Application of food chain transmission models to the typical Portuguese diet using the decision support system JRodos

Catarina Andreia Mamede Inácio[1,*]

Supervisors: Prof. Doutor Mário Reis[1] and Doutor Paulo Nunes[2]

[1]Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal; [2]Agência Portuguesa do Ambiente, Lisbon, Portugal

*Email: catarinainacio95@gmail.com

ABSTRACT

In a nuclear or radiological accident, a quick and efficient response is essential to the radiological protection of the population and the environment. The Chernobyl accident was a starting point for many projects in the area of Radiation Protection to help the preparedness and response of emergencies, one of them being the decision support system JRodos.

Integrated in JRodos, FDMT is the module for simulating the transfer of radioactive material in food chains and for the assessment of dose. The default data provided with the system is adapted to Central Europe, but it's possible to customize the system to regional and national conditions.

Data from the typical Portuguese diet (Mediterranean diet) and from national statistics was collected in order to use those products in the FDMT model. The worst conditions to create greater soil deposition and the foodstuff above the intervention levels were tested using this model.

As accidents with industrial radiation sources are a problem and likely to happen on the national level, a similar accident was simulated in Seixal steel mill, based on the Algeciras accident.

Results have shown that the worst meteorological conditions that caused greater ground deposition were light wind and precipitation. Regarding intervention levels, several were exceeded namely leafy vegetables, among others, depending on the simulation.

In the future, it would be necessary to consider more agricultural areas and add important foodstuffs such as wine and olive oil, as well as, customize the system with national parameters so that JRodos can have the FDMT model adapted to national conditions and consequently be able to optimize the response and preparedness in case of an emergency.

KEYWORDS: radiological emergency, nuclear emergency, decision support system, JRodos, FDMT, food chain, intervention level

INTRODUCTION

Nowadays, because of the lessons learned from past radiological and nuclear accidents, from epidemiological studies of the atomic bomb survivors and from the scientific community constant search for knowledge, it is known that exposures above certain levels of ionizing radiation causes prejudicial effects to human health and to the environment. To this end, the role of radiological protection and safety is fundamental to minimize and prevent the occurrence of accidents and unnecessary exposures.[1]

The objectives of this master's dissertation are to analyse the standard data in the decision support system JRodos which allows the simulation of radioactive emergencies throughout Europe and change it to specific parameters for Portugal, regarding the food chain. This is due to the fact that the model that simulates and predicts the radionuclide contamination and transfer of terrestrial food products and the resulting dose to exposed individuals (Terrestrial Food Chain Model and Dose Module or FDMT) has only implemented standard parameters for Central Europe.[2]

Following an accident in which radionuclides are released into the atmosphere, there are different paths in which individuals may be exposed to radiation: through the external exposure pathway by gamma radiation from radioactive plume and ground material (cloudshine and groundshine), through the inhalation of the same material, through the ingestion of contaminated food, and through absorption of radioactive material deposited on the skin.[3,4]

After the exposure, effects on human health may be immediate or delayed and may be grouped into deterministic or stochastic effects. Deterministic effects are characterized by a dose threshold below which there is no effect and from which damage results. Stochastic effects are randomized and the likelihood of their occurrence increases with increasing dose.[3,5,6] One of the primary goals in responding to a radiological emergency is to prevent the occurrence of deterministic effects. Prevention of stochastic effects is also important, as it is assumed that any dose, even low, may increase the risk of radiation effects.[3]

In emergency situations, reference levels are used instead of dose limits. They are defined as "dose levels, risk, or activity concentration above which it is not appropriate to allow exposures and below which safety and security optimization should continue to be implemented" and they are typically set below 100 mSv effective dose[1].[7,8]

In addition to these levels, there are intervention levels used for foodstuff and feedstuff. This levels refer to a predicted dose that can be reached or exceeded among the population, taking into account certain behaviours, whether a certain protective measure or action has not been taken. However, as the effects of low doses are unknown, it is not possible to specify a limit below which makes the consumption of certain foods safe. For this reason, intervention should only be undertaken if it is justified and optimized by maximizing benefits. A balance between the advantages and disadvantages of making a decision must be done, taking into account social and economic factors.[4,8,9] Maximum permitted levels of radioactive contamination of foodstuffs (CFILs) were set by the Council of the European Communities to ensure uniformity within the European Union (EU) and to protect the population, based on the reference level of 1 mSv per year and the assumption that 10% of the consumed food annually is contaminated.[2,10,11]

Radiological Emergencies and Nuclear Accidents

Radiological emergencies can originate from the misuse and negligence of radioactive sources in health, industry and research, acts of terrorism, among others, and also from accidents at nuclear power plants as happened in Chernobyl and Fukushima, usually involving

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[1] Refers to the effective dose that individuals receive during the first year after an accident and given realistic conditions.

serious deterministic effects for the health of the population and emergency teams.[3,12]

The 1986 Chernobyl accident was the most serious in the history of the nuclear industry, with several radioactive materials being released into the atmosphere and scattered across countries. Deficiencies in the management and response to accidents of this magnitude were detected, namely in response to the public, the lack of monitoring areas, communication networks and decision support systems for off-site emergency management. As a result, a number of actions have been triggered within Europe, including the establishment of research programs and monitoring activities to ensure preparedness for future radiological protection emergencies. One of these actions led to the development of a real-time decision support system for off-site nuclear emergency management called JRodos (Real-time Online DecisiOn Support System).[2,13,14]

This system proved to be useful when it was used in the Fukushima-Daiichi accident and it was possible to estimate radioactive plumes to check if Tokyo was included and how far countermeasures were needed.[15]

Accidents with orphan and industrial sources occur more frequently than nuclear accidents, but as they do not affect the public at a large-scale environment, they are less known among the public. According to world estimates, between 1966 and 2007, approximately 31 orphan source accidents occurred, resulting in the deaths of 42 members of the public including children. As the exact number of orphan sources in the world is unknown, it is estimated that there are many more unreported accidents.[1] Industrial accidents with orphan sources include accidents in steel mills where accidental melting of undetected orphan sources with other metallic waste occurs. 71 of such accidents have been confirmed from the early 1980s to 2000.[16–18] This accident cannot be predicted because some radiation sources are not detected by the detectors portals (if they exist and are in operation) if they are below about 56 cm of metallic waste. Another worrying fact is that the accident is not limited only to the steel mill but also has the potential to impact the environment outside the installation spreading to the atmosphere and consequently to other regions.[16,19]

The Algeciras (Spain) accident occurred on a steel mill in which an ^{137}C orphan source with 3700 GBq was inadvertently melted with scrap. This accident contaminated several facilities, released ^{137}Cs into the atmosphere and generated 5198 tonnes of radioactive waste.[20–22] Figure 1 shows the ^{137}Cs peak of the Algeciras accident, along with the peak of the Chernobyl nuclear accident and the initial variation regarding nuclear weapons testing.

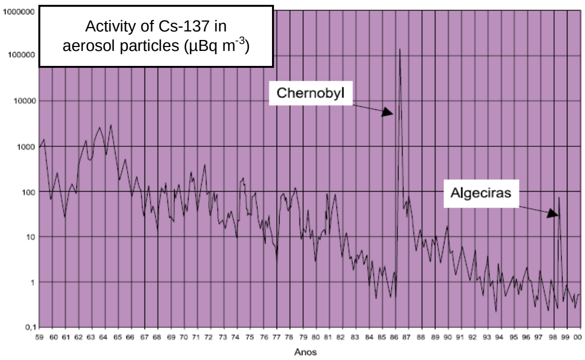


Figure 1: Variation of the activity of Cs-137 in aerosol particles between 1959 and 2000 in Orsayl, France.[37]

FOOD CHAIN RADIONUCLIDE TRANSFER

The atmosphere is one of the fastest ways to spread pollutants, including the radioactive ones. In emergency management in the event of a radiological or nuclear accident, the release of radionuclides into the atmosphere is the main problem as it can rapidly endanger the population through external exposure and inhalation. However, external exposure is not the only concern as internal exposure may occur through contamination of the soil, agricultural areas, animals and animal products that constitute the population's food.[15]

Radioactivity is removed from the atmosphere through three different processes: radioactive decay, dry and wet deposition. Radionuclides, upon deposition, may enter the food chain through direct deposition on exposed leaves or edible parts of plants, through absorption by plant roots and by water.[15,23] The fraction of radionuclides that are incorporated into plants depend on the time of year and the respective weather conditions, as well as on the radionuclide physicochemical characteristics and plant characteristics such as its type and state of development (season).[10,15,24]

Accidents that have the greatest impact on food chain contamination are those in which radionuclides are released in large quantities with long half-lives and are characterized by a high transfer rate to crops and animal products. Cesium (^{137}Cs and ^{134}Cs), iodine (^{131}I) and strontium (^{89}Sr and ^{90}Sr) isotopes are very important in foodstuff after an accident as they meet the characteristics described above and also due to the metabolism in the human body. Iodine is the only with a short half-life of approximately 8 days.[10,13,23]

Depending on the time of year, there will be greater variation in contamination, for example if the accident occurs before harvest or in the summer when animals are grazing outdoor, greater contamination of the animals is more likely than in winter. For animals, their main source of contamination is the ingestion of contaminated feedstuff and soil during grazing which may increase the contribution of radioactivity ingestion.[10,15]

Cesium-137

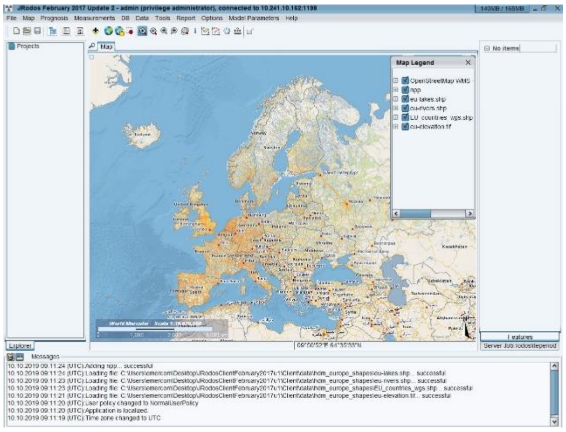
It is one of the most important radionuclides in nuclear accidents due to its potential health effects as it has a relatively long half-life of about 30 years. Exposure to ^{137}Cs can be done externally through gamma radiation from their decay products and internally if swallowed or inhaled. When ingested, it is evenly distributed throughout the body's soft tissues, particularly in the muscles, due to its potassium-like metabolic behaviour. Lower concentrations are found in bones and fat. Based on epidemiological studies, exposure to this radionuclide may result in the appearance of malignant tumours and decreased average life expectancy.[23–26]

JRODOS

The RODOS project started during 1989, and in the first decade its development was concentrated only on the models for the early phases of the emergency. In 2000, the growing importance of the late and rehabilitation phases were recognized, and the first developments of models involving the consequent phases were made. Subsequently based on user feedback, the software was restructured to make it a Java application which changed the name from RODOS to JRodos.[15,27]

The main objective for all users was for JRodos to be a system that provided decision support in the event of a radiological or nuclear accident anywhere in Europe from the early stages of the accident to years or decades after radionuclide release.[14]

It has several built-in chain-operated models, which are the basis for the so-called projects that include all inputs, messages and calculated results. Regarding its interface (figure 2), it has a static window with different components such as the project tree, message panel, properties panel, caption and central panel where can be seen the representation of the results of various types (maps, graphs, tables, text and histograms). It has icons with different functionalities and also has, for time-dependent results, a slider bar for easier viewing on the map and the ability to create time graphs for specific locations.[2,28]



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10.10.2019 09:11:24 (UTC):Adding npp... successful
10.10.2019 09:11:24 (UTC):Loading file: C:\Users\emercom\Desktop\JRodosClientFebruary2017u1\Client\data\hdm_europe_shapes\eu-lakes.shp... successful
10.10.2019 09:11:23 (UTC):Loading file: C:\Users\emercom\Desktop\JRodosClientFebruary2017u1\Client\data\hdm_europe_shapes\eu-rivers.shp... successful
10.10.2019 09:11:23 (UTC):Loading file: C:\Users\emercom\Desktop\JRodosClientFebruary2017u1\Client\data\hdm_europe_shapes\EU_countries_wgs.shp... successful
10.10.2019 09:11:21 (UTC):Loading file: C:\Users\emercom\Desktop\JRodosClientFebruary2017u1\Client\data\hdm_europe_shapes\eu-elevation.tif... successful
10.10.2019 09:11:20 (UTC):User policy changed to NormalUserPolicy
10.10.2019 09:11:20 (UTC):Application is localized.
10.10.2019 09:11:19 (UTC):Time zone changed to UTC
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Figure 2: JRodos graphic interface.

FDMT

FDMT is a model incorporated in JRodos that simulates the transfer of radioactive material and radiation exposure in food chains and, consequently, evaluates the dose by the relevant pathways (internal exposure via inhalation and ingestion, external exposure via plume (cloudshine) and deposition of radioactive material (groundshine) of the population or individually. It performs calculations from the radionuclide concentrations in the air and near ground from the results from atmospheric dispersion models and deposition models. The inputs used that are most relevant for the calculation are: concentration time integrated activity near ground surface; activity deposited by precipitation per unit area of soil and the amount of precipitation if wet deposition occurred and the date of deposition (day, month).[14,29]

FDMT has the ability to calculate activity concentrations in ready-to-eat food and indicates areas where concentrations are expected to exceed predefined levels from the start of the accident to decades later. It is also used to assess the development time of food concentrations in the late phases of an accident, along with meteorological and radiological measurements (radionuclide activity in air, precipitation activity, precipitation amount) where data of the Real-time Radiological Monitoring (EURDEP) from automated surveillance systems from 39 EU countries is used.[2,30]

The products considered in the FDMT can be adapted to specific situations in different parts of Europe. The list contains 21 feedstuffs (17 based on plants and 4 in animal products) and 34 foodstuffs (19 plant and 15 animal products) standard to Central Europe.[29]

A more detailed description of the calculations used and the factors behind the model results can be found in “Model Description of the Terrestrial Food Chain and Dose Module FDMT in RODOS PV6.0”. [29]

METHOLODY

In order to complete this work, firstly it was necessary a research and analysis about the type of accident that would be addressed. As inclusion criteria, it was assumed that the accident would have a probability of happening in Portugal, even if low, and would have to affect the population and the environment in some way to verify its implications. For this reason, the Algeciras accident was chosen as model, an accidental melt of an orphan source along with other metal waste.

To be able to understand the system, several initial simulations were performed according to a learning protocol provided by the Karlsruhe Institute of Technology (KIT). In addition, the JRodos user manual was read and other simulations were made autonomously and exploratory. Various parameters that would need to be modified to adapt to national conditions were identified, however, it was not possible to obtain sufficient relevant information to change them.

Foodstuff and feedstuff

Research was carried out on the subject of Mediterranean diet and on agricultural statistics in order to obtain the typical Portuguese products produced in greater quantities. It was concluded that wheat, maize, rice, rye, tomato, potato, cabbage, pumpkin, apple, pera rocha[2], orange, wine, olive oil, beef, pork, chicken, cheese and milk were the most commonly produced foods and used in the Mediterranean diet.[31] Crossing these foods with those implemented in the FDMT, the selected ones for the simulations were: rice, summer and winter wheat, summer and winter rye, maize, leafy vegetables, root vegetables, fruit vegetables, fruit, meat. beef, pork and chicken. In addition, grass, hay, maize, summer and winter wheat and rye were chosen as feedstuff.

The next step would be to create a radiological scenario in JRodos.

Location

The choice of the accident location was based on the type of accident. There were only two sites where large-scale metal smelting (Siderurgia Nacional do Seixal and Siderurgia Nacional da Maia) were used. ArcGis (Architecture Geographic Information System), using information contained in Carta de Ocupação dos Solos[3], was used to choose which site had the most surrounding agricultural zones and the Siderurgia Nacional do Seixal was chosen. The main reason was that this was a region composed mainly of irrigated areas in which the cultivation and production of fruit and vegetables (fruits, vegetables, legumes, among others) prevails, which is in agreement with the most consumed and produced food products.

Source Term

The source term is a set of parameters such as radionuclide type and activity, which are later used for dose calculation. A 75 TBq ^{137}C source was chosen, which is the typical activity of a ^{137}C radioactive source used in the industry.[25]

In this scenario, the distribution of this radioisotope is majorly to the gases and dust, (> 99%) so radioactivity is confined to the facility's gas cleaning systems. Very little is retained in molten materials or slag (<1%) and therefore, is not easily detected.[19] A typical steel mill can remove 99% of the dust from the gas stream and thus it is estimated that the amount emitted into the atmosphere is in the order of 1% of the total amount that has been melted in the furnace. Since JRodos does not have a specific scenario for this situation, a fire scenario was used. It was assumed that there was no filtering of outward dust and gases and no partition correction was made, so it is assumed that 100% of the ^{137}Cs are in the dust and released to the atmosphere in order to consider the worst case scenario.

Meteorological data

The parameters set for wind direction were chosen according to the predominance in that

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[2] A local variety of pear.

[3] Land Ocupation Document

zone of Portugal (315º and 270º) and according to the worst case scenario (225º) in which more agricultural areas would be affected.[32] Regarding wind intensity, it was chosen the average over the last 30 years (4m/s) and two other intensities, one below 4 m/s (2m/s) and one categorized as IPMA[4] (Instituto Português do Mar e da Atmosfera) yellow warning (20m/s).[33,34]

Atmospheric stability has been described and chosen by Pasquill classification and taking into account the wind intensity.[35]

Regarding precipitation, three conditions were chosen, one without precipitation or dry conditions (0 mm/h) and other two (10 mm/h and 30mm/h) taking into account the IPMA criteria for weather warnings.[34]

RESULTS AND ANALYSIS

315º Wind Simulations

Firstly, simulations were performed corresponding to the 315º wind direction. The ground contamination information (Bq/m²) was taken into account by both wet and dry depositions.

A cell that was representative of the simulation was chosen. That cell had to be mostly composed of agricultural zones and closest to the epicentre of the accident (cell 1077). According to the graphic of figure 3, corresponding to the simulation results, it was found that those with the highest contamination (of about 50 000 Bq/m²) had wind intensities of 2 and 4 m/s, precipitation of 10 and 30 mm/h and atmospheric stability B.

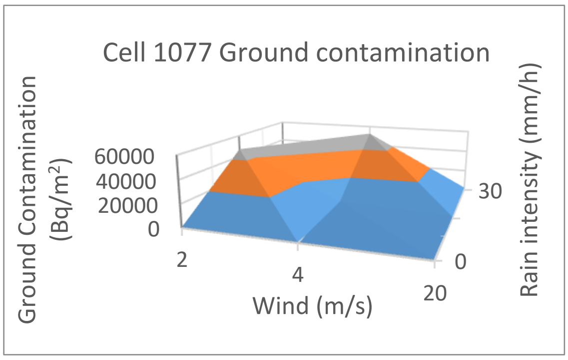
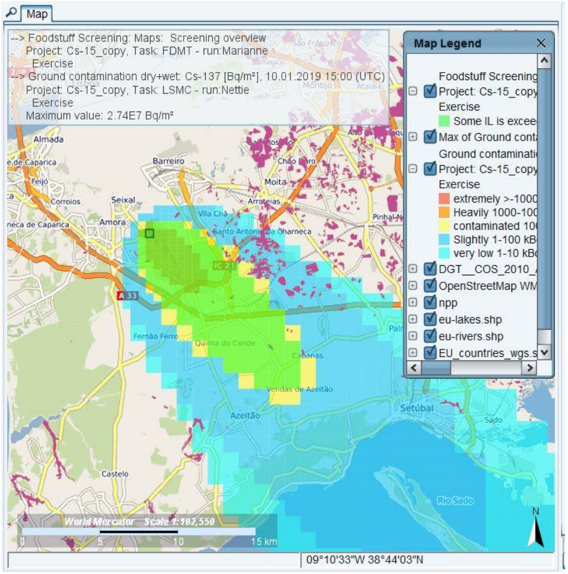


Figure 3: Ground contamination on cell 1077 from 315º wind simulations.

Concerning intervention levels, some were exceeded, namely in winter wheat, rye, leafy vegetables, fruits and cow's milk. In figure 4 it is possible to visualize the chosen cell together with the levels of contamination with the different colours (extremely contaminated, heavily contaminated, contaminated, slightly and very low) and in green where the intervention levels were exceeded.



```
--> Foodstuff Screening: Maps:  Screening overview
.   Project: Cs-15_copy, Task: FDMT - run:Marianne
.     Exercise
--> Ground contamination dry+wet: Cs-137 [Bq/m²], 10.01.2019 15:00 (UTC)
.   Project: Cs-15_copy, Task: LSMC - run:Nettie
.     Exercise
.   Maximum value: 2.74E7 Bq/m²
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Figure 4: Example of the results representation of the ground contamination (315º wind simulations), chosen cell and the intervention levels exceeded in light green.

225º Wind Simulations

The simulations were repeated, for the wind direction 225º. A different cell with the same characteristics as before (1326) was chosen.

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[4] Portuguese Institute of Sea and Atmosphere

According to the graph in figure 5, the three simulations with the highest ground contamination (about 900 000 Bq/m^2) had wind intensities of 2 and 4 m/s, precipitation of 10 mm/h and atmospheric stability of B, C and D.

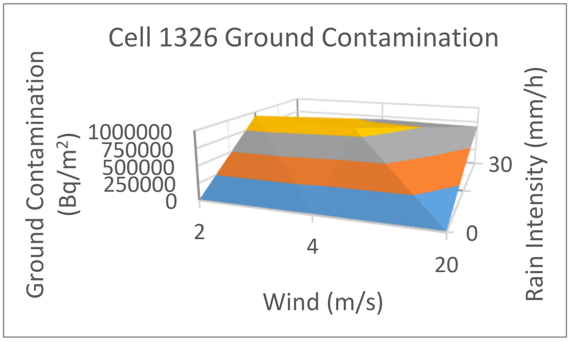

Figure 5: Ground contamination on cell 1326 from 225º wind simulations.

Intervention levels were exceeded in the following foodstuffs: winter wheat, rye, potatoes, leafy vegetables, root vegetables and fruit vegetables, with leafy vegetables having the highest value (964 000 Bq/kg) relatively to its intervention level (1 250 Bq/kg).

Figure 6 shows the representation of the results on the map along with the chosen cell location and where the intervention levels were exceeded.

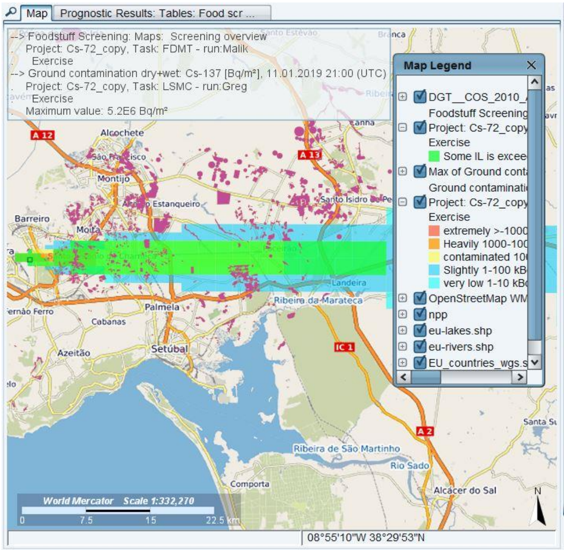
--> Foodstuff Screening: Maps: Screening overview
Project: Cs-72_copy, Task: FDMT - run:Malik
Exercise
--> Ground contamination dry+wet: Cs-137 [Bq/m²], 11.01.2019 21:00 (UTC)
Project: Cs-72_copy, Task: LSMC - run:Greg
Exercise
Maximum value: 5.2E6 Bq/m²

Figure 7: Example of the results representation of the ground contamination (225º wind simulations), chosen cell and the intervention levels exceeded in light green.

Again the simulations were repeated, but for the wind direction 270º and a new representative cell of the simulation was chosen.

According to the graph in Figure 7, the simulations with a higher maximum contamination value (of about 1 400 000 Bq/m^2) had as parameters wind intensity of 2 and 4 m/s, rain intensity of 10 mm/h and atmospheric stability of C, D and E.

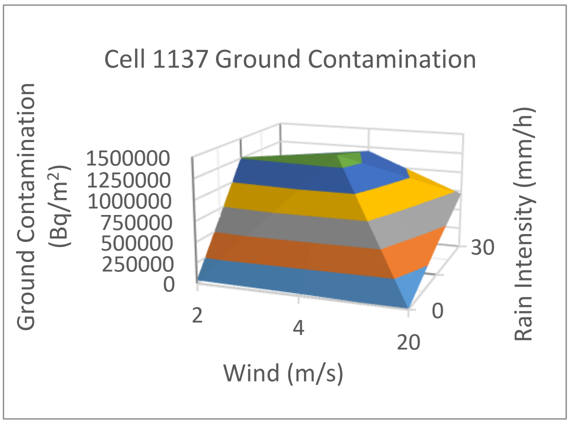

Figure 6: Ground contamination on cell 1137 from 270º wind simulations.

Regarding intervention levels, only leafy vegetables exceeded them, with a maximum value of 302 000 Bq/kg.

Figure 8 shows the representation of the results on the map, the location of the cell and where the intervention levels were exceeded.

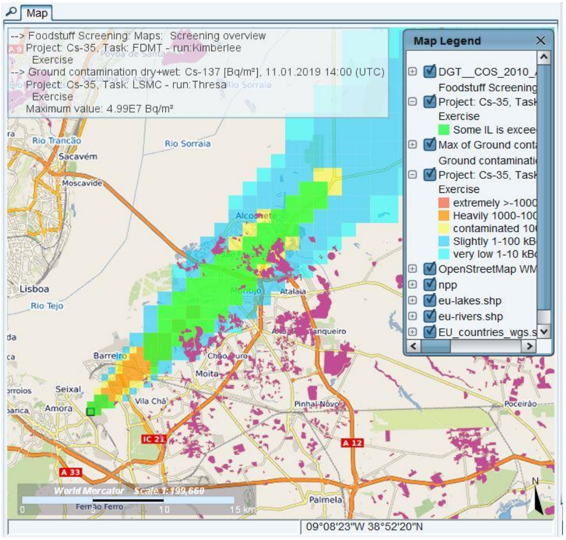
--> Foodstuff Screening: Maps: Screening overview
Project: Cs-35, Task: FDMT - run:Kimberlee
Exercise
--> Ground contamination dry+wet: Cs-137 [Bq/m²], 11.01.2019 14:00 (UTC)
Project: Cs-35, Task: LSMC - run:Thresa
Exercise
Maximum value: 4.99E7 Bq/m²

Figure 8: Example of the results representation of the ground contamination (270º wind simulations), chosen cell and the intervention levels exceeded in light green.

DISCUSSION AND CONCLUSIONS

In early stages of an accident, management options and responses should be made quickly for the most sensitive food products such as leafy vegetables, which if contaminated at the time of harvesting, there is a risk that the superficial edible parts will be contaminated.

There are countermeasures that can be taken on contaminated food, such as applying products to the soil to decrease radionuclide absorption (e.g. potassium-rich fertilizers to reduce ^{137}C absorption), food processing (decreases final activity concentrations), removal of crops immediately after deposition, removal of upper soil layers, restriction of sale and consumption, among others. However, the last three countermeasures generate a large amount of radioactive waste which causes environmental problems as well as economic and social problems.[10] For these reasons, countermeasures should be taken according to the intervention levels and consciously taking into account socio-economic factors. In defining and justifying these levels, consideration should be given to the dose-risk balance for stochastic effects and dose-response for deterministic effects. The severity of interfering with the normal life of individuals (routine disruption) as a consequence of the measures taken and the level and range of natural radiation exposure should be taken into account too.[8]

With this master's dissertation, it became evident that in the event of a radiological or nuclear accident occurring in Portugal or affecting Portugal, JRodos is a fundamental instrument for emergency management and response. In particular, it should be used to ascertain prognoses regarding foodstuff and regarding doses resulting from ingesting them, because the knowledge of the contamination levels over time is necessary to accident management.[15]

Regarding the customization of the simulations in JRodos, the parameters used, namely the meteorological data, are dominant conditions in Portugal and only served to verify the scenarios that were more likely to happen. Taking this into account, it can be concluded that the weather conditions that resulted in the highest contamination levels in the chosen cells were low wind intensities of 2 and 4 m/s, always under precipitation conditions that varied between 10 mm/h. and 30 mm/h and under atmospheric stability conditions ranging from moderately unstable to slightly stable.

The cells chosen were mostly irrigated agricultural areas, and in this type only products such as fruits, leafy vegetables, root vegetables and sometimes maize are produced. In the case of foodstuffs whose intervention levels have been exceeded, only wheat and rye can be discarded as they are not normally produced in irrigated agricultural areas. It is also important to note that in the simulations performed, the results presented are overestimated since the steel mills usually have filtration and cleaning systems which, in the event of an accident with ^{137}Cs, only 1% is released to the atmosphere.[19]

When exploring the JRodos system at various levels, it was possible to notice some inconsistencies in the results that were given, namely in the foodstuffs that exceeded the intervention levels. There are other reported problems in dose determination due to dose overestimation of contaminated food intake. One of these problems lies in the fact that for a given individual in industrialized societies there is a constant change in the distribution pattern between the origin of production and the consumer.

FUTURE CONSIDERATIONS

Although most foodstuffs, except turkey meat, olive oil and wine, are on the JRodos FDMT food list, it would be necessary to further optimize the system, such as creating radioecological regions and optimizing some parameters, such as harvest times, crop yields and plant production rates, typical diets, inhalation rates and animal production rates, and population consumption rates as feeding habits, weather conditions and animals are relatively different from region to region.[14]

In the future, it would also be necessary not only to consider irrigated areas as agricultural zones but some others too, add important foodstuffs for Portuguese industry and consumption such as wine and olive oil and acquire the necessary parameters for the customization of the system. However, it would be important first to understand to what extent one can consider grapes and olives as fruit and add only the processing factor to olive oil and wine.

Afterwards it is necessary to perform the simulations with these new parameters and foodstuffs to verify if it is correct and, if possible, to compare with another model of the food chain. With this, if an emergency that affected the national territory occurred, Portugal would have a support system for decision with the food chain model best suited to their national conditions.

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