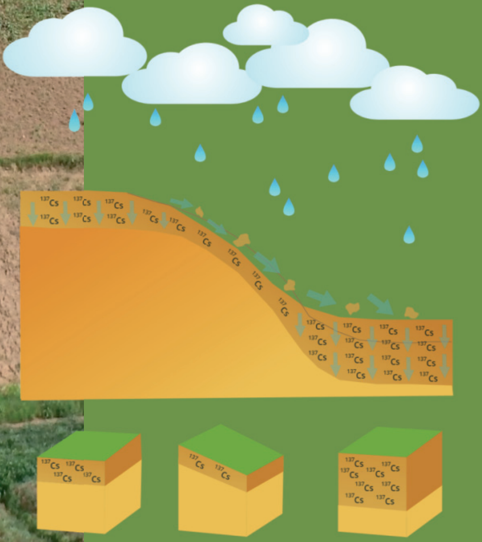
Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

USE OF ^{137}Cs FOR SOIL EROSION ASSESSMENT



Use of ^{137}Cs for soil erosion assessment

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Food and Agriculture Organization of the United Nations
International Atomic Energy Agency
Rome, 2017

Recommended citation
FAO/IAEA. 2017. Use of ^{137}Cs for soil erosion assessment. Fulajtar, E., Mabit, L., Renschler, C.S., Lee Zhi Yi, A., Food and Agriculture Organization of the United Nations, Rome, Italy. 64 p.

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ISBN 978-92-5-130050-3
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Foreword

Soil is the fundamental natural resource for humankind and many living organisms. It is the basis for food production and has several environmental functions. It plays a key role in water, nutrient and carbon cycles and serves as an environment for flora and fauna in and above the soil.

Soil is a fragile resource and its development from weathered rocks and sediments under the effect of water, air and living organisms requires time. The soil formation rate usually does not exceed 0.1 mm of soil layer per year and to form fertile soil suitable for agriculture often requires several hundred or even thousand years. In contrast the loss of soil can be a quick process, especially if barren soil is exposed to erosion by water or wind.

Combating soil erosion requires investment and, due to the limited resources, it should be targeted to critical areas and time period during the most vulnerable season. Comprehensive knowledge of spatial and temporal variability of erosion processes is urgently needed. Gaining reliable information is, however, challenging. Conventional methods for measuring soil erosion are labour intensive and time consuming, and data need to cover several decades to get a good representation of mean erosion rates. Furthermore, most conventional methods (except for geodetic method) do not provide information on the spatial distribution of erosion.

Isotope tracers can help to meet these deficiencies as some radionuclides and stable isotopes occurring in the environment can serve as environmental tracers and hence facilitate the investigation of these landscape processes. The soil erosion rates can be estimated using ^{137}Cs, a human-induced radionuclide of caesium released into the atmosphere during nuclear weapon tests more than half a century ago. The ^{137}Cs method for soil erosion assessment effectively provides long-term mean soil redistribution rates, representing the period since its release (mid-1950s) until the time of the ^{137}Cs sampling. Such information on spatial and temporal distribution of erosion is crucial also for soil erosion modelling and soil conservation programmes and provides essential information towards several strategic objectives of the Food and Agriculture Organization of the United Nations (FAO).

This publication provides a brief overview of the ^{137}Cs method and explains the principles and strengths of its applications in research towards climate-smart agriculture. It addresses a wide audience encompassing scientists and students, environmental specialists, agricultural managers and decision makers, farmers and individuals who are interested in soil conservation and sustainable land management. It summarizes the experience of research activities carried out by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.


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Executive summary

Soil erosion by water, wind and tillage are among the most common and important land degradation processes, with both on-site and off-site impacts. They affect more land than all other degradation processes put together. A total of 75 billion tons of fertile soil is removed every year from global soilscape by erosion. As a result, precious soil resources, which should be preserved for next generations, are continuously reduced. Every year approximately 12 million ha of land is lost. It is therefore important that erosion research is conducted to assess the soil redistribution rates, their spatial distribution and temporal dynamics in order to counteract this process.

The measurement of soil redistribution is not an easy task because soil erosion is caused by a number of processes running at different temporal and spatial scales. Conventional erosion measurement methods, such as erosion plots, volumetric, hydrological, and geodetic methods, are used for different erosion processes and they cover different spatial and temporal scales. Most conventional methods have severe limitations. They are associated with point data (measurement profiles) and do not provide information on spatial distribution of erosion. However the major disadvantage is that they are labour-intensive and require long monitoring periods. These disadvantages can be overcome by using ^{137}Cs as an erosion tracer.

The principle of the ^{137}Cs method for soil erosion assessment is based on the chemical characteristics of Caesium. The ^{137}Cs is a human-induced environmental radionuclide, released into the atmosphere by nuclear weapons testing in the 1950s and 1960s, whereby the radionuclide spread to the stratosphere and gradually descended to the land surface. In addition, smaller regional contaminations were caused by nuclear power plant accidents (such as the Chernobyl and Fukushima-Daiichi accident). When ^{137}Cs gets into contact with soil material, it binds firmly to soil colloids and is often not transferred by processes such as leaching or plant uptake. It can move only together with soil particles and this means that any change in ^{137}Cs inventories indicate the occurrence of processes of soil redistribution by physical agents (e.g. soil erosion).

The concept of reference sites was established to express loss and accumulation processes quantitatively. A reference site is an undisturbed site where neither erosion nor sedimentation occurs, so that the ^{137}Cs inventory represents the original fallout reduced only by radioactive decay. The principle of the method is based on comparison of studied and reference sites. If the studied site contains less ^{137}Cs than the reference site, it implies that the studied site is eroded. If its ^{137}Cs inventory is greater, it is affected by sedimentation. This simple relation is interpreted by conversion models in order to convert the differentiated ^{137}Cs inventories into soil erosion and sedimentation rates.

For successful interpretation of the ^{137}Cs method, proper selection of the reference site is crucial. The ^{137}Cs sampling should start with depth incremental sampling performed to determine the depth distribution of ^{137}Cs contamination; subsequent bulk core samples should then be collected following grid or multiple transect designs.

The analysing of ^{137}Cs content in the soil is done by gamma spectroscopy. ^{137}Cs can be easily measured by gamma spectroscopy because it provides a strong peak (at 662 keV energy) that is well identifiable in the gamma ray energy spectrum. After data collection (^{137}Cs inventories and calculated soil erosion rates), data processing and the interpretation of data follows. The obtained data can be used for various purposes, such as characterizing the erosion over a range of environments or land uses; estimating the impact of land management and crop rotation on the soil erosion; and assessing the efficiency of particular soil conservation measures. This publication describes the above steps, including data interpretation. It also describes the use of ^{137}Cs in combination with erosion modelling. The ^{137}Cs derived erosion data has great potential as a tool for validation of erosion models.

The primary purpose of erosion assessment with ^{137}Cs method is to provide information needed for identification of erosion hot spot areas and selection of conservation measures. This helps to implement the soil conservation programmes and thus ^{137}Cs method contributes to maintaining food security.

1 Introduction

The suggestion to use caesium-137 (^{137}Cs) as a tracer for soil erosion assessment originated in the 1960s when environmental scientists investigated land contamination by radionuclides released during nuclear weapons tests. It was found that some radionuclides released by these tests could be used as tracers to investigate landscape processes, such as water circulation and transport of soluble/insoluble compounds.

Initial studies on erosion assessment focused on strontium-90 (^{90}Sr). Menzel (1960) noticed that the loss of ^{90}Sr at sloping relief positions can be attributed to erosion. As ^{90}Sr is challenging to analyse, the attention soon turned to ^{137}Cs. Graham (1963) and Frere and Roberts (1963) began the investigations of ^{90}Sr and ^{137}Cs redistribution by soil erosion. Rorowski and Tamura (1965, 1970a, b) started to use ^{137}Cs as artificially added tracers to investigate correlation between soil erosion or soil loss and ^{137}Cs inventories at experimental plots. The ^{137}Cs method underwent significant development and became a well-established method for soil erosion quantitative assessment in the 1990s and early 2000s (Walling and Quine, 1990, 1991, 1992, 1995; Zupanc and Mabit, 2010; IAEA, 2014).

The *Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture* plays an important role in the development of the ^{137}Cs method. It was established in 1964 and represents a strategic partnership between FAO and IAEA, mobilizing the resources of both organizations to promote the application of nuclear science and technology for supporting the sustainable agriculture and secure food production.

In 1995 the Joint FAO/IAEA Division launched its first coordinated research project (CRP) on the 'Assessment of soil erosion through the use of ^{137}Cs and related techniques as a basis for soil conservation, sustainable production, and environmental protection (D1.50.05)'. Later activities aimed at FRN methods continued with several other CRPs ('Conservation Measures for Sustainable Watershed Management Using Fallout Radionuclides, D1.50.08'; 'Integrated Isotopic Approaches for an Area-wide Precision Conservation to Control the Impacts of Agricultural Practices on Land Degradation and Soil Erosion, D1.20.11'; and, recently, 'Nuclear Techniques for a Better Understanding of the Impact of Climate Change on Soil Erosion in Upland Agro-ecosystems, D1.50.17'). The Joint FAO/IAEA Division through the Soil and Water Management and Crop Nutrition (SWMCN) Subprogramme can be considered as the leading international institution in working and developing the ^{137}Cs method. The use of ^{137}Cs for the assessment of erosion is becoming well-established. It is widely used for erosion studies to provide key information on sheet and rill erosion rates and soil/sediment dynamics and redistribution. This work is supported by the international research community. The ^{137}Cs method was described several times in detail in several handbooks (Walling and Quine, 1993; Zapata, 2002; Mabit *et al.*, 2014), the last two being based on the results of the mentioned CRPs.

Later investigations identified few other radionuclides for soil erosion assessment. Lead-210 (^{210}Pb) (Walling and He, 1999) and beryllium-7 (^{7}Be) (Walling *et al.,* 2000) brought good results, and more recently innovative studies testing plutonium-239+240

($^{239+240}$Pu) were published (Alewell *et al.,* 2014). All these radionuclides are commonly termed as *fallout radionuclides (FRNs)* as they are fallen on land from the atmosphere. After the initial deposition FRNs provide a baseline to assess the soil redistribution – soil erosion, transport and deposition – in natural as well as managed (or cultivated) landscapes.

The further development of the ^{137}Cs method requires more widespread dissemination of knowledge to scientists and students specialised in soil erosion research as well as to wider audience of specialists e.g. agricultural decision makers and farmers. For this purpose, there is a demand for a short document that can explain the principles of the method clearly and briefly and to provide ideas about its applications for various research objectives. This publication attempts to provide the readers with this information. Additionally, it allows FAO Member Countries and IAEA Member States to benefit from the use of ^{137}Cs method for sustainable land management and soil conservation.

2 Purpose and methods measuring soil erosion

2.1 Soil erosion as landscape process

Landscape processes of air, water, rocks, soil, nutrients, pollutants and living organism redistribution and transformation are the results of complex interaction of a variety of individual processes from very dynamic processes such as air and water circulation, through medium-term processes, for example the seasonal dynamics of vegetation, up to long-lasting processes such as tectonic movement and rock weathering. The study of the magnitudes, spatial and temporal distribution of these processes is one of the basic objectives of Earth System Sciences.

Soil erosion is one of most common and most important group of landscape processes with an on-site and off-site impact. It is closely connected with the water cycle and the circulation of soluble basic nutrients, trace elements and pollutants. Several particular erosion processes participate in soil redistribution. Most important among them are water erosion (sheet, rill and gully) and wind erosion (Figure 2.1).

Figure 2.1. Examples of the main erosion processes: sheet, rill, gully and wind erosion.

Erosion processes show a wide geographical distribution (Figure 2.2) and affect large portion of land especially cultivated land and pastures occurring in arid and semi-arid areas. Erosion affects more land than all other degradation processes together. While most of the latter (e.g. contamination, compaction, salinization, etc.) result in deterioration of some soil properties, soil erosion result in complete removal of the whole upper, often most fertile soil layer and redistributes it down-slope in landscapes as sediments. Therefore the programmes for development of sustainable land use for agriculture and forestry have great importance for securing the overall development of society, sustainable land exploitation and food security.

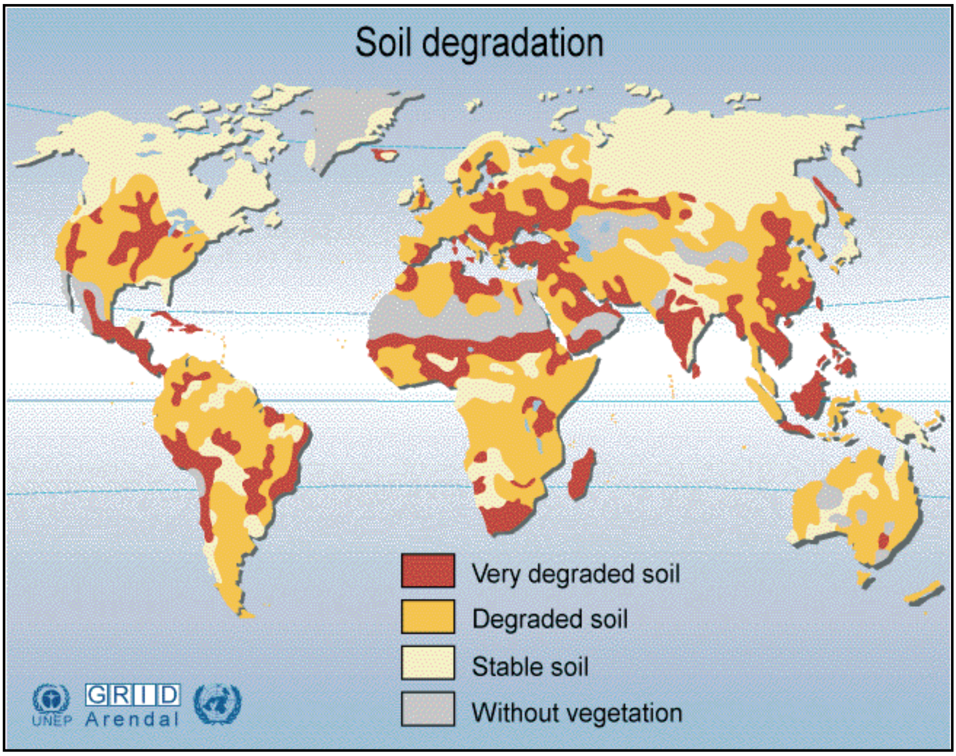

Figure 2.2. Geographical distribution of land degradation (UNEP, 1997).

The most basic task for erosion research is to assess soil redistribution rates, their spatial distribution, and temporal dynamics. These data are serving as primary information for all further investigations of erosion, its mechanisms, modelling of scenarios, predictions, and any other applied activities aimed at soil conservation.

There are five major thematic groups requiring quantitative data on soil erosion and sedimentation rates:

- Basic research (understanding of the mechanism of erosion processes);
- Identification of critical areas for land conservation;
- Testing of the efficiency of soil conservation measures;
- Deriving the input parameters for models; and
- Model calibration, validation and implementation for decision-making.

2.2 Soil erosion measurement methods

The measurements of soil redistribution is not an easy task because soil erosion is caused by several agents (mainly water, wind, animals and human), which can interact and are responsible for a wide range of processes running at different temporal and spatial scales. Water erosion such as *splash, sheet (interrill), rill, gully and lateral fluvial erosion* (e.g. *river bank erosion*) are stages of erosion caused by surface runoff from smaller to larger runoff volumes (Renschler and Harbor, 2002). Transport of sediments in water (and also wind) occurs as: *creep, saltation* and *suspension* (Figure 2.3).

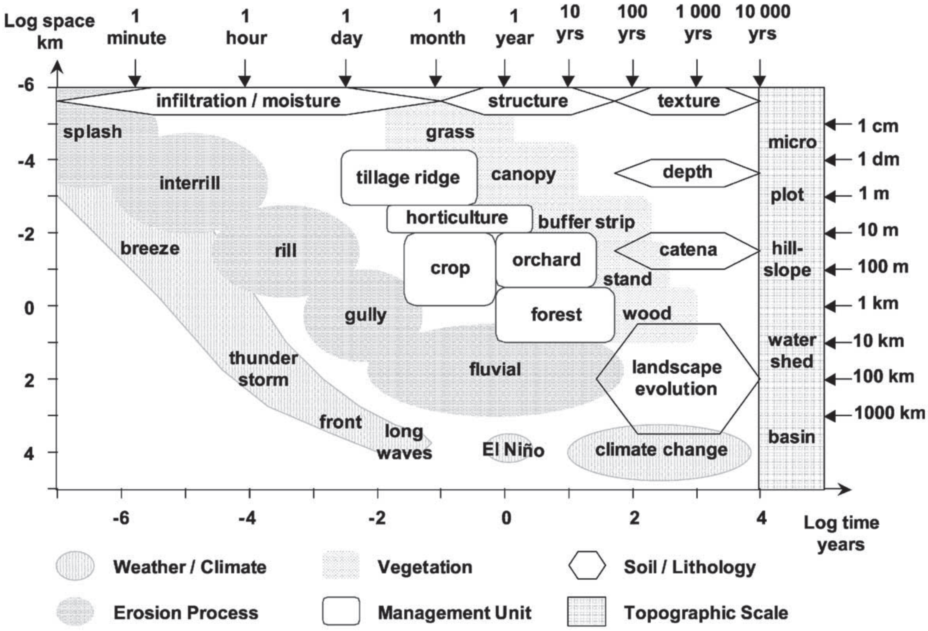

Figure 2.3. Time and space extent of atmospheric, topographic, soil and vegetation phenomenon important for dominant soil erosion processes. The management units indicate extent of human interest and impact (Renschler and Harbor, 2002).

Most important processes affecting cultivated land are sheet and rill erosion. In grassland, important impacts may have rill and gully erosion and in arid areas rill and gully erosion often combines with wind erosion.

Different erosion processes not only result in formation of different erosion features, but require also various approaches of measurement (Lal *et al.*, 1994). For this reason various approaches of erosion measurements were developed.

The most common are the following methods:

- Volumetric methods: the volume of rills and gullies is measured either by simple instruments (measuring tape, frame with profile pins) or by scanners;

- Erosion plots: a small part of slope is fenced to form separated rectangular plot, protected from runoff generated in surroundings (Figure 2.4). At the lowest end of the plot, the runoff generated within the plot and the transported sediment is trapped by furrow and derived to some of following collecting or recording devices:
    - The tank collecting and storing the whole volume of water and sediment (total collection method);
    - The device splitting runoff and sediment to several equal parts (multi-slot divisor) among which only one is further collected (thus only a small fraction of the runoff and sediment is collected and stored in order to save space and labour for sediment processing);
    - The dynamic devices (filled and emptied) measuring the discharge and sediment concentration (tipping buckets, Coshocton wheels);


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Figure 2.4. Example of erosion plots with total collection of sediment (Osikov, Slovakia).

- Hydrological methods: the sediment transported by watercourses can be either floating in the water (in suspension) or rolling on the river bed (as bed load). For each of these two groups of sediments, different methods are needed as they are controlled by different movement principles:
    - The determination of suspended sediment load is based on measurements of water discharges and concentration of suspended sediments. The discharge ($\mathrm{l\ s^{-1}}$ in small water courses and $\mathrm{m^{-3}\ s^{-1}}$ in rivers) is measured using the standard hydrological approach measuring the mean flow velocity in known hydrological profile, which are either the selected profiles in natural beds (in rivers), or artificial built up hydrological profiles such as sheet-iron Parshall flumes (Figure 2.5) used for very small linear

flows and stony or concrete hydrological profiles built in river beds of small water courses. The suspended sediment load (expressed as concentration of insoluble suspended soil material in $g\ l^{-1}$) is determined in water samples collected periodically using either hand sampling or automatic samplers.

- The bed load is measured with the aid of various mechanical bed load traps or bed load samplers.


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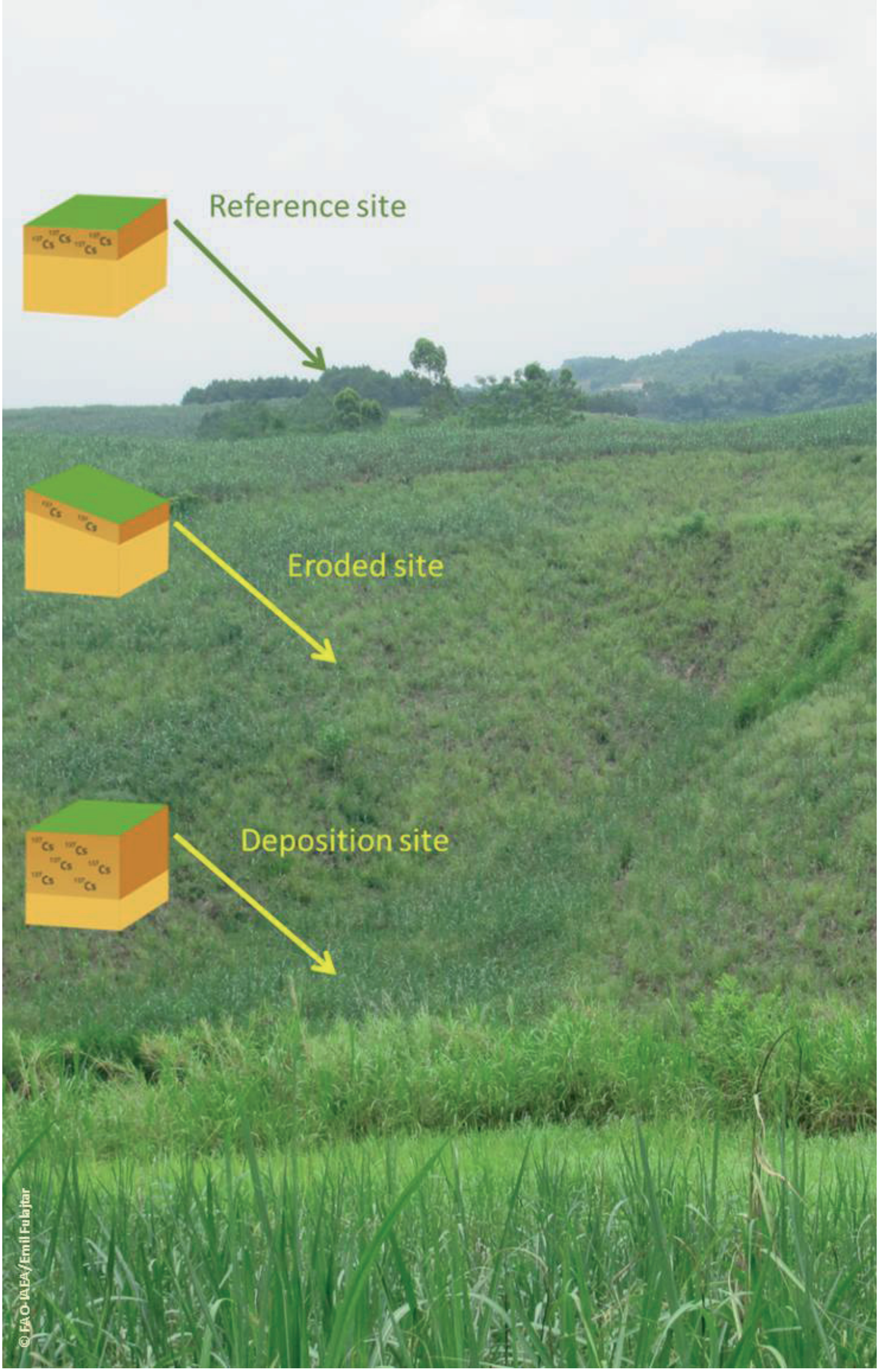
Figure 2.5. Example of Parshall flume used for measurements of suspended sediment (Lukacovce, Slovakia).

As soil erosion is a complex phenomenon to investigate, each assessment or measurement method has its conceptual and technical advantages and limitations and provides a different picture of the erosion rates. Different methods are mutually complementary and their combination improves the overall understanding of erosion. The selection of a particular method or their eventual combination should reflect the purpose of the study. The specific advantages and disadvantages of the ^{137}Cs method in comparison to conventional methods will be discussed in Chapter 9.



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3 Principles of ^{137}Cs method

3.1 Origin and basic characteristics of ^{137}Cs

Caesium (Cs) is the heaviest alkali metal (atomic number of 133), that occurs in nature. Alkali metals are known as the most electropositive elements of periodic table and are therefore very reactive. Caesium is rare component of rocks and does not have an important role in soil and life processes. When occurring in soil, it is presented mostly as positively charged cations bounded to mostly negatively charged clay minerals and organic matter (soil colloids).

The natural stable isotope of Cs is ^{133}Cs. Through human processes a whole range of artificial radioactive isotopes (with atomic mass varying from 125 to 145) can be created. The most important are ^{134}Cs (half-life of $t_{1/2}$=2.06 years) and ^{137}Cs ($t_{1/2}$=30.17 years). The ^{134}Cs resulted from past fallout from nuclear weapon tests and nuclear power plant (NPP) accidents such as Chernobyl and Fukushima-Daiichi. Because of its short half-life the ^{134}Cs isotope is not relevant for soil erosion assessment.

The ^{137}Cs was formed during nuclear bomb tests as well as NPP accidents as a product of Uranium decay. It further decays resulting in the formation of ^{137}Ba that is a final product of this decay chain. The decaying ^{137}Cs emits gamma-rays of high energy (662.66 Kev). Because of its relatively long half-life (30.17 years), the ^{137}Cs is an optimal erosion tracer. This is an important advantage of ^{137}Cs as compared to many other environmental radionuclides. Its measurement in environmental samples using gamma spectroscopy is relatively easy and accurate without the need of special chemical separation (Ritchie and McHenry, 1990).

In summary, the main sources of the ^{137}Cs present in the environment were the atmospheric nuclear weapon tests (*bomb-derived* ^{137}*Cs*, or *bomb* ^{137}*Cs*) and NPP accidents among which the most important was Chernobyl accident; therefore the term *Chernobyl* ^{137}*Cs* is used (Carter and Moghissi, 1977; Wise, 1980) (Figure 3.1). In 2011, another release of ^{137}Cs was caused by the Fukushima Daiichi NPP accident, but this ^{137}Cs fallout affected mostly Japan and Pacific Ocean and does not have significant importance for erosion studies around the world (Miller, 2014).

3.2 Spatial and temporal distribution of ^{137}Cs fallout

In contrast to the NPP-derived ^{137}Cs injected into the fast, dynamic weather processes of the troposphere, a larger portion of the bomb-derived ^{137}Cs got into the more stable stratosphere and therefore circulated around the Earth before gradually falling to the Earth's surface. The latter fallout was associated primarily with precipitation (wet fallout) and the dry fallout was important only locally, around the nuclear test sites (Ritchie and McHenry, 1990).

The spatial distribution of the bomb-derived ^{137}Cs fallout was determined by a combination of a) the location of the nuclear weapons test sites, b) the air circulation and c) the rainfall distribution pattern. Because most of the weapon tests were carried out in the Northern Hemisphere and the air exchange between the Northern and Southern hemisphere is limited, the soil contamination by bomb-derived ^{137}Cs is considerably higher in the Northern Hemisphere. In each hemisphere, the distribution follows a latitudinal zoning corresponding to the rainfall zones (Sutherland and de Jong, 1990; Davis, 1963; Bernard *et al.,* 1998).

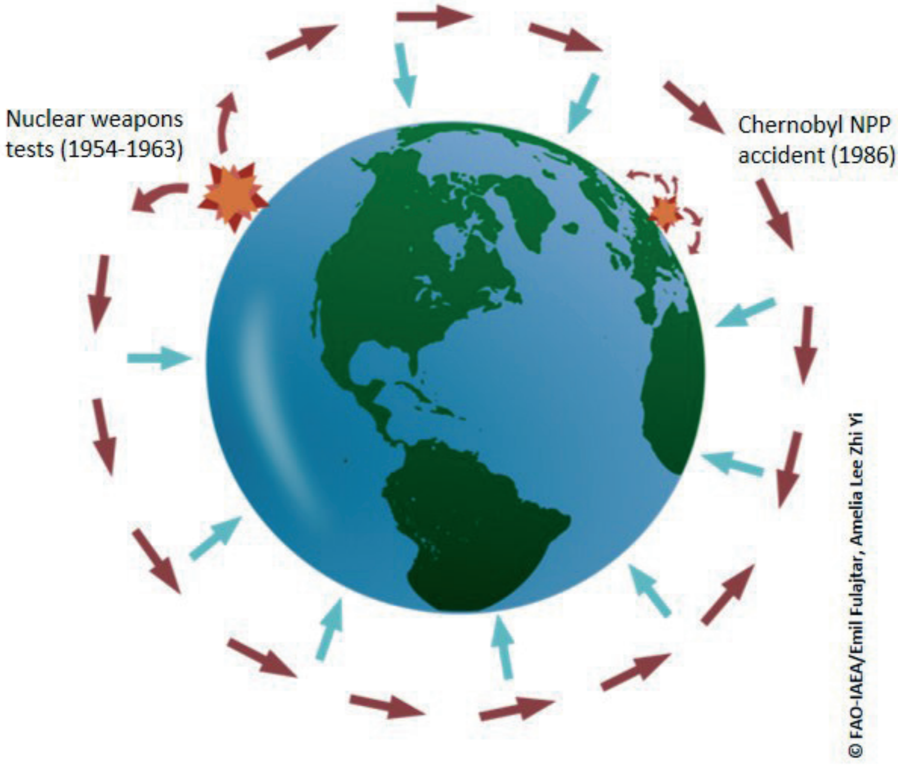


Figure 3.1. Origin of ^{137}Cs in the environment.

The global pattern of bomb-derived ^{137}Cs fallout indicates that inputs ranged from about 160 to about 3 200 Bq m^{-2} depending on latitude (Garcia Agudo, 1998). In the Southern Hemisphere the values range up to a few hundreds, while in the Northern Hemisphere they reach from 1 000 to more than 3 000 Bq m^{-2}. These values are sufficiently high for gamma spectroscopy measurements; therefore, the ^{137}Cs method can be used all over the globe. The ^{137}Cs inventories in the Southern Hemisphere are usually sufficient to be measurable if using appropriate detectors and counting times. However, with time they are gradually reduced by the radioactive decay. In future, the use of the ^{137}Cs method in Southern Hemisphere will become more and more difficult. In the last years, the alternative use of $^{239+240}$Pu as erosion tracer was successfully tested (Alewell *et al.,* 2014). This new soil tracer will become promising soil loss evaluation technique in the ever-decreasing ^{137}Cs activity areas.

An important parameter used for the calculation of soil redistribution rates is the temporal dynamic of the ^{137}Cs fallout. Although the first nuclear weapon tests were done already in 1945, the worldwide detectable ^{137}Cs fallout began in 1954 and the highest fallout record occurred in 1963. During the second half of the 1960s, the fallout intensity decreased abruptly. Then during the 1970s, a slow decreasing continued and during the first half of the 1980s, the fallout decreased to below detection limit.

The *Chernobyl ^{137}Cs* released during the NPP accident in 1986 was injected only into troposphere and it further spread over Russia and Europe in much lower height than the bomb-derived ^{137}Cs. It did not persist in atmosphere as long as the bomb-derived ^{137}Cs but it fell out within a few months. The distribution of *Chernobyl ^{137}Cs* is very heterogeneous as its fallout was determined by the rainfall distribution from the end of April-to May 1986. This irregular fallout makes the erosion assessment in Chernobyl affected areas more difficult. The *Chernobyl ^{137}Cs* fallout increased the existing bomb-derived inventories by several orders of magnitude in some European areas (WHO, 1986; Anspaugh *et al.,* 1988; Cambray *et al.,* 1987, 1988; Mabit *et al.,* 1999). For example in Central Russia the ^{137}Cs inventories after the Chernobyl accident reached 500 000 Bq m^{-2} (Golosov *et al.,* 1999). Another example of local ^{137}Cs fallout from NPP accident happened during Fukushima-Daiichi NPP accident in 2011 (*Fukushima-Daiichi ^{137}Cs*).

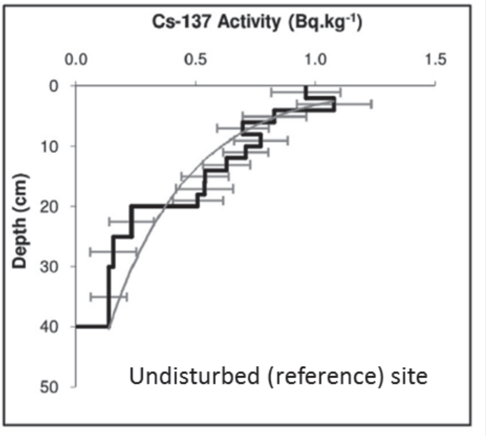
3.3 ^{137}Cs behaviour in soil

The early investigations of radionuclide occurrence and transformation in landscape, carried out in the 1960s and 1970s, were focused on their environmental impacts. A number of human-made radionuclides were investigated, ^{137}Cs being among them. It was found out that ^{137}Cs is strongly bound to soil colloids and is in principle non-exchangeable (Davis, 1963; Lomenick and Tamura, 1965; Eyman and Kevern, 1975; Ritchie and McHenry, 1990) and its uptake by plants is negligible (Dahlman *et al.,* 1975). The ^{137}Cs, if absorbed by the vegetation, is released to soil after plants die and decay (Davis, 1963; Rogowski and Tamura, 1970 a,b; Dahlman *et al.,* 1975). A lot of attention was paid to the investigation of the ^{137}Cs vertical distribution (see typical examples in Figure 3.2).

The investigation of land undisturbed by cultivation showed that the most ^{137}Cs occurs in the uppermost layer of soil and its content exponentially decreases with the soil depth. Many researchers reported such ^{137}Cs distribution profiles that are similar to those shown in the Figure 3.2 (Walling and He, 1993; Walling *et al.,* 1999).

As ^{137}Cs is non-exchangeable, it is not released into soil solution and cannot significantly migrate or take part in the chemical processes running in soil. However, some limited depth redistribution reaching usually 10 to 20 cm results from bioturbation carried by burrowing animals such as earthworms drilling up and down along the soil profile. This causes the slight diffusion of ^{137}Cs to soil layer immediately below the soil surface. Apart from that, some other physical-chemical processes such as freezing-thawing or wetting-drying of soils can contribute to dynamics in vertical diffusion of ^{137}Cs.

On cultivated land, the redistribution of ^{137}Cs is primarily the result of mechanical mixing associated with cultivation (e.g. tillage erosion). The ^{137}Cs is homogenously distributed over the whole depth of plough horizon and below that an abrupt decrease of ^{137}Cs content appears (compare with Figure 3.2).



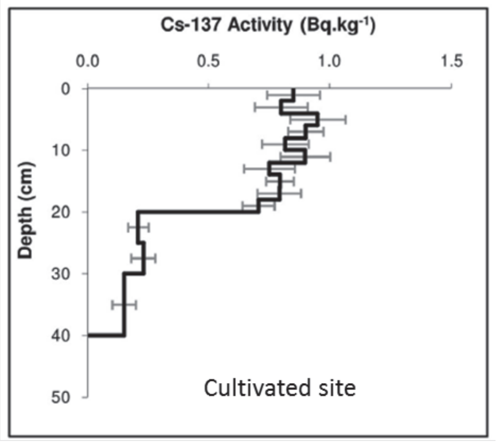


Figure 3.2. Typical vertical distribution of ^{137}Cs in soil profile of undisturbed and cultivated sites (Rabesiranana *et. al.*, 2016).

3.4 General principles of ^{137}Cs method used for soil erosion and sedimentation assessment

Except in some very acid sandy soils, the relative immobility of ^{137}Cs in agricultural soils under usual environmental conditions is the basic condition enabling its use as a soil erosion tracer. The ^{137}Cs method is based on following key assumption about ^{137}Cs baseline deposition and redistribution:

- The ^{137}Cs after (mainly wet) fallout from atmosphere is homogenously distributed over the landscape and is strongly bound to soil colloids in the uppermost soil layer (Figure 3.3);
- It is not significantly leached by water;
- It does not migrate as a result of chemical processes;
- Its uptake by plants is negligible; and
- It moves only as a result of mechanical processes mobilizing soil particles to which it is bound.

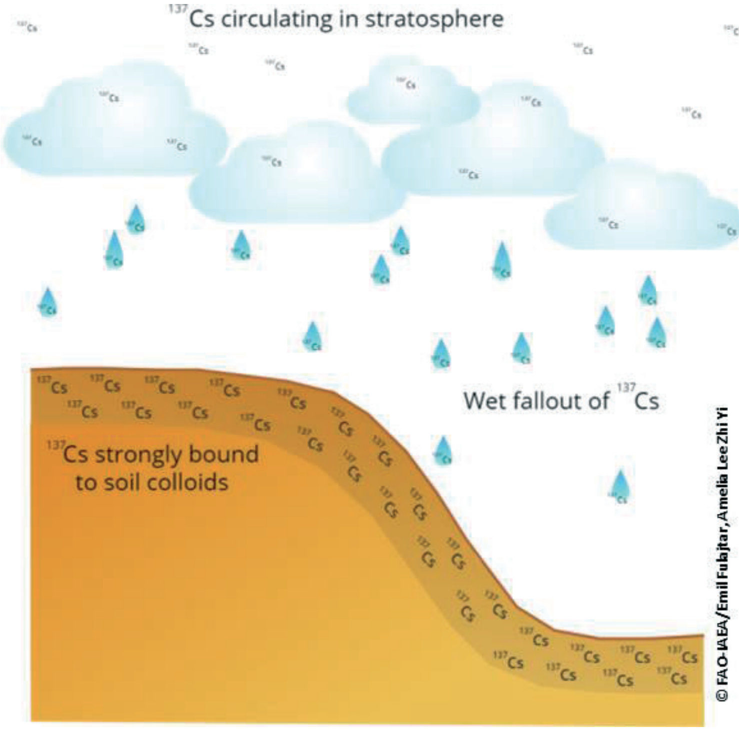


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Figure 3.3. Homogenous distribution of the fallen ^{137}Cs in area not affected by soil erosion.

Several mechanical processes of soil redistribution occur in landscape such as bioturbation, erosion, geomorphological processes, or human activities (tillage, digging, mining, construction, etc.). In most landscapes apart from urban areas, erosion is by far the most important among these mechanical processes. The ^{137}Cs method can provide an assessment of all major erosion processes caused by most common erosion agents such as water, wind and tillage. Most of these processes (splash erosion by raindrops, interrill/sheet erosion through surface water flow, rill erosion by linear runoff, all processes of wind erosion and tillage erosion) contribute to ^{137}Cs redistribution and are represented by erosion rates estimated by the ^{137}Cs method. The most advanced processes of linear water erosion, which transport largest volumes of soil and rock material (gully erosion, and fluvial/lateral river bank erosion) can be assessed indirectly by more complex methods, e.g. sediment fingerprinting using ^{137}Cs together with several other parameters (Walling, 2003).

The principle of the soil erosion assessment is based on the comparison of soil ^{137}Cs content at landscape positions affected by the soil redistribution dynamics (erosion, transport and sedimentation) to relatively stable landscape position which is not affected by such soil redistribution processes. Provided that ^{137}Cs can be moved only together with soil particles, then soil enrichment or depletion of ^{137}Cs at some landscape positions corresponds to removal or input of soil material from the surroundings (Figure 3.4). To assess how much of ^{137}Cs was lost or gained, information on the original ^{137}Cs input is needed.

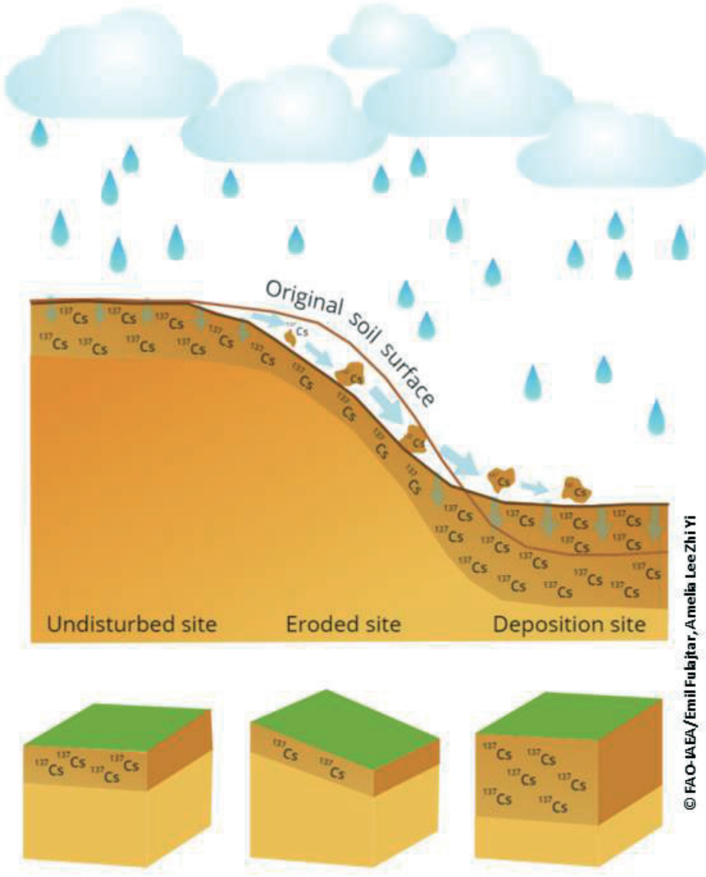

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Figure 3.4. Scheme of the ^{137}Cs and soil redistribution by erosion: undisturbed, eroded and deposition site.

To obtain such information a concept of *reference site* was introduced. A reference site is a stable *undisturbed area* where neither erosion, nor accumulation took place so it represents the initial ^{137}Cs fallout input (only reduced by radioactive decay). These stable locations are selected at flat surfaces where water runoff and associated soil erosion cannot originate. Most suitable are somewhat elevated landscape positions such as terraces or denudation plateaus. The lowest landscape positions such as alluvial plains are not suitable because they may be affected by deposition. At some alluvial plains the recent evidences of inundation may be lacking but it is not sure if and when it might occur in the past. Therefore if there is no other choice than to select the reference site at alluvial plain the reliable information on the history of flood is of highest importance.

The ^{137}Cs inventories at study sites where soil redistribution is expected are compared to that of the stable reference site. The landscape positions where the ^{137}Cs inventories are smaller than at the reference site are interpreted as eroded and those positions where they are greater are interpreted as deposition sinks. Those with ^{137}Cs inventories similar to reference site are either stable have a long-term balanced equilibrium of erosion and deposition.

An example of ^{137}Cs redistribution (at cultivated land) along the slope transect (comprising of stable site, erosion site and deposition site) is provided at Figure 3.5. The transect profiles indicate the reduction of ^{137}Cs content at the slope (as compared to stable profile at the plateau) and increase of ^{137}Cs content in valley bottom. The soil erosion and deposition rates can be calculated by conversion models which express the relation between the ^{137}Cs redistribution and soil redistribution (see Chapter 6).

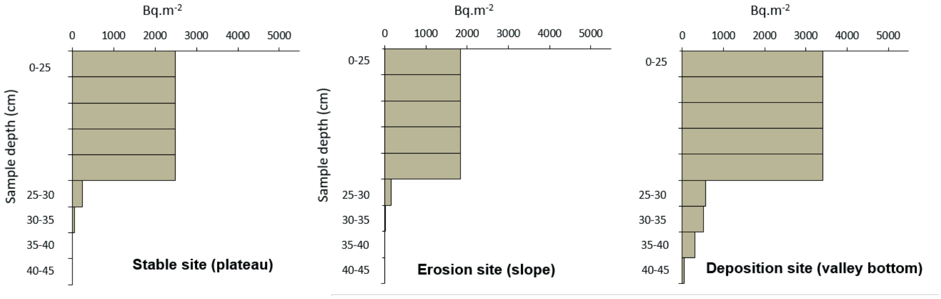

Figure 3.5. Example of the ^{137}Cs redistribution (at cultivated land) along the slope transect, Bohunice site, Slovakia (Fulajtar, 2000).

The detailed description of the ^{137}Cs method for the assessment of soil redistribution is provided by several guidebooks (Walling and Quine, 1993; Zapata *et al.*, 2002; IAEA, 2014). More information and discussion on the advantages and limitations of the ^{137}Cs method is provided by Mabit *et al.* (2013). A comprehensive bibliography on the use of the ^{137}Cs method for various purposes was prepared by Ritchie and Ritchie (2008). A simple video demonstrating the principles of the ^{137}Cs method (*Fallout Radionuclides in Soil Erosion*) was recently developed by the Joint FAO/IAEA Division and is available at http://www-naweb.iaea.org/nafa/resources-nafa/Soil-Erosion-web.mp4.

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4 Site selection and sampling strategy

4.1 Purposes of ^{137}Cs sampling

The sampling design is a critical step for the successful implementation of the ^{137}Cs method in soil erosion and sedimentation studies. The sampling strategy mainly depends on the *study objectives*, the *geographical focus* of the studied area and the heterogeneity of the relief, soilscape and land use.

According to *study objectives*, three types of studies can be recognised (Zapata *et al.*, 2002):

- Descriptive studies identify only basic characteristics of the site such as values of ^{137}Cs activity and basic statistical parameters of datasets, while the spatial aspect is not reflected;
- Analytical studies comparing two data sets or two studied sites; and
- Spatial distribution studies aimed on mapping of spatial distribution of erosion and sedimentation and calculating spatially related statistical parameters (gross and net erosion and deposition rates).

According to the *geographical focus*, these four types of soil redistribution studies can be recognised:

- Plot, field or hillslope studies;
- Floodplain studies;
- Catchment (or watershed) studies; and
- Reservoir sedimentation studies.

The most studies are aimed at mapping of erosion redistribution at field (or hillslope) scale. In order to evaluate a sediment hillslope budget, they include a reference site with nearly no erosion, a sediment source area (erosion > deposition), a transport area (erosion = deposition) and a sink area (erosion < deposition).

The investigations of reference sites can be classified as descriptive studies. In this chapter only sampling strategies for reference site and soil redistribution at field scale will be presented and discussed.

4.2 Study site selection, scale and data collection

For each intended study, a main objective must be formulated. Before selecting the study site, it should be investigated whether the erosion is active there. Erosion phenomena (for example rills and gullies, sink depressions, soil particles sorted by sheet runoff, etc.) can be observed and the farmers, municipal representatives or other local stakeholders familiar with the area should be interviewed. It is useful to select an area where the basic climate data are accessible, some soil survey has already been performed, the topographical data for DTM are available and land use history is known. The selected study site should not be too large to limit the heterogeneity and complexity of processes. Its size should correspond to research budget and staff number availability to ensure appropriate sample density. Later the study area can be extended.

The collection of environmental and management data should be done like for any other field pedological study (such as soil survey, land management or crop nutrition field experiments, etc.). Available pedological literature (including unpublished manuscripts and grey literature) related to the area of interest should be investigated. Interviewing of land managers or stakeholders (e.g. landowners or agricultural and municipal employees) in the area about current and historic extreme weather events and land management practices is highly recommended. They can provide key information on land use/cover changes, land management, climate, unusual weather events, erosion features, landslides, etc. The data collection should be dedicated at those pedological, climatic, land use and socio-economic data that are related to erosion and sedimentation processes.

Reconnaissance survey of the selected study area should 1) verify and interpret the collected background information; 2) complement missing geographical, climate, soil and land use information; 3) assess to which extend the area was/is disturbed by human activities, and 4) identify potential reference sites. Especially the latter task is very important. If an appropriate reference site is not available nearby the study site, it should be considered to select other study site locations in area where the reference site would be available. Especially in areas affected by Chernobyl ^{137}Cs the reference and study sites should be very close to each other because the fallout heterogeneity of Chernobyl ^{137}Cs is much higher than that of bomb ^{137}Cs.

4.3 Selection of undisturbed reference site

The reference site should be selected at flat surfaces where neither erosion nor sedimentation took place since the beginning of ^{137}Cs fallout in early 1950s. These sites should be preferentially at least slightly elevates (plateaus) as the low elevated areas (such as alluvial plains) could be affected by flood and sedimentation.

The reference site should be as close to the study site as possible. According to the original concept of the ^{137}Cs method the reference sites have to be selected in grassland (Zapata *et al.*, 2002; Mabit *et al.*, 2014). The grassland was understood as the most appropriate land use type as it is considered to be undisturbed and sufficiently homogenous.

In some areas no undisturbed land suitable for reference sampling is available. This happens usually in the following environments:

- Mountainous areas with sloping topography;
- Areas strongly affected by wind erosion including sand dune movements;
- Heavily managed or engineered landscapes such as urbanised, residential, industrial, mining or densely populated mixed use areas where most of land is disturbed by various human activities.

In such cases when reference site is not available the following approaches can be used:

- The reference value can be estimated using information on ^{137}Cs fallout. In some countries, the monitoring of radionuclide fallout has been recorded. In those countries where the data on fallout distribution are not available, the ^{137}Cs fallout can be estimated using the yearly precipitation amount and the latitude of the study site. Several equations directly relating ^{137}Cs atmospheric fallout to the average annual precipitation of study area have been developed in Canada, Europe and Australia (Bernard *et al.,* 1998; Basher, 2000);
- The initial fallout can be evaluated using the software package of Walling *et al.* (2002). The parameters needed are: longitude, latitude and the annual precipitation of the area under investigation. However, such estimation of fallout is not possible for countries affected by the Chernobyl or other NPP accident fallout as such fallout was very heterogeneous and did not depend on the long term global air circulation;
- Adopting the reference values from studies carried in surrounding or nearby areas with similar conditions.

If no information on initial ^{137}Cs input can be gained, the ^{137}Cs method cannot provide quantitative estimates of soil erosion rates but it can be used for relative or qualitative characterization of overall trends in soil distribution within a study area. An example of such study in mountainous area affected by Chernobyl fallout was provided by Froehlich *et al.* (1993).

4.4 Reference site data collection

When starting any soil sampling for ^{137}Cs determination, the thickness of ^{137}Cs contaminated layer should be determined to ensure that the whole ^{137}Cs inventory would be involved in the samples. This is achieved through depth incremental sampling. The depth incremental sampling enables also to assess the ^{137}Cs distribution profile.

According to this profile, it can be distinguished whether the soil was disturbed by human activities or affected by erosion and deposition. At the undisturbed land, the ^{137}Cs should be concentrated within the upper few centimetres of the soil profile and the decrease with soil depth should be exponential. At the cultivated site the ^{137}Cs activity is homogeneous throughout the whole thickness of ploughed horizon and below it the ^{137}Cs concentration drops abruptly.

When the depth distribution of ^{137}Cs is known, the bulk core samples can be taken. The depth of core samples should exceed the actual depth of ^{137}Cs contaminated layer by 10 cm (or at least 5 cm), to ensure that all ^{137}Cs is included in the sample. The reference site should be sampled along a regular grid. It is recommended that each sampling point should be represented by three replicate cores, which are bulked to constitute one sample for analysis. The number of samples depends on the variability of ^{137}Cs inventories at the reference site. It depends on random variability of soil properties such as soil bulk density, infiltration capacity, cracking and stoniness, the effects of vegetation cover and roots, etc. It is recommended that the variation coefficient of reference sample sets does not exceed 30 percent (Shutterland, 1996).

4.5 Sampling strategy at field scale

The sampling density depends on the study area, relief variability and the budget available. Three sampling design strategies can be adopted (Figure 4.1):

- Individual transect (A);
- Multiple transects (B); and
- Regular grid (C).

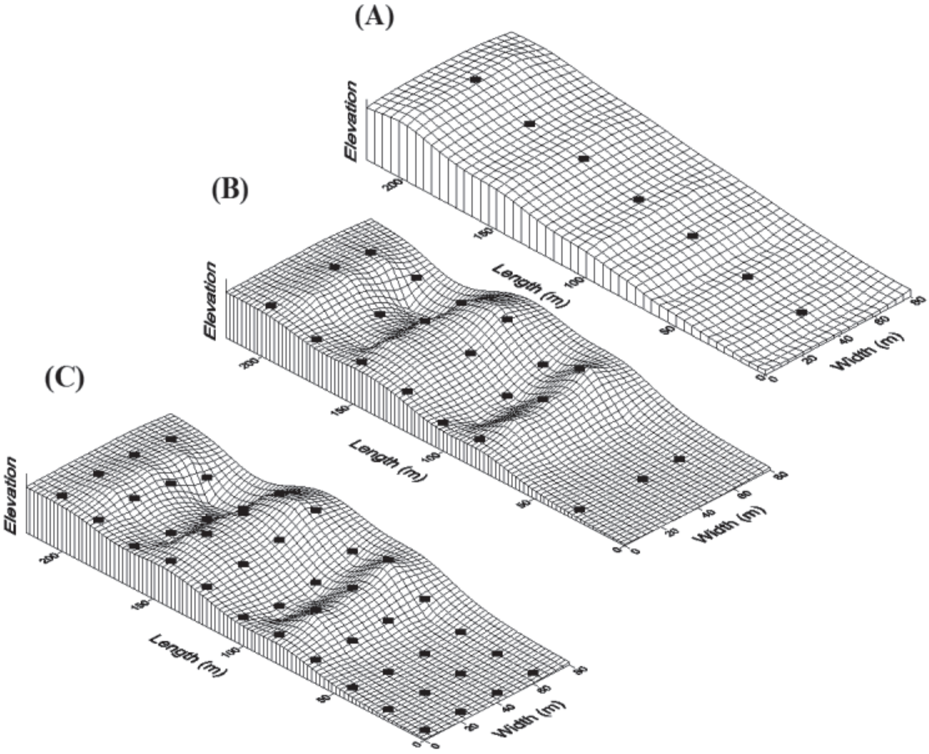

Figure 4.1. Basic sampling designs (Mabit *et al.*, 2014).

The individual transect approach is seldom used. It is useful for reconnaissance surveys or in other cases of preliminary investigations and other situations when more comprehensive sampling is not possible (for time or budget constraints, etc.). The multiple transect approach is based on the assumption that the variability of erosion and deposition processes is lower across the slopes than along the slopes. Therefore, the density of sampling points across the slope does not need to be as dense as along the slopes. This approach allows a more rational use of resources than the grid approach and is useful especially on steep, short and homogeneous slopes where no significant across-slope curvature exists. The number of samples along transect depends on the slope length and shape. The number of transects depends on the slope width, but generally at least three transects should be sampled. The grid approach is used when the topography is more complex (e.g. slopes with significant planar curvature).

More complex sampling designs (such as fan-like multiple transect design, composed designs involving both regular grids and multiple transects or regular grids with different densities) can be used if the relief or study objectives require a more complex picture on ^{137}Cs distribution.

4.6 Sample collection and sampling tools

Two methods are commonly used to collect soil samples:

- Bulk sampling;
- Depth incremental sampling.

Bulk samples can be collected by steel cylinder that is inserted to soil throughout the whole depth of ^{137}Cs contaminated layer. This depth should be investigated by depth incremental sampling that should be done prior to bulk sampling. The diameter of the tube is usually 7 to 10 cm (Wallbrink *et al.,* 2002) with a wall thickness of 5 mm adapted to investigate stony and compacted soil. To facilitate the core extrusion, the cutting edge of the tube should have a smaller internal diameter than the tube itself (Walling and Quine, 1993). The tube can be inserted manually by hammering or mechanically if using a motorized soil column cylinder auger set (Figure 4.2).

The depth incremental sampling helps to provide information on the ^{137}Cs depth distribution (vertical distribution over the soil profile). This is a key knowledge requested at the reference site and also at the study sites with uncultivated land as the conversion models for uncultivated land are based on ^{137}Cs depth distribution.

The depth incremental sampling requires special devices designed for this purpose, which are able to collect thin layers of soil (1, 2 or maximum 5 cm thick). The most common tool for depth incremental sampling is the *scraper plate* (Campbell *et al.,* 1988; Loughran *et al.,* 1992; Walling and Quine, 1993; Loughran *et al.,* 2002). It comprises a metal frame that is fixed on the soil surface and the metal plate which can move within the frame. The soil layers can be scraped successively by this metal plate. The plate can be shifted successively following the selected depth intervals.

More precisely the soil layers can be cut by the Fine Increment Soil Collector (FISC) developed by the SWMCN Laboratory (Mabit *et al.,* 2014). This device can cut thin layers within a few mm thick. If special sampling tools for incremental sampling are not available, the incremental samples can be obtained through slicing the bulk cores.

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Figure 4.2. Soil samples collection using a motorized soil column cylinder auger.

4.7 Collection of additional background information

The important part of the erosion investigation is to study and collect data on environmental or management processes that impact the erosion factors and therefore, erosion rates and spatial soil redistribution. Erosion is controlled especially by rainfall, soil properties, topography, and vegetation cover. At cultivated land the land management and human activities are other factors to be considered. The interpretation of the ^{137}Cs data and erosion rates calculated from ^{137}Cs inventories requires information on selected characteristics of erosion factors. Various approaches can be used to cover this item. The following minimal data set is recommended:

Topographical data:

- Geographical coordinates: latitude, longitude and altitude should be recorded by using Global Positioning Systems (GPS) or ideally by GPS-enabled sampling devices.
- GPS-indexed photographs of study and each sampling locations: the detailed photographical documentation is extremely valuable. It can help to illustrate the locations in addition to any quantitative data (Figure 4.3). It is recommended to make photographs of each location from various angles and if possible from an elevated viewpoint before and after sampling (use of flags). In addition the detailed photographs of each particular transect or sampling point is useful.
- Slope inclination: The field measurements of the inclination of each or multiple slope segments between particular sampling points within transect are required. Except of uniform slope segments, it is not sufficient to calculate the inclination from GPS data of variable slope segments as this approach may result in significant error (depending on the accuracy of the GPS used).
- Slope length: The field measurements of the distances between particular sampling points within transect are required. One may use distance measurement between sample locations and/or slope break points using measurement tapes or distance lasers. As for slope inclination, its calculation using slope distances and altitudes determined by GPS only is not recommended.

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Figure 4.3. GPS-referenced photo documentation of sample location.

Climate/Weather data:

- Precipitation: For erosive events the most detailed sequence of rainfall intensities per time period (year, month, day, hour, minute), event pluviographs (e.g. rainfall intensity graph recorded with a tipping bucket) or the total precipitation amounts per event duration are the most important data since rainfall intensities determine the amounts of soil being detached. Infiltration rates will determine surface runoff rates for erosion and transport. Standing water on soil will act as protection reducing the detachment of soil.
- Other climate parameters: Various parameters can be considered depending on the purpose of the study, use of models, etc. Maximum and minimum air temperature during an event will especially help to consider the effects of freezing and thawing of the precipitation and water in/on the soil. Together with dew point temperature and wind velocity the influence of evaporation and evapotranspiration would help to assess the antecedent soil moisture before a precipitation event. The solar radiation might also be helpful to determine the soil surface temperature as well as related parameters for vegetation growth.
- Station location(s) and measurement method(s): the spatial and temporal variability of weather data will assist to determine the variability of precipitation and weather events along a hillslope or with a catchment. In the latter case there might be multiple weather stations (Figure 4.4) available and interpolation methods for each climate parameter might be required (arithmetic mean, Thiessen polygons, isohyetal methodology).

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Figure 4.4. Weather station, Prague, Czech Republic.

Soil data:

- Soil classification: soil sample location and soil name with profile depth and description of each horizon will allow evaluating soil surface and subsurface properties and processes.
- Soil parameters for each horizon: colour, soil texture, organic matter, pH, carbonate content and rock content. Cation exchange capacity and soil albedo might also be recorded. Soil survey instructions can be found in soil survey manuals such as the US Soils Survey Manual (Soil Science Division Staff, 2017).

Land use and management data:

- Land use or cover: history or crop rotations or land uses since the ^{137}Cs fallout will enable to evaluate temporal variability of soil erosion processes impacted by the vegetation. Besides qualitative measures gathered through simple surveys, quantitative measurements through satellite, airborne or ground-based remote sensing such as leaf area indices (LAI) or biomass indicators such as the net primary production (NPP) can be very useful. Quantitative measures such as crop yields for a specific field or precision farming data of higher resolution crop yields when harvesting with GPS-crop yield monitors are useful to capture the vegetation response to indicate the main components of the local hydrologic water balance and soil redistribution processes.
- Land management: any data on crop rotation and land management practices that may have impact on infiltration and runoff as well as small scale surface roughness or micro depressions (e.g. furrow depth and width) are useful. Very important is the evaluation of tillage erosion that might have occurred over the years. Crop rotation sequences and changes in the crop rotation should be recorded if possible. Interviews with land managers and farmers especially about extreme events such as erosion or sedimentation events and their location are very useful. Remote sensing maps can contribute to reconstruction of land use history.

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5 Analysing ^{137}Cs data: gamma spectroscopy

5.1 Samples preparation

The gamma radiation emitted by environmental radionuclides occurring in soil is usually measured by laboratory gamma detectors (Figure 5.1) in soil samples which are collected in field and transported to laboratory. The sample preparation should involve the following steps (Walling and Quine, 1993; Pennock and Appleby, 2002):

- Air drying or oven drying at 60°C;
- Weighing;
- Grinding of large aggregates to pass through 2 mm mesh;
- Sample homogenization;
- Sieving the fine earth (0-2 mm);
- Weighing both fine and coarse fractions;

If the sample exceeds the quantity required for analysis, a representative sub-sample (e.g. 50 to 1 500 g depending on the counting geometry) of the fine fraction is submitted for analysis.

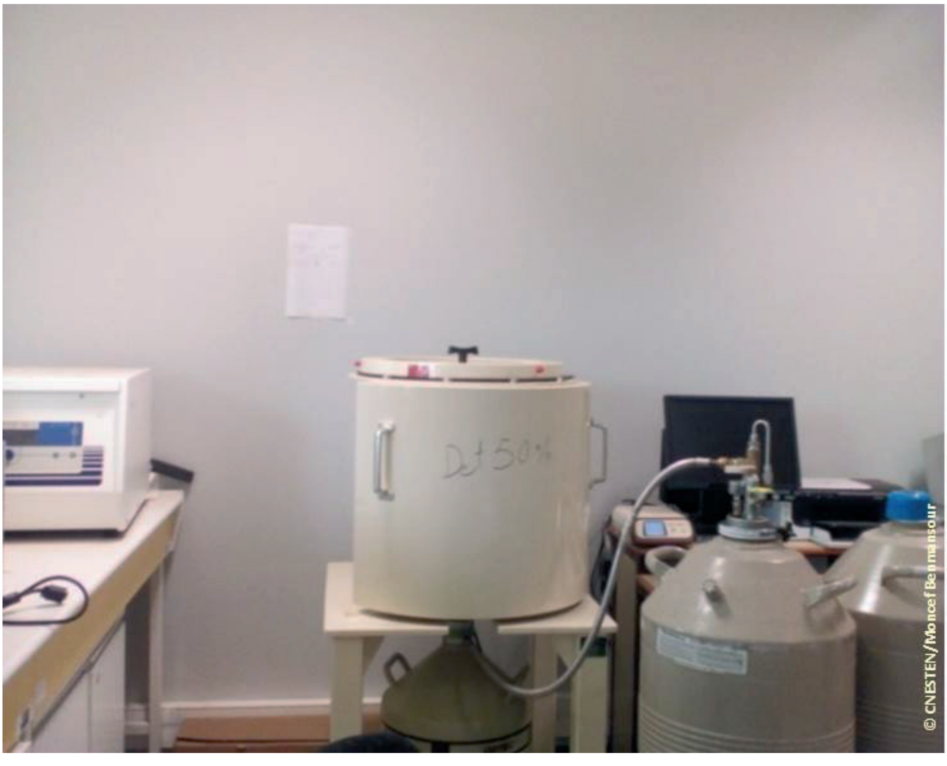

Figure 5.1. Laboratory gamma detector in lead shield and with nitrogen cooling (CNESTEN, Morocco).

However, it is possible to use also portable gamma detector (Figure 5.2), which can be carried to field and measure the in situ gamma radiation. The advantage of this approach is the acquiring of mean activity values representing large area. For assessment of soil redistribution processes it is better and more precise to interpret the soil samples measured in laboratory, but the portable detector can be used for reconnaissance surveys to check the overall range of activity levels. It is very helpful especially in Chernobyl affected areas where the ^{137}Cs inventories are very variable.

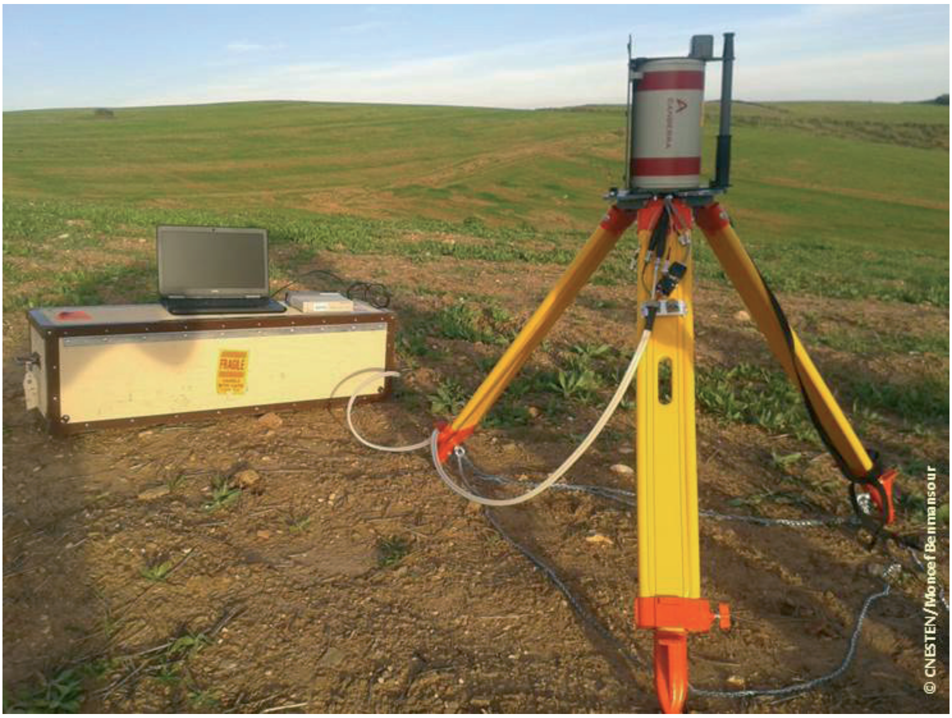

Figure 5.2. Portable gamma detector installed at selected study site (CNESTEN, Morocco).

5.2 Basic principles of gamma spectrometry

The ^{137}Cs is one of the radionuclides easiest analysed by gamma spectroscopy. Its measurement is facilitated by its clear energy peak at relatively high energy (662.66 Kev) that does not interfere with other existing radionuclides. Therefore, ^{137}Cs can be measured by standard gamma detectors, which are not sensitive to low energies.

As such measurement is not destructive, the soil samples analysed by gamma spectrometry can then be used further to perform other analyses such as basic soil analyses (e.g. soil texture, pH, organic matter content).

The principle of gamma ray detection is based on the interaction of gamma rays with germanium crystal, which emits electric signals when being exposed to gamma rays. These signals are characteristics for particular radionuclides and are recognized by the analyser and presented as peaks at the screen of computer connected to analyser. Each radionuclide can have one or several characteristic peaks at certain energetic level. The ^{137}Cs is characterized by well identifiable peak at energy of 662 keV (Figure 5.3). The collected spectral data are converted into activity of gamma radiation expressed in Bq kg^{-1}. The radionuclide activity per weight unit (mass activity) is converted into inventory (activity per unit area) expressed in Bq m^{-2}.

The methodology of gamma radiation detection and the equipment used underwent significant development since the mid-20th century. Traditionally, gamma spectroscopic analytical set comprises of high purity germanium semiconductor detector (HPGe detector) equipped with amplifier and connected to a multichannel analyser (MCA) and computer with software for data assessment. The detectors operate at very low temperatures and need efficient cooling. Usually liquid nitrogen is used in these processes but electrical cooling system is also a viable option. They need also lead shielding because the radiation of environmental samples is very low and the background radiation in laboratory needs to be eliminated.

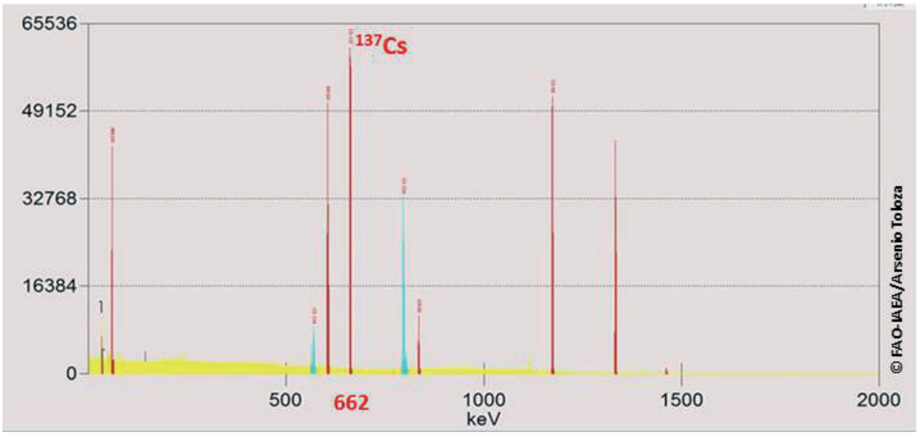

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Figure 5.3. Example of the main ^{137}Cs peak at 662 keV in gamma spectrum of soil sample.

Operating a gamma spectroscopic analytical set requires an experienced and skilled staff. The result of the measurement and its accuracy depends on several key factors such as the sample quantity and its activity, the counting time and the sample geometry. A gamma detector should be calibrated (using special multi gamma sources produced for this purpose) and the assessments of the measurement errors should be regularly checked (using specific reference materials).

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6 Conversion of ^{137}Cs data to soil loss values

The last key step of soil erosion and deposition assessment with the ^{137}Cs method is the conversion of ^{137}Cs data sets into soil erosion and deposition rates. Although the amount of eroded soil is directly proportional to ^{137}Cs activity redistribution, the quantitative mathematical expression of this relation is complex. The methodology underwent long development; several different approaches were tested and validated. They can be separated into two groups:

- Empirical models;
- Theoretical models.

The *empirical models* are based on calibration of ^{137}Cs activities with erosion rates measured at experimental plots. These are statistical models; therefore, they require the use of equations with parameters that fit the observations. The derived equations are site and time specific; they express the correlation between reduction of total ^{137}Cs inventory X (%) and soil loss Y (t ha^{-1} y^{-1}) and usually they have a form of exponential equations such as $Y=aX^{b}$ or $Y= a^{X}$ (with a, b as constants). These equations were developed in the early stage of the ^{137}Cs method development (Ritchie and McHenry, 1975; Elliot *et al.,* 1990; Loughran and Campbell, 1995).

The disadvantage of empirical relations was overcome by *theoretical models* that are based on the logical assumptions and algorithms for calculation of soil redistribution rates. Different theoretical assumptions are needed to express the conditions at undisturbed and at cultivated land. At undisturbed sites the ^{137}Cs is concentrated near the soil surface and it decreases exponentially with the depth. At cultivated land the ^{137}Cs is distributed homogeneously over the plough horizon and decreases abruptly immediately below the lower boundary of ploughed horizon (Figure 6.1). This difference requires different algorithms for soil loss calculation. Therefore, the models are usually grouped in two different groups:

- Models for undisturbed land;
- Models for cultivated land.

Several models were developed at Exeter University, UK (Walling and Quine, 1990; Walling and He, 1999) and they represent an integrated set that was worked out as user-friendly PC software (Figure 6.2). The software package (Excel add-in) can be downloaded from the website of the SWMCN Subprogramme http://www-naweb.iaea.org/nafa/swmn/models-tool-kits.html. The handling of this IT tool is very user-friendly. The dialogue window offers to select a particular model. The next steps are to fill the input data to predefined cells and finally it provides estimate of soil redistribution rates.

The calculation of soil erosion and deposition rates at undisturbed site is based on ^{137}Cs inventories and the ^{137}Cs depth distribution. Two approaches are used. The more simple approach considers the fixed ^{137}Cs fallout input and stable ^{137}Cs profile distribution. The depth distribution over the soil profile is mathematically described. If this distribution is characterized by simple mathematical function then the soil loss can be estimated by the proportion of the ^{137}Cs reference value removed at the examined site. This approach is used for the *Profile Distribution Model (PDM).* A more comprehensive approach takes into consideration time variant processes of: 1) the ^{137}Cs fallout and 2) the gradual post-depositional redistribution of ^{137}Cs within the soil profile, which is caused predominantly by bioturbation and several other processes. This approach is used by the *Diffusion and Migration Model (DMM).*

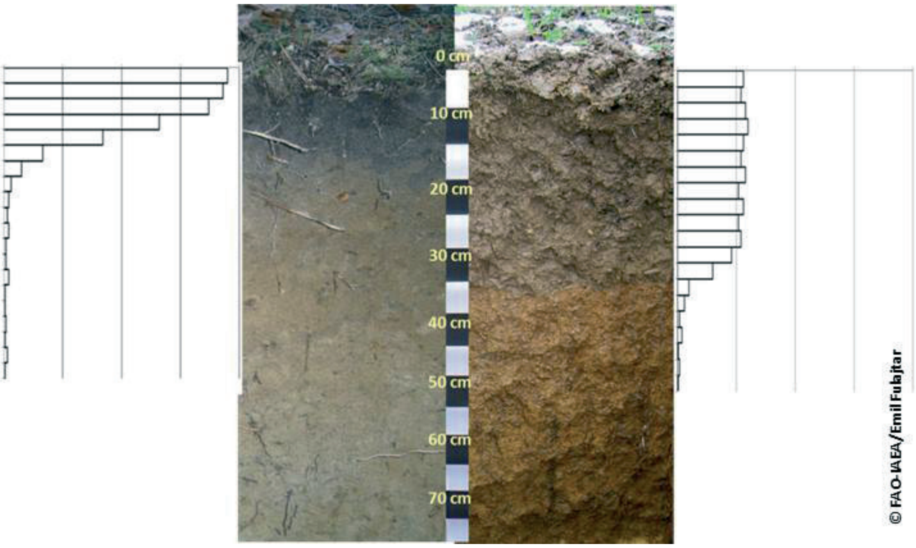


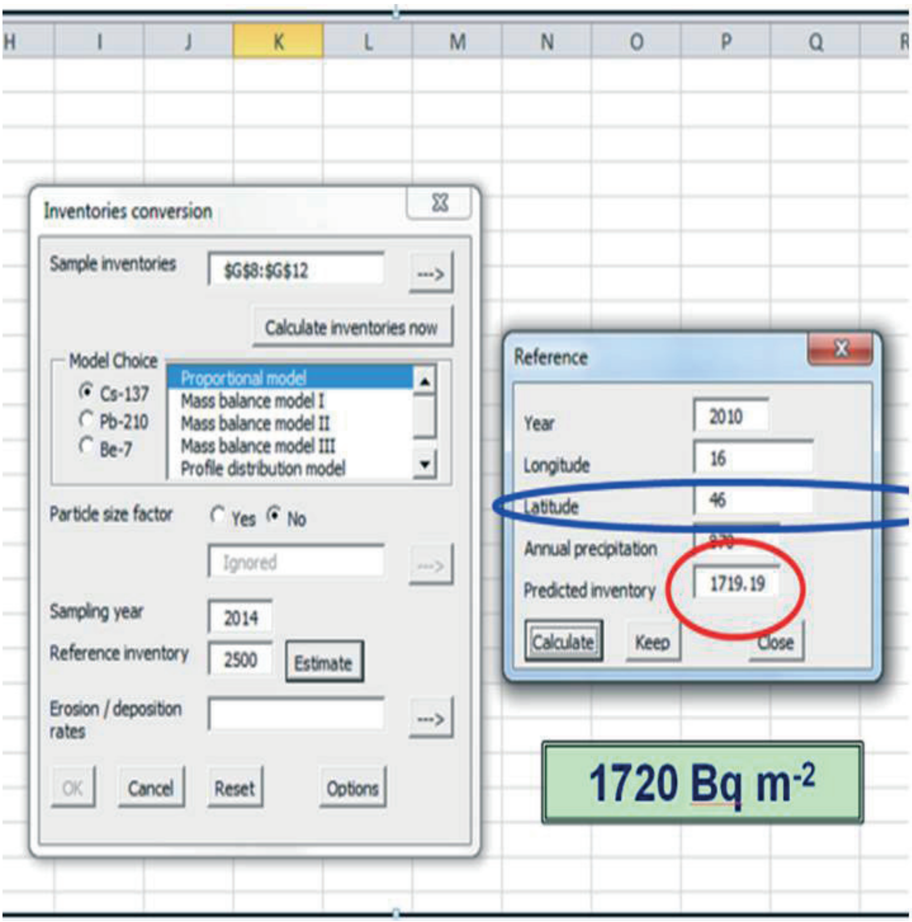
Figure 6.1. Exponential depth distribution of ^{137}Cs at undisturbed (left) and homogenous at cultivated (right) site requiring different concepts of conversion models.

The calculation of soil loss at cultivated land can be based on two theoretical concepts. The first one called proportional concept is very simple and it presumes that the removal of soil and ^{137}Cs are directly proportional. Model based on this concept is called the *Proportional Model (PM)*.

More complex approaches involve a mass balance concept, which considers the temporal dynamics of ^{137}Cs inputs and outputs resulting in the time-variant concentration of ^{137}Cs in soil. These changes in concentration affect considerably the relation between the ^{137}Cs loss and soil loss caused by erosion. The ^{137}Cs concentration in soil is controlled by several processes. Most important are 1) time variant ^{137}Cs fallout, 2) radioactive decay of ^{137}Cs (i.e. 30.17 years), 3) removal of freshly deposited ^{137}Cs by erosion prior to its incorporation into plough horizon by tillage, and 4) incorporation of subsoil material free of ^{137}Cs or having low ^{137}Cs content into eroded ploughed horizon by tillage.

The *Mass Balance Models (MBM)* were developed in mid-1980s. Different models use different approaches to handle the ^{137}Cs time-variant concentration in soil and consider some but not all processes and factors controlling it. More recently three mass balance models developed by Walling and He (1999) are used, e.g. *Mass Balance Model 1 (MBM1)*, *Mass Balance Model 2 (MBM2)* and *Mass Balance Model 3 (MBM3).*

More information on conversion models is provided by Walling and He (1999) and Mabit *et al.* (2014).



Inventories conversion

Sample inventories: $G$8:$G$12

Model Choice: ● Cs-137 ○ Pb-210 ○ Be-7

Proportional model

Particle size factor: ○ Yes ● No

Sampling year: 2014

Reference inventory: 2500

Erosion / deposition rates:

Reference

Year: 2010

Longitude: 16

Latitude: 46

Annual precipitation: [illegible]

Predicted inventory: 1719.19

1720 Bq m^{-2}

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Figure 6.2. Example of the use of ^{137}Cs conversion model software: assessment of the original ^{137}Cs fallout at a reference site.

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7 Data analysis, interpretation and presentation

7.1 Reference site

The validation of estimated initial ^{137}Cs fallout for an undisturbed reference site is a key requirement to get reliable values of soil redistribution rates for nearby sample sites affected by erosion or deposition.

The first criteria for reference site selection are flat topography and knowledge on land use/land cover history. The data interpretation at the reference site should be supported by descriptive statistics (average value, standard deviation, coefficient of variation) of the area ^{137}Cs inventories and by the ^{137}Cs depth distribution. Two features typical for distribution of ^{137}Cs at land undisturbed by post-depositional soil redistribution can help to validate the selection of the reference site and the representativeness of the obtained reference value: (1) the ^{137}Cs vertical depth distribution and (2) the horizontal spatial variability (the homogeneity of the initial ^{137}Cs fallout).

A valid selection of a reference site should fulfil at least these two conditions:

- The spatial variability of the ^{137}Cs fallout at the local scale (high and low values in a small area) should be as low as possible. It should be characterised by descriptive statistic as suggested by Sutherland (1991, 1996), Owens *et al.* (1996) and Mabit *et al.* (2012). A value of the coefficient of variation (CV) below 30 percent is a good indicator of a stable and undisturbed reference site. The number of soil samples needed to assess accurately the reference site (usually cca. 10 samples) depends on the variability and can be calculated considering the value of the CV.
- At reference site a clear exponential decrease of the ^{137}Cs activity with depth (around 80 to 90 percent of the ^{137}Cs included in the top 20 cm soil layer) is expected.

7.2 Presentation of the results of studies at field scale

At a studied field, the following ^{137}Cs information should be established:

- Inventories of ^{137}Cs (Bq m^{-2}) representing the total ^{137}Cs activity per area unit at the sampling points; and
- Depth distribution of ^{137}Cs along the vertical soil profiles (activity in Bq kg^{-1} per selected depth intervals in cm).

The inventories are calculated from the ^{137}Cs mass activity (see Chapter 5.2). Comparison between the inventories at the studied field and the reference site allows identifying the erosion and deposition zones. This ^{137}Cs spatial distribution permits to represent a soil erosion and sedimentation pattern. Its variability can be studied in relation to land use, soil proprieties and especially relief, e.g. the ^{137}Cs distribution along the slope transects (Figure 7.1).

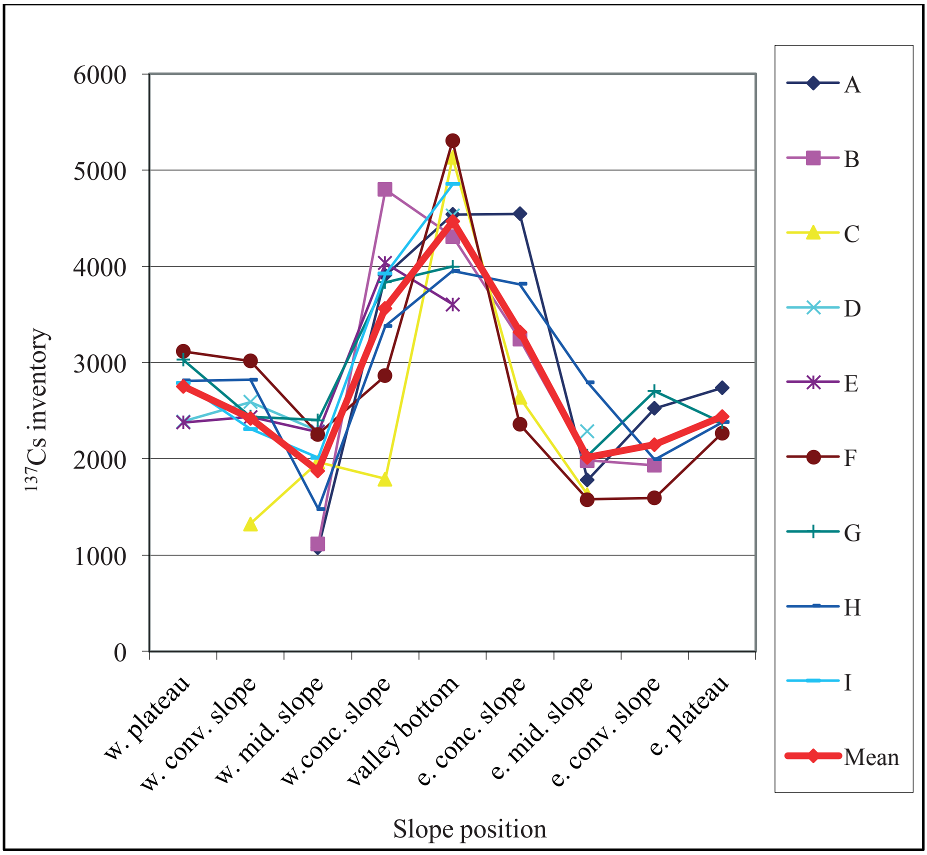

Figure 7.1. Example of the ^{137}Cs distribution along the slope transects (A-H) at Jaslovske Bohunice, Slovakia. The ^{137}Cs inventories are decreasing from plateaus to slopes and increasing in valley bottom where they reach their maximum values (Fulajtar, 2003).

The ^{137}Cs depth distribution profiles, associated with cultivated and/or uncultivated land, allow to see the profile shapes and to verify that they conform to the expected behaviour of ^{137}Cs in erosion and deposition areas.

Assuming an adequately representative sampling design, the ^{137}Cs inventory error depends mostly on the determination found by gamma spectrometry. Soil erosion or deposition rate for particular sampling point is quantified using conversion models to convert the ^{137}Cs inventories (Bq m^{-2}) to erosion or deposition rates (t ha^{-1} yr^{-1}), which were described in Chapter 6. The obtained values of soil redistribution rates can be represented with the aid of the following parameters (Quine and Walling, 1991; Walling and Quine, 1993; Mabit *et al.*, 2014):

- ***Erosion zone:*** the part of the studied field affected by erosion (area of studied field multiplied by the ratio of eroded sampled profiles and all sampled profiles);

- ***Deposition zone:*** the part of the studied field affected by deposition (area of studied field multiplied by the ratio of sampled profiles with deposition and all sampled profiles).
- ***Mean erosion in the erosion zone:*** the total mass of eroded soil material divided by the area affected by erosion;
- ***Mean deposition in the deposition zone:*** the total mass of deposited soil material divided by the area affected by deposition;
- ***Gross erosion in entire field:*** the total mass of eroded soil material divided by total area of studied field;
- ***Gross deposition in entire field:*** the total mass of deposited soil material divided by total area of studied field;
- ***Total erosion:*** the sum of all erosion values;
- ***Total deposition:*** the sum of all deposition values;
- ***Net erosion:*** the amount of soil leaving the studied field;
- ***Sediment delivery ratio:*** the ratio of net and gross erosion.

7.3 Data interpolation and soil redistribution mapping

The measured ^{137}Cs inventories and soil redistribution rates calculated by conversion models represent point data which are arranged in a grid over the area of interest. Such a data set provides valuable information not only on the soil redistribution rates but on the spatial variability of soil redistribution as well. The quality of this information depends on the processing of point data and creation of soil redistribution maps. If a digital elevation model (DEM) is available the 3D-visualisations of soil redistribution can be made (Figure 7.2).

Various simple or more sophisticated interpolation approaches can be employed. To obtain more realistic results, it is recommended to use advanced approaches for spatial interpretation of data. Geostatistical methods such as kriging can take into account the spatial variability based on the distance between points and even based on directions of processes (e.g. soil movement along a flow direction).

7.4 Data interpretation, utilization and communication

For interpretation and utilization of erosion assessments for practical purposes it is crucial to agree upon and implement a terminology that is easy to understand and that enables stakeholders to take actions. The concept of a *tolerable (or target) soil loss (T-value)* (Figure 7.3) describes the boundary between acceptable (legend of quarters of T in green) and unacceptable soil loss (multiple of T in red). Even though there is no defined tolerable negative soil loss, the amount of deposition is illustrated in two classes: below and above the negative T value (yellow colours).

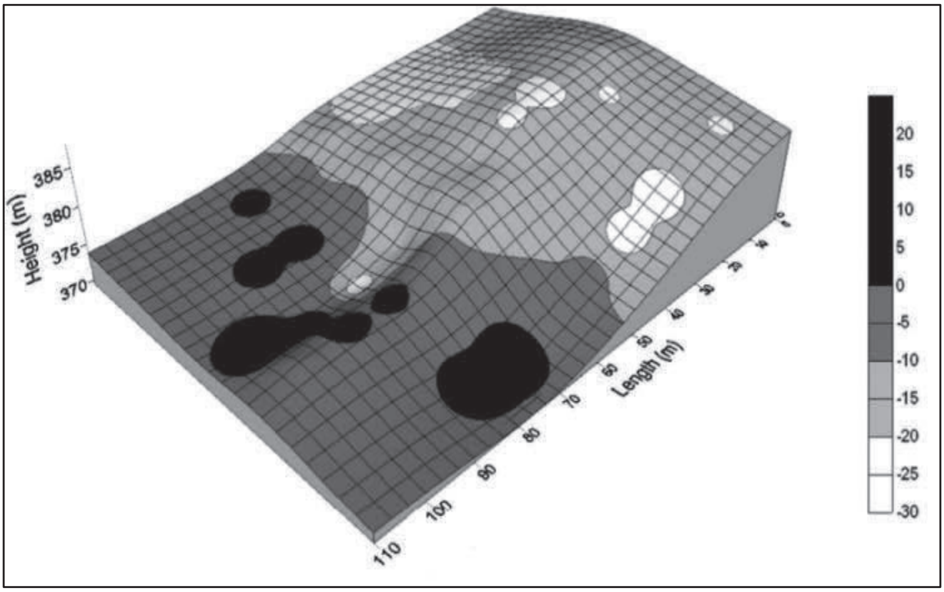

Figure 7.2. Example of 3-D visualisation of soil redistribution, Marchouch, Morocco. (Benmansour *et al*., 2013).

The identification of likely source areas such as upslope or upstream areas (on-site) and likely deposition areas such as down slope or down steam areas (off-site) enables a spatial identification of stakeholder responsibility (Figure 7.3). This enables stakeholders to put ^{137}Cs erosion and deposition values into perspective and stakeholders can better communicate to find an agreement on how to interpret the results and turn them into actionable items such as policies and regulations to recognize the problem and find best management practices (BMP) solutions.

The data obtained through the ^{137}Cs method have a historical information value what happened accumulatively since mid-1950s until the day of the measurement. This long-term data can then be used for various purposes among which the following are most important:

- Long-term erosion rate monitoring (this could be a couple of points);
- Investigation of the relative long-term temporal dynamic and spatial distribution of erosion rates (this requires more points; ideally in a raster pattern);
- Study of impact of erosion factors on long-term erosion rates at different/neighbouring sites;
- Verification, calibration and validation of soil erosion models;
- Testing the long-term efficiency of soil and water conservation measures (or BMPs).

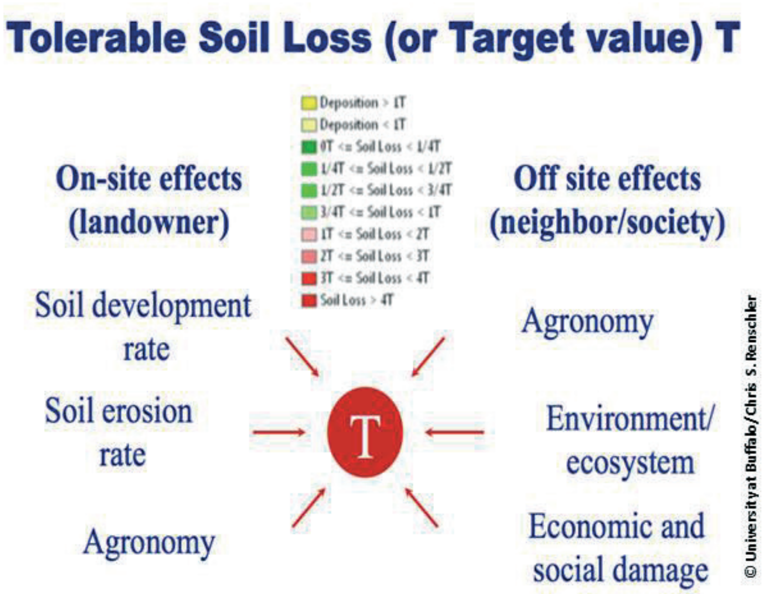

Figure 7.3. The concept of tolerable soil loss for stakeholders to put measurements (e.g. ^{137}Cs) and modelling (e.g. WEPP simulations) into actionable management.

The last purpose is very important to evaluate BMPs in land management (e.g. zero tillage, buffer strips, strip cropping, etc.) and to develop comprehensive, long-term soil conservation strategies and policies. If stakeholders want to assess short-term processes, the ^{137}Cs data should be done repetitively (adjacent to the previous sample location) combined with short-term observations of soil redistribution such as plot or catchment studies. In contrast to total annual (or average annual) on-site soil loss, event-based runoff and sediment yield data is collected at the lower boundary of a plot or even at the catchment outlet. A nested watershed approach with multiple outlet measurement points would be exceptional for researchers, but would be hard to implement at multiple locations due to costs. This event-based observation data together with long-term point data of ^{137}Cs samples, however, enable to successfully develop, validate and apply spatially distributed, process-based, continuous soil loss models.

Once such a process-based model is calibrated and validated for a particular hillslope site it can be used to assess soil redistribution based on a variety of scenarios representing changes in soil or vegetation management. If there are sufficient event-based climate data available the models can be used to derive statistical parameters to generate realistic long-term weather patterns (Meyer et al., 2008). There is also the opportunity to introduce climate change pattern and generate scenarios to assess the risk of runoff and sediment discharges of certain return periods of precipitation events (e.g. 100-year return periods of events without and with climate changes in temperature or precipitation).

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8 ^{137}Cs method – validation and use of erosion models

In contrast to just mathematically interpolating ^{137}Cs sample points, scientists have collected information on erosion processes and developed process-based models that enable them to fill the information gaps between sample points on the basis of understanding the processes in landscapes.

Since the development of the first, widely applied soil erosion model – the Universal Soil Loss Equation (USLE) by Wischmeyer and Smith (1958) - numerous regional and national versions of the empirical-USLE-type models were developed (e.g. Boardman and Poesen, 2006). These empirical soil loss equations were derived based on runoff and sediment yield data collected at the end of unit plot areas of a certain hillslope length. Alternatively, observations of the exposure depth of a physical marker over a particular time period, e.g. erosion pins, would quantify the eroded or deposited soil at a particular point along or at the end of a longer, sometimes complex hillslope with no inflow at the upper boundary. Such long-term empirical models were developed based on a large amount of quantitative data for a specific region, but when they should be applied in other region they need to be calibrated and validated by similar amounts of data collected in that region.

The ^{137}Cs method does the same as the erosion pins, but without the intensive instrumental setup for a fixed starting point and it covers a long period (since mid-1950s or after a NPP fallout). Once at studied slope the ^{137}Cs measurement is established, the follow up measurement campaigns (e.g. every 5 to 10 years) are able to provide multi-temporal data indicating the dynamics of erosion rates. Combining the ^{137}Cs method and empirical USLE-type, long-term soil erosion models enable us to calibrate and validate the models for a reference slope and furthermore the model can be used to extrapolate the information to surrounding fields. However, the original development of the model relies on a specific, uniform plot scale (USLE standard slope length is 22.13 m) that is usually much shorter than the variable, complex slopes prevailing in real landscapes. There is no accounting for confluence or diversion of flow patterns within those plots. Therefore, ^{137}Cs data in a raster grid sample pattern has the potential to validate models for complex hillslopes and validated models can be applied at neighbouring hillslopes and in an entire catchment.

The ^{137}Cs method is a unique way to create landscape erosion pattern since mid-1950s that can be compared not only with single hillslope models, but also spatially-distributed soil erosion models. Models that are capable of simulating soil redistribution along complex hillslopes and/or flow patterns have been developed since half a century. These soil loss and redistribution patterns can then be used together with runoff and sediment discharge data and gaging stations to create entire landscape budgets of water and sediment. Besides plot and hillslope data, floodplain and reservoir data of ^{137}Cs samples and total measures of sediments or sediment fluxes help to describe these landscape budgets.

The possibility of using soil redistribution rates estimated for ^{137}Cs data and process-based models in coordinated research effort, enables the international scientific community to create new higher resolution spatial and temporal modelling technologies to simulate not only historic events or time periods since the past. Once validated for different land use histories, it is possible to predict the spatial and temporal distribution of erosion for time periods with alternative land uses. Realistic scenarios for process-based models would help to assess the impacts of changes in soil, water and crop management and/or in climate.

Therefore, continuous process-based and catchment-based soil erosion models were developed over the past half-century that are now able to simulate scenarios and enable an event-based analysis. These process models can be verified and validated for a measurement site with long-term (^{137}Cs data) and short-term data (event-based or higher resolution data) and then transferred to neighbouring areas with minimum calibration of parameters. Process-based models require users to carefully study the consideration of processes that are represented (Figure 8.1); e.g. some locations would need to consider gully erosion processes while tillage erosion processes could impact others. The latter two examples would not be necessarily included in a model and would need to be considered when interpreting the results of the ^{137}Cs measurements.

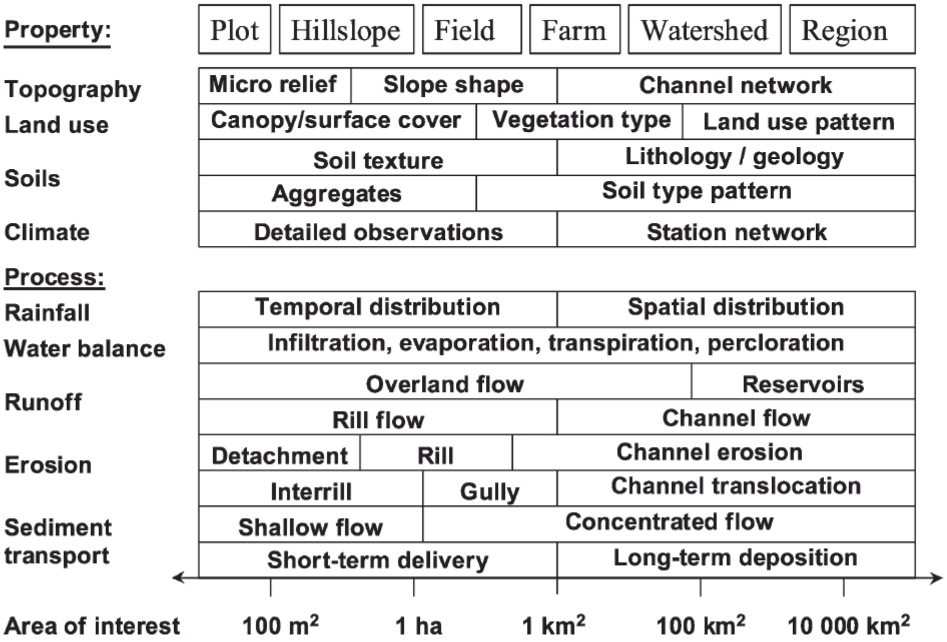


Figure 8.1. Scales of interest, spatial, and temporal variable properties important for dominant processes at an indicated scale (Renschler and Harbor, 2002).

8.1 ^{137}Cs data: finding right model and scale

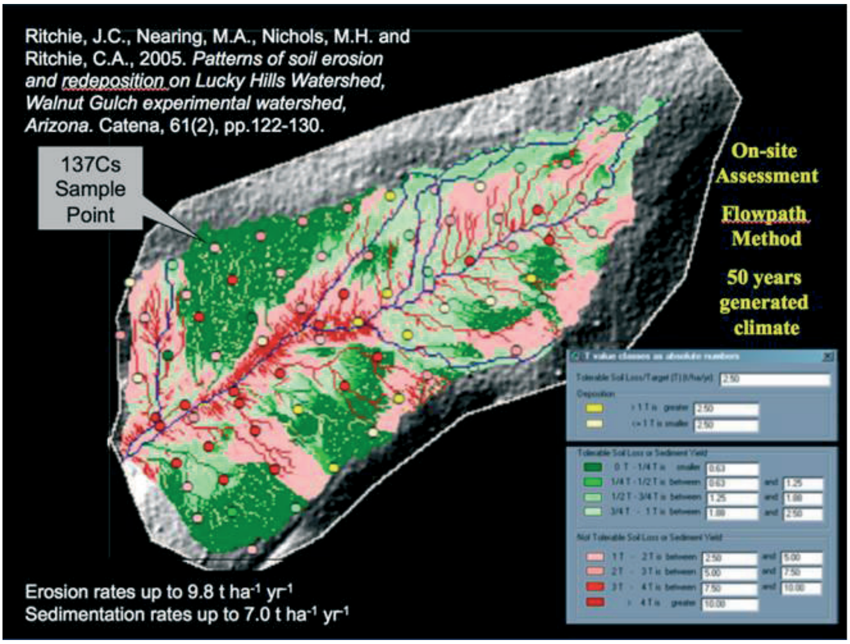
Given the critical importance of assessing the impact of temporal and spatial variability in soil erosion parameter data at different scales (Figure 8.1), surprisingly little emphasis has been placed on this in soil erosion simulation tool development and evaluation for practical decision making (Renschler and Harbor, 2002). In modelling, shorter time scales are typically associated with smaller spatial scales because finer time resolution requires more detailed modelling of hydrological and sediment transport processes, which usually means consideration of variability at more detailed spatial scales (Kirkby, 1998). At different scales, different groups of processes are dominant, so the effective focus of the model also changes with scale. Most modern watershed models focus on the prediction of water fluxes for particular space and time scale (Figure 8.1; Renschler and Harbor, 2002).

Hydrologic processes are often described in ways that depend on the model's scale. But the scale in which the model is designed to operate influences decisions about the level of spatial aggregation in input data, analysis, and model output. However, when the problem of interest is not at the scale of the model, scaling both data and model results is very complex (Renschler *et al.*, 1999). For example, empirical, process-based approaches to predict sheet and rill erosion rates can provide reasonable results to evaluate environmental and economic impacts of agricultural policy on a large scale (Carriquiry *et al.*, 1998), but do not yield accurate predictions of erosion variability on the field scale.

Nearing *et al.* (2005) provides an overview of a series of state-of-the-art soil erosion models and illustrates results of a model performance comparison for a particular site based on scenarios with changes in vegetation cover and climate change. Models that are widely used include the Revised Universal Soil Loss Equation (RUSLE) – an upgraded version of the empirically-based USLE (Renard *et al.*, 1997), the Limburg Soil Erosion Model (LISEM) (Jetten *et al.*, 1998), the kinematic runoff and erosion model KINEROS (Smith *et al.*, 1995), the widely-used Soil Water Assessment Tool (SWAT) (Arnold *et al.*, 1999) for larger watersheds, and the process-based Water Erosion Prediction Project (WEPP) model for single or multiple hillslopes in small watersheds (Flanagan and Nearing, 1995).

Renschler (2003) developed the Geospatial Interface of WEPP (GeoWEPP) enabling geospatial application of the WEPP model using GIS data to assess the impacts of spatial and temporal land management and climate change through scenarios. Geospatial tools like the GeoWEPP use the idea of a T-value (Figure 7.3) to assist stakeholders in the quest for understanding the history of soil erosion, floods and sedimentation and assess the predicted land use, land management and climate change scenarios.

The soil loss pattern can then be compared with point-based ^{137}Cs measurements as well as runoff and sediment yield data at a catchment outlet (Figure 8.2). The event-based runoff and sediment yield measurements enable to compare model results with observations at the watershed outlet.



T value classes as absolute numbers

Tolerable Soil Loss/Target (T) (t/ha/yr): 2.50

Deposition

> 1 T is greater 2.50
<= 1 T is smaller 2.50

Tolerable Soil Loss or Sediment Yield

0 T - 1/4 T is smaller 0.63
1/4 T - 1/2 T is between 0.63 and 1.25
1/2 T - 3/4 T is between 1.25 and 1.88
3/4 T - 1 T is between 1.88 and 2.50

Not Tolerable Soil Loss or Sediment Yield

1 T - 2 T is between 2.50 and 5.00
2 T - 3 T is between 5.00 and 7.50
3 T - 4 T is between 7.50 and 10.00
> 4 T is greater 10.00

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Figure 8.2. ^{137}Cs-based soil loss and simulated soil loss based on generated weather.

8.2 ^{137}Cs data and process modelling: powerful new tools

Validated process-based models enable scientists and practitioners then to create new, powerful scientific soil loss prediction tools to support better soil and water conservation decision-making and policy-making through "what if"-scenarios (Figure 8.3). They also help to better plan and deal with contaminated soils after a NPP disaster or accident with radioactivity being released.

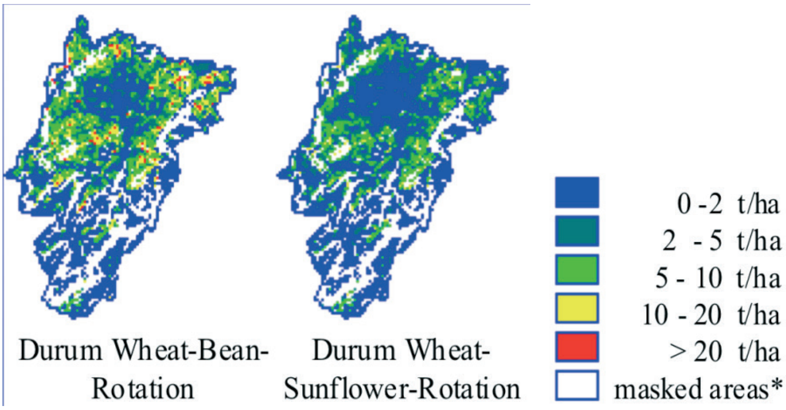

Figure 8.3. Modelling of soil erosion for selected crop rotation scenarios, Guadalteba Watershed, Andalusia, Spain (Renschler, 1996).

It can be concluded that the experience with combined use of the ^{137}Cs method of erosion assessment and erosion modelling brought up to now the following new developments:

- The ^{137}Cs method can be used for soil conservation in combination with erosion models. This combined approach may provide more comprehensive assessment of soil erosion involving information on long-term mean soil erosion rates and detailed spatial patterns of soil redistribution (provided by ^{137}Cs) as well as various scenarios of short-term soil erosion dynamics under different land uses and managements (provided by erosion models).

- The ^{137}Cs method can be used for calibration and validation of erosion models. Most easily it can be used for calibration and validation of empirical models such as the USLE because the USLE and USLE-type empirical models are working with empirical factors, such as rainfall erosivity or R-factor, that can be expresses in annual cumulative values. This approach is close to long-term mean soil erosion rates derived from ^{137}Cs inventories. Despite of their simplicity the USLE is still very useful for soil conservation because it is not demanding for a lot of input data and thus can be applied for large territories.

- Very helpful for calibration and validation of erosion models is the combined use of ^{137}Cs and conventional methods (experimental plots, hydrological profiles) to create catchment (or watershed) models. These models can provide water and sediment budget calculations that are especially useful for water resource management and planning such as water reservoirs.

- Apart from the information on erosion rate the ^{137}Cs data provides very valuable information especially on spatial distribution of soil redistribution rates. Calibration and validation of erosion models is usually based on erosion measurements at experimental plots and suspended sediment load measurements at water courses in small catchments. These data represent usually very few spatial locations. This limited spatial information can be significantly extended by ^{137}Cs data which are usually related to large number of locations creating grid over the area of interest.

- Use of ^{137}Cs data for calibration and validation of process-based (or physically based) models, which are built on event-based data are more challenging. However ^{137}Cs data points in the landscape provide the ultimate measured pattern for process-based models for a particular time period (since mid-1950s or after a NPP disaster). The complex calibration and validation of detailed process-based models may require a much larger, coordinated data collection of input parameters. However, those validated model could then be used without further calibration when transferred into neighbouring areas with similar climate and land use.

- The use of the ^{137}Cs method for erosion models calibration and validation requires special emphasis on the systematic collection of input data in addition to ^{137}Cs data. The data set should be accommodated according to the needs of each particular model to be used. For that reasons it is important to know prior to developing study design whether the intended ^{137}Cs study will be used for erosion models and for which model. The use of older ^{137}Cs data sets is often problematic because some complementary geographical data are missing and must be estimated or generated using secondary methods, which reduce their accuracy and representativeness.

- The use of the ^{137}Cs method either in combination with erosion models or for their calibration and validation can be done by two approaches: 1) the retrospective approach (using ^{137}Cs data from one time horizon and assessing the period between the ^{137}Cs fallout and the time of ^{137}Cs sampling), or 2) the monitoring approach collecting ^{137}Cs data from several (at least two) time horizons and assessing the periods between these time horizons). If using this approach, it is recommended to repeat the ^{137}Cs sampling once upon 5 or 10 years. This approach is very demanding for precise recording of the sampling positions, because if the later sampling would not fit to the position of the former sampling the values would not be comparable.

- When using ^{137}Cs data for calibration and validation of erosion models, it is important to use multiple transect design and ensure that transects follow the slope direction (and hence the runoff direction). The regular grid is less appropriate as the erosion models consider the relations along the slope or runoff contributing areas. It is possible to use also data sets from regular grids but in such case the operator should try to identify the mutual relation between the data points considering the slope directions and the representativeness of the results is lower as the points from the regular grid will mostly not be arranged in lines along the slope directions.

- When using ^{137}Cs data in combination with other methods (such as conventional measurements of soil erosion rates, erosion modelling, remote sensing or experimental rain simulation) the interpretation should always carefully consider the different erosion processes, spatial and temporal scales covered by particular methods. Most erosion models estimate water erosion processes at slope, plot or small catchment scales. Some models are aimed solely either on wind or on tillage erosion. Each conventional erosion measurement method covers different processes. The experimental plots represent the sheet and initial stages of rill erosion, the volumetric method represents rill and gully erosion and the suspended sediment load measurements at hydrological profiles represents erosion by those rills and gullies which are interconnected with water courses and bank erosion by water course. Most measurements represent the temporal scales of event, season, year or several years. The ^{137}Cs method represents overall rates of soil redistribution by all processes and it covers long periods either since the ^{137}Cs fallout (recently 64 years; 1954-2018) or various medium term periods (e.g. the periods between two samplings if the ^{137}Cs is sampled repeatedly). These differences in processes and temporal and spatial scales represented by different methods should be always carefully considered when comparing the results from different methods.

8.3 Example of using ^{137}Cs method for WEPP model verification in Morocco

To illustrate the benefits for a combined ^{137}Cs measurement transect and a hillslope modelling study, a recently studied transects along a single 90m-long hillslope (within a 1-hectare field section of a small agricultural watershed near Marchouch, Morocco was used (Benmansour *et al.*, 2013). Like most of the ^{137}Cs measurements taken so far, the measurement design was not planned with a modelling exercise in mind. A coordination of modelling exercise and data sampling in the field would enable to consider flow pattern and accumulation as well as conversion and diversion of flow in the landscape. The flow path can be determined by using contour lines of a topographic map (Figure 8.4) or a flow accumulation algorithm on a DEM in a GIS. Therefore the following study should be seen as an example to illustrate what can be done with already existing data.

The 90m-transect with a 10m-distance between each of the nine ^{137}Cs measurement location is an ideal distribution for a landscape section with parallel sheet flow to verify and validate a process-based erosion model at the hillslope scale. The previously mentioned Water Erosion Prediction (WEPP) model (Flanagan and Nearing, 1995) was used in this study for illustration purposes.

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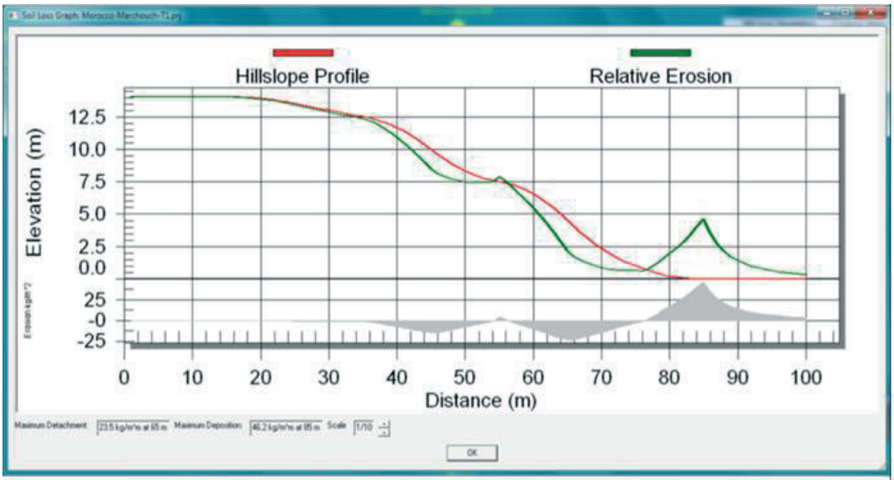
Figure 8.4. Direction of contour lines and crop rows at Marchouch study site, Morocco.

Besides the *topographic data* of the slope (slope segment length and slope inclination), the WEPP model requires *long-term climate data* (in this case generated 100-year worth of data based on the precipitation dynamic of a couple of years of standard meteorological data from a nearby station were utilized), *soil-sampling data* (standard soil survey data such as soil profiles with soil texture, organic matter, rock content as well as some estimated model parameters such as hydraulic conductivity and shear stress), and *land use data* (a continuous winter wheat rotation was the best assumption since detailed crop data for the past 60 years are missing). More details on data gathering, model parameters estimation and model equations can be taken from Flanagan and Nearing (1995).

Figure 8.5 illustrates the difference between hillslope profile (red line) and the relative erosion (green line). The grey-shade curve at the bottom of the graph illustrates erosion along the slope ranging from nearly 25 t ha^{-1} yr^{-1} in the upper section of the slope and deposition values of more than 25 t ha^{-1} yr^{-1} at the bottom of the slope.



Maximum Detachment: 23.5 kg/m^2 at 65 m
Maximum Deposition: 46.2 kg/m^2 at 85 m
Scale: 1/10

Distance (m):	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
^{137}Cs (t/ha/yr):	-13.76	-10.00	**-26.42**	**-22.20**	-19.84	-13.07	-16.60	**-28,38**	**2.50**	**12.78**
^{210}Pb (t/ha/yr):	-17.85	-9.66	-4.13	-17.57	-14.55	-15.15	-10.05	**0.10**	**6.33**	-9.52

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Figure 8.5. Soil Redistribution – WEPP vs. Isotope Derived Transect at Marchouch, Morocco.

The ^{137}Cs measurements for each of the nine sample locations (Table 8.1) were used to make the erosion rate estimation. Gained values were categorized to four classes: slight erosion up to 10 t ha^{-1} yr^{-1} (orange), medium erosion between 10 and 20 t ha^{-1} yr^{-1} (red), strong erosion more than 20 t ha^{-1} yr^{-1} (bold red) and deposition (green). The sampling and model simulation do not match exactly, but they match the overall soil redistribution pattern and the order of magnitude.

For a more detailed analysis one should use the GIS and model to determine the flow path first and then sample the ^{137}Cs measurement points accordingly. This illustrates that GIS, sampling and modelling can and should be ideally used in combination to contribute to more comprehensive understanding of soil redistribution. As previously indicated a range of values of input parameters such as climate and land use can be applied to evaluate various scenarios that may help to identify the optimal land use policy.

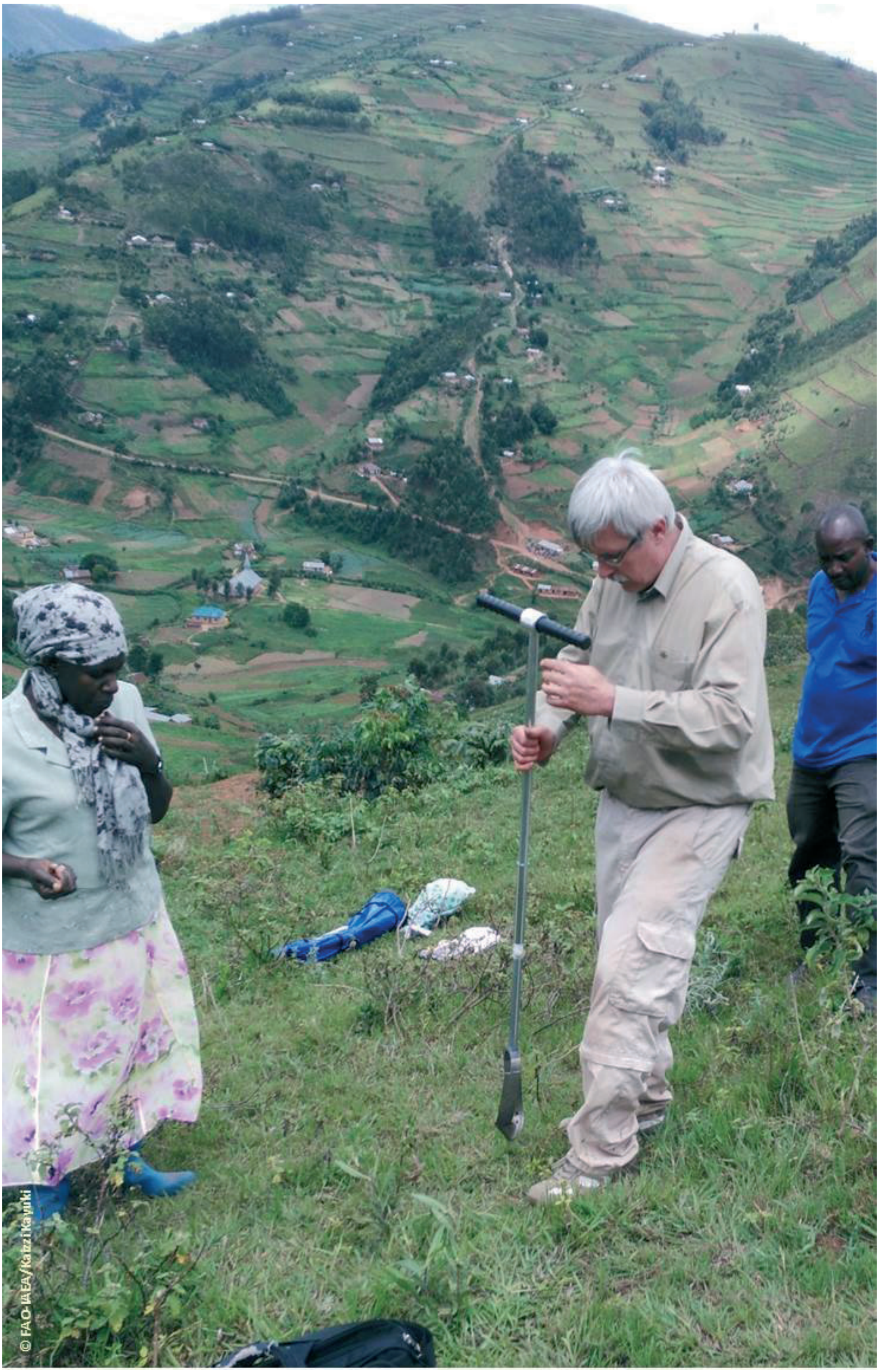
Table 8.1. Land use and Climate Change analysis using 100-years of generated weather, Marchouch, Morocco.

a) Winter wheat (conventional tillage)

Period	Precipitation ($mm\ y^{-1}$)	Runoff ($mm\ y^{-1}$)	Soil Loss ($kg\ m^{-2}\ y^{-1}$)	Sediment Yield ($t\ ha^{-2}\ y^{-1}$)
Current	415.8	42.4	2683	26.1
2030	395.9	41.7	2869	27.8
2060	374.6	40.7	2955	28.7
2090	348.2	42.2	3521	34.1

b) Fallout (without vegetation)

Period	Precipitation ($mm\ y^{-1}$)	Runoff ($mm\ y^{-1}$)	Soil Loss ($kg\ m^{-2}\ y^{-1}$)	Sediment Yield ($t\ ha^{-2}\ y^{-1}$)
Current	415.8	107.0	5874	58.7
2030	395.9	102.5	5631	56.3
2060	374.6	96.3	5341	53.4
2090	348.2	90.3	4990	49.9



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9 Advantages of ^{137}Cs method

The methodology of soil erosion rate assessment and measurements is a result of almost 100 years of research. Several methods were developed and refined (e.g. volumetric methods, geodetic methods, erosion plots, hydrological methods, radionuclide methods, etc.) by the contributions of the international scientific community. Each method has different assumption, principle, covers different spatial and temporal segments of erosion-sedimentation cycle, and reflects particular soil redistribution processes participating in this cycle. Therefore the data obtained cannot be schematically compared. Each presented dataset has to be specified in terms of method used, temporal and spatial scale covered and particular processes represented. Moreover, each method has its advantages and limitation, which should be considered already before starting any study and the method most appropriate for the study objective should be selected. Some methods are complementary and can provide useful results if used jointly.

The ^{137}Cs is an excellent tracer for studying soil erosion processes. It is the more mature and most widely used FRN for soil erosion assessment. Its wide applicability was demonstrated by the bibliography provided by Ritchie and Ritchie (2008). The ^{137}Cs method has the following advantages, modified according to Mabit *et al.* (2008) and Zupanc and Mabit (2010):

- The obtained data represent long-term (recently over six decades since the ^{137}Cs fallout until the sampling period) soil redistribution rates. This is probably the main asset provided by the ^{137}Cs method. Long- or medium-term data on soil redistribution magnitudes are difficult to acquire by conventional methods and they are very valuable for studying the development of landscape and soilscape. Data can be used for soil conservation programmes and for soil erosion model validation.
- The obtained values represent an overall soil redistribution rate integrating all processes responsible for mechanical movement of soil particles (e.g. water, wind and tillage erosion), eventually other processes, such as gravitation processes (creep, landslides, etc.). This is an advantage for studies focused on overall assessment of erosion impact on landscape development. Data on overall erosion rates is very scarce. Among the conventional methods, only the geodetic method (erosion pins) reflects the impact of all erosion processes. Most other conventional methods reflect particular processes of water erosion. Measurements at experimental plots provide information only on initial stages of water erosion (rill and sheet erosion). Volumetric methods reflect advanced stages of rill erosion and gully erosion. Hydrological methods represent advanced stages of rill and gully erosion and linear erosion by permanent watercourses such as riverbed erosion and riverbank erosion. Other specific methods have been designed for specific investigation of erosion processes other than water erosion (e.g. tillage and wind erosion).
- The obtained values provide retrospective information. It is a unique feature that past erosion rates can be estimated from samples collected at present

time. Retrospective data cannot be gained by conventional methods. The ^{137}Cs method can provide also perspective data if the ^{137}Cs sampling is periodically repeated in time.

- The obtained data provide information on the spatial distribution of soil redistribution rates if the sampling design is based on grid or multiple transects (Figure 9.1). This is a clear advantage as compared to conventional methods (such as erosion plots or hydrological method), which provide data attributed to one or few profiles with installed measurement equipment.
- There is no need for costly and labour intensive long-term monitoring programs. The fieldwork required is easy to manage. The results can be obtained from a single site visit or short field campaigns.

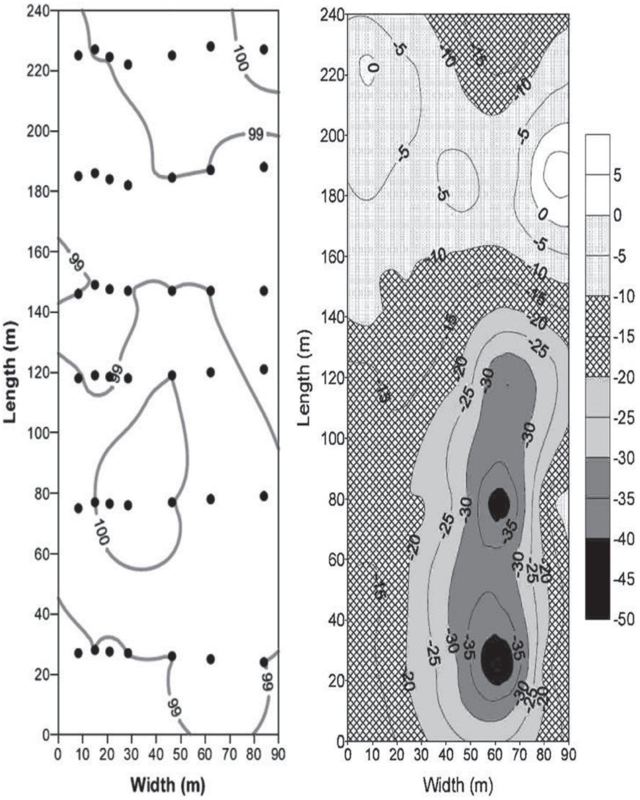

Figure 9.1. Sampling grid for ^{137}Cs determination and the resulting map of soil redistribution created by ordinary kriging, Boyer Site, Canada (Mabit *et al*., 2008)

10 Activities performed by the Joint FAO/IAEA Division and further perspectives

The ^{137}Cs method is today widely used by the international erosion research community and has gained much popularity since the 1990s when user-friendly models for converting ^{137}Cs inventories into soil redistribution rates became widely available. Since 1995 – when the Joint FAO/IAEA Division launched its first *CRP* on the assessment of erosion by FRNs, it has become one of the leading institutions developing these FRN methods. Probably the most important results of upgrading the FRN methodology to a higher level are the methodological handbooks published by Zapata (2002) and IAEA (2014). The Joint FAO/IAEA Division is refining the ^{137}Cs method also through applied research conducted at its laboratories in Seibersdorf.

Apart from research activities, the Joint FAO/IAEA Division, through IAEA technical cooperation projects (TCPs), disseminates the ^{137}Cs method to FAO and IAEA Member States. Until now, this specific technical support was provided to more than 70 countries worldwide.

All necessary information about the activities of the Joint FAO/IAEA Division in research and technical cooperation on the ^{137}Cs methods and other related FRNs and isotopic techniques is available through the SWMCN Subprogramme website http://www-naweb.iaea.org/nafa/swmn/index.html, the Soils Newsletter and the Annual Reports of the SWMCN Laboratory, Seibersdorf http://www-naweb.iaea.org/nafa/swmn/public/newsletters-swmcn.html.

In future, particular attention will be paid towards extending the use of the ^{137}Cs method to the assessment of soil conservation efficiency and to erosion modelling. The assessment of soil land use and management impact and soil conservation efficiency has been extensively developed. CRPs provide examples of such studies, including the assessment of terracing in Morocco and Madagascar (Benmansour *et al*., 2013; Rabesiranana *et al*., 2016).

The potential of using the ^{137}Cs method for validating the models has not been fully recognized yet. Erosion rates estimated by the ^{137}Cs method can be used to cross-validate the erosion models and test the scenarios to find optimal land and soil management strategies and policies for sustainable food production. The ^{137}Cs method can be used also to monitor soil erosion and sedimentation dynamics if the sampling is repeated at the same site either periodically or occasionally (for example after extreme erosion events). Combining the ^{137}Cs method with other FRNs (such as ^{210}Pb and ^{7}Be) can provide more comprehensive information on erosion dynamics and spatial distribution.

Glossary

Activity - concentration of radionuclide in measured sample detected through its radiation and expressed in Becquerels per unit mass.

Alkali metals – group of elements (column in the Mendeleev's periodic table) involving lithium (Li), sodium (Na), potassium (K), rubidium (Rb) caesium (Cs) and francium (Fr) characterized by high reactivity at normal atmospheric temperatures and pressures. Alkali metals readily lose their outermost electron and form cations with +1 charge.

Bomb-derived ^{137}Cs - ^{137}Cs unintentionally released to the atmosphere by the past surface nuclear weapons tests.

Chernobyl accident – accident of nuclear power plant in Chernobyl, Ukraine (26th April 1986).

Chernobyl ^{137}Cs - ^{137}Cs released to atmosphere by the Chernobyl Nuclear Power Plant (NPP) accident.

Cosmogenic radionuclides – natural radionuclides (such as ^{3}H, ^{7}Be, ^{14}C, ^{32}P) originated as a result of cosmic ray spallation of atoms (expelling of neutrons and protons from the atom nucleus by high energy cosmic rays). The only cosmogenic radionuclide important for erosion research is ^{7}Be that is formed by spallation of nitrogen and oxygen.

Deposition – complex of geomorphological process depositing soil or rock material mobilised and transported from other areas. Deposition takes place usually (but not necessarily) in depressions or low elevated, flat areas when the transporting agent loses the kinetic energy and the transported material exceeds the transporting capacity of the transporting agent. The deposition by wind can occur also on elevated and convex landforms.

Erosion - complex of geomorphological processes driven by several erosion agents (water, wind, tillage, snow, ice, animals, etc.) accusing detachment and removal of soil or rock particles from land surface in affected area.

Erosion rate – amount of soil or rock material eroded from unit area during unit time. Usually it is expressed either as mass in tons per hectare per year or as volume in mm per year.

Erosion plot – most commonly used conventional approach of erosion measurements. The erosion is quantified for certain land area fenced by artificial boundaries (such as metal sheets). The soil eroded by surface runoff is captured to collection tanks.

Fallout radionuclides – radionuclides that are getting to terrestrial and aquatic environment by fallout from atmosphere. This term was introduced in erosion research and refers to those radionuclides which are usable as erosion tracers (i.e. ^{137}Cs, ^{210}Pb, ^{7}Be, $^{239+240}$Pu). The fallout is dry and wet (washing by rainfall).

Gamma detector – analytical equipment aimed on measurement of the gamma radiation.

Gamma radiation – one of three types of electromagnetic radiation (alfa, beta and gamma radiation) emitted by unstable radioactive nuclei of atoms (radionuclides). Gamma radiation corresponds to emission of photons and is the strongest of the three main radiation types. It does not have mass and charge and travels much further that alfa and beta radiation.

Gamma spectrometry – analytical method for determination of gamma radiation emitted by radionuclides based on assessment of their energy spectra.

Geogenic radionuclides – natural radionuclides originating from bedrock substratum. For erosion research the most important geogenic radionuclide used as erosion tracer is ^{210}Pb, which originates as a product of ^{238}U radioactive decay series. Part of the ^{222}Rn, which is one of the decay product of this series evaporates from soil to atmosphere and is decomposing to ^{210}Pb, which falls to land surface and ocean.

Half-life – period during which half of the amount of radioactive isotope decays (its activity is half of the original activity).

Human-induced radionuclides – radionuclides introduced into environment by human activity. For erosion research the most important human-induced radionuclides, which may be used as erosion tracers are ^{137}Cs, ^{239}Pu and ^{240}Pu released from surface nuclear weapon tests.

Inventory - activity of radionuclide per surface area representing the amount of radionuclide occurring in soil within the unit surface area.

Isotope – atom that differs from the other atom of the same chemical element by number of neutrons. Isotopes can be either stable or radioactive.

Kriging - widely used method in spatial analysis of interpolation modelling using a Gaussian process utilising distance-weighted averages.

Multislot divisor – device used for splitting runoff at erosion plots in order to save the storage space of collector. Using this device enables to collect only small fraction of the runoff.

Parshal fume – hydrological device serving as artificial hydrological profile on small watercourses for measurements of discharge and picking samples for measurements of suspended load.

Radioactive decay – process of decomposition of unstable isotopes (radionuclides) by emitting radiation and gradual losing part of the energy and mass until the radionuclide is transformed to stable isotope.

Radionuclide – isotope which is unstable due to having an excess energy in its nucleus. It emits radiation and gradually loses energy and mass until it is transformed to stable isotope.

Reference site – well representative site where the ^{137}Cs inventory is not affected by erosion, accumulation or other geomorphological processes moving soil material such as gravitation processes (landslides, creep, solifluction) neither by human processes of land mass translocation (construction, mining activities). The reference site represents the original fallout input of ^{137}Cs reduced only by radioactive decay.

Reference slope – term used in erosion modelling for a series of measurement points along a linear slope transect which is used as a “reference” for validating a model for a hillslope segment that can be used to extrapolate results to other similar hillslopes. It should not be confused with reference site used for FRN methods.

Sedimentation – originally referring to processes of deposition of soil and rock particles from water (sedimentation in narrow sense). In wider sense, it refers also to all processes of soil and rock deposition by all transporting agents when they lose the transporting capacity.

Tipping bucket – device used for measurement of discharge and suspended sediment at erosion plots. It comprises of one or two containers having oblique shapes. Such containers when filled by collected runoff lose balance and flip over. As a consequence of flipping, water is poured and the container returns to its original position. The flipping motion is recorded by a counter. While flipping small portion of water with suspension is trapped by pipe and drained to sample container to be used for measuring suspended sediment load.

Undisturbed site – land that is not disturbed by human activities, especially agricultural practices (e.g. tillage).

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ISBN 978-92-5-130050-3

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I8211EN/1/11.17