Estimating Nutrient Loads from Two Streambank Erosion Sites on the West Branch Delaware River, Delaware County, New York

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Abstract

In 1994, the New York State Department of Environmental Conservation identified the Cannonsville Reservoir and its source water, the West Branch Delaware River (WBDR), as priority water bodies in need of Total Maximum Daily Load (TMDL) development for total phosphorus (TP). The phosphorus reduction efforts that followed were largely successful. The Cannonsville Reservoir was removed from the phosphorus restricted list in 2002 and the WBDR was removed from the NYS 303(d) impaired list in 2004. However, 2019 records of elevated median annual TP concentration of the WBDR along with a return of the Cannonsville Reservoir to near-eutrophic levels indicate that TP loading issues may not be resolved.

DCSWCD sought to estimate the volume of sediment and mass of TP and total nitrogen (TN) loaded from two locations, 2.3 kilometers apart, on the WBDR where streambank erosion was thought to be severe. It was hypothesized that these locations of severe streambank erosion contributed substantially to the overall nutrient load of the Cannonsville Reservoir between 2009 and 2019.

In order to estimate sediment load volumes and nutrient load masses due to streambank erosion at the study sites, three approaches were combined: the first was an analysis of eroded land volume; second, soil nutrient concentrations and physical properties at the affected locations were measured; and third, these data were combined to estimate nutrient load masses introduced to the river. In a 10-year period it was estimated that 33,000 metric tons of soil, 49 metric tons of TN, and 9.3 metric tons of TP were loaded into the WBDR from the two study sites. The average TP loading rate of 930 kg/yr from these sites amounts to 2.1% of the non-point source TP load, and 1.7% of the total TP TMDL for the Cannonsville Reservoir.

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Introduction

The Cannonsville Reservoir, located in Delaware County, NY, is the third largest of New York City's reservoirs with a capacity of 362 billion L (95.7 billion gal; NYCDEP, 2021). The 19 km (12 mi) long reservoir has an average depth of 19 m (61 ft) and area of 1,903 ha (4,703 ac; NYSDEC, 2014). In 1994, the New York State Department of Environmental Conservation (NYSDEC) identified the Cannonsville, among other New York City reservoirs, as a priority water body in need of Total Maximum Daily Load (TMDL) development for phosphorus (NYSDEC, 2000). In 1997, Phase 1 TMDLs were set for the Cannonsville Reservoir requiring phosphorus concentrations not to exceed 20 µg/L, a standard which was reaffirmed in 2000 with a Phase II TMDL (NYSDEC, 2000). The 2000 NYSDEC report states that the specific 20 µg/L concentration limit was determined as a threshold "to protect primary and secondary contact recreational uses from impairment due to aesthetic effects," also stating that the limit "indirectly provides considerable protection for the drinking water use by limiting eutrophication."

Because of far-reaching regulations resulting from the TMDL and the City's filtration avoidance determination, substantial efforts were implemented to limit the release and conveyance of phosphorus across the Cannonsville Reservoir's watershed. These efforts included construction of advanced wastewater treatment plants and improved management of agricultural practices and stream corridors, among others. The phosphorus reduction efforts were largely successful and the WBDR was subsequently removed from the 303(d) list in 2004 with total phosphorus concentrations in the river and reservoir persisting around 15 µg/L (Hoang et al., 2019; NYCDEP, 2017). However, 2019 records of elevated median annual total phosphorus (TP) concentration of the WBDR along with a return of the Cannonsville Reservoir to near-eutrophic levels indicate that phosphorus loading issues may not be resolved (NYCDEP, 2020).

One nutrient influencing factor that has been difficult to quantify due to its episodic and non-point source nature is streambank erosion (Knighton, 1998). Computer models such as the "Soil and Water Assessment Tool" (SWAT) have made great strides to estimate sediment and nutrient flux from the landscape since its development in the early 1990s (Gassman et al., 2007). However, implementation of SWAT in the WBDR watershed distilled the chaotic mechanisms of streambank erosion into two simplistic factors, calibrated by an anecdotal estimate of sediment loading due to streambank erosion (Tolson et al., 2000). The SWAT model has continued to improve with the addition of increasingly realistic channel variables yet, the model still lacks empirical streambank erosion data (Arnold et al., 2012). Recent efforts by the Delaware County Soil and Water Conservation District (DCSWCD) made attempts to more accurately quantify nutrient loads due to streambank erosion, beginning with two case studies of severe streambank erosion along the West Branch Delaware River.

The DCSWCD, as dictated by New York State Soil & Water Conservation Districts Law, has the ability "to conduct surveys, investigations, and research relating to the character of soil erosion, floodwater, sediment damages, nonpoint source water pollution…" (NYS, 1940). In addition, a contractual partnership with New York City Department of Environmental Protection (NYCDEP), entrusts the DCSWCD to manage streams and stream corridors within the New York City watershed of Delaware County, NY. As such, the DCSWCD has long sought to investigate and document sources of erosion along waterways. In recent years, the DCSWCD observed the excessive streambank erosion of agricultural fields at certain locations along the WBDR. These instances have been driven by tributaries carrying excessive bedloads of gravel and cobble to the main stem of the WBDR (Gladstone et al., 2006). These materials persist as depositional features for years where the WBDR is incapable of transporting the added sediment effectively. Gladstone et al. detailed this process in the West Branch Delaware River Management Plan:

> The processes of stream erosion and deposition go together. If the stream cannot carry the available sediment load, then some sediment will drop out — raising the streambed. The stream widens in response to this — causing bank erosion — since it needs a certain cross sectional area to convey its discharge. As a result of aggradation and widening more of the stream bank is exposed to flood flows. Especially in the absence of riparian vegetation that could otherwise hold banks in place, this encourages further erosion and increases the sediment load that the stream must move. A spiral of events begin, the result of which is the destabilization of the stream. While in theory a stream will stabilize or reach a new equilibrium condition over time, the time required may be very long, and the stream will not stabilize if the disturbance that caused the destabilization persists. (Gladstone et al., 2006)

Due to the District's focus on water quality improvement, the DCSWCD sought to estimate the volume of sediment and mass of TP and total nitrogen (TN) loaded from two locations where erosion due to these processes was most severe. It is hypothesized that these locations of severe streambank erosion contributed substantially to the overall nutrient load of the Cannonsville Reservoir.

This study evaluated streambank erosion that occurred between 2009 and 2019 from two sites that are 2.3 km (1.4 miles) apart on the West Branch Delaware River (Figure 1). Birdsong farm is located 2.4 km (1.5 miles) north of Delancey, NY; the 283 m (929 LF) of active streambank erosion that was investigated occurred at a hay field without riparian forest tree cover. Erosion at Birdsong farm is driven by extreme near-bank stress due to increasing deposition around an in-stream island opposite the eroding right streambank.

River Haven Farm experienced similar streambank erosion issues just upstream of the hamlet of Delancey, NY. The right streambank had 404 m (1,326 LF) of active erosion with a left bank section of 84 m (275 LF) that had eroded. The land use consisted of 380 m of continuous corn (right bank), 24 m of wetland (right bank), and 84 m of hay field (left bank). Neither bank had riparian forest tree cover. A tributary known as Bagley Brook meets the WBDR directly across from the eroding continuous corn field where it has built a delta bar. The delta bar has grown in size between 2009 and 2019. Consequently, the river's hydraulics have been altered in a way that has caused excessive erosion to continue. Presence of this growing delta bar has resulted in the near-bank stress rating on these eroding streambanks to be assessed as extreme.

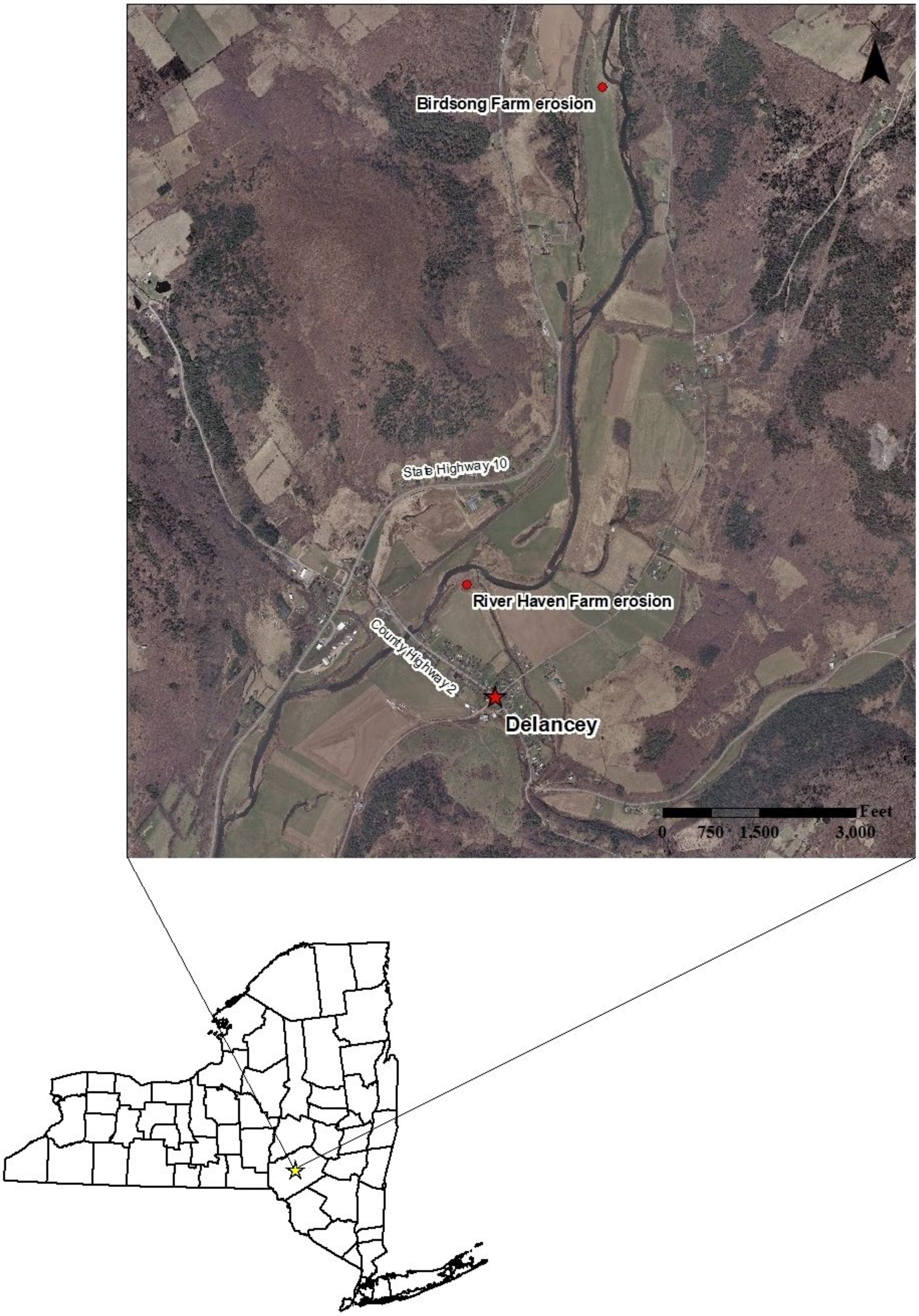

Figure 1: Location map showing the study sites at River Haven and Birdsong Farms near the hamlet of Delancey, NY.

Figure 2: Photograph of streambank erosion at Birdsong Farm in 2019 (looking upstream).

Figure 3: Photograph of streambank erosion at River Haven Farm in 2019 (looking upstream).

Methods

In order to estimate sediment load volumes and nutrient load masses due to streambank erosion at the study sites, three approaches were combined: the first was an analysis of eroded land volume; second, soil nutrient concentrations and physical properties at the affected locations were measured; and third, these data were combined to estimate nutrient load masses introduced to the river.

Sediment volume estimation

The migration of the WBDR's eroding banks were measured in ArcGIS using 2009 orthoimagery superimposed with global positioning system (GPS) points that surveyed the 2019 location of the river's streambank. Streambank locations, as of 2009, were delineated by tracing their extents in 2009 orthoimagery using the "create a feature" tool in ArcGIS. Streambank positions, as of 2019, were recorded in the field using a Trimble Geo7x handheld data collector. Positions were recorded at every break in planform and elevation of actively eroding streambanks within the study area; this allowed for the accurate survey of the position of the streambank. GPS positions were then post-processed using data from the closest New York State DOT GPS base station.

Once the 2009 and 2019 streambank locations were delineated, the eroded area between the streambank positions was digitized into shapefiles within ArcGIS. Finally, the area of these shapefiles was calculated using the "calculate geometry" tool within ArcGIS.

Eroded areas were further subdivided into mappable units based upon the Natural Resources Conservation Service's (NRCS) Delaware County, NY, soil survey which classifies soils into distinct soil map units or types (NRCS, 2019). The Birdsong Farm study site has one soil type while the River Haven Farm site has four soil types.

Bank heights were measured to the nearest tenth of a foot with a stadia rod at each GPS point in order to document changes in streambank elevation. The third dimension of bank height was introduced to estimate eroded sediment volumes. Average bank heights were calculated for each segment between recorded GPS points. For each plot, a weighted average height was calculated from the individual segments according to Equation 1 where $\bar{h}$ is overall segment weighted average bank height, h_i is average bank height of an individual segment, and l_i is the length of an individual segment.

$$\overline{h} = \sum_{i=1}^{n} \mathrm{h}_i l_i / \sum_{i=1}^{n} l_i \qquad \text{(Equation 1)}$$

It was assumed that a) bank heights in 2009 were the same as they were in 2019 and b) that the floodplain/agricultural field and streambed elevations were consistent elevations, laterally, through the eroded area. While this cannot be verified, as we have no bank height measurements from 2009, 1-meter DEM from 2009 shows that floodplain elevation was consistent enough with 2019 bank elevations that the analysis could proceed. With an eroded area per plot and corresponding weighted average bank height ($\overline{h}$), an eroded volume can be calculated by Equation 2 where V_S is eroded soil volume, and A_S is eroded soil area.

$$V_S = A_S * \overline{h} \qquad \text{(Equation 2)}$$

Soil sampling

Topsoil (top 0.2 m of the soil profile) and subsoil (0.2 m depth and below; total bank height varied from 0.4 to 2.4 m) composite samples were collected at each segment of bank erosion for each soil type. Considering the historical agricultural use of the study plots, we expected that topsoil would differ from subsoil in physical and chemical characteristics due to many decades of tillage, rock picking, and manure and fertilizer incorporation. Nutrient concentrations were expected to be substantially greater in topsoil samples than in subsoil samples.

Soil samples were taken at 15 m (50 ft) intervals along eroded bank segments for each distinct soil type. The eroded bank-face sample locations were scraped back to expose a clean soil profile before sampling. Samples were thoroughly mixed in a bucket to form the composite sample representing each soil type and then taken to Adirondack Environmental Services, Inc. in Albany, NY, for analyses. One to three kg of soil were collected for each composite sample; a single 200 mL jar was filled to represent each sample. A total of twelve composite samples from six bank erosion locations were collected and analyzed in October and November of 2019. This sampling methodology was selected in order to capture differing nutrient concentrations resulting from differences in land use and soil properties, with budgetary constraints for time and cost.

Total phosphorus (TP) was determined through Standard Method 4500-P-E, while total nitrogen (TN) was determined using SW-846 test method 9056A for nitrate and nitrite, and Standard Method 4500-N C for total Kjeldahl nitrogen.

Bulk density samples were collected for topsoil and subsoil at each segment of bank erosion for each soil type through the use of bulk density sampling rings of known volume. Bulk density rings with a volume of 90.59 cm^3 were tapped into representative faces of the streambank soil profile using a piece of dimensional lumber and a hammer (the dimensional lumber ensured that the force of the hammer was evenly distributed over the rim of the ring so that an unskewed cross-section of the soil profile could be obtained). The bulk density ring containing the sampled soil was then excavated from the bank and the protruding soil from each end was scraped flush with a straight edge. Twelve bulk density samples were collected in total. Samples were heated in a microwave oven in 5-minute increments until the sample mass stopped decreasing, indicating that the sample had dried. Bulk density was calculated by Equation 3 where ρ_B is bulk density, M_S is the dry mass of soil, and V_S is volume of the soil.

$$\rho_B = M_S / V_S \qquad \text{(Equation 3)}$$

Bulk density allows for the conversion of soil volume to soil mass by Equation 4 where the preceding variables are rearranged:

$$M_S = \rho_B * V_S \qquad \text{(Equation 4)}$$

Once samples were removed from the collected composite for nutrient analysis, the remaining soil was analyzed for particle size to determine the fraction of soil less than 2 mm in size. This fine earth (F-E) fraction was assumed to contain the major portion of material that nutrients were adsorbed to and present in. F-E sized fraction is the common size of sediment analyzed for phosphorus content in soils (Pierzynski, 2000). The F-E fraction has also been the focus of studies into in-channel stream sediment phosphorus content and other studies of phosphorus loading due to streambank erosion (Klotz, 1985; Ross et al., 2018). In addition, the F-E fraction is the size class of sediment load in rivers carried in the water column and known as "suspended sediment" (Gray et al., 2000; Rosgen, 2009). This process was performed by DCSWCD staff using a modified version of ASTM method D422-63 (ASTM, 2007). Soil moisture was removed using a microwave instead of a drying oven. In addition, sieves that sorted material larger than 2 mm varied slightly in size from specified ASTM sieves. It was also unnecessary to separate soils into smaller fractions once they passed the #10 (2 mm) sieve. Sieves were hand shaken until materials were fully sorted. A minimum of 1 kg of soil was processed for each sample. The mass of the fine earth fraction was then determined as a fraction of the whole soil mass.

Nutrient load estimation

With known soil volume, bulk density, mass of fine earth fraction, and soil nutrient concentration, mass of TP and mass of total TN could then be calculated by Equation 5 and Equation 6, respectively, where M_{TP} is mass of TP, C_{TP} is concentration (in mass per unit mass) of TP, M_{TN} is mass of TN, C_{TN} is concentration of TN, and M_F is mass of fine earth fraction. Mass of eroded TP and TN was then calculated for each erosion plot.

$$M_{TP} = C_{TP} * M_F \qquad \text{(Equation 5)}$$

$$M_{TN} = C_{TN} * M_F \qquad \text{(Equation 6)}$$

Results

Soil types and study plot delineation

Superimposition of the NRCS soil survey in ArcGIS allowed for the delineation of study plots based on soil type. It was determined that River Haven Farm had bank erosion at five distinct soil map units (Table 1 and Figure 4). Soil units included Barbour loam (map symbol Bc), Barbour-Trestle complex (Bg), Basher silt loam (Bs), and Fluvaquents-Udifluvents complex (Ff). Barbour loam was present in two plots, RIV-1 and RIV-3. These plots were sampled and delineated as two separate plots due to their separation by the Basher silt loam map unit. RIV-4 appears to span the Barbour Loam and Fluvaquents-Udifluvents complex, but for this study was considered a closer fit to Fluvaquents-Udifluvents complex after assessment of topography and wetland characteristics in the field.

Streambank erosion at Birdsong Farm occurred within a single Barbour loam map unit. As such, the study area was initially considered a single plot (Table 1 and Figure 5).

Birdsong and River Haven sites each have one plot, RIV-1 and BIR-1, that were comparatively larger than the others in area and length. The significantly larger plot at RIV-1 plot was subdivided in two plots while the lone BIR-1 plot was subdivided into three plots. These subdivisions reduced the length of erosion at each plot subdivision and allowed for a more representative weighted average bank height to be used in volume calculations. Because these plots were defined by a single soil map unit, it was assumed that their physical and chemical characteristics were uniformly distributed (i.e., one composite nutrient sample, one particle size fraction, and one bulk density represented the topsoil and subsoil of both RIV-1A and RIV-1B, however their actual eroded volume, mass, etc. would differ).

Table 1: Soil map units and NRCS surface texture ratings of study plots at River Haven and Birdsong Farms.

Study plot	Map unit name	Map unit symbol	Surface texture rating	Land use
RIV-1	Barbour loam	Bc	Loam	Corn
RIV-2	Basher silt loam	Bs	Silt loam	Corn
RIV-3	Barbour loam	Bc	Loam	Corn
RIV-4	Fluvaquents-Udifluvents complex, frequently flooded	Ff	Gravelly silt loam	Wetland
RIV-5	Barbour-Trestle complex	Bg	Loam	Hay
BIR-1	Barbour loam	Bc	Loam	Hay

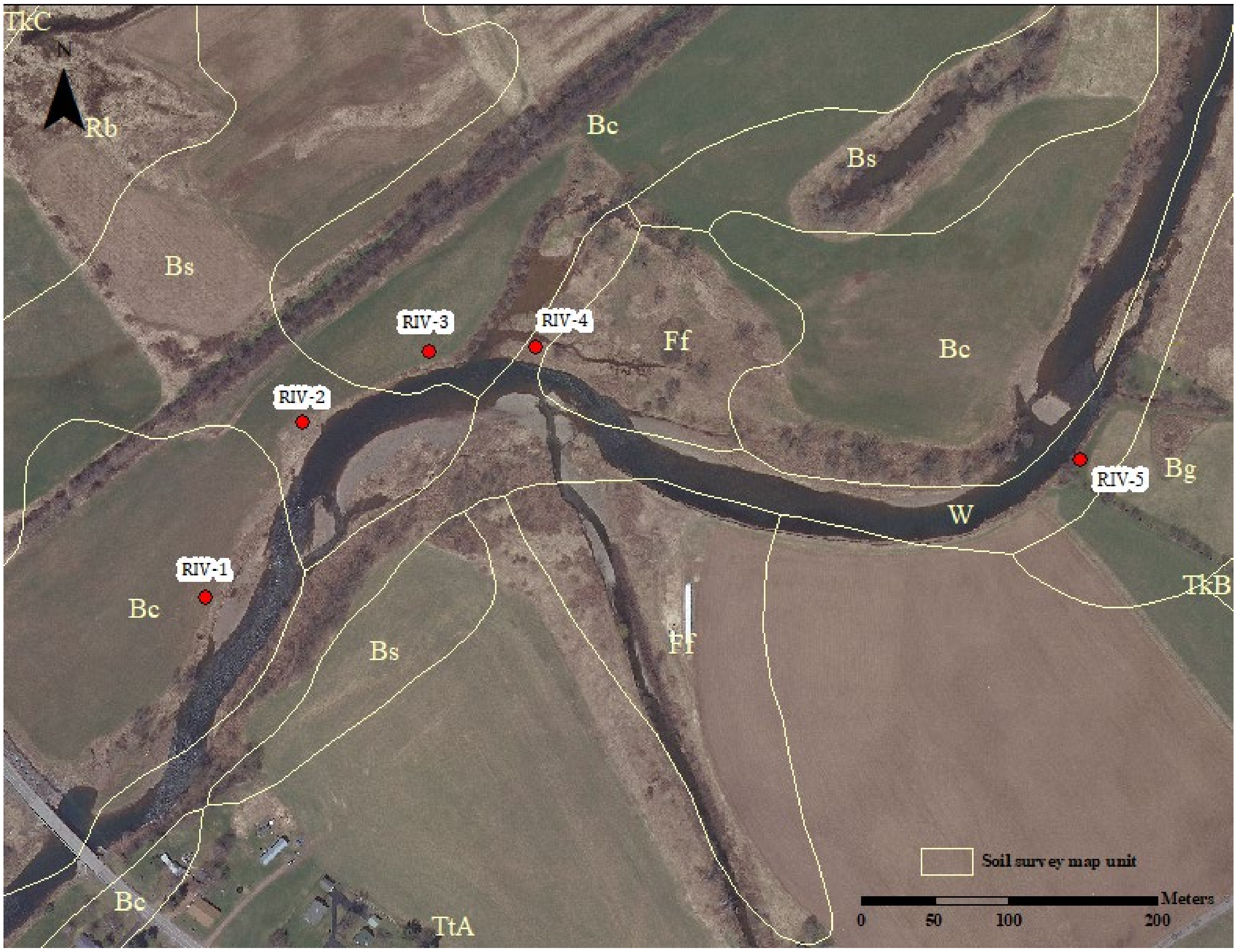

Figure 4: NRCS soil survey map showing soil map units and location of study plots (superimposed on 2009 orthoimagery) at River Haven Farm. Labels identify plots with a three-letter prefix "RIV" for River Haven and a number that increases leading upstream. Note: Soil delineations were originally compiled from orthographic images taken before 2000 (Day, 2021; NRCS, 2019). Lateral migration of the stream banks since then is evident.

Figure 5: Soil survey map showing soil map units and location of study plot (superimposed on 2009 orthoimagery) at Birdsong Farm. The label identifies the plot with a three-letter prefix “BIR” for Birdsong.

Spatial analysis

One hundred and five GPS points were recorded at River Haven Farm in three parts on 6/12/2019, 6/14/2019 and 6/20/2019. Fifty-seven GPS points were recorded on 6/20/2019 at Birdsong Farm. Precision of GPS points was verified by recording four control points on the County Highway 2 bridge in Delancey on bridge components that were readily identifiable on orthoimagery. Horizontal precision, a metric recorded by the GPS unit for each of the four points, was 0.2 m. These points all plotted on their intended positions when superimposed on 2009 orthoimagery and showed no measurable error at this scale.

Horizontal precision of points recorded at Birdsong and River Haven was very similar to that of the control points on the County Highway 2 bridge. The median horizontal precision of points at each location was 0.2 m. Precision was so consistent that first and third quartile values were also 0.2 m for points at each location. Six points at Birdsong Farm had horizontal precision values that were considered outliers, ranging from 0.3 m to 1.2 m (Figure 6). Three points at River Haven had horizontal precision values that were considered outliers. These precision values ranged from 0.3 m to 1.8 m (Figure 6). GPS points with horizontal precision values considered to be outliers were removed from the erosion delineation process and subsequent area calculations.

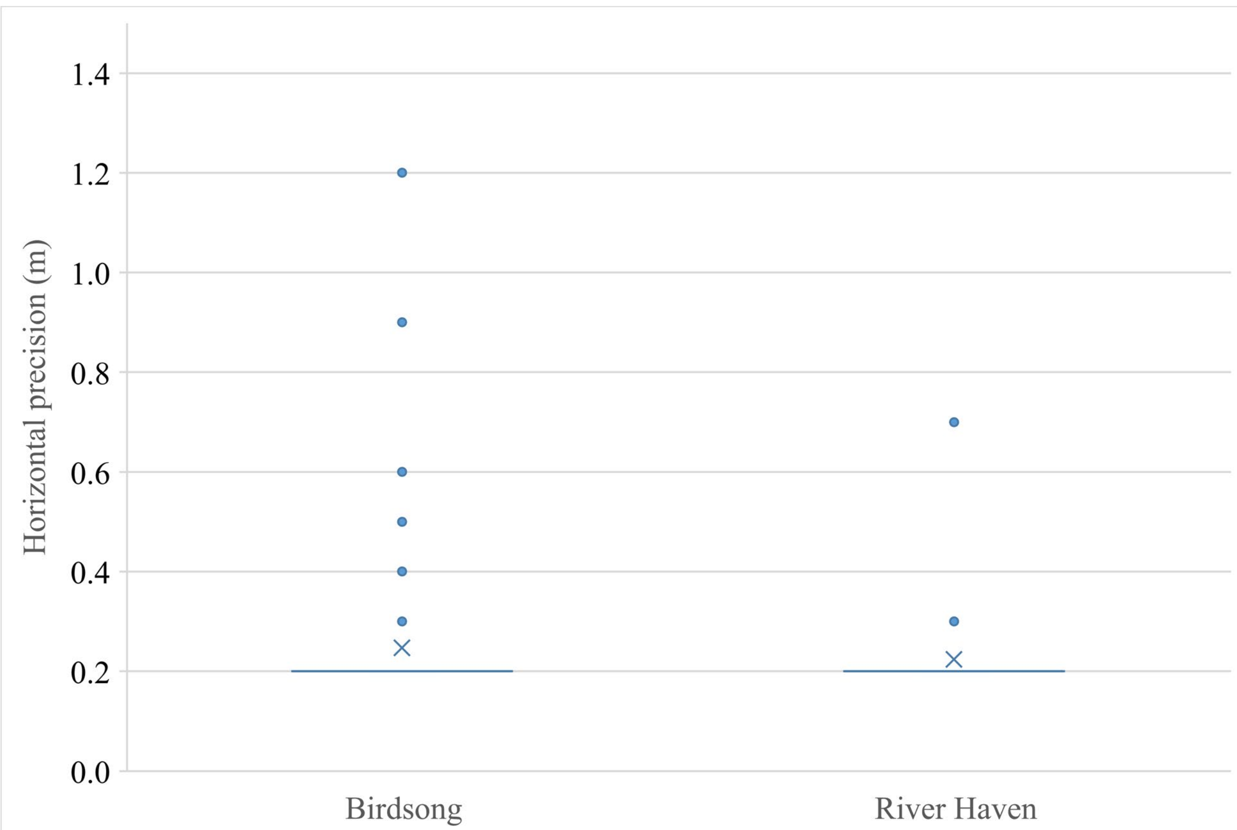

Figure 6: Boxplot of GPS point horizontal precision at Birdsong and River Haven locations.

Weighted average bank heights for River Haven plots ranged from 1.0 m to 1.4 m (Table 2). Total combined eroding bank length of these plots was 546 m. Total combined eroded area for River Haven plots was 9,200 m^2, equivalent to 0.92 hectares (2.3 acres; Figure 7). Total eroded volume of these plots between 2009 and 2019 was approximately 11,000 m^3 or, roughly, 926 16 yd^3 dump truck loads (Table 2).

Table 2: Compilation of soil map units, weighted average bank height, erosion length, erosion area, and erosion volume for River Haven Farms plots. Differences that arise between summation of individual plots and listed totals are due to significant figures.

Plot	**Soil Map Unit**	**Bank Height (m)**	**Erosion length(m)**	**Erosion Area (m^2)**	**Erosion Volume (m^3)**
RIV-1A	Bc	1.4	98	2.2E+03	3.0E+03
RIV-1B	Bc	1.0	101	2.3E+03	2.3E+03
RIV-2	Bs	1.2	77	1.2E+03	1.5E+03
RIV-3	Bc	1.4	105	1.4E+03	2.0E+03
RIV-4	Ff	1.1	68	1.3E+03	1.4E+03
RIV-5	Bg	1.4	97	8.5E+02	1.2E+03
Total	-	-	**546**	**9.2E+03**	**1.1E+04**

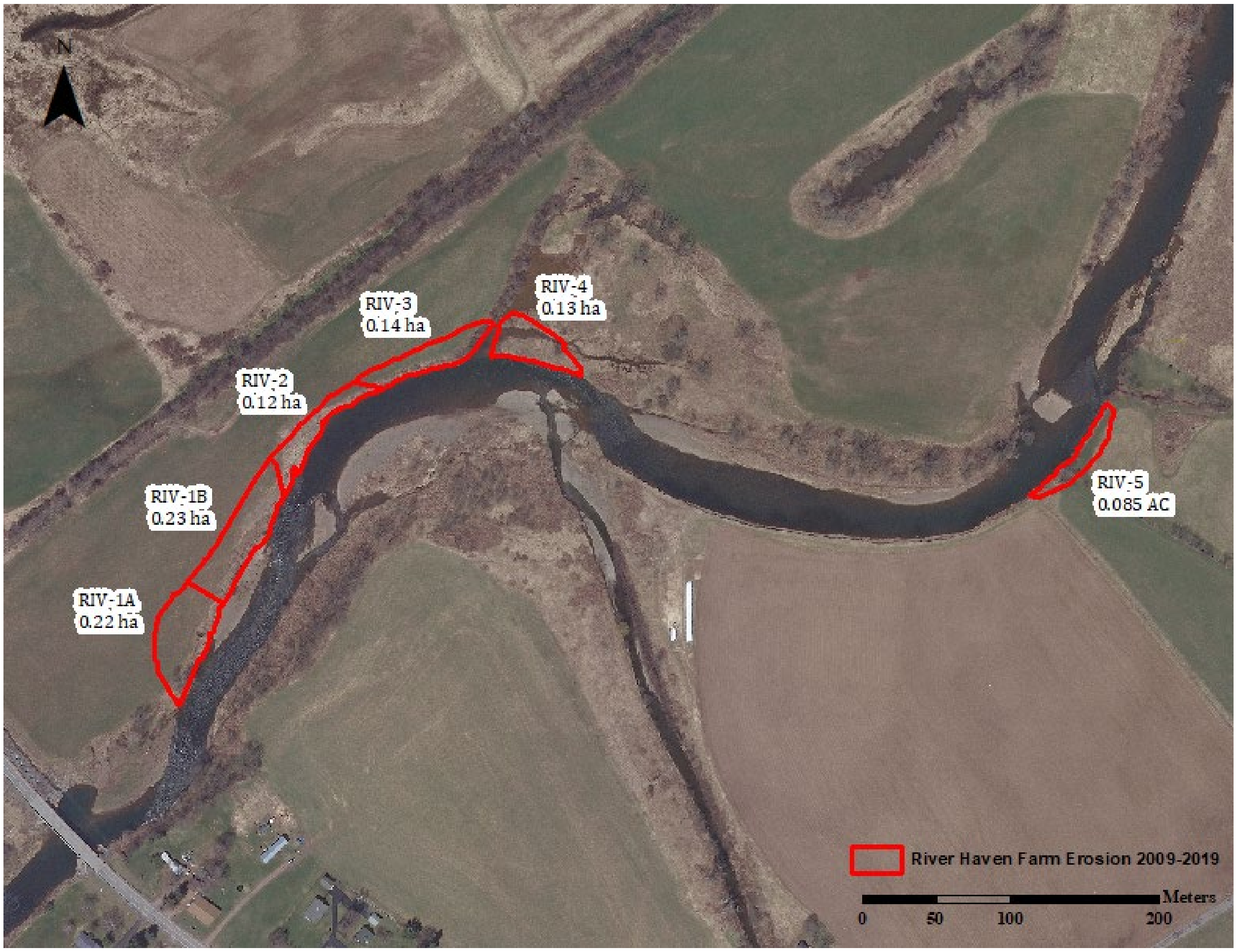

Figure 7: Superimposition of 2019 erosion extents on 2009 orthoimagery at River Haven Farm, with plot identification.

Birdsong Farm plots yielded weighted average bank heights that ranged from 1.2 m to 1.4 m (Table 3). Total combined eroded lengths for these continuous plots was 278 m. Eroded area of Birdsong plots totaled 8,900 m^2, or 0.89 hectares (2.2 acres; Figure 8). Total eroded volume of these plots between 2009 and 2019 was approximately 12,000 m^3, or roughly 995 16 yd^3 dump truck loads.

Table 3: Compilation of soil map units, weighted average bank height, erosion length, erosion area, and erosion volume for Birdsong Farms plots.

Plot	Soil Map Unit	Bank Height (m)	Erosion length (m)	Erosion Area (m^2)	Erosion Volume (m^3)
BIR-1A	Bc	1.4	100	5.4E+03	7.6E+03
BIR-1B	Bc	1.3	93	2.9E+03	3.7E+03
BIR-1C	Bc	1.2	85	6.2E+02	7.7E+02
Total	-	-	**278**	**8.9E+03**	**1.2E+04**

Figure 8: Superimposition of 2019 erosion extents on 2009 orthoimagery at Birdsong Farm, with plot identification.

Fraction of fine-earth sediment

Topsoil F-E fraction ranged from 0.805 to 0.978 with an average of 0.903 and median of 0.915 (Figure 9). Subsoil F-E fraction ranged from 0.359 to 0.897 with an average of 0.626 and a median of 0.605. Three subsoils had F-E fraction of less than 0.500. These were subsoils of RIV-1, RIV-2, and RIV-3.

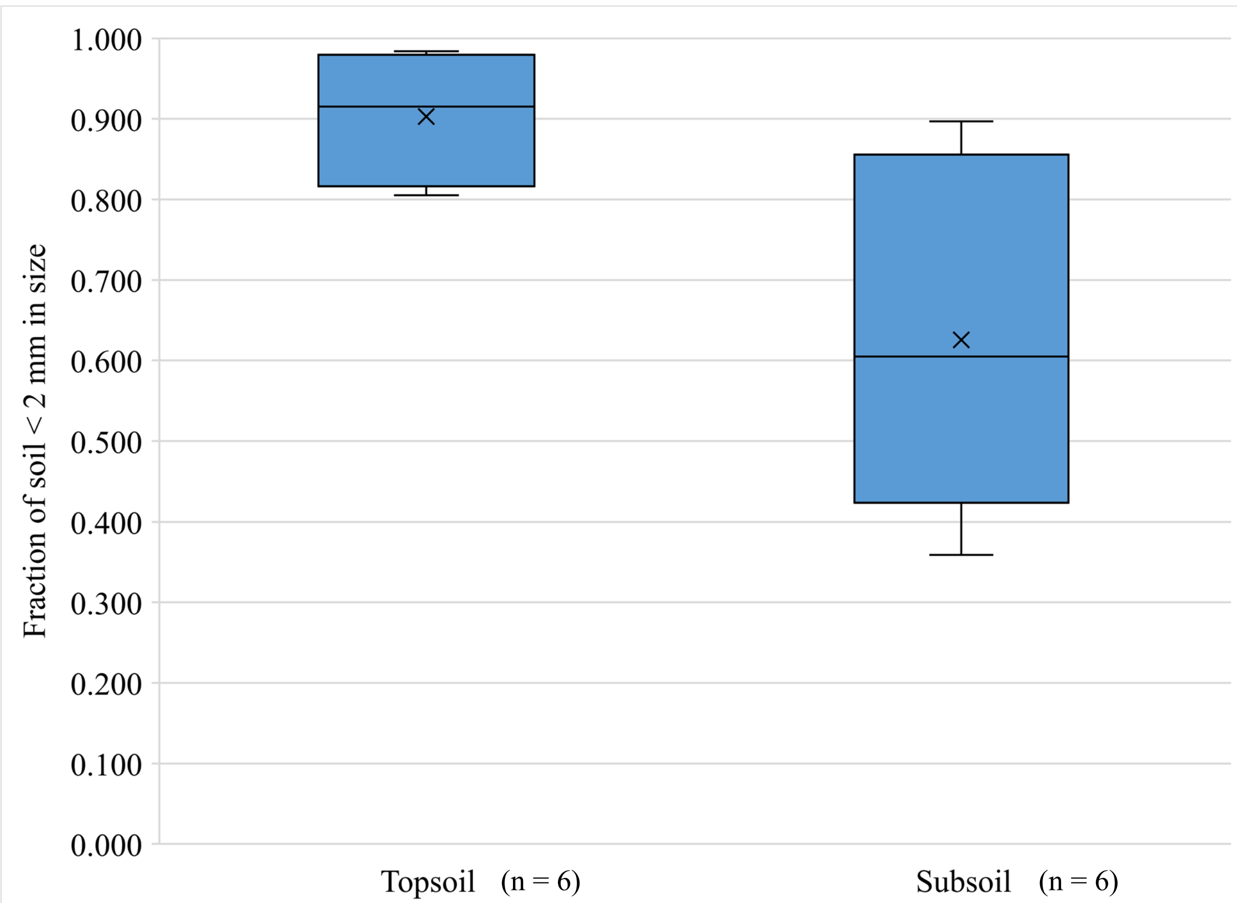

Figure 9: F-E fractions of topsoil and subsoil samples for all study plots.

Bulk density

Study plot topsoil bulk density ranged from 1.3 g/cm^3 to 1.58 g/cm^3 with a median of 1.50 g/cm^3 and a mean of 1.46 g/cm^3 (Figure 10). Subsoils ranged from 1.28 g/cm^3 to 1.47 g/cm^3 with a median of 1.40 g/cm^3 and a mean of 1.39 g/cm^3.

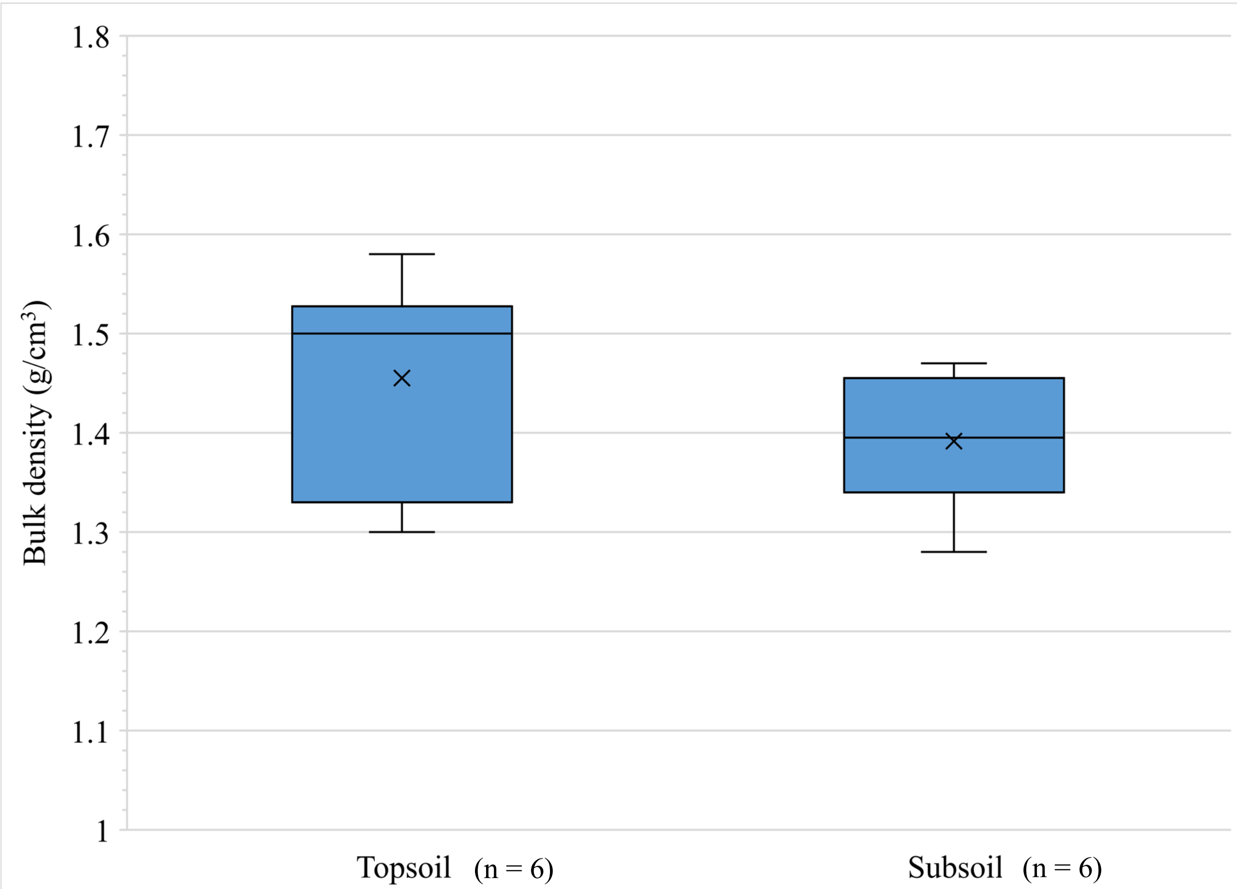

Figure 10: Boxplot of topsoil and subsoil bulk densities at all study plots.

With the exception of RIV-3, all topsoil bulk densities were greater than subsoil densities within the same plot. This relationship may be due to the historical agricultural land use of these plots. Tillage occurs in the topsoil layer and tends to result in soil compaction, increasing bulk density.

Nutrient concentrations

Twelve total composite soil samples were analyzed for TN and TP constituents; six being topsoil and six being subsoil samples. Topsoil TP concentrations ranged from 171 mg/kg to 524 mg/kg with a mean of 392 mg/kg and standard deviation of 134 mg/kg (Figure 11). Subsoil TP concentrations spanned a range of 247 mg/kg to 466 mg/kg with a mean of 365 mg/kg and a standard deviation of 86 mg/kg.

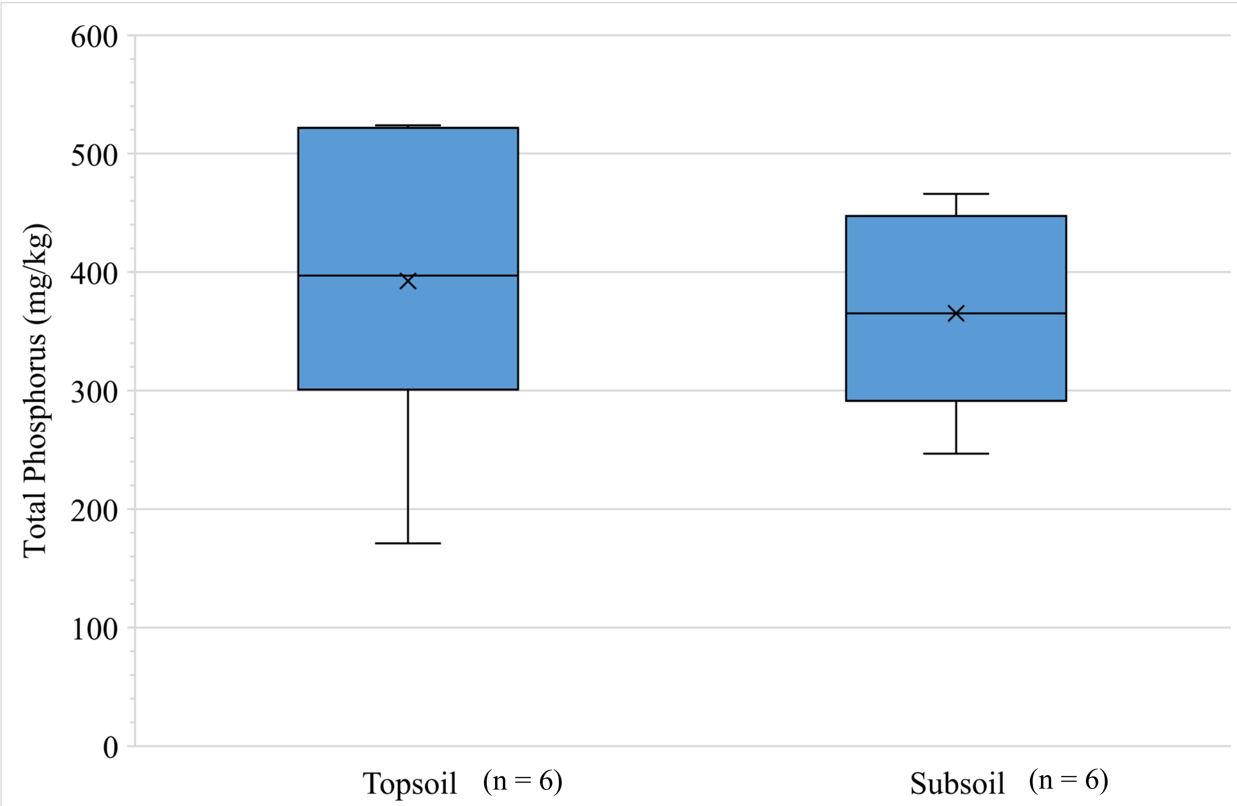

Figure 11: Boxplot of total phosphorus concentrations for topsoil and subsoil of study plots.

Topsoil TN concentrations ranged from 776 mg/kg to 3480 mg/kg with a mean 2236 mg/kg and a standard deviation of 1101 mg/kg (Figure 12). Subsoil TN concentrations ranged from 624 mg/kg to 2490 mg/kg with a mean of 1512 mg/kg and a standard deviation of 746 mg/kg. This indicates that TN concentration varied more widely than TP in topsoil and subsoil samples. It is also worth noting that only two samples contained nitrogen in a form other than organic nitrogen. Topsoil samples of RIV-1 and RIV-4 each had small amounts of nitrate while no samples were found to contain a detectable amount of nitrite.

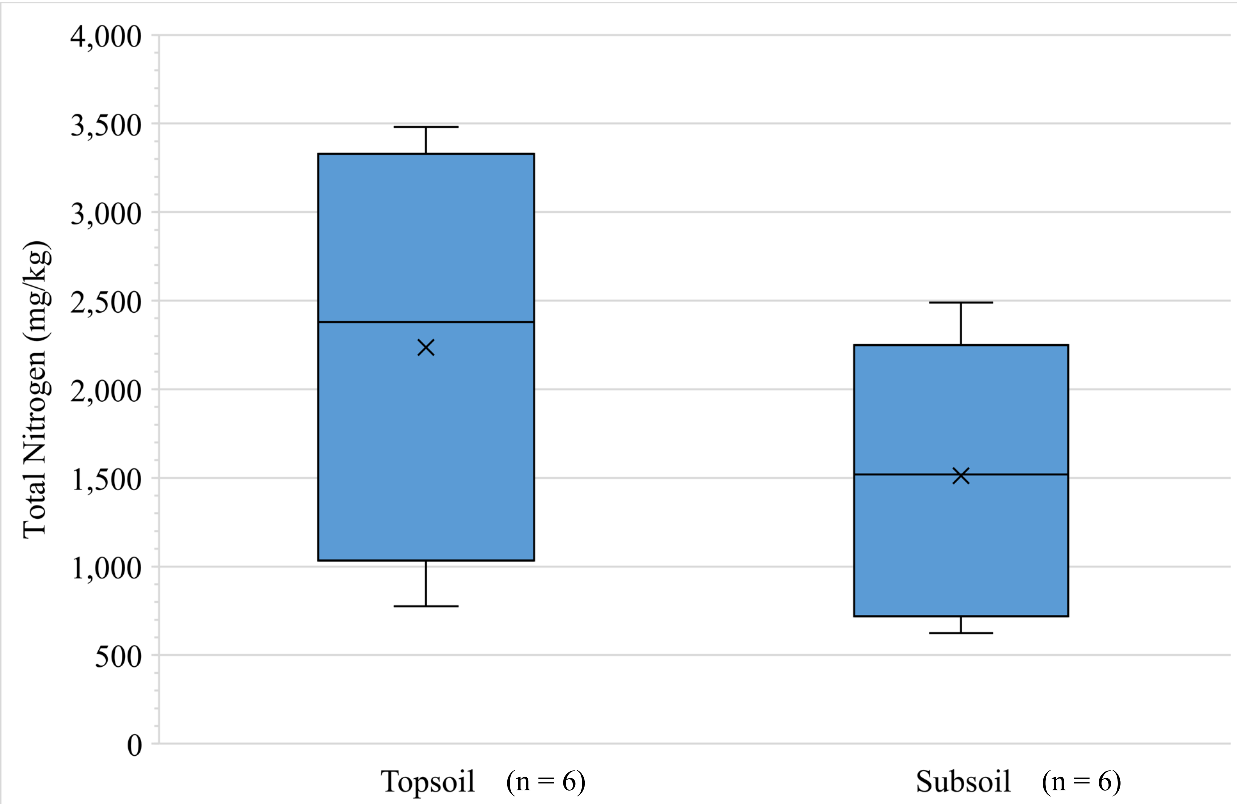

Figure 12: Boxplot of total nitrogen concentrations for topsoil and subsoil of study plots.

Topsoil nutrient concentrations were expected to be higher than subsoil nutrient concentrations in study plots. While these samples constituted a small population (n=6), a two-tailed, two-sample t-test for data with unequal variance was used to determine significance. The t-test comparing TP concentrations between topsoil and subsoil samples gave a p-value of 0.68. This p-value was far higher than the p-value of 0.05 that would distinguish a statistically significant difference between the populations at a 95% confidence level. Thus, the null hypothesis that there was no significant difference between the TP concentrations in topsoil and subsoil was not rejected. The t-test comparing TN concentrations in topsoil and subsoil gave a p-value of 0.21. This value, again, was higher than the p-value of 0.05 that would indicate a statistically significant difference between TN concentrations in topsoil and subsoil. As such, there is no statistically significant difference between TN concentrations in topsoil and subsoil.

Total phosphorus concentrations appear to vary by land use with wetland streambank samples having highest average concentration of 482.5 mg/kg and single highest sample concentration of 524 mg/kg (Figure 13). Samples from land/streambanks used for corn production had the second highest individual concentration of 521 mg/kg, but also the lowest individual concentration of 171 mg/kg and an overall lowest average concentration of 318.5 mg/kg. Samples from hay field streambanks had relatively consistent TP concentrations combining for an average of 417 mg/kg.

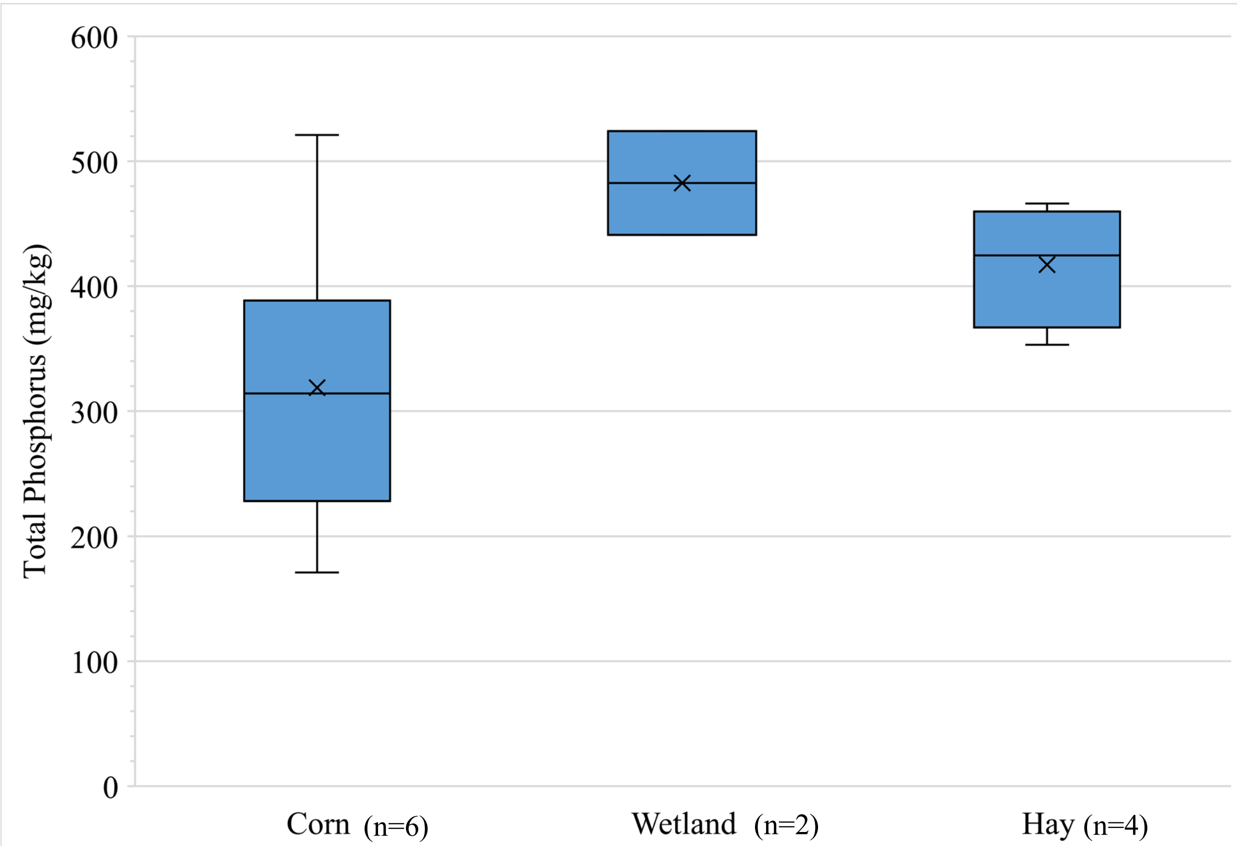

Figure 13: Boxplot of total phosphorus concentrations by land use.

The highest average TN concentration was found in hay streambanks with 2640 mg/kg though hay banks also had the greatest range of concentrations (Figure 14). Corn streambank samples produced the lowest average TN and lowest single sample TN concentrations of 1180 mg/kg and 624 mg/kg, respectively.

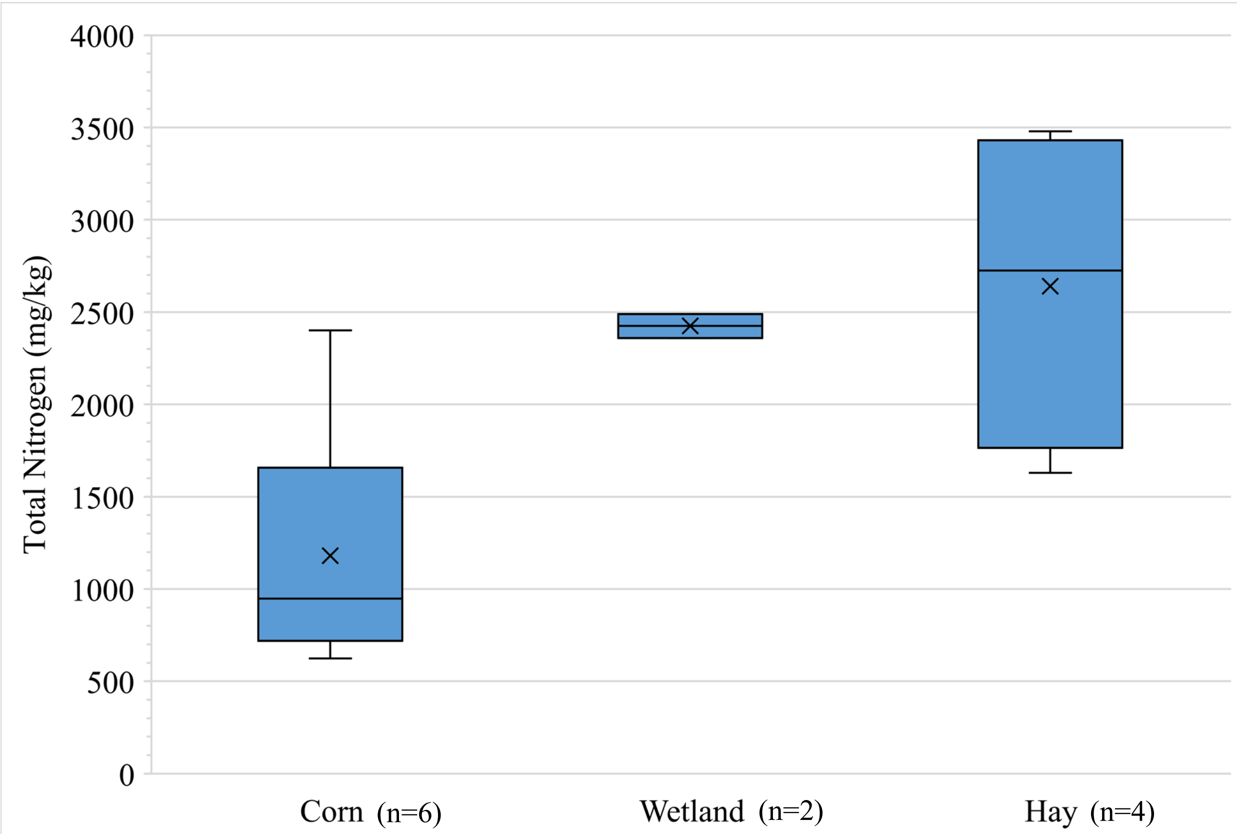

Figure 14: Boxplot of total nitrogen concentrations by land use.

Eroded soil and nutrients

Total eroded soil mass from all combined plots during the 10-year study period was estimated to be 33,000,000 kg, or 33,000 metric tons (Table 4). Eroded TP for all combined plots was determined to be 9,300 kg, or 9.3 metric tons. Total eroded TN mass for all plots amounted to 49,000 kg, or 49 metric tons. The two study sites loaded similar masses of soil into the West Branch Delaware River with plots at Birdsong Farm contributing 17,000,000 kg of soil and River Haven Farm plots contributing 16,000,000 kg of soil (Table 5). Nutrient loading was less evenly distributed between the two sites with River Haven responsible for loading approximately 3,200 kg of TP and 12,000 kg of TN while Birdsong introduced approximately 6,100 kg of TP and 37,000 kg of TN.

Table 4: Study plot totals for eroded soil mass, eroded TP mass, and eroded TN mass. Differences that arise between summation of individual plots and listed totals are due to significant figures.

Plot	Eroded soil mass (kg)	Eroded TP mass (kg)	Eroded TN mass (kg)
RIV-1A	4.3E+06	6.3E+02	1.5E+03
RIV-1B	3.3E+06	5.1E+02	1.2E+03
RIV-2	2.1E+06	3.0E+02	1.4E+03
RIV-3	2.8E+06	4.6E+02	1.5E+03
RIV-4	1.8E+06	7.4E+02	3.9E+03
RIV-5	1.6E+06	5.6E+02	2.3E+03
BIR-1A	1.1E+07	3.9E+03	2.3E+04
BIR-1B	5.2E+06	1.9E+03	1.1E+04
BIR-1C	1.1E+06	3.9E+02	2.4E+03
Total	**3.3E+07**	**9.3E+03**	**4.9E+04**

Table 5: Study site totals for eroded soil mass, eroded TP mass, and eroded TN mass.

Site	Eroded soil mass (kg)	Eroded TP mass (kg)	Eroded TN mass (kg)
Birdsong Farm	1.7E+07	6.1E+03	3.7E+04
River Haven Farm	1.6E+07	3.2E+03	1.2E+04
Total	**3.3E+07**	**9.3E+03**	**4.9E+04**

Discharge

The Walton, NY, West Branch Delaware River gage (USGS gage 01423000) was used to monitor flow for this study. The gage is ~19 km (~12 miles) downstream of the River Haven study site and has a drainage area of 860 km^2 (332 mi^2). Drainage area at the River Haven site is 629 km^2 (243 mi^2) while drainage area at the Birdsong site is 575 km^2 (222 mi^2). While actual discharge would have been lower at the study sites because they have smaller drainage areas, the record of discharge at the Walton gage should reflect the proportional magnitude of flow relative to the metric of bankfull discharge. Bankfull discharge is considered the flow at which significant sediment transport occurs (Rosgen, 2009).

Thirteen discharges during the study period reached or exceeded the estimated bankfull discharge of 186 m^3/s (6580 cfs) at the Walton, NY, West Branch Delaware River gage (Figure 15 and Table 6; USGS, 2016). For the purpose of this analysis, any discharge within 10% of the 186 m^3/s threshold was considered "bankfull" as bankfull discharge is a small range and not a set threshold. Of the thirteen bankfull and greater discharges, seven are higher than what is considered the bankfull range, making them flood level discharges. Unfortunately, it cannot be known how each discharge affected the total amount of erosion, considering that erosion was not measured after each flow event. It can, however, be assumed that each bankfull, or greater, discharge impacted erosion.

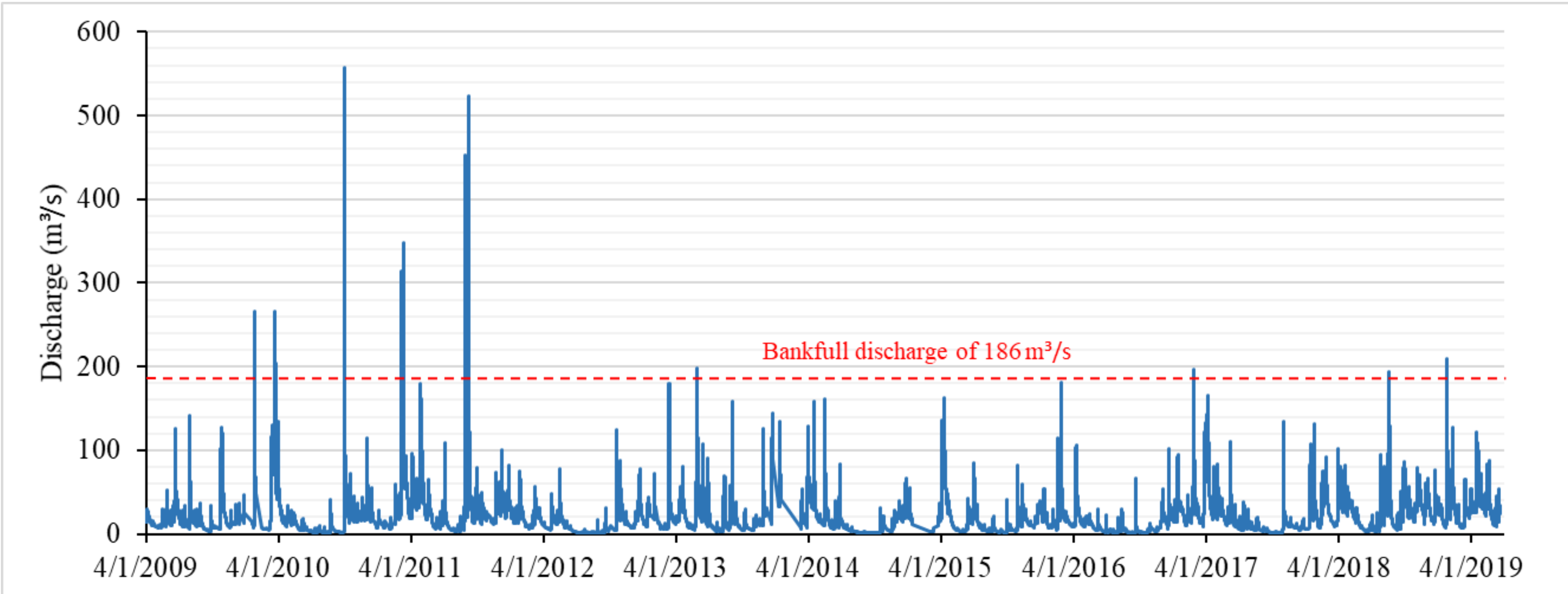

Figure 15: Hydrograph of discharge at the West Branch Delaware River USGS gage at Walton, NY, for the duration of the study; 4/1/2009 – 6/20/2019 (USGS, 2019).

Table 6: Peak event discharges at the Walton, NY, West Branch Delaware River USGS gage (01423000) between 4/1/2009 and 6/20/2019 with event recurrence intervals (USGS, 2019).

Date	Discharge (m^3/s)	Recurrence Interval (years)
10/1/2010	558	16.29
9/8/2011	524	12.64
8/29/2011	453	7.50
3/11/2011	348	3.60
3/6/2011	314	2.84
1/25/2010	266	2.06
3/23/2010	266	2.06
1/25/2019	210	1.49
5/30/2013	198	1.40
2/25/2017	197	1.39
8/18/2018	194	1.37
2/25/2016	181	1.30
3/12/2013	180	1.29

Discussion

Estimate quality

Estimation of nutrient loads at the two case study sites is the result of a straightforward method of measurement, laboratory analysis, and dimensional analysis. Known best practices were adhered to in sample collection, GPS processing, and nutrient laboratory analysis. Best practices were modified during particle size analysis for practical reasons.

ASTM method D422-63 (2007) is the "standard test method for particle-size analysis of soils" and is commonly used for particle-size analysis. Due to possession of necessary equipment and staff experience, the particle-size analysis was performed in-house. Divergence from ASTM methods began with the drying process. Several publications (Gaspard, 2002; Usmen et al., 1986) justify the utility and use of microwave ovens in place of conventional drying ovens in removing moisture from soil samples. For this reason, microwave ovens were used in our study to dry soils in preparation for sieving.

Study methods diverged from method D422-63 again in sieve selection. Our goal in particle-size analysis was solely to determine the fraction of sediment smaller than 2 mm in size, the fraction of material that contains nutrients. The sieves in our possession adhere to specifications for stream sediment particle-size analysis. The sieve size ranges are close to those specified in D422-63, varying slightly. The overlap in sieve size was the #10, or 2 mm, sieve. The substitution of sieve sizes was inconsequential, as the sieves larger than the #10 only serve to sort larger particles so that F-E sized particles would not be obstructed on their path to the #10 sieve. Additionally, D422-63 calls for five sieves smaller than 2 mm in size. Sorting of sediment smaller than 2mm in size was unnecessary for our purposes as we hoped to analyze TP content within the full range of sediment sizes that compose the F-E fraction.

The final departure from ASTM D422-63 was in scale specifications. D422-63 calls for a scale sensitive to 0.1% of mass retained on the # 10 sieve. The scale used during the study was only sensitive to 1.0% of retained mass. Use of this scale still carried significant figures that exceeded the final allowable significant figures of our estimates. For this reason, this departure was considered inconsequential.

Nutrient loading estimates were also dependent on two assumptions: that 2009 bank heights were the same as 2019 bank heights and that soil samples collected in 2019 accurately reflect the nutrient content of the soil eroded since 2009. The assumption that 2019 bank heights were the same as 2009 bank heights is based on observations in fluvial morphology that bankfull floodplains remain relatively constant in elevation. Leopold et al. (1995) contend that "flow over the surface of the flood plain is often irregularly distributed and velocities may be high enough to produce scour rather than deposition." The implication of this insight is that 2009 bank heights may have been slightly higher or slightly lower than those measured in 2019 despite being a part of the same fluvial feature.

Two-foot contours from 2009 LIDAR remote sensing (1 m DEM) show likely terrain elevations in the study areas prior to significant erosion. Contours at Birdsong Farm show elevations decreasing from the streambank back towards the center of the hay field in plots BIR-1A and BIR-1B. The maximum decrease in elevation from 2009 to 2019 bank height appears to be ~0.3 m (~1 ft), making the calculated erosion estimate at this site a conservative one. LIDAR contours at the River Haven Farm study area show a small depression in RIV-4 with a depth of less than 0.6 m (2 ft). This wetland depression is ~40 m L by ~8 m W. This would indicate that values calculated at RIV-4 are a slight overestimate.

An uncertainty analysis was performed in an attempt to quantify the amount of error that bank height may contribute to calculations. A 3 cm (0.1 ft) change in bank height over the entire study area made a ± 2% difference in loaded TP and TN masses. Likewise, a 15 cm (0.5 ft) change in bank height resulted in a ± 11% change in loaded TP mass and a ± 10% change in loaded TN mass over the entirety of the study area. While uncertainties will remain, our future investigations into excessive streambank erosion will utilize unmanned aerial vehicle (UAV) survey technology. Survey utilizing UAV technology will have higher resolution and will enable the use of DEM differencing analysis methods to determine volumetric losses.

The Nutrient Management Program within the Watershed Agricultural Program (WAP) typically samples participants' agricultural fields for key crop and water quality nutrients every three years (Sheridan, 2021). A review of data for the fields in question showed no significant change in Morgan-P (a measure of plant available phosphorus) in any of the fields for the duration of the study. Nitrogen constituents are not typically sampled and, as a result, could not be reviewed. While Morgan-P does not represent TP, the relative consistency of this measure through the duration of the study may indicate that there was also no substantial change in overall TP concentration. One could make the argument that agricultural field conditions would differ from the vegetated riparian zone on a river's margins. This makes sense conceptually due to differences in vegetation and amendments made to agricultural fields. By 2009, the riparian zone at each of the study sites had been eroded away leaving only agricultural fields in contact with the river. As such, it can be assumed that there was no miscalculation due to misrepresentation of eroding riparian zone.

Nutrient load: scale and context

The estimated nutrient loads from Birdsong and River Haven farms appear to be quite large in quantity. These sites were brought to our attention by anecdotal observation that large volumes of streambank soils were missing after flow events. Subsequent GIS analysis targeting the ten most erosive management units of the West Branch Delaware River (Gladstone et al., 2006) determined that these two sites were the largest erosional reaches on the river. This determination suggests that these sites are potential problems for water quality yet, in order to evaluate the true impact of sediment and nutrient loading from these locations, one must have context at the watershed scale.

A 2000 TMDL report prepared by NYSDEC for the Cannonsville Reservoir estimated the non-point source total phosphorus load to the reservoir to be 44,968 kg/yr with the overall total phosphorus TMDL for the Cannonsville set at 53,650 kg/yr (NYSDEC, 2000). The average TP loading rate for the combined study sites was 930 kg/yr, amounting to 2.1% of the non-point source load, and 1.7% of the total TMDL for the Cannonsville Reservoir. In addition, the estimated 930 kg/yr TP load from the study sites is higher than the combined TP loading goal of 744 kg/yr for the four municipal waste water treatment plants upstream of the Cannonsville Reservoir (NYSDEC, 2000). It should be noted that two factors limit this direct comparison of TP loading at the study sites to the original TMDL estimates. The first being that overall TP loading to the Cannonsville Reservoir has been reduced substantially since the creation of the TMDL in the year 2000; this would increase the percentage contributed to overall TP load by the study sites. In addition, our estimate of the study site contributions of the TMDL are based on the assumption that all loaded sediment is transported to the reservoir. Overbank flooding conditions result in some portion of suspended sediment being deposited on floodplains and removed from transport. The sand fraction, due to its greater mass, may also be deposited in the channel (if not deposited on a floodplain) before it reaches the reservoir and may take more than one flow event to reach the reservoir. The portion of the total load from the study sites that makes it to the reservoir cannot be known at this time. During flows closer to bankfull (majority of flow in channel) it can be assumed that the majority of sediment loaded from the study sites remains in the channel with silt and clay particles making it to the reservoir in a matter of hours. Flows substantially larger than bankfull have out-of-bank flooding that will result in greater deposition of F-E materials on floodplains, thus reducing contribution to the reservoir.

In addition to the discussion of TP loading and destination, consideration should be made as to what proportion of loaded TP is bioavailable. Bioavailable P is the readily available form of phosphorus to plants and is most responsible for algal and plant growth related to eutrophication; in the context of water sampling this form of phosphorus is typically known as soluble reactive phosphorus (SRP). Streambank samples were not tested in a way that individual phosphorus constituent concentrations could be discerned. The regular spreading of cow manure on the study site fields however means that these fields will have a higher concentration of SRP than unamended soils as the phosphorus in cow manure is predominantly bioavailable (Sheridan, 2021). The WAP's most recent soil tests for Morgan-P (a measure of plant available phosphorus for crops) for the study fields were analyzed in an attempt to estimate the proportion, by mass, of bioavailable phosphorus. It should be noted that Morgan-P and SRP are not directly comparable and WAP sampling methods and locations differed from the study, making these estimates less than reliable. In light of these differences, it was estimated that Morgan-P at Riverhaven Farm composed roughly 1.3 to 1.7% of TP while Morgan-P composed about 0.35% of TP at Birdsong Farm. Future testing could be performed to investigate the bioavailable phosphorus content at these study sites, but estimates of TP loading are still of great value as TP is the metric of concern for regulatory agencies. Phosphorus constituents may also transform and cycle after they enter the river and reservoir.

While the study sites described here appear to have an outsized contribution of sediment and nutrients to the watershed, they are by no means the only eroding streambanks in the watershed. To provide a watershed-wide context, the total length of erosion of the combined study sites comprise 0.0004% of the total 2131 km (1,324 mi) of streambank length within the watershed. An assessment of the main stem of the West Branch of the Delaware River completed by the DCSWCD in the early 2000s found 29.6 km (18.4 mi) of active streambank erosion out of the total 157.9 km (98.1 mi) of streambanks (Gladstone et al., 2006). This means that 18.7% of streambanks were actively eroding at the time of the assessment. In addition, many tributaries to the West Branch are, anecdotally, and through further assessment, unstable (Coryat, 2018). Assessments of the tributaries Steele Brook and an unnamed tributary to Elk Creek in 2017 found that linear streambank erosion percentages of these streams were 16.2% and 24.2%, respectively. While these streams were known to have issues, if the linear erosion percentage of Steele Brook was quartered and applied to all tributaries in the basin, it would still amount to an additional 80 km of actively eroding streambanks in the Cannonsville watershed. Although many tributaries do not have the F-E content or historical agricultural amendments of the West Branch main stem, we believe that streambank erosion is likely an unmeasured but substantial contributor to overall sediment and nutrient load in the Cannonsville basin. To give greater context though, stream feature inventory assessments should also be completed on stable tributaries in order to facilitate a greater understanding of natural erosion rates. Past efforts and requirements have placed an emphasis on assessing only "problem" streams that may negatively affect water quality. The Cannonsville basin would benefit from the assessment of an occasional stable stream in order to understand how widespread the problem of excessive erosion is.

Contrary to the assertion that streambank erosion is likely an unmeasured but substantial contributor to overall sediment and nutrient load, a 2007 study by Nagle et al. that used bomb-derived radionuclide ^{137}CS to determine the sources of fine sediment in the West Branch Delaware River contended that "bank erosion accounted for little or none of the fluvial sediment" in the West Branch Delaware River. The Nagle study specifically analyzed silt and clay sediments found in channel depositions. One might argue that our study is not comparable as streambank soils were not sieved into fractions smaller than sand. A test was performed, however, in which F-E fractions were suspended in water. Clay and silt were determined to be present in both composites based on settling times.

While the Nagle study was performed prior to the start of this study, it coincided with the 2006 published Stream Feature Inventory assessment of the West Branch Delaware River that documented the active erosion of 18.7% of all streambanks on the main stem of the river. This revelation, when considered with the findings of this 2009-2019 study that most of the sampled streambanks along the main stem had a majority fine-earth fraction of sediment, further demonstrates how Nagle's assertion is at odds with the DCSWCD's findings.

Native soil phosphorus concentrations vary by region depending on parent material and degree of weathering. Beyond this, anthropogenic alterations may also affect soil phosphorus concentration. A handful of recent studies in the northeastern United States investigated total phosphorus concentrations in streambank soils. A study of an undisturbed coniferous forested watershed in Acadia National Park in Eastern Maine found average streambank and near streambank TP to be 334 mg/kg (SanClements et al., 2009). Another study of streambank soils along an agricultural reach of the Mad River in Vermont determined that TP concentrations varied from 622 mg/kg at a deciduous riparian forest area to 1066 mg/kg at an agricultural field in hay production (Ross et al., 2018). TP concentrations of our own study primarily fall between TP concentrations of these locations in Maine and Vermont, with some exception. Glacial till material, the primary glacial deposit topping bedrock and underlying soils in WBDR watershed uplands, was sampled in the Steele Brook subbasin to get an idea of baseline TP concentrations of parent sediments. TP concentration of this glacial till was 217 mg/kg, though only one sample was taken. This would indicate that parent material in the WBDR basin can have fairly low TP content relative to the valley bottom alluvium and other northeastern streambank soils. It seems likely that agricultural amendment and routine flooding, which builds fine sediment on the floodplain, has increased TP concentration of West Branch Delaware River streambank soils sampled in this study.

The case studies presented in this document make the comparison between TP loading from the study sites and the total estimated TP budget, but there is no existing budget for sediment or nitrogen in the Cannonsville basin. For this reason, context regarding the large amount of sediment and nitrogen loaded at these locations is incomplete.

Conclusions

Our study estimated sediment, TP, and TN loads from two instances of excessive streambank erosion on the West Branch Delaware River. The estimated average 930 kg of TP loaded yearly from these sites comprises a substantial portion, over 2%, of the total non-point source TP load for the entire Cannonsville Basin (as of the year 2000). It is likely that the overall percentage of TP loaded due to all streambank erosion is even greater when considering the widespread evidence of streambank erosion on the West Branch and its tributaries. The more nutrient dense streambank soils of the West Branch main stem are likely the greatest source of nutrients from bank erosion due to historical agricultural use along the river.

While streambank erosion is a natural process, excessive instances such as the ones at River Haven and Birdsong farms are likely the result of human influence and land use over many years. Mitigation of these erosional sources of sediment and nutrients can be achieved through the implementation of stream stabilization practices. Without such an intervention, these instabilities will continue to erode at an excessive rate.

Bank erosion, with its corresponding sediment and nutrient loading has been a difficult phenomenon to enumerate for good reason. It is widespread in scope, and can be complex in its nature. The efforts made in this study likely scratch the surface in defining the contribution of streambank erosion to the overall sediment and nutrient budget of the Cannonsville Reservoir watershed. Efforts by the DCSWCD to quantify sediment and nutrient loading will continue, utilizing bank erosion models to predict less severe but more widespread erosion, and advanced survey by unmanned aerial vehicles to survey eroding agricultural streambanks with greater accuracy and precision. Stream feature inventories of stable/reference streams as well as further studies that can accurately fingerprint fine sediment sources, estimate total watershed sediment loads, estimate total watershed nitrogen loads, and reassess total phosphorus loads will also go a long way toward fostering a clearer understanding of the source and scale of these water quality constituents.

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