Sediment fingerprinting in the Lower Little Bow River using Cs-137 as a tracer

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The Lower Little Bow River watershed is a source of irrigation water for southeast Alberta. However, sediment in the river can be detrimental to both irrigation pump equipment and the health of the river. In order to understand and manage how sediment moves through a watershed, a study of sediment sources was conducted along a reach of the Lower Little Bow River employing fingerprinting techniques. The radionuclide cesium-137 was used as a tracer to determine whether the sediment in the river is being generated by surface or subsurface erosion processes. The main sources of sediment were found from subsurface erosion of an irrigation return-flow channel, coulee walls, and the river's stream banks. This demonstrates that subsurface erosion is the principle generator of sediment in the Lower Little Bow. Through measurement of multiple points along the reach, the study also determined that the composition of the suspended sediment load did not change as it moved downstream in the river.

Keywords: soil erosion, sedimentation, sediment fingerprinting, cesium-137, irrigation, Alberta

Introduction

The sources of suspended sediments in watersheds can be identified through the technique of fingerprinting using environmental tracers. Employing this technique, Davis and Fox (2009) demonstrated that nutrient-bound sediments within a watershed can cause significant deleterious effects on the aquatic ecosystem as well as water quality. This decline is linked to eutrophication, where an increase in nutrient concentration causes excessive algal growth on the surface of water (Barthod et al. 2015). Moreover, contaminants such as industrial chemicals, metals, and pathogens can be transported within watersheds by sediment acting as a vector. As a result, the amount and nature of sediment and its transport can have a significant impact on the ecology, food web, mortality, reproductive stress, and economic value of

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a watershed ecosystem (Koiter et al. 2013a). In the Lower Little Bow River (LLBR) considered in this study, the large amount of sedimentation occurring is a concern for these reasons. More sediments will result in turbidity and siltation, creating opportunities for nutrient transfer and damaging equipment such as irrigation pumps. In order to manage and improve the health of sediment-affected watersheds, it is essential to discover the sources of those sediments.

Study area

The focus area for this study was the LLBR watershed, located within the Oldman River basin of southeast Alberta, Canada (Figure 1). The study was conducted in a 2565-hectare sub-catchment located at 112°37'30"W, 50°00'00"N that was originally part of an Agriculture and Agri-Food Canada Watershed Evaluation of Beneficial Management Practices (WEBs) project (AAFC 2013). Weather in the LLBR watershed is characterized by strong chinook winds and a regional average annual precipitation of approximately 386 mm a year (AAFC 2013). Its watershed is a mixed grass sub-region with geology mainly dominated by sand and coarse gravel and its surface material is mostly glacial till (Miller et al.2011). The classifications of soils found in the study area are Orthic Dark Brown Chernozems, Rego Dark Chernozems, and Orthic Regosols (Rahbeh et al. 2013). Agricultural uses within the watershed include cereals, forages, and intensive livestock and cow-calf operations (AAFC 2013; Rahbeh et al. 2013).

The Travers Reservoir, rainfall, and irrigation return flow are major factors affecting the flow rate within the LLBR (Little et al. 2003). Water for irrigation in the local area is supplied from the river itself, as well as by the Lethbridge Northern Irrigation District (Little et al. 2003; Rahbeh et al. 2011). Irrigation is a cause of concern in the LLBR due to its potential for sediment delivery to the river through irrigation return flow channels (NRCB/CEAA 1998). While irrigation is valuable to agricultural producers, its contribution to sediment loading of the river can have detrimental effects as it can impair pumps used downstream of irrigation return flow channels, necessitating repairs and leading to decreased crop growth and herding.

Cesium-137 (^{137}Cs) as a tracer

Sediment fingerprinting has been used in order to determine better management practices for controlling non-point source pollutants within watershed ecosystems. For example, surface run off is considered a non-point source because of its ability to contribute sediment and or nutrients from a large area rather than a single point source such as a channel. This requires management techniques that can be applied over a larger area rather than management of a single point. By understanding what sources are contributing to the sediment within a river better management practices can be applied to control their negative effects. Fortunately, there are many different biophysical and geochemical properties of sediment and soil that can be used as tracers for linking sediments back to their sources (Koiter et al. 2013a; 2013b). In order to determine the proportion of each source con-
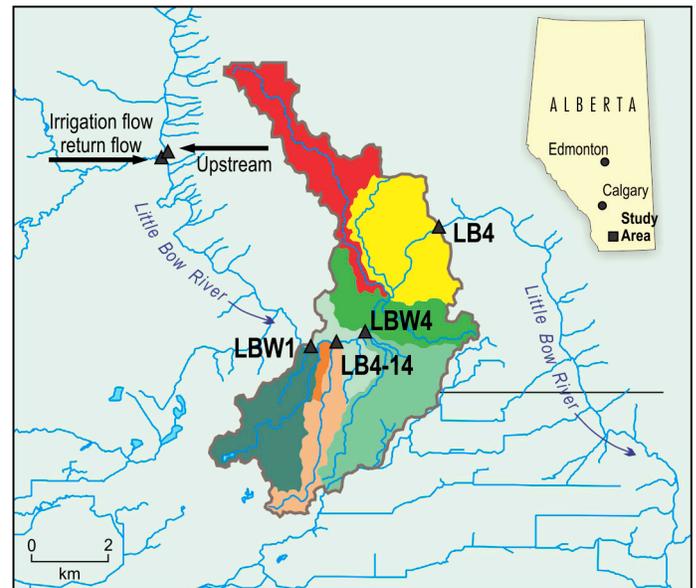

Figure 1
Map showing the Lower Little Bow River with the four sediment collection sites LBW1, LB4-14, LBW4, and LB4 relative to the Upstream and Irrigation Return Channel sediment samples (Map source: © Her Majesty the Queen in right of Canada)

tributing to the suspended sediment load in a watershed, these natural tracers are measured both in potential sources and in the sediment (Davis and Fox 2009).

Radionuclides are environmental tracers than can label soil particles through the process of adsorption to clay minerals and organic matter, both of which have high specific surface areas. This adsorption between radionuclide fallout particles and clay minerals or organic matter can then be measured as a value for the activity of the radionuclide within soil or sediment samples (Koiter et al. 2013a). One readily available radionuclide in the environment is ^{137}Cs, which has a half-life of 30.2 years. Its presence can be linked back to a peak deposition over the period of 1950s–1960s when Cold War thermonuclear weapons testing released them into the atmosphere (Krishnappan et al. 2009; Koiter et al. 2013b). As a result, the presence or absence of ^{137}Cs in soil can be an indicator in distinguishing surface from subsurface materials, determining whether land has been disturbed or remains untouched, and revealing whether soil has been deposited or eroded (Koiter et al. 2013a). For instance, Smith and Blake (2014) showed that an important step in sediment fingerprinting is statistically differentiating the properties that identify target sediment sources; as ^{137}Cs settled onto the landscape, the radionuclide only adsorbed into 10–15 cm of surface topsoil. This range provides the statistical capability to distinguish between surface soils, which will show adsorption of ^{137}Cs, and subsurface materials which will not. ^{137}Cs also demonstrates the highly conservative properties necessary for use as a tracer, resulting from its non-exchangeable behaviour in the soil matrix (Li et al. 2010). Thus ^{137}Cs can be uniquely identified to differentiate be-

tween surface and subsurface sources of sediment contributing to suspended sediment in an aquatic system.

[137]Cs was used in this study to pursue two objectives: first, to examine ^{137}Cs activity in the sediment as it moves downstream in the reach, and second, to determine if surface or subsurface erosion is the main cause of sediment influx into the Lower Little Bow River.

Methods and materials

Methods of sediment and soil collection
Two general sample types were taken in this study: first, source samples were used to gain information about soil at potential erosion sites contributing to the river, and second, suspended sediment samples were taken in the water once the materials had entered. The sites chosen for suspended sediment collection were locations originally used by Alberta Agriculture and Rural Development to monitor water flow and quality on the LLBR. Four of these monitoring stations—LBW1, LB4-14, LBW4, and LB4—were sampled as part of WEBs between 2009 and 2013 in a sub-catchment of the LLBR (Figure 1). The suspended sediment samples were collected using time-integrated samplers, in this case tubes used to collect sediment by allowing water to enter and exit through small openings thereby reducing flow enough to deposit sediment as it passed through the tubes (Roddan 2008). One tube was placed at each station and sampled periodically throughout June to December. In 2013, only LBW1 and LB4 were sampled. These were included as part of the previous 2012 sample inventory.

The sediment sources chosen for examination were areas considered to be potential contributors to the sediment load of the river. These source areas included coulee walls, irrigated and non-irrigated cropland, native pastures, and stream banks. All were sampled near to and upstream of the sediment traps along transects extending away from the river, with samples taken at lower, mid, and upper slope positions. Samples were collected from the surface to a depth of 10 cm, and in 10-cm increments to a depth of up to 30 cm on the land and up to 60 cm from stream banks. Coulee wall samples were taken intermittently down the face of the wall. All samples were dried and sieved down to 2.0 mm then shipped to the Environmental Radiochemistry Lab in the Department of Soil Science at the University of Manitoba for analysis. Source samples were collected throughout the same 2009–2013 time period as the sediment samples.

Two areas outside of the reach of the river and sub-catchment were also sampled. An upstream sediment source was sampled in order to discriminate sources contributing to the sediment load from sources further upstream, and an irrigation return flow channel was sampled upstream from the other sediment collection sites. As Figure 1 shows, the irrigation return flow channel was upstream relative to the other sediment collection sites, however, it was downstream of a sample taken to represent the upstream sediment entering the reach from the larger watershed. A sample was collected from the outlet of the irrigation return flow channel due to a concern that sediments from

irrigated fields and the erosion of the channel itself result in a large amount of sediment being delivered to the river.

Gamma ray spectrometer methods
Sediment and soil samples were analyzed for ^{137}Cs activity using gamma ray spectrometry (Wallbrink et al. 1999). Analysis was carried out for up to 24 hours per sample depending upon the amount of soil used and the concentration of [137]Cs. Samples were placed in containers and packed to ensure a uniform geometry and bulk density. The height of the sample in the container and the gamma detector efficiency for that container geometry were recorded. Depending on the amounts of sample available, containers with different geometries were used. The amount of activity was determined from the gamma spectrum obtained from each sample and in order to account for decay, each measurement was corrected back to a single date based on the first year of sampling: 1 January 2009. The following equation was used to determine ^{137}Cs activity (Slavicek 2011), and once the value of ^{137}Cs activity was obtained, it was used to determine whether ^{137}Cs was present and at what levels in the landscape.

$$\text{Cs activity} = \Sigma\text{Cs} / 0.85 \times \text{Eff-137} \times 1/e\text{-}\lambda t$$

where

Cs activity is the activity of Cs-137 at time of sampling (dps)
ΣCs is the counts per second (cps) of 662 Kiloelectron volt (keV) photo peak
Eff-137 is the counting efficiency for Cs-137 at 662 keV for the sample geometry used (container)
0.85 is the percent of the 662 keV peak of Ba-137M
λ is decay constant for Cs-137 (years)
t is elapsed time (years) between sampling and counting

The mean ($X = (\Sigma x)/n$) and standard error ($s = \sigma/(\sqrt{n})$) of ^{137}Cs activity for a sample area can be determined by using the ^{137}Cs activity in Becquerels per kilogram (Bq/kg). This was done by grouping the areas that had been sampled into similar source types and comparing these source types to the ^{137}Cs activity levels found in the sediment sampling sites. Five types were distinguished from the total amount of soil samples collected and were assigned names according to their origin. The classification utilized Agricultural Land, Coulee Walls, Irrigation Return Flow, Stream Bank, and Upstream as source types. The mean and standard error values were used to identify whether or not ^{137}Cs is present in the area sampled and to calculate the average activity level for the source as well as the average activity level of the sediment collected at that site over the five-year period. An analysis of variance was done on the average values of ^{137}Cs activity for the four sites, LBW1, LB4-14, LBW4, and LB4, to demonstrate any change in activity between them.

Results

^{137}Cs activity in source material

The nature of ^{137}Cs activity in the soil is a useful tool in understanding both surface soil erosion processes, such as rill or sheet erosion, and subsurface soil erosion processes such as gully or channel erosion. During erosion processes silt, clay, and light organic particles are preferentially detached and transported. These particles make up the majority of sediments suspended in streams and deposited in waterbodies. Coarser particles like sands and gravels may not be detached and transported by the river, and even if they are, they may settle out and be deposited along the flow path as conditions change and transport capacity decreases. As a result, river-borne sediments tend to be enriched with finer materials and depleted of coarser ones. The sediment detached and transported by the river will also become concentrated in ^{137}Cs, since it preferentially binds with the clay and organic material in soil. Where soil containing ^{137}Cs is the only source of sediments, the concentration in or activity of ^{137}Cs in the sediment will be markedly higher than the soil from which it originated due to this enrichment process.

The activities of ^{137}Cs found in the LLBR sediment sources varied significantly. The highest level of activity was found in the Agricultural Land sources, likely because this was the sample area with the greatest amount of surface material (Figure 2). Here, ^{137}Cs would have been initially deposited from the atmosphere in the 1950s. When all sites are considered, the measured ^{137}Cs activity on average was 5.43 Bq/kg. The subsurface sources had significantly lower levels of ^{137}Cs activity, with the Coulee Walls source having 0.31 Bq/kg and the Stream Banks source having 0.77 Bq/kg (Table 1). These differences in activity between sources demonstrate that surface material will contain more ^{137}Cs in comparison to the amounts found in subsurface material.

Upstream and Irrigation Return Flow sources

The Upstream and Irrigation Return Flow source samples both had ^{137}Cs present. The sediments contained an average ^{137}Cs level of 3.47 Bq/kg, while the Irrigation Return Flow sediments had an average of 0.27 Bq/kg (Table 1). This demonstrates that the sediment source had an influx of ^{137}Cs-rich material from the land surface higher up the river, which was carried in the sediment load into the study reach of the LLBR. Conversely, low levels of ^{137}Cs were found in sediments from the Irrigation Return Flow source. This demonstrates that the majority of the sediments entering the river from this channel originated in subsurface sources, most likely from the irrigation return flow channel itself (Figures 2 and 3).

^{137}Cs activity in sediments

Fifty sediment samples were collected over the five-year study period. ^{137}Cs was present in the samples at each of the four sites in the LLBR. This demonstrates that at some point, sediments rich in ^{137}Cs from the land surface entered the river. When an-

Table 1
Average ^{137}Cs activity in Bq/kg for sources and sediments in the LLBR

	Samples	Mean	n	Standard Error
Source	Upstream	3.47	5	0.29
	Irrigation return flow	0.27	8	0.11
	Agricultural land	5.43	104	0.45
	Coulee wall	0.31	6	0.26
	Stream bank	0.77	45	0.15
Sediment	LBW1	1.27	15	0.14
	LB4-14	1.22	10	0.10
	LBW4	1.47	10	0.18
	LB4	1.43	15	0.13

alyzed using gamma spectrometry, the average levels of ^{137}Cs activity ranged from 1.22 Bq/kg to 1.47 Bq/kg (Table 1). In order to assess whether the suspended sediment composition significantly changed as it moved downstream through the sites at LBW1, LB4-14, LBW4, and LB4, average levels of ^{137}Cs activity for each of these sites were compared. If the difference in means was significant it would indicate that the amount of ^{137}Cs activity changed during the movement downstream, suggesting that a different source other than those identified for the upstream areas must be contributing sediments into the river to change the suspended sediment composition. With a p-value of 0.54 (p > 0.05) it was found that there was no significant difference of ^{137}Cs activity between the LBW1, LB4-14, LBW4, and LB4 sites. This demonstrates that the suspended sediment composition does not significantly change as it moves downstream and that the sources sampled throughout the reach are consistent moving from upstream to downstream between the four sites. Moreover, it shows there is no source that is contributing significant amounts of sediment to the river downstream that is different from sampled sources upstream (Figure 3). However, the sediment samples still read much higher than the average ^{137}Cs activity downstream at the four sites (Figure 3). The ^{137}Cs activity of the Upstream sediment sources was 3.47 Bq/kg compared to the sediments found at the other four sites, which ranged from 1.22 to 1.47 Bq/kg (Table 1). This significant difference in activity demonstrates that upstream of LBW1, LB4-14, LBW4, and LB4 sites more ^{137}Cs-rich material is being added at some point. It also demonstrates that there is significant change in the sediment composition as it moves from the Upstream site to the four downstream sites.

Discussion

Source ^{137}Cs activity related to sediment ^{137}Cs activity

The activity levels of ^{137}Cs in the study area sources can be compared to the average amount of ^{137}Cs found in the sediments collected at the four downstream sites: LBW1, LB4-14, LBW4, and LB4. Sediments from gully or channel erosion will have little or no radionuclides present, while surface erosion processes such
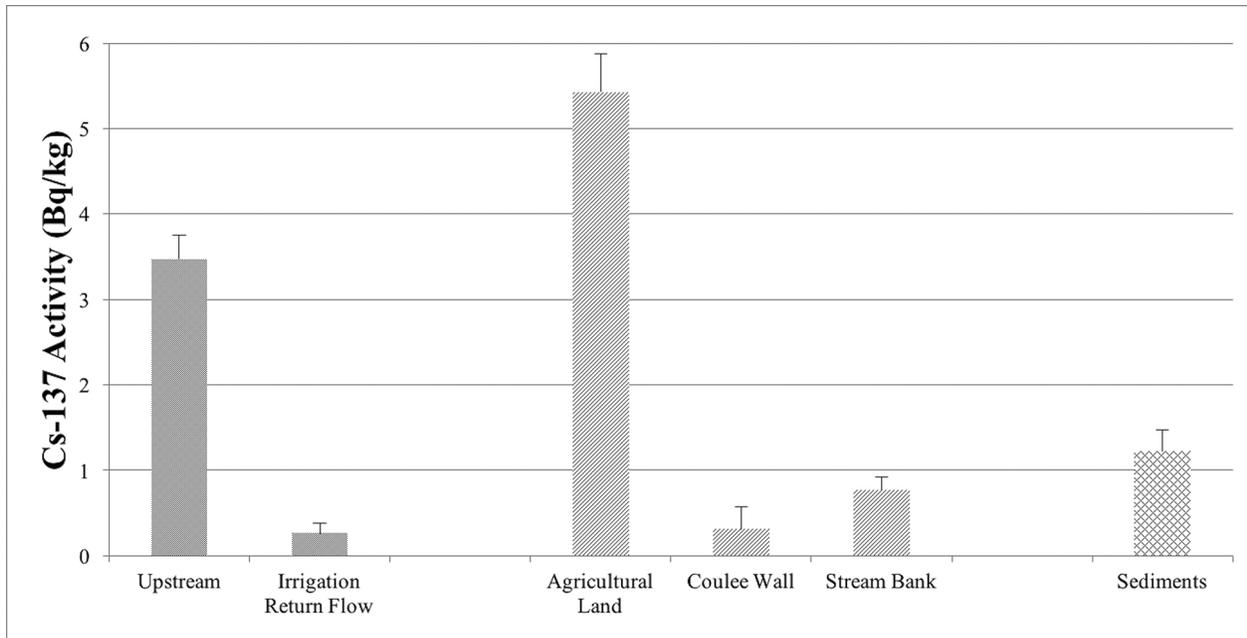
Figure 2
[137]Cs activity for different sediment sources throughout the LLBR study area in comparison to the average ^{137}Cs activity for LBW1, LB4-14, LBW4, and LB4
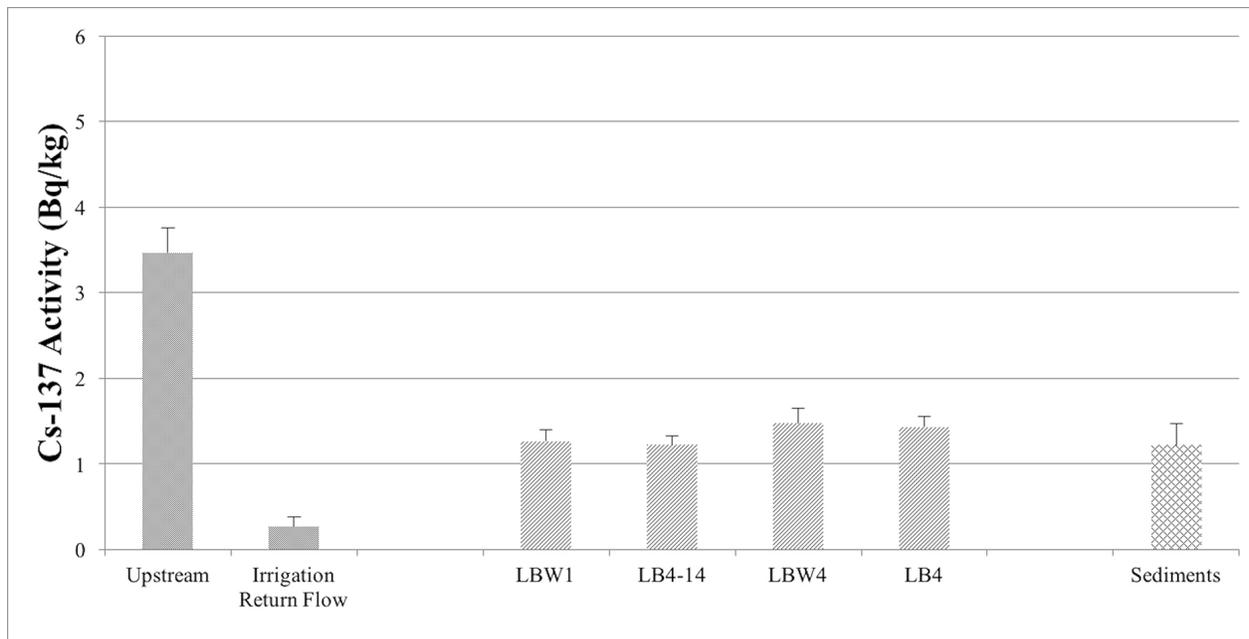

Figure 3
[137]Cs activity of sediment at monitoring stations throughout the LLBR study area in comparison to the average ^{137}Cs activity for LBW1, LB4-14, LBW4, and LB4

as sheet and rill erosion will have significantly higher amounts of radionuclides present (Olley et al. 2013). The ^{137}Cs enrichment of fine sediments explains which sources are contributing the most to the sediments in the river. If surface material was the sole source of the sediment in the river, samples would show either the same ^{137}Cs activity or higher than the source due to enrichment (sediment ≥ source). As seen in Figure 3, the Agricultural Land sources had the highest amount of ^{137}Cs activity while the average sediment ^{137}Cs activity is significantly lower than this source. These findings lead to the conclusion that the main cause of sediment into the LLBR is not from agricultural land. In a similar study conducted in Georgia, Mukundan et al. (2010) apportioned sources for streams within the southern Piedmont region as having 60% of the suspended sediment load from stream bank erosion, and only 10–15% from pasture land sources. The LLBR study is consistent with these results, as demonstrated in Figure 3 where the Coulee Walls and Stream Banks sources both had lower than the average sediment ^{137}Cs activity. They are lower because both sources contribute sediment through the erosion of subsurface material, which does not contain high concentrations of [137]Cs (Olley et al. 2013). This further demonstrates that the main cause of sediment influx into the LLBR is from the erosion of subsurface sources. This method is not specifically apportioning how much each different subsurface source is contributing, but it can distinguish that the sediment loading is not caused by surface erosion from the Agricultural Land source.

Sediment ^{137}Cs activity related to Upstream and Irrigation Return Flow sources

In a study done by Olley et al. (2013) using the ^{137}Cs method, it was found that the dominant source of sediment in river catchments is channel erosion. This conclusion is supported by the LLBR results, where most of the erosion processes contributing sediment were subsurface and channel erosion. The Upstream and Irrigation Return Flow sediment samples were both taken upstream and out of the reach of the sites where the sediment and soil sources were sampled in the LLBR (Figure 1). The upstream sediment ^{137}Cs activity was significantly higher than the average sediment ^{137}Cs activity, and the ^{137}Cs activity for the irrigation return flow was minimal due to the sediment being scoured from channel erosion. As seen in Figure 1, the Irrigation Return Flow samples were taken downstream from the Upstream sample site. In order for upstream sediments to have the ^{137}Cs activity decrease to the amount that is found on average for LBW1, LB4-14, LBW4, and LB4 sites, a large influx of non-^{137}Cs-rich sediment would be required to dilute the ^{137}Cs activity. The irrigation return flow is a non-^{137}Cs-rich source that could be diluting the upstream sources by the addition of sediment to the river from channel scouring. Further study of how much irrigation return flow channels are contributing to sediments in the LLBR will determine whether they should be managed differently and whether they are the main reason for sediment loading in the river.

In the Mukundan et al. (2010) study multiple tracers were used to fully apportion sources of sediment entering the streams

of a watershed. The use of multiple tracers gave a better understanding of what may be causing sediment loading in a watershed, which in turn was able to facilitate mitigation efforts. In this study of the LLBR, using only ^{137}Cs as a tracer, it was difficult to determine exactly how much each source was contributing to the total sediment load. While it was possible to conclude that the suspended sediment load was mostly derived from subsurface sources, how much each individual source was contributing was not determined using ^{137}Cs alone. The ability to apportion these sources precisely would allow for proper mitigation practices to be considered. It is known that irrigation return flow channels, coulee walls, and stream banks are all contributing as subsurface sources, but each needs to be managed in a different way if it is the main contributor of sediment.

Conclusion

The method of using ^{137}Cs as a tracer in this sediment fingerprinting study has shown that the main cause of sediment delivery into the LLBR is from subsurface erosion processes. This was concluded based on observations of sediment samples from sites representative of subsurface erosion, such as irrigation return flow channels, coulee walls, and stream banks. However, as the ^{137}Cs data have shown with the Irrigation Return Flow source activity and the Upstream source activity, it is difficult to know from the tracer alone whether the irrigation return flow channel is the main source of sediment into the LLBR in this reach of the river or whether it is similar in proportion to the other subsurface erosional sources like coulee walls and stream banks. In order to specifically apportion how much each source is contributing to the total suspended sediment load, other sediment tracers should be combined with ^{137}Cs and used with more sophisticated sediment fingerprinting methods. Other techniques such as colour analysis in diffuse reflectance spectrometry, alpha and gamma spectroscopy, or geochemistry using other spectrometry methods to look at other radionuclides could be used in combination to trace sediments, while the source apportions could be modeled using un-mixing models such as mixSIAR.

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