# Stream Corridor Sources of Suspended Sediment and Sediment-Bound Phosphorus from an Urban Tributary to the Great Lakes

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## Abstract

Potential sources of suspended sediment and sediment-bound phosphorus (sedP) were studied in the Kinnickinnic River (51 square kilometers), a heavily urbanized tributary to Lake Michigan (90% urban land use) in Milwaukee, Wisconsin. The river is 60% concrete lined channels, with few unlined reaches. From September 2019 through August 2020, an integrated study of sediment budget and sediment fingerprinting was conducted to quantify upland and stream corridor sources of suspended sediment and sedP using Sediment Source Assessment Tool (SedSAT) methods with a suite of trace elements. Passive suspended sediment samplers were installed at three sites. Soft, fine-grained streambed sediment was collected at 10 rapid geomorphic assessment (RGA) sites. An inventory of bank erosion and soft-sediment deposition was done at each of the 18 RGA sites, which were selected to represent a range of stream sizes and geomorphic conditions. Sources of suspended sediment varied with streamflow; the primary source was from roadways in residential areas followed by eroding streambanks. Industrial/commercial areas contributed 1% of the suspended sediment at the streamgage during the study period, whereas green space contributed 18% of the suspended sediment at a mid-basin monitoring location downstream of an unlined reach. The dominant sources of streambed sediment, like suspended sediment, throughout the basin were eroding banks and residential areas, with green space and industrial/commercial area signatures present locally. In contrast with previous studies in agricultural and mixed-use basins, the urban Kinnickinnic River had limited storage of soft sediment, due to the hydrologically flashy system and concrete lined channels. However, eroding streambank sources contribute 50% of the streambed sediment, but only 9% of suspended sediment within this tributary to the Great Lakes.

## Introduction

The Kinnickinnic River (51 km$^2$) is the smallest of three rivers flowing through Milwaukee, Wisconsin to a confluence at the Milwaukee River Estuary (Figure 1). Like many Wisconsin rivers and streams, sediment and phosphorus have the potential for negative effects on aquatic habitat, biological communities, and dissolved oxygen concentrations (SEWRPC 2007; Kort and Taylor 2018; Gellis et al 2016). Roughly 32 km of the Kinnickinnic River are considered impaired waters by the Wisconsin Department of Natural Resources (DNR), specifically chloride, phosphorus, and unspecified metals, with observed chronic aquatic toxicity, low dissolved oxygen, and degraded biological communities (Kort and Taylor 2018; WIDNR 2022).

The Kinnickinnic River is a part of the total maximum daily load (TMDL) and estuary management plan of the Milwaukee Estuary (CDM Smith 2018), where urbanization and impervious surfaces have increased streamflow and peak flashiness (Gellis et al. 2017; CDM Smith 2018). Pavement sediment from impervious surfaces can be an important contributor to urban stream sediment, especially when the sediment can be a vector for common urban contaminants (Gellis et al. 2020; Owens et al. 2001). Total phosphorus (TP) annual average loading is 5,783 kilograms per year (kg/yr) with an estimated 78% from urban runoff (CDM Smith 2018). Total suspended solids (TSS) annual average loading is 2,404 metric tons per year (mT/yr), with roughly 98% contributed from urban runoff (CDM Smith 2018). The high estimated contributions from urban runoff, in conjunction with weak streambank and streambed stability, has delivered increased pollutant loadings and sediment to the estuary (U.S. Environmental Protection Agency 1997; Gellis et al. 2016). This study used an integrated sediment fingerprinting and stream corridor-based sediment budget to quantify the proportions of sediment-bound phosphorus (sedP) and sediment loadings from upland and in-channel sources. Additional elemental analysis of streambed and suspended sediment offered a unique spatial sourcing of anthropogenic elemental contamination.

# Study Area

The Kinnickinnic River drains the southern portion of Milwaukee, WI and is overwhelmingly influenced by urban land use (Figure 1). Roughly 60% of the stream network is concrete lined, with half of the concrete sections flowing completely underground (SEWRPC 2007; CDM Smith 2018), while the remaining sections are unlined but are incising and heavily eroding laterally (CDM Smith 2018). Estimates from the 1970s through mid-2010s suggest 1 to 1.5 meters of bed material has been eroded (CDM Smith 2018). The stream drains a watershed of more than 84% urban land cover (SEWRPC 2015; Kort and Taylor 2018), with major land use contributions from roads and highways, residential and commercial sections, and industrial areas, along with the General Mitchell International Airport (Figure 1). Legacy urbanization is considerable, as 90% of basin area has been fully developed for 40 years and 40% of that area is comprised of impervious surface (Kort and Taylor 2018; SEWRPCTR-39 2007; CDM Smith 2018). In the pre-settlement era, the watershed was dominated by glacial lake features and ground moraines with sugar maple, basswood, and oak forests, while the flatter and swampier southern quarter of the basin would have seen black ash and tamarack swamps (CDM Smith 2018). Total precipitation over the study period from September 16, 2019, through August 31, 2020, was 44 inches, measured at General Mitchell International Airport (NOAA station USW00014839) (Menne et al. 2012a; 2012b).

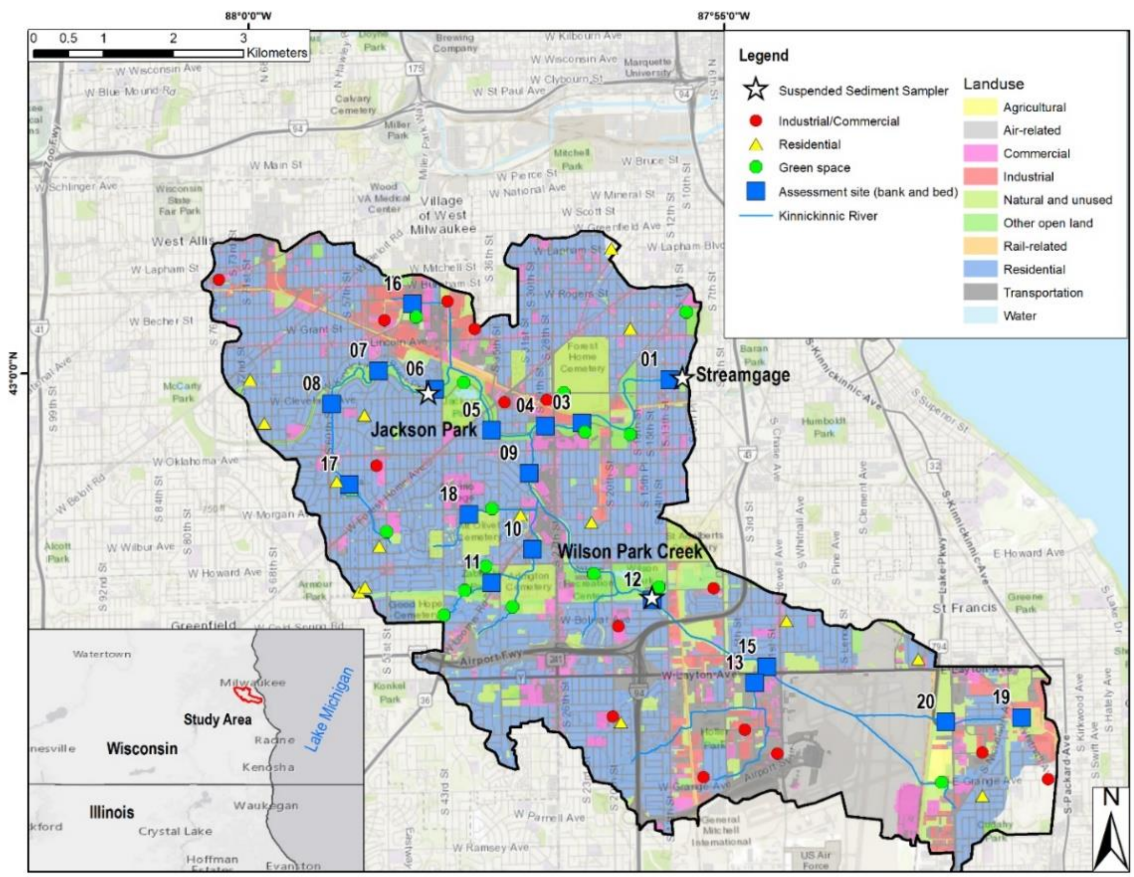


**Figure 1**. Kinnickinnic River basin, Wisconsin. Major land use categories, rapid geomorphic assessment (RGA) site locations, and sampling sites are shown. Land use from Southeastern Wisconsin Regional Planning Commission (2015).

# Methods

Study methods followed an integrated approach used for suspended sediment and sediment-bound phosphorus (sedP) source apportionment applied in Plum Creek (Fitzpatrick et al. 2019) and Apple Creek (Blount et al. 2022), which includes field-based rapid geomorphic assessments (RGAs), field and geographic information system (GIS) based sediment and sedP budgets, and sediment source apportionment through sediment fingerprinting tools. There are advantages in using these multiple lines of evidence, rather than an individual method for quantifying and sourcing fluvial sediment and P, including results that can help aid the decision-making process for best-management practice implementation and target specific TMDL reduction.

## Field Based Rapid Geomorphic Assessments

Field-based RGAs were conducted in fall 2019 along 150-m reaches and adhered to the bank erosion, streambed measurement, and data collection methods detailed in Fitzpatrick et al. (2019). Bank erosion estimates were done categorically, using the Wisconsin Natural Resources Conservation Service (NRCS) (2015) field guide, describing the physical characteristics of the bank surface. Due to the small watershed size and ongoing Milwaukee Metropolitan Sewerage District (MMSD) restoration of a 500-meter section in the lower reach of the Kinnickinnic River (Bergquist 2019), there was only capacity for 18 RGA reaches instead of the preferred 30 reaches (Fitzpatrick et al. 2019, Blount et al. 2022). The 18 RGA reaches were selected to provide a representative description of geomorphic conditions along the stream corridor by way of slope, channel type (concrete lined and unlined), riparian land use, and Strahler stream order (WDNR 2017, SEWRPC 2015). The extent of concrete lined channels provided a new and significant trait that crossed all stream orders and slopes. The Wisconsin DNR (WDNR 2017) streamlines provided the base for reach selection where all 18 RGA reaches were placed along perennial channels. Eroding streambank and soft streambed sediment samples were collected at each of the reaches where present and subsampled for geochemical analysis, particle size, organic carbon content, and sedP concentrations.

## Stream Corridor Budget of Erosion and Soft Sediment Deposition

The stream corridor sediment and sedP budget for erosion and soft sediment deposition were calculated following the Fitzpatrick et al. (2019) methodologies. Bank erosion estimates, soft sediment deposition estimates, and measured sedP concentrations from both were normalized by reach length. The reach estimates were applied to the Wisconsin DNR (2017) 1:24,000 stream network segments based on similar geomorphic setting, presence of concrete, and riparian land use. A cumulative sum of bank erosion and soft sediment deposition for all segments lengths provided the corridor sediment and sedP budget for the Kinnickinnic River. Estimates were also calculated for bank erosion and soft sediment deposition for subbasins upstream of each in-situ suspended sediment sampler.

## Sediment Source Apportionment

Sediment source apportionment is a technique based on identifying the combination of chemical tracers that most accurately differentiate between sources of sediment in the watershed (Gellis and Noe 2013). The fluvial (suspended and soft streambed) sediment in the channel has a unique chemical signature that is a composite from the upland and streambank sources and can be used to determine the proportion of sediment derived from each contributing source group.

**Source and Target Site Selection and Sampling:** Upland source sampling sites in the watershed were randomly selected in ArcMap 10.6.1 (ESRI 2018) using Southeastern Wisconsin Regional Planning Commission (SEWRPC) land use data (SEWRPC 2015) to articulate specific source groups (Figure 1). Upland source groups in this study were residential, industrial/commercial, and green space. Sediment source sampling followed methods from Fitzpatrick et al. (2019) and Blount et al. (2022), with modifications for green space and residential sites; 15 sites were sampled for every upland source group. The in-channel source group, streambank, was limited to only 10 of the 18 RGA sites because of the limited basin area and length of unlined reaches. One duplicate sample from each source group was analyzed for quality assurances; to include one target sample from the streamgage. Since the watershed is heavily urbanized, the sampling effort had to combine roadways along parks, cemeteries, and open green space within the basin, cumulatively characterized as green space from here on. Additionally, residential sources are described here as curbs of streets within residential neighborhoods; typically low-density, single-family homes. Target samples were soft streambed sediment collected at 10 of the 18 RGA reaches, and suspended sediment samples collected with *in situ* passive samplers at the streamgage on the Kinnickinnic River at 11th St (USGS 04087159), at Jackson Park (JP), and at Wilson Park Creek (WPC). Target samples were collected according to the methods described by Fitzpatrick et al. (2019) and Blount et al. (2022) over the representative periods listed in Table 1.

**Table 1.** Suspended sediment samples analyzed during the study. Dashes represent insufficient sample collected for analysis.

| Collection date | Representative period | Samples collected |
|---|---|---|
| 10/22/19 | 9/16/19 - 10/22/19 | Streamgage, JP |
| 1/6/20 | 10/22/19 - 1/6/20 | Streamgage, JP, WPC |
| 1/31/20 | 1/6/20 - 1/31/20 | -- |
| 3/5/20 | 1/31/20- 3/5/20 | -- |
| 4/3/20 | 3/5/20 - 4/3/20 | -- |
| 5/1/20 | 4/3/20 - 5/1/20 | -- |
| 5/29/20 | 5/1/20 - 5/29/20 | Streamgage |
| 6/29/20 | 5/29/20 - 6/29/20 | Streamgage, JP |
| 7/26/20 | 6/29/20 - 7/26/20 | Streamgage, JP, WPC |
| 8/31/20 | 7/26/20 - 8/31/20[1] | Streamgage, JP, WPC |

-- indicates insufficient sample collected for analysis due to no runoff events and/or frozen conditions
[1]Duplicate QA sample collected

**Laboratory Analyses:** Samples were stored and processed following methods detailed in Fitzpatrick et al. (2019) and Blount et al. (2022), including wet sieving with a 63-micron (µm) Teflon sieve, before analysis of particle size, organic matter content, and a suite of 60 major and trace elements (Table 2) on the <63-µm fraction of the sample (Shelton and Capel 1994). Particle size and organic matter analyses were completed at the USGS Cascades Laboratory in Vancouver, WA. Organic matter content was analyzed using the I-5753 method for loss-on-ignition (LOI). Particle size distributions were completed with a SediGraph 5120 and used to compute median particle size ($d_{50}$). The Wisconsin State Laboratory of Hygiene used the ESS INO Method 420.0 Thermo Finnigan ELEMENT2 High Resolution ICP-MS (EPA Method 200.8) method and the milestone microwave digestion system (ESS INO IOP 550.0) for elemental analyses (Wisconsin State Laboratory of Hygiene 2016a; 2016b). The analyses included P concentrations in sediment, and a near total digestion using three acids. Organic content, particle size, and elemental data are publicly available in Blount et al. (2023).

**Table 2.** Elemental indicators used for fingerprinting analysis of sediment. Elements with symbols in bold were significant for at least one target sample. * Element failed the conservative (bracket) test for at least one target sample.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ag* | Bi | **Cs** | Gd | **La** | **Na** | Pd | S* | Sr* | **V** |
| **Al** | **Ca*** | Cu | Hf | **Li*** | Nb | **Pr** | Sb | **Ta*** | W* |
| As* | Cd* | **Dy** | Hg* | **Lu** | **Nd** | Pt | **Sc*** | **Th*** | **Y** |
| B | Ce | **Eu** | **Ho** | **Mg** | **Ni*** | Rb | Se | **Ti** | **Yb** |
| Ba | **Co*** | **Fe** | Ir | Mn* | P | Rh* | **Sm** | **Tl** | **Zn*** |
| Be* | **Cr*** | **Ga** | K* | **Mo*** | **Pb*** | Ru* | Sn | **U** | **Zr** |

**Statistical methods:** The Sediment Source Assessment Tool (SedSAT) was used to determine the fraction of sediment contributed by the sources to each target sample (Gellis et al. 2016; Gorman Sanisaca et al. 2017). SedSAT uses a package of statistical procedures to normalize for differences between source and target sediments based $d_{50}$ and LOI (Gellis and Noe 2013), to differentiate the chemical signatures among sediment sources using linear discriminant function analysis (DFA), and to apply an unmixing model to apportion the fraction of sediment from each source contributing to the target sediment sample. Details of the SedSAT method and procedures are available in Gorman Sanisaca et al. (2017); default values were used for this study. SedSAT was run independently for each target sample and the full source sample set was used for all target samples, which for the streambed sediment samples and the suspended sediment samples from Jackson Park (JP) and Wilson Park Creek (WPC) meant that not all source samples were located within their sub-watershed contributing area. One residential sample was removed from analysis as an outlier because the sample's concentration of one tracer, beryllium (Be), was more than three standard deviations above the mean concentration of the residential source group (Gorman Sanisaca et al. 2017). There were no missing values for tracer concentration, LOI, or $d_{50}$ among the source and target sample datasets. Following Gorman Sanisaca et al. (2017), a leave-one-out Monte Carlo simulation (n = 1,000 iterations) and source verification test (SVT) for each target sample were conducted to validate the model results. The SVT runs all source samples through the unmixing model for each target sample to determine how accurately the unmixing model would assign the source samples to their correct (known) source. For the purposes of presenting the SVT results, a source sample was classified to a source group based on the source with the largest percentage contribution determined by the unmixing model. Source samples that were "misclassified" did not have their known source group as the primary source identified by the unmixing model.

**Flow-weighted apportionment:** We used a flow-weighted approach to scale the suspended sediment fingerprinting results because discrete water samples for suspended sediment and total phosphorus concentrations were not collected at the streamgage (USGS 04087159) during the study period. Source apportionment of suspended sediment and sedP from the roughly monthly *in situ* suspended sediment samples from the streamgage, JP, and WPC were based on proportioning the fraction of flow measured during the representative sampling period of each suspended sample (Table 1). The fraction of flow for each representative period relative to the entire study period (9/19/19 to 8/31/20) was used to scale the source apportionment of suspended sediment. The flow-weighted estimated source apportionments for each sample period were summed over the study period to provide an overall estimate of relative source apportionment over the study for each sampling location.

# Results

## Sources of Sediment and Sediment-Bound Phosphorus

Concentrations of sedP in upland, streambank, and fluvial sediment samples ranged from 150 to 2,200 mg/kg (parts per million [ppm]) throughout the Kinnickinnic River (Figure 2a). SedP concentrations were highest in suspended sediment, with a median concentration of 1,000 ppm (± 190 ppm standard deviation). SedP concentrations in soft streambed sediment deposition (780 ± 500 ppm) were lower on average than suspended sediment, but also included the sample with the highest sedP concentration (RGA 16, Figure 7) among all source and target groups at 2,200 ppm. The source groups with the highest median sedP concentrations were residential (800 ± 200 ppm) and streambanks (690 ± 340 ppm).

The Kinnickinnic River basin is overwhelmingly comprised of urban land use, making it an interesting setting to consider the sediment-quality guidelines defined by the Wisconsin Department of Natural Resources (WIDNR 2003), specifically a subset of seven metals of interest and their probable effect concentrations (PEC), above which deleterious impacts to benthic organisms are likely (MacDonald et al. 2000). Among the selected metals of interest, there were two PEC exceedances each in copper and manganese in a streambank and streambed sediment sample (Blount et al. 2023). The remaining metals of interest had several PEC exceedances across the source and target groups (Figure 2b-f). The streambank and streambed sediment groups had the most PEC exceedances among the sample groups, while suspended sediment samples had relatively few exceedances limited to nickel and zinc. Nickel concentrations were elevated only among samples collected within the stream corridor (streambank, streambed, and suspended sediment) (Figure 2b). Zinc was similarly elevated among the stream corridor sediments, as well as one PEC exceedance each in the industrial/commercial and green space source groups (Figure 2c). Lead concentrations exceeding the PEC were present in samples from all source groups and in streambed sediment samples (Figure 2d). Chromium had PEC exceedances in all source and target groups except for residential and suspended sediment, with most occurring in the industrial/commercial, streambank, and streambed groups (Figure 2e). Three source samples, from the green space, residential, and streambank groups, as well as one streambed sediment sample, had mercury concentrations that exceeded the PEC (Figure 2f).

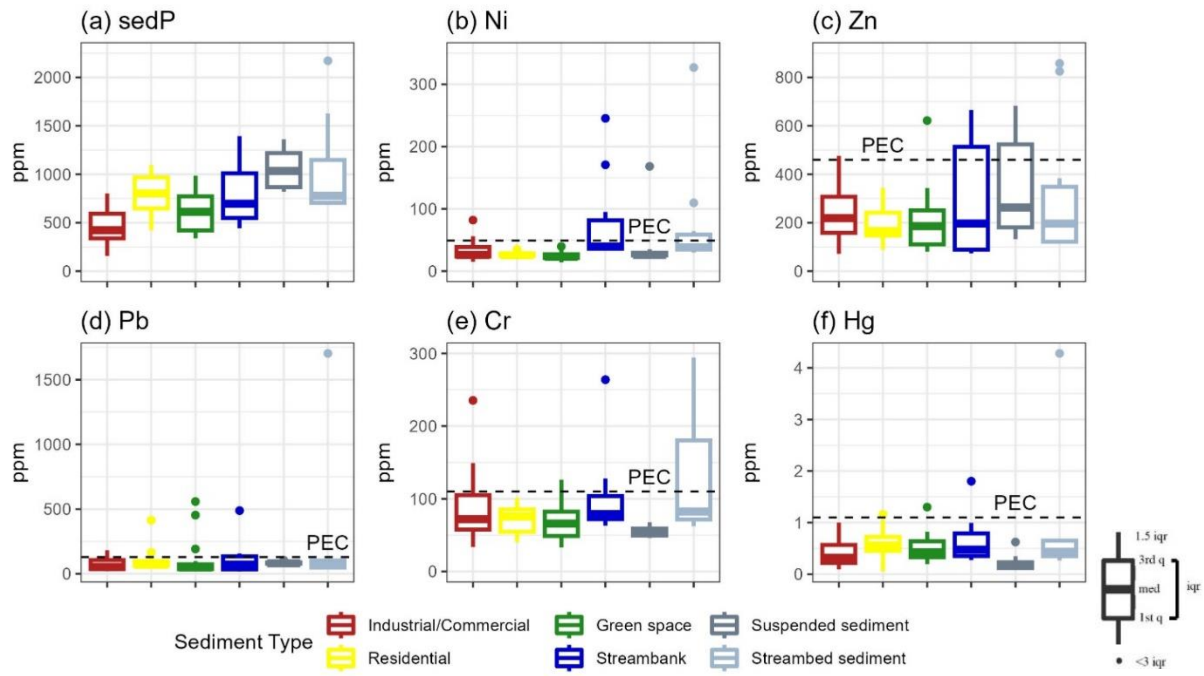


**Figure 2**. (a) Sediment- bound phosphorus (sedP), (b) nickel (Ni), (c) zinc (Zn), (d) lead (Pb), (e) chromium (Cr), and (f) mercury (Hg) concentrations in source and target sediment samples in the Kinnickinnic River. The dashed line in panels (b)-(f) indicates the consensus-based sediment quality guideline probable effect concentration (PEC) (WIDNR 2003; Macdonald et al. 2000) for each of these urban metals of interest, above which harmful effects on benthic organisms are likely. Each box spans the range from the $1^{st}$ to $3^{rd}$ quartile values (interquartile range, IQR), the central line indicates the median value, the whiskers define 1.5 times the IQR, and the dots indicate values >3 times the IQR.

Bank erosion and soft sediment deposition were distributed unevenly through the basin due to the presence of concrete lined channels and subterranean sections. Based on the RGA results (Blount et al., 2023) bank erosion, streambed scour, and indicators of channel incision were common in reaches not lined by concrete. Historically, there has been 1-1.5 meters of streambed erosion since the 1970s in unlined reaches (CDM Smith 2018). There was no bank erosion or soft streambed deposition downstream of the JP and WPC confluence because all channels were concrete lined (Figure 3).

**Table 3**. Bank erosion (mT/yr), streambed sediment (mT), and sediment-bound phosphorus (sedP) (kg) estimates above the Jackson Park (JP) and Wilson Park Creek (WPC) suspended sediment samplers and for the Kinnickinnic River stream network to the streamgage.

| Basin | Stream length (km) | Bank erosion (mT/yr) | Bank erosion sedP (kg/yr) | Streambed sediment (mT) | Streambed sedP (kg) |
|---|---|---|---|---|---|
| **JP (north) Branch** | 5.4 | 600 | 370 | 170 | 46 |
| **WPC (south) Branch** | 12.5 | 75 | 97 | 210 | 300 |
| **Full network at streamgage** | 35.2 | 1100 | 780 | 470 | 470 |

The stream corridor sediment budget indicates that an estimate of 1,100 mT/yr from bank erosion upstream of the Kinnickinnic River streamgage (Figure 3, Table 3). The TMDL estimates from CDM Smith (2018) for TSS annual average were roughly double, 2,400 mT/yr. The north branch that passes through Jackson Park contains nearly half of the entire basin's bank erosion estimate. The southern branch, that includes General Mitchell International Airport (Figure 1) and recently restored sections along Wilson Park Creek, is predominantly concrete lined and contributes less than 10% of the estimated bank erosion yield. SedP contributions from bank erosion upstream of the streamgage were estimated to be 780 kg/yr, whereas the TMDL provides an annual loading of TP at 5,800 kg/yr.

Soft streambed sediment does not have direct representation in the TMDL annual loads, but the information can be helpful in determining potential lag times between upland nonpoint source management actions related to a TMDL, with successful TP and suspended sediment monitoring results at a watershed outlet (Fitzpatrick et al. 2019; Blount et al. 2022). We estimate there is 470 mT of soft sediment stored within the channel bed, with a roughly even split of sediment storage between the two subbasins; of 210 mT in the WPC subbasin and 170 mT in the northern JP subbasin (Table 3, Figure 1). While the WPC basin is dominated by concrete lined channels, there were areas measured within some of the concrete lined sections below the airport with soft sediment deposition. Streambed sediment and related sedP in soft sediment deposition upstream of the JP (north) branch (table 3) indicate that hydraulic conditions and erosive flows limit the potential for soft sediment storage. The WPC (south) branch, with 10% of the estimated bank erosion of JP, had more soft sediment deposition (210 mT) and related sedP (300 kg) than JP. More gentle slopes and sources of non-bank derived sedP are potentially influencing the amount of soft sediment and sedP downstream of the airport (Figure 1).

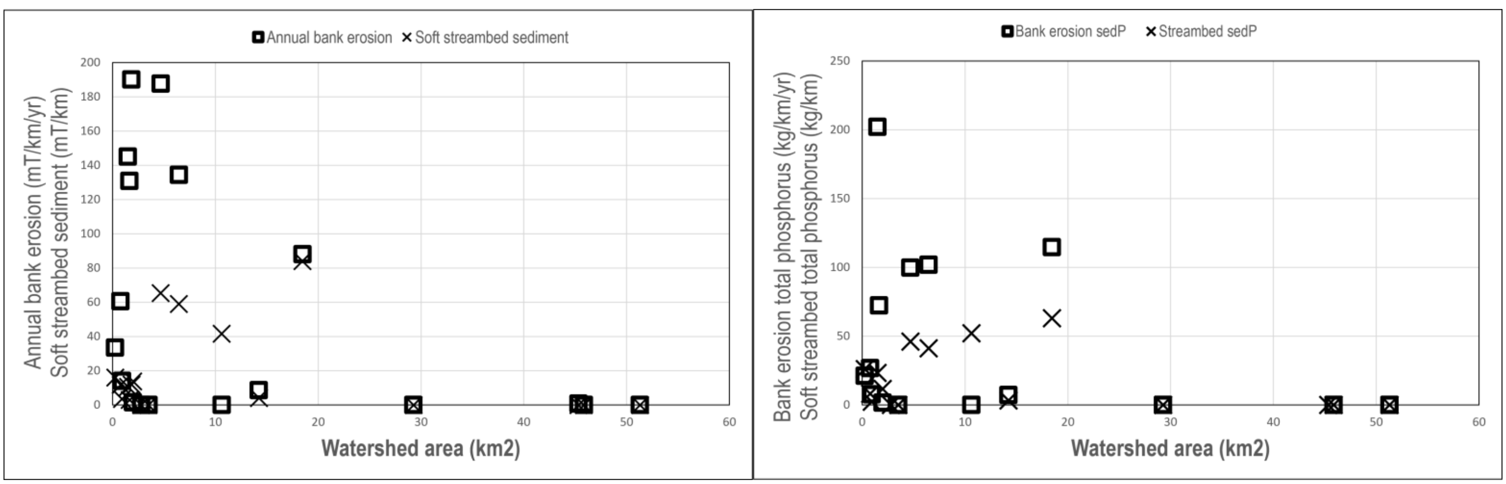


**Figure 3.** Spatial distribution of stream corridor sources and sinks of (a) sediment and (b) sedP in the Kinnickinnic River.

## Source Apportionment

More than half of the tracers analyzed were found to discriminate between source groups for at least one target sample. Of the 60 tracers, 34 were discriminant for at least one target sample (Table 4), and each target sample had 6 to 16 discriminant tracers that were significant for discriminating between sources. The top discriminant tracers for suspended and streambed sediment target samples were very similar, with uranium (U), gallium (Ga), calcium (Ca), lithium (Li), and titanium (Ti) comprising the top discriminant tracers in all streambed and suspended sediment target samples (Table 4) (Blount et al. 2023).

**Table 4**. Summary of top discriminant tracers among all target samples. "DFA Rank" is from the discriminant function analysis in SedSAT, "Mean Pi" is the average percentage of source samples independently discriminated by the tracer; concentration range in ppm, *except for calcium (Ca) in percent (%).

| Discriminant Tracer | DFA Rank | | Mean *Pi* | Concentration Range within Source Type (ppm or *%) | | | |
|---|---|---|---|---|---|---|---|
| | High | Low | | Industrial/ Commercial | Residential | Green space | Streambank |
| U | 1 | 2 | 0.802 | 0.47 - 2.9 | 0.70 - 2.8 | 1.2 - 2.9 | 2.0 - 3.0 |
| Ga | 1 | 5 | 0.779 | 1.8 - 10.4 | 3.2 - 9.8 | 3.8 - 12.5 | 9.4 - 19.3 |
| Ca* | 1 | 5 | 0.751 | 6.0 – 20. 7 | 7.0 – 15.2 | 3.5 – 18.5 | 4.2 – 13.4 |
| Li | 1 | 7 | 0.713 | 5.0 - 29 | 7.7 - 29.3 | 6.7 - 29.7 | 28.5 - 64.0 |
| Ti | 1 | 3 | 0.672 | 785 – 5,839 | 2,013 – 4,174 | 1,371 – 4,961 | 2,417 – 6,249 |

**Source Verification:** The SVT results demonstrate that all models distinguished between source groups in general, with few source samples misclassified to another source group (Figure 4). Overall, 3.5% of samples were misclassified (50 instances in 1,425 classifications). One green space sample was frequently misclassified as residential, accounting for 14 of the 50 total instances. There were a few streambed samples (RGA 15 and 20) and suspended sediment samples (8/31/20 at the streamgage, 1/6/20 at JP, 8/31/20 at WPC [Table 1]) that exhibited some overrepresentation of the residential source group pulling samples from the other source groups. The 8/31/20 sample at JP had many streambank samples misclassified to the green space source group. Misclassification of source groups occurs when there is not a clearly distinct chemical signature to differentiate between source groups. Compared to previous studies following the same SedSAT methods (Fitzpatrick et al. 2019; Blount et al. 2022), models in this study were very successful at differentiating between source groups.

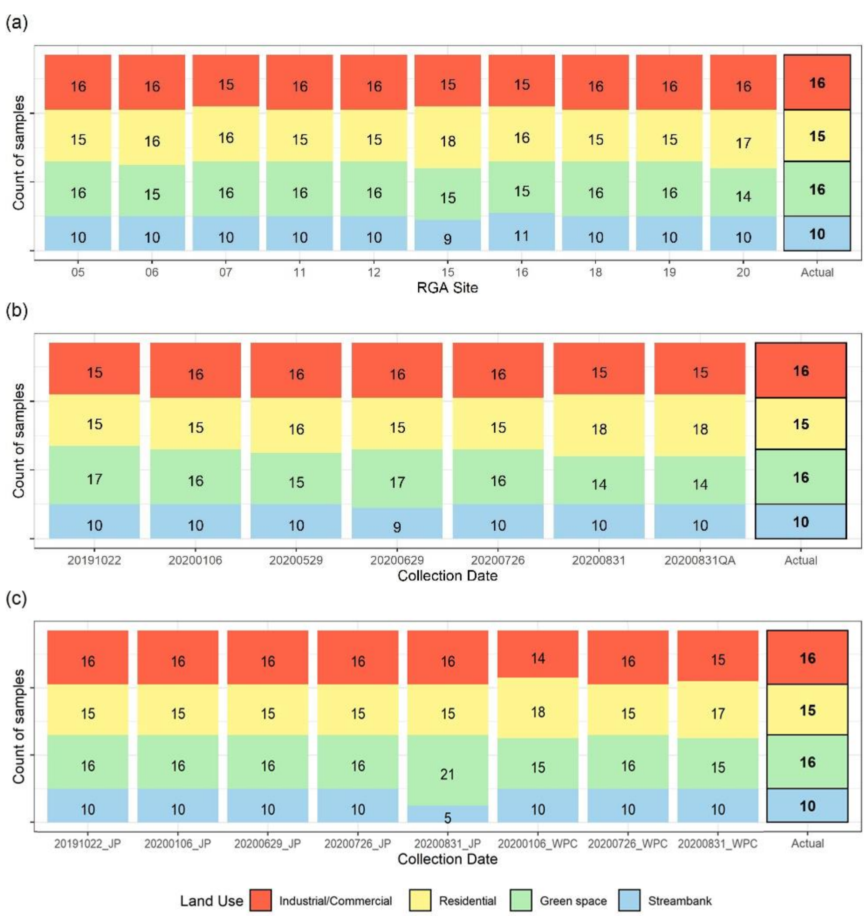

**Figure 4.** Source verification test results for (a) streambed sediment collected at rapid geomorphic assessment (RGA) sites, (b) suspended sediment samples collected at the streamgage, and (c) suspended sediment samples collected at Jackson Park (JP) and Wilson Park Creek (WPC). Values in the figure indicate the count of samples that were classified to each source group.

**Suspended Sediment Apportionment:** Sediment fingerprinting analysis shows how source contributions to suspended sediment differed over the study period based on seasonal flow conditions using discharge measured at the streamgage (Figure 5a). The results from the SedSAT tool represent the relative contribution from each source in the watershed to the target sample over the period aggregated by the suspended sediment sample; they do not incorporate suspended sediment load. At the streamgage, residential areas were the primary source contributing to the passive suspended sediment samples throughout the study period, with values ranging from 53-100% relative contribution (Figure 5b). Streambanks were a substantial source in the 10/22/19 and 7/26/20 samples (18% and 47%, respectively) when there were several moderate increases in discharge, but streambanks were not a primary source during the periods that experienced the highest discharge. There were minimal contributions from industrial areas in the fall of 2019 (4-5%) and no contribution from green space in the streamgage samples. Relative contributions from suspended sediment collected at JP from residential areas (51-65%) and streambanks (21-43%) were consistently highest throughout the study period, and green space contributions were present in the fall of 2019 and summer 2020 samples (7-24%) (Figure 5c). Suspended sediment samples at WPC were similarly attributed to residential contributions regardless of variation in discharge (84-100%), with some contribution from streambanks during the highest flow periods with samples collected on 1/6/20 and 8/31/20 (14% and 16%, respectively) (Figure 5d). There was no industrial/commercial contribution at JP and WPC.

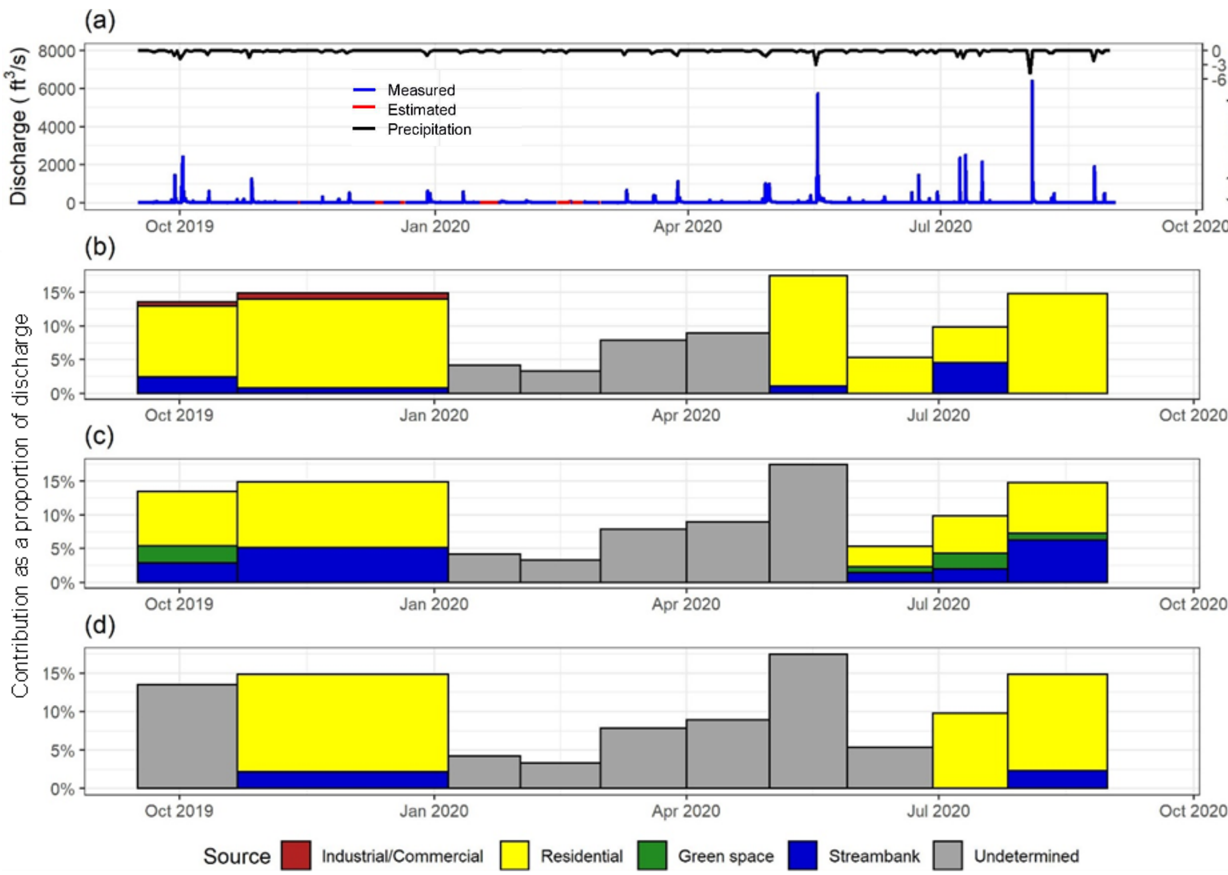


**Figure 5**. Flow-weighted source apportionment results from suspended sediment samples collected at (b) the streamgage, (c) Jackson Park (JP), and (d) Wilson Park Creek (WPC), relative to (a) discharge measured at Kinnickinnic River at 11st St. (USGS 04087159) (USGS 2022) and precipitation measured at USW00014839 in Milwaukee, WI (Menne et al. 2012a; 2012b).

A summation of the flow-weighted suspended sediment SedSAT results provides an approximation of total proportional source contribution over the duration of the study. At the streamgage, residential areas contributed 65% of estimated suspended sediment, followed by streambanks (9%) and a small contribution from industrial/commercial areas (1%) (Figure 6a). The periods over the winter and spring 2020 for which there was insufficient sample collected for laboratory analysis accounted for 24% of the estimated suspended sediment for which we do not have SedSAT results (i.e., "undetermined") (Figure 6a). The estimated proportional suspended sediment derived from residential areas at JP and WPC was similar at 34% and 35%, respectively (Figure 6b and c). At JP, 18% of estimated suspended sediment was attributed to streambanks, the highest of any of the locations sampled, and it was the only location with contributions from green spaces (7%). WPC had a small fraction of the estimated suspended sediment attributed to streambanks (4%). Since there were fewer suspended sediment samples collected at JP and WPC compared to the streamgage, the fraction of total flow over the study period that was unsampled, and therefore fraction total proportional suspended sediment contribution with undetermined source was higher at 42% and 61%, respectively.

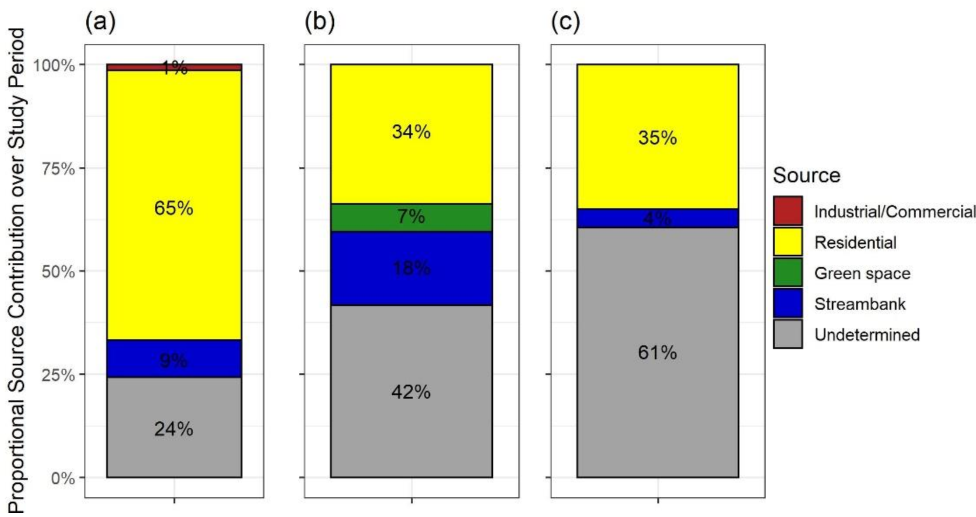


**Figure 6**. Flow-weighted source apportionment of suspended sediment over the study period at (a) the streamgage, (b) Jackson Park (JP), and (c) Wilson Park Creek (WPC).

**Streambed Sediment Apportionment:** Sediment fingerprinting analysis of soft streambed sediment deposition represents a temporal integration of sediment that has been deposited on the channel bed and gives insight into the spatial variability of sediment source contributions throughout the watershed. Overall, source apportionment showed that the streambed sediment was primarily composed of material derived from streambanks (62%) and residential areas (30%) on average. Green space was a substantial source for several samples (RGA 11,16,18, 19) but on average was not a major source of streambed sediment (7%). There was minimal contribution from industrial areas on average (1%).

Regardless of contributing area or location in the watershed, streambed sediment samples were predominantly derived from streambank contributions (Figure 7). Samples located close to the few green spaces within the watershed showed contribution from those areas (RGA 11, 16, and 18, primarily). Streambed samples from RGA 12, 16, and 19 showed a small contribution from industrial/commercial areas, which is expected given their proximity to industrial zones concentrated in the northern and southern parts of the watershed (Figure 7). RGA 06, co-located with the JP suspended sediment sampler, and RGA 07 locations are known to experience a lot of erosion and sediment transport (Blount et al. 2023; Kort and Taylor 2018), and their streambed sample source apportionment results show similar contributions from streambank and residential areas, which indicates that the sediment being stored on the unlined streambed is a combination of riparian bank erosion and the adjacent urban residential land use. The unlined sections of the Kinnickinnic River had a coarse-grained substrate relating to the elevated peak flows and driving bar occurrence overtop of the concrete sections (Blount et al. 2023; CDM Smith 2018; Kort and Taylor 2018).

There were streambed sediment samples co-located with the suspended sediment samplers at JP and WPC (RGA 06 and 12, respectively), which allowed comparison between the streambed and suspended sediment sourcing at those locations. Streambed sediment from RGA 06 at JP was predominantly derived from streambank contributions (76%) with the remainder derived from residential areas (24%), while the suspended sediment samples were derived from residential (58%), streambanks (30%), and green space (13%) on average. Streambed sediment from RGA 12 at WPC similarly showed a much larger contribution from streambanks (95%) compared to WPC suspended sediment (10% on average), while the suspended sediment samples were predominantly derived from residential contributions (64%).

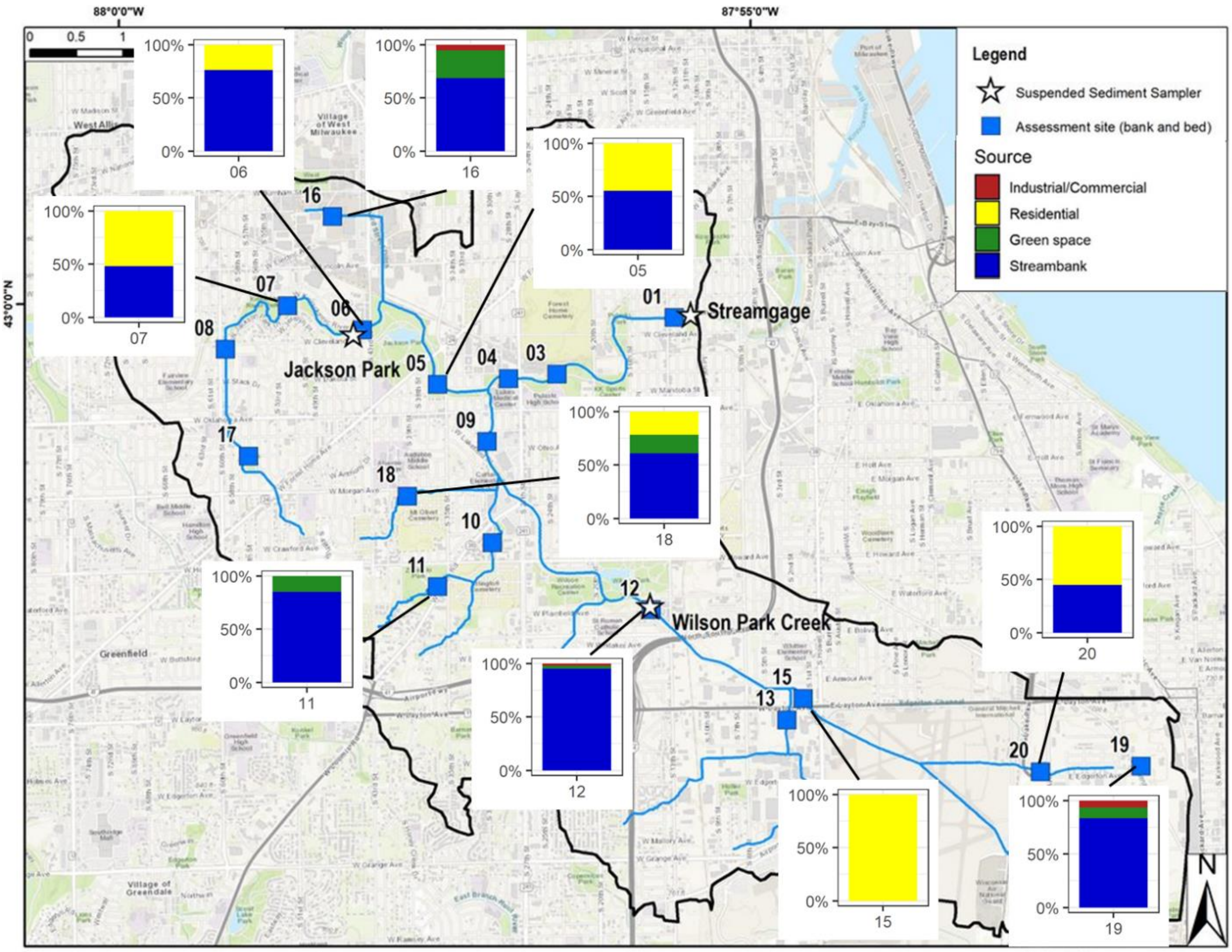


**Figure 7**. Source apportionment results of streambed sediment samples. Numbered locations refer to the corresponding rapid geomorphic assessment sites and site identification number.

# Discussion and Conclusions

The TMDL estimates a load of 2,400 mT/yr for TSS, with an estimated 98% sourced from urban runoff in the Kinnickinnic River basin (CDM Smith 2018). This is consistent with expectations for a near-completely urban watershed with historically impervious surfaces (Kort and Taylor 2018). While the TMDL does not distinguish between in-channel erosion and upland sources, our integrated sediment budget and fingerprinting approach specifically allowed for some insights into the relative contribution of these sources.

During the study period, our methods were able to link residential and streambank sources to contributing over 75% of the sediment moving past the gage over the study period. Residential sediment was the dominant source at the streamgage. Contributions from bank erosion and some green space were highest at JP compared to WPC and the streamgage due to the most unlined channels and greenspace upstream. In contrast, WPC, which is mainly concrete lined, had less bank erosion and green space in the subbasin. Streambank erosion is present in only first and second order unlined channels (Figure 3). JP suspended sediment source apportionment shows this relationship with 18% streambank sourced contributions, whereas in WPC contributions were under 5%. In other studies, mixed use and urban watersheds in the Midwest have presented more varied suspended and streambed sediment sourcing (Gellis et al. 2017; Devereaux et al. 2010; Blount et al. 2022) while agricultural basins were typically dominated by streambank erosion as the source of suspended and streambed sediment (Fitzpatrick et al. 2019; Williamson et al. 2020). The relatively high contribution of sediment from streambank erosion to soft sediment deposition indicates a continued source of streambank-derived sediment when the soft sediment is resuspended and transported downstream. However, the sediment that was actively transported as suspended sediment during the study period did not have the same dominance from streambank erosion contributions and was instead primarily derived from upland residential sources.

Notable features within the basin such as concrete lined sections, subterranean conduits beneath major infrastructure, and the possible influence of the airport runoff on sedP concentrations reduce the relative contributions from streambank sources. However, our RGAs indicated active streambank erosion and incision in reaches that were not concrete lined, contributing a roughly 1,100 mT/yr. Recent and ongoing restoration efforts have mitigated channel erosion locally (Bergquist 2019), but unlined eroding reaches upstream of Jackson Park are likely providing bank-sourced material to downstream reaches (Kort and Taylor 2018; Blount et al. 2023). Streambank erosion sedP plays a role in the overall TP load in the Kinnickinnic River (~780 kg/yr), however, to a far lesser extent than that of nearby agricultural watersheds like Plum Creek (~6,600 kg/yr) or Apple Creek (~3600 kg/yr) (Fitzpatrick et al. 2019; Williamson et al. 2020; Blount et al. 2022). Residential areas had the highest median sedP concentration of all source groups, while the median sedP concentration of suspended sediment samples were highest of any group analyzed (Figure 2). Suspended sediment became enriched in P compared to source sediment as it was transported through the stream network, even in this urbanized watershed (Fitzpatrick et al. 2019; Blount et al. 2022). The TMDL estimates 5,783 kg/yr of TP load, with approximately 78% (4511 kg/yr) derived from urban runoff and the remaining 22% (1272 kg/yr) contributed from point source inputs along the Kinnickinnic River (CDM Smith 2018). Our sediment budget estimated sedP contribution from bank erosion at roughly 780 kg/yr. While bank erosion was not distinguished as a separate source within the urban runoff partition in the TMDL P load calculations, this estimate provides a metric that may be useful for managers to consider in meeting TMDL load reductions.

The consensus-based guidelines developed by Macdonald et al. (2000) provide metrics on which to interpret sediment quality and potential toxicity to benthic organisms, and many of the metals are known to be dangerous for human and aquatic health (SEWRPC, 2007). There are several indicators in the tracer concentration data that indicate there is likely legacy contamination in the steam corridor sediment. Concentrations of several metals of interest were above PEC in stream corridor sediment samples located near concentrated industrial land use areas, such as streambank and streambed samples from RGA 16 and 19 (Figure 1) (Blount et al. 2023); however, there were also PEC exceedances among stream corridor samples located in what are currently more natural or residential areas (such as streambanks at RGA 05, 06, and 12 and streambed sediment at RGA 07 and 11) (Blount et al. 2023), implicating legacy sediment as the likely source of the contamination. Additionally, median concentrations of chromium, mercury, manganese, nickel, and lead were higher in the streambank and streambed sediments than in the industrial/commercial samples we collected. In fact, the highest outlier concentrations measured in all the metals of interest were from a single streambed sample located near an area of concentrated industrial land use in the northern part of the basin (RGA 16), with concentrations ranging from 1.3 to 13.1 times the PEC thresholds for each metal (Figure 1; MacDonald et al. 2000; Blount et al. 2023). Legacy contamination in streambanks or streambed sediment may result in metal tracer concentrations that are higher than sediment from other source areas or in suspended sediment. Erosion of these contaminated streambanks and resuspension of streambed material can mobilize these contaminants. Suspended sediment had very few instances of PEC exceedance across the metals of interest we considered, indicating that the sediment that is actively transported in the channels does not display the same contamination levels as the streambank and streambed legacy sediment.

Previous studies by the authors on Apple Creek (Blount et al. 2022) and Plum Creek (Fitzpatrick et al. 2019), both in the Lower Fox River Basin, were conducted to help inform previously established TMDLs and implement best management practices to reduce TSS and TP loads entering Lake Michigan. While this previous work identified streambank erosion as the driving contributor to TSS and at least a major consideration for sedP, the Kinnickinnic River has point source considerations and expansive residential areas contributing to sediment (CDM Smith 2018). Plum Creek, Apple Creek, and the Kinnickinnic River; in order of increasing urbanization and impervious surfaces, have shown their effects on water quality and sediment transport. Urban streams provide for an immediate vector of all sources of sediment to be transported in streams because of their flashy peak flows (Gellis et al. 2020, CDM Smith 2018). Routine "flushing" of impervious watersheds by way of these conditions, is realized in the Kinnickinnic watershed, such that streambed sediment storage is an order of magnitude smaller compared to the agricultural basins (Fitzpatrick et al. 2019, Blount et al. 2023). The relatively high concentrations of industrial related metals in streambanks and remaining streambed sediment indicate that although relatively small, the streambed sediment could be serving as a source of legacy contaminants to benthic organisms.

In the agriculturally influenced basins of Plum Creek and Apple Creek, streambank sourced sediment and sedP contributions to the total apportionment increased with drainage area. The Kinnickinnic River samples did not have such a relation, likely due to the interruption of downstream sections with more concrete-lined channels (CDM Smith 2018). Sources for streambed sediments are influenced by their immediate land use source; however, streambank erosion was still the primary source contributing over 50% in all samples except RGA 15. Comparison of sedP concentrations among Kinnickinnic and the two agricultural basins show contrasts among the common source and target groups. There were minor differences in sedP concentrations of streambank samples, where the median in the Kinnickinnic River was higher than in Apple Creek but lower than in Plum Creek. The residential source group in this study had higher median sedP concentrations than a similar residential source group in Apple Creek, which is possibly an indicator of long-term use of phosphorus fertilizers or absence of street sweeping in the Kinnickinnic basin, which is regularly done in Appleton, WI, Apple Creek's urban area. Among the common target sample groups, median sedP of suspended sediment samples in the Kinnickinnic River was comparable to Apple Creek (Blount et al. 2022) and lower than Plum Creek (Fitzpatrick et al. 2019), while there was little difference in median sedP concentration of streambed sediment samples among the three studies. Suspended sediment was enriched in sedP compared to source groups, even in this urban basin relative to Apple Creek and Plum Creek.

Sediment fingerprinting discriminated between streambank, residential, commercial/industrial, and green space sources in the Kinnickinnic River watershed. Given the strong verification test results, we were able to identify residential and streambank sources as the dominant driver of suspended sediment passing the streamgage. Streambed sediment was linked overwhelmingly to streambank, with adjacent land use influences, like residential and green space or industrial/commercial, contributing locally. The stream-corridor sediment budget estimate for streambank erosion could contribute roughly half of the annual TMDL TSS, whereas the estimated TP contributions were 13% of the annual TMDL value. Urban contaminants exceeded PEC concentrations within the streambed samples we collected and indicate a potential for legacy contamination that is being actively eroded out of the streambank and streambed as well as the presence of active point source contamination. However, these elevated concentrations were local and were not represented in downstream sites or suspended sediment samples. The sediment source apportionment results and budget estimates indicate that while residential and the urban upland are the dominant contributors for sediment, bank erosion may contribute a substantial portion from unlined reaches susceptible to flashy erosive flows.

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