ACTA GEOLOGICA HISPANICA, v. 35 (2000), nº 3-4, p. 239-249

Estimates of soil erosion and deposition of cultivated soil of Nakhla watershed, Morocco, using ^{137}Cs technique and calibration models

S. BOUHLASSA, M. MOUKHCHANE and A. AIACHI

Laboratoire de Radiochimie. Faculté des Sciences. B.P. 1014 - Rabat. Maroc.

ABSTRACT

Despite the effective threat of erosion, for soil preservation and productivity in Morocco, there is still only limited information on rates of soil loss involved. This study is aimed to establish long-term erosion rates on cultivated land in the Nakhla watershed located in the north of the country, using ^{137}Cs technique. Two sampling strategies were adopted. The first is aimed at establishing areal estimates of erosion, whereas the second, based on a transect approach, intends to determine point erosion. Twenty-one cultivated sites and seven undisturbed sites apparently not affected by erosion or deposition were sampled to 35 cm depth. Nine cores were collected along the transect of 149 m length.

The assessment of erosion rates with models varying in complexity from the simple Proportional Model to more complex Mass Balance Models which attempts to include the processes controlling the redistribution of ^{137}Cs in soil, enables us to demonstrate the significance of soil erosion problem on cultivated land. Erosion rates rises up to 50 t ha^{-1} yr^{-1}. The ^{137}Cs derived erosion rates provide a reliable representation of water erosion pattern in the area, and indicate the importance of tillage process on the redistribution of ^{137}Cs in soil. For aggrading sites a Constant Rate Supply (CRS) Model had been adapted and introduced to estimate easily the depositional rate.

Key words: Soil loss. Caesium 137. Erosion rate. Cultivated land. ^{137}Cs Calibration models.

RÉSUMÉ

Malgré la menace réelle que constitue l'érosion pour la preservation, la pérennité et la productivité des sols au Maroc, les données fiables de terrain restent limitées et peu significatives. Cette etude se propose, pour combler ce flagrant deficit, de quantifier les pertes en sol par erosion sur le long terme, dans le bassin versant de Nakhla au nord du pays, en utilisant la technique de ^{137}Cs. Deux strategies d'échantillonnage ont été adoptées. La premiere vise l'établissement de l'érosion moyenne dans le champ, tandis que la seconde, basée sur l'échantillonnage d'un transect, conduit à l'estimation de l'érosion ponctuelle. Des carottes de 35 cm de long ont été collectées sur 21 champs de labours et 7 sites sous forêt ou matorral denses, apparemment non érodés. 9 carottes ont été prélevées sur un transect en terrain cultivé, long de 149 m. L'évaluation des vitesses d'érosion, en utilisant des modèles de conversion de la perte en ^{137}Cs en perte en sol, de plus en plus complexes, allant du modèle proportionnel simple aux modèles d'équilibre de masse, qui tiennent compte de certains processus de redistribution du ^{137}Cs dans le terrain, met en evidence l'importance de l'érosion dans les champs de culture, laquelle peut atteindre 50 t ha^{-1}an^{-1}. Les résultats obtenus reflètent les variations relatives de l'érosion dans le bassin et indiquent l'importance de l'effet du labour dans le déplacement des sols. Dans les sites de redeposition, les vitesses d'accumulation des sediments ont été calculées à l'aide du modèle CRS, qui a été introduit pour faciliter l'exploitation des modèles d'équilibre de masse.

Key words: Soil loss. Caesium 137. Erosion rate. Cultivated land. ^{137}Cs Calibration models.

INTRODUCTION

In Morocco, water erosion concerns several millions hectares of land and causes numerous damages. It results in a serious on-site durable and continuous soil and fertility losses from cultivated land and severe off site consequences such as a dam silting and water pollution. Despite the potential hazards to the long- term productivity of arable land due to erosion, there is only limited information on rates of soil loss involved and no extensive studies on the problem and its quantification are available. The only data we could find are the periodical echosounding measurements undertaken on sediment deposited in dams and very few reliable data on erosion rates derived from limited erosion plot studies. ^{137}Cs technique as has been demonstrated in many studies around the world, affords a valuable tool to estimate medium-term rates of soil loss and sediment deposition in a watershed (He and Walling, 1997; Loughran, 1989).

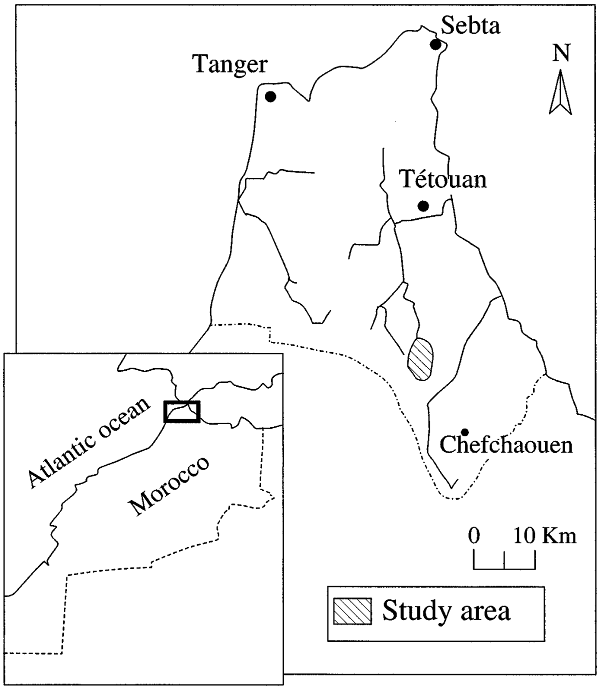

Figure 1. Location of the study area.

Walling and Quine (1990) and Walling and He (1997) have reported and discussed the many empirical relationships and theoretical models, which have been used to convert ^{137}Cs measurements to quantitative estimates of erosion and deposition.

The objectives of this study are: 1) to document the levels of ^{137}Cs on cultivated and non-eroded soils in a catchment located in the north of Morocco, characterised by evident high erosion rate, 2) to estimate erosion or deposition rates on cultivated land using empirical model, 3) to estimate a point erosion or deposition rates on a slope transect sampled and finally 4) to discuss the results and methods to assess the impact of main erosion factors.

MATERIAL AND METHODS

Study area

Nakhla catchment is located at 35° 20' to 35°28'N and 5°20' to 5°25' W, 20 km south of Tetouan town, in Northern Morocco, in the Rif Zone. It is bordered in the east by calcareous - dolomitic mountains and in the west by a mudstone massif called "Tiserene". Basin area is about 109km^2 (figure 1). Watershed receive about 63 hm^3 yr^{-1} of precipitation regulated by Nakhla dam located at the outlet of the catchment.

The capacity of Nakhla dam has decreased from 9 Mm^3 in 1961 to 4.92 Mm^3 in 1996 with an average annual siltation of 0.18 Mm^3. Analysis of periodical echosounding measurements undertaken on deposited sediments in the dam indicates an overall erosion rate in the watershed increasing from 12 t ha^{-1} yr^{-1} between 1961 and 1967 to 55, 2 t ha^{-1} yr^{-1}, recorded between 1994 and 1996 (Laabdi, 1979), with a mean value of 15.15 t ha^{-1} yr^{-1}.

The climate in the area is Mediterranean subhumide. Annual precipitation varies between 660 and 804 mm, recorded by the three meteorological stations located in the watershed. Mean annual temperature at the dam meteorological station is 17.7° C, varying from minimum of 2.2° in February to a maximum of 37.8° C in August. Raining regime is characterised by irregularity: dry period in summer but with storms and wet period in autumn and spring.

Altitude in Nakhla basin varies from 1808 m at south - east to 160 m at dam location. Three slope inclination classes could be distinguished: 0 to 9 %, 9 - 25 % and > 25%. Soils in this Mediterranean zone are thin and slope inclination important. Pedologic study (Naimi and Bouabid, 1997) in this area identifies a lithosol in the east part of the catchment and old or no developed soils constituted by silt or clay and silt, underlayed by marne and flysch in the major part of the basin. Natural vegetation constituted by Quercus suber, Pistacia lentiscus and Olea europaea and reforested area with Pinus halepensis and Pinus maritima cover some 38% of the catchment. 37% is used for agricultural activities, mainly for cereal, maiz and beans growing.

Sampling sites

Two sampling strategies were adopted. The first aimed at establishing the areal estimate of erosion for cultivated soil, whereas the second, based on a transect approach intends to determine the point erosion. 21 cultivated (figure 2) and 7 uncultivated sites with apparently non-eroded soils are selected in the catchment. All the sites are distributed in the watershed at distances that did not exceed 6km from the closest meteorological station.

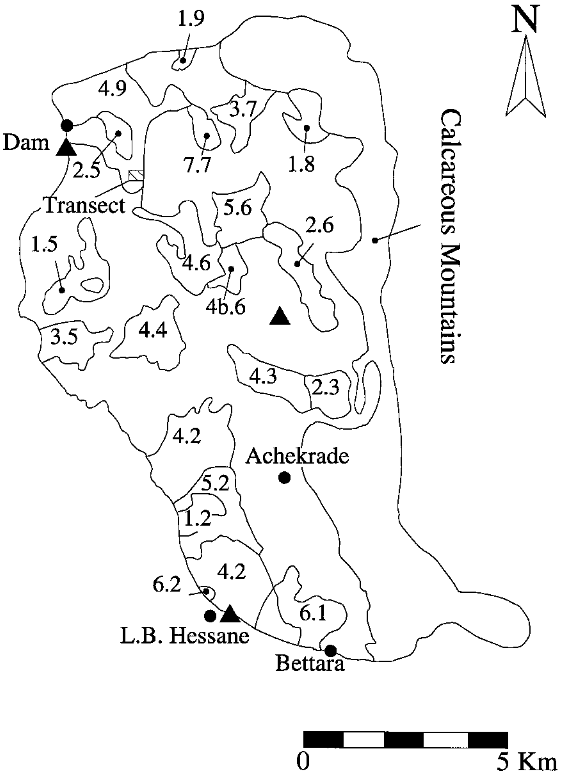

Figure 2. Cultivated land sampling; ● Village location; ▲ Pluviometric station; Numbers, i.e 4.9 for exemple are cultivated field codes. Location of the sampled transect.

At each site, five cores were collected using 500mm long steel core with 50 mm diameter. The samples were taken at the corners and the centre of 4*4 m square parcel from mid slope position in landscape. The core samples were divided in 5 cm depth increments that were dried at

Table 1. Characteristics of undisturbed soil sampling sites

Sampling site	Slope inclination (%)	Land use	Mean annual precipitation (mm)	Soil texture	^{137}Cs inventory Bq m^{-2}
C1-6	>25	Forest	800	Sandy-clayey	3129
C6b-7	10	Forest	800	Clayey-sandy	3037
C3-9	10	Forest	800	Clayey	3250
C1-2	10	Bush	660	Clayey-silty	2846
C1-3	9	Bush	760	Sandy	1671
C7-4	10	Dense Forest	760	Sandy	2379
C4-5	10	Bush	760	Sandy-clayey	2280

40°C, weighed and passed through 2 mm sieve before analysing by gamma spectroscopy.

As in the most used approach for ^{137}Cs method, the ^{137}Cs loss is determined by comparing the ^{137}Cs inventory for individual sampling site to a reference value obtained from undisturbed non-eroding area. The choice of suitable reference sites should be careful. The reference site should have received the same annual precipitation and should have similar geomorphological parameters than the sampled cultivated field.

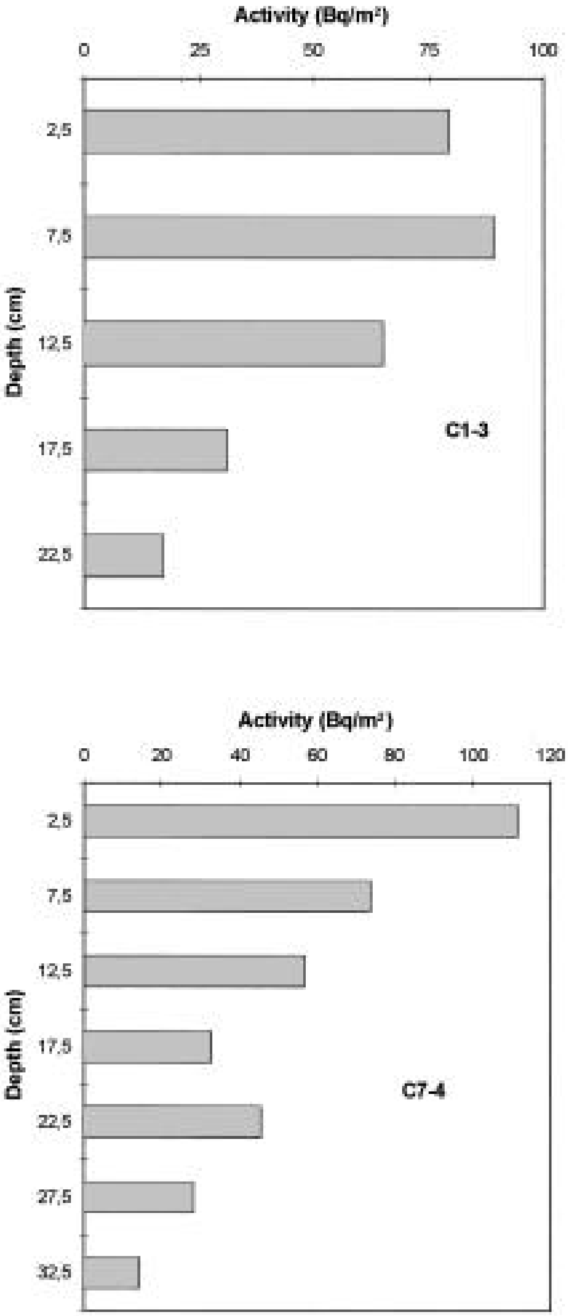

Figure 3. Depth distribution of ^{137}Cs for the local reference sites C1-3 and C7-4.

Despite some spatial variation in ^{137}Cs activity in areas receiving the same annual precipitation, which was considered by Kiss et al. (1988) to be largely caused by the difference in local meteorological conditions during the maximum ^{137}Cs fallout period, the mean annual precipitation seems to be an important parameter (Davis, 1963; Lance et al., 1986).

Seven uncultivated and undisturbed sites were selected near the meteorological stations, in the catchment with different slope inclinations than have the reference sites in the watershed. Table 1 lists some characteristics of these sites. As de Jong et al. (1983) showed that there are little or no ^{137}Cs redistribution within uncultivated basins, only one or two cores were collected from midslope position in landscape.

A 149 m long transect located near the Nakhla dam, going across a gentle sloping cultivated field was also sampled. Nine cores were collected at 12 or 20 m intervals approximately from up-slope to down-slope (Table 2). The local ^{137}Cs reference inventory was estimated on the cores collected from the dense bush area with smooth slope ≤5°, located at 40 meters from the cultivated field.

The ^{137}Cs arbitrary activities for each core are determined on NaI(Tl) detector system when more than one core was collected from the site. The mean representative core was then analysed on HPGe system analysis as when only one core was sampled.

RESULTS AND DISCUSSION.

Local reference inventory

Table 1 reports the caesium-137 inventories for cores collected from the seven assumed undisturbed sites. The values seem to reflect variations, which are more depending on mean annual precipitation than on land use and slope inclinations. The ^{137}Cs inventories range from 1670 to 3850 Bq m^{-2}. The range of ^{137}Cs inventory values seems too greet despite of the change of rainfall ranging from 660 to 800 mm yr^{-1}. However some discrepancy probably due to different local meteorological conditions in the maximum ^{137}Cs fallout period, as suggested by

Table 2. Characteristics of the point sites sampled on the transect across a cultivated soil.

Sampling point	1	2	3	4	5	6	7	8	9
Slope Angle (°)	5	5	10	15	10	20	0.0	15	2
Slope length (m)	10	20	40	10	10	20	20	20	9
Soil texture	Clayey silty	Clayey silty	Clayey silty	Clayey silty	Clayey silty	Clayey silty	Clayey silty	Sandy	Sandy

Kiss et al. (1988), was showed on bush sites with equal slope inclination but receiving 660 and 760 mm yr^{-1} of rainfall. This spatial variability in the inventories indicates clearly that the reference site must be as closer as possible from the sampling site or it should have the same precipitation history.

The typical distribution of ^{137}Cs in reference sites is illustrated in figure 3. ^{137}Cs is distributed along the profile with decreasing concentration, but more than 60% of ^{137}Cs remains within the top 12.5 cm from the surface. Such broad distribution may be related to the sandy soils of all the reference sites.

Areal estimates of erosion for cultivated soils

In order to use ^{137}Cs data to estimate rates of soil erosion for cultivated land, it is necessary to convert ^{137}Cs loss or gain to rates of soil erosion or aggradation respectively. This conversion was achieved using the Proportional Model and the Simplified Mass Balance Model described by Walling and He (1997).

The Proportional Model can be represented as follows:

$$Y = 10 \cdot B \cdot D \cdot X / 100T$$

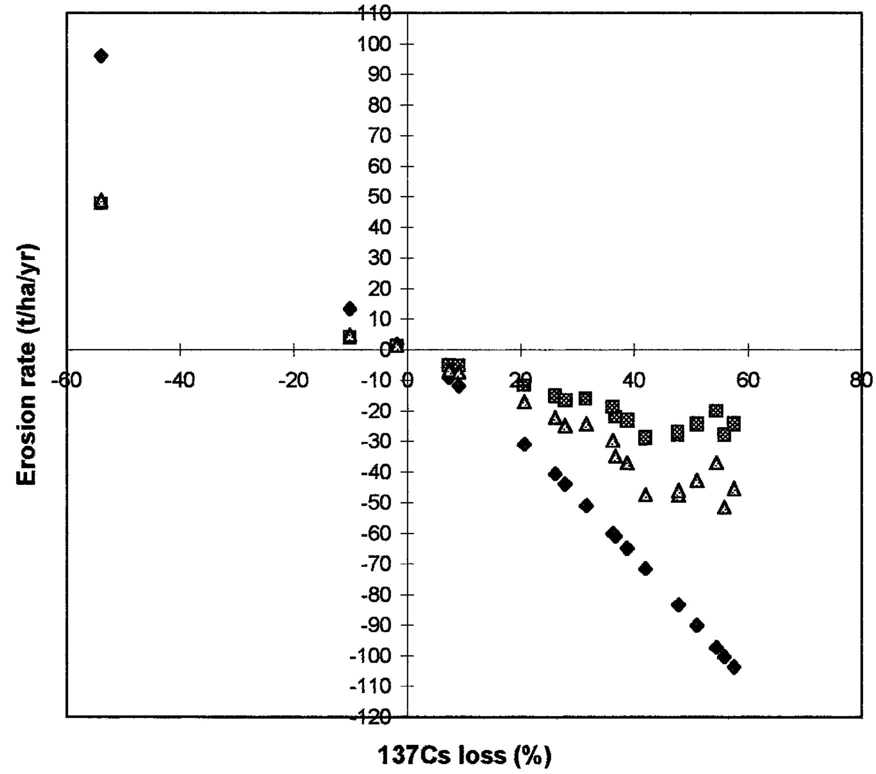

Figure 4. Erosion and deposition rates versus ^{137}Cs loss or gain in percentage. ◆ Richie's equation; ▨ Proportional model; ▲ Simplified Mass Balance Model

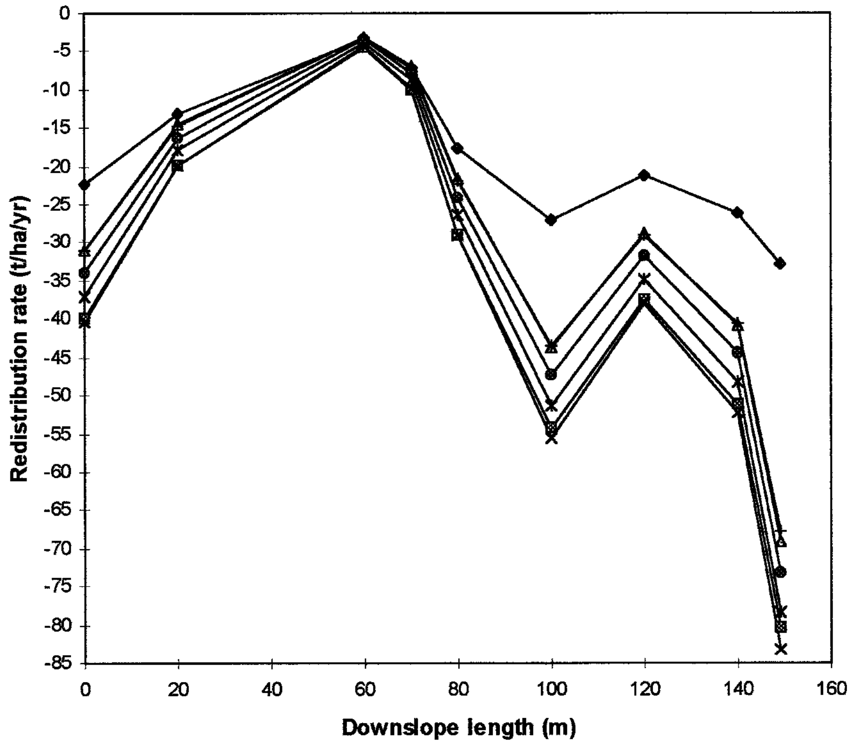

Figure 5. Pattern of net erosion rates along the transect calculated by Proportional Model, Simplified Mass Balance Model and Mass Balance Model 2 with $0.0 \leq \gamma \leq 0.4$. ◆ Proportional Model; ■ Simplified Mass Balance Model; ▲ Mass Balance 2, γ=0.4 Mass Balance Model 2, γ = 0.3 ; ● Mass Balance Model 2, γ = 0.2; ✱ Mass Balance Model 2, γ=0.1 ; × Mass Balance Model 2, γ = 0.0

where: Y - mean annual soil loss (t ha^{-1} yr^{-1}). D - depth of plough or cultivation layer (m). B - bulk density of soil (kg m^{-3}). X - percentage of ^{137}Cs loss or gain. T - time elapsed since initiation of ^{137}Cs accumulation (yr)

The Simplified Mass Balance Model for eroded site can be expressed as:

$$Y=10D*B\ [1-X/100)^{\frac{1}{(t-1963)}}]$$

where t is the sampling year.

For the depositional sites, the lack of ^{137}Cs data concerning the mobilised sediment from the upslope contributing area, did not allow us to calculate the deposition rate using the Walling and He (1997) formula. We introduced another model derived from the Constant Rate Supply Model (CRS) developed by Appelby and Oldfield (1978) for estimating lake sedimentation rate.

This model would constitute an advantageous alternative, since it requires only the data from the deposition site.

In the CRS model, based on constant sediment accumulation flux, the depositional rate r is given by:

$$\frac{\delta \ln A(z)}{\delta(B(z)\cdot z)} = -\frac{\lambda}{r}$$

where : A(z) - cumulated radioactivity (Bq/m^2) up to depth z of the core. B(z) - density of sample at dept z (Kg. m^{-3}). λ - radioactive constant of ^{137}Cs (0.023 yr^{-1}). r - depositional rate (kg m^{-2} . yr^{-1})

So the slope of Ln A(z) = f (B(z).z) will be $-\lambda/r$ which lead to value of depositional rate r.

Table 3 reports the values estimated by different models. We include therein the erosion or deposition rate calculated by Ritchie's empirical relationship:

$Y = 0.87X^{1.18}$ (Ritchie and McHenry, 1990).

Although the comparisons of measured inventories with the local reference value provide useful qualitative information on soil erosion and deposition, the quantita-

Table 3. Erosion rates estimates using Proportional Model, Simplified Mass Balance Model and Ritchie's model. For Simplified Mass Balance depositional rates (positive values) are calculated using CRS model.

Site	^{137}Cs loss	Erosion rate	Erosion rate	Erosion rate
	(%)	Ritchie model (t ha^{-1} yr^{-1})	Simplified Mass Proportional model (t ha^{-1} yr^{-1})	balance and CRS (t ha^{-1} yr^{-1})
C6-1	31,5	-51	-15,9	-24,2
C4-2	55,84	-100,2	-28	-51,5
C5-2	47,74	-83,3	-28	-47,6
C6-2	36,6	-60,9	-22,2	-35
C2-3	-1,78	1,7	1,2	1,5
C4-3	-10,16	13,4	3,9	4,7
C4-4	36,14	-50	-18,8	-29,6
C1-5	-53,86	96,0	47,6	48,8
C2-5	38,62	-64,9	-23,2	-37
C3-5	7,28	-9,1	-5,1	-6,7
C2-6	26,05	-40,8	-15,1	-22,1
C4-6	51,02	-90,1	-24,1	-42,8
C4bis-6	54,51	-97,4	-20,3	-36,9
C5-6	27,82	-44,0	-16,7	-24,8
C3-7	20,62	-30,9	-11,9	-16,8
C7-7	41,98	-71,6	-28,8	-47,2
C1-8	9,14	-11,8	-5,4	-7,2
C1-9	47,78	-83,4	-26,8	-46,0
C4-9	57,5	-103,7	-24,3	-45,4

tive estimates of soil redistribution depend upon the existence of reliable relationship between the measured ^{137}Cs inventory at a specific sampling point and the rate of erosion or deposition at this point. Workers using the ^{137}Cs technique in soil erosion investigations face difficulties in selecting an appropriate model. Walling and He (1997) have reported many empirical relationships and theoretical models, which have been used to convert ^{137}Cs measurements to quantitative estimates of erosion and deposition rates, and discussed the limitations of these models.

Although the Proportional Model and Simplified Mass Balance Model requires only data on ^{137}Cs inventories and on plough layer depth, they do not take into account the possible removal of freshly deposited ^{137}Cs, before its incorporation in the plough layer. The Simplified Mass Balance Model attempts to overcome another limitation of the Proportional Model by taking into account the dilution of ^{137}Cs in the plough layer after surface lowering by erosion, but assumes that total ^{137}Cs fallout occurred in 1963 instead of over the period from 1954 to the mid 1970. All these assumptions may results in underestimation or overestimation of soil loss.

The Ritchie's relationship based on spatially averaged values of ^{137}Cs collected between 1960s to early 1970s from plots and small watersheds, probably, may overestimates the contemporary erosion rates.

Despite these actual limitations, the values derived from the models may provide reliable pattern of erosion and deposition rates in the watershed and they permit to demonstrate the impact of management system and agricultural practices on erosion processes in area.

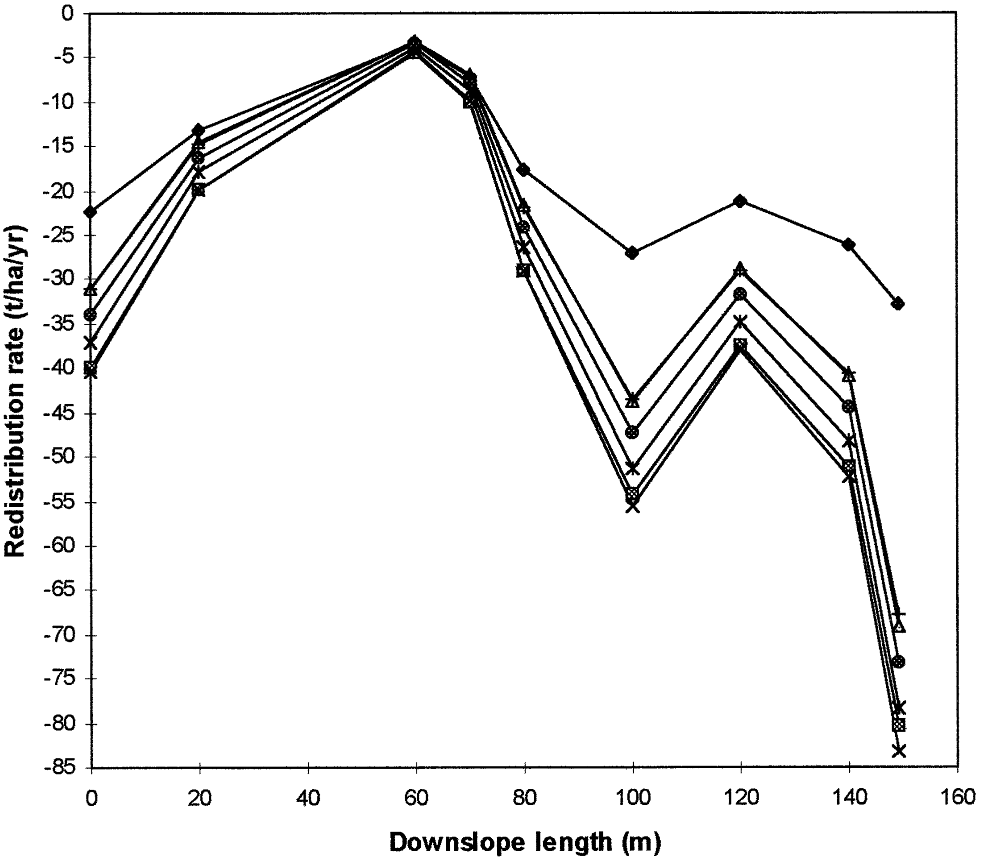

Figure 6. Net erosion rates calculated by " Mass Balance Model 3 " with different γ: 0.0≤ γ ≤0.4. ◆ Tillage redistribution; ● γ = 0.0; ■ γ = 0.1; ▲ γ = 0.2, ✕ γ = 0.3 ; ✶ γ = 0.4.

A comparison of the erosion results obtained using the three models (figure4) shows a consistently agreement between Proportional Model and Simplified Mass Balance Model for ^{137}Cs loss less than 20% (X (20%). Results deviate and a net discrepancy appear between the two models when ^{137}Cs loss is higher than 20((X (20%). Erosion rates obtained by Ritchie's model remain always higher. Calculated erosion rates range generally in this order: proportional model values (simplified mass balance values (Ritchie model values.

Point estimation of erosion for cultivated soil

The erosion or sedimentation rates have been calculated using the selected models for cultivated soils proposed by Walling and He (1997), namely in ascending complexity the Proportional Model, the Simplified Mass Balance Model, the Mass Balance Model 2 and the Mass Balance Model 3 which takes in account tillage contribution to erosion. The models and calculations procedures are detailed in the above-cited paper.

Table 4. Average erosion rates calculated by calibration models.

Model	Proportional	Simplified Mass Balance	Mass Balance 2 γ = 0.3	Mass Balance 3 γ =0.3
Average erosion rate (t ha^{-1} yr^{-1})	-16.6	-31.1	-24.4	-37.5

The Mass Balance Model 2 takes into account both the temporal variation in ^{137}Cs fallout and the fate of the freshly deposited ^{137}Cs fallout, while the Mass Balance Model 3 calculates, more over the tillage redistribution in the flow directions which was neglected in Mass Balance Model 2.

In Mass Balance Model 2 the erosion rate R is estimated by the equation:

$$A(t)= A(t_0)e^{-(\frac{R}{d}+\lambda)(T-t_0)}+\int_{t_0}^{t}[1-\gamma(1-e^{-\frac{R}{H}})]\, I(t')e^{-(\frac{R}{d}+\lambda)(t-t')}dt'$$

While deposition rate can be calculated by another equation:

$$R=\frac{A_{ex}}{\int_{t_0}^{t} C_d(t')e^{-\lambda(t'-t')}dt'}$$

where: A(t_0) (Bq m^{-2}) is ^{137}Cs inventory at year t_0,

$$A(t_0)=\int_{1954}^{t_0} I(t')e^{-\lambda(t'-t0)}dt'$$

I(t) (Bq m^{-2}yr^{-1}) - annual ^{137}Cs deposition flux; γ - Proportion of annual ^{137}Cs input susceptible to be removed by runoff; d(kg m^{-2}) - plough layer cumulative mass; H- relaxation mass depth; H = 4 kg m^{-2}; C_d(t') (Bq kg^{-1}) - ^{137}Cs concentration of deposited sediment; A_{ex} (Bq m^{-2}) - total local ^{137}Cs inventory less reference inventory

For Mass Balance Model 3, the variation of total ^{137}Cs inventory A(t) is expressed as:

$$\frac{dA(t)}{dt}=(1-\Gamma)*I(t)+R_{t,in}*C_{t,in}(t)-R_{t,out}*C_{t,out}(t)-R_w*C_{w,out}(t)-\lambda*A(t)$$

For point experiencing water erosion, Γ is the percentage of ^{137}Cs fallout removed before its incorporation in plough layer. For point experiencing deposition the expression will be:

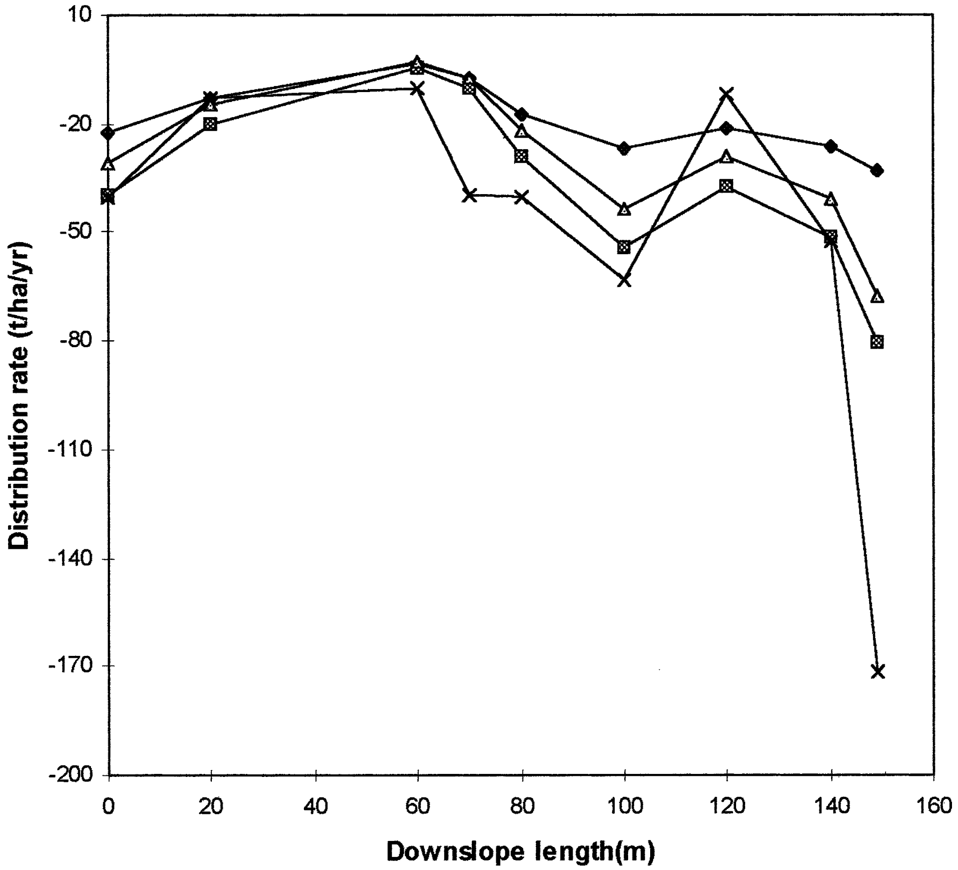

Figure 7. Net erosion rates estimates by Proportional Model, Simplified Mass Balance Model, Mass Balance Model 2 and Mass Balance Model 3 with γ fixed at 0.3. ◆Proportional Model; ■ "Simplified Mass Balance Model" ▲ "Mass Balance Model 2"; X "Mass Balance Model 3".

$$\frac{dA(t)}{dt}=I(t)+R_{t,in}*C_{t,in}(t)-R_{t,out}*C_{t,out}(t)+R_w*C_{w,in}(t)-\lambda*A(t)$$

$C_{t,in}$; $C_{t,out}$; $C_{w,out}$; $C_{w,in}$ (Bq kg^{-1}) are ^{137}Cs concentrations of sediment associated with tillage input, tillage output, water erosion output and water erosion input respectively. R_w and R'_w (kg m^{-2}yr^{-1}) are water erosion rate and water induced deposition rate respectively.

The net erosion is given by:

$R=R_{t,out}-R_{i,in}+R_w$ for eroded point

and $R=R_{t,out}-R_{t,in}+R'_w$ for aggrading site

The tillage contribution is calculated from the equation:

$$R_{t,out}-R_{t,in}=\Phi\,(\sin\beta_{in}-\sin\beta_{out})/L$$

where β_{in} and β_{out} are the slope angles in degrees before and after the point sampled, L(m) is the slope length, and Φ (kg m^{-1}yr^{-1}) is a constant.

Figure 5 summarises the erosion rates estimates along the transect, obtained by Proportional Model, Simplified Mass Balance Model and Mass Balance Model 2 with different coefficients (, which represent the proportion of annual ^{137}Cs input susceptible to be removed by runoff ($0 \leq \gamma \leq 0.4$). These values are alike to reproduce the runoff estimates in the study area, which fluctuate between 0 and 30 %. The erosion rates calculated by Proportional Model stay always lower than the three other models estimate. Otherwise the Simplified Mass Balance Model and Mass Balance Model 2, with $\gamma = 0.0$, or no removal of freshly deposited ^{137}Cs fallout, lead to the same and important erosion rate estimates. As expected when the removal proportion of freshly deposited ^{137}Cs varies from 0.1 to 0.4 the erosion rates calculated by the Mass Balance Model 2 decreases.

Figure 6 shows the erosion rates calculated by Mass Balance Model 3. In order to separate contribution of tillage to soil redistribution, the figure reproduces the tillage redistribution and the net erosion rate, which is the algebraic sum of water erosion and tillage redistribution. The overall pattern of ^{137}Cs redistribution appears to be dominated by water erosion. Within the Mass Balance Model 3 hypothesis, soil tillage makes a significant contribution to total soil redistribution; this contribution remains although globally lesser than water induced erosion.

Figure 7 reproduces the net erosion rates estimated by Proportional Model, Simplified Mass Balance and Mass Balance Models 2 and 3; the γ value is fixed at 0.3 for the two last models. Patterns of downslope variation in ^{137}Cs derived erosion rates show a relatively good agreement, but there is a clear difference in the magnitudes of rates. In an ascending order the estimates are: Proportional Model erosion rate < Mass Balance Model 2 erosion rate < Simplified Mass Balance Model erosion rate < Mass Balance Model 3 erosion rate. The average erosion rate values estimated by the models range between 16 to 38 t ha^{-1} yr^{-1} as shown in table 4.

Despite the limited signification of the average values, which explicitly constitute an over simplification of the erosion mechanism and processes, these values could be used to define the variation margin of the areal erosion rate, for the field where the transect samples were collected. In our case these areal erosion rates estimated by Proportional Model and Simplified Mass Balance Model, are 24.3 and 45.4 t ha^{-1}yr^{-1} respectively. The values lie within the limits established on the transect, and are in agreement with them.

These average values could also be used to appreciate the effects of tillage, runoff and ^{137}Cs dilution. Comparison of results obtained by Mass Balance Model 3 and Mass Balance Model 2 would reflect the tillage contribution to erosion. It would be about 35%. The runoff contribution estimated by comparing Mass Balance Model 2 and Simplified Mass Balance Model would be around 20%, and finally the dilution effect due to the plough layer lowering, derived from the difference between Mass Balance Model 2 and Proportional Model reaches 32%.

CONCLUSION

Since the spatial variability of ^{137}Cs core inventories has not been thoroughly studied, the areal erosion rates calculated from few ^{137}Cs profiles for cultivated soil (table 3), are in good agreement with echosounding derived erosion rate from sedimentation in dam located at the outlet of the basin, and confirm the significance of soil erosion problem for cultivated field. The approach has a merit to highlight the impact of agricultural practices and contributes to assessment of long term erosion rates for area where other quantitative data are lacking. The globally underestimated erosion rate obtained by Proportional Model, in comparison with Simplified Mass Balance Model, indicates clearly the dilution effect of soil within the plough layer by soil containing ^{137}Cs below the original plough depth.

The analysis of result of gradual displacement of soil along a 149 m transect using Proportional Model, Mass Balance Models 2 and 3 proposed by Walling and He (1997) indicates a clear contribution of tillage to soil redistribution. Although there is clear difference in the magnitude rates derived from the models, the ^{137}Cs derived erosion rates is likely to provide a reliable representation of variation of water erosion along the transect and also in the study area.

Otherwise, the introduction of constant rate supply model (CRS) to calculate depositional rate in an aggrading site, would constitute an easier and efficient approach to estimate the depositional rate using the Mass Balance Models, since the CRS model requires only the ^{137}Cs data along the core profile collected at the aggrading site.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the International Atomic Energy Agency within the CRP on " sediment assessment studies by environmental radionuclides and their application to soil conservation measures". Discussions with Dr. E. Garcia -Agudo and Prof. D.E. Walling concerning the methodology and their comments have proved invaluable.

REFERENCES

Appelby, P.G., Oldfield, F., 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena, 5, 1-8.

Davis, J.J., 1963. Cesium and its relationship to potassium in ecology. In V. Shultz and A. W. klement (eds.): Radioecology, Reinholt, WA.

He, Q., Walling, D.E., 1997. The distribution of fallout ^{137}Cs and ^{210}Pb in undisturbed and cultivated soils. Appl. Radiat. Isotopes, 48, 677-690.

de Jong, E., Begg, C.B.M. Kachanoski, R. G., 1983. Estimates of soil erosion and deposition from Saskatchewan soils. Can. J. Soil Sci. 63, 607-617.

Kiss, J.J., de Jong, E., Martz, L.W., 1988. The distribution of fallout Cesium^{137} in southern Saskatchewan, Canada. J. Environ. Qual., 17(3),445-451.

Lance, J.C., McIntyre, S.C., Naney, J.W., Rousseva, S.S., 1986. Measuring sediment movement at low erosion rates using ^{137}Cs. Soil Sci. Soc. Am. J., 50, 1303-1309.

Laabdi, M., 1979. Production de sediments et perte en elements fertilisants par erosion dans le bassin versant de Tlata. Memoire de 3e Cycle, I. A. V., Hassan II, Rabat (Maroc), 128P.

Loughran, R.J., 1989. The measurement of soil erosion. Prog. Phys. Geog., 13, 216-233.

Naimi, M., Bouabid, R., 1997. Bassin versant Nakhla. Etude pedologique au 1/50.000. Ministere de l'Environnement, Rabat (Maroc), 88P.

Ritchie, J.C., McHenry, J.R., 1990. Application of Radioactive fallout Caesium 137 for measuring soil erosion and sediment accumulation rates and patterns : A review. Jour. Environ. Qual., 19, 215-233.

Walling, D.E., He, Q., 1997. Models for converting ^{137}Cs measurements to estimates of soil redistribution rates on cultivated and uncultivated soils. Report to IAEA, University of Exeter, U. K.

Walling, D.E., Quine, T.A., 1990. Calibration of Caesium 137 measurement to provide quantitative erosion rate data. Land Degrad. Rehabil., 2, 161-175.