

Assessment of Soil Erosion at the Watershed Scale From ^{137}Cs Measurements

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ABSTRACT

The Boyer River (Québec, Canada) drains a 217 km² watershed that is under cultivation at 60%. The last 2 km of the river bed had always been used for reproduction by Rainbow Smelts (*Osmerus mordax*). This fish population, which plays an important ecological role in the St. Lawrence estuary, has dramatically declined over the last decades. Siltation and excessive algal growth in the spawning area were identified as the major causes of the fish population decline, suggesting that soil erosion, nutrient and sediment transport are major processes involved in the environmental problem. In this context, ^{137}Cs appears as an interesting tool to investigate the magnitude and spatial distribution of long-term soil movements taking place in the watershed. Sampling of cultivated fields, river banks, bottom sediments and forested sites were thus undertaken to help understand the erosive behaviour of the watershed. Results obtained so far suggest in-field erosion rates up to 13 t ha⁻¹ yr⁻¹ and net outputs reaching 11 t ha⁻¹ yr⁻¹. These results agree well with estimates obtained from the USLE. The ^{137}Cs data also suggest that more than 75% of the sediments deposited in the spawning area would originate from cultivated fields and less than 25% from stream banks.

INTRODUCTION

Erosion is a major process in soil and water degradation, resulting in reduction of upstream soil productivity and pollution of downstream water bodies. On and off-farm costs have been estimated to be millions of dollars per year in Canada (DCH and LRRI, 1986). Assessing the severity of erosion under a variety of soil-slope-crop combinations from plot measurements, either under natural or simulated rainfalls, is resource and time consuming. Besides, erosion plots cannot reproduce all the processes that take place at the field or watershed scale. Identifying, at this level, the sources actually contributing to the measured suspended solids loadings is a even more complicated task. (Lal, 1994).

Cesium-137 (^{137}Cs), a fallout product from the atmospheric atomic tests carried out in the late 1950's and early 1960's, is an excellent soil movement marker, and thus an interesting tool to achieve the aforementioned tasks. Measuring the spatial redistribution of ^{137}Cs in the landscape affords a fast and rather economical way to estimate the result of global soil movements that took place in the last 35-40 years. By comparing the ^{137}Cs inventory of cultivated

sites to that measured under stable and non-erosive conditions (forest cover, very old prairies), soil loss and deposition can be estimated and their spatial extent delineated. The use of this isotope has been reported worldwide over the last two decades (Bernard et al., 1998; Ritchie and McHenry, 1990). Most studies have been performed on areas not exceeding a few tens of ha. However, the potential of using ^{137}Cs alone, or in combination with other indicators or soil properties, for watershed studies have been discussed and demonstrated (Owens et al., 1997; Walling et al., 1993).

This technique was thus used to investigate the erosive behavior of a small agricultural watershed in Québec Canada.

The watershed

The Boyer River watershed is located approximately 35 km east of Québec City and drains a 217 km² area (Figure 1). Annual precipitation averages 1100 mm in the region and the mean annual flow at the outlet is 4,24 m³ s⁻¹. The total relief reaches 270 m. Soil textures range from clay loams to sandy loams. Agricultural land occupies over 60% of the watershed area and forests most of the remaining 40%. There are some 275 farm operations in the watershed. Dairy farming and hay crops dominate in the lower half of the basin. In the upper half, hog production is well developed and corn and small grains cover large areas. Generally, the cultivated fields are long and relatively narrow. Cultivation is done up and down slope.

Environmental issue

A spawning area occupies the last 2 km of the river bed. Until recently, it supported a large Rainbow Smelt (*Osmerus mordax*) fish population. This fish species is environmentally important, being part of the diet of many marine animals of the St. Lawrence estuary (Robitaille and Vigneault, 1990). Starting in the mid-1960's, the smelt population gradually declined to a near-zero level.

Continuous degradation of water quality, particularly from high levels of suspended solids, phosphorus and high sedimentation rates in the spawning area, have been pointed out as the major cause for the decline of the fish population (Robitaille and Vigneault, 1990).

These facts suggest that soil erosion may be an important part of the problem. ^{137}Cs was therefore considered as an interesting technique to investigate the severity and the spatial extent of long term soil movements within and out of the cultivated fields. This technique was used to assess the contribution of soil erosion to the environmental problems

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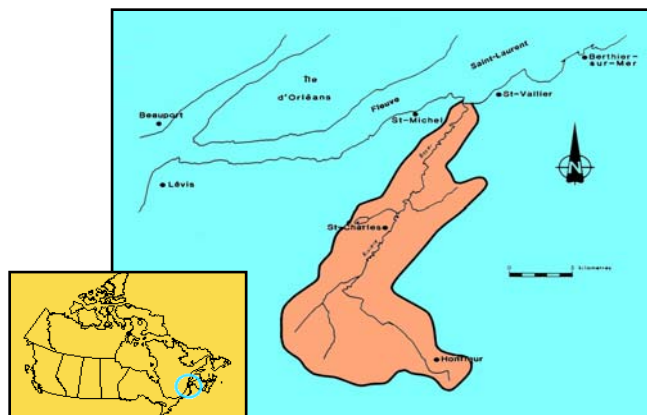


Figure 1. Location of the Boyer River watershed (Québec, Canada).

encountered in the river system. In this context, ^{137}Cs measurements can help to:

- identify the areas with the highest past erosion and sediment production;
- set priorities for implementation of corrective measures;
- optimize the chances of success of corrective actions, i.e. maximize environmental benefits at lowest possible cost.

On-going research program

The research work on the experimental watershed was initiated during the summer of 1996. ^{137}Cs measurements have been done:

- in woodlots that experienced no soil loss or deposition, to establish the amount of ^{137}Cs fallout received in the area, from which soil movements can be assessed in cultivated fields, following the procedure established by de Jong et al. (1982);
- in cultivated fields, that are selected to represent the main soil-cropping system combinations encountered in the basin;
- on streambank soils;
- on bottom sediments.

Eight stations under forest cover were sampled. For each station two sites were sampled. At each site, three undisturbed soil samples were collected in the 0-30 cm depth. The samples were divided in 10 cm increments and the three subsamples were bulked by depth for ^{137}Cs determination.

Nine cultivated fields have been sampled on a variable grid basis so data could be spatialized to produce complete soil movement budgets. A minimum of two transects, in the dominant slope direction, were sampled. The distance between sampling points on the transects was adjusted to the local topography, and generally did not exceed 50 m. Three soil samples were collected at each point: one in the plow layer, one in the first 10 cm below the plow layer, and another one in the 10-20 cm slice below the plow layer. This way, the total ^{137}Cs inventory could be measured.

The banks of the main river and its tributaries were also sampled in twelve locations. At each site, the top portions of

both right and left banks were sampled at the 0-10 cm depth only.

Three sediment samples from the spawning area (last 2 km of the river bed), were also collected at the 0-10 cm depth and counted for ^{137}Cs .

The samples were air-dried and their <2mm fraction were counted for ^{137}Cs , following the procedure described by de Jong et al. (1982). The counting time was set to maintain the counting error to less than 10%. For surface samples, 7000 seconds were generally sufficient. When necessary, the counting time was increased up to 50000 seconds. All determinations were adjusted to June 30th 1996.

Soil movements in the fields were estimated by comparing the ^{137}Cs inventory of the sampled stations to that measured under forest cover, using Kachanoski's (1993) model:

$$SM = P R^{-1} [1 - (CS_c / CS_b)^{1/n}] \quad (1)$$

where

- SM: Soil movement ($\text{t ha}^{-1} \text{yr}^{-1}$)
- P: Mass of the plow layer (t ha^{-1})
- R: Ratio of the ^{137}Cs concentration of eroded sediments to that of the plow layer soil
- CS_c : ^{137}Cs inventory of cultivated sites (Bq m^{-2})
- CS_b : ^{137}Cs inventory of benchmark sites (Bq m^{-2})
- n: number of years since peak ^{137}Cs fallout

The point data were then spatialized to the entire field areas by kriging.

The relative contribution of cultivated fields and banks to the sediments deposited in the last 2 km of the river bed was assessed by comparing the ^{137}Cs concentration of the surface soil of these two sources to that measured on the three sediment samples. The model presented by Peart and Walling (1988) was used:

$$C_c = (P_s - P_b) / (P_f - P_b) * 100 \quad (2)$$

where

- C_c : Contribution of fields
- P_s : ^{137}Cs on bottom sediments (Bq kg^{-1})
- P_b : ^{137}Cs on bank soils (Bq kg^{-1})
- P_f : ^{137}Cs on field soils (Bq kg^{-1})

RESULTS

A map of the spatial variation of the residual ^{137}Cs activity of fallout in the watershed was produced from the measurements done under forest cover (Fig. 2). It ranged from 2600 to 3700 Bq m^{-2} and exhibited a double gradient. The highest activity was encountered in the northeast part of the basin and declined steadily in the southwest direction, down to the point where the riverbed switches from a south-north to an east-west orientation. From there, in the upstream direction, the ^{137}Cs activity rises again. This part of the watershed is located in the Appalachian piedmont. Most likely, the precipitation increases with altitude (orographic effect), which would explain the increased ^{137}Cs inventory in the area. Such a spatial structure made it impossible to use a single value for ^{137}Cs fallout over the whole watershed. For the estimation of soil movements from cultivated fields, the local values obtained from the fallout map (Fig. 2) were thus used.

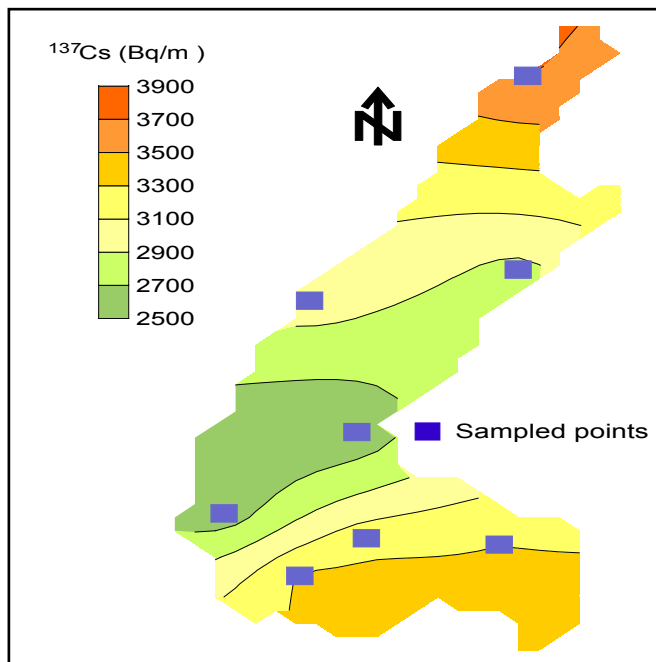


Figure 2. Location of the sampled forested sites and spatial variability of ^{137}Cs inventory.

Soil movement budgets were calculated for the nine studied fields, after spatializing the point data to the entire field areas by kriging. Activities within an interval of $\pm 10\%$ around the estimated value for local fallout were considered as indicating no net soil movement. Values below this interval were interpreted as indicative of a net soil loss, and values over the interval, of net deposition. Such a budget for one of the studied fields is presented in Table 1 and figure 3. No significant net soil movement occurred on 16% of the field area (in blue on Fig. 3). This does not preclude any soil movement, but simply means that any loss was counterbalanced by deposition. Two thirds of the field area suffered a net soil loss (in red on Fig. 3), at a mean rate of $4.7 \text{ t ha}^{-1} \text{ yr}^{-1}$. When averaged over the entire field area, this means a rate of $3.2 \text{ t ha}^{-1} \text{ yr}^{-1}$. Soil loss was particularly important on the shoulder-shaped portion of the field, located between 300 and 350 m. It was estimated that net deposition (in green on fig. 3) occurred on 17% of the field area. The depositional area is located around 200 m from the top of the field, on a relatively flat section, just below a steeper stretch. Obviously, some material coming from upstream deposited in this area. An average deposition rate of $0.7 \text{ t ha}^{-1} \text{ yr}^{-1}$ was calculated. From these figures, it was estimated that this particular field yielded an average $3 \text{ t ha}^{-1} \text{ yr}^{-1}$ of sediments, which represents a sediment delivery ratio of 94% (Table 1).

For the nine sampled fields, gross erosion and deposition ranged between -13 and $+4 \text{ t ha}^{-1} \text{ yr}^{-1}$ respectively. The net amount of material leaving the fields varies from ~ 0 to $11 \text{ t ha}^{-1} \text{ yr}^{-1}$. These results indicate that soil erosion involves soil volumes that are much more important than what net losses reveal. Deposition and redistribution within fields are important components of the erosive process that cannot be assessed from conventional measurements. The soils of the sampled fields belong to the dominant soil

series encountered in the watershed and are representative of more than 75% of the soil cover. Extrapolating the results of the nine sampled fields on the basis of the soil series covered by the sampled fields and their spatial extension in the watershed leads to estimating that cultivated fields would generate around $2.5 \text{ t ha}^{-1} \text{ yr}^{-1}$ of sediments to the river system. This figure compares well with an estimate of $3 \text{ t ha}^{-1} \text{ yr}^{-1}$ obtained from the USLE (Landry, 1998). From the ^{137}Cs measurements, it was noted that the fields located on the lower half of the watershed seem to generate the largest sediments loads, despite lower soil erodibilities and frequent forage covers, related to the dominant dairy farming land use. However, slopes in this area are short and steep. At the opposite, the sediment production is apparently smaller in the upper part of the watershed, despite higher soil erodibilities and more frequent annual crop cover. On the other hand, longer and smoother slopes in this area probably produce many deposition occasions. Therefore, the ^{137}Cs measurements suggest that in the lower half of the watershed, erosion would be occasional, being linked to prairie turnover, but severe. At the opposite, the upper part of the watershed would experience lower rate erosion, due to the topography, although more frequent under a wider spread annual plant cover. On the banks, ^{137}Cs concentrations ranged between 0 and 23 Bq kg^{-1} . On the three bottom sediment samples, they varied from 0.9 to 1.6 Bq kg^{-1} .

From these data, using a model presented by Peart and Walling (1988), it was estimated that $\sim 75\%$ of the bottom sediments would originate from the cultivated fields and that the banks would produce the other 25%. This estimate is valid only for the three sediment samples that were analyzed and is based uniquely on ^{137}Cs concentrations.

Table 1. Soil movement budget for one the studied fields of the Boyer river watershed (Canada).

Field section	Rate ($\text{t ha}^{-1} \text{ yr}^{-1}$)	Area (%)
Stable	0	16
Erosional		
Mean erosion [†]	4.7	67
Gross erosion [‡]	3.2	100
Depositional	0.7	17
Outlet	3	100
Sediment delivery ratio	94%	

[†]Average rate in the erosional zone

[‡]Rate averaged over the entire field area

PRELIMINARY CONCLUSIONS AND FUTURE WORK

The results obtained so far confirm that soil erosion most likely plays a major role in the environmental problem of the Boyer River watershed, despite that gross and net rates appear as moderate. The field studies also confirm that soil redistribution and deposition within field limits are two important components of the erosive process, which are clearly revealed by ^{137}Cs measurements. The radiocaesium measurements also suggest that the upstream section of the

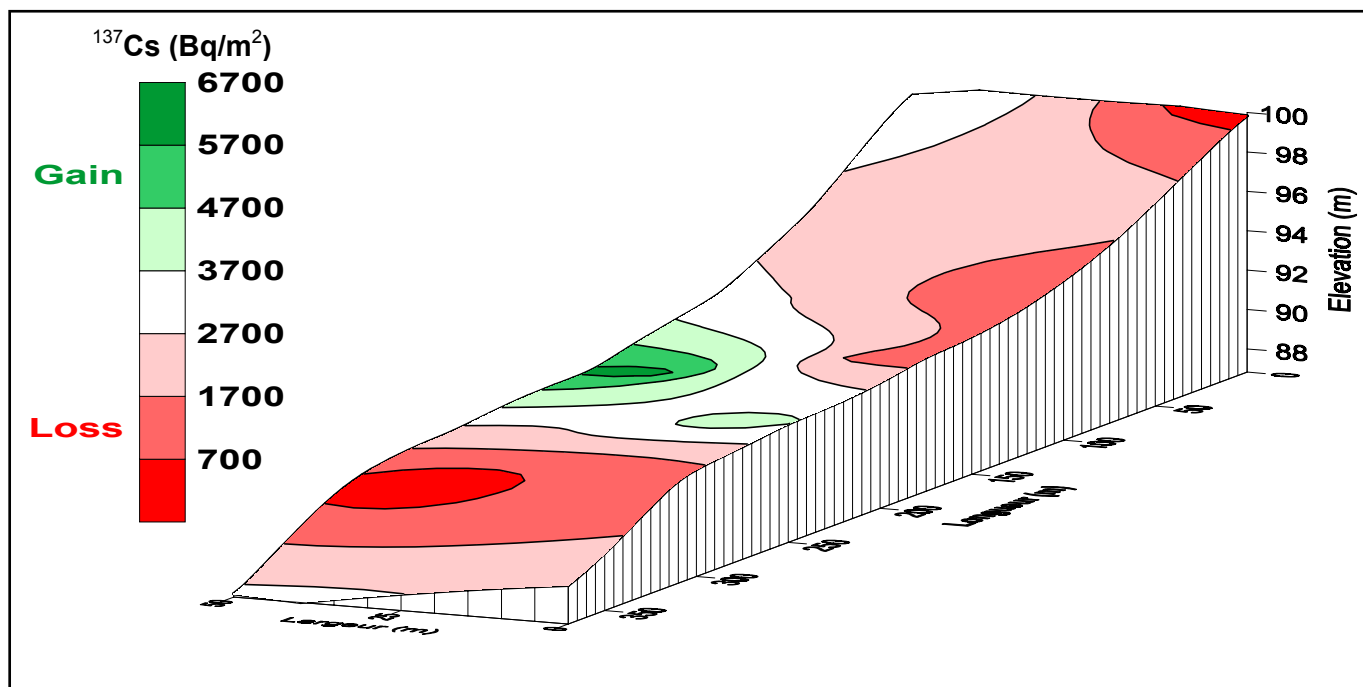


Figure 3. ^{137}Cs redistribution within the limits of one of the sampled fields in the Boyer River watershed.

watershed behaves differently from the downstream portion, in terms of soil erosion. Field erosion seems more important than streambank erosion as a source of sediments in the spawning area. Therefore, conservation tillage practices should be an important component of any restoration program.

Finally, some drawbacks of the ^{137}Cs technique should be acknowledged, since they may influence the erosion/deposition assessments obtained from it. The major drawbacks are related to the soil surface conditions at the time of fallout deposition. As discussed by VandenBygaert et al. (1999), if significant soil redistribution occurred during or immediately after fallout deposition, then the assumption of uniform deposition may not apply totally. The radio-caesium measurements would then underestimate soil losses and overestimate deposition.

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