DETERMINING RELATIVE CONTRIBUTIONS OF ERODED LANDSCAPE SEDIMENT AND BANK SEDIMENT TO THE SUSPENDED LOAD OF GOODWIN CREEK USING RADIONUCLIDES

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Abstract: Identifying the major contributors to the fine suspended sediment load of a stream allows for better focus of Best Management Practices. This study was designed to quantify the relative proportion of eroded surface soils and collapsed bank sediment in the fine suspended sediment load of multiple runoff events in Goodwin Creek, MS using activities of ^{7}Be and ^{210}Pb$_{xs}$. Each source material must have a unique radionuclide signature relative to the other to quantify the contributions from the different source areas to the suspended sediment load. Due to different erosion processes controlling the sediment delivery to streams, namely sheet erosion and bank collapse, eroded surface soils will have higher activities of the ^{7}Be and ^{210}Pb$_{xs}$ than collapsed bank sediment. The fine suspended sediment, which is a mixture of eroded surface soils and collapsed bank sediment, will have an intermediate radionuclide signature that is quantified in terms of the relative contribution from both source materials. A simple two-end member mixing model would determine the relative contribution from each source area to the total fine sediment load. The radionuclide signature of suspended sediments would lie roughly along the mixing line between the signatures of the two end-member sources of sediment. Data presented here focus on one runoff event and suggest that eroded surface soils are more abundant in the suspended sediment early in the runoff event; however, collapsed bank sediment dominates the suspended load later in the runoff event.

INTRODUCTION

The anthropogenically enhanced delivery of sediment to streams leads to detrimental problems both on the landscape and within the channel. The loss of topsoil can significantly lower crop yields. In addition, increased sediment loads can diminish water quality and ecosystem health. Sediment-bound nutrients and contaminants are transmitted through the food chain resulting in depleted fish stocks (Smith et al., 2001) and eutrophication, as in the Gulf of Mexico (Rabalais et al., 1991). Finally, the deposition of this sediment fills reservoirs and waterways, polluting drinking supplies and limiting ship traffic. Identifying the major contributors of the sediment would allow better focusing of Best Management Practices (BMPs) to curb these increased sediment loads.

A sediment budget is a common practice of evaluating sediment loads to a system; however, most budgets merely provide a net balance and can not identify major sources of sediment. If each source of sediment had a unique signature associated with it, then these sources could be differentiated in the budgets and individually accounted. This study was designed to differentiate sediment sources to the fine suspended sediment load of a sand and gravel bed stream in Northern Mississippi, Goodwin Creek. In this system, freshly eroded surface soils from the landscape and collapsed bank sediment comprise the fine suspended sediment load. The activities of two naturally occurring radionuclides, ^{7}Be and ^{210}Pb$_{xs}$, relative to one another will provide the unique signature of both sediment contributors. Because of the limited number of sediment characteristics used to differentiate the sediment, only relative proportions of the eroded surface soils and collapsed bank sediment will be determined in the sediment load of a sampled runoff event.

BACKGROUND

A more detailed explanation of the theory behind the use of ^{7}Be and ^{210}Pb$_{xs}$ to quantify the proportion of eroded surface soils relative to the amount of collapsed bank material and/or resuspended bed sediment in the fine suspended sediment load of streams is presented in the following references: Wilson (2003); Matisoff et al. (2005); Wilson et al. (2005). A brief summary of the theory is presented within this paper, which focuses on a case study of the technique in Goodwin Creek, MS.

^{7}Be and ^{210}Pb$_{xs}$, which are attached to aerosol particles in the atmosphere, are delivered to the landscape mainly during precipitation events. The radionuclides quickly and strongly bond to surface soils. The relatively high activities of ^{7}Be and ^{210}Pb$_{xs}$ in the precipitation decrease as the two radionuclides are mixed with previously delivered ^{7}Be and ^{210}Pb$_{xs}$ in surface soils, which have undergone radioactive decay (Matisoff et al., 2005; Wilson et al., 2005). Surface soils, which still have relatively high activities of ^{7}Be and ^{210}Pb$_{xs}$, are eroded from the landscape as runoff initiates and transported through streams. As the eroded sediment is transported downstream, sediment from stream banks is entrained into the flow. Additions of bank material, which have low activities of ^{7}Be and ^{210}Pb$_{xs}$, further decrease the radionuclide activities of the suspended fine sediment (Matisoff et al., 2005; Wilson et al., 2005). Collapsed bank sediments will have relatively low activities of ^{210}Pb$_{xs}$ and ^{7}Be because they receive little atmospheric input due to near-vertical slopes (Whiting et al., 2005). Moreover, stream bank failure typically removes large volumes of material (Thorne, 1992). The high-activity soil at the top of the bank is diluted by a much larger volume of low activity soil from deeper in the soil column of the bank.

Suspended sediment in Goodwin Creek is a mixture of eroded surface soils and collapsed bank sediment. The fine suspended sediment has an intermediate radionuclide signature that is quantified in terms of the relative contribution of the two source materials. High radionuclide activities suggest a large proportion of recently eroded landscape-derived material. Conversely, lower activities in the suspended sediment suggest dilution by bank material. The different erosion mechanisms affecting surface soils and bank sediments produce these different signatures. A simple two-end member mixing model would determine the relative contribution of each source area to the total fine sediment load. The radionuclide signature of suspended sediments would lie roughly along the mixing line between the signatures of the two end-member sources of sediment.

METHODS

Study Site: Activities of ^{7}Be and ^{210}Pb$_{xs}$ from precipitation samples and soil, bank, and suspended sediments collected in the Goodwin Creek, MS, watershed (Figure 1) will be used to accomplish the objective identified above. The Goodwin Creek watershed is an experimental watershed situated in the bluff hill region of north central Mississippi, administered by the National Sedimentation Laboratory of the U.S. Department of Agriculture's Agricultural Research Service in Oxford, MS. The watershed is well instrumented to measure stream flow, sediment load, precipitation, channel characteristics, soil and land use characteristics, and other watershed parameters.

The 21.24-km^2 Goodwin Creek watershed consists of broad ridges and relatively narrow valleys filled with alluvial deposits. Soils are silty loams, which erode readily when surface cover is removed. The average annual precipitation in the watershed is 1400 mm/y. Major runoff events associated with intense erosion are commonly a result of severe thunderstorms in late winter or spring. The flow regime at Goodwin Creek is flashy, and over 77% of the annual runoff amount comes during the wet period between December and May. The watershed is mostly rural but with only 13% of its total area being cultivated. These agricultural lands are located predominantly in the lower half of the watershed (Kuhnle et al., 1996). A more complete description of the watershed can be found in USDA-ARS (2005).

Runoff Event: The sampled runoff in the Goodwin Creek watershed occurred on January 7, 2005. During the three months prior to the runoff event, 550 mm had fallen over the study area. Rainfall associated with the sampled runoff event totaled 27.69 mm and began shortly after 00:00 CST, lasting until 17:30 CST. The most intense rainfall occurred between 12:00 and 15:00 CST. Discharge in Goodwin Creek began to increase at approximately 04:00 CST and peaked at 11.78 m^3/s at 15:21 CST. This peak stage has a recurrence interval of approximately 0.5 yr (Kuhnle et al., 1999).

Field Methods: Samples were collected from both the landscape and stream banks to determine the background activities of ^{7}Be and ^{210}Pb$_{xs}$ of the potential source areas. Profiles of the radionuclide activities in the soil column were collected in two fields, which contained soybeans the previous growing season, 9 days before the sampled runoff event. These fields were located immediately adjacent to the stream banks. Three locations were sampled in each field. High resolution profiles were developed by inserting a three-sided box corer with uniform sampling intervals every 0.4 cm and a sampling area of 232.83 cm^2 into the side of a soil pit in the field. The box core was removed and sampled at the 0.4-cm interval to a depth of 4.0 cm. Only the top 1.2 cm was used to establish soil profiles because of the limited penetration of ^{7}Be (Wallbrink and Murray, 1996; Bonniwell et al., 1999). These samples were dried at 60^{o} C, ground to a fine consistency, and passed through a 63 μm sieve. The samples were analyzed using gamma spectroscopy to determine activities of ^{7}Be and ^{210}Pb$_{xs}$.

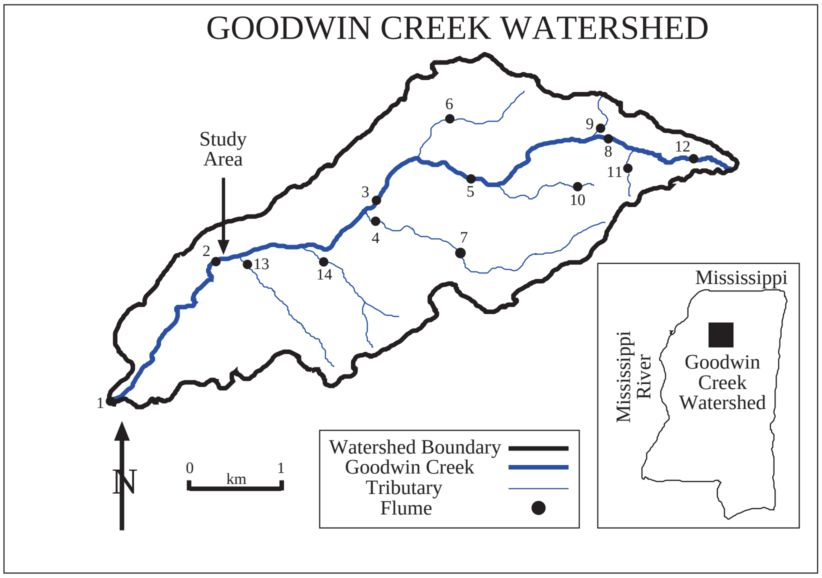

Figure 1 Map of the Goodwin Creek watershed.

A set of six more soil profiles were collected at similar locations after a later rain event. These soils were dried, weighed, and lightly crushed to less than 2 mm. A dispersant, $(NaPO_3)_6$, was added to each sample, and each mixture was placed on a shaker overnight. The sand particles were removed using a 53 μm sieve. The remaining mixture was placed in an automated, large-volume, particle size separator, similar to that in Rutledge et al. (1967) to separate the silt and clay fraction. All three size samples were dried, weighed, and placed in a standardized geometry for analysis using gamma spectroscopy to determine their radionuclide activities. Enrichment coefficients were determined for each size fraction relative to the total activity of the bulk sample. The enrichment coefficients were applied to the soil radionuclide profiles to account for the preferential erosion of the clays (Rhoton et al., 1979).

Three vertical cores of 1-m length and a surface area of 5.07 cm^2 were collected from an actively eroding stream bank upstream of the fields containing the soil profiles. Cores were collected in 33 cm intervals. Each interval was dried at 60^o C and separated into size fractions using the automated, large-volume, particle size separator mentioned above. The samples are currently being analyzed by gamma spectroscopy to determine activities of ^{7}Be and $^{210}Pb_{xs}$.

Water and suspended sediment were collected from Goodwin Creek during the above mentioned runoff event. Plastic buckets, with a sampling volume of 20 L, were lowered from a bridge into the center of a supercritical flume in Goodwin Creek just downstream of the soil and bank samples. Sampling in the super critical flume insured the samples would be well mixed. An average of 15.5 L of water and suspended sediment was collected 28 times at regularly spaced intervals during the runoff event. Samples were sieved with a 63 μm sieve, dried, and weighed. The finer (silt and clay, combined) samples were analyzed using gamma spectroscopy to determine activities of ^{7}Be and $^{210}Pb_{xs}$.

Precipitation samples were collected at four locations near the sampling area. Buckets with a surface area of 630 cm^2 were placed atop a 1-m stand immediately after the soil profiles were collected. The buckets were retrieved immediately after the suspended sediment samples were collected. The four precipitation samples were pooled. The radionuclides were retrieved by precipitating them on a $Fe(OH)_3$ floc. The floc was collected in a standardized sampling geometry and analyzed for its radionuclide activity using gamma spectroscopy.

The resulting radionuclide activities of the precipitation samples were distributed exponentially to a depth of 1.2 cm over an average soil profile to determine the activity of the eroded sediment (Wilson et al., 2003). The high partition coefficients of the radionuclides ($K_d \sim 10^4$ to 10^6; Wilson, 2003) result in rapid and strong bonding to the soil surface. The resulting radionuclide profile can be represented by an exponential function (Owens et al., 1996;

Wallbrink and Murray, 1996; Wilson et al., 2003). The exponential function can be used to determine the average activities of the radionuclides eroded from the landscape surface.

Gamma spectroscopy was used to determine the activities of ^{7}Be and $^{210}Pb_{xs}$ in the soil, bank, and suspended sediments samples, as well as the precipitation samples. Samples were counted in standardized geometries for at least 82800 seconds on a High Purity Germanium (HPGe) gamma detector and then for an additional 300 seconds with a standardized sealed source to account for self-adsorption of the ^{210}Pb photon (Cutshall et al., 1983). Counting efficiencies for ^{210}Pb were established using a standard radionuclide solution; ^{7}Be efficiencies were interpolated from the resulting curves of the efficiencies of the radionuclides present in a mixed solution (Bonniwell, 2001; Wilson, 2003).

RESULTS

The atmospheric fluxes of ^{7}Be and $^{210}Pb_{xs}$ to the Goodwin Creek watershed measured during the sampled runoff event were 7.70 ± 0.30 mBq/cm^2/d and 0.463 ± 0.055 mBq/cm^2/d, respectively. The ^{7}Be / $^{210}Pb_{xs}$ ratio of the precipitation during this event, 16.6 ± 2.1, is very close to an observed global average of 16 (Baskaran et al., 1997; Matisoff et al., 2005). Moreover, plotting the atmospheric influxes of ^{7}Be and $^{210}Pb_{xs}$ to Goodwin Creek between January and June 2005 (Figure 2) show the general ratio is maintained over time with the slope of the linear fit being approximately 15. The strong correlation between the ^{7}Be and $^{210}Pb_{xs}$ in the atmospheric influx supports the use of the two radionuclides relative to one another as a tracer.

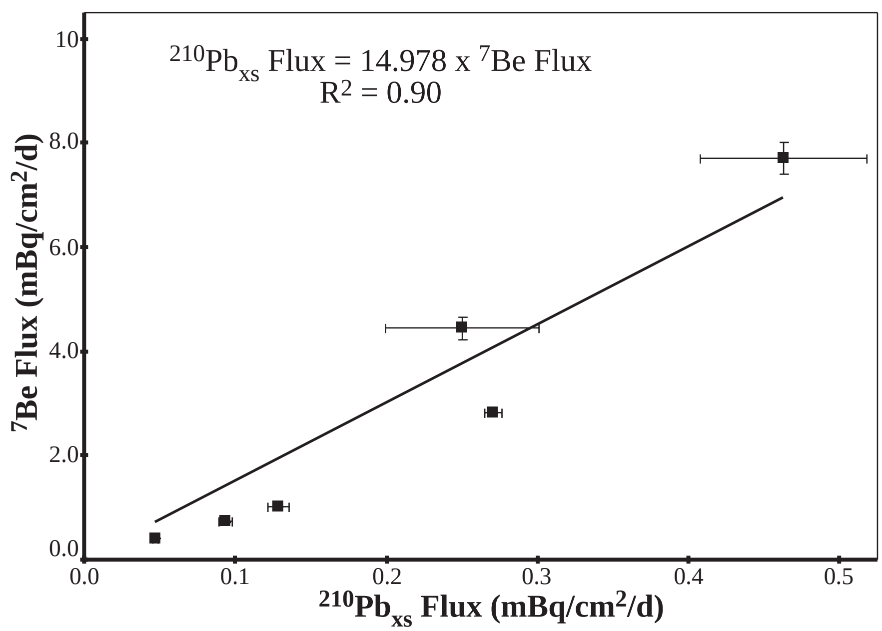

Figure 2 Atmospheric influxes of ^{7}Be and $^{210}Pb_{xs}$ to the Goodwin Creek watershed.

The activities of ^{7}Be and $^{210}Pb_{xs}$ from the samples collected in the soybean fields adjacent to the stream were averaged to develop a composite profile for the landscape (Figure 3a). The atmospheric influxes of ^{7}Be and $^{210}Pb_{xs}$ were distributed exponentially over these profiles (Figure 3b). From these constructed profiles, the activities of the eroded surface soils were assumed to be the surface activity, or the activity at depth = 0 cm suggested from an exponential fit through the data (Wilson et al., 2003). The surface activities (^{7}Be: 239 ± 31 mBq/g; $^{210}Pb_{xs}$: 192 ± 2 mBq/g) were used as the signature of the eroded surface soils. Enrichment coefficients, or the ratio of the activity of the clay particles relative to the activity of the bulk sample averaged 5.13 ± 0.82 and 5.28 ± 0.58 for ^{7}Be and $^{210}Pb_{xs}$, respectively.

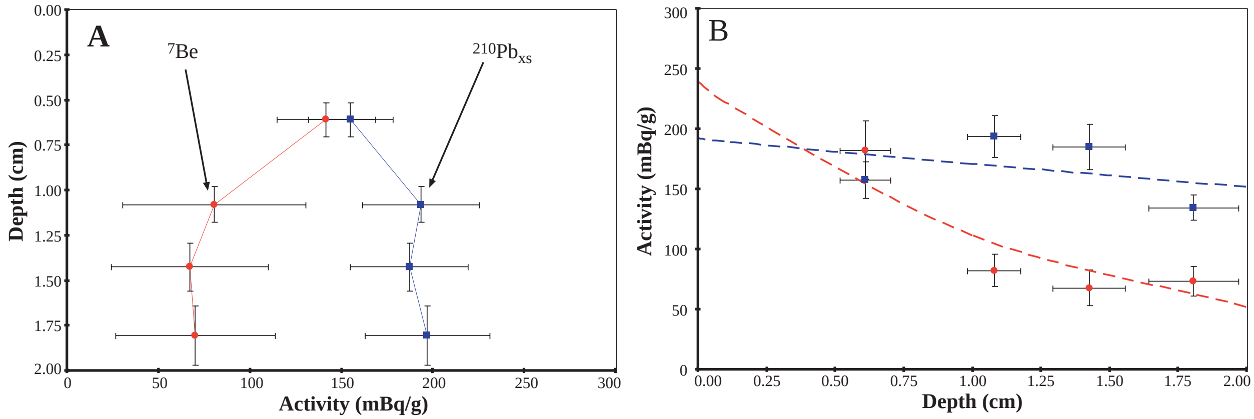

Figure 3 (a) Composite profiles of ^{7}Be and $^{210}Pb_{xs}$ on the Goodwin Creek landscape prior to the sampled runoff event. (b) Composite profiles with exponential fits of ^{7}Be and $^{210}Pb_{xs}$ on the Goodwin Creek landscape with atmospheric influxes added.

The activities of ^{7}Be and $^{210}Pb_{xs}$ from the bank cores are assumed to be zero. This is because integration of activities over the length of the bank face would incorporate a vast majority of soil particles deficient in ^{7}Be and $^{210}Pb_{xs}$. Cores are currently being counted to confirm this assumption. In support of this assumption, ^{7}Be is found only within the top few centimeters of the soil column, and the total ^{210}Pb is dominated by supported ^{210}Pb at depth, i.e., $^{210}Pb_{xs}$ is near zero (Wallbrink and Murray, 1996; Bonniwell et al., 1999; Wilson et al., 2003).

As a result of the runoff event, discharge (Figure 4a) at the sampling site peaked at 11.78 m^3/s nearly 15 hours after the precipitation commenced and returned to base flow approximately 33 hours later. Fine suspended sediment concentration nearly mimicked the flow hydrograph. The concentration peaked at 1161 mg/L almost simultaneously with the flow discharge. There was enrichment in clay particles in the suspended sediment relative to the soils (Figure 4b). The percent clay in the suspended sediment ranged from 15% to 34%. The highest fractions were observed at the beginning and end of the event. Clay fraction in the soils averaged 10 ± 1%, based on the samples used for the radionuclide enrichment coefficient.

The activities of ^{7}Be and $^{210}Pb_{xs}$ in the fine suspended sediment collected during the runoff event average 91.4 ± 54.6 mBq/g for ^{7}Be and 12.3 ± 5.3 mBq/g for $^{210}Pb_{xs}$. The two radionuclides follow a similar pattern over the runoff event (Figure 4b). Activities generally increase during the initial stage of the rising limb of the hydrograph (Brigham et al., 2001). However, as the flow discharge and fine suspended sediment concentration sharply increase approximately 14 hours after the runoff event began, the radionuclides decrease substantially. The activities then begin a rise throughout the remainder of the sampling period, but the activities do not reach similar values to the activities at the beginning event. Changes in the clay fraction of the fine suspended sediment correspond to those of the radionuclide activities.

DISCUSSION

The average activities of ^{7}Be and $^{210}Pb_{xs}$ of the eroded surface soils and collapsed bank sediment were plotted relative to each other in Figure 5a. The two source areas plot at different ends of the figure suggesting the two activities used in relation to one another can provide a unique signature for each source material. When the activities of ^{7}Be and $^{210}Pb_{xs}$ of the fine suspended sediment collected during the event are added to the graph, each sample plots between the two average source activities. Moreover, they plot along a mixing line between the two source materials. Each fine suspended sediment sample was projected at right angles on the mixing line. The position where each sediment sample projects onto the line dictates the relative percentage of each source material contained in that sample.

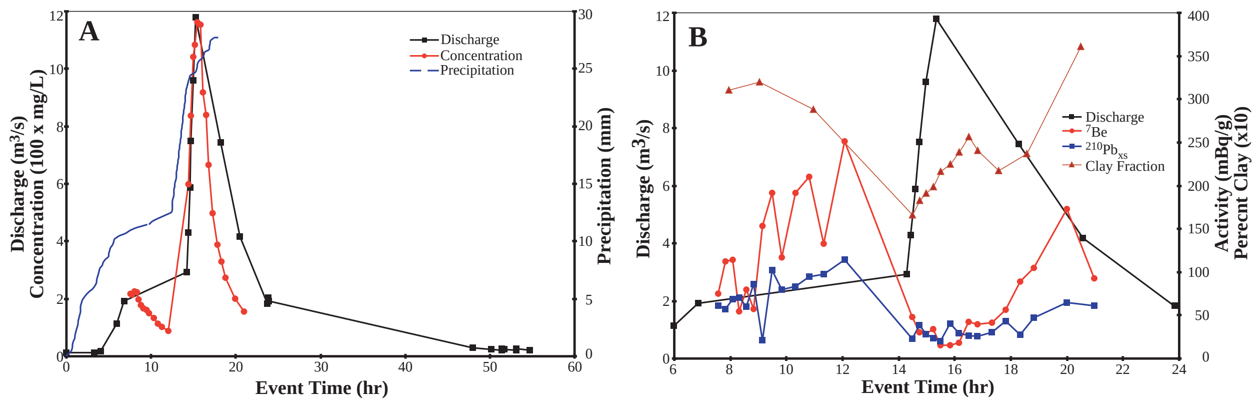

Figure 4 (a) Flow discharge, fine suspended sediment concentration and precipitation for the sampled runoff event on January 7, 2005 at Goodwin Creek and (b) ^{7}Be, $^{210}Pb_{xs}$, and clay content of the fine suspended sediment collected during the same runoff event.

The results of the two end-member mixing model are presented in pie charts in Figure 5b. The red and blue portions of the pie charts represent the proportions of collapsed bank sediment and eroded surface soils in the fine suspended sediment samples, respectively. Due to the limited spacing on the figure in the early stages of the rising limb and the peak of the hydrograph, select samples were plotted to show the general trend of the results.

The proportion of eroded surface soils increases through the beginning stages of the rising limb of the hydrograph to dominate the sample. As the stage, discharge, and fine suspended sediment concentration sharply increases (only flow discharge is represented in Figure 5b), the mixing model suggests that the proportion of eroded surface soils decreases substantially. This decrease corresponds to decreases in activities of ^{7}Be and $^{210}Pb_{xs}$ and clay content of the fine suspended sediments (Figure 4b). An increase in discharge would allow for suspension and transport of coarser and less reactive silt particles prompting the decreases in radionuclide activity and clay content. In addition, the increase of water in the channel and resulting shear stresses would engulf more bank material prompting collapse and entrainment into flow.

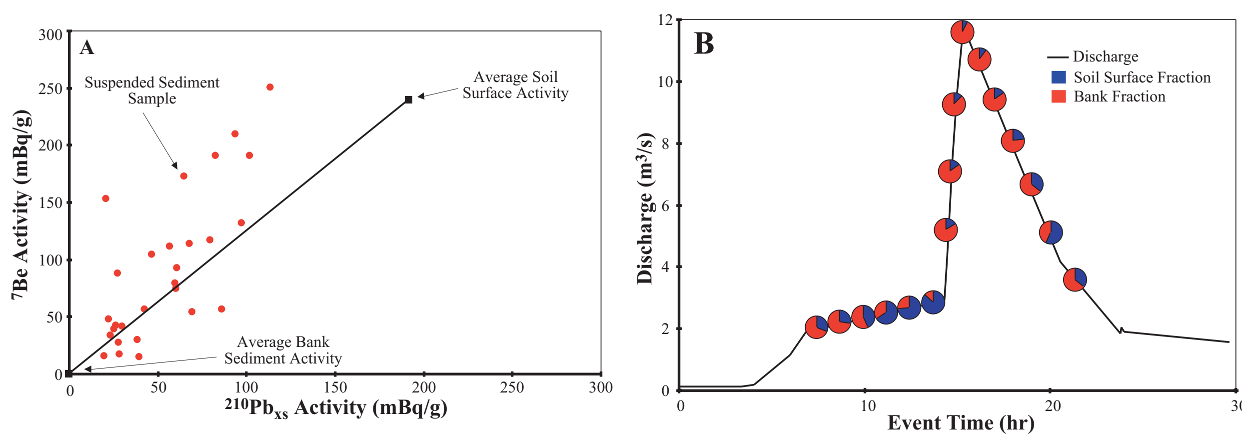

Figure 5 (a) Two end-member model for determining relative proportions of eroded surface soils and collapsed bank sediment in the suspended load of the sampled runoff event on January 7, 2005 at Goodwin Creek, which relates activities of ^{7}Be and $^{210}Pb_{xs}$ in the fines suspended sediment to the activities of the source areas, and (b) Results of the two end-member model.

CONCLUSION

Previous studies in determining sediment sources (Peart and Walling, 1986; Walling and Woodward, 1992) have shown that precision in identifying sources increases with the number of site characteristics used in the analysis.

This study is greatly simplified using only activities of ^{7}Be and $^{210}Pb_{xs}$ in its analysis. Therefore, results presented here are only relative contributions of eroded surface soils and collapsed bank sediment. This novel method shows promise but future comparison to more complex sediment source studies is warranted.

The results presented within this study suggest that eroded surface soils were in a greater proportion relative to bank sediments in the early stages of the runoff event. As discharge and suspended sediment rapidly increased through the peak of the runoff event, radionuclide activities, clay content of the fine suspended sediment, and relative proportion of eroded surface soils decreased. These results are for a single runoff event. More runoff events need to be sampled before the frequency of this pattern can be established.

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