DETERMINING THE RESIDENCE TIME OF MERCURY-CONTAMINATED FINE-GRAINED SEDIMENT IN THE HYPORHEIC ZONE OF A GRAVEL BED RIVER USING RADIONUCLIDE DATING METHODS

by

Suzann Nicole Pomraning

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Geology

Fall 2011

Copyright 2011 Suzann Nicole Pomraning
All Rights Reserved
DETERMINING THE RESIDENCE TIME OF MERCURY-CONTAMINATED
FINE-GRAINED SEDIMENT IN THE HYPORHEIC ZONE OF A GRAVEL
BED RIVER USING RADIONUCLIDE DATING METHODS

by

Suzann Nicole Pomraning

Approved: ____________________________________________________________
James E. Pizzuto, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____________________________________________________________
Susan McGeary, Ph.D.
Chair of the Department of Geological Sciences

Approved: ____________________________________________________________
Nancy Targett, Ph.D.
Dean of the College of Earth, Ocean, and Environment

Approved: ____________________________________________________________
Charles G. Riordan, Ph.D.
Vice Provost for Graduate and Professional Education
ACKNOWLEDGMENTS

Thank you to my advisor, Dr. Jim Pizzuto for his guidance, support, and encouragement throughout this project. I also appreciate the insight and assistance provided by my committee members, Dr. Kyungsoo Yoo and Dr. Chris Sommerfield. I am grateful for field work assistance from Dajana Jurk, Stephanie Stotts, Josh Collins, and Scott Gregory. Thank you to Beth Weinman, Chunmei Chen, and Cristina Fernandez for helping me with the laboratory equipment. I would also like to thank my family, friends, and professors at both Clarion University of Pennsylvania and University of Delaware for their support throughout my education.

Financial support for this project was provided by the DuPont Company.
# TABLE OF CONTENTS

**LIST OF TABLES** ........................................................................................................ vii  
**LIST OF FIGURES** ..................................................................................................... viii  
**ABSTRACT** ................................................................................................................ xi

Chapter

1 INTRODUCTION ........................................................................................................... 1  
1.1 History of mercury pollution in the South River, Virginia ............................... 1  
1.2 Importance of fine-grained sediment in the hyporheic zone ......................... 2  
1.3 Cycling of fine-grained sediment in the hyporheic zone............................... 3  
1.4 The use of radionuclides to determine sedimentation rate ............................ 4  
1.5 Pilot study on the hyporheic zone of the South River using  
    radionuclide dating techniques ............................................................................ 5  
1.6 Focus of this study ............................................................................................... 7  

2 STUDY AREA .............................................................................................................. 9  
2.1 Geomorphic setting ............................................................................................ 9  
2.2 Study site ............................................................................................................ 10  
2.3 Recent History of Dooms Dam ......................................................................... 12  
2.4 South River bed material composition .............................................................. 13  
2.5 Climate and hydrology ..................................................................................... 14  
2.6 Scour chain locations ....................................................................................... 15  

3 METHODS .................................................................................................................. 17  
3.1 Geomorphic characterization .......................................................................... 17  
    3.1.1 Grain size ........................................................................................................ 17  
    3.1.2 Longitudinal profile ..................................................................................... 17  
    3.1.3 Hydrograph Monitoring .............................................................................. 18  

iv
3.2 Scour chains .................................................................................................................. 18
  3.2.1 Installation ............................................................................................................... 18
  3.2.2 Threshold of Sediment Motion .......................................................................... 20
  3.2.3 Monitoring of the scour chains ......................................................................... 21
  3.2.4 Statistical test of scour chain data .................................................................... 22
3.3 Sampling bed sediment ............................................................................................. 23
  3.3.1 Initial sampling program ..................................................................................... 24
  3.3.2 Obtaining sand samples from the bed ................................................................. 26
  3.3.3 Suspended silt and clay samples .......................................................................... 28
  3.3.4 Surface sand samples .......................................................................................... 30
3.4 Sample Preparation .................................................................................................... 30
3.5 Mercury analysis ......................................................................................................... 31
3.6 Loss on ignition ........................................................................................................... 32
3.7 Surface area analysis .................................................................................................. 32
3.8 Radionuclide activity ................................................................................................. 33
3.9 Activity measurement .................................................................................................. 36
3.10 $^{210}$Pb activity calculation ....................................................................................... 38
  3.10.1 $^{210}$Pb Detector Efficiency ($\varepsilon$) ................................................................. 38
  3.10.2 Yield ($\gamma$) ........................................................................................................ 41
  3.10.3 Core 11-4-09 and suspended clay and silt activity calculation ..................... 42
  3.10.4 $^{210}$Pb activity calculations for 7-15-10 sand samples and surface sand ...... 43
3.11 $^7$Be and $^{137}$Cs activity measurements .................................................................... 43
  3.11.1 Efficiency ($\varepsilon$) ............................................................................................... 43
  3.11.2 Yield ($\gamma$) .......................................................................................................... 44
  3.11.3 Activity calculation for all samples ..................................................................... 44
3.12 Counting statistics ..................................................................................................... 44
  3.12.1 Minimum detectable activity (MDA) ................................................................. 44
  3.12.2 Error calculations ............................................................................................... 45
LIST OF TABLES

Table 2-1. Characteristic types of streambed material along the South River (Pizzuto, unpublished data). ................................................................. 14

Table 2-2. Flow gaging stations and selected information for the South River between Waynesboro and Port Republic, Virginia. .................. 15

Table 3-1. The cores used for each depth interval sample and the weight of each sample for core 11-4-09. ................................................................. 31

Table 4-1. Peak flows for each measured event for scour chain monitoring. 49

Table 4-2. Surface area for core 11-4-09 and the suspended sediment sample................................................................................................. 52

Table 4-3. Surface area for sand samples from 7-15-10 and the surface sand samples. .......................................................................................... 53

Table 5-1. The ages of sediment based on $^7$Be and excess $^{210}$Pb activities found in Core 11-4-09. ................................................................. 58

Table 5-2. Values selected for modeling the radionuclide activity of bed sediment using equations 5-2 and 5-3. ........................................ 61

Table 5-3. Sediment ages based on activity modeling. Year of deposition is calculated by subtracting the age from 2009, the year when samples were collected. ......................................................... 65

Table 5-4. Large flow events that occurred during scour chain monitoring. The values of significant scour and fill are listed in the last column. Positive values indicate bed scour. Negative values indicate fill. .................................................................................. 68
LIST OF FIGURES

Figure 1-1. Activity of excess $^{210}$Pb in two cores collected in February 2009 (Pizzuto, unpublished data). The activities of suspended sediment samples are indicated by fuchsia points plotted at a depth of 0 cm on the x-axis. .................................................. 6

Figure 1-2. The calculated ages of sediment in two cores from South River, Virginia (Pizzuto, unpublished data). The grey dashed line indicates an apparent sediment accumulation at a rate of 2.2 mm/year. ................................................................. 7

Figure 2-1. The location of the South River in Virginia (after Pizzuto et al., 2006), and of the study site. The direction of flow is indicated with an arrow. ................................................................. 10

Figure 2-2. Aerial photograph of the study site near RRM 4.3 taken in 2005. ....... 11

Figure 2-3. Location of bedrock outcrops along the South River (image from Narinesingh, 2009). The thick black lines indicate the location of bedrock outcrops on the riverbanks and the bed. The grey line is the centerline of the channel. The location of Dooms Dam is indicated by a yellow triangle and the red circle is the study site. ...... 13

Figure 2-4. Location of the scour chain transects near RRM 4.3 .................. 16

Figure 3-1. Scour chains used to measure scour and fill of the bed. (A) Scour chain attached by U-bolt to a Platypus brand anchor. (B) Scour chain installed in the channel. .................................................. 19

Figure 3-2. Illustration of how scour chains provide a reference for measuring scour and fill in bed elevation. (a) A scour chain is installed at low discharge. (b) A large discharge event causes bed to lower and scour chain to be exposed. (c) Fill occurs on top of the exposed chain. (Figure from Nawa and Frissell, 1993) ............... 22

Figure 3-3. Location of five coring sites near RRM 4.3 in November 2009. The green points labeled 1-5 are the coring locations. The point labeled 4.3 indicates the relative river mile. ........................................ 25
Figure 3-4. Methods of core retrieval. (a) The rotating post-hole digger used to remove the first core. (b) Hammering the core barrels into the gravel bed. ................................................................. 25

Figure 3-5. Photographs of the core being prepared for sampling. (a) The core barrel being placed on the platform before it was placed in the jack system. (b) The core barrel placed in the jack system. (c) Sediment was removed in 5 centimeter increments from the top of the core barrel................................................................. 26

Figure 3-6. The 55-gallon drum inserted into the river bed.................................. 27

Figure 3-7. Surveys were taken inside of the core with an auto level and stadia rod to determine the depth of sediment that was sampled for each interval ................................................................. 28

Figure 3-8. Suspended sediment samplers in place at RRM 3.5. The sampler outlined in yellow was 0.61 meters above the low water stage and used in this study to collect suspended sediment prior to April 2010................................................................. 29

Figure 3-9. The U-238 decay series with elemental half-lives expressed in years (y), months (mn), and days (d). (Image from www.olivermagand.com) ................................................................. 34

Figure 3-10. An illustration of peak and background energies. The diamond icons represent peak channels in the ROI. The triangle icons represent the continuum that is used to calculate the background input of gamma radiation................................................................. 37

Figure 4-1. Grain size distribution of the bed material at RRM 4.3. ............... 47

Figure 4-2. Survey of the bed and water surface at RRM 4.3......................... 48

Figure 4-3. Scour and fill results from scour chain and cross section data. Negative values indicate fill and positive values indicate scour. ....... 50

Figure 4-4. Total mercury concentrations measured in core 11-4-09. The hollow diamond point at a depth of 0 cm marks the mercury concentration in the suspended sediment sample......................... 51
Figure 4-5. Loss on ignition results from sand core 7-15-10 and the surface sand samples. ............................................................... 52

Figure 4-6. $^7$Be activity with depth in Core 11-4-09 normalized by surface area. The diamond represents the $^7$Be activity in the suspended sediment. The horizontal width of each box is the calculated activity error. ............................................................... 54

Figure 4-7. $^{137}$Cs activity normalized by surface area in Core 11-4-09. The horizontal width of each box is the calculated activity error. The diamond indicates that there is no $^{137}$Cs activity in the suspended sediment sample. .................................................................................. 55

Figure 4-8. Excess $^{210}$Pb activity in Core 11-4-09 normalized by surface area. The diamond represents the activity of $^{210}$Pb in the suspended sediment. The horizontal width of each box is the calculated activity error. ............................................................... 56

Figure 5-1. Calculated values of $A_y$ from equation 5-2 plotted against the measured activity of $^7$Be from Core 11-4-09. The “arms” around each point represent error. ............................................................... 62

Figure 5-2. Calculated values of $A_x$ from equation 5-3 plotted against the measured activity of excess $^{210}$Pb from Core 11-4-09. The “arms” around each point represent error. ............................................................... 62

Figure 5-3. The cumulative age distribution of fine sediment in core 11-4-09. ............................................................................................................. 63

Figure 5-4. Range of mercury concentrations the South River based on Monte Carlo simulations (from Skalak and Pizzuto, in press). ............... 66

x
ABSTRACT

Fine-grained sediment and associated contaminants mediate important geochemical cycles in the hyporheic zone of gravel-bed rivers, but the residence time of fine particles in these environments has rarely been measured. The activity of $^{210}\text{Pb}$, $^{137}\text{Cs}$ and $^7\text{Be}$ was measured in samples from four cores obtained on November 2, 2009 from a representative section of the bed composed of a mixture of sand, pebbles, and cobbles. The median grain size is 25.5 mm, the 84th percentile grain diameter is 57.8 mm, and 5.7% of the bed is composed of sediment smaller than 2 mm (sand sized or smaller sediment). Sediment cores were sampled at five centimeter depth increments and each sample was sieved to extract the silt- and clay-sized particles. After freeze-drying the samples, equivalent depth intervals from all the cores were combined to yield a spatially averaged sample with depth intervals of 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm and 20-25 cm. Radionuclide activities were measured using a Canberra low energy germanium detector (model GL2020R). The activity of $^{210}\text{Pb}$ and $^7\text{Be}$ at the time of deposition was estimated from suspended sediment samples collected during a high flow event (recurrence interval 0.24 years) that occurred on November 13, 2009. A two-component age model was used to rectify the difference in ages obtained from single samples that contained both ‘young’ sediment (age determined from $^7\text{Be}$ activity) at depth and ‘old’ sediment (age determined from $^{210}\text{Pb}$ activity). Modeling results indicate that the residence time of the silt-clay fine fraction of the hyporheic zone is approximately 38 years. Scour chains and bed elevation measurements were also used to document relative bed elevation change. Even if all ongoing sources of mercury to the South River are removed, several decades will be
required for the South River to cleanse its hyporheic zone of contaminated silt and clay through episodic scour and fill.
Chapter 1

INTRODUCTION

1.1 History of mercury pollution in the South River, Virginia

A rayon acetate fiber manufacturing facility in Waynesboro, Virginia, was operated from 1929 to 1950 by the DuPont Company. Because of the use of mercuric sulfate in production and unsuitable waste disposal methods, mercury was released into the South River. In the 1980s, a state-administered trust fund was established to create a 100-year mercury monitoring program for fish, water, and sediment in the South River.

Researchers expected the mercury levels to decrease over time, but data collected in the 1990s indicated that mercury levels have remained steady in fish and sediments (www.southriverscienceteam.org/publications/fact-sheets/index.html, accessed 6/12/2011). In the fall of 2000, the South River Science Team (www.southriverscienceteam.org) was formed to find solutions to the South River’s mercury problem. The South River Science Team is an interdisciplinary team of scientists, state and federal regulation agencies, industry representatives, members of the public, and environmental groups who collect and interpret information to help mitigate legacy mercury contamination in the South River watershed. The South River Science Team is actively studying different components of the ecosystem in an attempt to characterize the extent of pollution. Ultimately, the goal is to develop and implement
management and remediation plans focused on solving the environmental challenges caused by mercury in the South River.

1.2 Importance of fine-grained sediment in the hyporheic zone

The hyporheic zone is the zone below and adjacent to the stream bed in which groundwater and surface water mix. The term hyporheic is derived from Greek roots – hypo, meaning under or beneath, and rheos, meaning a stream (rheo means “to flow”) (Smith, 2005). Many different definitions exist for the hyporheic zone depending on the area of study. White (1993) defined the hyporheic zone as ‘the saturated interstitial beneath the stream bed, and into the stream banks, that contain some proportion of channel water, or have been altered by channel water infiltration’.

Knowledge of the residence time of fine-grained particles in the hyporheic zone of a river is fundamental to understanding the cycling of contaminants and for developing management strategies for controlling contamination. Sand, silt, clay, and fine organic matter stored in the matrix of the gravel river bed are important because these materials influence ecological processes and cycling of contaminants and nutrients.

Contaminated particles are currently being eroded from the banks of the South River and are temporarily stored in the hyporheic zone (Flanders et al., 2010). Mercury, a contaminant linked to the degradation of surface waters, is transported primarily in the particulate state attached to fine particles. As these fine particles move through the river system, they are deposited in the gravel matrix of the river bed. Once deposited, the
sediment can be transformed from inorganic mercury to methylmercury by a process called mercury methylation. Anoxic conditions have a large role in this cycle.

Once mercury is methylated, it is absorbed or consumed by small organisms which are then eaten by larger biota. Because these organisms are efficient at collecting and storing methylmercury, over time their bodies accumulate the methylmercury contained in their food. From this process, small amounts of mercury in the environment can result in high concentrations of mercury in fish and other large organisms. Fish species of particular concern are smallmouth and largemouth bass because they are at the top of the food chain and are popular with anglers in the South River. Fish consumption advisories have been in place on the South River and South Fork Shenandoah River for nearly three decades.

1.3 Cycling of fine-grained sediment in the hyporheic zone

During a flood event, decreases and increases in the vertical position of a streambed are known as scour and fill, respectively. Scour and fill of bed material is a key component of the cycling of fine-grained sediment in the hyporheic zone. A study by Montgomery et al. (1996) explored the relationship between bed scour and salmon egg burial depths in two creeks near Juneau, Alaska, and Puget Sound, Washington. Scour depths measured by 104 scour chains in the low-gradient, gravel-bedded rivers had a roughly exponential distribution. Depths ranged from 0 to 60 cm with an average scour depth of 13.4 cm during approximately bankfull events. Bankfull flows are typically related to discharges with recurrence intervals of 1 or 2 years (Wolman and
Leopold, 1957; Wolman and Miller, 1960; Dury, 1973; Williams, 1978). A probability model of scour and fill depths in gravel-bed channels was created by Haschenburger (2004). From this model, it was determined that scour and fill occurs on the scale of decimeters annually in gravel-bedded rivers.

1.4 The use of radionuclides to determine sedimentation rate

Fallout radionuclide analyses have proven to be useful for determining rates of geologic processes in a variety of sedimentary environments. Stihler et al. (1992) used $^{210}$Pb and $^{137}$Cs techniques to date lacustrine sediments that were previously dated by counting rhythmtes interpreted as varves. By measuring the radionuclide activity, they found that the sedimentation rate was an order of magnitude lower than the estimate based on counting rhythmite beds. The $^{210}$Pb and $^{137}$Cs data demonstrated that the rhythmite layers in the lake sediment were not annual varves and other interpretations based on the varve-derived sedimentation rates should be reevaluated.

Singer and Aalto (2009) successfully employed $^{210}$Pb to measure sediment accumulation patterns on engineered floodplains. By analyzing the activity of $^{210}$Pb with depth in sediment cores, they were able to distinguish discrete flood events from normal atmospheric $^{210}$Pb deposition. One core showed an elevated level of excess $^{210}$Pb activity that rapidly decreased to background levels in the upper 12 centimeters of the core, which they termed an “ingrown meteoric cap”. The core was interpreted as having no apparent sediment accumulation based on the decreasing nature of excess activity within the cap. They interpreted this pattern of decreasing excess $^{210}$Pb activity as meteoric
fallout that has been collecting in this core for approximately 20 years, after a scour event that occurred in the 1980s. This demonstrates that the $^{210}$Pb profile of floodplain sediments can be ‘reset’ by large flood events that have a force strong enough to scour away the previous, older flood deposits.

Recent research suggests that these tools might also be useful for determining rates of sediment storage and reworking in river beds. Fisher et al. (2010) dated sand-sized sediment in the Ducktrap River of coastal Maine using $^7$Be. Their results suggest that reach-scale variability in unit stream power and in-channel obstruction frequency affect sediment storage times. Transport-limited reaches provide longer-term sediment sequestration, generally greater than 100 days. Supply-limited reaches have shorter sediment sequestration timescales, usually fewer than 100 days at less than bankfull discharges.

1.5 Pilot study on the hyporheic zone of the South River using radionuclide dating techniques

In a 2008-2009 pilot study (Pizzuto, unpublished data), the age of mercury-rich, fine-grained (sand-sized and smaller) sediment in sand and pebble deposits of the South River hyporheic zone was measured. These sediments were located on the inside of a river bend that is slowly migrating. This migration causes erosion of the outer bank and deposition of sediment on the inside of the bank, creating an accreting point bar platform where sediments are accumulating.
Age was calculated using $^{210}\text{Pb}$ activity (Figure 1-1) and supported by the age-depth relationship of $^{137}\text{Cs}$ peaks, which mark sediment deposited around 1963-1964 (Ritchie and McHenry, 1990). Bed material from these two areas was as much as 100 years old at depths of 25 cm. These sediment ages suggest a long term sediment accumulation rate of approximately 2.2 mm/year (Figure 1-2). This sedimentation rate could be attributed to the slow lateral migration of the channel and point bar accumulation at the sampling sites. Based on these data, the mercury contained in these deposits is likely to persist indefinitely.

**Figure 1-1.** Activity of excess $^{210}\text{Pb}$ in two cores collected in February 2009 (Pizzuto, unpublished data). The activities of suspended sediment samples are indicated by fuchsia points plotted at a depth of 0 cm on the x-axis.
Figure 1-2. The calculated ages of sediment in two cores from South River, Virginia (Pizzuto, unpublished data). The grey dashed line indicates an apparent sediment accumulation at a rate of 2.2 mm/year.

Sand and pebble deposits on accreting point bars from the pilot study comprise only a small portion of the bed material in the South River. The current study focuses on mud and sand-sized sediment which is intermixed with larger, gravel-sized sediment near the thalweg of the channel, a more spatially extensive portion of the river where aggradation of the streambed is unlikely.

1.6 Focus of this study

The goal of this study is to determine the residence time of mercury-contaminated fine-grained sediment in the hyporheic zone. Residence time is the average amount of time that sediment of interest spends in the hyporheic zone. The focus of this study is on a representative section of the river with sand and cobble bed material because these areas are abundant along the South River. It was hypothesized that the time required for the South River to remove mercury-contaminated sediment
stored in the sand and cobble sections of the hyporheic zone through natural processes can be estimated using radionuclide activities.

This study is different than other studies that use fallout radionuclides for dating sediment because the gravel bed is not a constantly accreting surface. The traditional pattern of exponential decay with depth that is observed in constant flux models is not expected in an active river channel. This study is an exercise to test if this method of dating sediment in an active channel is possible, not to apply methods that assume net accumulation of sediment with time (Stihler et al., 1992).

The initial radionuclide activity will be determined from sediment suspended in the channel, and then the radioactive decay formula will be used to compute the age of bed samples. Knowledge of the age distribution of these samples leads to a computation of the average amount of time that sediment spends in the bed (residence time) using the methods of Bolin and Rodhe (1973). In order to determine residence time using this method, two assumptions must be made. The first assumption is that the mass of fine sediment is constant with time. The second assumption is that the hyporheic zone is “well-mixed”. In this context, well-mixed means that all fine sediment in the hyporheic zone has an equal probability of being eroded or removed from the bed surface.

Based on a previous study by Haschenburger (1999), I hypothesize that the bed should be scoured and filled on a scale of decimeters annually. I also hypothesize that the fine particles near the surface of the bed are affected by the turbulence and scour related to high discharge events several times per year.
Chapter 2

STUDY AREA

2.1 Geomorphic setting

The South River is a single-thread, sinuous, gravel-bed (average sediment diameter > 2mm) river that flows north from Waynesboro to Port Republic, Virginia, in the Valley and Ridge Geomorphic Province of Virginia (Figure 2-1) (Bingham, 1991). The South River merges with the North River to create the South Fork of the Shenandoah River, which in turn joins the Potomac River at Harpers Ferry, Virginia. Deposits of the South River valley include alluvium, fluvial terraces, and alluvial fans with frequent outcrops of Paleozoic clastic and carbonate sedimentary rocks (Gathright et al., 1977; Gathright et al. 1978).
**Figure 2-1.** The location of the South River in Virginia (after Pizzuto et al., 2006), and of the study site. The direction of flow is indicated with an arrow.

2.2 Study site

To locate our study site along the South River, we used a relative river mile (RRM) designation. RRM 0 is located at the footbridge from the Invista parking lot to the Invista plant in Waynesboro. RRM increases downstream (to the north) from
Waynesboro. The study site is located near RRM 4.3 (38°06’05”N and 78°52’11”W) (Figure 2-2).

**Figure 2-2.** Aerial photograph of the study site near RRM 4.3 taken in 2005.
2.3 Recent History of Dooms Dam

The South River has a long history of mill dam construction and demise. Historical aerial photographs show multiple mill dams along the South River; most dams were breached after 1957. Dooms Dam (Figure 2-3), the last remaining partially intact dam, was first breached in 1976, while a second breach occurred between 2002 and 2005 (Pizzuto and O’Neal, 2009).

The removal of mill dams due to structural failure or human interference affects the sediment supply to areas both upstream and downstream of the dam. When a dam is breached, the sediment that was deposited due to the backwater effect upstream is put into motion. Sediment transported downstream can destabilize banks and change channel planforms. The study site is located 0.6 miles upstream from Dooms Dam (at RRM 4.9), so sediment in the bed may be affected by the breaching (Pizzuto and O’Neal, 2009). There are also bedrock outcrops just upstream and downstream from the study site (Figure 2-3) that may affect sediment dynamics. The possibility of deep erosion at this study site is limited because bedrock is difficult to erode, providing stabilization to the bed surface.
**Figure 2-3.** Location of bedrock outcrops along the South River (image from Narinesingh, 2009). The thick black lines indicate the location of bedrock outcrops on the riverbanks and the bed. The grey line is the centerline of the channel. The location of Dooms Dam is indicated by a yellow triangle and the red circle is the study site.

2.4 South River bed material composition

The streambed in the South River is composed of different types of material that varies spatially. The type of sediment likely influences the level of sequestration of mercury in the streambed. Table 2-1 outlines characteristic types of streambed sediment
along the South River including silt and clay, sand and pebbles, sand and cobbles, cobbles, and boulders and bedrock. The sediment type focused on in this study is sand and cobble because of its medium to high relative spatial extent.

Table 2-1. Characteristic types of streambed material along the South River (Pizzuto, unpublished data).

<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>Relative Spatial Extent</th>
<th>Likely Relevance to Mercury Problem</th>
<th>Status of Understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt and Clay</td>
<td>Low</td>
<td>High</td>
<td>Large deposits are well understood</td>
</tr>
<tr>
<td>Sand and Pebble</td>
<td>Medium?</td>
<td>unknown</td>
<td>A 2008-2009 study by Pizzuto documented long residence time of sequestered fine particles</td>
</tr>
<tr>
<td>Sand and Cobble</td>
<td>Medium-High?</td>
<td>unknown</td>
<td>Focus of this study</td>
</tr>
<tr>
<td>Cobble</td>
<td>High?</td>
<td>Low?</td>
<td>Poorly understood</td>
</tr>
<tr>
<td>Boulder and Bedrock</td>
<td>Low-Medium?</td>
<td>Very Low?</td>
<td>Well-mapped</td>
</tr>
</tbody>
</table>

2.5 Climate and hydrology

The region has a humid temperate climate with average January temperatures of 6.1°C, average July temperatures of 29.4°C, and annual precipitation of 95.5 cm. Precipitation is highest from March to September and slightly lower from October through February. The average annual snowfall total at Waynesboro is 166.7 cm (66.0 inches) (www.waynesboro.va.us/about.php). The U.S. Geological Survey maintains flow
gages for the South River near Waynesboro, Dooms, and at Harriston (Table 2-2). The station at Waynesboro is primarily used for this study and located just upstream from Waynesboro, Virginia.

**Table 2-2.** Flow gaging stations and selected information for the South River between Waynesboro and Port Republic, Virginia.

<table>
<thead>
<tr>
<th>USGS Station Name</th>
<th>USGS ID #</th>
<th>Period of Record</th>
<th>Drainage Basin Area (km²)</th>
<th>1 Month Flow (m³/s)</th>
<th>1 Year Flow (m³/s)</th>
<th>5 Year Flow (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South River near Waynesboro</td>
<td>01626000</td>
<td>1952-Present</td>
<td>329</td>
<td>16.6</td>
<td>57.8</td>
<td>125.0</td>
</tr>
<tr>
<td>South River near Dooms</td>
<td>01626850</td>
<td>1975-1996, 2006-Present</td>
<td>383</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>South River at Harriston</td>
<td>01627500</td>
<td>1925-Present</td>
<td>549</td>
<td>26.2</td>
<td>108.0</td>
<td>211.0</td>
</tr>
</tbody>
</table>

2.6 Scour chain locations

Scour chains were installed in two areas of the South River for monitoring scour and fill of the bed. In August 2010, two cross sections of scour chains were installed near the RRM 4.3 study site; one at RRM 4.282 and one at RRM 4.302 (Figure 2-4). Each transect consists of five scour chains spanning the center of the channel and spaced at two meter intervals beginning 8 meters from a pin installed on the right bank.
Figure 2-4. Location of the scour chain transects near RRM 4.3.
Chapter 3

METHODS

3.1 Geomorphic characterization

3.1.1 Grain size

In November 2009, grain size was measured using the Wolman pebble count method (Wolman, 1954) at RRM 4.3. A total of 194 sediment particles were randomly selected from the bed of the study area. A gravelometer was used to determine the size class. Sediment that was 2 mm and smaller was classified as sand.

3.1.2 Longitudinal profile

A longitudinal profile of the bed and water surface was surveyed during a low flow using an auto level and stadia rod at the study site on November 5, 2009. The auto level was placed on a gravel bar and the stadia rod was placed at six positions following the thalweg over approximately 215 meters. The stadia rod positions were chosen by a person wading down the thalweg of the river. The auto level and stadia rod were used to measure water depth, distance from the auto-level to the stadia rod, angle between stadia rod positions, and elevation of
the bed relative to the auto level. Trigonometry was used to calculate the distance between stadia rod positions.

3.1.3 Hydrograph Monitoring

Data from the ‘South River near Waynesboro, Virginia’ gauging station from the USGS website (http://waterdata.usgs.gov/nwis/uv/?site_no=01626000) was monitored for discharge data during the study. There are 59 years of data available, making it possible to calculate flood recurrence intervals for this station. The recurrence interval is an estimate the probability of the occurrence of a given discharge.

Flood recurrence intervals are calculated by ranking the daily mean flows from highest to lowest. The rank, m, is the magnitude ranking. The number of observations, n, is the total number of days that observations were recorded.

Using these values, the flood recurrence interval, RI, can be determined:

$$RI = \frac{(n+1)}{m} \quad (Equation \; 3-1)$$

3.2 Scour chains

3.2.1 Installation

Scour chains were installed at the study site on August 25 and 26, 2010. The discharge at Waynesboro was approximately 100 cfs on August 25 and approximately 75 cfs on August 26. Two transects of scour chains were installed, with five scour chains spanning each transect. Steel pins were installed on each bank to identify the scour chain transects, one on the right bank and two
on the left bank (when looking downstream). The first scour chain on each transect is located 8 meters from the right bank pin and the subsequent chains are spaced 2 meters apart. Transects are located at RRM 4.292 and RRM 4.302.

The chains are made of 0.6 cm (0.25 inch) steel; the links are approximately 2.5 cm (1 inch) long and have a yellow plastic coating. Each scour chain was attached to a Platypus brand anchor with a U-bolt (Figure 3-1A). An approximately 1.5 m (5 foot) long steel rod was inserted into the driving hole of the anchor and a slide hammer was used to install the anchor and chain into the bed of the river. Each scour chain was inserted between 30 and 40 centimeters into the bed. The remaining length of chain laid on the surface of the bed facing downstream after installation (Figure 3-2B).

**Figure 3-1.** Scour chains used to measure scour and fill of the bed. (A) Scour chain attached by U-bolt to a Platypus brand anchor. (B) Scour chain installed in the channel.
3.2.2 Threshold of Sediment Motion

Sediment in the stream can be put into motion when forces acting on the sediment (drag or shear force) exceed forces keeping it in place (its submerged weight). The Shields Number (also called Shields Parameter) can be used to quantify whether a particle should be moving during a certain flow event. When the calculated Shields Number is greater than or equal to 0.03 in a gravel bed river (Buffington and Montgomery, 1997), the forces acting on the sediment are sufficient enough to put it into motion. It is essentially a ratio between the forces tending to move the grain (τ, average stress) and the forces tending to keep the grain in place. The average stress acting on the grain can be calculated using equation 3-2:

\[ \tau = \rho g D S \]  
\((Equation 3-2)\)

where \(\rho\) is the water density (kg/m\(^3\)), \(D\) is the water depth (m), \(g\) is the force of gravity (m/s\(^2\)), and \(S\) is the slope of the water surface.

Then \(\tau\) can be used in equation 3-3 to determine the Shields Number:

\[ \frac{\tau}{(\rho_s - \rho)gD_s} \geq 0.03 \]  
\((Equation 3-3)\)

where \(\tau\) is average stress acting on the grain, \(\rho_s\) is the mineral density (kg/m\(^3\)), and \(D_s\) is the median sediment diameter (m).

The slope of the channel was calculated from data collected during the longitudinal profile survey in November 2009. A MATLAB water depth prediction program designed by Pizzuto (unpublished) was used to determine
water depth at various flows based on the channel cross section at RRM 2.292 and other parameters.

### 3.2.3 Monitoring of the scour chains

Scour and fill were monitored by measuring cross sections at each scour chain transect with an auto level and by measuring the length of each scour chain before and after each high flow event. The recorded length of a single scour chain is the mean of three to five measurements that were taken from upstream, downstream, right, and left sides of the scour chain. Measurements were conducted after flows reached or exceeded 45.3 m$^3$/s at the Waynesboro monitoring station. This value does not have significance, it is simply the lowest flow sampled during this study.

Figure 3-2 illustrates how flow events cause the length of a scour chain to increase. If there has been no scour or fill between measurements, then the scour chain will be the same length as the previous measurement. The scour chain will appear shorter when fill has occurred and the chain is buried beneath sediment. If the scour chain is longer when measurements are taken, scour has occurred.
Figure 3-2. Illustration of how scour chains provide a reference for measuring scour and fill in bed elevation. (a) A scour chain is installed at low discharge. (b) A large discharge event causes bed to lower and scour chain to be exposed. (c) Fill occurs on top of the exposed chain. (Figure from Nawa and Frissell, 1993)

Scour chains register only one apparent cycle of scour and fill between measurements, so the apparent scour or fill of the bed is attributed to the largest flood event between each set of measurements.

The amount of scour or fill was calculated for each scour chain after measurements were taken by subtracting the mean of the previous scour chain lengths from the mean of the current measurements. The scour or fill for the surveyed cross sections was calculated by subtracting the previous relative bed elevation measurement from the current relative bed elevation.

3.2.4 Statistical test of scour chain data

Measurement error can provide a false scour or fill signal. The $D_{50}$ grain size for this area of the South River is 2.55 cm, so placing the rod on top of the
grain will yield a result that differs from placing the rod beside the same grain. The median grain diameter was compared to the values of scour and fill on the final histogram as one indicator of error.

To find the magnitude of scour that can be accepted as real and not measurement error, the detection limit (L_D) is calculated from the scour data. The L_D is the depth of scour necessary to exceed measurement error with 95% probability. The L_D depends only on the distribution of measurement errors when the distribution of measurement errors is the same as the distribution of apparent scour (Currie 1968).

Measurement errors were calculated using scour chain length measurements. Each scour chain was measured at least three times. The mean of the length measurements was subtracted from each individual measurement and recorded as ‘error’. The standard deviation of the ‘errors’, \( \sigma_e \), was then used to determine the L_D with equation 3-4 from Currie (1968):

\[
L_D = 3.29\sigma_e \quad (Equation \ 3-4)
\]

3.3 Sampling bed sediment

Cores were taken two separate times at RRM 4.3 using two different methods. Sediment samples must be dry and weigh 20 or 70 grams when they are analyzed with a gamma spectrometer. These weights are chosen based on the standards available in the laboratory because the sediment samples must have the same geometry, density, and
weight as the standards. It is typically better to have a 70 g sample if there is enough material available because the count rate is increased with a greater amount of sediment.

Five cores were collected from the bed during the first sampling program in November 2009. In order to create silt and clay-sized sediment samples that weigh 20 g, equal depth intervals had to be combined from multiple cores. The second sampling program used a different method to remove the sand-sized sediment from the bed. 70 g of sand was retrieved from each depth interval without having to combine samples from multiple locations in the channel.

### 3.3.1 Initial sampling program

With the help of personnel from URS, Inc. and the South River Science Team, five cores were collected near RRM 4.3 in November 2009 (Figure 3-3). A diamond-tipped core barrel attached to a rotating, motorized posthole digger was used to extract Core 1 from the gravel-bed channel (Figure 3-4A). This method was replaced for Cores 2-4 by using a hammer to pound the core barrels into the bed because the rotating core mixed the sediment (Figure 3-4B). The cores were removed from the bed and placed on a platform (Figure 3-5A) that was attached to a table jack used to push the sediment towards the top of the core (Figure 3-5B). Samples were removed from the top of the core in 5-cm increments (Figure 3-5C), placed in plastic bags, and transported to the lab for further preparation and analysis.
**Figure 3-3.** Location of five coring sites near RRM 4.3 in November 2009. The green points labeled 1-5 are the coring locations. The point labeled 4.3 indicates the relative river mile.

**Figure 3-4.** Methods of core retrieval. (a) The rotating post-hole digger used to remove the first core. (b) Hammering the core barrels into the gravel bed.
**Figure 3-5.** Photographs of the core being prepared for sampling. (a) The core barrel being placed on the platform before it was placed in the jack system. (b) The core barrel placed in the jack system. (c) Sediment was removed in 5 centimeter increments from the top of the core barrel.

**3.3.2 Obtaining sand samples from the bed**

In July 2010, the river bed was sampled near RRM 4.3. A 55-gallon drum was cut in half, and the bottom was removed, creating a cylinder about 75 cm high and about 75 cm in diameter. It was placed on the surface of the gravel bed and ~3 cm layers were sampled to a depth of 40 cm. As sediment was removed, the cylinder was inserted farther into the bed in order to keep surrounding sediment from entering the sampling area (Figure 3-6). The sediment was
removed from the cylinder with large metal spoons and placed in a sieve to separate the sand fraction. At least 70 g of sand were sieved from each layer. The sand from each ~3 cm section was placed in a plastic bag and transported back to the lab for preparation and analysis.

**Figure 3-6.** The 55-gallon drum inserted into the river bed.

Surveys were taken with an auto level and stadia rod between every sampled layer to determine layer thickness (Figure 3-7). Five points were surveyed within the core barrel and the mean was used for depth calculations.
3.3.3 Suspended silt and clay samples

The radionuclide activity of suspended sediment was used to estimate the initial activities of $^{210}$Pb, $^{137}$Cs and $^7$Be at the time of deposition in the hyporheic zone. Suspended sediment was captured using Rubbermaid bins measuring approximately 100 x 40 x 30 centimeters which were installed in August 2009. The bottom of each bin was covered with cobbles and a plastic bag was used as a liner. The top opening was covered with a ~5 mm wire mesh screen to keep debris from entering the sampler. The top of the sampler used in the early sample collections was 0.61 meters above the low water stage at RRM 3.5 (Figure 3-8).
Figure 3-8. Suspended sediment samplers in place at RRM 3.5. The sampler outlined in yellow was 0.61 meters above the low water stage and used in this study to collect suspended sediment prior to April 2010.

New samplers were placed at RRM 2.572 and 2.578 in April 2010 after the high flows in February 2010 destroyed the samplers at RRM 3.5. The new samplers are 5-gallon buckets with ~2.5 cm holes drilled in the lid to keep out debris. The bottoms of these buckets were filled with cobbles and lined with a plastic bag. The water surface was 0.485 m below the top of the sampler placed at RRM 2.578 and 0.465 m below the top of the sampler at RRM 2.572 on April 2, 2010 when the samplers were installed. Based on the river stage at the time of installation and the distance of the samplers above the water surface, a gage height of about 1.66 m at the South River near Dooms was needed to inundate these samplers.
3.3.4 Surface sand samples

Four surface samples were taken from the surface of the channel near RRM 4.3 in June 2010 to determine the initial radionuclide activity for the sand samples taken from the bed in July 2010. Sediment was taken from the top 2 cm of the gravel bed spanning the entire channel. Only the sand fraction was retained after sieving each sample in the field. At least 70 grams of sediment were collected for each of the four samples, placed in a plastic bag, and transported back to the lab for analysis.

3.4 Sample Preparation

The five sediment cores that were collected and composited in November 2009 (referred to as core 11-4-09) and the suspended sediment sample required wet sieving to remove the silt and clay-sized sediment fraction (all particles greater than 4 φ). Each 5-cm interval of four of the five cores was sieved individually. The sediment in Core 1 was not used for analysis because it was too mixed by the motorized post-hole digger that was used to remove the core.

At least 20 g of dry sediment are required for radionuclide analysis. None of the individual five cm core intervals held 20 g of silt and clay after being wet sieved, so the intervals from the five cores were combined to create one sample of each five cm depth interval. All depth intervals did not include sediment from all of the cores (Table 3-1). Because only two cores reached a depth of 20-25 cm, very fine sand (sediment
measuring between 3 and 4 $\phi$) had to be added to the 20-25 cm depth sample in order to reach a weight of 20 g.

**Table 3-1.** The cores used for each depth interval sample and the weight of each sample for core 11-4-09.

<table>
<thead>
<tr>
<th>Depth Interval</th>
<th>Cores included in the sample</th>
<th>Silt and Clay (g)</th>
<th>Very Fine Sand (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5 cm</td>
<td>2, 3, 4 and 5</td>
<td>20.00</td>
<td>0.00</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>2, 3, 4 and 5</td>
<td>20.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>2, 3, 4 and 5</td>
<td>20.00</td>
<td>0.00</td>
</tr>
<tr>
<td>15-20 cm</td>
<td>3, 4 and 5</td>
<td>20.00</td>
<td>0.00</td>
</tr>
<tr>
<td>20-25 cm</td>
<td>4 and 5</td>
<td>12.70</td>
<td>7.30</td>
</tr>
</tbody>
</table>

The sand samples (identified by the sampling date of 7-15-10) and surface samples did not require wet sieving. The 70 g samples required for gamma counting was available for all depth intervals and the surface samples.

To create samples with the consistent density and geometry ideal for gamma counting, all of the samples were freeze-dried using a Labconco FreeZone. After the samples were completely dried, they were placed in aluminum cans and sealed to prepare for gamma spectroscopy.

### 3.5 Mercury analysis

Samples from core 11-4-09 and the fine suspended sediment sample were sent to Brooks Rand Labs to be analyzed for percent total solids (%TS) and total inorganic mercury. All samples were received, prepared, analyzed, and stored according to Brooks Rand Labs Standard Operating Procedures (BRL SOPs) and EPA method 1631.
3.6 Loss on ignition

Loss on ignition (LOI) was measured on the 7-15-10 sand samples and the surface sand samples. This method is used to determine the amount of volatile substances and organic material contained in a sample (chiefly organic matter). Samples were weighed in a clean, dry crucible to get the mass prior to combustion after they were dried in an oven to evaporate the moisture. Approximately 2 g of each sample were then heated in a furnace for 24 hours at 425°C. Samples and crucibles were cooled in a dessicator before measuring the post-combustion weight of the sample. LOI was calculated by dividing the change in sample weight (ΔM) by initial sample weight (M_i) and multiplying by 100 (equation 3-5).

\[
LOI = \left( \frac{\Delta M}{M_i} \right) \times 100
\]  
\(\text{(Equation 3-5)}\)

3.7 Surface area analysis

Surface area measurements were taken using a Micromeritics Tristar 3000 surface area and porosity analyzer. These measurements are used to normalize radionuclide activity based on surface area of the samples. Measurements were taken from both uncombusted and combusted samples for core 11-4-09 and the suspended silt and clay-sized sediment. For all of the sand and surface sand samples, surface area was measured on only the samples that had been combusted.
3.8 Radionuclide activity

Understanding rates of deposition and resuspension requires using particle bound radioactive tracers that have suitable half-lives for the timescale of the study. Both $^7$Be and $^{210}$Pb are continuously supplied from the atmosphere, so the activity in suspended sediment can provide a measure of the time since the particles were tagged by sorption of these radionuclides (Matisoff et al., 2005).

$^{137}$Cs (half life, $t_{1/2}$, of 30.2 years) is of anthropogenic origin. The most significant source was thermonuclear weapons testing in the 1950s and 1960s. The peak activity was recorded in 1963-64. $^{137}$Cs fallout rapidly adheres to catchment soils and sediments. High activity of this radionuclide represents the short period of time when the sediment was exposed to the fallout (Ritchie and McHenry, 1990).

$^7$Be is a naturally occurring fallout radionuclide produced by cosmic ray spallation of nitrogen and oxygen, mainly in the upper atmosphere (Lal et al., 1958). Once $^7$Be reaches the sediment surface, it is strongly held by solid particles in natural environments (You et al., 1989). The half life of $^7$Be is short ($t_{1/2}= 53.4$ days), so the sediment residing on the river bed should contain little of that radionuclide if the sediment is older than a few months.

$^{210}$Pb is naturally produced as a decay product of $^{238}$U ($t_{1/2}= 4.5 \times 10^9$ years). Through a series of short-lived nuclides, $^{238}$U decays to $^{226}$Ra ($t_{1/2}=1600$ years), which then decays to the noble gas $^{222}$Rn ($t_{1/2}= 3.82$ days) (Figure 3-9). In the gaseous form, some $^{222}$Rn escapes from the geosphere to the atmosphere where it continues to decay through several short-lived nuclides to $^{210}$Pb ($t_{1/2}= 22.3$ years). Upon deposition to
Earth’s surface, this $^{210}\text{Pb}$ is known as ‘excess’ $^{210}\text{Pb}$. The fraction of $^{222}\text{Rn}$ which does not escape to the atmosphere continues to decay in continental rocks and produces *in situ* or ‘supported’ $^{210}\text{Pb}$ (McDonnell and Kendall, 1992).

**Figure 3-9.** The U-238 decay series with elemental half-lives expressed in years (y), months (mn), and days (d). (Image from www.olivermagand.com)

Excess $^{210}\text{Pb}$ is removed from the atmosphere by both wet and dry deposition and sorbs strongly to particulate matter. The levels of excess $^{210}\text{Pb}$ and supported $^{210}\text{Pb}$ are used to determine residence time of sediment in the riverbed. Recently deposited sediment will have relatively high levels of excess $^{210}\text{Pb}$ because of its recent exposure to the atmospheric deposition. The excess $^{210}\text{Pb}$ activity levels decrease by radioactive decay to extinction, and after this occurs the total $^{210}\text{Pb}$ levels measured equal the background, supported levels of $^{210}\text{Pb}$. The levels of excess $^{210}\text{Pb}$ activity in a sample
can be determined by subtracting the supported $^{210}\text{Pb}$ from total $^{210}\text{Pb}$ (Equation 3-6). The activity of supported $^{210}\text{Pb}$ which cannot be directly measured, is equal to the activity of $^{226}\text{Ra}$, because it is the geogenic contributor of supported $^{210}\text{Pb}$ (Matisoff et al., 2005).

$$^{210}\text{Pb}_{xs} = ^{210}\text{Pb}_{total} - ^{210}\text{Pb}_{supported} \quad \text{(Equation 3-6)}$$

In this study, two different methods were used to calculate the amount of supported $^{210}\text{Pb}$ that was contained in each sample. The first method, termed the $^{226}\text{Ra}$ method, was used to calculate $^{210}\text{Pb}$ for all samples by determining the activity of $^{226}\text{Ra}$. The activity of $^{226}\text{Ra}$ cannot be measured directly because its photopeak overlaps with the photopeak of $^{235}\text{U}$ at 186 keV. To determine the activity of $^{226}\text{Ra}$, I measured the activity of $^{234}\text{Th}$ at 63 keV and assume that it is in secular equilibrium with $^{238}\text{U}$. Because there is a constant ratio between $^{235}\text{U}$ and $^{238}\text{U}$ of 0.04605 (Murray et al., 1987), we can determine the contribution of $^{235}\text{U}$ from the measurement of $^{234}\text{Th}$. The activity of $^{226}\text{Ra}$ is determined by subtracting the activity of $^{235}\text{U}$ from the total activity at the 186 keV line.

The second method, termed the $^{214}\text{Pb}$ method, was used to determine the excess $^{210}\text{Pb}$ activity for the sand samples obtained on 7-15-10 and the surface sand samples. This method determines the amount of supported $^{210}\text{Pb}$ by measuring the activity of $^{214}\text{Pb}$, a parent in the decay chain. When enclosed in an airtight container for at least 21 days, $^{214}\text{Pb}$ reaches secular equilibrium with $^{226}\text{Ra}$. Using this method, the amount of
supported $^{210}$Pb can be determined more directly, inducing less calculation and measurement error.

### 3.9 Activity measurement

The type of detector used for activity measurement is a Canberra low energy germanium detector (LEGe, model GL2020R). Germanium detectors produce a gamma-ray spectrum that consists of a large number of channels in each of which are accumulated counts which fall into a small energy range. Within this spectrum, a gamma-ray appears as a distribution of counts, approximately Gaussian, about a central point which represents the specific gamma-ray’s energy (Gilmore and Hemingway, 1995).

Measurement of each peak area is a simple summation of the number of counts in each peak channel and a subtraction of the background beneath the peak. All samples were counted for 24 hours because of the low count rate that is found in environmental samples. Samples were analyzed for $^7$Be, $^{137}$Cs, and $^{210}$Pb activity by determining the number of counts in specified energy regions of interest (ROI) for each radionuclide. ROIs were set up around a peak in the spectrum by visual inspection. The gross number of counts in the peak is calculated as the sum of all counts in the ROI. To find the net counts, the background continuum is subtracted from the gross counts by fitting a line to the background channels on either side of the peak. Background can arise from many sources including other gamma-ray interactions with the detector or general radiation
from the shielding and detector. Figure 3-10 shows the general principle of dividing peak and background or continuum channels.

**Figure 3-10.** An illustration of peak and background energies. The diamond icons represent peak channels in the ROI. The triangle icons represent the continuum that is used to calculate the background input of gamma radiation.

The activity of radionuclides in a sample is calculated using equation 3-7:

\[
A = \frac{C}{t \cdot \varepsilon \cdot \gamma \cdot m} \tag{Equation 3-7}
\]

where \(A\) is the radionuclide activity (Bq/g), \(C\) is the total net peak area counts, \(t\) is the count time (seconds), \(\varepsilon\) is the detector efficiency, \(\gamma\) is the radionuclide yield, and \(m\) is the mass of the sample (g). The net peak area is calculated for each peak individually.

Efficiency and yield are specific to each radionuclide.

Efficiency is the fraction of photons that are emitted from the sample that actually reach and are counted by the detector specific to detector and sample geometry. Yield is
the probability that a photon with a particular energy will be emitted during the specific decay of that nuclide. More detailed discussions of efficiency and yield are provided in subsequent sections.

3.10 $^{210}$Pb activity calculation

3.10.1 $^{210}$Pb Detector Efficiency ($\varepsilon$)

Before activity calculations can be completed, additional steps must be taken to calculate the efficiency of the detector at low energies ($< 100$ keV). Self-attenuation occurs when photons are absorbed by particles in the sample matrix before reaching the detector. Self-attenuation of sample radiation occurs at low energies (generally $< 100$ keV) at different intensities depending on the radionuclide in question and the density of the sample. In general, attenuation increases with increasing sample matrix density. The efficiency for low energy radionuclides is calculated as the product of the unattenuated sample efficiency multiplied by the sample self-attenuation factor (Cutshall et al., 1983). Unattenuated sample efficiency is the efficiency of the detector if the mineral matrix that is holding the radioactive sample was removed. If the distance that a photon must travel increases, then the amount of attenuation due to the sample matrix will increase as well.

In this study, the efficiency was calculated for a uranium ore standard, BL-5 Uranium Ore from the Canada Centre for Mineral and Energy Technology.
with certified $^{210}\text{Pb}$ activity was used as the standard. The BL-5 standard used for efficiency calculations for core 11-4-09 and the suspended silt and clay samples has 0.3946 grams of BL-5 mixed with 19.6054 grams of sediment with the same mineralogical composition as the core 11-4-09 samples and low $^{210}\text{Pb}$ activity. The BL-5 standard used for efficiency calculations for sand core 7-15-10 and the surface sand samples is one gram of BL-5 mixed with 69 grams of sediment similar to the mineralogy of the sand core 7-15-10 samples. The counting efficiency of the BL-5 standard ($\varepsilon_{\text{BL-5}}$) is calculated as the measured activity from the BL-5 standard at the 46.5 keV line (in counts per second) divided by the certified activity from the BL-5 standard (in counts per second).

Next, the self-attenuation of the BL-5 standard is determined. Another radionuclide source with known activities is counted on top of both an empty can and the BL-5 standard for a short amount of time (approximately 3-5 minutes each). The self-attenuation factor ($F_{\text{SA}}$) for the BL-5 standard at 46.5 keV is:

$$F_{\text{SA}} \text{ of the BL-5 standard} = \frac{(Count_2/Count_1) - 1}{\ln(Count_2/Count_1)} \quad (\text{Equation 3-8})$$

where $\text{Count}_1$ is the counts per second (cps) at the 46.5 keV energy peak for the ‘mixed gamma source’ on top of the ‘empty can’ spectrum. This count gives you a baseline for which to compare the ‘mixed gamma source’ counts over an empty can to the counts that result from the ‘mixed gamma source’ counted over a different standard in $\text{Count}_2$. 

39
$Count_2$ is the total cps at the 46.5 keV energy peak for the ‘mixed gamma source’ on top of the ‘BL-5 standard’ minus the cps at the 46.5 keV energy peak for the ‘BL-5 standard’ counted alone. This shows the contribution of the ‘BL-5 standard’ to the total counts for $Count_2$. This also shows the photon attenuation which results from the ‘BL-5 standard’ beneath the ‘mixed gamma source’.

The unattenuated efficiency ($\varepsilon_u$) can be calculated by dividing the efficiency of the BL-5 standard by the self-attenuation factor of the BL-5 standard (Equation 3-9), both of which were determined in previous steps.

$$\varepsilon_u = \frac{\varepsilon_{BL-5}}{F_{SA\ of\ the\ BL-5}} \quad (Equation\ 3-9)$$

The self-attenuation factor ($F_{SA}$) of the sample is calculated next. The mixed gamma source is placed on top of the empty can and on top of each sample for approximately 3-5 minutes each. Each of these resulting spectra are analyzed for peak areas at an energy of 46.5 keV to determine counts per second. The self-attenuation factor ($F_{SA}$) of each sample at 46.5 keV is:

$$F_{SA\ of\ the\ sample} = \frac{(Count_2 / Count_1) - 1}{\ln(Count_2 / Count_1)} \quad (Equation\ 3-10)$$

where:

$Count_1 = cps \ at \ the \ 46.5 \ keV \ peak \ for \ the \ ‘mixed \ gamma \ source’ \ on \ top \ of \ the \ ‘empty \ can’ \ spectrum.$
\( \text{Count2} = \text{(cps at the 46.5 keV peak for the ‘mixed gamma source’ on top of each individual ‘sample’) - (cps at the 46.5 keV peak for each ‘sample’ counted alone)} \)

The efficiency of \( ^{210}\text{Pb} \) can then be calculated:

\[
^{210}\text{Pb efficiency} = (\varepsilon_u) \times (F_{SA} \text{ of the sample}) \quad \text{ (Equation 3-11)}
\]

where the unattenuated efficiency \( (\varepsilon_u) \) and self-attenuation factor \( (F_{SA}) \) of the sample were calculated in previous steps.

### 3.10.2 Yield \((\gamma)\)

\( ^{210}\text{Pb} \) is unstable and disintegrates to \( ^{210}\text{Bi} \). Not all disintegrations are at the gamma energy level. There is also a chance that photons can have energy levels that fall within the alpha, beta, or X-ray decay energy ranges. A single disintegration has a 4.25\% (±0.04\%) chance of emitting a photon with the energy of 46.5 keV (Browne, 2003). This 4.25\% is referred to as yield, intensity, or abundance and is the probability that a photon with a particular energy will be emitted following the decay of an atom of that nuclide. \( ^{214}\text{Pb} \) has a yield of 37.6\% (±0.04\%) and \( ^{226}\text{Ra} \) has a yield of 3.5\% (±0.06\%) (www.nndc.bnl.gov/nudat2/, accessed 2/2009).
3.10.3 Core 11-4-09 and suspended clay and silt activity calculation

The excess $^{210}$Pb activity in core 11-4-09 and the suspended silt and clay sample was calculated using the $^{226}$Ra method to determine the amount of supported $^{210}$Pb. The gamma spectrum was analyzed for peaks at 46.5 keV for total $^{210}$Pb activity, 63 keV for $^{234}$Th activity, and 186 keV for the activity of both $^{235}$U and $^{226}$Ra since they have overlapping energies. Self absorption corrections were used for the efficiency of $^{234}$Th (El-Daoushy and Hernández, 2002).

After the peak area measurement is completed, the net peak counts (C) for $^{234}$Th are divided by its yield ($\gamma$, 0.032), efficiency corrected for self absorption ($\varepsilon$), and count time (t, seconds) to calculate activity in Becquerel’s (Bq).

$$^{234}\text{Th Activity (Bq)} = \frac{C}{\gamma\varepsilon t} \quad \text{(Equation 3-12)}$$

Because of the constant ratio between $^{235}$U and $^{238}$U, and given that secular equilibrium is reached between $^{234}$Th and $^{238}$U, the activity of $^{235}$U can be determined from $^{234}$Th. The activity of $^{235}$U is:

$$^{235}\text{U activity} = ^{234}\text{Th activity} \times 0.04605 \quad \text{(Equation 3-13)}$$

The activity for $^{235}$U is now known, so the activity of $^{226}$Ra can be determined by removing the activity of $^{235}$U from the total activity at 186 keV using equation 3-14.

$$^{226}\text{Ra activity (cps)} = \text{Total activity at 186 keV (cps)} - ^{235}\text{U activity (cps)} \quad \text{(Equation 3-14)}$$
Now, the activity of excess $^{210}\text{Pb}$ can be determined:

$$\text{Excess }^{210}\text{Pb activity} = \text{total }^{210}\text{Pb activity} - ^{226}\text{Ra activity} \quad (\text{Equation 3-15})$$

To convert the units from Bq to Bq/g, the activity is divided by the sample weight (g). To convert to Bq/m$^2$ the activity per gram (Bq/g) is divided by sample surface area (m$^2$/g).

### 3.10.4 $^{210}\text{Pb}$ activity calculations for 7-15-10 sand samples and surface sand

The $^{210}\text{Pb}$ activity of coarse bed sediment was calculated using the $^{214}\text{Pb}$ method of $^{210}\text{Pb}$ activity calculation. Samples were sealed in an airtight aluminum can for at least 21 days to allow for ingrowth of $^{222}\text{Rn}$ and for $^{214}\text{Pb}$ to come into secular equilibrium with $^{210}\text{Pb}$. Spectra were acquired for each sample and the peaks were analyzed for total $^{210}\text{Pb}$ at 46.5 keV and $^{214}\text{Pb}$ at 352 keV. Excess $^{210}\text{Pb}$ was calculated as the difference between total $^{210}\text{Pb}$ and $^{214}\text{Pb}$ because $^{214}\text{Pb}$ is in secular equilibrium with $^{226}\text{Ra}$, the geogenic contributor of supported $^{210}\text{Pb}$.

### 3.11 $^7\text{Be}$ and $^{137}\text{Cs}$ activity measurements

#### 3.11.1 Efficiency ($\varepsilon$)

Efficiency changes with energy level, sample geometry, and sample density. For $^{137}\text{Cs}$ efficiency is determined using a mixed gamma source that has known $^{137}\text{Cs}$ activity. The activity that is actually measured by the detector is then compared to the activity that is known in the sample to determine efficiency. The efficiency for $^7\text{Be}$ must be indirectly calculated because it is not present in
the calibrating source. However, it is simple to determine the efficiency of $^7$Be using the full-spectrum efficiency curve, created from the known activity of radionuclides from the mixed gamma source. The calibration curve is generated in the Genie gamma spectrometry software. From this calibration curve, the efficiency of short-lived radionuclides (like $^7$Be) can be calculated. Self-attenuation corrections are not necessary for $^7$Be or $^{137}$Cs because they are emitted at energies greater than 100 keV.

3.11.2 Yield ($\gamma$)

The yield for $^7$Be is 10.52\% (±0.06\%) at 477.6 keV. The yield for $^{137}$Cs is 85.1\% (±0.20\%) at 661.7 keV (Browne, 2007).

3.11.3 Activity calculation for all samples

Activity was calculated for both $^7$Be and $^{137}$Cs by dividing the net counts by count time (sec), sample weight (g), yield, and efficiency specific to each nuclide. This provided units of Bq/g. To determine activity per unit area the activity in Bq/g was divided by the surface area, measured in m$^2$/g.

3.12 Counting statistics

3.12.1 Minimum detectable activity (MDA)

MDA is the least amount of activity measureable for specific radionuclides, and is typically equated to the activity equivalent to the detection
limit, $L_D$ (Gilmore and Hemingway, 1995). The $L_D$ is the minimum number of counts necessary to be 95% certain that significant count rate was detected. MDA is in terms of activity, so $L_D$ is converted from a count rate to an activity. Equation 3-16 shows the method of calculating MDA in terms of activity (Gilmore and Hemingway, 1995):

$$ MDA = \frac{2.71+4.65\sigma}{t \varepsilon \gamma m} \quad (Equation \ 3-16) $$

where $\sigma$ is the square root of the number of background counts in the region of interest, $t$ is the count time (sec), $\varepsilon$ is the detector efficiency, $\gamma$ is the gamma yield for each specific radionuclide, and $m$ is the sample weight (g).

If the activity of the specific radionuclide in question is greater than its MDA, then there is a 95% confidence level that the detector can measure activity in the sample. However, MDA is not the minimum activity detectable, so even activities below calculated MDA can be considered statistically significant.

### 3.12.2 Error calculations

With a stochastic process such as radioactive decay, there is always a level of error associated with calculations. In radionuclide peak area measurements, the peak error is a factor of both the gross counts and the background counts since the net counts are the background counts subtracted from the gross counts. The error for each peak was calculated using equation 3-17 (Gilmore and Hemingway, 1995):

$$ MDA = \frac{2.71+4.65\sigma}{t \varepsilon \gamma m} \quad (Equation \ 3-16) $$
\[
\text{var}(A) = \sum_{i=L}^{U} C_i + n^2 \left[ \sum_{i=L+1}^{L-1} C_i + \sum_{i=U+1}^{U+m} C_i \right] / 4m_i^2
\]  

(Equation 3-17)

where \( \text{var}(A) \) is the activity variance, \( L \) is lower background region, \( U \) is the upper background region, \( C_i \) is the number of counts, \( n \) is the number of channels within the peak region, and \( m_i \) is the total number of channels in the upper and lower background regions. This equation provides the variance for each radionuclide peak. From this, we can calculate the activity standard deviation, \( \sigma_A \), which is the square root of the variance.

The principle of error propagation was used to take yield and efficiency errors into account. The error associated with yield for each radionuclide was found at http://ie.lbl.gov/toi/index.asp. The error associated with detector efficiency was determined by the Genie software.
4.1 Geomorphic characterization

4.1.1 Grain Size

The median sediment diameter at RRM 4.3 is 25.5 mm and the 84th percentile grain diameter is 57.8 mm. About 5.7% of the sediment is composed of particles smaller than 2 mm (i.e. sand sized and smaller) (Figure 4-1). Additional grain size information can be found in Appendix B.

Figure 4-1. Grain size distribution of the bed material at RRM 4.3.
4.1.2 Longitudinal Profile

The slope of the water surface at RRM 4.3 was determined by fitting a straight line to the water surface points. The slope of the water surface is 0.00048 and the slope of the bed is 0.00092 (Figure 4-2).

Figure 4-2. Survey of the bed and water surface at RRM 4.3.

4.2 Scour chains

Scour chains lengths and cross sections were measured at the RRM 4.292 and 4.302 scour chain transects. Measurements were made four times after the peak flows listed in Table 4-1 occurred and once immediately after installation. The Shields Number, flow depth, and recurrence interval are also listed for each event. The slope of the water surface (0.00048) was used to calculate Shields Numbers.
Table 4-1. Peak flows for each measured event for scour chain monitoring.

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Flow (m³/s)</th>
<th>Flow Depth (m)</th>
<th>Recurrence Interval (years)</th>
<th>Shields Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 28, 2010</td>
<td>56.6</td>
<td>2.8</td>
<td>0.95</td>
<td>0.03</td>
</tr>
<tr>
<td>December 1, 2010</td>
<td>84.9</td>
<td>3.2</td>
<td>2.25</td>
<td>0.04</td>
</tr>
<tr>
<td>March 10, 2011</td>
<td>45.3</td>
<td>2.6</td>
<td>0.61</td>
<td>0.03</td>
</tr>
<tr>
<td>April 16, 2011</td>
<td>229.4</td>
<td>4.2</td>
<td>12.76</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Scour and fill occur when the force exerted on the sediment exceed the force that is keeping the sediment stationary. When high flows occur, it is more likely that sediment will become mobile than during low flows. The Shields Number was calculated for each flow event that was measured during this study. Each calculated Shields Number is greater than or equal to 0.03, meaning that forces are strong enough to cause sediment movement. When the sediment is in motion, scour and fill of the bed is possible.

All changes in scour chain length and relative bed elevation measurements are compiled in the histogram below (Figure 4-3). The 50th percentile grain size measurement (D₅₀, 2.55 cm) is plotted to compare with the scour and fill measurements. The detection limit (L_D, +/- 3 cm) is also plotted above the histogram. The scour and fill beyond the L_D can be considered actual scour or fill with 95% probability. The significant scour events are associated with the largest flows.
4.3 Suspended sediment sampling

The high flow event that occurred on November 13, 2009 had a magnitude of 28.6 m$^3$/s (a recurrence interval of 0.24 years). The suspended sediment sample was collected from this flow.

4.4 Mercury concentrations

Figure 4-4 displays the mercury concentrations in parts per million (ppm) for core 11-4-09 and the suspended silt and clay samples. These values are of interest.
because mercury concentrations vary depending on when the sediment was deposited in the river (Skalak and Pizzuto, in review).

**Figure 4-4.** Total mercury concentrations measured in core 11-4-09. The hollow diamond point at a depth of 0 cm marks the mercury concentration in the suspended sediment sample.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Mercury Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

**4.5 Loss on ignition**

LOI values ranged from 0.23% to 0.62% for the sand samples taken on 7-15-10 from the channel (Figure 4-5). The surface sand samples had relatively higher LOI values ranging from 1.72% to 2.88%.
Figure 4-5. Loss on ignition results from sand core 7-15-10 and the surface sand samples.

4.6 Surface area

Surface area after organic material removal ranged from 13.88 to 23.30 m²/g for the silt and clay samples in core 11-4-09. The suspended sediment sample had a surface area of 18.60 m²/g after organic matter removal which falls within this range.

Table 4-2. Surface area for core 11-4-09 and the suspended sediment sample.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Surface Area (m²/g)</th>
<th>Error (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5 cm</td>
<td>22.8</td>
<td>0.07</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>23.3</td>
<td>0.10</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>19.6</td>
<td>0.07</td>
</tr>
<tr>
<td>15-20 cm</td>
<td>18.2</td>
<td>0.07</td>
</tr>
<tr>
<td>20-25 cm</td>
<td>13.9</td>
<td>0.04</td>
</tr>
<tr>
<td>Suspended sediment</td>
<td>18.6</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*Note: “Error” refers to the measurement error incurred by the machine during data collection.
Surface area for the sand samples after organic material was removed by combustion ranged from 1.7 to 3.3 m²/g. Three of the four surface sand samples had surface areas greater than the range found for the sand samples taken from the channel. The surface sand samples had surface areas that ranged from 3.1 to 4.4 m²/g.

**Table 4-3.** Surface area for sand samples from 7-15-10 and the surface sand samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Surface Area (m²/g)</th>
<th>Error (m²/g)</th>
<th>Sample</th>
<th>Surface Area (m²/g)</th>
<th>Error (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-3 cm</td>
<td>3.3</td>
<td>0.02</td>
<td>23-27 cm</td>
<td>2.1</td>
<td>0.01</td>
</tr>
<tr>
<td>3-5 cm</td>
<td>2.9</td>
<td>0.01</td>
<td>27-30 cm</td>
<td>2.3</td>
<td>0.01</td>
</tr>
<tr>
<td>5-7 cm</td>
<td>2.9</td>
<td>0.02</td>
<td>30-34 cm</td>
<td>1.9</td>
<td>0.01</td>
</tr>
<tr>
<td>7-9 cm</td>
<td>2.9</td>
<td>0.02</td>
<td>34-40 cm</td>
<td>1.9</td>
<td>0.01</td>
</tr>
<tr>
<td>9-11 cm</td>
<td>2.1</td>
<td>0.01</td>
<td>&lt; 40 cm</td>
<td>1.7</td>
<td>0.01</td>
</tr>
<tr>
<td>11-13 cm</td>
<td>2.7</td>
<td>0.01</td>
<td>Surface 1</td>
<td>4.1</td>
<td>0.02</td>
</tr>
<tr>
<td>13-16 cm</td>
<td>2.7</td>
<td>0.01</td>
<td>Surface 2</td>
<td>4.4</td>
<td>0.01</td>
</tr>
<tr>
<td>16-19.5 cm</td>
<td>2.1</td>
<td>0.01</td>
<td>Surface 3</td>
<td>3.9</td>
<td>0.01</td>
</tr>
<tr>
<td>19.5-23 cm</td>
<td>1.8</td>
<td>0.01</td>
<td>Surface 4</td>
<td>3.1</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*Note: “Error” refers to the measurement error incurred by the machine during data collection.*
4.7 Radionuclide activity in Core 11-4-09 and suspended sediment

4.7.1 $^7$Be activity

All of the samples from Core 11-4-09 exhibited $^7$Be activity. The highest levels of activity were found at a depth of 20-25 centimeters (Figure 4-6).

**Figure 4-6.** $^7$Be activity with depth in Core 11-4-09 normalized by surface area. The diamond represents the $^7$Be activity in the suspended sediment. The horizontal width of each box is the calculated activity error.
4.7.2 $^{137}$Cs activity

$^{137}$Cs activity was below MDA in the 0-5 cm and 5-10 cm samples from Core 11-4-09. The 20-25 cm depth sample had the highest levels of $^{137}$Cs activity at $1.3 \times 10^{-4}$ Bq/m$^2$. There was no $^{137}$Cs activity detected in the suspended sediment sample (Figure 4-7).

Figure 4-7. $^{137}$Cs activity normalized by surface area in Core 11-4-09. The horizontal width of each box is the calculated activity error. The diamond indicates that there is no $^{137}$Cs activity in the suspended sediment sample.
4.7.3 Excess $^{210}$Pb activity

Core 11-4-09 exhibited excess $^{210}$Pb activity in all depth samples and the suspended sediment (Figure 4-8). The highest level of activity in the core was found in the 0-5 cm section and the lowest activity was in the 5-10 cm section. The suspended sediment activity was higher than the activity in all core samples.

Figure 4-8. Excess $^{210}$Pb activity in Core 11-4-09 normalized by surface area. The diamond represents the activity of $^{210}$Pb in the suspended sediment. The horizontal width of each box is the calculated activity error.
5.1 Age interpreted from $^7$Be and excess $^{210}$Pb activity results

Varying magnitudes of flow events can cause old sediment to be eroded and deposited in other areas of the stream. This mechanism can result in older sediment being deposited on top of young sediment in the hyporheic zone. It can also result in young sediment being deposited at depth in the hyporheic zone, beneath older sediment. Because of this, models for analyzing radionuclide data that rely on superposition of young sediment on top of old sediment may not be appropriate.

A conceptual model was created to address the inverse sediment age distribution found in river bed sediments. Based on this model, sediment depth can be ignored and the focus is placed on the sediment radionuclide activity, and thus, age based on the radioactivity decay equation.

The exponential decay formula can be used to convert radionuclide activity to age with an initial activity estimate based on the suspended sediment samples (Equation 5-1).

$$t = -\frac{1}{\lambda}\ln\left(\frac{A}{A_0}\right)$$  

(Equation 5-1)
where \( t \) is the age of sediment, \( \lambda \) is the radionuclide-specific decay constant, \( A \) is the radionuclide activity in the sample, and \( A_0 \) is the initial activity from the suspended sediment sample.

The ages of sediment based on \(^7\)Be and excess \(^{210}\)Pb using the exponential decay formula is found in Table 5-1. These were determined using the radioactivity calculated from the samples, not taking error into account. The age of sediment ranges from 0.33 to 0.52 years when calculated using the \(^7\)Be activities. The age of sediment ranges from 8.6 to 73.8 years when calculated using the excess \(^{210}\)Pb activities. This age disparity is addressed by creating a model to rectify the age difference of the sediment.

**Table 5-1.** The ages of sediment based on \(^7\)Be and excess \(^{210}\)Pb activities found in Core 11-4-09.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(^7)Be age (years)</th>
<th>Excess (^{210})Pb age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5 cm</td>
<td>0.37</td>
<td>8.6</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.52</td>
<td>73.8</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.39</td>
<td>15.9</td>
</tr>
<tr>
<td>15-20 cm</td>
<td>0.41</td>
<td>40.5</td>
</tr>
<tr>
<td>20-25 cm</td>
<td>0.33</td>
<td>28.8</td>
</tr>
</tbody>
</table>

The ages based on \(^7\)Be and excess \(^{210}\)Pb activities indicate that all of the November 2009 samples contain sediments that have been present in the bed on the timescale of a few weeks or months (“young” sediment) and also sediment that has been present in the bed on the timescale of years to decades (“old” sediment). The “young” sediment is associated with the activity levels of \(^7\)Be because it has a short half-life of
only 53.2 days. The “old” sediment is associated with excess $^{210}\text{Pb}$ because of its relatively longer half-life of 22.3 years.

This sediment age dichotomy could be attributed to contamination during coring. As the sample cores were removed from the channel, water washed down through the core possibly carrying fine particles downward through the core. This movement of sediment through the core could be the reason that there are both “young” and “old” sediments in all of the samples from November 2009. The young sediment that was originally near the top of the core could have been transported downward through the core during sampling.

Another possible cause of young sediment mixing with old sediment in the channel is through sedimentation processes that occur in the hyporheic zone. Water washing downwards through the hyporheic zone due to natural processes could carry young sediment deeper into the bed, thus resulting in young sediment found in the deeper core samples. If small amounts of fine sediment can be deposited anywhere in the hyporheic zone, then depositional processes can create samples of mixed ages.

It is inappropriate to calculate ages using only the exponential decay formula because of the distribution of ages found in each sample. A model was created to account for the contamination due to the movement of “young” sediments down through the core during sampling or by natural processes. This model determines an activity for each radionuclide in each section of the core by fractionating the sediment based on “old” and “young” ages. Equations 5-2 and 5-3 were used to calculate the activity of the radionuclides of interest in each core section.
\[ A_y = \left[ f \cdot A_{0y} e^{-k_y t_y} \right] + \left[ (1 - f) \cdot A_{0y} e^{-k_y t_x} \right] \quad \text{(Equation 5-2)} \]

where \( A_y \) is the total calculated activity of \(^7\text{Be}\) in the core section, \( f \) is the fraction of “young” sediment of age \( y \), \( A_{0y} \) is the measured activity of \(^7\text{Be}\) in the suspended sediment sample, \( k_y \) is the decay constant of \(^7\text{Be}\), and \( t_x \) and \( t_y \) are the ages of the “old” and “young” sediment, respectively.

\[ A_x = \left[ f \cdot A_{0x} e^{-k_x t_y} \right] + \left[ (1 - f) \cdot A_{0x} e^{-k_x t_x} \right] \quad \text{(Equation 5-3)} \]

where \( A_x \) is the total calculated activity of \(^{210}\text{Pb}\) in the core section, \( f \) is the fraction of “young” sediment of age \( y \), \( A_{0x} \) is the measured activity of \(^{210}\text{Pb}\) in the suspended sediment sample, \( k_x \) is the decay constant of \(^{210}\text{Pb}\), and \( t_x \) and \( t_y \) are the ages of the “old” and “young” sediment, respectively.

The two terms in these equations represent contributions from the “young” sediment and the “old” sediment to the total calculated activity for each radionuclide. The goal of this modeling activity was to make the calculated activity equal the measured activity by adjusting the sediment age and value of \( f \). The variable \( f \) represents the “young” sediment that may have been mixed with the older sediment through sedimentation processes or as a result of coring. \( f \) is a different value for each depth interval, but constant for both equations when evaluating the same depth interval (Table 5-2).

The parameters in Equations 5-2 and 5-3 were adjusted until the calculated activity of \(^7\text{Be}\) and \(^{210}\text{Pb}\) were equal to their measured activities (within error) for each section of
core 11-4-09. Since the \( f \) value and ages are constant for both equations when evaluating the same depth interval, adjusting these values has an effect on the calculated activities both \(^{210}\)Pb and \(^{7}\)Be. The goal of the comparison between the calculated activities and the measured activities of \(^{7}\)Be and \(^{210}\)Pb is to find a combination of \( f \) values and ages that correctly estimate the measured activities.

Table 5-2 shows the results of the activity modeling. The age of the “young” sediment, \( t_y \), is equal to zero because it is very young. The calculated age of the core sediment is \( t_x \). Figures 5-1 and 5-2 are the plots of calculated activity versus measured activity used to determine \( f \) values and ages.

**Table 5-2.** Values selected for modeling the radionuclide activity of bed sediment using equations 5-2 and 5-3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( f ) value</th>
<th>( t_x ) (years)</th>
<th>( t_y ) (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5 cm</td>
<td>0.40</td>
<td>6.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.10</td>
<td>55.0</td>
<td>0.0</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.25</td>
<td>15.0</td>
<td>0.0</td>
</tr>
<tr>
<td>15-20 cm</td>
<td>0.22</td>
<td>42.0</td>
<td>0.0</td>
</tr>
<tr>
<td>20-25 cm</td>
<td>0.35</td>
<td>32.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Figure 5-1. Calculated values of $A_y$ from equation 5-2 plotted against the measured activity of $^7$Be from Core 11-4-09. The “arms” around each point represent error.

Figure 5-2. Calculated values of $A_x$ from equation 5-3 plotted against the measured activity of excess $^{210}$Pb from Core 11-4-09. The “arms” around each point represent error.
Figures 5-1 and 5-2 show that the calculated activities from Core 11-4-09 correlate with the measured activity of $^7\text{Be}$ and excess $^{210}\text{Pb}$ within error estimates. The age of the samples (t in Table 5-2) can be used to estimate a residence time of fine sediment based on sediment activity modeling by creating a cumulative age distribution.

5.2 Age data interpreted as residence time in the hyporheic zone

The cumulative age distribution of sediment can be used to determine the probability that sediment found in the channel is less than or equal to any age. It can also be used to determine the residence time of fine sediment in the hyporheic zone. Residence time is the average amount of time that sediment spends in the hyporheic zone. The cumulative age distribution of the sediment from the 11-4-09 core is displayed in Figure 5-3.

**Figure 5-3.** The cumulative age distribution of fine sediment in core 11-4-09.
The residence time of the sediment in the hyporheic zone can be estimated if two assumptions are satisfied. The first assumption is that the mass of fine sediment stored is constant with time. The second assumption is that the particles in the hyporheic zone have an age distribution that is constant with time. In this context the term particles refers only to fine sediment (very fine sand, silt, and clay). It does not refer to the entire bed of the South River at RRM 4.3, which also includes more coarse material.

Accepting these assumptions, reservoir theory can be employed as a method of determining the average age of sediment in the hyporheic zone (Bolin and Rodhe, 1972).

Residence time is equal to the inverse of the slope of the cumulative distribution when it is evaluated at zero. For this distribution, the slope of the line when evaluated at zero is 0.028. The inverse of the slope is the residence time of the silt, clay, and fine sand near RRM 4.3 in the South River, VA, approximately 36 years.

5.3 Age interpreted from $^{137}$Cs activity results

The top two samples of Core 11-4-09 (0-5 cm and 5-10 cm) had $^{137}$Cs activity levels below MDA (Table 5-3). This is consistent with what is expected when comparing the sediment age to the ages that were estimated with activity modeling. The peak discharge of $^{137}$Cs to the atmosphere occurred in 1963, so $^{137}$Cs levels below MDA nine years before this date (based on the age of the 5-10 cm section) and 40 years after this date (based on the age of the 0-5 cm section) are expected.
Table 5-3. Sediment ages based on activity modeling. Year of deposition is calculated by subtracting the age from 2009, the year when samples were collected.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age (years)</th>
<th>Year of Deposition</th>
<th>$^{137}$Cs Activity (Bq/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5 cm</td>
<td>6</td>
<td>2003</td>
<td>not detected</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>55</td>
<td>1954</td>
<td>not detected</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>15</td>
<td>1994</td>
<td>$6.04 \times 10^{-5}$</td>
</tr>
<tr>
<td>15-20 cm</td>
<td>42</td>
<td>1967</td>
<td>$7.42 \times 10^{-5}$</td>
</tr>
<tr>
<td>20-25 cm</td>
<td>32</td>
<td>1979</td>
<td>$1.32 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Detectable levels of $^{137}$Cs were found in the 10-15, 15-20, and 20-25 cm samples. The years of deposition for these three samples are constrained by the samples that displayed no detectable activity (5-10 cm deposited around 1954 and 0-5 cm deposited around 2003). Since the peak $^{137}$Cs release to the atmosphere was in 1963, it is likely that these samples (10-15, 15-20, and 20-25 cm) would have detectable $^{137}$Cs activity. The highest $^{137}$Cs levels were found in the 20-25 cm section. According to the sediment age based on modeling, this peak correlates to 1979, 16 years after the peak discharge to the atmosphere occurred. These sediment ages (taking error into consideration) correlate with expected levels of $^{137}$Cs for this time period.

5.4 Mercury concentrations in 11-4-09 core

Skalak and Pizzuto (in review) examined mercury concentrations of sediment deposits in the South River. It was found that mercury on suspended particles reached peak concentrations of 900 ppm in 1950. Mercury concentrations have subsequently decreased by two orders of magnitude to current values. Nearly 800 kg of mercury were
stored in the deposits in 1956, while only 80 kg remains today (Skalak and Pizzuto, in review).

The “Dooms Dam core” (Figure 5-4) can be used to partially constrain sediment age based on mercury concentrations. Mercury concentrations are at background levels when mercury was first being used for rayon production in 1930. Concentrations of mercury in the Dooms Dam core increased until the peak around 1950. After 1950, mercury concentrations rapidly decreased but never returned to pre-production, background levels.

**Figure 5-4.** Range of mercury concentrations the South River based on Monte Carlo simulations (from Skalak and Pizzuto, in press).
Mercury concentrations in Core 11-4-09 range from 12.0 to 21.4 ppm. These mercury concentrations agree with sediment age estimates calculated from radionuclide activity. The maximum age of sediment calculated from radionuclide activity modeling was approximately 55 years. If the oldest sediment from Core 11-4-09 was deposited in the mid- to late-1950s, low mercury concentrations are expected because of the rapid decrease in mercury concentration after the peak near 1950. Also, the residence time is estimated to be on the scale of a few decades, resulting in mercury concentrations at post-release background levels.

**5.5 Scour chains**

The detection limit ($L_D$) was used to determine whether the magnitude of observed scour and fill events exceed measurement error with 95% probability. The calculated $L_D$ was 3.0 cm. Scour or fill depths beyond the 3.0 cm threshold are considered significant. Table 5-4 summarizes the data collected during scour chain monitoring. ‘Frequency of Scour’ and ‘Frequency of Fill’ are the number of scour or fill measurements (from scour chains or cross section measurements) that exceed the 95% probability threshold during each flow event.
Table 5-4. Large flow events that occurred during scour chain monitoring. The values of significant scour and fill are listed in the last column. Positive values indicate bed scour. Negative values indicate fill.

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Flow (cfs)</th>
<th>Recurrence Interval (years)</th>
<th>Frequency of Scour</th>
<th>Frequency of Fill</th>
<th>Significant Scour (+) and Fill (-) values (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 28, 2010</td>
<td>56.6</td>
<td>0.95</td>
<td>2</td>
<td>0</td>
<td>+3.3, +3.2</td>
</tr>
<tr>
<td>December 1, 2010</td>
<td>84.9</td>
<td>2.25</td>
<td>1</td>
<td>8</td>
<td>-3.2, -4.8, -3.2, +5.1, -3.4, -4.8, -3.7, -3.1, -4.4</td>
</tr>
<tr>
<td>March 10, 2011</td>
<td>45.3</td>
<td>0.61</td>
<td>7</td>
<td>2</td>
<td>+19.9, +4.8, +3.5, -3.8, +3.1, -3.5, +3.8, +3.2, +3.4</td>
</tr>
<tr>
<td>April 16, 2011</td>
<td>229.4</td>
<td>12.76</td>
<td>5</td>
<td>8</td>
<td>+4.8, +8.3, -4.4, +4.4, -3.6, -3.9, -3.5, -3.3, -6.6, -4.5, +6.1, +3.5, -3.5</td>
</tr>
</tbody>
</table>

16.7% of the total scour chain measurements recorded can be considered “real” measurements by exceeding the 95% probability threshold or $L_D$. The large flow event that occurred on April 16, 2011 with a recurrence interval of 12.76 years accounts for 13 of the 33 statistically significant events.

The 12-year return period flow is associated with a higher frequency of statistically significant scour and fill events than the smaller flows. Since the recurrence interval for this flow is high, one would expect more of the statistically significant measurements to be related to scour instead of fill, which is not the result of these data. Instead, more of the significant measurements are related to fill, meaning that this area of the stream accumulates sediment that is transported during high flows.

The smaller flows account for 20 of the 33 observed scour measurements from this study. According to these data, significant scour and fill can occur during flows with
a recurrence interval of 0.61 or greater, but a greater amount of significant events occur at larger flows.

One would expect greater amounts of scour at larger magnitude flows, but the data show that smaller flows have a greater proportion of scour events to fill events. For example, the 12-year flow resulted in eight significant fill measurements, but only five significant scour measurements. It is important to note that most of these values are near the 3.0 cm threshold of significance.

These results are unexpected but as mentioned in the Methods chapter, scour chains register one apparent cycle of scour and fill. These data are used to represent one individual event, when in reality multiple smaller events may have had an effect on the resulting measurements. Measurements were taken as soon as possible after a large flow event, but it takes a short amount of time for scour or fill of bed sediment to occur.
Chapter 6

CONCLUSIONS

6.1 Residence time and its effect on mercury contamination in the South River

The residence time, or average amount of time sediment spends in the hyporheic zone, of fine sediment in the South River is approximately 36 years. With a residence time on the scale of a few decades, most of the mercury that was introduced to the bed of the South River between 1929 and 1950 (59 to 80 years ago) should already be eroded and transported downstream. The high levels of mercury still observed in the South River’s hyporheic zone are likely due to contaminated sediment contributions from the floodplains and banks. Contamination will likely persist in the hyporheic zone until the external sources cease to contribute mercury-contaminated sediment.

6.2 Scour chain data

It is presumed that greater magnitude flow events result in greater scour activity, but data collected during this study do not support that conclusion. Smaller magnitude flows exhibited a greater frequency of scour, while larger flows exhibited a greater frequency of fill.

Flow events with magnitudes between 0.61 and 12.76 year recurrence intervals all had statistically significant scour and fill. This supports the conclusion that significant
scour can occur at all magnitudes of flow, not only large flow events. Greater than 50% of the significant scour observations were within one cm of the threshold of significance, so further study should be conducted to determine longer-term scour and fill patterns.

The scour data support the age results obtained from the radionuclide activity modeling. The depth of sediment with an average age of approximately 36 years (the residence time) is 25 cm, so regular scour at depths less than 25 cm is expected from a short-term study. The data from this study do not show what magnitude of flow is necessary for scour to reach depths of 25 cm.

6.3 Study methods and future studies

This study was an exercise to determine whether residence time could be estimated based on age data from an active river channel. Instead of creating a model that follows the laws of superposition, this study assumes that sediment is well-mixed. This implies that older sediment does not necessarily need to underlie young sediment.

The attempt to obtain more radionuclide data from sand samples resulted in the majority of excess $^{210}$Pb sample activities below MDA (Appendix A). This could be remedied by collecting fine sediment samples instead of sand samples. Fine sediment has higher radionuclide activity per unit weight than sand samples because of the increased amount of surface area. If sand-sized sediment is the focus of a future study, a greater mass of sediment or a different gamma detection system could be used to increase the amount of activity detected.
In order to understand the fate of mercury-contaminated sediment in the hyporheic zone of the South River, future studies could utilize radionuclide dating methods to determine the residence time of fine-grained sediment in other spatially extensive bed and/or bank materials.
REFERENCES

www.nndc.bnl.gov/nudat2/

www.olivermagand.com

www.southriverscienceteam.org

www.southriverscienceteam.org/publications/fact-sheets/index.html

www.waynesboro.va.us/about.php


Narinesingh, P.. A sinuous gravel-bedded river with frequent bedrock exposures: The statistics of its planform compared with a freely meandering river and the suitability


Appendix

APPENDIX A

RADIONUCLIDE ACTIVITY AND SURFACE AREA OF ALL SAMPLES
<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth Interval (cm)</th>
<th>Surface Area (m²/g)</th>
<th>Pb-210 Activity (Bq/g)</th>
<th>Pb-210 Activity Error (Bq/g)</th>
<th>Pb-210 Activity (Bq/m²)</th>
<th>Pb-210 Activity Error (Bq/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>11-4-09 Core</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0-5</td>
<td>22.82</td>
<td>6.23E-02</td>
<td>1.02E-02</td>
<td>2.73E-03</td>
<td>4.49E-04</td>
</tr>
<tr>
<td>2</td>
<td>5-10</td>
<td>23.30</td>
<td>8.72E-03</td>
<td>1.20E-02</td>
<td>3.74E-04</td>
<td>5.16E-04</td>
</tr>
<tr>
<td>3</td>
<td>10-15</td>
<td>19.60</td>
<td>4.32E-02</td>
<td>1.13E-02</td>
<td>2.20E-03</td>
<td>5.76E-04</td>
</tr>
<tr>
<td>4</td>
<td>15-20</td>
<td>18.19</td>
<td>1.73E-02</td>
<td>1.09E-02</td>
<td>9.51E-04</td>
<td>5.99E-04</td>
</tr>
<tr>
<td>5</td>
<td>20-25</td>
<td>13.88</td>
<td>2.09E-02</td>
<td>1.12E-02</td>
<td>1.51E-03</td>
<td>8.09E-04</td>
</tr>
<tr>
<td><strong>11-13-09 Suspended Sediment Sample</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>6-15-10 Surface Sand Samples</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>7-15-10 Sand Samples</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0-3</td>
<td>3.33</td>
<td>6.66E-04</td>
<td>--</td>
<td>2.00E-04</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>3-5</td>
<td>2.90</td>
<td>4.74E-04</td>
<td>--</td>
<td>1.63E-04</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>5-7</td>
<td>2.91</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>7-9</td>
<td>2.89</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>9-11</td>
<td>2.11</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>6</td>
<td>11-13</td>
<td>2.69</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>13-16</td>
<td>2.70</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>8</td>
<td>16-19.5</td>
<td>2.11</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>19.5-23</td>
<td>1.84</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>23-27</td>
<td>2.15</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>11</td>
<td>27-30</td>
<td>2.30</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>30-34</td>
<td>1.90</td>
<td>5.18E-05</td>
<td>--</td>
<td>2.73E-05</td>
<td>--</td>
</tr>
<tr>
<td>13</td>
<td>34-40</td>
<td>1.88</td>
<td>Not detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>below 40</td>
<td>1.70</td>
<td>6.98E-04</td>
<td>--</td>
<td>4.10E-04</td>
<td>--</td>
</tr>
<tr>
<td>Sample</td>
<td>Depth Interval (cm)</td>
<td>Surface Area (m²/g)</td>
<td>Cs-137 Activity (Bq/g)</td>
<td>Cs-137 Activity Error (Bq/g)</td>
<td>Cs-137 Activity (Bq/m²)</td>
<td>Cs-137 Activity Error (Bq/m²)</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>------------------------</td>
<td>-----------------------------</td>
<td>-------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>11-4-09 Core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0-5</td>
<td>22.82</td>
<td>Not Detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>5-10</td>
<td>23.30</td>
<td>Not Detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>10-15</td>
<td>19.60</td>
<td>1.18E-03</td>
<td>1.60E-04</td>
<td>6.04E-05</td>
<td>8.17E-06</td>
</tr>
<tr>
<td>4</td>
<td>15-20</td>
<td>18.19</td>
<td>1.35E-03</td>
<td>2.56E-04</td>
<td>7.42E-05</td>
<td>1.41E-05</td>
</tr>
<tr>
<td>5</td>
<td>20-25</td>
<td>13.88</td>
<td>1.83E-03</td>
<td>2.20E-04</td>
<td>1.32E-04</td>
<td>1.59E-05</td>
</tr>
<tr>
<td>11-13-09 Suspended Sediment Sample</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>N/A</td>
<td>18.60</td>
<td>Not Detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>6-15-10 Surface Sand Samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>N/A</td>
<td>4.12</td>
<td>4.84E-04</td>
<td>3.76E-03</td>
<td>1.17E-04</td>
<td>9.12E-04</td>
</tr>
<tr>
<td>2</td>
<td>N/A</td>
<td>4.37</td>
<td>1.95E-04</td>
<td>4.02E-04</td>
<td>4.45E-05</td>
<td>9.21E-05</td>
</tr>
<tr>
<td>3</td>
<td>N/A</td>
<td>3.93</td>
<td>1.13E-04</td>
<td>4.02E-04</td>
<td>2.88E-05</td>
<td>1.02E-04</td>
</tr>
<tr>
<td>4</td>
<td>N/A</td>
<td>3.12</td>
<td>1.58E-04</td>
<td>4.02E-04</td>
<td>5.08E-05</td>
<td>1.29E-04</td>
</tr>
<tr>
<td>7-15-10 Sand Samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0-3</td>
<td>3.33</td>
<td>4.27E-04</td>
<td>--</td>
<td>1.28E-04</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>3-5</td>
<td>2.90</td>
<td>2.59E-04</td>
<td>--</td>
<td>8.92E-05</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>5-7</td>
<td>2.91</td>
<td>2.97E-04</td>
<td>--</td>
<td>1.02E-04</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>7-9</td>
<td>2.89</td>
<td>Not Detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>9-11</td>
<td>2.11</td>
<td>Not Detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>6</td>
<td>11-13</td>
<td>2.69</td>
<td>Not Detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>13-16</td>
<td>2.70</td>
<td>3.31E-04</td>
<td>--</td>
<td>1.22E-04</td>
<td>--</td>
</tr>
<tr>
<td>8</td>
<td>16-19.5</td>
<td>2.11</td>
<td>2.01E-04</td>
<td>--</td>
<td>9.55E-05</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>19.5-23</td>
<td>1.84</td>
<td>Not Detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>23-27</td>
<td>2.15</td>
<td>Not Detected</td>
<td>--</td>
<td>Not Detected</td>
<td>--</td>
</tr>
<tr>
<td>11</td>
<td>27-30</td>
<td>2.30</td>
<td>1.89E-04</td>
<td>--</td>
<td>8.25E-05</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>30-34</td>
<td>1.90</td>
<td>1.99E-04</td>
<td>--</td>
<td>1.05E-04</td>
<td>--</td>
</tr>
<tr>
<td>13</td>
<td>34-40</td>
<td>1.88</td>
<td>3.46E-04</td>
<td>--</td>
<td>1.84E-04</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>below 40</td>
<td>1.70</td>
<td>4.00E-04</td>
<td>--</td>
<td>2.35E-04</td>
<td>--</td>
</tr>
</tbody>
</table>
APPENDIX B

GRAIN SIZE RESULTS
Grain size results from field sampling on November 5, 2009.

<table>
<thead>
<tr>
<th>Grain Diameter (mm)</th>
<th>Total Count $^a$</th>
<th>Cumulative $^b$</th>
<th>Percent finer than $^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>11</td>
<td>11</td>
<td>5.67</td>
</tr>
<tr>
<td>2.8</td>
<td>0</td>
<td>11</td>
<td>5.67</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>12</td>
<td>6.19</td>
</tr>
<tr>
<td>5.6</td>
<td>10</td>
<td>22</td>
<td>11.34</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>40</td>
<td>20.62</td>
</tr>
<tr>
<td>11</td>
<td>13</td>
<td>53</td>
<td>27.32</td>
</tr>
<tr>
<td>16</td>
<td>14</td>
<td>67</td>
<td>34.54</td>
</tr>
<tr>
<td>22.6</td>
<td>20</td>
<td>87</td>
<td>44.85</td>
</tr>
<tr>
<td>32</td>
<td>32</td>
<td>119</td>
<td>61.34</td>
</tr>
<tr>
<td>45</td>
<td>23</td>
<td>142</td>
<td>73.20</td>
</tr>
<tr>
<td>64</td>
<td>31</td>
<td>173</td>
<td>89.18</td>
</tr>
<tr>
<td>90</td>
<td>15</td>
<td>188</td>
<td>96.91</td>
</tr>
<tr>
<td>128</td>
<td>6</td>
<td>194</td>
<td>100</td>
</tr>
</tbody>
</table>

$^a$ Number of grains that are smaller than or equal to the ‘Grain Diameter’ but larger than the next smaller ‘Grain Diameter’

$^b$ Total number of grains less than or equal to ‘Grain Diameter’

$^c$ Percentage of grains less than or equal to ‘Grain Diameter’