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# Tracing the origin of fine-grained fluvial sediment using radionuclides with management implications

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ABSTRACT

This paper reports a study of the origin of fine-grained river sediments and their potential impact to a reservoir that supplies drinking water. Excess sediment may affect water quality and decrease the storage capacity of the reservoir. Three sediment cores were taken in 2011 from the Rockaway River in New Jersey that leads into the reservoir to determine the sources of the sediment and propose remediation actions. The coring sites spanned an area upstream in the watershed to just above the reservoir, and the sites varied in land use. Sediment was analyzed in one to two centimeter intervals to determine the radionuclide activity of excess $^{210}$Pb and $^{137}$Cs. The sediment activity level at two of the sites (the ones farthest up- and downstream) show predominantly low levels of excess $^{210}$Pb and $^{137}$Cs, suggesting that the sediment is coming from deeper sources such as river channel widening/lateral migration and hillslope failures and/or legacy sediment sources. The sediment from site 2 exhibited higher activity of excess $^{210}$Pb, suggesting more surficial sources of sediment or relatively recent sediments and likely tied to widespread urbanization. The different radionuclide profiles between the cores suggest spatial variation in the sediments' sources, with the sources varying between surficial and deeper ones. Establishing the origin of this sediment would help to derive management solutions to lessen sediment delivery, stabilize and/or remove legacy sediment supplies to minimize downstream impacts.



## Introduction

Excess river sediments can negatively impact both water quality and quantity. Excess sediment loads have been identified as a major cause of impairment (USEPA, 2007). Excess sediment indirectly affects water quality by transporting organic substances through adhesion. Excess sediment has the ability to directly decrease water quality as well. These negative effects include loss of water storage in reservoirs and behind dams (Walling, 2009), altered aquatic habitat (Cooper, 1992; Wood and Armitage, 1997; Bunn and Arthington, 2002), and altered channel capacity and flooding regimes (Knox, 2006). Often, water quality measures are addressed through the establishment of total maximum daily loads (TMDLs). Sediment currently ranks as the fifth ranking cause of TMDLs, with pathogens listed first under the Clean Water Act (USEPA, 2012). The establishment of sediment TMDLs varies by state, however, with New Jersey, the location of the present study, having zero listed rivers, while neighboring Pennsylvania has over 3500 instances of impairments from sediment listed. The TMDL sets a benchmark for water quality criteria. In order to establish a benchmark, an understanding of source of the pollutant is often necessary (Collins et al., 2012a).

Identifying the source of excess river sediment is critical for mitigation efforts. A background, or natural, amount of sediment in rivers exists as fluvial systems transport water and sediment across the landscape as part of the larger hydrologic and geologic systems. Human activities, however, alter and accelerate these natural processes. Knowing the origin of the excess sediment facilitates development of proper mitigation efforts. In many cases, sediment from a watershed can be categorized as originating from shallow, surficial sources or from deeper sources. For example, shallow sources may originate from overland flow (Hortonian or saturation) on uplands that erodes to depths of millimeters to centimeters. Hillslope failure, river channel widening, and/or construction activity may mobilize sediment from deeper (i.e., meters) sources. Aeolian deposition may be a third source, although no evidence supports aeolian deposition as a significant source to the rivers studied here. The relative contributions from

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these sources may change both temporally and spatially in a river. These changes allow only limited conclusions to be drawn from a single data point, limiting the success of a mitigation effort that is applied uniformly across a watershed.

Contemporary sediment sources are frequently augmented and supplemented by legacy sediment. Legacy sediment comes from anthropogenic sources and activities, such as disturbances in land use/cover and/or surficial processes (James, 2013). For rivers, legacy sediments can originate from incised floodplains (Walter and Merritts, 2008), impoundments behind dams (Merritts et al., 2011), increased hillslope erosion due to historic deforestation (DeRose et al., 1993; Jennings et al., 2003), and anthropogenic activities such as construction and land use changes (Wolman and Schick, 1967; Croke et al., 2001). Legacy sediment can also deliver high loads of contaminants to river systems (Cave et al., 2005; Lecce et al., 2008). The current supply of sediment is high (Hooke, 2000), as humans are one of the greatest current geomorphic agents. Consequently, combining legacy sediment with increased anthropogenic geomorphic activity makes it even more important to identify the source of sediments in rivers.

Sediment sources can be distinguished using the radionuclides lead-210 ($^{210}$Pb) and cesium-137 ($^{137}$Cs). $^{210}$Pb is a naturally-occurring isotope resulting from the decay of $^{238}$Uranium in rock to eventually $^{222}$Radon. This gas diffuses into the atmosphere and decays into excess $^{210}$Pb, which eventually settles to the ground. This diffusion process creates a fairly consistent level of excess $^{210}$Pb in the atmosphere and minimizes local differences that exist in the production of radon. Rain and settling can subsequently result in the deposition of excess $^{210}$Pb, with a half-life of 22.3 years. This atmospheric deposition of excess $^{210}$Pb, is added to the background levels that originate from the decay of radon in the soil. "Excess" atmospheric $^{210}$Pb occurs because, if the material (in this case the sediment) is isolated from the source (i.e., the atmosphere), this level will decay and decrease in activity. As this excess $^{210}$Pb is then correlated with the time of surficial exposure, it is commonly used as a sediment tracer (e.g., D'Haen et al., 2012; Foster et al., 2007; Whiting et al., 2005; Matisoff et al., 2002).

$^{137}$Cs is also used as a sediment tracer, although its source is different. It is the byproduct of nuclear fission through reactors and weapon activities, and is not naturally found in the world. A global signature of peak $^{137}$Cs activity exists in sediment representing the mid-1960s as a result of the common atmospheric testing of nuclear weapons. Global deposits of relatively high $^{137}$Cs activity also correspond to the nuclear accidents in Chernobyl, Ukraine in 1986 and Fukushima, Japan in 2011. As its half-life of 30.2 years is similar to $^{210}$Pb, $^{137}$Cs is often used in parallel with excess $^{210}$Pb to identify the sources of sediment.

Sediment derived from shallow, surficial erosion, such as through overland flow, would typically have higher amounts of excess $^{210}$Pb than sediment from deeper sources that have been isolated from the atmosphere for a longer time. Samples with higher activity readings of excess $^{210}$Pb indicate sources from upland/surface erosion, while samples with lower readings suggest sources from depths that have not recently been exposed to the atmosphere (Feng et al., 2012). Surficial sources eroded in the uplands and/or floodplains contribute to higher activity levels. Deeper sources, with lower or nonexistent excess $^{210}$Pb levels, might come from sources that expose and transport sediment, such as hillslope failure or river bank erosion.

Many previous studies have used radionuclides to determine sediment sources (e.g., reviewed in Brown et al., 2009; D'Haen et al., 2012; Mukundan et al., 2012) for more than 20 years (e.g., Joshi et al., 1991). These studies have used tracers in mountain streams to determine particle transit times (Bonniwell et al., 1999), watershed sediment budgets (Walling et al., 2006), sources of suspended sediments (Collins et al., 1998; Mukundan et al., 2010), floodplain deposition and erosion (Humphries et al., 2010), and land use changes (Foster et al., 2007).

Information for sediment sources derived from $^{210}$Pb and $^{137}$Cs has also been combined with numerical models to produce sediment budgets for watersheds. Generally, these studies have used radionuclides and/or other sediment tracers with some combination of transport, mixing, storage, and depositional models with a randomization component (e.g., Monte Carlo simulation) to determine potential contributing sources to the sampled sediment. This approach identifies the often diffuse nature of sediment sources from the sediment sample. For example, numerical modeling elucidated the percent contributions of sediment (and associated possible statistical deviations) from various catchment land uses (Collins et al., 2012b,c). However, model limitations include the amount and timing of storage in system (Parsons, 2012), assumptions about unmeasured terms (Parsons, 2012), and the need for validated input data (Collins and Walling, 2004). Like any scientific model, the limitations and assumptions should be recognized to prevent over-reaching.

In a previous study, the authors validated the regional correlation between excess $^{210}$Pb with urban watersheds and little to none excess $^{210}$Pb with channel/bank areas. Feng et al. (2012) examined two proximal watersheds ~20 km to the southeast of the Rockaway River, New Jersey, that established radionuclide for the area. Sediment with excess $^{210}$Pb depletion was found in the river channel bank areas and uplands and surficial sediment contained excess $^{210}$Pb accumulation. In the urban river, excess $^{210}$Pb accumulated in the river sediment area but was depleted in the river sediment from the more rural stream (Feng et al., 2012). Additionally, no detectable $^{137}$Cs was found in either river channel bank or river channel bottom sediment. Previous studies determined the activity of these radionuclides in fluvial sediment, and use either their depletion or concentration to interpret the watershed processes. As these radionuclides are atmospherically-deposited and fix readily to fine-grained particles, they can indicate deposition processes that concentrate them or erosional processes that deplete them.

Using radionuclides as tracers, this study addressed the following questions. First, what is the origin of fine-grained fluvial sediment draining into a reservoir that supplies drinking water? Second, how do the sources vary longitudinally along the river channel? Third, what do the sediment records reveal regarding the continuity of sedimentation? In other words, does the accumulated sediment originate from different sources over time?

While it is more common to sample depositional environments such as deltas or lakes, or suspended sediment, this study focused on the sediment present in the river channel. Our approach provides snapshots of the sources of sediment along the river channel and how those sources may change along the river. As this sediment can still impact water quality and aquatic habitat (e.g., burial of gravel beds needed for fish spawning) and is still being transported downstream during floods, this approach offers a different perspective from the usual method of sampling suspended sediment and retrieving samples from depositional environments.

## Site description

The Rockaway River (5th order), in northern New Jersey, supplies the Boonton Reservoir. This reservoir is a major source of drinking water and part of a larger regional water supply system that provides water for over five million New Jersey residents. Samples were collected at three sites along the main stem in order to ascertain the spatial variability of the sediment sources.

Site 1 (39 km$^2$ upstream drainage area; 40.954233° N, 74.571099° W), the farthest upstream site, is mostly surrounded