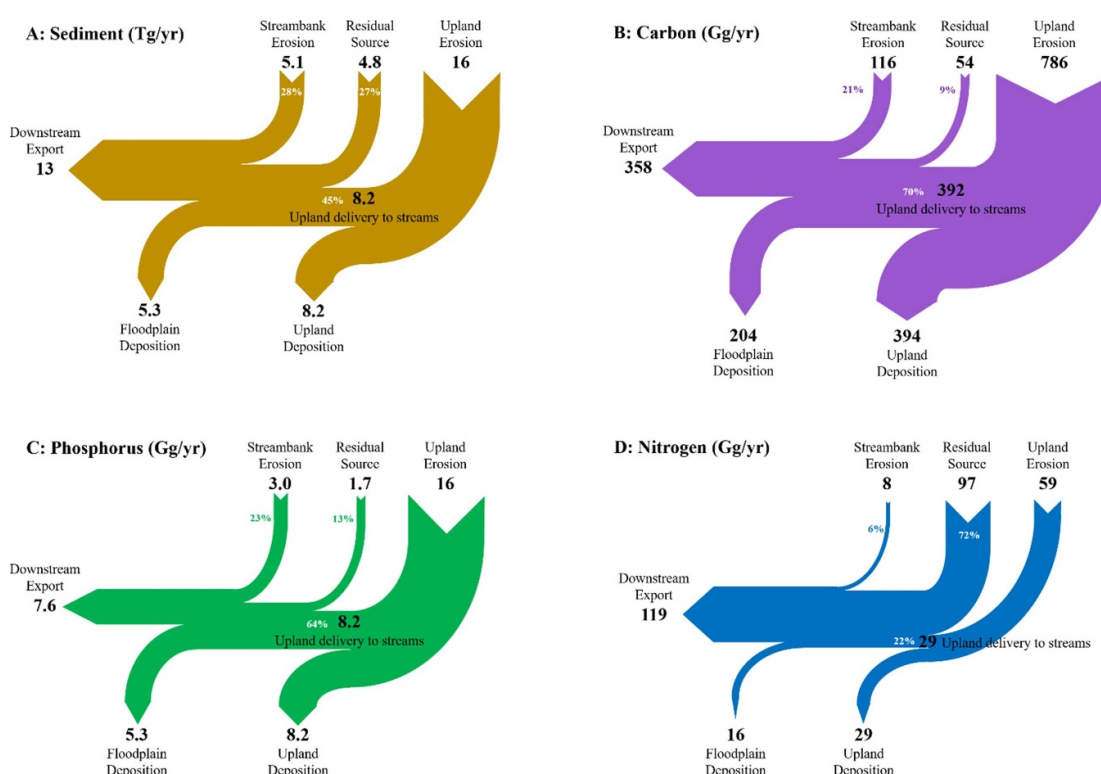


Figure 6. Watershed mass balance load budgets of (A) sediment, and attached (B) carbon, (C) phosphorus, and (D) nitrogen for the nontidal Chesapeake Bay watershed. Budget residual term is calculated from mass balance of estimated terms and includes all unestimated sources and sinks of both dissolved and particulate forms. Downstream export estimates total (dissolved and particulate) phosphorus and nitrogen loads and only particulate carbon loads (not including dissolved carbon). Percent contribution of sediment and elemental source terms are included.

than streambank load), but large for nitrogen, phosphorus, and organic carbon attached to sediment (96%, 85%, and 84%, respectively). In other words, floodplains have disproportionate impacts on nutrient and organic matter transport. However, geomorphic change in individual stream reaches had widely varying influence on downstream loads. Some of that variability is evident as differences in sediment budget terms across the major physiographic regions (supplementary figure S5).

4. Discussion

At a regional scale, measurements typically are too rare, and quantitative tools unavailable, to predict rates of geomorphic change in floodplains and streambanks and their influence on sediment and associated nutrient fluxes for all streams. This novel approach to combine widespread measurements using decadal-scale dendrogeomorphology with geospatial predictors of floodplain and streambank

change enabled small-scale prediction of the influence of stream geomorphic processes on watershed material budgets throughout the U.S. Mid-Atlantic. Emerging from the analysis are several new insights into watershed transport processes that improve understanding of watershed geomorphic change and can enable better targeting of best management practices intended to reduce downstream pollutant loading and restore local stream habitat quality (Novotny and Chesters 1989, Carbonneau *et al* 2012, Noe *et al* 2020a).

We first conclude that landscape variation in streambank erosion and floodplain deposition is most influenced by upstream land use, topography, and drainage area. This new information on the drivers and correlates of streambank erosion and floodplain deposition generates novel insights into a region with centuries of human disturbance and resulting altered fine sediment storage and fluxes (Noe *et al* 2020a). Many of the watershed attributes that were predictive of downstream streambank erosion are likely a proxy for the stream hydraulics and flow energy that erodes streambanks. Drainage area directly relates to stream power that influences the erosive energy available to cause channel geomorphic change (Church 2002), and developed and pasture land uses both have less soil infiltration that generates flashier stream flow in contrast to wetlands and forests (Bharati *et al* 2002, Hopkins *et al* 2015). Increasing urbanization, in particular, is a well-known cause of downstream channel change (i.e. the urban stream syndrome; Paul and Meyer 2001). Many studies that have related upstream development and imperviousness to stream health have identified thresholds of land use between 1%–15% (Schueler *et al* 2009, King *et al* 2011) that leads to degradation of stream aquatic biota, compared to the large increases in streambank lateral erosion that we found in watersheds with more than 27% development of the upstream watershed (equivalent to 14% impervious; regression using Noe *et al* 2020b). Other factors such as vegetation and sediment characteristics also have been shown to control streambank erosion at local scales (Nanson and Hickin 1986, Wynn and Mostaghimi 2006, Noe *et al* 2020a). Notably, stream channel-floodplain geomorphometry estimated for the local stream reach had relatively little predictive influence on regional streambank erosion rates in this study, but have been effective predictors within small watersheds (Schenk *et al* 2013, Hopkins *et al* 2018).

Floodplain vertical change also increased associated with metrics that relate to stream power (drainage area, Topographic Wetness Index, and development land use). These attributes could lead to greater amounts of overbank inundation at downstream floodplains (Scott *et al* 2019). Because those watershed attributes also increase streambank erosion, it is likely that increased sediment loads in the streams

also increase delivery of sediment to the floodplain during times of hydrologic connection. The geomorphometric shape of the local stream reach also explained floodplain deposition, similar to findings in smaller watersheds of the U.S. Mid-Atlantic (Schenk *et al* 2013). In particular, sediment retention increased as the width of active floodplain across the stream valley increased up to roughly 75 m. This is not surprising as a larger floodplain geomorphic surface is likely to support more sediment trapping. However, the lack of increasing sediment flux by floodplains wider than 75 m suggests that delivery or deposition is minimal to interior areas of floodplain more distant from the sediment loads of the stream channel or adjacent uplands (Mertes 1997).

Second, regional sediment is eroded from a mixture of sources over decadal time scales, including upland sheetwash erosion, streambank erosion, and unknown sources. That unknown source of sediment was derived as a mass budget residual term after accounting for the other terms in the budget, and its magnitude highlights the need for additional research. Unmodeled sediment erosion sources in that budget residual is likely attributable to erosion of gullies and headwater streams smaller than the mapped NHDPlusV2 stream network, vertical incision of streambeds following watershed disturbances (Madej and Ozaki 1996), and erosion of streambanks behind former milldams (Walter and Merritts 2008). In the Chesapeake, streambank erosion as percent of total sediment sources in our hybrid statistical-simulation modeled budget is intermediate compared to widely varying empirical estimates of streambank sources from sediment fingerprinting studies in small watersheds (Noe *et al* 2020a). Elsewhere, similar hybrid budgeting approaches applied to disturbed landscapes identified that near-channel erosion was the dominant source of downstream sediment load that represented an effective target for management (Cho *et al* 2018). However, in landscapes with large amounts of historic human disturbance, continued erosion of sediment storage zones can lead to long-term elevated sediment loading even after the implementation of management practices that reduce contemporary erosion of soils (Trimble 1999).

Third, the equivalent mass of sediment that is eroded from streambanks in upstream portions of watersheds in the disturbed U.S. Mid-Atlantic region is deposited downstream where nontidal floodplain trapping is active. Active floodplain trapped material throughout the regional landscape but greatest rates were found in the Piedmont, where sediment yield is large, and the Coastal Plain, where lowlands are extensive and flat (Noe *et al* 2020a), providing valuable ecosystem services (Costanza *et al* 1997). The net balance of stream sediment loads changed from erosional to depositional as the landscape flattened,

from moderately erosional in the Appalachian Plateau, to slightly depositional in the Piedmont, to strongly depositional in the Coastal Plain, supporting prior conceptual models and measurements of smaller scales that highlight the role of topography in determining sediment balance (Hupp 2000, Portenga *et al* 2019). Floodplain trapping rates increased with drainage area, likely due to increasing duration and volume of floodplain inundation (Scott *et al* 2019). Deposition of sediment in downstream floodplains can offset upstream streambank erosion of legacy sediment stored in floodplains (Wohl *et al* 2015), and obscure or overwhelm the effects of decreasing upland erosion through time due to implementation of soil best management practices (Trimble 1999, Smith and Wilcock 2015). In fact, most sediment eroded from upland soils in disturbed watersheds is stored in colluvium or floodplains for very long times (Costa 1975, Walter and Merritts 2008, Pizzuto *et al* 2017). The integrated time scales measured through dendrogeomorphology (from about 20–50 yrs in this study) likely dampened the detection of extreme runoff events that can generate most geomorphic reworking of fluvial sediments and could lead to short-term imbalance of streambank erosion and floodplain deposition.

Fourth, geomorphic changes in stream valleys also have large impact on nutrient transport processes in watersheds. Nitrogen and phosphorus loading to streams through streambank erosion can have a large role in watershed sources of pollutants (Fox *et al* 2016, Jiang *et al* 2020), whereas floodplain deposition of sediment-bound nitrogen, phosphorus, and carbon leads to substantial removal from flowing waters (Hoffmann *et al* 2009, Noe and Hupp 2009, Sutfin *et al* 2016). Geomorphic change in stream valleys had a much larger effect on phosphorus than nitrogen watershed budgets, which is not surprising given the predominance of dissolved nitrogen loads versus particulate phosphorus loads in the Mid-Atlantic (Noe *et al* 2020a). Interestingly, regional floodplain deposition strongly exceeded streambank erosion of C, N, and P due to the enrichment of nutrients on deposited floodplain sediment compared to eroding streambank sediment and not due to differential sediment fluxes. This nutrient enrichment of depositing floodplain sediment could be due to large increases in watershed nutrient inputs since the mid-20th century compared to prior centuries (Brush 2009) when most stream valley sediment was deposited. Storage and sequestration in floodplain soils is also vital to fluvial carbon dynamics and storage (Sutfin *et al* 2016) and our regional estimation of long-term annual sequestration rates highlights the importance of floodplain deposition to watershed carbon budgets.

In conclusion, these findings highlight the influence of geomorphic change by floodplains and their streambanks on sediment, nutrient, and carbon contributions at regional scales, with relevance

to other geographic settings with intensive human land use. Identification of the effects of streambank erosion and floodplain deposition on regional watershed mass balances, although notoriously difficult, is essential for improved understanding of stream geomorphic change and effective targeting of watershed management programs. The combination of new systematic data collection on stream valley geomorphic change, and statistical explanation and extrapolation using geospatial data on watershed and stream attributes, along with other process and statistical models, can enable prediction of geomorphic change at the scale of stream reaches throughout large regional watersheds.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.5066/P93OUWYZ>.

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Conflict of interest

Authors declare no competing interests.

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