Sediment provenance and transport in a mixed use, mid-sized, impaired mid-Atlantic watershed, Saucon Creek, Pennsylvania

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Sediment provenance and transport in a mixed use, mid-sized, impaired mid-Atlantic watershed, Saucon Creek, Pennsylvania

By

Rachel T. Baxter

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Sediment provenance and transport in a mixed use, mid-sized, impaired mid-Atlantic watershed, Saucon Creek, Pennsylvania

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ABSTRACT

The Saucon Creek watershed in eastern Pennsylvania drains approximately 150 km² of mixed use land that includes a significant legacy impact of mill dams and mill pond sediments. The watershed is impaired and undergoing a TMDL study driven by the hypothesis that high sediment loads are responsible for the impairment. The watershed has been instrumented to create a sediment budget in the context of its hydrology and response to storm events over summer and fall seasons of 2011, including many typical smaller to mid-size storms and a few extreme events such as the recent Hurricane Irene on 28 August 2011. A specific goal is to produce a model which links suspended sediment to turbidity given that turbidity is an easier proxy for continuous measurements over time including through flood hydrographs. Suspended sediment provenance is being assessed through a fingerprinting approach using the fallout radionuclide $^{210}\text{Pb}$. Sampling and sediment processing in the radiogenic analysis is designed to account for the effects of grain size and total organic matter. Results indicate that the flux of suspended sediment in the trunk channel in the upper watershed approaches 15 m³ over an average 48 hour fall storm to several times that amount during hurricanes with an average discharge of 500,000 m³ and average precipitation of 3 cm. The provenance of this sediment appears to be a mixed contribution from both overland and legacy sources in which the overland sources dominate the steeper headwater portions of the watershed and legacy sediments dominate in the lower reaches. These results are consistent with earlier estimates that relate annual suspended sediment flux to channel widening, a phenomena clearly documented in historic air photos.
INTRODUCTION

Excess sediment is a major source of pollutants in rivers around the world (Sundborg and Rapp, 1986). The Environmental Protection Agency (EPA) has identified excess suspended sediment to be the leading cause of water quality impairment in the United States (EPA doc. 1998). In the United States, annual sediment yields have increased over the last 300 years which is believed to be greatly attributed by land-use changes from past and present human activity (Wolman, 1967). Increasing sediment delivery to rivers in the northeast have been particularly observed with land-use transitions moving from forestlands to agricultural and grazing fields to more developed suburban and urban areas (Wolman and Shick, 1967). Increasing loads of fine sediment negatively impacts the aquatic life and biotic integrity of a stream. Initially, excess sediment destroys the natural habitat of macroinvertebrates, the porous gravel stream bottom, by imbedding the stream bottom with fine grain sediment. A decline in macroinvertebrates subsequently affects organisms in higher tropic levels and the overall health of the stream.

The Pennsylvania Department of Environmental Protection (DEP), required under the Clean Water Act, must identify all impaired water bodies that do not meet water quality standards. To comply with section 303 (d) of the Act, a total maximum daily load (TMDL) must be performed on all unattaining water bodies. A TMDL is a quantitative analysis set to define water quality standards by assessing the total amount of pollutant loading that can enter a stream without causing impairment. On a local scale, Saucon Creek located in Lehigh and Northampton Counties, Pennsylvania has been identified as
an impaired water where the identified source of pollutant is excess sediment. A TMDL is being performed on Saucon Creek where the maximum allowable amount of pollutant, suspended sediment, must be assessed.

The goal of this study is to quantify the provenance and amount of suspended sediment moving through the main channel and major tributaries of the Saucon watershed. Implicit in this study is the timely question of how much of the sediment impairing Saucon is derived from overland flow linked to specific current land use activities and how much of the sediment is derived from recruitment of legacy sediments. Legacy sediments are locally stored in floodplains and indicative of soil erosion during past land use practices. The data collected in this study will inform hydrologic models being applied by the State and local regulatory bodies so that they can develop the criteria for objective remedial actions within the TMDL process.

This study builds on a long record of scientific literature dedicated to understanding suspended sediment dynamics, fluxes, and budgets of a watershed. Of importance are the foundational studies of Dietrich and Dunne (1978), Peart and Walling (1988), and Hudson (1990). Suspended sediment transported by rivers commonly represents a mixture of sediment derived from different sources in the watershed (Collins et al., 1997; Walling, 2005). Two commonly accepted sources of suspended sediment in rivers come from the surrounding land sources through overland flow transport and from the stream channel through bank collapse and failure. Some studies expand on the overland flow component and describe physical erosion and sediment transport models of landform
evolution (Emmett, 1970; Foster and Meyer, 1975; Dunne, 1978; Julien and Simons, 1985; Prosser and Rustomji, 2000; WenJie, 2011). Other studies explore sedimentation with respect to bank failure issues (Simon, 2000; Merritts et al., 2004; Walter and Merritts, 2008; Gellis and Walling, 2011). Walter and Merritts (2008) argue a key component of channel evolution in northeastern streams is bank collapse of legacy sediment deposited by milldams in 17th through early 20th century. An analysis of historic maps in the mid-Atlantic region shows some of the highest densities of milldams and millponds in eastern Pennsylvania in 1840. Today, tens of thousands of breached milldams cause bank incision on many meandering streams, now fill terraces rather than once stable floodplains, in the mid-Atlantic piedmont (Walter and Merritts, 2008). Previous studies on Saucon Creek and nearby local streams have determined that the channel banks are widening due to stream bank erosion (Bennett, 2008; Galster, 2008).

We hypothesize that Suspended sediment is negatively impacting Saucon Creek from two unconstrained sources of sediment: (1) the remobilization of legacy sediment in stream banks and (2) sediment washed from overland flow and surface runoff. The source of suspended sediment in Saucon Creek is hypothesized to be a mixed contribution of surface sediment delivered by overland flow and legacy sediment from bank erosion. The question of sediment provenance in Saucon Creek will be explored using suspended sediment concentration estimates and sediment fingerprinting techniques. This study will calculate the suspended sediment flux moving through the stream channel through direct monitoring and provide insights to sediment sourcing through this quantification. Next,
this study will also estimate sediment provenance using sediment fingerprinting techniques, specifically short-lived radiogenic isotopes of lead.

The first part of this study quantifies the amount of suspended sediment moving through Saucon Creek channels using turbidity as a proxy for suspended sediment concentration. This approach has been suggested in applied in several published studies (Lewis, 1996; Lewis and Eads, 2001). Actual suspended sediment concentrations are directly measured by automated samplers and grab samples through the rising, peak, and falling limbs of a discharge hydrograph (Leopold et al., 1964; Garcia, 1999). Turbidity is continuously monitored with in-stream sondes. Inferences on sediment sources will be performed on sediment analysis with relation to discharge.

Sediment fingerprinting techniques serve as viable means for interpreting the provenance of suspended sediment over traditional direct monitoring techniques that may be confining due to operational and sampling difficulties (Imeson, 1974; Klages and Hsieh, 1975; Peart and Walling, 1988; Peart, 1993; Collins et al., 1998; Gellis and Landwehr, 2006;). The fingerprinting approach relies on two key steps (1) selection of the tracing property capable for discriminating potential sediment sources and (2) comparison of fingerprint property of measured suspended sediment samples to known source samples in order to determine the source of suspended sediment (Walling et al., 1999; Collins, 1998; Collins and Walling, 2002; Davis and Fox, 2009;). Some common fingerprint tracers used in the past include chemical properties (Devereux et al., 2010), physical properties (Grimshaw and Lewin, 1980), mineralogic properties (Slattery et al., 1995),
stable isotopes (Fox and Papanicolaou, 2007), and radioisotopes (Peart and Walling, 1986; Walling and Woodward, 1992; Murray et al., 1993; Walling et al., 1993). A sediment fingerprinting approach has been coupled with a sediment budget approach increasingly in previous literature to better quantify sediment fluxes within a watershed. For example, a sediment budget may be used to not just estimate the amount of sediment transported by a river but also calculate the amount of sediment derived from each contributing source while considering intermediate sediment storage and sinks (Walling et al., 2001; Wallbrink et al., 2002; Gellis and Walling, 2011; Viparelli et al., 2011).

This study will use the short-lived radionuclide, $^{210}$Pb, to provide insight on sediment provenance in Saucon Creek using a sediment fingerprinting approach. Unsupported $^{210}$Pb is a common fallout radionuclide used in sediment source fingerprinting to distinguish between surface and subsurface sediment sources (Walling and Woodward, 1992; Walling et al., 1993). $^{210}$Pb is a naturally occurring radionuclide in the atmosphere and continuously falls onto the Earth’s surface over time. It is well understood that $^{210}$Pb activity decreases with soil depth, as its half-life of 22.3 years is relatively short with respect to soil formation, and an undisturbed soil should reflect exponential decay of $^{210}$Pb with soil depth (Walling and Woodward, 1992; Du and Walling, 2012). High $^{210}$Pb activity is hypothesized to indicate surface erosion and overland flow from hillslopes, cultivations, or urbanized areas and low $^{210}$Pb activity is expected to be a channel bank source of legacy sediment. Suspended sediment samples analyzed for $^{210}$Pb will be used to establish a relative contribution of the two potential sources of sediment transported through Saucon Creek: surface soil source or bank erosion.
This study has broader impacts beyond the immediate goal of quantifying the suspended sediment provenance and concentration for a single mixed-use watershed in the mid-Atlantic region. It contributes to a body of knowledge of fluvial form and process that was inspired by many formative studies in the eastern U.S. (Leopold et al., 1964). Specifically, there remains a keen interest in exploring the response of rivers and their change in form with respect to varying watershed attributes and land uses. Dunne and Leopold (1978) provide a more in-depth summary of fluvial geomorphology with respect to river channels and morphology channel changes. Initially, channel evolution in streams was described with classic successional flow models (Schumm et al., 1984; Simon and Hupp, 1986). More recently, but in a regulatory-accessible way, channel processes and channel evolution is more thoroughly described through a controversial classification scheme proposed by Rosgen (1994). In particular, his classification of disturbed meandering streams is predicted to observe issues with accelerated bank erosion, sediment supply, and sediment deposition. The Saucon Creek watershed and quantification of suspended sediment provenance and volume provides an independent test of the concepts that have shaped regulatory policy for the past two decades.

BACKGROUND INFORMATION

Study Area

The Saucon Creek drains approximately 150 km² watershed of mixed-used land located in Lehigh and Northampton counties, Pennsylvania. The main stem is approximately 28
km in length but there are nearly 40 km of major stream channel considering the five main tributaries. A map of the study area shows the main stem and five subwatersheds with their respective tributaries, the three types of sampling sites, major roadways, and the ten municipalities located in Saucon Creek Watershed (Figure 1). The watershed comprises mixed-used agriculture, forest, recreational, industrial, suburban, and urban land-use (Figure 2). The study basin is underlain mainly by Cambro-Ordovician carbonates and calcareous shale and to a lesser degree some Cambrian siliclastics and Precambrian crystalline rocks (Figure 3). Annually, Saucon Creek receives approximately 100 cm of rainfall.

Figure 1. Map of Saucon Creek watershed study area with three types of sampling locations labeled (1) gaging station sites where discharge and turbidity was monitored over time, (2) radiogenic stream sampling locations where suspended sediment in muddy stream water in 2010 and 2011 heavy storm was analyzed for radioisotopes, and (3) radiogenic surface sampling sites analyzed for radioisotopes. The Saucon Creek watershed is located in Lehigh and Northampton County, PA.
Figure 2. Land-use map of Saucon Creek watershed. Six identified land-use types include agricultural, forest, golf course, industrial, suburban, and urban. A 2005 aerial photograph from the Pennsylvania Geospatial Data Access website was digitized by the Lehigh Valley Conservation District to create the land-use shape file layer for this map.
Short-lived Radionuclides

Short-lived radionuclides, such as $^{210}\text{Pb}$, can be used to date sediments (Figure 4) (Suominen, 1999). Naturally occurring $^{238}\text{U}$ decays in the lithosphere to the noble gas $^{222}\text{Rn}$. $^{222}\text{Rn}$ evaporates into the atmosphere where, through a decay series, decays into $^{210}\text{Pb}$. Unsupported $^{210}\text{Pb}$ has a short residence time in the atmosphere, approximately 10 days, and washes out of the atmosphere where it is rapidly adsorbed and incorporated into sediment on the Earth’s surface. $^{210}\text{Pb}$ has a relatively short half-life of 22.3 years.
and decays with soil depth (Figure 5) (Ehlke, 2002). Short-lived radionuclides have been used to identify sources of sediment transported by river bodies in previous literature (Peart and Walling, 1986; Walling and Woodward, 1992; Murray et al., 1993; Walling et al., 1993; Du and Walling, 2012;). The methods in this study are adopted from the past studies which use radiogenic isotopes to discriminate potential sources of suspended sediment.

Figure 4. $^{210}$Pb cycle adapted from Suominen (1999). Principle of $^{210}$Pb sediment dating method where $^{238}$U in the bedrock decays to a noble gas, $^{222}$Rn, which evaporates into the atmosphere. $^{222}$Rn decays in the atmosphere to $^{210}$Pb. Unsupported $^{210}$Pb falls out of the atmosphere and is deposited on to sediment where it becomes stable. With a half-life of 22.3 years, $^{210}$Pb decays with soil depth and can be used to date sediments.

Figure 5. Activity concentration of short-lived radionuclide $^{210}$Pb decreases with soil depth (Ehlke 2002).
METHODS

Geospatial data and sampling locations

A USGS Digital Elevation Model (DEM) at 3 meter resolution was extracted as a grid from www.seamless.usgs.gov which spanned the study watershed of Saucon Creek. The DEM was imported into ArcMap 10 and converted to the UTM projected coordinate system (WGS 1984) fixed and filled for any holes using the raster calculator in Spatial Analyst Tools. The watershed was delineated using multiple hydrology functions in the Spatial Analyst Tools a pour point at the base of the watershed was created. A bedrock geology layer was imported from the USGS seamless server and cut out using the shape file of the Saucon Creek watershed. Land-use coverage, courtesy of Erin Frederick at the Lehigh Valley Conservation District, was digitized with a 2005 aerial photograph downloaded from the Pennsylvania Geospatial Data Access website (Saucon Creek TMDL Alternatives Report).

The three types of sampling sites established include gaging station sites, radiogenic stream sediment sites, and radiogenic surface sediment sites (Figure 1). Gaging stations monitor discharge and the concentration of suspended sediment. These sites are marked on the main stem as G1 and G2, and on Silver Creek and Polk Valley tributaries as GT1 and GT2. Radiogenic stream sediment sampling sites are used to sample turbid water during storm events for the isolation of suspended sediment for radiogenic isotope tracing. These sites are marked as R1 to R5 (Figure 1). Radiogenic surface sample
sediment sites S1-S7 indicate where surface soils were collected and analyzed for their radioisotope concentrations.

**Discharge and discharge rating curves**

A cross section of the stream area was surveyed at each gaging station site using a Topcon total station. Along each cross section, an Onset HOBO water level data logger was installed at the deepest point, anchored to the stream bottom and protected for water flow using an automotive brake rotor, to monitor water depth. The in-stream data logger needed to be corrected with a stream side barometric pressure data logger, installed in a nearby tree or rock, in order to adjust for changes in the prevailing air pressure. The water level data loggers are sensitive for a 0-4 meter depth range and can resolve changes in stream depth of 2-3 millimeters and logged values every 15 minutes from approximately August through December 2011. Data logger pressure is converted to water depth using *Onset* software.

Stream velocity measurements were taken along the cross section transect at gaging station sites G1, G2, and GT1 during varying stream discharge and mean water depth conditions. Locations of sites G1, GT1, and GT2 were at rectangular culverts under a bridge and site G2 was tightly constrained by high, stable banks. A Marsh McBirney Flo-Mate velocity meter was used to measure stream velocity in 0.5 to 1 meter intervals across the stream. The cross sectional area of each rectangular increment, every 0.5 or 1 meters, was calculated by multiplying the width with the specific stream water level
height at that increment. Discharge, $Q$, of each cross sectional increment was found by multiplying the area of the increment by the respective velocity:

$$Q = U * A \quad \text{(1),}$$

where $U$ is the velocity read by the flow meter in m/s and $A$ is the wetted area of the channel cross section in m$^2$.

The total stream discharge at the cross section was calculated by a summation of the discharge from each increment:

$$Q_t = \sum U_{i-f} * A_{i-f} \quad \text{(2),}$$

where $Q_t$ is the total discharge of the stream in m$^3$/s, $U_{i-f}$ is the velocity of each increment (initial through final) in m/s, and $A_{i-f}$ is area of each rectangular increment (initial through final) in m$^2$.

Discharge is plotted against water depth for the different flow conditions resulting in a discharge rating curve (Figure 6). Given the mostly regular, rectangular cross-section of the channels, a linear regression was used on all discharge rating curves.
Figure 6. Hydrology rating curves express the relationship between discharge and water depth. Velocities were measured with Marsh-McBirney flow meter and converted to discharge using Equations 1 and 2. All linear regressions had $R^2$ values greater than 0.9 indicating a robust fit.

No in-stream velocity measurements were completed at gaging station site GT2 so mean flow velocity was modeled using the Manning’s equation. This equation expresses the flow velocity as a function of bed roughness ($n$), hydraulic radius ($R$) and bankful slope ($S$). The hydraulic radius, $R$, is calculated as a function of water depth, $h$, logged by the water level logger:

$$ R = A / p = A / 2h \cdot w $$.  

(3)
where the area of the cross section, A, is divided by the wetted perimeter, p, or 2h*w (height and width of the water level in the stream).

Using a measured channel bed slope (S) of 0.004, the velocity is derived from:

\[ U = \frac{1}{n} \times R^{2/3} \times S^{1/2} \] (4),

where the total flow velocity, U, in m/s moving through the cross section is calculated with the coefficient of roughness, n, the hydraulic radius, R, and the bed slope, S. The coefficient of roughness is taken to be 0.04, which is typical for a natural stream with a cobble-gravel bottom and few pools.

**Suspended sediment and turbidity - suspended sediment relationships**

Suspended sediment samples were collected at all gaging station sites. At sites G1 and G2, Teledyne ISCO automated water samplers and integrated in-depth samplers were used for suspended sediment collection while at sites GT1 and GT2 only integrated in-depth samplers were used. Samples were tested for both suspended sediment concentration (g/L) and turbidity (NTU).

To measure suspended sediment concentration, a known volume of a well-mixed sample was filtered using a pre-dried and pre-weighed Whatman glass microfiber filter, GF/F, with a 0.7µm pore size. Filters containing sediment were dried and weighed. The total weight of suspended sediment in the sample was calculated by subtracting the final dry
mass of the filter by the initial dry mass. The suspended concentration, \( S_s \), was calculated by dividing the sediment weight by the volume filtered:

\[
S_s = \frac{m_f - m_i}{v}
\]

(5),

where the final mass, \( m_f \), of the filter is subtracted by the initial mass, \( m_i \) and divided by the volume filtered, \( v \).

Turbidity was measured using a bench-top Hach turbidimeter calibrated with sealed turbidity standards (Hach). A turbidity – suspended sediment relationship was created at each gaging station site with the suspended sediment concentrations and corresponding turbidity values. Continuous measurement of turbidity was gathered at sites G1 and G2 using an in-stream YSI data sonde with a turbidity sensor. The data sonde at site G1 was owned and operated by Lehigh University and the data sonde at site G2 by the Pennsylvania DEP. All continuously logged turbidity values were converted to suspended sediment concentration constrained by the ISCO-collected suspended sediment data. Similarly, commercial standards were used to calibrate the bench-top turbidimeter and the in-stream sondes. Both in-stream sondes were calibrated using a two point calibration operating on the same commercial standards.

The two in-stream sondes performed unequally. In particular, the sonde at G2 exhibited frequent unsteady behavior. It is possible that some of the unsteadiness occurred because the sondes were alternately buried and re-excavated by bedload during the large storms.
Both sondes were anchored to the stream bottom with rebar and rocks, enclosed and protected by a PVC pipe with large holes. The pipe and sonde were placed parallel to the stream length and the turbidity sensor faced downstream. Considering the entire time series, it is obvious that during small storms and base flow conditions the sondes rarely exceed 300 NTU. As a result, that number is used as reasonable threshold to provide two separate analyses. In the first analysis, the sonde readings are capped at 300 NTU, which serves the purposes of greatly reducing the unsteadiness in the data, but which provides a rather conservative minimum estimate of the amount of suspended sediment in transport.

In the second analysis, all of the data are considered despite the unsteadiness in the sonde behavior. This analysis provides a less conservative estimate of the amount of suspended sediment in transport, but the uncertainties on the measurement are also commensurately higher. The remainder of this paper will consider results using the first analysis of turbidity values capped at 300 NTU, however for comparison, the results using all turbidity values in the second analysis are included in Appendix C.

**Sediment provenance**

Suspended sediment and soils were collected and analyzed for the short-lived radioisotopes $^{210}\text{Pb}$, $^{137}\text{Cs}$, $^{214}\text{Pb}$, $^{214}\text{Bi}$, $^7\text{Be}$, $^{234}\text{Th}$, and $^{40}\text{K}$. Soil samples were dried and disaggregated prior to sieving through a 1.00 mm mesh sieve in order to capture the $<1.00$ mm medium-fine sand fraction. This is 10 times larger than the commonly used sieve size of 0.063 mm, from where radionuclides are believed to bind (Collins *et al*., 1997; Gellis and Landwehr, 2006; Devereux *et al*., 2010). Soil samples, S1-S7, were collected from forest, legacy, agricultural field, retention basin, and construction site land
uses (Figures 1 and 7). Of the seven radiogenic nuclides measured, the analysis in this study focuses almost exclusively on $^{210}$Pb as its presence and behavior is well established in the literature (Walling and Woodward, 1992; Walling et al., 1993; Walling et al., 2003; Whiting et al., 2005; Mizugaki, 2008; Yin and Li, 2008; Fukuyama et al., 2010; Du and Walling, 2012).

Figure 7. Multiple land samples were tested for $^{210}$Pb activity in the Saucon Creek watershed. Five identified sources in the Saucon Creek watershed are legacy, forest, agricultural field, retention basin, and a construction site. Legacy sediment represents the lowest concentrations of $^{210}$Pb while forest samples represent the highest concentrations.

Similarly, suspended sediment samples in turbid storm waters were collected during large storm events in 2010 and 2011 to measure their radiogenic nuclide concentrations. The sampling was accomplished from bridges and stream banks using 20-liter plastic pails with snap-top lids. Samples were not needed to be collected at a particular stream depth.
following the assumption that all fine particles are well-mixed throughout the water column (Vanoni, 1975). Sampling runs were timed to capture suspended sediment during the rising, peak, and falling limbs of the discharge hydrograph. In September 2010, 40 liters of water were collected in two separate sampling runs at sites R1, R2, R4, and R5. The first sampling run occurred during the rising limb of the hydrograph and the second run occurred near the peak. In total, 80 liters of water were collected at each site resulting in 300 liters of sediment-laden water that was allowed to settle. In August, 2011, during the passage of the storm remnant of Hurricane Irene, 80 liters of water was collected at sites R1 through R5 in three sampling runs corresponding to the rising, peak, and falling limb of that storm's discharge hydrograph. In total, 240 liters of water was collected at each site and collectively the sampling runs generated 1200 liters of water. The water samples were allowed to settle in the plastic buckets for approximately two weeks. Afterwards, all of the clear, sediment-free water was decanted and discarded and the remaining sediment-concentrated water was left to air dry in a laboratory with regulated airflow to prevent cross contamination. The remaining, desiccated material was a combination of mineral sediment all < 1 mm grain size, mixed with particulate organic matter. Approximately 5-30 g of this material, depending on desiccated volume, was scraped from the bottom of the bucket and sent to MicroAnalytica laboratories for radiogenic analysis.
RESULTS

The data collected to evaluate the provenance and flux of sediment in the Saucon Creek watershed are assembled from hydrologic, suspended sediment, and short-lived radionuclide concentrations. These data have been collected during base flow and storm flow conditions over summer-fall seasons in 2010 and 2011 at several sites located along the Saucon main channel and some of its major tributaries (Figure 1).

Discharge and discharge rating curves

Long term discharge rates illustrate the sequencing and magnitude of storm events in the summer and fall seasons of 2011. Distinct rating curves at each gaging station site are used to estimate long term discharge with logged water depths in Saucon Creek (Figure 8a). A linear regression was the best fit to represent the relationship between discharge and water level and all regressions had an $R^2$ value greater than 0.9 indicating a robust fit (Figure 6). The rating curve equation was used to calculate stream discharge values with the logged water level values over time:

$$Q = m*h + b \quad (6),$$

where discharge, $Q$, is solved for with the regression slope, $m$, water level values, $h$, from the data loggers in meters, and the y-intercept, $b$, of the regression slope.
Figure 8a and 8b. Precipitation and level logger-derived water depths data for gaging stations on the Saucon main channel and two of its major tributaries. Refer to Figure 1 for station locations. (a) Long time-series of data for the duration of the study. (b) Detail of data for a single late-summer storm event.
Calculating the flux of sediment moving through the Saucon Creek channel heavily depends on knowing the discharge and discharge unsteadiness at the monitoring sites. Several trends and patterns in discharge were observed as a function of location in the watershed, with respect to the kind and duration of the storm, and with respect to the antecedent moisture conditions (Figure 8a). Peak flows for all sites were reached during Hurricane Irene where 15.8 cm of rain fell over a 48 hour period on 27-29 August 2011 (Figure 8b). During a given storm, water depth increases on the rising limb of the hydrograph among all monitoring sites nearly synchronously. Some hydrographs, particularly those that are responding to a rainstorm following a preceding dry period, are distinctly asymmetric with a steep rising limb and gentle, drawn-out falling limb (Figures 9-11). In contrast, there are other hydrographs that are nearly symmetrical in their rising and falling limbs (Figures 12-14). These discharges respond to precipitation events that occur during a wet period or season.

Figure 9. Site G1 during a storm event on 13-15 October 2011. Discharge (m³/s), precipitation (cm), turbidity (NTU), and conductivity (µS/cm) are all represented on unique x-axes. 12 m³ of suspended sediment traveled through the creek during this 48 hour storm event.
Figure 10. Site G2 during a storm event 13-15 October 2011. 101 m$^3$ of suspended sediment traveled through the creek during the 48 hour storm event.

Figure 11. Site G1 during a 16-18 November 2011 storm event. 9 m$^3$ of suspended sediment traveled through this storm event.
Figure 12. Site G1 during 19-21 October 2011 storm event. 11 m$^3$ of suspended sediment traveled through this storm event.

Figure 13. Site G1 during a 22-24 November 2011 storm event. 47 m$^3$ of suspended sediment traveled through this storm event.
There is an observed variation in lag time between precipitation and the rising limb of the hydrograph during storm events. Some storms appear to have a short lag time (Figures 9-11, 13, and 15-18) while other storms appear to have a longer lag time (Figures 12 and 14). Most storms that have a short lag time between precipitation and the rise of the hydrograph also are preceding a dry period, as noted above. Storms that have a longer lag time between precipitation and the initial rise in the hydrograph generally precede a wet period.
Figure 15. Site G1 during storm event, Hurricane Irene, on 27-29 August 2011. Largest magnitude storm for 2011. 58 m$^3$ of suspended sediment traveled through the creek during this storm event.

Figure 16. Site G2 during storm event, Hurricane Irene, 27-29 August 2011. Largest magnitude storm for 2011. 289 m$^3$ of suspended sediment traveled through the creek during this storm event.
Figure 17. Site GT1 during Hurricane Irene. Site located in mid watershed tributary with forest for dominate land-use. 8 m$^3$ of suspended sediment traveled through the tributary during this storm event.

Figure 18. Site GT2 during Hurricane Irene. Site located in mid-lower watershed with mixed land-use upstream of this gaging station including a heavy influence of golf courses, forest, suburban, and urban areas. 293 m$^3$ of suspended sediment traveled through the creek during this storm event.
The magnitude of discharge varies among storms in Saucon Creek which can be related to the average or bankfull conditions. The largest two events during the monitoring period occurred consecutively, Hurricanes Irene and Hurricane Lee, on 27 August and 6 September 2011. Peak discharge at G1 and G2 during Hurricane Irene reached 45 m$^3$/s and 12 m$^3$/s, and 28 m$^3$/s and 9 m$^3$/s during Hurricane Lee, respectively. These storms were substantially larger than all other monitored storms and only during these storms did water levels reach beyond bankfull and into the floodplains.

_Suspended sediment and turbidity - suspended sediment relationships_

Sediment samples measured for both turbidity and suspended sediment concentrations were used to create a turbidity – suspended sediment relationship at each gaging station site (Figure 19). A linear regression best captures the overall relationship between turbidity and suspended sediment concentration. Variations in the slope of the regression may be seen among gaging station site locations in Figure 20. A tributary gaging station site, GT2, had the steepest regression slope. On the main channel, the downstream site, G2, had a steeper regression slope than the upstream site, G1 (Figure 20).
Figure 19. Turbidity – suspended sediment relationships at four gaging stations, G1, G2, GT1, and GT2. Turbidity measured with benchtop Hach turbidimeter and suspended sediment concentrations calculated in laboratory with dry and weigh technique. Linear regressions used on relationships among all sites.

Figure 20. Sediment rating curves among all monitoring sites. Site GT2 has the steepest regression curve while site G1 has the lowest.
Continuously monitored turbidity values logged every 15 minutes at sites G1 and G2 were converted to suspended sediment values using the linear regression equation on the turbidity – suspended sediment relationship:

$$[S_S] = [S_T] - b/m$$  \(7\),

where \([S_S]\) is suspended sediment concentration from both grab and ISCO-collected samples, \(m\) is regression slope, \([S_T]\) is sample turbidity in NTU units.

A plot of measured NTU of the standards and samples for the two turbidity instruments, both in-stream and benchtop, shows a nearly perfect 1:1 relationship (Figure 21). Therefore, the analysis proceeds on the assumption that in-stream NTU measurements are the same as those made by the bench-top meter which has been used to establish the NTU-suspended sediment relationship (Figure 19).

![Figure 21. Field turbidity sonde and benchtop turbidity meter 1:1 comparison with suspended sediment grab samples.](image)
**Flux of suspended sediment**

Suspended sediment fluxes show considerable variation with respect to the monitoring sites and with respect to the size and duration of the storms. Contributing to this variation are natural factors such as discharge unsteadiness, sediment availability, and sediment delivery to the main channel via tributaries. Also contributing to the variation is operation performance issues with the turbidity loggers, a point that is addressed below.

The most common response in sediment flux behavior to a given storm event everywhere in the watershed is a sharp rise in suspended sediment during the rising limb of the hydrograph, a peak in sediment concentration the precedes the peak in the hydrograph, and rapid decrease in sediment concentration during the falling limb of the hydrograph (Figure 9). A typical peak suspended sediment concentration for an average (non-hurricane) rainstorm is 0.36 g/L (Figure 9). The total mass of suspended sediment, \( m_s \), is the integrated area under the sediment curve in Figure 9, which for this storm is \( 2.38 \times 10^7 \) g (Equation 8).

\[
m_s = S_c \times Q \times 15 \text{ min} \times t \times \frac{1 \text{ L}}{0.001 \text{ m}^3} \times \frac{60 \text{ s}}{\text{min}} \quad (8),
\]

where \( S_c \) is the suspended sediment concentration (m/L), \( Q \) is discharge, 15 minutes is the time in which \( S_c \) and \( Q \) are taken over, and \( t \) is the time period of the measured flux, in this case 48 hours.
The volume of sediment eroding off the land over per unit of time (individual storm, season, or year) may be calculated from the mass of suspended sediment. The formula used to calculate sediment volume flux, $V_s$, in m$^3$ is

$$V_s = \frac{m_s}{\rho_s} \quad (9),$$

where $m_s$ is the mass of sediment in kg and $\rho_s$ is the average density of soil, here taken to be 2000 kg/m$^3$. All suspended sediment masses and volume fluxes calculated among the four gaging stations (sites G1, G2, GT1, and GT2) over different time periods (individual storms, season, and year) are listed in Table 1.

Minimum estimates for the flux of suspended sediment traveling down the main channel of Saucon Creek at gaging station sites G1 and G2 were calculated over approximately 2 months, or 70 days, during 27 August 2011 to 3 November 2011 (Figures 22 and 23). At site G1, an estimated 1350 m$^3$ of suspended sediment traveled through the creek over the 70 days (Figure 22). This is slightly less, but comparable, to the amount of suspended sediment which traveled through site G2 over the same duration of 70 days, estimated to be 1600 m$^3$ (Figure 23). The suspended sediment fluxes calculated are underestimations because turbidity was capped at 300 NTU. The turbidity sensor behaved best at the upstream site whereas downstream the turbidity records show far more irregular and spikey behavior that are difficult to interpret in terms of sediment concentrations (Figures 22 and 23). The downstream turbidity sensor also did not return to the expected low base flow signal in the end of September and middle of October (Figure 23).
Figure 22. Total length of record at gaging station G1 in upstream location of the main channel. Discharge, precipitation, and turbidity are recorded over a 70 day monitoring period.

Figure 23. Total length of record at gaging station G2 in downstream location of the main channel. Discharge, precipitation, and turbidity are recorded over a 70 day monitoring period.
Estimates for the minimum amount of sediment moving through Saucon Creek in a 70 day period can be scaled to estimate annual sediment flux. The 70 day estimate is roughly 20% of a year, but little sediment moves during the winter months when the ground and stream are commonly frozen. Similarly, this particular record spans two seasons that were wet, including two storms derived from remnants of hurricanes. Clearly, there are uncertainties with extrapolating a partial year record with these characteristics to the entire year, but expanding the sediment-flux by a factor of four (rather than five) should reasonably account for the overestimates generated of the wet year and no sediment movement in the winter months. The formula used to calculate sediment volume and scaling up by a factor of 4 can estimate annual sediment fluxes at sites G1 and G2 (Equation 9). This calculation indicates that a minimum annual volume of soil transported by Saucon Creek at site G1 is 5400 m$^3$ and at site G2 is 6400 m$^3$. Curiously, there is not a large difference in the volume of soil that is moving through the Saucon channel from the upstream to downstream site, but the downstream site, G2, is larger. Since the mass calculations are a minimum, particularly at G2 site, this value can be used to calculate a minimum volume of soil that is uniformly stripped off of the area of the watershed upstream of the site. If all of the sediment was being contributed by overland flow, the amount stripped by mechanical erosion in a year (E) would be

$$E = \frac{V_s}{A_{db}}$$  \hspace{1cm} (10),

where $A_{db}$ is the upstream contributing area of the drainage basin in m$^2$. If the upstream contributing area is ~150 km$^2$ ($1.5 \times 10^8$ m$^2$), then the amount of erosion of soil-density...
material is 0.000042 m/yr (0.042 mm/yr or 42 m/my). Cast in terms that are perhaps easier to understand, 6000 m$^3$ would be a cube of soil approximately 18 m on a side passing by the downstream site every year.

There are multiple ways to estimate an annual sediment flux from a 70 day monitoring period. Another option is to examine the annual weather data in 2011 by counting the total number of distinct average and large storm events and scaling up from these numbers. The number of average storms, fourteen in 2011, can be multiplied by the average storm sediment flux to provide the first part of an annual sediment flux. Large storms must also be accounted for, so this number can be added to the number of large storms, two in 2011, multiplied by the large storm sediment flux to provide an overall estimate of annual sediment flux using this storm quantity approach. This method does not account for between storm and smaller storm sediment fluxes and provides an extreme underestimation of the minimum volume of sediment transported in Saucon Creek to be 330 m$^3$ of soil for site G1 and 1700 m$^3$ of soil for site G2. Inter-annual patterns in climate may be important to look at in order to determine differences in sediment fluxes between wet and dry years—2011 was a very wet year.

Sediment fluxes can be estimated at the tributary gaging station sites, GT1 and GT2 over their short, but total length of monitoring record. Gaging station site GT1 on Polk Valley tributary has a total record of 24 days from 15 August 2011 to 7 September 2011, and gaging station site GT2, on Silver Creek tributary, has a total record of 12 days from 27 August 2011 to 7 September 2011 (Figures 24 and 25). Suspended sediment
concentrations at the tributary sites were based upon actual measurements from grab samples using the dry and weigh technique rather than from estimations using the sediment rating curves. Over 24 days, 13 m$^3$ of suspended sediment was estimated to have traveled through site GT1 (Figure 24). In exactly half the time, 462 m$^3$ of suspended sediment was estimated to move over 12 days (Figure 25). No increase in turbidity is observed in discharge hydrograph during the 6 September storm, Hurricane Lee, at both tributary sites, GT1 and GT2. All available sediment may have been flushed a week prior during Hurricane Irene or there were not enough samples taken throughout this second hurricane to capture turbidity peaks (Figures 24 and 25).

Figure 24. Total length of record at gaging station GT1 on Polk Valley tributary of Saucon Creek. Discharge, precipitation, and turbidity are recorded over a 24 day monitoring period.
The good fortune of having a monitoring experiment in place during a season that included two hurricanes provides insight into the suspended sediment transport during infrequent, but large magnitude events (Figures 15 and 16). At the G1 site, sediment is mobilized during the rising limb of the hydrograph and peaks just before its crest (Figure 15). Suspended sediment concentration falls steeply and quickly following the peak, dropping quicker and more abruptly than discharge (Figure 15). Upon closer inspection, two distinct pulses of suspended sediment mirror two pulses of rainfall during the rising limb of the hydrograph (Figure 15). In contrast, at the G2 site, there is a very unsteady turbidity signal with six distinct peaks, with the first peak occurring during the rising limb of the hydrograph, similar to upstream (Figure 16).
The suspended sediment flux for Hurricane Irene was estimated to be $58 \text{ m}^3$ at site G1 and $289 \text{ m}^3$, over four times higher, at site G2 over a 48 hour period. These are underestimations as turbidity was assumed to cap at 300 NTU for suspended sediment calculations. Two tributary sites provide estimated values for the suspended sediment flushed through during Hurricane Irene, as well (Figures 17 and 18). Based upon grab samples rather than turbidity loggers, $8 \text{ m}^3$ of sediment was estimated to travel through site GT1 and $293 \text{ m}^3$ was estimated to travel through site GT2.

Suspended sediment flux estimations were calculated during a number of smaller and much more commonly seen storms at sites G1 and G2 over the monitoring period (Figures 9-14). Only one storm was well captured at both sites G1 and G2 which produced clear enough turbidity signals to estimate suspended sediment flux, which took place on 14-16 October 2011 (Figures 9 and 10). At site G1, turbidity mimics discharge in the first peak while in the second peak, turbidity peaks on the rising limb of the hydrograph before discharge peaks (Figure 9). At site G2, there are two distinct hydrographs with an unstable turbidity signal. Turbidity is maximized at 300 NTU for the longest period of time between the two discharge peaks. Suspended sediment estimated to pass through the upstream and downstream site over the 48 hour storm event on 14-16 October was 12 and 101 m$^3$, respectively (Figures 9 and 10).

Three more storms in the upper watershed, at site G1, produced clear signals of suspended sediment fluxes where $11, 9$ and $47 \text{ m}^3$ of sediment is estimated to travel through the channel during 48 hour storm events on 19 October, 16 November and 22
November (Figures 11-13). The storm on 19-21 October also has two peaks reverse in magnitude and pattern from the previous storm a week prior (Figure 9 and 12). First, the sediment peak precedes the hydrograph peak, which is the commonly-observed condition, but for this storm, the second peak in suspended sediment concentration mimics the hydrograph (Figure 12). Specifically, on 16-18 November, sediment concentration mirrors discharge until the falling limb of the hydrograph, where the sediment concentration does not return to its base level (Figure 11). On 22-24 November, the first peak signals sediment is recruited during the rising limb of the discharge hydrograph while in the second peak, sediment tracks closely with discharge (Figure 13). Another storm was captured at site G2 during 23-25 September where sediment increased before discharge, with multiple sediment peaks following throughout the first half of the storm (Figure 14). In all smaller and more commonly observed storms at sites G1 and G2, conductivity is inversely proportional to discharge (Figures 9-14).

**Sediment provenance**

Soil samples representing several different land coverages and land uses in the Saucon Creek watershed have different, but characteristic concentrations of short-lived radiogenic isotopes, such as $^{210}\text{Pb}$, that allow them to be used as a sediment provenance fingerprint (Figure 7). Forest soils expressed the highest concentrations of $^{210}\text{Pb}$ whereas the legacy sediments expressed the lowest concentrations, following the expected vertical decay of unsupported $^{210}\text{Pb}$ with soil depth (Figures 4, 5, and 7) (Walling and Woodward, 1992; Walling *et al.*, 1993; Fukuyama *et al.*, 2010). The soil in a runoff retention basin
has the second highest $^{210}$Pb activity (Figure 7). Soil from tilled cornfields and a construction site have low activity, consistent with activities that actively bring buried, relatively low-concentration material to the surface.

The $^{210}$Pb results are consistent with variability in the source of suspended sediments (non-uniform sediment contribution) as well as variability in sediment sources during a given storm (unsteady sediment contribution). An example of sediment source unsteadiness is demonstrated by a comparison of $^{210}$Pb concentrations over time in the discharge hydrograph in large storms that occurred in 2010 and 2011 (Figures 26 and 27). Suspended sediment samples tested for $^{210}$Pb were taken twice during the 2010 storm and at four locations along the stream (Figure 26). A third sampling time interval and a fifth sampling location, site R3, was added to the 2011 storm sampling protocol with the intent to identify the discrepancy between $^{210}$Pb concentration in time and space (Figure 27). Sampling throughout a discharge hydrograph illustrates how the sediment source changes as the storm progresses. For both the 2010 and 2011 storms, the highest $^{210}$Pb concentrations are observed during the rising limb of the hydrograph and approaching the peak while lower concentrations are noted during the peak or the falling limb (Figures 26 and 27). Spikes of $^{210}$Pb concentration in both years are seen in the same mid-upstream region of the watershed.
Figure 26. Sediment source unsteadiness in suspended sediment samples analyzed for $^{210}$Pb activity during a large 2010 storm in Saucon Creek. Suspended sediment samples collected at 4 locations along the stream distance and during 2 sampling intervals (rising limb and peak of hydrograph).

Figure 27. Sediment source unsteadiness in suspended sediment samples analyzed for $^{210}$Pb activity during a large 2011 storm (Hurricane Irene) in Saucon Creek. Suspended sediment samples collected at 5 locations along the stream distance and during 3 sampling intervals (rising limb, peak, and falling limb of hydrograph).
Irrespective of sampling time during the discharge hydrograph, there is a consistent pattern of where the highest concentrations of $^{210}$Pb are being delivered along the Saucon channel. The sampling locations R2 and R3 in the mid-upper watershed consistently show the highest $^{210}$Pb concentrations (Figures 26-28). In 2010, the highest $^{210}$Pb concentration was observed at site R2 and in 2011, the highest $^{210}$Pb concentration occurred in the mid-watershed at the newly added sampling site R3. At sites R4 and R5 in the lower portion of the watershed, the lowest concentrations of $^{210}$Pb are observed. The maximum activities of $^{210}$Pb from both 2010 and 2011 are compared in Figure 28 and the overall trend in higher $^{210}$Pb activity mid-upstream and lower activity downstream is clear (Figure 28).

Figure 28. Sediment source non-uniformity among suspended sediment samples analyzed for $^{210}$Pb in 2010 and 2011 storm. Maximum $^{210}$Pb activities at each site in both 2010 and 2011 storm events. $^{210}$Pb activity varies among location in watershed.
DISCUSSION

Hydrologic, sediment, and radiogenic data can provide insights on the provenance and flux of suspended sediment moving through Saucon Creek. Different hydrograph shapes were observed, possibly because of differences in the preceding hydrologic conditions, location in the watershed, surrounding land use, season, and storm magnitude. Turbidity – suspended sediment relationships varied among gaging station location, which may indicate a trend in sediment size and composition throughout the watershed.

Comparisons of discharge and suspended sediment patterns show two distinct trends in timing. One observation is that peak suspended sediment concentration occurs in the rising limb of the hydrograph. The other observation is that suspended sediment concentration varies with the discharge hydrograph. These observations can be interpreted in terms of sediment recruitment from different sources.

Sediment fluxes and erosion rates may be compared to a previous study which may express the difference in temporary and long term sediment storage in the Saucon Creek watershed (Gellis and Walling, 2011). Sediment provenance estimations may be induced from unsteady and non-uniform radionuclide concentrations of $^{210}\text{Pb}$ in Saucon Creek. The variations in $^{210}\text{Pb}$ concentrations may reflect different land cover and land use throughout the watershed. Sediment provenance interpretations may conflict between both suspended sediment concentrations and $^{210}\text{Pb}$ concentrations estimates over a hydrograph and along stream distance. These ideas are explored in depth in the following sections.
*Discharge and discharge rating curves*

Different discharge hydrograph shapes may demonstrate trends in antecedent moisture conditions, season, and location in the watershed. A short or long lag time between precipitation and discharge may reflect the distinct preceding hydrologic conditions. More specifically, a shorter the lag time between precipitation and discharge may indicate drier soils were preceding the storm and a longer lag time may indicate moist soil from recently preceding storm(s). For typical storms at site G1, hydrograph shapes follow a general single curve with each precipitation event (Figures 9, 11-13, and 15). At site G2, a single rain event often produces a single smooth hydrograph, but sometimes it produces multiple spikes in the hydrograph, indicating a lag effect in multiple flood waves from different tributaries acting as individual subwatersheds upstream of this site (Figures 10, 14, and 16).

A linear relationship was chosen to best express the discharge and water depth relationship among all gaging station sites (Figure 6). Discharge values over bankfull flows will not be accurately representative with a linear regression, but for simplification and safety purposes this was chosen because it was not possible to measure discharge over bankfull conditions. A model could better predict discharge beyond bankfull conditions in the future.

Water depth increases among sites nearly synchronously during storms, but to different degrees (Figure 8a and 8b). The small differences among the rise in discharge reflect to what degree each site responds to precipitation. Similar to results in Bennett’s work on
the Saucon, there is no large difference in discharge response time at site G2, the most downstream site on the main stem, from all other upstream sites both tributary and main stem (Bennett, 2008). This may indicate that water added to the trunk channel greatly depends on discharge input from all tributaries, especially ones closest to its site.

**Suspended sediment size and composition**

Turbidity – sediment regression slopes vary among sites suggesting a pattern to the quality of sediment with respect to grain size or composition (Figures 19 and 20). A lower slope of the rating curve may indicate coarser particles which do not scatter light as efficiently whereas a steeper slope would indicate lighter, finer particles that can scatter light, making the stream water murkier. The turbidity – sediment regression at the upstream site, G1, has a lower slope in comparison to the downstream site, G2, which indicates that the overall suspended load is coarser upstream, consistent with the general observation that bedload and suspended load fine downstream (Leopold and Wolman, 1957; Leopold et. al., 1964; Leopold and Emmett, 1997). Following this analysis, Silver Creek is predicted to have the coarsest suspended sediment grain size whereas Polk valley Run has the finest suspended loads. This may be because natural sorting and fining down does not occur as well in a disturbed area, in this case, that flows through a golf course.
**Suspended sediment fluxes and insights to sediment provenance**

The timing of sediment concentration with respect to the discharge hydrograph may lead to the discovery of the major sources of sediment. Individual storm events exhibit hydrographs and sediment concentration curves that argue for sediment being recruited from two distinct reservoirs. In our conceptual model for stream sediment flux we assume that one reservoir is an in-channel source that is readily available, but limited in volume. This is referred to as a sediment-limited part of the system when the sediment curve peaks prior to peak discharge indicating all available sediment is flushed before the discharge peak. The other reservoir is the soils of the watershed and this source is not as readily available, requiring overland flow to entrain it and transport it to the channel. This is referred to a water-limited part of the system, observed when sediment mirrors the discharge hydrograph because sediment is available and entrained throughout the hydrograph. There is some period of time preceding a storm in which sediment becomes available either in the channel, banks, or landscape and the availability of this sediment dictates these patterns to follow during storms.

These two patterns of sediment movement may tell us something about where the sediment is coming from during these storm events. Intuitively, in sediment limited events, water in the stream rises, unstable banks collapse, and there is a pulse of sediment prior to peak discharge. It follows that sediment is predominately from bank and channel recruitment in sediment limited events. By definition, in water limited events, sediment is entrained by overland flow and stream sediment would be expected to rise and fall with the hydrograph.
The two patterns of sediment-limited and water-limited behavior are apparent in Hurricane Irene and the storms to follow in the fall of 2011, most clearly visible at the upstream site (Figures 9, 11-13, and 15). Each storm in Figures 9, 12, and 13 have two distinct hydrograph peaks, one reflecting a sediment-limited event and the other reflecting a water-limited event. During the storm on 14-16 October, sediment begins to move mirroring the first small discharge hydrograph. On the second and higher discharge hydrograph, sediment becomes entrained and moves until its supply is exhausted just before the peak of this hydrograph, acting as sediment limited system (Figure 9). On the 19-21 October storm event, two subsequent storm peaks with similar rainfall offer two different sediment shapes. In the first peak, turbidity peaks before discharge indicating a sediment limited event in which the sediment moved is dominated by bank failure. During the second discharge peak, sediment supply is limited by water and most likely delivered to the stream through overland flow (Figure 12). On 22-24 November, the same type of phenomena is occurring—the first peak indicates sediment is from bank source and the second from overland flow (Figure 13). The single discharge peak on 16-18 November clearly reflects a water limited event, as turbidity mimics discharge (Figure 11).

It is important to consider the impact of rainfall intensity and storm sequencing when looking at discharge and turbidity. The chronological order of storm and within storm discharge peaks may contribute to which pattern of sediment behavior (sediment vs. water limited) is seen. In the 22-24 November storm, during the first discharge peak,
rainfall is gentle yet consistent over time and sediment is mobilized during the rising limb. During the second discharge peak, rainfall intensity builds but does not trigger sediment to peak before discharge, rather sediment and discharge are mirror images of each other (Figure 13). The same amount of sediment moves over both peaks but there is considerably greater discharge in the second peak. As available sediment moves easily at the beginning of a storm event, it may take more discharge to move the same amount of sediment in a second discharge peak of the storm (Figure 13). If there are two storm events in a relatively short period of time, the first storm may flush the readily available and loosened sediment in the channel and off the landscape so a preceding storm of the same magnitude may yield a smaller sediment output.

Storm sequencing leads to the issue of antecedent moisture condition. This issue appears to be present during two storms less than a week apart, on 14-16 October and 19-21 October (Figures 9 and 12). The first storm is preceded by a dry period, indicated in the long term record, and experiences a short lag time between precipitation and discharge whereas the second storm experiences a longer lag time (Figures 9 and 12). Because of dry conditions soil macroporosity would likely be low preceding 14 October leading to rainfall quickly reaching the river traveling over the hardpan soil. Less than a week later during the second storm on 19 October, the landscape would be already moist and thus rain would be able to infiltrate the soil to create subsurface flow, which is significantly slower than overland flow, and therefore increase the lag time of discharge after rainfall. It is clear that in the upstream site, there is an impact of storm sequencing.
Land use variation among gaging stations may also influence the lag times observed between precipitation and discharge. Each gaging station is considered a subwatershed, and all land use types draining into each respective gaging station can be summed by area (Figure 29). Looking at only the two main stem gaging stations, site G1 has a mixed land use between agricultural, forested, and suburban areas. It is important to note that the suburban area is low density housing. This land use may influence the longer lag time between precipitation and peak discharge at site G1. For example, on 19-21 October, this land use above site G1 may contribute to the longer lag time observed between precipitation onset and peak discharge (Figures 12 and 29). With minor impervious surfaces present in the G1 watershed, rainfall may be delivered to the creek more slowly with slower moving, subsurface flow. Downstream, the land use at site G2 is more complicated and drains a larger area which is dominated by suburbs composed of higher density housing with (decreasing in order of magnitude) forested, agricultural, golf course, urban, and industrial areas (Figure 29). The lag time between precipitation onset and peak discharge is often shorter at site G2 which may be due to the difference in land use and can be observed during a storm 23-25 September (Figure 14). More impervious surfaces drain into the subwatershed G2 which may shorten this lag time. Site G2 has many more tributaries feeding in which may contribute to the extended timer period of peak discharge and the spikey turbidity signal (Figures 12 and 14). Overall, land use plays an important role in sequencing and lag times between precipitation, discharge, and suspended sediment.
Figure 29. Land-uses among all gaging stations, sites G1, G2, GT1, and GT2. Land-use values at each gaging station representative of all land-use above the particular gaging station point in the watershed.
Trends exist in sediment-limited and water-limited patterns with respect to storm magnitude and storm placement among multiple-pulsed storms. Water-limited patterns, when turbidity and discharge follow each other, are typically found in very small storms with a small discharge (Figures 11-13). When there is a double-pulsed storm with two rainfall peaks, the smaller, second peak exhibits a water-limited pattern while the first, larger peak exhibits a sediment-limited pattern (Figures 12 and 13). This illustrates that when the landscape is wet a few hours after a storm, discharge and turbidity curves are symmetric in this succeeding smaller storm event.

During Hurricane Irene at the upstream site, G1, turbidity peaks before discharge indicating a sediment-limited system (Figure 15). Two pulses of turbidity and precipitation occur during the rising limb of the hydrograph which present an apparent conflict. This double pulse of turbidity and rainfall could mean that sediment is recruited from overland flow, however, intuitively in a sediment limited system (especially during the rising limb of a hydrograph), sediment is believed to be recruited from stream banks and bed. This conflict in sediment source identification may be more related to a stream morphology issue at this particular site. A large streamside grass field floods readily at this upstream site, even during small storms, which may allow for easy overland sediment recruitment (Figure 2). At this particular upstream site, overland flow must dominate over bank failure as a source of sediment during these pulses of rain. The sediment patterns during this storm may reflect both a stream morphology effect and an antecedent moisture condition effect as well.
Downstream during Hurricane Irene, at site G2, the initial flush of sediment is reflected by the first turbidity peak, with the succeeding peaks indicating lag times of sediment being flushed from other subwatersheds upstream of this site (Figure 16). Site G2 is an integration of multiple subwatersheds, possibly explaining the multiple peaks in turbidity during this event of such magnitude. Because this event was a storm of record, it may only be in this case where low flow mud is experienced. During the falling limb of the hydrograph the turbidity maxes out at 300 NTU for almost 12 hours, which could indicate actively moving bedload and burial of the meter by a sand-gravel bar (Figure 16). On a later storm at the downstream site, on 14-16 October, turbidity appears to maximize at 300 NTU multiple times, while remaining at 300 NTU for almost 24 hours (Figure 10). The extended peak in turbidity occurring between the two discharge peaks may be attributed to actively moving bedload in combination with the sensor being intermittently obstructed (Figure 10).

Conductivity measurements among all storms indicate the contributions of groundwater and surface water. In all storms highlighted in Saucon Creek, conductivity dips inversely with discharge showing a greater signal of surface water during these dips (Figures 9-16). Conductivity will also show the phases of recovery in the stream. During a large storm event with extended period of high flows, the initial low conductivity indicating a surface water source may begin to rise and indicate more of a mixed surface water and groundwater source. This can begin to be seen in Figures 10 and 16 at the downstream site, G2.
**Saucon watershed-scale erosion rates**

Observed suspended sediment fluxes can be used to estimate watershed-scale erosion rates. The estimated erosion rate of 42 m/my for the entire Saucon Creek watershed in this study is also representative of an Appalachian landscape erosion rates estimated in the mid-Atlantic region in previous studies which approximately range between 20-40 m/my (Sevon, 1989; Milliman and Syvitsky, 1992; Pazzaglia and Brandon, 1996; Matmon, 2003; Price et al., 2008). This indicates temporary storage in the Saucon watershed mimics those in the Appalachian Mountains.

**Sediment provenance**

Sediment fingerprinting is one of the best direct approaches used in sediment sourcing according to recent literature (Collins et al., 1998; Collins and Walling, 2004; Davis and Fox, 2009). Radiogenic isotopes have been used to discriminate between two main source types of sediment in a watershed—upslope regions and channel banks (Gellis and Walling 2011). In Saucon Creek, two main sources of sediment identified as surface sediment or channel-bank legacy sediment contribute to the murky sediment-laden stream water during storm events (Figure 7). Surface sediment is understood to be delivered to Saucon Creek through the process of overland flow or surface runoff while legacy sediment is understood to be recruited from bank erosion. The most obvious source for high $^{210}$Pb-concentration soil is the forested land cover. In contrast, the most obvious source for low-concentration $^{210}$Pb is the legacy sediments (Figures 26 and 27).
Two surface samples that represent the largest sediment sources in Saucon Creek come from forest and legacy sediment. Other sampled surface sources may reflect sediment sinks rather sources (Figure 7) (Gellis and Walling, 2011). The retention basin logically has the second highest $^{210}\text{Pb}$ activity, as it serves as a collection site for upland radiogenically hot sediment. Both the tilled agricultural field and construction basin have moderately low activities, reflecting a mix of highly active $^{210}\text{Pb}$ surface soils with deeper subsurface, radiogenically cold sediment (Walling and Woodward, 1992; Fukuyama et al., 2010).

Suspended sediment samples fingerprinted in a 2010 and 2011 storm indicate distinct processes occurring upstream and downstream are overland flow and channel bank recruitment (Figures 26 and 27). In these storms, higher activity of $^{210}\text{Pb}$ indicates more of an overland flow component whereas lower $^{210}\text{Pb}$ activity indicates a greater legacy sediment source. In the rising limb of the hydrograph in 2010, $^{210}\text{Pb}$ activity slightly increases downstream meaning there initially may have been some overland flow in the first time period of the storm (Figure 26). Near peak discharge, overland flow appears to be highest upstream due to the strong signal of $^{210}\text{Pb}$ while bank erosion appears to dominate downstream. It is logical that bank failure dominated downstream because as discharge and channel width increase downstream there is more power to induce bank collapse. A dilution effect may also have been occurring downstream from the convergence of multiple subwatersheds which led to lower a $^{210}\text{Pb}$ signal. In the 2011 storm during Hurricane Irene, a similar pattern of events occurred along Saucon Creek (Figure 27). At the most upstream point, $^{210}\text{Pb}$ activity is low throughout the hydrograph
which may not only indicate bank erosion dominated but also suggest that the watershed area is small and the stream was too weak at this point to deliver a lot of hot sediment through overland flow. This agrees with the similar results found by Gellis and Landwehr (2006) where low $^{210}$Pb activities were found with low discharges which indicated channel banks rather than overland flow as the source of sediment. The highest signal of overland flow occurred at 16 km during the rising limb of the hydrograph where there may have been a slug of runoff carrying sediment (Figure 27). Bank failure in the downstream portion of the watershed also appeared to be the dominate process in 2011, especially later in the hydrograph.

The scale of $^{210}$Pb activity is almost two-fold in the 2010 storm than the 2011 storm (Figures 26 and 27). While deposition rates of naturally occurring radionuclides on the land surface are constant over time, the storm events and conditions preceding these two storms may dictate to what strength of $^{210}$Pb activity is seen on surface samples. In 2010, a total of 4.5 cm of rain fell the month prior this late September storm and in 2011, a total 17.8 cm of rain fell the month preceding this late August hurricane. The significantly greater rainfall that preceded the 2011 event of Hurricane Irene may contribute to the lower $^{210}$Pb activities because greater rainfall prior to the sampled storm may have washed away the hottest surface sediment. While both storms were their largest annual events, Hurricane Irene in 2011 was a flood of record and topped the 2010 storm in magnitude with 15.8 cm of rain over 9.2 cm of rain in their 48 hour storm period. Greater rainfall during the sampled storm may have diluted the radiogenically hot surface sediment in the storm event. Suspended sediment traveling through the stream may
reflect lower $^{210}$Pb activity if the antecedent moisture condition of the surrounding landscape was dry in any recent past storms in which the hottest surface samples were more easily flushed through the watershed over the hardpan prior to the storm sampled. Issues arise among varying storm magnitudes and antecedent conditions when trying to compare sediment fingerprinting results over multiple storms.

Figure 28 represents sediment source non-uniformity among stream location. Following the interpretation that hot sediment is sourced from overland flow rather than bank erosion, a general sediment sourcing trend can be seen in Saucon Creek among storms. Looking at the maximum $^{210}$Pb activities along stream distance in both 2010 and 2011 storms, there first is a low signal of $^{210}$Pb activity at the highest watershed site (Figure 28). Overland flow dominates mid-upstream with the highest $^{210}$Pb activity between sites R2 and R3, along 16-18 km in stream distance. The decreasing $^{210}$Pb concentrations between 2-8 km indicates bank erosion is dominating downstream. It can be concluded with confidence that a combination of both banks and overland flow are non-uniformly sources of sediment in Saucon Creek.

There are unanswered questions about the possible attachment of radionuclides to the soil particles. It is largely understood that nuclide attachment is in the fines but it is unknown to what degree organics and colloidal material play a role independent of fine inorganic grain size. Methods to confine or remove the organics prior to testing radionuclide activity in sediment samples may become tricky. The organics may be removed out of a sample by ashing, however, the radionuclides are believed to remain (Walling, 2005).
Two sediment samples from the 2011 storm were split to ash half of the sample. When the $^{210}\text{Pb}$ activities of both ashed samples were compared to those unashed samples, the ashed samples yielded a higher signal of $^{210}\text{Pb}$ in both cases. This supports the theory that while the organics are removed in an ashed sample, the radionuclides are not, and if anything, they concentrate.

Seasonality may also be a factor when considering organics. It would be important to understand the role of leaf litter as there is more decomposing plant material in the fall. When decomposed leaves are washed down the stream in the fall, radionuclides attached to these leaves may produce higher activities in collected suspended sediment. On the contrary, when deciduous trees have a thick canopy in a forest during the spring and summer months, there may be an accumulation of radionuclides on the flora in which blocks collection of surface sediment on a forest floor. It would be important to understand if radionuclides are available to wash off leaves on trees during rainfall in the spring or summer or if they becoming immediately attached and will not remobilize until fall foliage and decomposition.
CONCLUSIONS

The conclusions this study in Saucon Creek exploring the sediment transport and provenance are the following:

● The minimum estimate for the flux of suspended sediment moving through Saucon Creek in an average storm in 2011 is 15 m$^3$ of soil.

● The minimum estimate for the flux of suspended sediment moving through Saucon Creek in a large storm in 2011 is 60 m$^3$ of soil.

● The minimum estimate for the flux of suspended sediment moving through Saucon Creek annually is 5500 m$^3$ of soil.

● The estimated watershed erosion rate in Saucon Creek of 42 m/yr is representative of previous estimates for Appalachian Mountain erosion rates.

● Data is consistent with a mixed contribution of surface and legacy sediment contributing to the suspended sediment moving through Saucon Creek.

● Overland flow dominates upstream and bank erosion of legacy sediment dominates downstream.

● Overland flow dominates during the early part of a large storm in the rising limb of a storm discharge hydrograph.


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Figure A1. Gaging station site G1 over 70 days with raw turbidity values.

Figure A2. Gaging station site G2 over 70 days with raw turbidity values.
Figure A3. Gaging station site G1 during Hurricane Irene on 27-29 August 2011. Turbidity reflects raw values recorded by sonde and is not cut off at 300 NTU.

Figure A4. Gaging station site G2 during Hurricane Irene on 27-29 August 2011. Turbidity reflects raw values recorded by sonde and is not cut off at 300 NTU.
Figure A5. Gaging station site G2 during storm on 23-25 September 2011. Turbidity reflects raw values recorded by sonde and is not cut off at 300 NTU.

Figure A6. Gaging station site G2 during storm on 13-15 October 2011. Turbidity reflects raw values recorded by sonde and is not cut off at 300 NTU.
Figure A7. Lag time between peak discharge and peak turbidity among two gaging station sites on the main stem, G1 and G2. Lag time is greater on site G2 which is downstream of site G1.

Figure A8. Lag time between peak discharge and peak turbidity compared to the total discharge over each 24 hour storm event.
Figure A9. Lag time between peak discharge and peak turbidity against the total suspended sediment flux over each 24 hour storm event.

Figure A10. Total suspended sediment flux versus total discharge flux on each storm event on sites G1 (blue) and G2 (red). Linear regression equations displayed for site G1 and G2. The greater the total discharge flux is over a 24 hour storm event, the greater the total suspended sediment flux over that same period of time.
APPENDIX B

All tables are included in electronic form in Microsoft Excel spreadsheets.

Table A1: Suspended Sediment and Turbidity
Master spreadsheet of measured suspended sediment, field turbidity, and benchtop meter turbidity among upstream, downstream, and two tributary sites of Saucon Creek. Data for the development of sediment-turbidity rating curves included here.

Table A2. Cross Section and Discharge
Master spreadsheet of discharge along four cross sections (upstream, downstream, and two tributary sites) during varying conditions (i.e. varying water level) to develop hydrology rating curve.

Table A3: Discharge, Turbidity, Precipitation, and Conductivity
Master spreadsheet of water level, calculated discharge, turbidity, calculated suspended sediment, conductivity, and precipitation with time among upstream, downstream and two tributary sites of Saucon Creek

Table A4. Radiogenic Data
Activities of seven short-lived radioisotopes (\(^{210}\)Pb, \(^{214}\)Pb, \(^{214}\)Bi, \(^{137}\)Cs, \(^{7}\)Be, \(^{234}\)Th, \(^{40}\)K) on suspended sediment samples collected from two large storm events (2010 and 2011), surface sediment samples, and stream bed sediment samples along Saucon Creek.
APPENDIX C

Picture A1. Muddy Saucon Creek with visible suspended sediment at site GT2.

Picture A2. Suspended sediment imbedded in a gravel and cobble stream bed in a Pennsylvania stream.
Picture A3. Imbedded stream bed on Saucon Creek near site G1.

Picture A4. Healthy array of typical macroinvertebrates found in Pennsylvania streams—aquatic sowbug, segmented worm, caddisfly larvae, mayfly, stonefly, aquatic beetle, and midge.

Picture A6. View of site G2 on main stem at Cummings Farm.

Picture A7. View of tributary Black River Run, just a before convergence into main stem of Saucon Creek at site G2.
Picture A8. Use of total station to measure cross sectional area and dimensions of selected stream cross section, in these pictures, at site G2.


Picture A10. Flooding of field just before ahead bridge over site G1 during Hurricane Irene. Field floods before bridge, which is higher in elevation.
Picture A11. Six pictures of flooding at site G2 on Cummings Farm property during Hurricane Irene.
A12. Site R1 at Cozy Corners Road bridge after peak discharge during Hurricane Irene. Flood plain plants matted down from over bankfull flows.

A13. Site R2 at Lanark Road bridge during Hurricane Irene sampling collection of sediment.
A14. Site R3 at Camp Meeting Road bridge during Hurricane Irene sampling collection for radioisotope analysis.

A15. Site R4 at Old Mill Bridge off of Reading Road during Hurricane Irene flooding.

A16. Site R5 at Saucon Creek baseball fields, post major flooding and post peak discharge of Hurricane Irene.
A17. Visible suspended sediment traveling through Black River Run by Bingen Road bridge during rising limb of hydrograph in Hurricane Irene.

A18. Flooding in upper watershed of Saucon Creek during Hurricane Irene. Intersection between 309 and Center Valley Parkway flooded at least 3 cars.

A19. Flooding in lower watershed of Saucon Creek during Hurricane Irene at Walnut Street bridge.
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