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EVANET-TERRA – evaluation and network of EC – decision support systems in the field of terrestrial radioecological research

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Abstract. The EC 3rd and 4th framework programs have produced several models and Decision Support System (DSS) in order to assess the radioactive contamination of terrestrial ecosystems. However a critical evaluation of such systems had not been undertaken. The EVANET-TERRA network has been established in order to perform such a task. A comprehensive methodology have been adopted; the uncertainty and sensitivity analysis have been performed in order to establish the differences between conceptual and constructed model, while the model-scenario comparison has been used to determine how the predictions fit empirical data. A synthesis of the current state-of-the-art regarding terrestrial radioecological models has been produced and recommendations have been made for further research needs.

1. INTRODUCTION

Accidental releases of radionuclides do not respect any national borders and can be dispersed over long distances. As a result, contamination of land, production areas, and food products requires a joint effort of all countries affected and not solely of individual countries. An adequate management plan needs to consider both national and international needs, and must be based on the understanding of the site-specific processes involved.

Such an assessment requires the application of models which aim to predict the behaviour of radionuclides in terrestrial environments and the effects of countermeasure interventions.

In the 3rd, 4th and 5th EC framework programs, a variety of models have been developed in the frame of several projects in order to predict the behaviour of radionuclide in terrestrial environments. Some of these models have been implemented in computerised Decision Support Systems (DSS). These DSSs represent an important tool for decision makers, since they allow the estimation of effective intervention strategies for each contamination scenario.

Due to the variety of models and DSSs, it has become essential to develop a critical evaluation of the "state-of-the-art" of radioecological models. This assessment comprises several objectives: it aims to classify the approaches of the various models/DSSs in order to determine their essential features, identify similarities and differences among them and finally assess their applicability domain regarding possible improvements and implementation.

The present paper aims to provide an overview on the "state-of-the-art" for the of the 3rd, 4th and 5th EC framework programs and few examples of the models testing outcome will be presented and briefly discussed, for more information on this aspect of the EVANET-TERRA project relevant reading are suggested, [1].

2. METHODOLOGY

Modelling may be undertaken for a number of reasons, but the most common aim is to predict the behaviour of a system under particular circumstances when it is impossible, or at least undesirable, to experiment with the system itself. Therefore, one of the main concerns of models evaluation is usually the accuracy with which the model fits the known historical data, in other words how well the model can mimic the real system. Although this test is essential for decision-making procedures, it does not allow a full investigation of the model structure dynamics. In the frame of the EVANET-TERRA, a comprehensive methodology has been implemented. Three tests have been performed: Uncertainty Analysis, Sensitivity Analysis and the Scenario-model comparison.

2.1 Uncertainty analysis

The aim of the Uncertainty Analysis (UA) is to determine how certain is the output nominal value and how much variability is associated to such an output, as function of the uncertainty or variability of inputs and model parameters.

To obtain such information, it is essential to have the model prediction expressed in a probabilistic format, therefore a probability density function needs to be established. The output uncertainty can be quantified by statistical parameters such as STD, while the Coefficient of Variability or the NR_p can be adopted as indexes to compare outputs uncertainty.

2.1.1 Monte Carlo sampling

The method suggested in the literature to evaluate the probability distribution of model outputs is the Monte Carlo Sampling (MCS) [2], [3] which has been performed through the application of the software Crystal Ball Pro. [4].

The MCS is described as follows: considering a set of input data $a_1 \ldots a_m$, and a set of model parameters $p_1 \ldots p_m$, which are described by a probability distribution, the simulation process selects randomly one value for each variable based on its probability distribution. This process is repeated for N times. N sets of values $a_{1(i)} \ldots a_{m(i)}$ (for i = 1 to N) are obtained and the corresponding model predictions, $Y_{(i)}$, i = 1 to N, are estimated.

2.1.2 Comparison of model outputs uncertainty

The uncertainty of the model prediction can be analysed considering standard statistical parameters or coefficients, such as STD or coefficient of variability. However, such statistical parameters may not provide a good estimation of output uncertainty if applied on a non-normal distribution. A novel index, the Normalised Range at a confidence interval of probability 75%, equation 1, has therefore been developed and applied. The NR_{75} is independent on unit and scale and distribution type and can be used to compare outputs which are described by different distribution, as lognormal or exponential.

$$NR_{75} = \frac{Range}{\bar{x}} \quad (1)$$

where:
$\bar{x}$ is the population mean.
Range is the distribution range width for a confidence interval of a probability *P* for the mean $\bar{x}$.

2.2 Sensitivity analysis

The SA is performed to increase the confidence in the model design and prediction since it establishes the fractional contribution of input and model parameters to the variance of the model forecasts. The SA is a complementary analysis of the UA as it can be used to determine the model variables or parameters which can be accounted for the model output uncertainty.

The Sensitivity Analysis has been performed applying the Rank correlation coefficient (RCC). The RCC uses the standard Correlation Coefficient (CC) approach to establish the relationship between inputs and outputs. However, the CC may not provide an accurate estimation if the relationship between inputs and outputs is not linear. To overcome this limitation, the Rank transformation on the distribution is performed as part of the RCC. The main feature of this coefficient is that it is distribution-independent and it is consequently possible to estimate the contribution of the inputs uncertainty on the output variance although the parameters are described by different distributions [5].

2.3 Scenario-model comparison

Two scenario have been considered to test the model prediction power: South Finland regarding the rural environment and the Bad Waldsee forest located in South Germany for semi-natural environment. These two scenario have been chosen since their data have not been used in the development or parameterisation of any of the considered models.

The data from the South Finland scenario, used previously in the VAMP project, refer to the ^{137}Cs deposition following the 1986 Chernobyl accident and cover a four-year period from 1986 to 1990. The food products considered are: beef (Bq/kg), dairy milk (Bq/l), pork (Bq/kg) and cereals (Bq/kg).

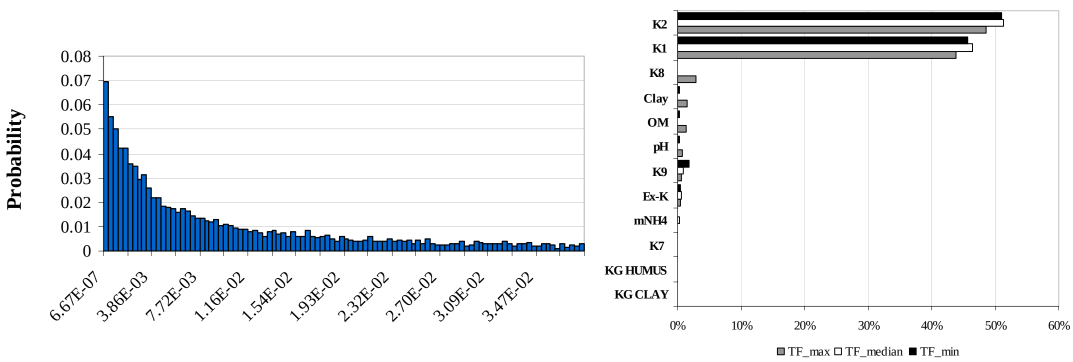
The data from Bad Waldsee forest cover a longer period from 1986 to 2000, and took into consideration the measurements of ^{137}Cs activity concentration in Roe Deer meat (Bq/kg) [6].

The degree of agreement between models prediction and measured data has been obtained using the Geometrical Reliability index k_{md} applied by Goor F. and Avila R. [7].

3. RESULTS AND DISCUSSION

3.1 Uncertainty and sensitivity analysis

An example of the uncertainty and sensitivity analysis: the SAVE rural model [8].



a) b)

Figure 1. Uncertainty and Sensitivity analysis performed on the predicted TF by the Absalom model.

The predicted TF values is characterised by an exponential distribution and high level uncertainty is related to it, figure 1a. The source of this uncertainty may be due to the high model sensitivity to the model parameters k_2 and k_1, rank correlation coefficient is 50% and 45% respectively, figure 1b. The model output uncertainty is entirely influenced by these model parameters and inputs have therefore been relegated to a secondary role.

3.2 Scenario-model comparison

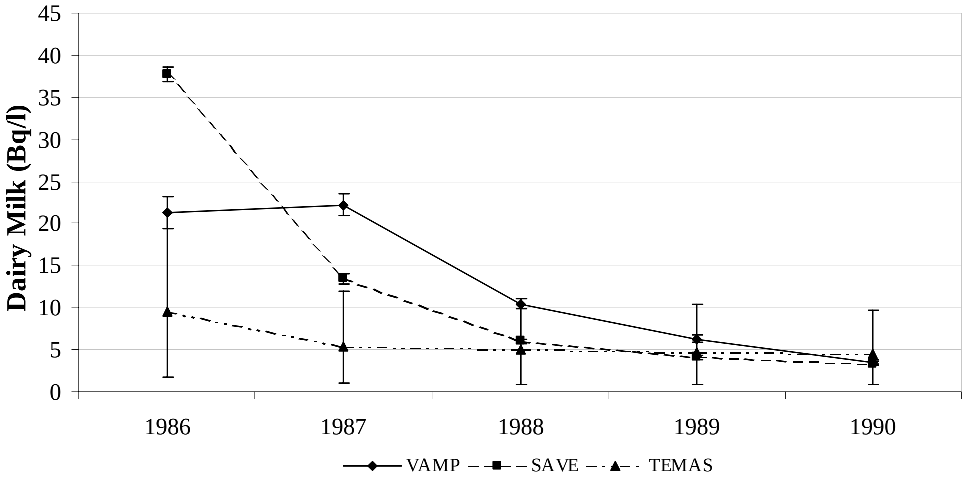


Figure 2. Mode-Scenario comparison. SAVE and the TEMAS predict a ^{137}Cs activity concentration in dairy milk which is very different between 1986 and 1988, however in the last two year considered the two models provide similar prediction.

Initially SAVE predicts higher activity than the empirical data, factor of 0.56, while TEMAS underestimates the ^{137}Cs activity in cow milk (Bq/l) as much as a factor of 2.25, figure 2. In the subsequent years both models indicated an exponentially declining trend. SAVE predicts a progressively decline which leads the forecast to a gradual increase of prediction accuracy, k_{md} 1.6. TEMAS is characterised by a rapid decrease between 1986 and 1987 and then a slow decline rate, figure 2, k_{md} 2.1.

4. "STATE-OF-THE-ART"

The models and DSSs developed in the 3rd and 4th EC framework program have been reviewed in order to outline the state-of-the-art regarding terrestrial radioecological models, however in addition to those models even SATRATEGY DSS, developed in the 5th EC frame program, has been included, since it is a direct evolution of the SAVE DSS, which is part of the set of DSS considered by the EVANET-TERRA project.

Terrestrial ecosystems can be broadly subdivided in three main categories: rural environment, semi-natural environment and urban environment. Such a categorisation has been used to classify the models and DSSs considered.

4.1 Rural environment

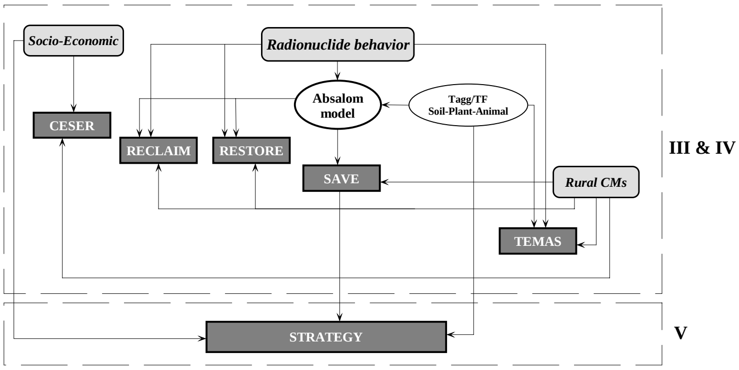


Figure 3. Connections between models and DSSs developed within the 3rd, 4th and STRATEGY, 5th EC framework programs.

Within the 3rd and 4th EC framework programs, five DSSs have been developed: SAVE, TEMAS, RESTORE, RECLAIM, CESER and STRATEGY, figure 3. Only five of them have been designed to estimate the behaviour of radionuclides in the environment. On the other hand, the aim of CESER is to implement an innovative methodology which would assess the potential side-effects of long-term countermeasures in rural systems following a radionuclide deposition.

A Multicriteria Decision Making technique has been developed for this purpose. The output of the CESER DSS is a list of countermeasures ranked from the most suitable to the least suitable. The selected countermeasures are not only based on the dose reduction but also on the environmental, socio-economic side-effects that they produce in a given scenario.

Although RECLAIM and RESTORE DSS have been produced by two different projects, RECLAIM can be considered as a particular application of RESTORE DSS; and for the purpose of this project, they are considered as a single DSS, figure 3.

The radionuclide behaviour in the environment, in respect of activity concentration in food products is considered in SAVE, RESTORE and TEMAS. The model implemented in SAVE, developed by Absalom J. [8], is the same model implemented in RESTORE, which is a semi-mechanistic model for the prediction of the migration of ^{137}Cs from soil to plants. TEMAS and the Absalom model are the only two models which have been developed regarding the migration of ^{137}Cs from soil to plant and animals within the 3rd, 4th EC framework program.

The primary difference in these two models is that the Absolom model estimates the Transfer Factor soil-plant considering soil chemical characteristics such as pH, exchangeable K^+, clay and organic matter content, while the second one evaluates the Transfer Factor soil-plant by taking into account soil physical characteristics, as soil texture an bulk density.

With regards to countermeasures, two main approaches have been developed and implemented: the CESER-TEMAS, which considers the countermeasure side-effects and estimates the most suitable countermeasure for the scenario, and the SAVE-RESTORE which estimates the effectiveness of the selected countermeasure from the dose reduction point of view.

In the 5th EC framework program, the DSS STRATEGY has been developed, and is characterised by several direct and indirect links to the DSS previously analysed.

STRATEGY is a direct evolution of SAVE. It uses the Absalom model to estimate the activity concentration in food products, however when dealing with countermeasures, it does not use the methodology implemented in SAVE but uses an approach which is indirectly derived from the CESER-TEMAS methods. It evaluates a suitable strategy of countermeasures for a given scenario, which is based on the assessment of environmental, socio and economic side-effects of each countermeasure and assesses interactions among countermeasures. In that sense, the 5th EC framework program represents a considerable development of the countermeasure aspect of DSSs.

On the other hand, the animal-plant pathway has been uniformly modelled adopting the T_{agg} approach. Consequently, none of the models considers the physiological aspect of radionuclide uptake.

4.2 Semi-natural environment

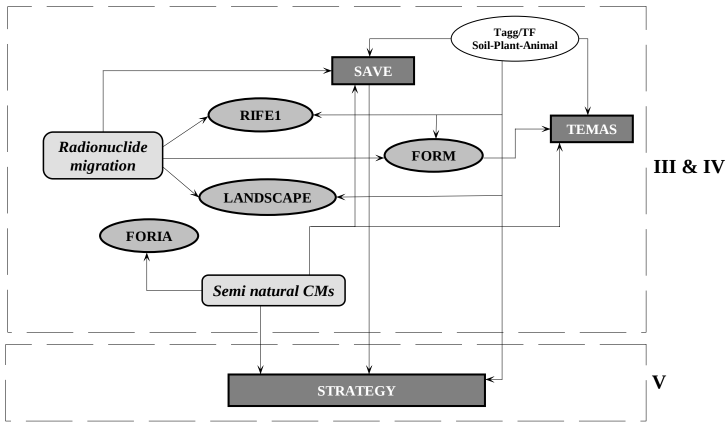


Figure 4. Connections between models and DSSs developed within the 3rd, 4th and STRATEGY, 5th EC framework programs.

Four models have been developed in the 3rd and 4th EC framework programs, which estimate the contamination of food products in a forest system: RIFE1, LANDSCAPE, FORM, which is the IAEA forest model which has been implemented in the TEMAS DSS, and finally the semi-natural model developed within the frame of SAVE, figure 4.

RIFE1 and FORM are dynamic compartment models, and they are characterised by a similar model design. Whereas RIFE1 estimates the tree contamination, and therefore the timber contamination, as function of the tree biomass through the use of a logistic equation to simulate the plant growth, FORM does not present such a feature.

LANDSCAPE is a more complex model, composed by six sub-models. It has been, however developed applying the dynamic compartment approach used for RIFE1 and FORM.

SAVE adopts a T_{agg} model to estimate the transfer of ^{137}Cs between soil-plant.

Two main approaches have been applied for the long-term changes of ^{137}Cs activity concentrations in wild animals: a T_{agg} approach for SAVE, RIFE1 and FORM and a dynamic compartment model, LANDSCAPE.

However only SAVE, TEMAS and FORIA estimate the effects of countermeasures implementation. Unlike SAVE, which estimates the effect of a selected countermeasure in respect of the dose reduction, TEMAS and FORIA considers the countermeasure side effects. FORIA does not have any model to estimate the forest contamination, but its peculiarity lies in the provision of all the possible countermeasures which can be applied for a given scenario, providing for each of them the list of side effects.

STRATEGY implements the same semi-natural model developed for SAVE, a T_{agg} model. However, the semi-natural countermeasures have not been as much explored as in the rural environment.

In conclusion, semi-natural models have been extensively developed during the 3rd and 4th EC framework programs but 5th EC framework program did not see any further development. Equally, countermeasures for semi natural models have not been investigated to the same extent as for the rural environment.

4.3 Urban environment

Only two urban models have been developed in the 3rd and 4th EC framework programs: the Balanov and the Meckbach model. Whereas the latter has been implemented in RESTORE, the former has been used in the TEMAS DSS first and later in the STRATEGY DSS in the 5th EC framework program, figure 5.

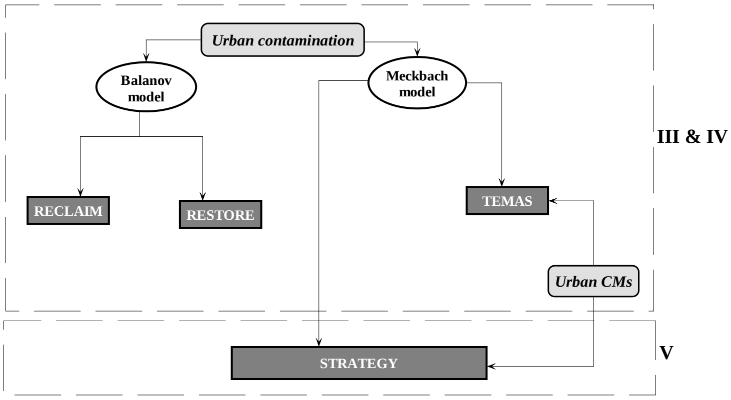


Figure 5. Connections between models and DSSs developed within the 3rd, 4th and STRATEGY, 5th EC framework programs.

Their application domains differ substantially. Meckbach model provides more flexibility in its application as it has been designed to a town/city scenario while the Balanov model has only been developed for countryside communities. In addition, the Meckbach model used in STRATEGY implements a more developed version to the one used in TEMAS, as it introduces a new urban scenario, which is the “industrial area”. Therefore, the Meckbach model can be considered the only model appropriate model to a European town or city.

5. CONCLUSIONS

The investigation of the state-of-the-art regarding terrestrial radioecological modelling has revealed several findings.

The models for rural environment application have been extensively explored in the 3rd and 4th EC framework programs and innovative features such as the estimation of countermeasure suitability based on the side-effects and dose reduction, proposed initially by CESER and TEMAS, have been further developed and implemented in STRATEGY in the 5th EC framework program.

On the other hand, semi-natural environment models have not been subject to a similar evolution trend. Between the 3rd and 4th EC framework programs, several models have been developed to evaluate radionuclides, in particular the ^{137}Cs translocation into food products. The consideration of countermeasures suitability, based on the side effects and dose reduction has been as well approached. The 5th EC framework, nevertheless, has not fully explored some of these innovations. More precisely, the model implemented in STRATEGY to estimate the contamination of semi-natural products is the same T_{agg} model implemented in SAVE and the countermeasure aspect is mainly related to dietary advices on the food consumption. In addition, no real evaluation of countermeasures strategies is present as it was the case for rural models.

Providing these findings, further evaluation of the semi natural environment models is therefore necessary. In particular, some of the radionuclides migration models produced within the 3rd and 4th EC framework program should be further developed. Equally, a development of countermeasures management is also required in order to obtain a similar approach to the one implemented for the rural sector.

Another important finding is the use of "spatial the distribution" to describe model inputs and outputs. Such a feature, which have been implemented in some of the models /DSSs considered in the EVANET-TERRA project, enables to offer more realistic information on the scenario investigated, and therefore it might be an important, if not essential, tool for decision makers.

Finally, although the aim of terrestrial and freshwater models/DSSs was to address long -term problems related to terrestrial or freshwater systems, a real connection among these two DSS categories is missing. Further attention needs therefore to be given to these two systems in order to thoroughly assess the interconnection which exists between them.

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