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Using ^{137}Cs as a tool for the assessment and the management of erosion/sedimentation risks in view of the restoration of the Rainbow Smelt (*Osmerus mordax*) fish population in the Boyer River basin (Québec, Canada)

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ABSTRACT

The Boyer River (Québec, Canada) drains a 217 km^2 watershed that is under cultivation at 60%. The last 2 km of the river bed has always been used as a spawning ground by Rainbow Smelts (*Osmerus mordax*). This fish population, which plays an important ecological role in the St.Lawrence River estuary, has dramatically declined over the last decades. Siltation and excessive algal growth in the spawning area were identified as the most probable causes of the fish population decline; suggesting that soil erosion, nutrient and sediment transport are major factors underlying the environmental problem.

In this context, ^{137}Cs provides an effective tool for investigating the magnitude and spatial distribution of long-term soil redistribution taking place in the watershed. Sampling of cultivated fields, riverbanks, 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 of up to 13 t ha^{-1} yr^{-1} with net outputs reaching 11 t ha^{-1} yr^{-1}. These results agree well with estimates obtained from the USLE. The ^{137}Cs data indicate that fields located in the upstream half of the basin produce smaller sediment loadings than those in the downstream portion, despite higher soil erodibilities and more frequent ose for annual crops. They also suggest that more than 75% of the sediment deposited in the spawning area originates from cultivated fields, and less than 25% from streambanks.

Keywords: Soil erosion, Sedimentation, ^{137}Cs, Watershed.

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 amount to millions of dollars per year in Canada (DCH and LRRI, 1986). Use of erosion plots to assess the severity of erosion under a variety of soil-slope-crop combinations, either under natural or simulated rainfall, is costly and time consuming. Furthermore, erosion plots do not reproduce all the processes that take place at the field or

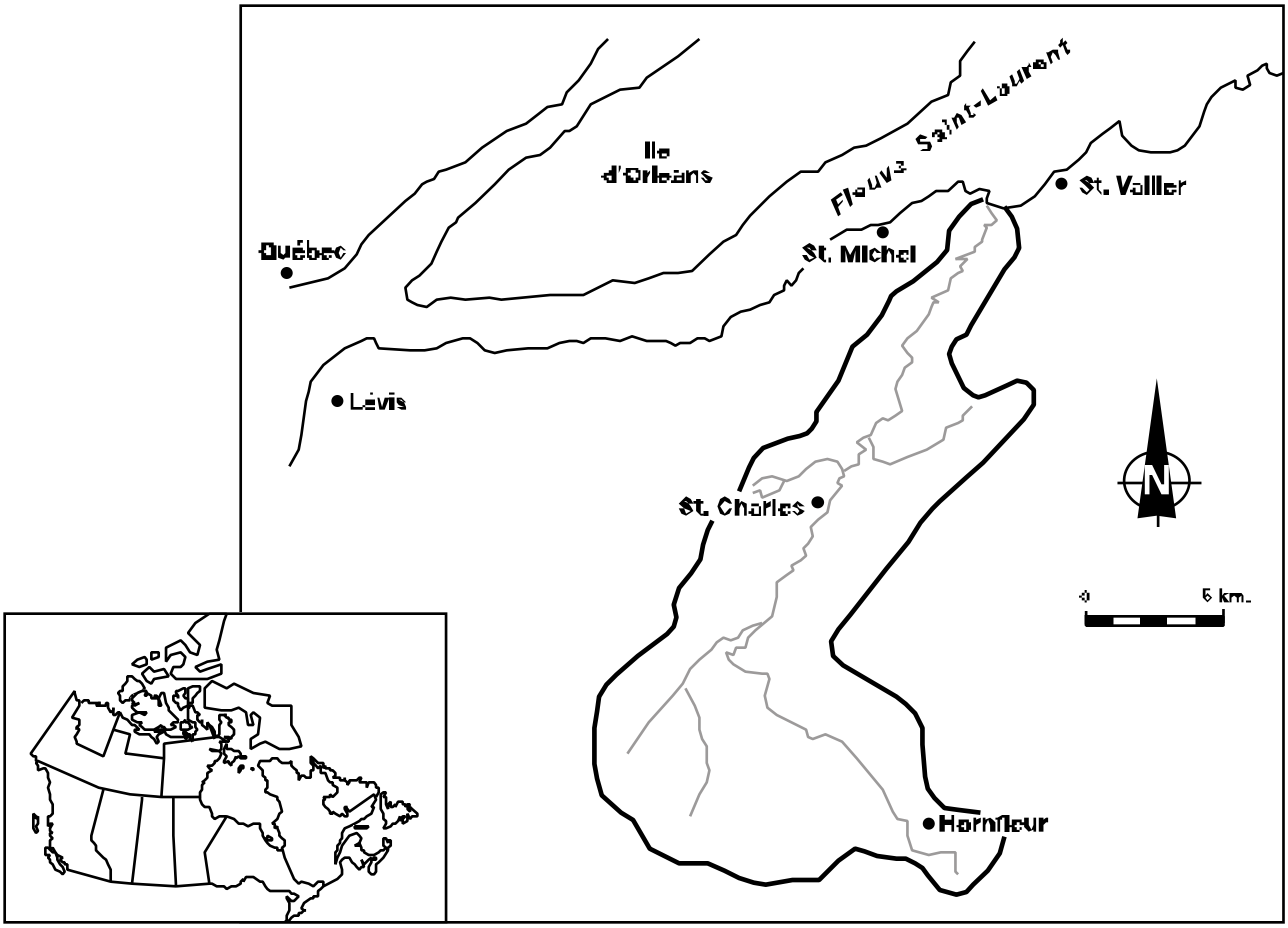

Figure 1. Location of the Boyer River watershed (Québec, Canada).

watershed scale. Identifying, at this level, the sources actually contributing to the measured suspended sediment load of a stream is an even more complicated task (Lal, 1994).

^{137}Cs, a fallout product from the atmospheric atomic tests carried out in the late 1950's and early 1960's, is an excellent tracer of soil movement and thus a useful tool for undertaking the aforementioned tasks. Measuring the spatial redistribution of ^{137}Cs in the landscape affords a fast and economical way of estimating the result of soil redistribution that took place over the last 35-40 years. Both soil loss and deposition can be estimated and their spatial extent delineated.

The use of this isotope has been reported world-wide over the last two decades (Walling and Quine, 1992; Ritchie and McHenry, 1990). In Québec (Canada), it has been used to assess erosion rates at the field and small watershed scales (Mabit et al., 1999; Bernard and Laverdière, 1992). So far, most studies using this isotope 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 has been discussed and demonstrated (Owens et al., 1997; Walling et al., 1993). This technique was thus employed to investigate the erosive behaviour of a small agricultural watershed in Québec (Canada).

MATERIALS AND METHODS

The Boyer River watershed

The Boyer River watershed is located approximately 35 km east of Québec City (Québec, Canada) and drains an area of 217 km^2 (Figure 1). Annual precipitation averages 1100 mm in the region, and the mean annual flow at the outlet is 4.24 $m^3\ s^{-1}$. 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 and cultivation is done in the main slope direction.

Environmental issue

A spawning area occupies the lowest 2 km of the river channel. 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 River estuary (Robitaille and Vigneault, 1990). Starting in the mid-1960's, the smelt population gradually declined to a near-zero level (Figure 2).

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

These facts suggest that soil erosion may be an important factor in the problem. ^{137}Cs was therefore considered as a useful technique for investigating the severity and the spatial extent of long term soil redistribution within and out of the cultivated fields. The technique has therefore been used to assess the contribution of soil and bank erosion to the environmental problems encountered in the river system. In this context, ^{137}Cs measurements can help to:

a) identify the areas most at risk from erosion and sediment production;
b) set priorities for implementation of corrective measures;
c) optimise the chances of success of remedial actions, i.e. maximise environmental benefits at lowest possible cost.

Soil sampling and ^{137}Cs determinations

The investigation of the experimental watershed was initiated during the summer of 1996 and is still on-going. ^{137}Cs measurements have been undertaken (Fig. 3):

a) in woodland areas, to establish the ^{137}Cs reference level from which soil redistribution can be assessed in cultivated fields;

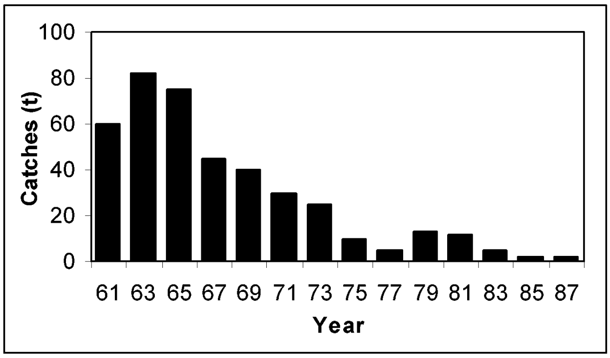

Figure 2. Temporal variation of commercial smelt catches in the Québec City area (from Robitaille and Vigneault, 1990).

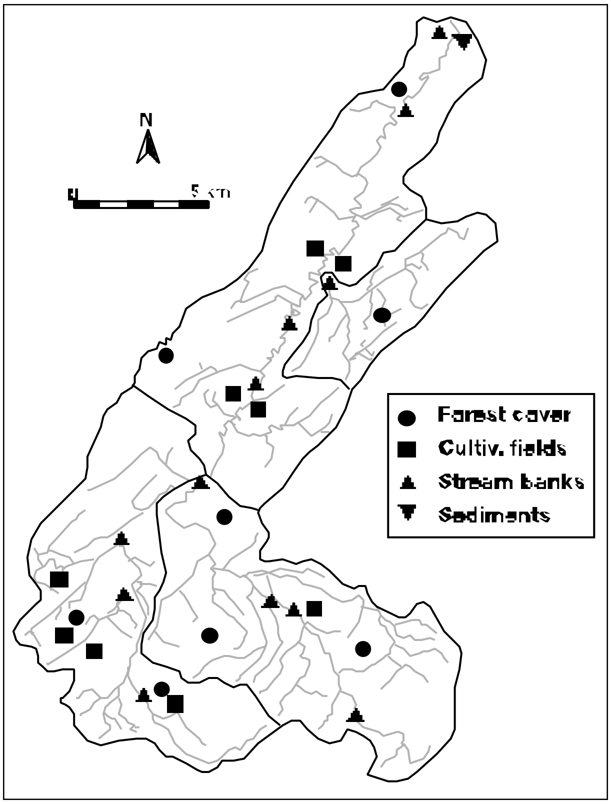

Figure 3. Location of the sites sampled for ^{137}Cs in the Boyer River watershed.

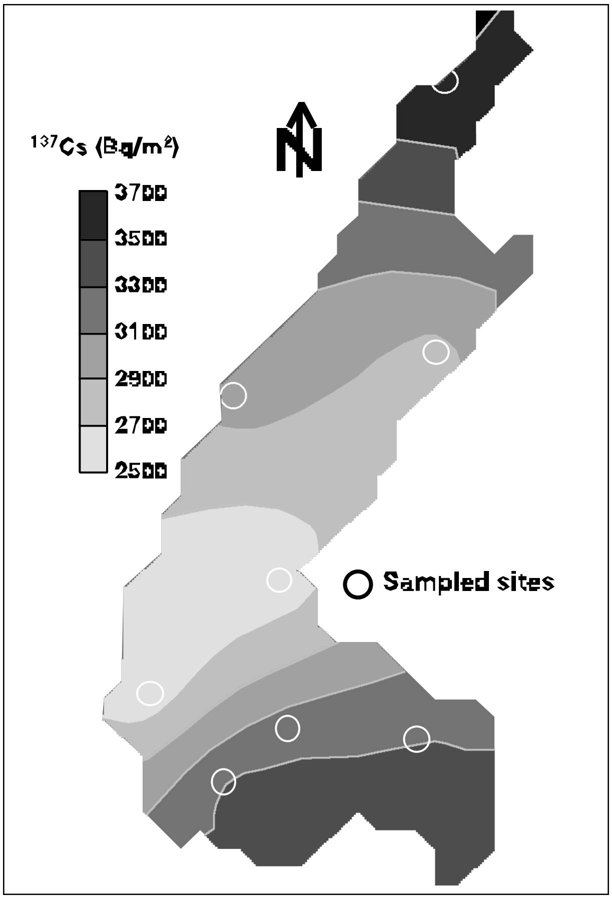

Figure 4. Spatial variability of the ^{137}Cs reference inventory across the study watershed.

b) in cultivated fields, selected to represent the main soil-cropping system combinations encountered in the basin;
c) on streambank soils;
d) on bottom sediments.

Eight locations under forest cover were sampled. For each location, two sites were sampled. At each site, three undisturbed soil cores were collected from the 0-30 cm depth. The cores were subdivided into 10 cm increments and the three subsamples were bulked by depth for ^{137}Cs determination.

To date, nine cultivated fields have been sampled on a variable grid basis to permit spatial interpolation of the resulting data and produce complete soil redistribution budgets. A minimum of two transects, in the dominant slope direction, were sampled in each field. The distance between sampling points on the transects was adjusted to the local topography, and generally did not exceed 50 m. Three soil cores were collected at each point. The cores were bulked for the following depth increments: 0-20, 20-30 and 30-40 cm. This way, the total ^{137}Cs inventory could be measured.

The banks of the main river and its tributaries were also sampled at twelve locations. At each location, both right and left banks were sampled. The samples were collected from the upper half of the banks, in the 0-10 cm depth only. Three sediment samples from the spawning area (last 2 km of the river bed), were also collected and counted for ^{137}Cs.

All 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:

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

where

SM: Soil movement (t ha^{-1} 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
CSc: ^{137}Cs inventory of cultivated sites (Bq m^{-2})
CSb: ^{137}Cs inventory of benchmark sites (Bq m^{-2})
n: number of year since peak ^{137}Cs fallout

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

The relative contribution of cultivated fields and banks to the sediment 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 in the three sediments samples. The model presented by Peart and Walling (1988) was used:

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

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 reference ^{137}Cs activity in the watershed was produced, based on the measurements made under forest cover (Figure 4). The values range from 2600 to 3700 Bq m^{-2} and exhibit 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 river bed switches from a south-north to an east-west orientation. From there, in the upstream direction, the ^{137}Cs activity rises again most likely as a result of an orographic influence.

Such a spatial structure precludes the use a single value for the ^{137}Cs reference activity over the whole watershed. For estimation of soil redistribution in the cultivated fields, the local values obtained from the fallout map (Figure 4) were used.

Soil redistribution budgets were calculated for the nine studied fields, after interpolating the point data to the entire field areas. Activities within an interval of ± 10% around the estimated reference 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 greater than this interval, of net soil deposition. Such a budget for one of the studied fields is presented in table 1 and Figure 5. No significant net soil movement occurred on 16% of the field area (in white on Fig. 5). This does not preclude soil movement, but simply means that any loss was counterbalanced by deposition. Two thirds of the field area suffered a net soil loss (in dark grey on Fig. 5), at a mean rate of 4.7 t ha^{-1} yr^{-1}.

When averaged over the entire field area, this provides a rate of 3.2 t ha^{-1} 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 light grey on Fig. 5) occurred over 17% of the field area. The depositional area is located around 200 m from the top of the field, in a relatively flat zone, just below a steeper stretch. Material coming from upslope is clearly deposited in this area. An average deposition rate of 0.7 t ha^{-1} yr^{-1} was calculated. From these figures, it was estimated that the net erosion rate for this particular field was 3 t ha^{-1} yr^{-1}, which represents a sediment delivery ratio of 94% (Table 1).

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

Field section	Rate (t ha^{-1} 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

For the nine sampled fields, gross erosion and deposition ranged between -13 and +4 t ha^{-1} yr^{-1} respectively. The net ouput of material from the fields varied from ~0 to 11 t ha^{-1} yr^{-1}. These results indicate that soil erosion involves soil volumes that are significantly greater than revealed by net losses. Deposition and redistribution within the fields are important components of the erosive process that cannot be assessed using 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 of the basin. Extrapolating the results of the nine sampled fields on this basis leads to an assessment that cultivated fields would contribute around 2.5 t ha^{-1} yr^{-1} of sediment to the river system. This value compares well with an assessment of 3 t ha^{-1} yr^{-1} obtained by using the USLE and a locally derived sediment delivery ratio (Landry, 1998).

From the ^{137}Cs measurements, it was noted that the fields located in the lower half of the watershed seem to generate the largest sediments inputs, despite lower soil erodibilities and good forage cover, related to the dominant dairy farming land use. However, slopes in this area are short and steep. In contrast, the sediment production is apparently lower in the upper part of the watershed, despite higher soil erodibilities and more frequent annual crop cover. The longer and smoother slopes in this area probably provide many opportunities for deposition. Therefore, the ^{137}Cs measurements suggest that in the lower half of the watershed, erosion

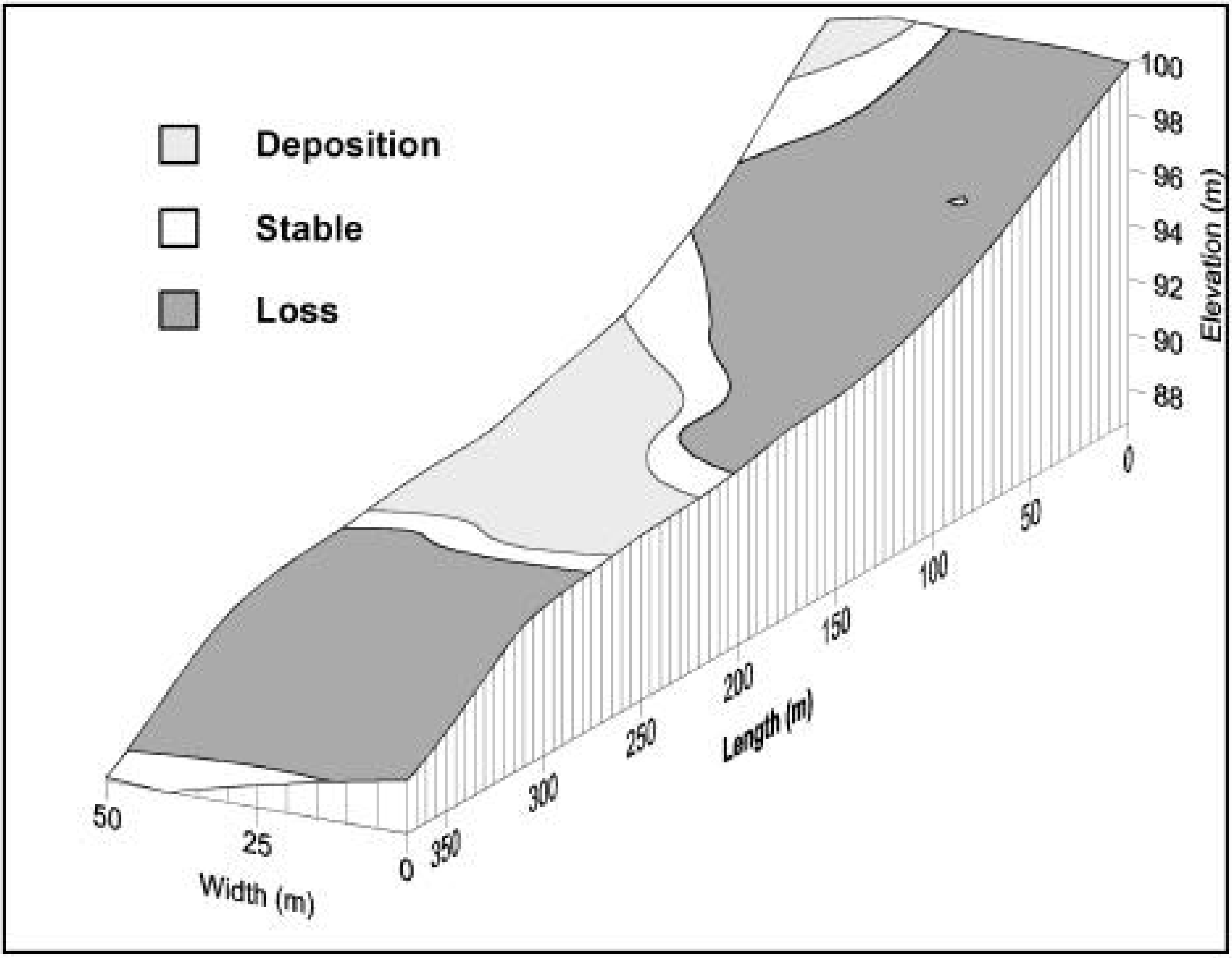

Figure 5. Net soil redistribution estimated from ^{137}Cs measurements, within one of the sampled fields in the Boyer River watershed.

would be less frequent, being linked to prairie turnover, but severe. In contrast, the upper part of the watershed would experience lower erosion rates, due to the topography, although more frequently under annual plant cover.

The soils of cultivated fields and riverbanks were retained as the most probable contributors to the sediments deposited in the spawning area. The ^{137}Cs concentrations ranged between 6.3 to 12.5 Bq kg^{-1} for the surface layer of cultivated fields, from 0 to 23 Bq kg^{-1} for bank material and between 0.9 to 1.6 Bq kg^{-1} for the three bottom sediment samples. From these data, using the model presented by Peart and Walling (1988), it was estimated that ~75% of the bottom sediments would originate from the cultivated fields and that the banks would produce the other 25%. However, this estimate is derived from the only three sediment samples that were analyzed and is based on ^{137}Cs concentrations solely. Also, soil samples from lower positions on the banks would most likely present lower ^{137}Cs concentrations. Using a radiocaesium concentration averaged over the bank depth in the mixing model would then result in a lower contribution from the banks. Finally, the use of other soil properties would probably enhance the capability of the measurements to predict the actual origin of deposited material and could modify the estimated contribution of each potential source (Walling et al., 1993). Therefore, these results should be considered as preliminary.

PRELIMINARY CONCLUSIONS

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 the fact that gross and net rates appear to be moderate. The field studies also confirm that soil redistribution and deposition within field limits are two important components of the erosion process, which are clearly revealed by ^{137}Cs measurements. The radiocaesium measurements also suggest that the upstream section of the watershed behaves differently from the downstream portion, in terms of soil erosion and sediment yield. Field erosion seems more important than streambank erosion as a source of sediment in the spawning area. Therefore, conservation tillage practices should be an important component of any restoration program.

In the coming years, the sampling of additional fields and forested sites is planned. A particular attention will be given to suspended and bottom sediment sampling. The objectives will be to improve the map of the spatial distribution of fallout and to collect more information to better assess the origin of the suspended and the bottom sediments. To meet this last objective, parameters other than ^{137}Cs, such as physico-chemical and magnetic properties, will be measured on soils and sediments.

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