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Research

Updated radiological risk assessment for the “Radon” type surface disposal facility in Chisinau, Moldova

2021:03

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SSM perspective

Background

Bilateral cooperation between Sweden and the Republic of Moldova in nuclear and radiological safety and security has been ongoing since 2010, focusing on activities aimed at strengthening the institutional capacity of the National Agency for Regulation of Nuclear and Radiological Activities in Moldova (NARNRA) as well as infrastructure development in radioactive waste management, handling and treatment at the Radioactive Waste Management Company`s Special Facilities 5101 and 5102.

In 2019, SSM funded development of a geoscientific and radiological measurement program at the National Radioactive Waste Management site outside Chişinău and provided assistance in carrying out an environmental and radiological risk assessment of a near-surface Radon-type facility of historical radioactive waste at the site (Radiological risk assessment for the "Radon" type surface disposal facility in Chişinău, Moldova, SSM Report 2019:12). The objective of the risk assessment was to support future governmental decisions on the possible retrieval and treatment of this legacy waste. The assessment addressed potential future radiological consequences of the disposal facility, i.e. the consequences of migration of various radionuclides for staff, population and the environment, for the case where the disposal facility will remain as before (the zero alternative scenario).

Results

This report is an update of the previous environmental and radiological risk assessment and is funded by the Swedish International Development Agency (SIDA) as part of a project on design and construction of a storage facility for radioactive waste at the National Radioactive Waste Management in Moldova. The updated assessment comprises a dynamic biosphere model based on the site specific data that is compared to the simplified model used in the previous report. In addition, the effect of neglecting interception in the irrigation is evaluated and a set of fully probabilistic simulations and sensitivity analysis are conducted. The updated report confirms the results of the previous assessment of potential radiological impacts of the disposal facility, but also identifies areas that may be considered for further model development.

Relevance

This study is relevant for other countries in the former Soviet Republic with similar legacy radioactive waste disposal sites and so has a wider significance. The combination of the ISAM and updated BIOMASS methodologies and the use of GIS techniques to provide detailed site-specific data from the digital elevation model for the local topography illustrates how practical limits for the well dilution can be estimated from topographic maps of the kind that are often available from national geographic surveys. The used methods here – based on a straightforward interpretation of water balance – can be used to bound well dilution as a first approximation to site-specific conditions. Model results can therefore be used as part of a screening process to determine if more detailed site investigation might be needed. This demonstrates a significant improvement compared to earlier approaches before the advent of GIS (geographic information systems) methods. As a relatively simple and inexpensive approach it has much to recommend it for preliminary studies of potential radiological impact.

Need for further research

Environmental and radiological risk assessment for legacy radioactive waste disposal facilities are essential for decision-making on remediation and retrieval activities. This study demonstrate the use of a simplified approach to guide decision-making on retrieval and remediation. Depending on factors such as the inventory, properties of the disposal facility and its setting and potential radiological consequences, further research may be warranted to justify simplified approaches. There remain significant uncertainties in the representation of the near-surface hydrology that could be addressed by further research.

Project information

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Reference: SSM2019-12

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Content

1. Introduction

This report is an update of the previous report (Xu and Kłos, 2019) and includes improved model descriptions and simulations in respective of the following:

- A dynamic biosphere model based on site specific data compared with the simpler approximation used in the previous report
- The effect of neglecting interception in the irrigation
- A set of fully probabilistic simulations and sensitivity analysis.

The RADON-type Central Radioactive Waste Disposal Facility (CRWDF) was established by a special decree, issued by the Government of the USSR on 15 October, 1960. The architecture of the facility is similar to those which were established also in other Republics of the former Soviet Union. The disposal of radioactive waste in Moldova began in 1961.

The long-term conditions and potential radiological consequences of the legacy radioactive waste stored in the RADON-type disposal facility outside Chişinău (Special Facilities 5101, 5102) is of concern for the central government authorities of the Republic of Moldova. Radiological investigations performed by the National Center of Preventive Medicine in 1998 showed increased contamination of radionuclides Sr-90 and Ra-226 of soil and groundwater in the vicinity of the disposal facility.

Swedish Radiation Safety Authority (SSM) supported a collaborative project during 2017-2018 with the aim of developing a site descriptive model for the near-surface disposal facility and its surroundings that could serve as a basis for developing a radiological safety assessment. Site characterisation and compilation of an inventory have been completed and documented in three reports, "Geomorphological and infrastructure assessment of the radiological object", "Relevant data about the near-surface disposal facility "RADON" and the site RWMC in Chişinău" as well as "Hydrogeological and geotechnical conditions of radioactive waste deposit from Uzinelor 210 str. mum. Chişinău , objects 5101 and 5102". Hereafter, they are mentioned as "Radiological Object Report", "Site Report" and "Hydrogeological Report".

Xu Environmental Consulting AB is requested by SSM to perform a radiological risk assessment of the "zero alternative scenario" for the RADON-type of near-surface disposal facility, to determine the implications of carrying out no remedial actions at the site. The objective of this risk assessment is to assess the long-term safety conditions of the facility and its potential radiological impact on humans and the environment as well as to provide a basis for decision making regarding the decommissioning of the legacy radioactive waste.

In this assignment we adopted ISAM and BIOMASS methodologies to perform the risk assessment for the RADON-type of near-surface disposal facility. In 1997, IAEA launched a Co-ordinated Research Project on Improvement of Safety

Assessment Methodologies for Near Surface Disposal Facilities (ISAM). The particular objectives of the project were to:

- provide a critical evaluation of the approaches and tools used in post-closure safety assessment for proposed and existing near-surface radioactive waste disposal facilities;
- enhance the approaches and tools used;
- build confidence in the approaches and tools used.

The project ran until 2000 and resulted in the development of a harmonised assessment methodology – the ISAM project methodology (IAEA 2004a,b) shown in Fig. 1, which was applied to a number of test cases. The ISAM project primarily focused on developing a consensus on the methodological aspects of safety assessment, especially i) specification of the assessment context, ii) description of the waste disposal system, iii) development and justification of scenarios, iv) formulation and implementation of models and v) analysis of results and building confidence. However, given the resource constraints in the ISAM project, illustration of the application of the methodology is limited to an interpretation of the Test Cases, for example, the resulting models are not site-specific in that they are not descriptive of a single site but are more generically applicable to sites with arid climates.

The IAEA Programme on BIOsphere Modelling and ASSessment (BIOMASS) was launched in 1996 (IAEA 2003a). The programme was concerned with developing and improving capabilities to predict the transfer of radionuclides in the environment. The objective was to develop the concept of a standard or reference biosphere for application to the assessment of the long-term safety of repositories for radioactive waste (see Fig. 2). Subsequent development of the methodology is being being published (IAEA, 2020) and key features of the revised methodology are also applied in this project.

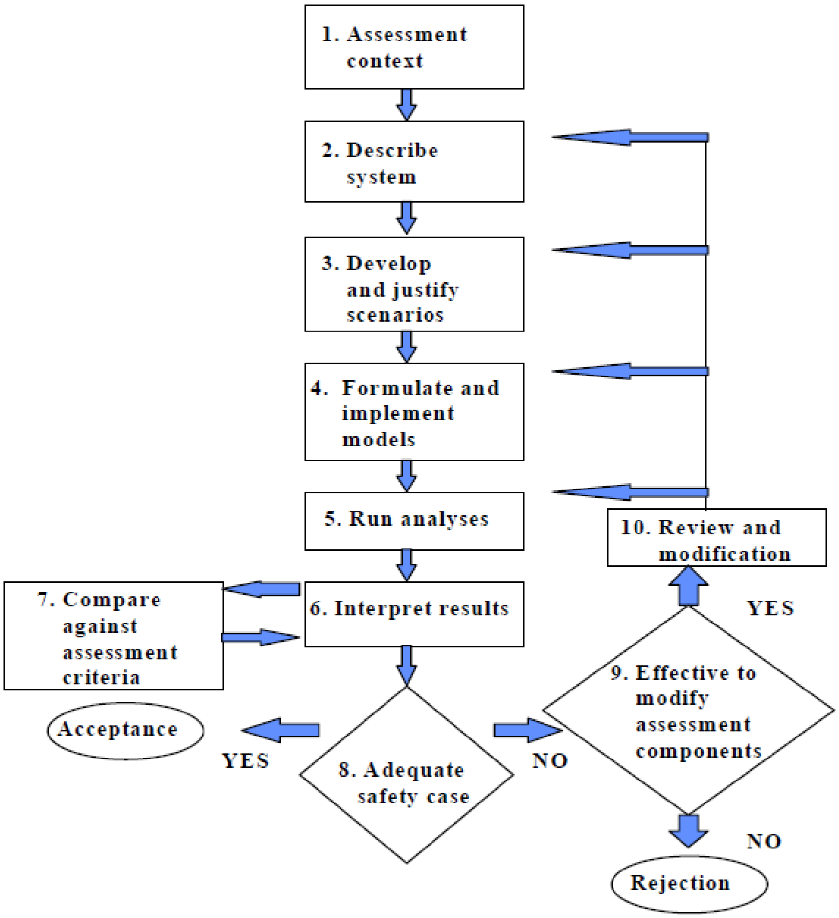


Fig. 1 The ISAM project methodology (IAEA 2004a)

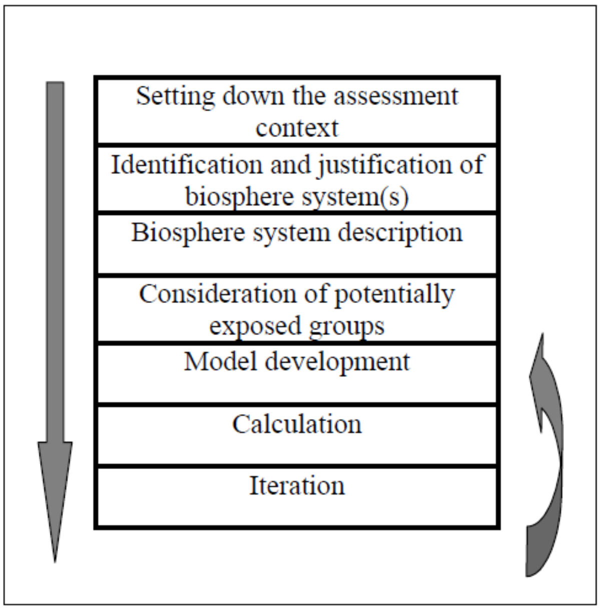


Fig. 2 The BIOMASS methodology (IAEA 2003a)

2. Assessment context

This chapter describes the performance of the first step, Assessment Context according to the ISAM methodology (see Fig. 1).

2.1 Purpose of the assessment

The long-term conditions and potential radiological consequences of the legacy radioactive waste stored in the RADON-type disposal facility outside Chişinău (Special Facilities 5101, 5102) is of concern for the central government authorities of the Republic of Moldova. Radiological investigations performed by the National Center of Preventive Medicine in 1998 showed increased contamination of radionuclides Sr-90 and Ra-226 of soil and groundwater in the vicinity of the disposal facility.

The objective of this risk assessment is to assess the long-term safety conditions of the facility and its potential radiological impact on humans and the environment as well as to provide a basis for decision making regarding the decommissioning of the legacy radioactive waste.

2.2 International guidance

Currently the legal framework in the field of radioactive waste management in Moldova is under development. For the time being, there are no legal requirements for undertaking risk assessments for near-surface disposal facilities. Therefore, this risk assessment is based on the international standards and best practices.

The specific criteria of the near-surface disposal set in IAEA SSR-5 (IAEA 2011) are:

- A disposal facility (considered as a single source) is so designed that the calculated dose or risk to the representative person who might be exposed in the future as a result of possible natural processes affecting the disposal facility does not exceed a dose constraint of 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year.
- In relation to the effects of inadvertent human intrusion after closure, if such intrusion is expected to lead to an annual dose of less than 1 mSv to those living around the site, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted.
- If human intrusion were expected to lead to a possible annual dose of more than 20 mSv (see ICRP 2007, Table 8) to those living around the site, then

alternative options for waste disposal are to be considered, for example, disposal of the waste below the surface, or separation of the radionuclide content giving rise to the higher dose.

- If annual doses in the range 1–20 mSv (see ICRP 2007, Table 8) are indicated, then reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimization of the facility's design.

The key components of the methodology for the radiological impact assessment after closure set in International Atomic Energy Agency SSG-29 (IAEA 2014) are:

- A systematic description of the disposal system;
- Identification of the various features, events and processes that may affect how the facility will perform and evolve;
- Identification of scenarios for evolution of the site;
- Conceptual, numerical and computer models of relevant parts of the disposal system (e.g. the waste in the near field, the engineered barriers, the host rock and the surface environment of the facility).

2.3 Assessment philosophy

In order to provide a basis for decision making regarding the decommissioning of the legacy radioactive waste this assessment is supposed to use as much site specific data as possible. SSM suported a site investigation project during 2017-2018 that aims to develop a site descriptive model for the near-surface disposal facility and its surroundings. The site investigation was documented in three reports as mentioned previously. Furthermore, instead of using a stylised biosphere object as recommended in the ISAM approach a realistic biosphere object based on site specific topographic information was identified (details are given in section 4.3).

The main endpoints of the assessment are calculated annual effective doses to humans and environmental concentrations. The calculated annual effective doses are compared with the specific criteria given in section 2.2 and environmental concentrations are compared with Environmental Media Concentration Limits (Brown et al., 2014).

2.4 Timeframes

In this assessment, as with most of safety assessments (IAEA 2004a), a 300 year institutional control period is assumed. Fig. 3 illustrates the radioactivity as a function of time. As can be seen in the figure, Cs-137 dominates radioactivity at the beginning but decays to an insignificant level after 100 years. After that Pu-

239 dominates. It has been shown in the figure that 4% of the total activity remains after 100 000 years.

Fig. 4 shows the radiotoxicity as a function of time. One way to describe the radiotoxicity is by calculating the committed effective dose from ingestion of radionuclides directly. The radiotoxicity of the nuclear waste can be considered as a basis for the risk assessment timescale. The radiotoxicity in the waste disposed in the disposal facility is dominated by long-lived radionuclide Pu-239. Fig. 4 shows that about 10% of radiotoxicity remains after 100 000 years.

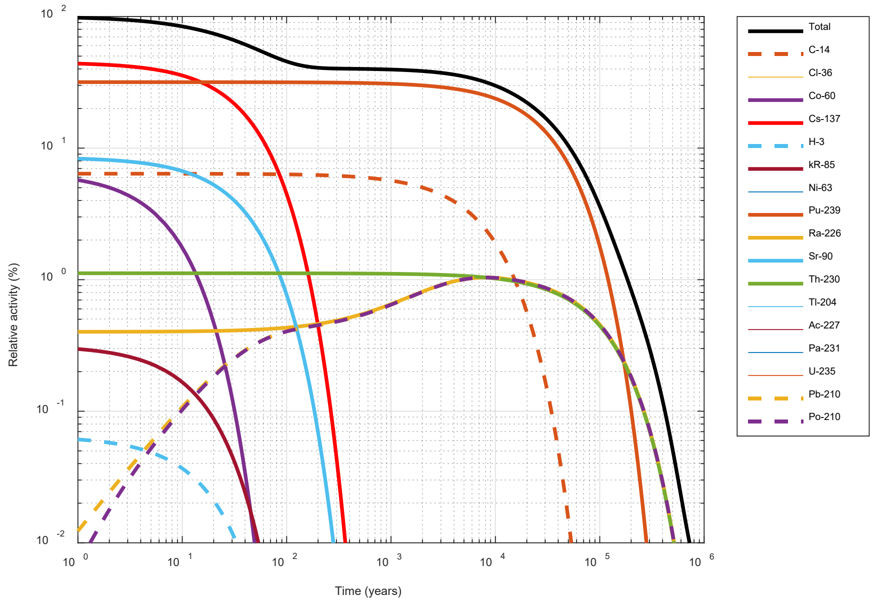


Fig. 3 Percentage contribution to the total activity as a function of time.

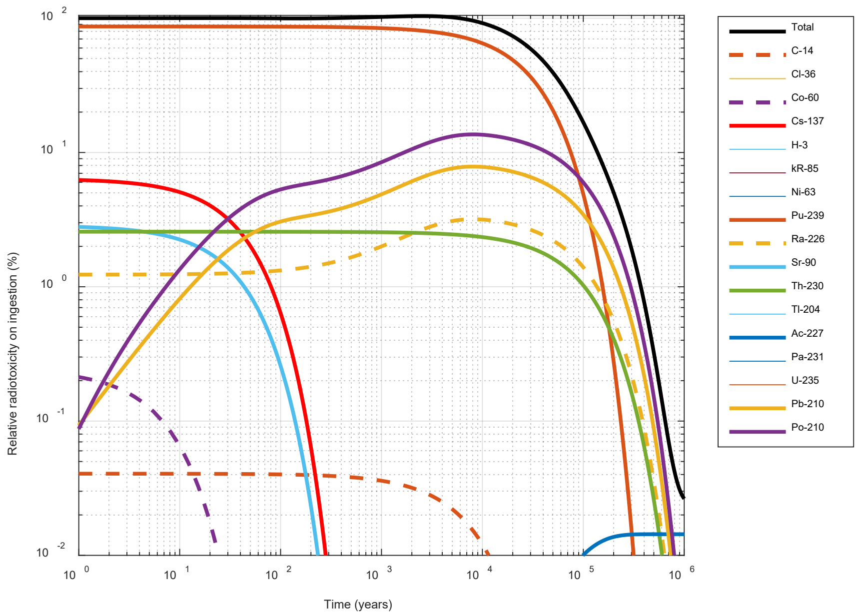


Fig. 4 Percentage contribution to total radiotoxicity as a function of time.

3. System description and site characteristics

This chapter describes the whole system that includes descriptions of the disposal facility and the site characteristics according to the ISAM methodology (see Fig. 1).

3.1 Description of the waste disposal facility

In the Site Report the radioactive waste disposal facility is described. The facility essentially consists of four reinforced concrete vaults for solid waste disposal and covers an area of 75 m^2 (15 m × 5 m). As the depth of the Vaults is 3 m, the total disposal capacity reaches 225 m^3 (see Fig. 5).

The vaults, numbered I to IV, are covered by prefabricated reinforced concrete panels (width about 80 cm, height about 24 cm). The panels were placed on the concrete crown of the vaults (about 8 cm height). Gaps of around 10 cm width between two panels were sealed with cement mortar (concrete). In the middle of the top of the Vaults there are opening lids to load the waste. The size of the lid is about 900 × 1400 mm, the size of the opening covered by the lid is about 700 ×1200 mm (see Fig. 6). With the assumption of the 35 cm wall thickness around the Vaults and between the compartments, the inner side lengths of the Vaults would be respectively 360, 380, 310, 360 cm, and the width is 430 cm. Based on the pictures taken on the inner content of Vault IV, the depth of the Vault would be about 2.75 m, so the capacity of the four Vaults can be estimated to be 42, 45, 36 and 42 m^3. The total capacity estimated is about 165 m^3.

Regarding the shape and position of the loading hole, the Vault cannot be filled completely, since wastes were only thrown in through the opening without special placement measures, hence Vault I, II and IV could be filled by around 30 m^3 of waste each, while Vault III could be filled up by about 20 m^3 waste. Taking into account that Vault III is filled up only by 70 % of its capacity, and Vault IV contains only 1 m^3 waste, the total volume occupied by the disposed waste is around 75 m^3.

Four vaults do not provide satisfactorily isolation (see Fig. 7). According to the operator's description an elevated groundwater table was observed inside the vault IV during the late '90s (Site Report, p. 95). As noted above, radionuclides Sr-90 and Ra-226 in soil and groundwater in the vicinity of the disposal facility were detected by the National Center of Preventive Medicine in 1998.

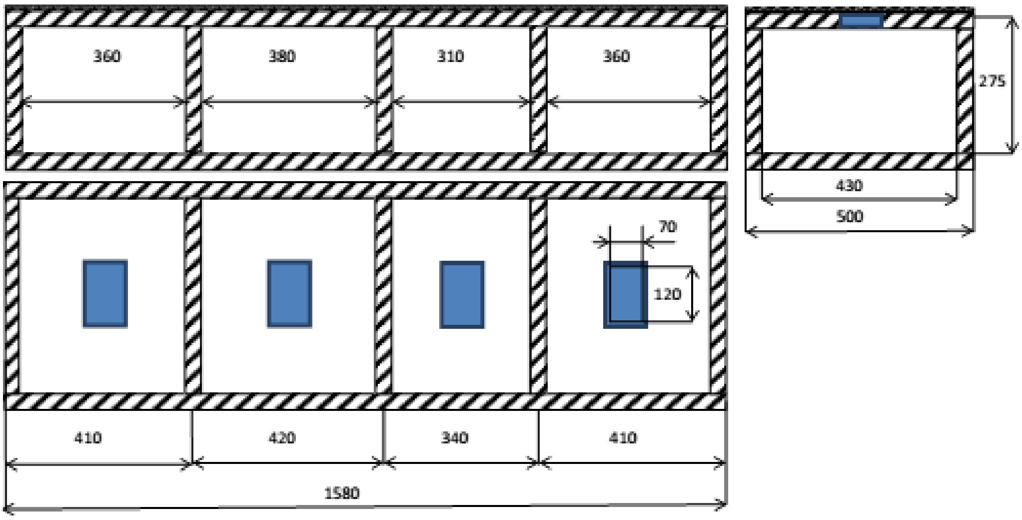


Fig. 5 Vault layout and cross section.

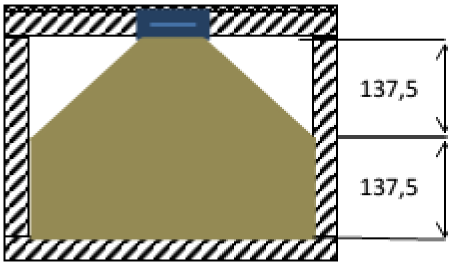


Fig. 6 Schematics of waste position in the vault.

Fig. 7 Condition of the facility (Site Report, p.88).

The activities of the isotopes are summarised for each vault and each waste form. The waste packages are mainly categorised in three categories:

- Unstable waste form,
- Stable waste form,
- Disused Sealed Radiation Source (DSRS).

All vaults and waste type specific data are presented in the Table 1.

3.2 Site characteristics

The near-surface disposal facility is located in the Chişinău municipality, and the terrain adjacent to the facility falls within the limits of the city, Chişinău within an area of 454.83 ha. The location of the disposal facility is shown bordered by the white boundary and the studied site by the red boundary (see Fig. 8).

3.2.1. Hydrogeological and Geotechnical conditions of studied site

The Hydrogeological Report describes hydrogeological and geotechnical conditions at the site. The surface is characterised by the different inclination (see Fig. 9) from middle (between 3 and 6 grade) to intensive slope inclination (more 6 degrees). The neighbouring terrain is characterised mostly by high inclination (more 6 degrees). The elevation in the internal terrain of the site varies from 81 to 118 m. The outside neighbouring terrain is characterised by the altitude from 81 to 130 m. The greatest slopes are found towards the south and east part of the study area.

Table 1 Vault and waste type specific inventory (Bq) estimated for 2015.

Vault No.	I		II			III		IV	
Waste type	Unstable	DSRS	Unstable	Stable	DSRS	Unstable	DSRS	Unstable	DSRS
^{3}H			2.93E+08	1.94E+08				4.00E+06	
^{14}C	3.68E+08	2.76E+08	4.06E+10	5.91E+09	7.36E+08	7.08E+08			
^{36}Cl							3.70E+07		
^{60}Co	2.44E+05	5.84E+07	1.94E+10	7.04E+07	2.98E+10	4.06E+07	2.03E+08		1.08E+08
^{63}Ni									3.07E+04
^{85}Kr					1.28E+09		4.29E+08		7.01E+08
^{90}Sr	4.20E+07	1.50E+08	1.98E+10	2.91E+08	3.24E+10	4.06E+07	1.16E+10		4.36E+08
^{137}Cs		2.33E+07	1.58E+08	7.33E+08	3.08E+11	4.11E+08	1.74E+10	1.28E+04	1.47E+10
^{204}Tl		2.19E+05		2.57E+05	1.03E+05				
^{226}Ra	1.92E+09		2.18E+07	3.66E+06	1.10E+09	3.66E+06			3.43E+06
^{230}Th					8.51E+09				
^{239}Pu		1.11E+09			1.43E+11		9.42E+10		2.98E+09

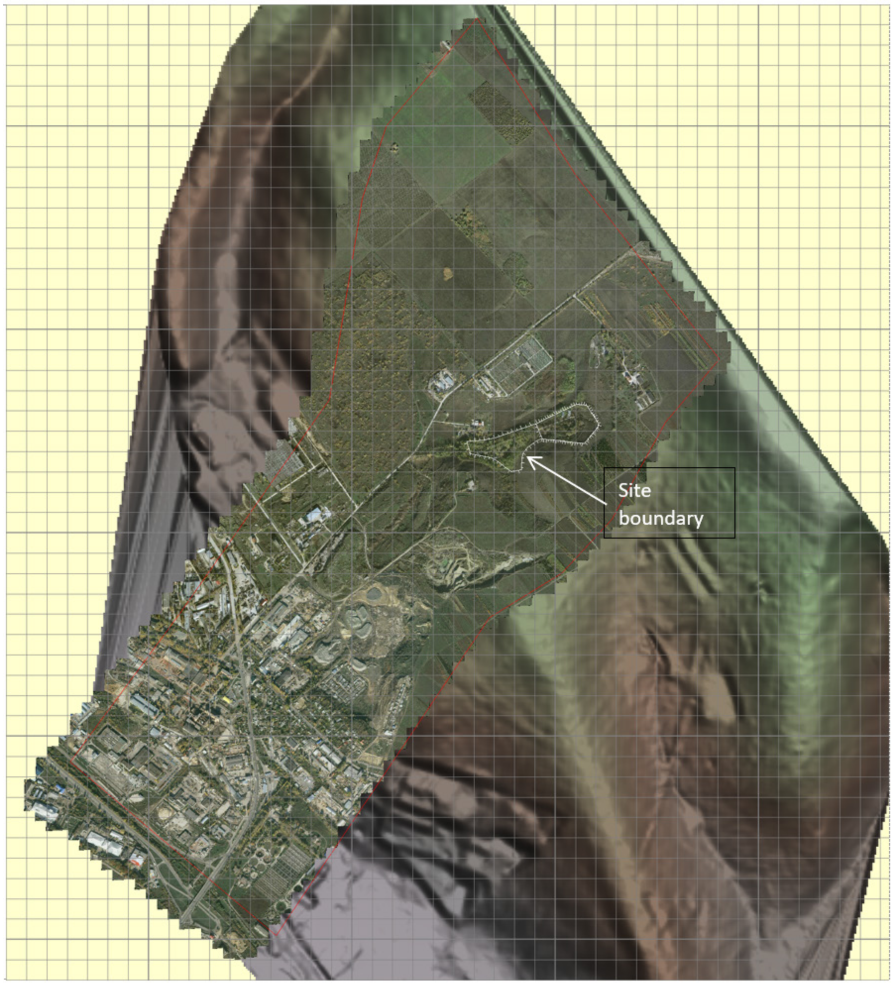


Fig. 8 Map of the site. The location of the disposal facility is shown bordered by the white boundary.

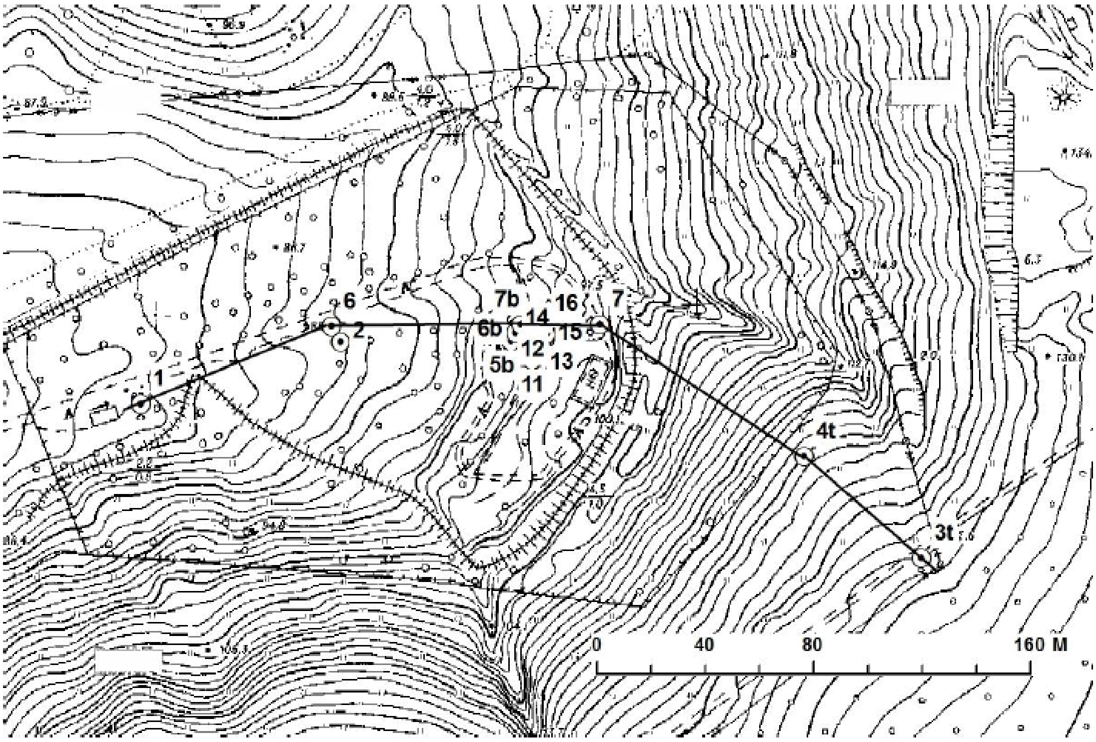
The upper part of geological section is characterised by small thickness of Quaternary loam and Neogene sandy-clay formation. These rocks are covered by agriculture (layer 1) and artificial (layer 2) soils. Quaternary loam (layer 3) has no subsidence properties. The Neogene formation comprises sandy loam (layers 4, 7) layered with clay and clay layered with sands (layers 5, 6). The upper parts of the clays, which are located at slopes with high inclination, are intensively fractured. The location of geological layers is presented in the geological section (Fig. 10). This clay is dense, dry, semi dry, fractured, with fine sand layers and carbonate inclusions. The groundwater can seasonally form at shallow depth (under flooding) due to the presence of clays at shallow depth (3-4 m).

The hydraulic conductivity (filtration coefficient) varies from 0.1 to 1.0 m/day for sandy loam in the aeration zone and from 0.5 – 1.5 m/day in water saturated zone. The clay with sand layers has different values in horizontal and vertical directions. The effective porosity is about 0.4. The filtration coefficient of horizontal oriented fine sand layers ranges from 0.2 to 0.5 m/day. The filtration coefficient for clay layers is changed from below of 0.001 m/day for dense clay layers to 0.4 /day for fractured clay layers. The filtration characteristic of the aeration zone varies over a large interval and depends on the degree of the fracturing and stratification.

Groundwater is situated at different levels: from 1.5 to 11.0 m (elevation 81.0 – 88.6 m above the sea level, WGS84). Rising groundwater is indicated by its appearance at the 1.3 – 1.8 m level and this is seen to occur during the wet season, with an unfavourable influence on slope stability. The principal water bearing rocks are sandy loam, which show a fluid consistency (a liquid state according to Atterberg limits) in saturated zone. The groundwater is aggressive to concrete according to water quality analysis: sulphates 955 mg/L, hydrocarbonate 8.11 mg-eq/L.

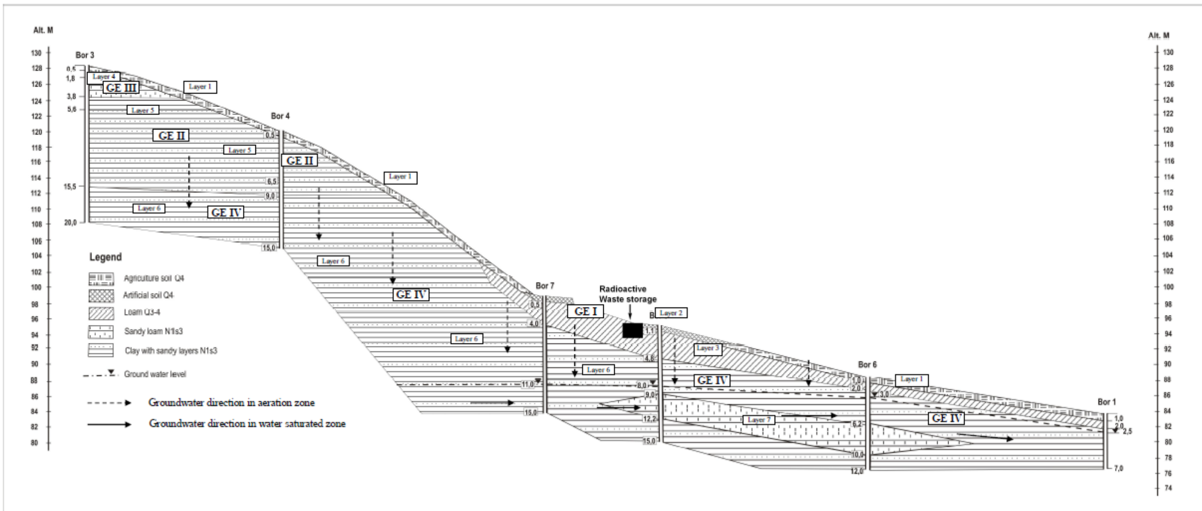
Rocks were separated into four geotechnical elements (GE):

- GE I – quaternary loam (layer 3)
- GE II – fractured neogene clay (layer 5)
- GE III – sandy loam (layer 4)
- GE IV – neogene dense clay (layer 6).



Executed	Bogdevici O.		Object: Hydrogeological and geological conditions for radioactive waste deposit from Uzinelor 210 str. mun. Chișinău	Page	Scale
Verified	Bogdevici O.		Map of actual material	1	1:2000

Fig. 9 Map of actual materia (Hydrogeological Report).



Scale horizontal -1:1000; vertical – 1:400

Borehole.	3		4		7		5		6		1
Elevation m	128,29		120,0		99,2		95,2		88,5		83,5
Distance, m		57,0 m		85,0 m		37,0 m		66,0 m		75,0 m	

Executed	Bogdevici V.		**Object:** Hydrogeological and geological conditions for radioactive waste deposit from Uzinelor 210 str. mun. Chișinău
Verified	Bogdevici O.		**Geological section by line I – I'**

Fig. 10 Geological section by line I-I' (shown in Fig. 9)

3.2.2. Meteorological data

In the Republic of Moldova, the systemic observations on climate indices started in 1886 and have continued via the hydro-meteorological monitoring network of the State Hydrometeorological Service (Site Report).

The nature of observed climate changes in the Republic of Moldova has been identified through the trends and variability of basic climatic indices (The Third National Communication of the Republic of Moldova under the United Nations Framework Convention on Climate Change. Ministry of Environment of the Republic of Moldova/ UNDP Environment. - Ch.: "Imprint" Plus Ltd.2013 - 413 p).

Observations of air temperature and precipitation show a spatial distribution of monthly, seasonal and annual average values. Fig. 11 shows linear trends in the evolution of mean air temperature (C/year - left side), and precipitation (mm/year - right side) for two instrumental observation time spans at Chişinău Meteorological Station (Site Report).

The climate of the Republic of Moldova is moderate-continental and is characterised by mild and short winter, with little snow and long-lasting summer, with a low amount of precipitation. The average annual air temperature is 8-10° C, the highest temperature is +41.5 °C and the lowest temperature is −35.5 °C.

According to the available information on the meteorological conditions at the disposal site, an average precipitation of 573 mm/y, maximum precipitation of 744 mm/y and minimum precipitation of 425 mm/y. For the vegetated area around the repository a value of 80% has been selected to represent normal evolution evapotranspiration conditions.

Projections of future climate scenarios for the Republic of Moldova suggest that what are currently considered to be extreme rare events for absolute maximum temperatures of 34-35°C for the baseline period of 1961-1990 will possibly become mean maximum summer temperatures. Projections for Europe more generally indicate that the risk of floods increases in Northern, Central and Eastern Europe and that today's 100-year droughts will return every 50 years especially in Southern and South-Eastern Europe, including in the Republic of Moldova (Lehner et al., 2006).

C/year

mm/year

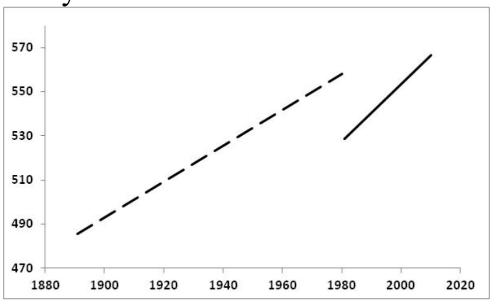


Fig. 11 Linear trends in the evolution of mean air temperature (C/year - left side), and precipitation (mm/year - right side) for two instrumental observation time spans at Chişinău Meteorological Station (dashed line: 1887-1980 and continuous line: 1981-2010)

3.2.3. Land use

The general characterisation of land use around the site is shown in Table 2. The data show the dominance of infrastructure land (built-up areas), which represents 42.8% of the total area. Agricultural land is the second largest, with 38.1% and the non-agricultural ones with a share of 19.1% (Table 2). Spatial spread by mode of use is shown in Fig. 12a.

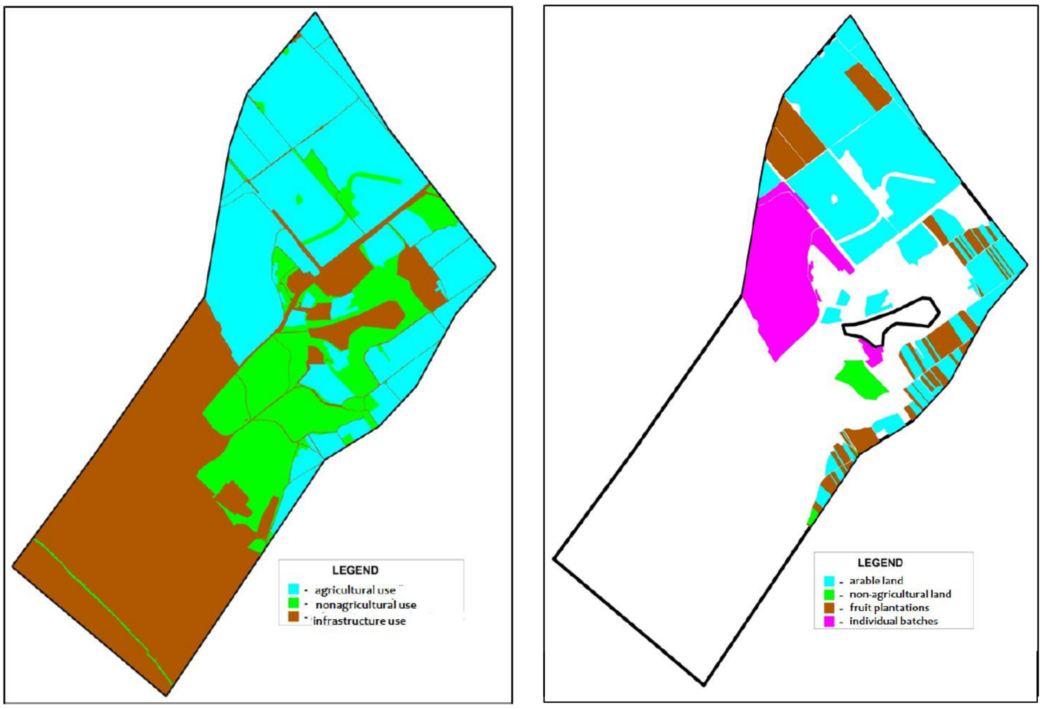
The land for agricultural use within the site includes 108 objects with a total area of 219,163 ha (Table 3). Five categories of land are found in the site: arable, pasture, fruit plantations and individual lots. The arable land category has the largest spread, constituting 59.2% of the agricultural land (see Fig. 12b and Table 3). Individual (back-up) lots account for 21.7%, 16.6% of the agricultural land was planted with fruit trees. Grassland occupies only 2.5% of agricultural land.

Table 2 General characterisation of non-agricultural use

Use	No. of objects	Surface, Ha	% of total object surface
Agricultural	108	219.163	38.1
Non-agricultural	100	109.912	19.1
Infrastructure	123	245.973	42.8
TOTAL	**331**	**575.05**	**100**

Table 3 General characterisation of agricultural use

Category of use	No. of objects	Surface, Ha	% of total agricultural surface
Arable	49	129.643	59,2
pastures	3	2.58	2,5
Fruit trees	48	36.43	16,6
Individual lots	8	47.52	21,7
TOTAL	**108**	**219.163**	**100**



a) usage mode b) agricultural categories

Fig. 12 Land use maps.

4. Preparation of the risk assessment

This chapter describes the performance of Steps 3 and 4 according to the ISAM methodology (Fig. 1) as well as identification of biosphere system according to BIOMASS methodology (Fig. 2).

4.1 Selection of scenario

SSG-23 (IAEA, 2012) states that "*scenarios are used to describe possible evolutions of the disposal system and its environment. The potential migration of radioactive substances from the disposal facility, their movement in the environment and resulting radiation risks are quantitatively analysed by means of conceptual and mathematical models.*"

The ISAM project developed a systematic assessment framework to provide a formal basis for both performance assessment and external review of the logic of the underlying assumptions adopted in a safety case. This approach helps to provide assurance that the assessment has effectively addressed all potentially relevant Features, Events and Processes (FEPs) and takes account of the ways in which combinations of these FEPs might produce qualitatively different outcomes. The systematic approach also provides the setting for demonstrating how uncertainties associated with the future evolution of the disposal system have been addressed and assimilated into the safety case.

A list of FEPs relevant to the assessment of long term safety of near surface disposal facilities developed in the ISAM project can be found in the Appendix C of IAEA (2004a). Scenario generation approaches were defined and applied in three ISAM Test Cases, namely for safety assessment of RADON, vault and borehole test cases.

The basis of the approach adopted by the RADON Test Case to generate scenarios might be summarised as the following (see also Fig. 13):

- Screen the ISAM FEP list on the basis of the assessment context and system description
- Develop and agree a simplified Design Scenario as the main case of the safety assessment
- Identify a limited number of representative Alternative Scenarios rather than comprehensively identify every possible alternative scenario by revisiting the screened ISAM FEP list, with particular attention on external FEPs.
- Identify a limited number of scenarios due to inadvertent intrusion of disposal facilities after the institutional control

Different terms are used to categorise scenarios in international safety standards, national regulations and international projects. In the ISAM approach scenarios are divided into three groups, Design Scenario, Alternative Scenario and Human Intrusion Scenarios. The Design Scenario is defined such that geosphere and biosphere conditions remain as they are at present, with a normal evolution of the engineering barriers and near field. Alternative Scenarios are defined as naturally disturbed performance (erosion, flooding, earthquake, earth creep, frost heave, plant and animal intrusion). The Human Intrusion Scenario is defined as human intrusion including road construction, house building and agriculture on site.

Based on FEPs screening, general scenarios for RADON test case may be divided into three groups: undisturbed performance, naturally disturbed performance and inadvertent intrusion. All these cases should in general be considered for both on-site and off-site human residence. Combining these scenarios with required FEPs, produces a list of general scenarios, illustrated in Fig. 14. This greatly simplifies the procedure of generation of scenarios in this assessment, i.e., combing site specific conditions we are able to select scenarios for the assessment. Calculation cases included in the scenario are defined to assess uncertainties. Descriptions of selection of scenarios and calculation cases are given below.

4.1.1. Design scenario

The design scenario is based on the probable evolution or also called reference evolution of external conditions, and realistic, or, where justified, pessimistic assumptions with respect to the internal conditions. From the map of slope gradients (Fig. 8) one can see that the disposal facility is located on a relatively high altitude. This means that the disposal facility could be a recharge area. The design scenario, SCE1 with the initial state that the engineered barrier is partly degraded is selected where a small farm system is located adjacent to the disposal facility. Identification of the farm system as a biosphere object is given in section 4.3.1. This design scenario or also called leaching scenario is a relevant type of normal evolution scenario. The use of a farm system is a means to ensure that a comprehensive range of exposure pathways is assessed. Two options of water source for the farm system in SCE1 are given in Fig. 14 for discussion, namely well water or surface water. As set out in section 4.3.2 well water is the most likely source of drinking and irrigation for the farm system. Based on this site specific information the calculation case can be defined as a well exposure pathway. A variant case to the well exposure pathway is a further pessimistic assumption case, i.e., there is no engineered barrier (concrete wall is completely degraded at the initial state). This kind of case is often called “What if” scenario in the recent published IAEA safety standards (e.g. IAEA 2012, 2014) to illustrate the robustness of various natural and engineered barriers. However, in order to be consistent with the ISAM classification of scenarios we define this “What if” scenario here as a variant case of the design scenario.

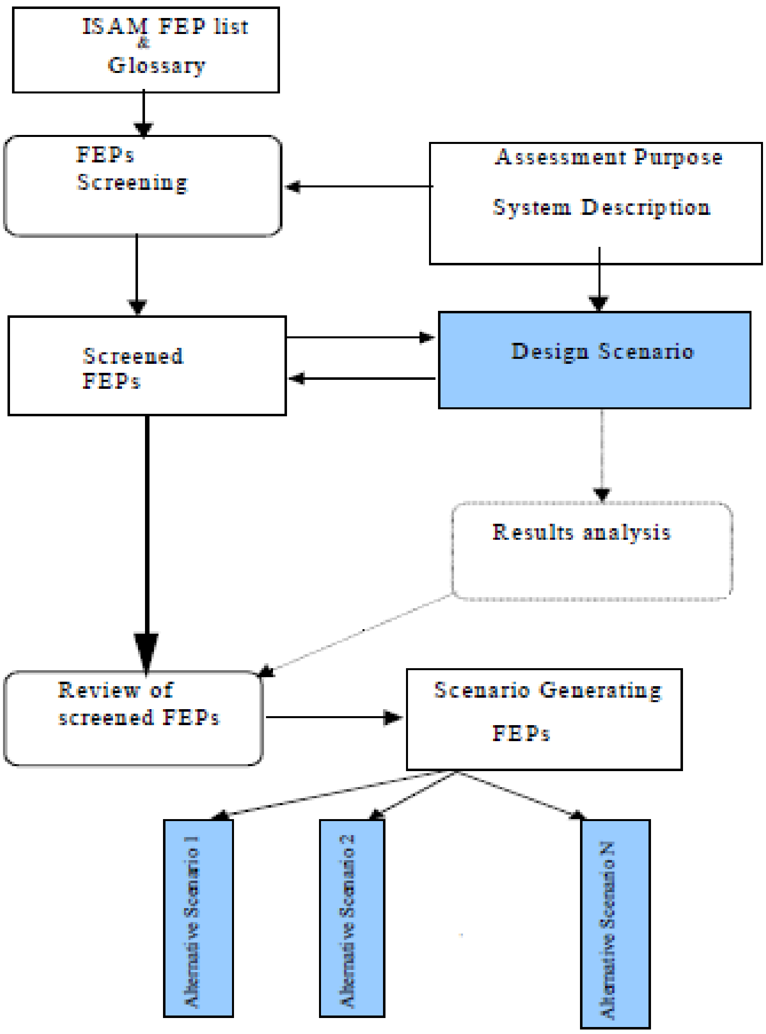


Fig. 13 The RADON Test Case Scenario Generating Approach (IAEA 2004a).

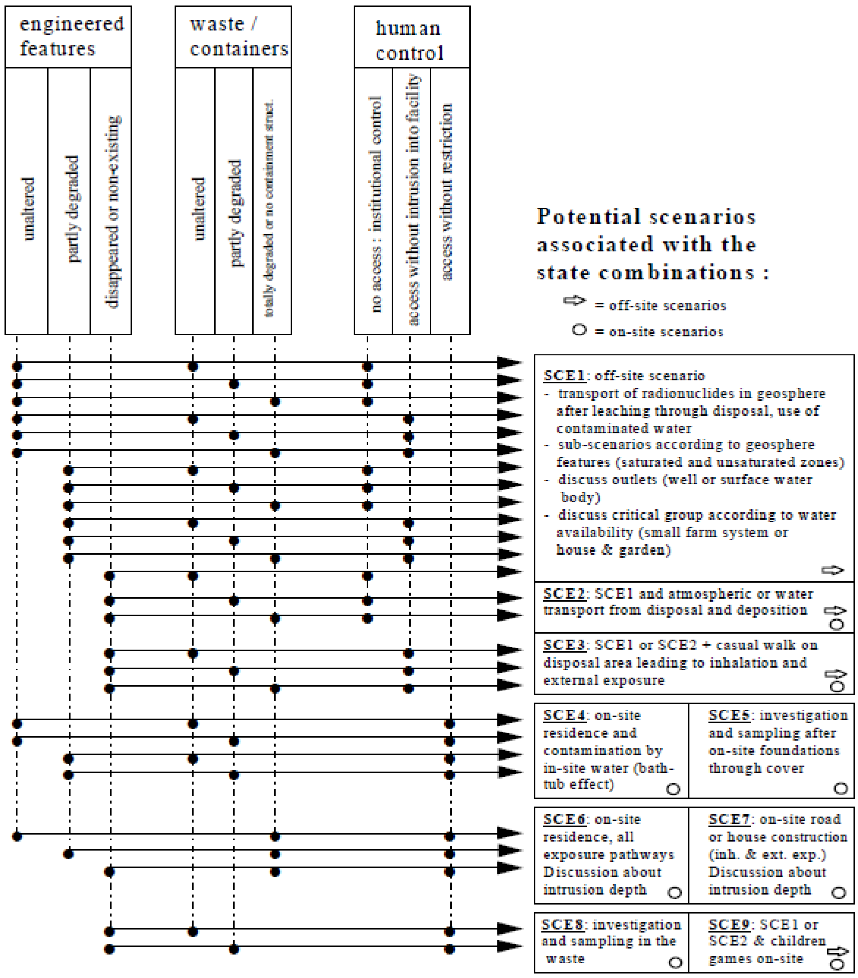


Fig. 14 Generation of a Set of Scenarios (SCE) According to Various States of the Disposal and Human Behaviour Components (IAEA 2004a)

4.1.2. Alternative scenarios

Scenarios that may deviate the reference evolution for the long-term safety of the disposal facility are selected as alternative scenarios. Since the main safety function for the existing facility is the concrete walls of the vault, possible routes to violation of the safety function are used to identify the alternative scenarios. According to the Site Report "*there is a danger of land flooding in torrential rainfall or snow melting during the winter/spring season*" and "*Projections for Europe more generally indicate that the risk of floods increases in Northern, Central and Eastern Europe and that today's 100-year droughts will return every 50 years especially in Southern and South-Eastern Europe, including in the Republic of Moldova.*". Precipitation data has been recorded in the Republic of Moldova in the period 1891-2010. The data shows that the mean value of annual precipitation is 540 mm. The most significant value of annual precipitation, 915 mm, was recorded in 1912 and 531 mm for summer season in 1948. Another external event mentioned in the Hydrogeological Report is that "*Thus we can conclude that groundwater formation at high inclination slope will provoke landslide events on studied site.*"

Flooding and landslides cases are selected as the alternative scenarios. Since flooding will be happen once every 50 years the cumulative frequency of this rare event, P can be written as:

$$P = 1 - 0.98^t \qquad \text{Eq. (1)}$$

in which t is the time.

The frequency that the flooding will occur for the time scale of the performance is shown in Fig. 15. For the landslides scenario no frequency is assigned.

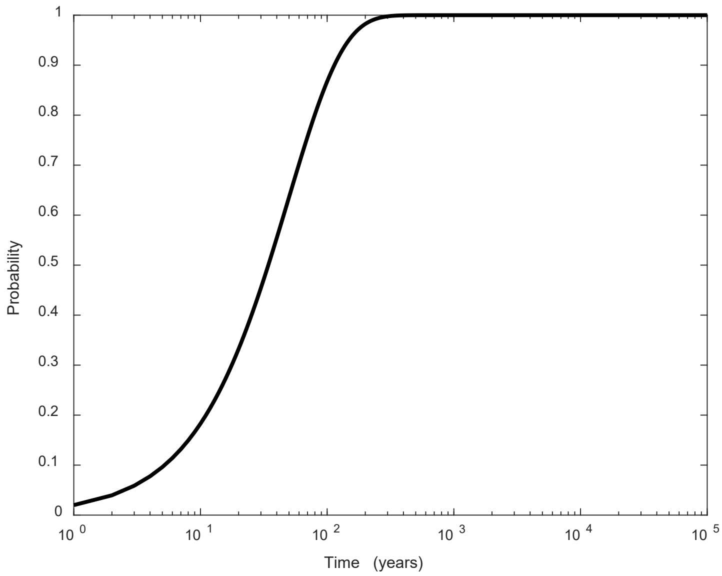


Fig. 15 Cumulative distribution function for the frequency that the flooding will occur as a function of time.

4.1.3. Human intrusion scenarios

Three human intrusion scenarios are selected according to Fig. 14 to assess the disturbed evolution of the disposal facility i.e., i) on-site residence and contamination by leachate (bathtub effect, SCE4); ii) on-site residence scenario (SCE6); iii) the road construction scenario (SCE7) in order to illustrate the damage to humans intruding into the disposal facility after institutional control.

4.2 Conceptual and Mathematical models

Once the scenarios are generated the next step is to develop conceptual and mathematical models for the scenario and finally implement mathematical models using computer tools. The test case for RADON type disposal facility demonstrated in the ISAM report (IAEA 2004b) simplifies our assessment considerably in that we do not need to screen the ISAM FEP list to develop conceptual and mathematical models. Instead we can adopt the conceptual and mathematical models from the test case with minor modifications based on the site specific information in our assessment.

4.2.1. Modelling of design scenario

The conceptual model for the design scenario is shown in Fig. 16. A time period for concrete degradation is assumed as 500 years (IAEA 2004b). In this assessment it is considered that the concrete wall has been partly degraded at the initial state since it is mentioned in Chapter 1 that leakage of radionuclides in the vicinity of the disposal facility was detected in 1998. In the simulation 10% of infiltration as the initial value is assumed and the infiltration increases linearly to 100% at 500 years. Here, we assume that there is no retardation of radionuclides in the waste material itself. This means that no account is taken of sorption of radionuclides on the waste.

The calculation case for the well exposure pathway assumed that water infiltrating the waste percolates through the unsaturated zone to the water table (aquifer), ca. 1 m below and then migrates along with the local groundwater flow into the vicinity of a well, located beyond the site boundary. Release mechanisms, transport media and exposure mechanisms for the calculation case are identified in Table 4.

For the purposes of long-term assessments of radioactive waste disposal, concentrations of radionuclides in certain biosphere media (for example the atmosphere, crops and animals) can often be assumed to be in equilibrium with their donor media. The concentration in a crop grown in the soil can be assumed to be in equilibrium with the concentration in the soil and any irrigation water applied. It is believed that this approach is valid because the processes affecting the concentrations in such media are rapid compared with those affecting concentrations in the donor media, particularly because of the long-term nature of the release (IAEA 2004b). Therefore, a simple approximation expression is used to estimate concentration of soil in the previous report (Xu and Kłos, 2019). A complete dynamic model for the biosphere object is developed in this report (see section 4.3.2). A comparison of the results obtained from the simple approximation and the dynamic model is given in section 5.1.1.

A compartment model structure is used to describe the transport processes for the disposal system. A compartment model is an approximation since it is a discretisation of continuous transport process and radionuclide concentrations. Generally speaking increasing the number of compartments increases the accuracy of the results, but at the cost of modelling time and model complexity. Further guidance on discretisation of compartment models is available elsewhere (e.g. Kirchner, 1998; Xu et al., 2007). Fig. 17 shows the constructed compartment models for the well case. Compartments within the dashed line shown in Fig. 17 are virtual compartments, i.e., they are expressed by analytical equations (see Eq. (9) and Eq. (12)). All the transfer rates between compartments are described below.

The ordinary differential equation (OED) for each model compartment (N) may include inflows from outside the system (source), outflows from the system (sink) and transfer of radionuclides between connected compartments, decay and ingrowth of the radionuclide. For the i^{th} compartment, the ODE of a compartment (k) has the following general form:

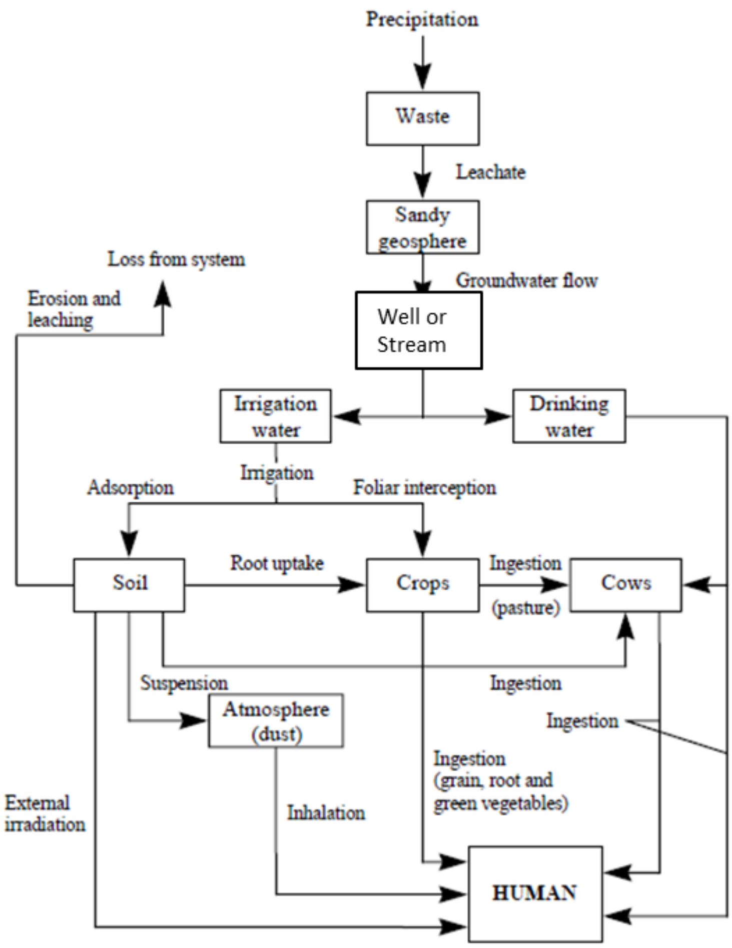


Fig. 16 Conceptual model for the design scenario (IAEA 2004, Volume I).

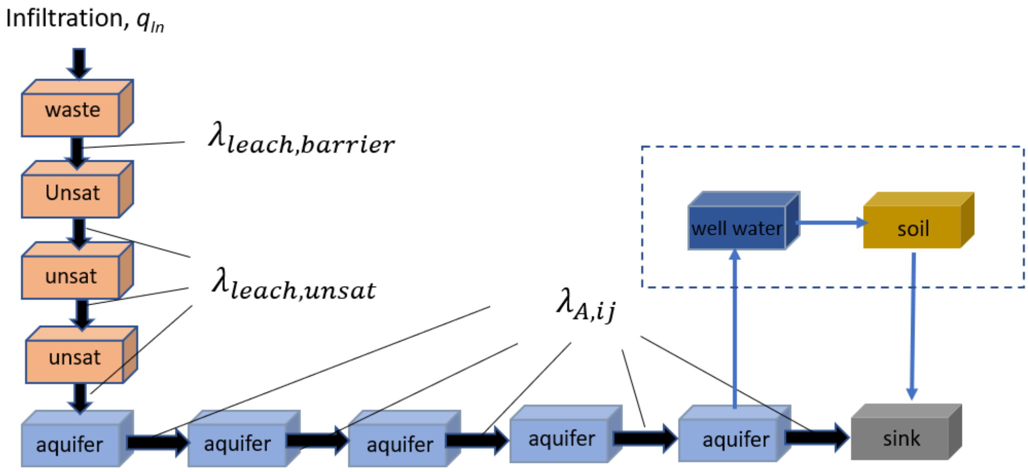


Fig. 17 Constructed compartmental model of radionuclide transport for the calculation case of well exposure pathway of SCE1.

Table 4 Release mechanisms, transport media and exposure mechanisms for the well on case of design scenario, SCE1

Scenario (calculation cases)	**Transport Media**	**Contaminant Transport Mechanisms**	**Human Exposure Mechanisms**
SCE1: Leaching (well exposure pathway)	Waste Geosphere Well (irrigation and drinking) Soil Crops Cows Atmosphere (dust)	Advection Dispersion Water abstraction for irrigation and drinking water Root uptake Adsorption Ingestion of water, pasture and soil by cows Leaching	Ingestion of water, crops, and animal produce Inhalation of dust External irradiation from soil

$$\frac{dN_i}{dt} = \left[\sum_{j\neq i} \lambda_{ji} N_j + \lambda_N M_i + S_i(t)\right] - \left[\sum_{j\neq i} \lambda_{ij} N_i + \lambda_N N_i\right] \qquad \text{Eq. (2)}$$

where *i*, *j* indicate compartments; *N*, *M* are the amounts [Bq] of radionuclides *N* and *M* in a compartment (*M* is the precursor of *N* in a decay chain); *S(t)* is a time dependent external source of radionuclide *N*, [Bq/y]; λ., λ_N is the decay constant for radionuclide *N* (in 1/y); and λ_{ji} , λ_{ij} are transfer coefficients [1/y] representing the gain and loss of radionuclide *N* from compartments *i* and *j*.

For the calculation case of well exposure pathway, the transfer coefficient $\lambda_{leach,barrier}$ is expressed as:

$$\lambda_{leach,barrier} = \frac{q_{in}}{\theta_w DR} \qquad \text{Eq. (3)}$$

where q_{in} is the infiltration [m/y]; θ_w is water filled the porosity of the concrete wall of the vault [-]; D is depth of the wall through which the radionuclide is transported and R is the retardation factor (-) and given as:

$$R = 1 + \frac{\rho K_d}{\theta_w} \qquad \text{Eq. (4)}$$

where ρ is the density of the concrete wall [kg/m^3]; K_d is the sorption coefficient of the concrete [m^3/kg].

The transfer coefficient $\lambda_{leach,unsat}$ is expressed as:

$$\lambda_{leach,unsat} = \frac{q_{in}}{\theta \varepsilon DR} \qquad \text{Eq. (5)}$$

where q_{in} is infiltration [m/y], θ is the total porosity in the medium [-]; ε is the degree of saturation of the medium; *D* is depth of the medium through which the radionuclide is transported [m]; *R* is the retardation coefficient given by:

$$R = 1 + \frac{\rho_{unsat}(1-\theta)K_d}{\varepsilon\theta} \qquad \text{Eq. (6)}$$

where ρ_{unsat} is the bulk density of the medium [kg/m^3]; K_d is the sorption coefficient of the medium[m^3/kg], ε is the degree of saturation of the medium.

Transport of solute in the aquifer in general is described by an advection-dispersion partial equation. The compartmental model can be used to approximate the solution of this solute transport problem. Xu et al., (2007) shows that discretisation of a transport path into a few number of compartments results in a solution that is still close to the analytical solution, and the amount of numerical dispersion is similar to the amount of physical dispersion. The rule of thumb is the number of compartments required should exceed Pe/2, where Pe is the Peclet number. As can be seen in Fig. 17, five compartments are used in the modelling. The transfer co-efficient $\lambda_{A,ij}$ is expressed as

$$\lambda_{A,ij} = \frac{q}{L/n\,\theta_w R_w} \qquad \text{Eq. (7)}$$

where L is the total transport length [m]; n is a number of compartments [-]; θ_w is the porosity of the medium [-]; R_w is the retardation coefficient of the medium [-]; q is Darcy velocity given by

$$q = -\mathrm{K}\frac{\partial \mathrm{H}}{\partial x} \qquad \text{Eq. (8)}$$

where K is the hydraulic conductivity of the medium [m/y]; ∂H/∂x is the hydraulic gradient [-].

Once the radionuclide discharge flux to the well is determined the activity concentrations for well water C_{well} can be determined, in which the expression for determining the activity concentrations for the well water is slightly modified from the original ISAM expression:

$$C_{well} = \frac{Q_{geo}}{V_{well} R_{sat}} \qquad \text{Eq. (9)}$$

where Q_{geo} is the flux of the radionuclides into the well (flux discharged to the well) [Bq/y]; V_{well} is the well capacity [m^3/y]. Further discussion of this well capacity will be given in section 4.3.2.

The dose to a member of the critical group for these two calculation cases of the design scenario can be expressed as (in [Sv/y]):

$$Dose = Dose_{inh} + Dose_{ext} + Dose_{ing} \qquad \text{Eq. (10)}$$

where $Dose_{inh}$, $Dose_{ext}$ and $Dose_{ing}$ are the doses due to the inhalation, external exposure and the ingestion pathways [Sv/y].

The dose due to inhalation is expressed as:

$$Dose_{inh} = A_{soil} \cdot b_r \cdot 8766 \cdot \left[dust_{act}\%_{occup} + dust_{norm}\left(1 - \%_{occup}\right)\right] DF_{inh} \qquad \text{Eq. (11)}$$

Where b_r is the breathing rate [m^3/h]; 8766 are the hours in a year [h/y]; $dust_{act}$ and $dust_{norm}$ are the dust concentrations during ploughing and non-ploughing activities [kg/m^3]; $\%_{occup}$ is the occupancy factor for ploughing activities [-]; DF_{inh} is the dose factor for inhalation [Sv/Bq]; A_{soil} is the concentration of the radionuclide in the soil [Bq/kg], which can be expressed by a simple approximation as:

$$A_{soil} = C_{well} \frac{irr}{(1-\theta)\rho_{soil} Th_{soil} \lambda_{eff}} \qquad \text{Eq. (12)}$$

where irr is the irrigation rate [m/y]; ρ_{soil} is the soil dry bulk density [kg/m^3]; Th_{soil} is the soil thickness [m]; λ_{eff} is an effective decay rate which can consists of radionuclide decay constant and the percolation of water through the soil column described in section 4.3.2 (Eq. (30)).

The dose due to external exposure is expressed as

$$Dose_{ext} = A_{soil} \cdot 8766 \cdot DF_{ext} \qquad \text{Eq. (13)}$$

where DF_{ext} is the external exposure dose factor [Sv/h per Bq/kg].

The dose due to ingestion is expressed as:

$$Dose_{ing} = Dose_{ing\_water} + Dose_{ing\_crop} + Dose_{ing\_animal} \qquad \text{Eq. (14)}$$

where $Dose_{ing\_water}$ is the dose due to water ingestion [Sv/y]

$$Dose_{ing\_water} = Ing_{wat} \cdot C_{well} \cdot DF_{ing} \qquad \text{Eq. (15)}$$

where Ing_{wat} is the individual ingestion rate of freshwater [m^3/y]; and DF_{Ing} is the dose coefficient for ingestion [Sv/Bq]; Kd_w is the distribution coefficient for water/particles [m^3/kg]; and $part$ is the suspended particle concentration [kg/m^3] in the water (assumed to be zero for well water.

$$Dose_{ing\_crop} = \sum_{root,green,grain} \left[Ing_{crop} \left(A_{soil} \cdot TF_{crop} \right) DF_{ing} \right] \qquad \text{Eq. (16)}$$

where Ing_{crop} is the consumption rate of crop including root vegetables, green vegetables and grain [kg/y]; TF_{crop} is the soil to plant concentration factor for the crop including root vegetables, green vegetables and grain [Bq/kg fresh weight per Bq/kg dry soil].

The dose due to animal product consumption is expressed as

$$Dose_{ing\_animal} = \sum_{beef,milk} \left[Ing_{animal}\left(q_{water}C_{well} + q_{soil}A_{soil} + q_{pasture}A_{soil}TF_{pasture}\right) \times TF_{animal}DF_{ing}\right] \quad \text{Eq. (17)}$$

where Ing_{animal} is the annual animal product consumption rate (beef or milk) [kg/y]; q_{water} is the daily animal water intake [m^3/day]; q_{soil} is the daily animal soil intake [kg/day] $q_{pasture}$ is the daily animal pasture intake [kg/day]; $TF_{pasture}$ is the soil to plant concentration factor for the pasture [Bq/ kg fresh weight per Bq/kg dry soil]; TF_{animal} is the transfer coefficient to the animal product [day/kg].

All the mathematical expressions above are adopted from ISAM report Vol. II (IAEA 2004b) and IAEA TECDOC-1380 (IAEA 2003b) except Eq. (12) which is a simple approximation. The concentration of soil A_{soil} [Bq/kg dry] is governed by a first order differential equation:

$$\frac{dA_{soil}}{dt} = -A_{soil}\lambda_{eff} + C_{water}\frac{irr}{(1-\theta_w)\rho_{soil}Th_{soil}} \quad \text{Eq. (18)}$$

Assuming $dA_{soil}/dt=0$, A_{soil} is expressed as Eq. (12). Comparison of results obtained from this simple approximation and a dynamic biosphere model are discussed in section 5.1.1.

4.2.2. Modelling of human intrusion scenario

As mentioned earlier three human intrusion scenarios are selected, namely on-site residence and contamination by leachate (bathtub effect) SCE4, the on-site residence scenario SCE6 and the road construction scenario SCE7 (see Fig. 14). The conceptual models for these three scenarios are shown in Fig. 18 – 20. Release mechanisms, transport media and exposure mechanisms for these three scenarios are identified in Table 5.

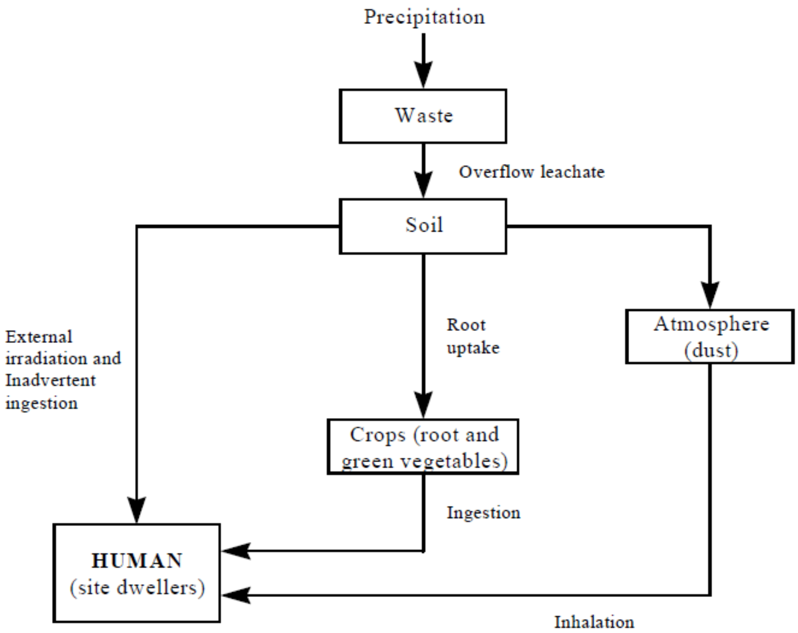


Fig. 18 Simplified representation of the conceptual model for the Post-closure Bathtubbing Scenario (IAEA 2004b)

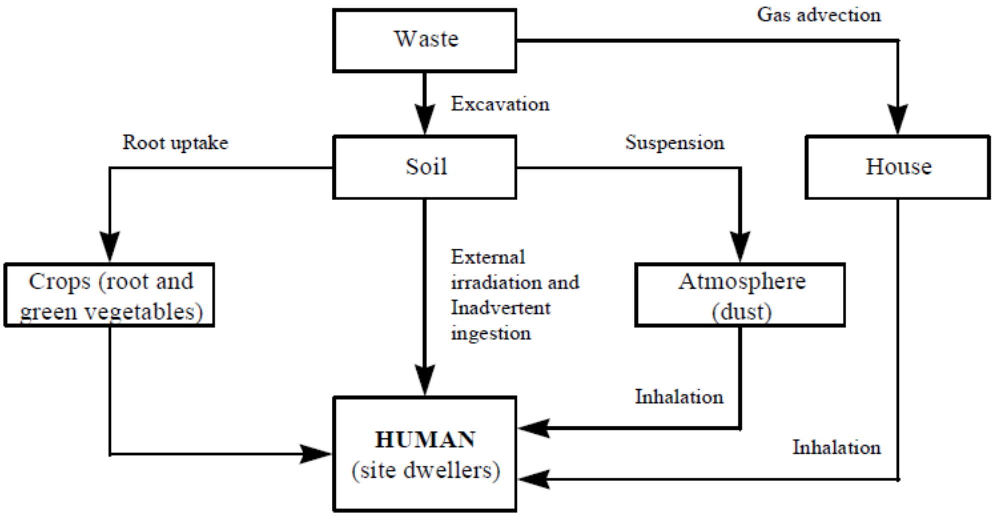


Fig. 19 Simplified representation of the conceptual model the Post-closure On-site Residence Scenario SCE6 (IAEA 2004b)

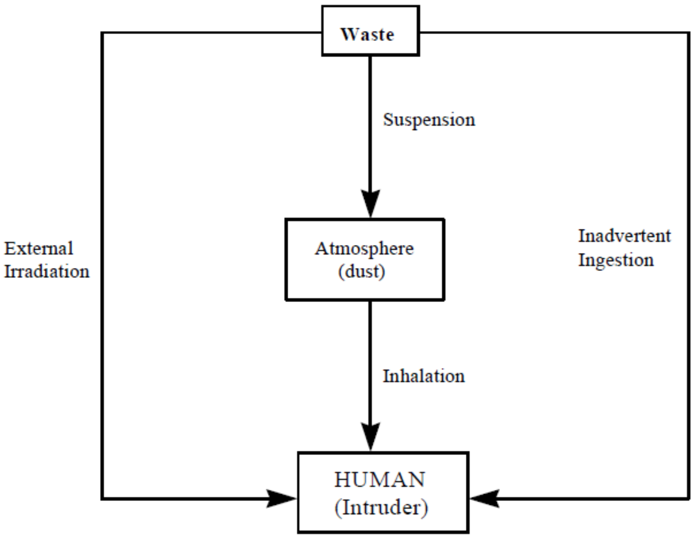


Fig. 20 Simplified representation of the conceptual model the Post-closure Road Construction Scenario SCE7 (IAEA 2004b)

For three human intrusion scenarios there are analytical solutions available in IAEA's technical document 1380 (IAEA 2003b). Descriptions of the solutions are given below.

Bathtubbing scenario (SCE4)

The analytical solution of the concentration of radionuclides in the overflowing leachate C_{disp} [Bq/m^3] used in evaluation of the bathtubbing scenario is expressed as:

$$C_{disp}(t) = e^{-\lambda t}\frac{A_{mi}}{V_{dispunit}(\omega_{ed} + \rho_{bd}Kd_d)} \quad \text{Eq. (19)}$$

where $e^{-\lambda t}$ is the radioactive decay before the scenario [-]; A_{mi} is the initial activity in the disposal unit [Bq]; $V_{dispunit}$ is the volume of the disposal unit [m^3]; ω_{cd} is the moisture content of the disposal unit [-]; ρ_{bd} is the dry bulk density in the disposal unit [kg/m^3]; Kd_d is the radionuclide distribution coefficient in the disposal unit [m^3/kg].

The dose due to "bath-tub" effect is a sum of external dose ($Dose_{ext}$), inhalation dose ($Dose_{inh}$) and ingestion dose ($Dose_{ing}$).

$$Dose_{ext} = \frac{OF}{\rho_{soil} \cdot Th_{soil}} C_{disp}(sf \cdot t_{in} + t_{out})DF_{ext} \quad \text{Eq. (20)}$$

where OF is the water overflow to the garden during one year [m]; ρ_{soil} is the soil dry bulk density of the soil [kg/m^3]; Th_{soil} is the soil thickness [m]; C_{disp} is the concentration of radionuclides in overflowing leachate [Bq/m^3]; *sf* is the shielding factor [-]; t_{in} is the time spent indoors [h/y]; t_{out} is the time spent outdoors [h/y]; DF_{ext} is the external exposure dose factor [Sv/h per Bq/kg].

Table 5 Release mechanisms, transport media and exposure mechanisms for three human intrusion scenarios

Scenarios	**Contaminant Release Mechanisms**	**Contaminant Release Media**	**Contaminant Transport Media**	**Contaminant Transport Mechanisms**	**Human Exposure Mechanisms**
SCE4: Bathtubbing	Leaching	Leachate	Overflow leachate Soil Atmosphere (dust) Crops	Overflow of leachate Suspension Root uptake Adsorption	Ingestion of crops Inadvertent ingestion of soil Inhalation of dust External irradiation from soil
SCE6: On-site residence	Excavation	Excavated waste	House Soil Atmosphere (dust) Crops	Root uptake Adsorption Suspension	Ingestion of crops Inadvertent ingestion of soil Inhalation of dust External irradiation from soil
SCE7: Road construction	Excavation	Dust	Atmosphere (dust)	Suspension	Inadvertent ingestion of contaminated material and waste Inhalation of dust External irradiation from contaminated material and waste

$$Dose_{inh} = \frac{OF}{\rho_{soil} \cdot Th_{soil}} C_{disp}(dust_{in} br_{in} t_{in} + dust_{out} br_{out} t_{out}) DF_{inh} \quad \text{Eq. (21)}$$

where $dust_{in}$, dustout are the indoor and outdoor dust levels [kg/m^3]; br_{in}, br_{out} are the indoor and outdoor breathing rates [m^3/h]; DF_{inh} is the dose factor for inhalation [Sv/Bq].

$$Dose_{ing} = \frac{OF}{\rho_{soil} \cdot Th_{soil}} C_{disp}\left(TF_{vegt} Q_{vegt} + Q_{soil}\right) DF_{ing} \quad \text{Eq. (22)}$$

where TF_{veget} is the soil to plant concentration factor for the vegetable [Bq/kg fresh weight per Bq/kg dry soil]; Q_{veget} is the vegetable consumption rate [kg/y]; Q_{soil} is the inadvertent soil ingestion rate [kg/y]; DF_{ing} is the dose factor for ingestion [Sv/Bq].

On-site residence scenario (SCE6)

The analytical expression of activity to which the on-site resident is exposed, A_{res} [Bq/kg of waste], is given by:

$$A_{res} = A_m e^{-\lambda t_1} \cdot dil \quad \text{Eq. (23)}$$

where A_m is the initial concentration of the radionuclide disposed waste [Bq/kg]; λ is the radioactive decay constant [1/y] (if required other mechanisms contributing to diminishing the radioactivity could also be incorporated in an effective decay term (λ_{eff})); t_1 is the time before exposure starts [y]; dil is the dilution factor [-].

The dose due to on-site residence is a sum of external dose ($Dose_{ext}$), inhalation dose ($Dose_{inh}$) and ingestion dose ($Dose_{ing}$).

$$Dose_{ext} = A_{res}(sf \cdot t_{in} + t_{out}) DF_{ext} \quad \text{Eq. (24)}$$

$$Dose_{inh} = A_{res}(dust_{in} br_{in} t_{in} + dust_{out} br_{out} t_{out}) DF_{inh} \quad \text{Eq. (25)}$$

$$Dose_{ing} = A_{res}\left(TF_{vegt} Q_{vegt} + Q_{soil}\right) DF_{ing} \quad \text{Eq. (26)}$$

Road construction scenario (SCE7)

The analytical solution of the activity concentration to which the intruder is similar to the Eq. (23) and is expressed as A_{int} [Bq/kg of waste], which is given by

$$A_{int} = A_m e^{-\lambda t_1} \cdot dil \quad \text{Eq. (27)}$$

where A_m is the initial concentration of the radionuclide disposed [Bq/kg of waste]; λ is the radioactive decay constant [y] (if required other mechanisms contributing to diminishing the radioactivity could also be incorporated in an effective decay term (λ_{eff})); t_1 is the time before intrusion starts [y]; *dil* is the dilution factor [-].

The dose due the road construction scenario can be expressed as (in [Sv/y]):

$$Dose = A_{int}\left(Q_{soil}DF_{ing} + DF_{ext} + b_r \cdot dust \cdot DF_{inh}\right)t_2 \qquad \text{Eq. (28)}$$

where A_{int} is the activity to which the intruder is exposed [Bq/kg of waste]; Q_{soil} is the inadvertent soil ingestion rate of the intruder [kg/h]; DF_{ing} is the dose factor for ingestion [Sv/Bq]; DF_{ext} is the external exposure dose factor [Sv/h per Bq/kg]; b_r is the breathing rate of the intruder [m^3/h]; *dust* is the dust level experienced by the intruder [kg/m^3]; DF_{inh} is the dose factor for inhalation [Sv/Bq]; t_2 is the exposure duration [h].

4.2.3. Modelling of alternative scenarios

Two scenarios are selected as alternative scenarios, namely the flooding scenario and landslides scenario.

The model used for the flooding scenario is the same to the model used for the bathtubbing scenario (Eq. (19)). Once the concentration of radionuclides in the overflowing leachate C_{disp} is determined rest of calculations are exact the same as in the bathtubbing scenario (see section 4.2.2).

For the landslides scenario we assume that the result of the on-site residence scenario can cover this case.

4.3 Biosphere objects and mathematical models

4.3.1. Identification of biosphere objects

The BIOMASS methodology (IAEA 2003a) was illustrated with Example Reference Biospheres (ERBs) using generic biosphere models. ERB2b model deals with the discharge of contaminated groundwater or surface water to overburden media in the biosphere (see Fig. 21), which has similarities to the farm system to be considered in the SCE1. The dimensions of biosphere objects are important since the total area largely determines the overall water balance in the landscape and has significant impact on the final calculated doses.

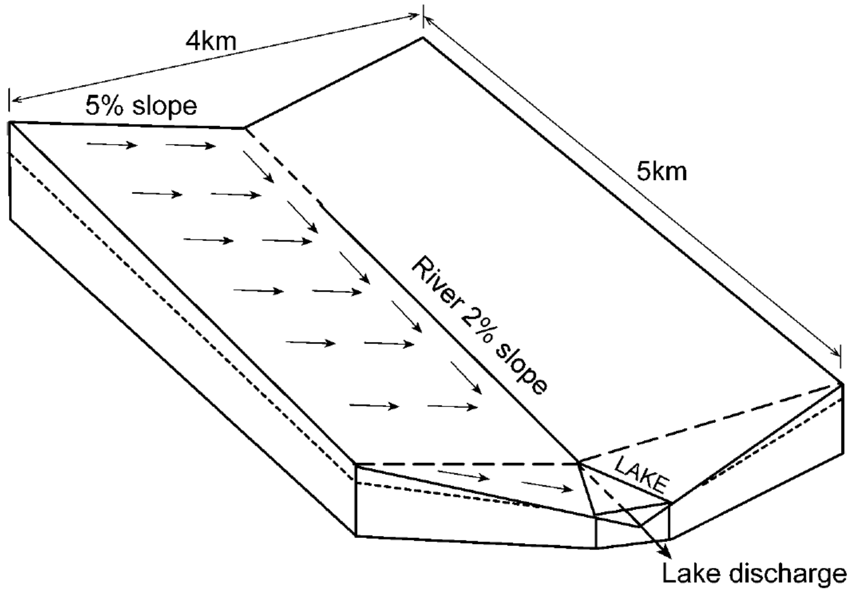


Fig. 21 Site-generic interpretation of a stylised landscape dose objects. Illustration of the ERB2b catchment, (IAEA 2003a, Figure C11.3).

In this assessment the GIS tool Global Mapper 19.1[1] is used to obtain catchment areas consistent with local topography and identify the relevant object areas based on the site specific DEM (digital elevation model) data provided in the Radiological Object Report. The details of identification of catchment areas can be found in Guerfi et al., (2019).

Fig. 22 shows identified catchments and potential streams on the map of the site from the watershed analysis in the GIS tool. The stream paths are *potential* since they represent the local low points of the topography determined by the 8-point pour algorithm in the mapping software, i.e., the path where particles dropped onto the surface of the terrain would accumulate. In this way they represent the preferential flow path where streams would flow if the local aquifer were to outcrop at the surface. They are therefore treated as indications of the surface flow system associated with the local watershed configuration.

The disposal facility is within a single catchment of area 1 140 907 m^2 (green shading). Just south of the flow system outlet from this landscape object there is a confluence with the watershed to the west, with area 1 453 830 m^2 (red shading). The area for the dose calculations would be located in the southern area (purple). This covers a large area but the focus is on the area downslope from the confluence of boundary of the drainage system. The water balance of the object can be conservatively derived from the red and green areas, areas are listed in Table 6.

[1] Copyright © 2019 Blue Marble Geographics

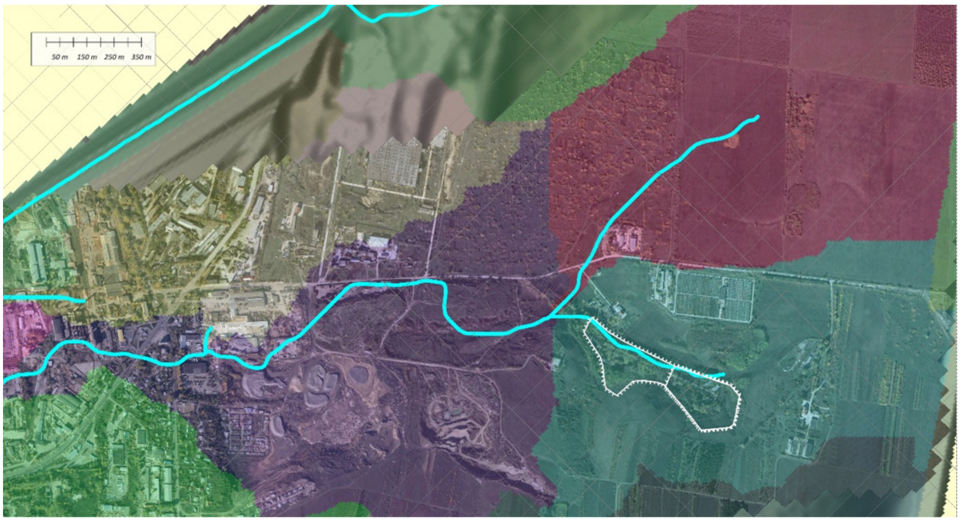


Fig. 22 Catchments and surface drainage streams around the disposal site

When identifying the candidate areas for the *biosphere objects or the farm system* the requirement is to determine locations in the landscape where the highest concentrations of radionuclides remobilised from the disposal facility can occur and then to set potential exposure pathways, as defined in SCE1. The focus is therefore on areas as close to the disposal site boundary as possible.

The aim of the identification is to define areas in the landscape for *potential exposure*, they need not necessarily correspond to identified areas in the present day landscape. The procedure is as follows:

1. Look for potential areas in the landscape (aided by the orthophoto) and the topographic map of the site (the DEM)
2. Candidate areas should be
    a. Close to the main drainage path as identified from analysis of the DEM, since radionuclides leached from the repository will be transported in groundwater or the flowing surface water. If wells are considered in the modelled system placing the objects close to the axis of the drainage system means that the concentration in the local near-surface aquifer will not be underestimated
    b. Close to the disposal facility site boundary so as to avoid excessive spatial dilution
    c. Large enough to supply the dietary needs of at least a small family group of, say, four adults. This is typically up to 2×10^4 to 10^5 m^2.
3. Account should be taken of the confluence of drainage systems from different watersheds

Two candidate objects are indicated in Fig. 23. The first object is closest to the disposal facility site boundary and is situated on the land adjacent to the drainage stream that runs through the waste site itself and is along boundary of the drainage system of the western catchment. The second object is identified by an area along the valley floor of the combined drainage system. The areas of the two objects are, respectively, 2.1×10^4 m^2 and 1.8×10^4 m^2.

According to the landuse map (Fig. 12) the area of object 1 is currently agricultural land with woodland along the drainage system. It is selected as the closest location with potential for cultivation to the site boundary. The distance between the object 1 and the disposal facility is about 300 m.

Object 2 is classed as non-productive land and natural pasture. For assessment purposes there appears to be no reason why the two areas could not be cultivated, although the land area close to the stream path is relatively steep. According to the orthophoto, the drainage system is not necessarily above ground so a well in the two areas, used for cultivation purposes is the most realistic approximation.

Table 6 Areas of subcatchments in the map (Fig. 22).

landscape area	enclosed area m^2
Disposal site catchment (green)	1.1E+06
Western catchment (red)	1.5E+06
Downstream catchment (purple)	1.2E+06

4.3.2. Formulation of mathematical models for the biosphere object

Site description

The ISAM methodology is illustrated using a specific example based around the Vaalputs site in the Republic of South Africa (IAEA, 2004a). The application of the resulting models (IAEA, 2004b) makes use of data from similar climate analogues around the planet, for example from the Yucca Mountain site in the western USA. The ISAM methodology is widely applicable but the resulting models are not *site-specific* in that they are not descriptive of a single site but are more generically applicable to sites with arid climates.

The customisation of the ISAM model for the Chişinău site in Moldova incorporates site-descriptive material to develop a clearer expression of the FEPs specifically relevant to the site in question. The model of the vault and for the release and transport of radionuclides through the geosphere are well represented by the ISAM model, with minor adjustments to parameterisation relating to water fluxes in the system. In the biosphere, however, there are site-specific details that can be used to both simplify the structure of the biosphere dose model and to better represent key features.

Fig. 23 shows the results of an analysis topography of the Chişinău site, emphasising the surface drainage system (a small surface water stream which is non-permanent) and the topography of the site and two candidate biosphere objects, downstream from the repository location, beyond the disposal facility boundary. Of the two candidate objects shown in Fig. 23, Object 1 just outside the disposal facility site boundary is selected for the dose calculations:

- It is the closest to the disposal facility site boundary, so that the concentrations in local groundwater resources will be higher with the reduced importance of dispersion in the groundwater flow system,
- It is part of the local catchment area that collect water that flows though the RADON facility itself (Fig. 23), again minimising dilution of surface water resources, and
- Although neither object is particularly high quality land, it is the better of the two for cultivation.

The selected object is an area of land (2.1 hectare), forming part of a valley on either side of the main drainage channel from the local catchment in which the repository is situated. The stream is small and non-permanent, making well water the most likely source of drinking and irrigation that need by assumed for the representation of the exposed group. The area is somewhat restrictive but is sufficient for a small family group, practicing subsistence agriculture. Doses calculated in this model will therefore by expected to be somewhat conservative.

Review of Biosphere FEPs

A systematic review of the ISAM interaction matrix has been caried out to determine which FEPs are active at the site. Fig. 24 compares the interaction matrix used in the development of the ISAM example model and final interaction matrix developed here to define the biosphere submodel.

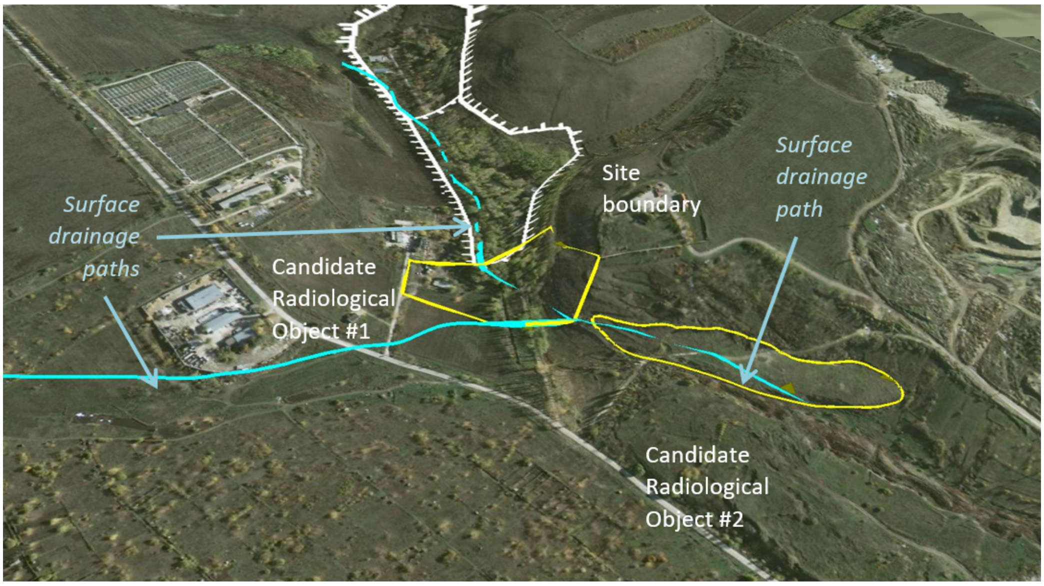
The model for biosphere dose calculations is set out in Section 4.2.1 (Eq. 9 to 18). Review of the ISAM interaction matrix in the context of the system description in Section 4.3.1 allows a site-specific biosphere dose model to be formulated following the guidance in Kłos and Thorne (2020) that was developed as part of the MODARIA II update of the BIOMASS methodology (IAEA, 2020). The emphasis is on turning conceptual models defined by the interaction matrix for a site into mathematical descriptions suitable for the dose assessment. There are three stages:

i. Review of ISAM biosphere interaction matrix (IAEA, 2004b, Fig. B.6, shown Fig. 24a) identify local factors of relevance from the site. The non-relevant interactions are identified and taken out of consideration and the model is restructured and simplified where possible so that the number of leading diagonal elements is reduced where possible but extended (nesting sub-models) if required.
ii. The final version of the interaction matrix (Fig. 24b) therefore contains all of the relevant model components (leading diagonal elements – the LDEs) as well as all of the interactions that need to be represented mathematically in the model. In practical terms, the LDEs become the key reservoirs of

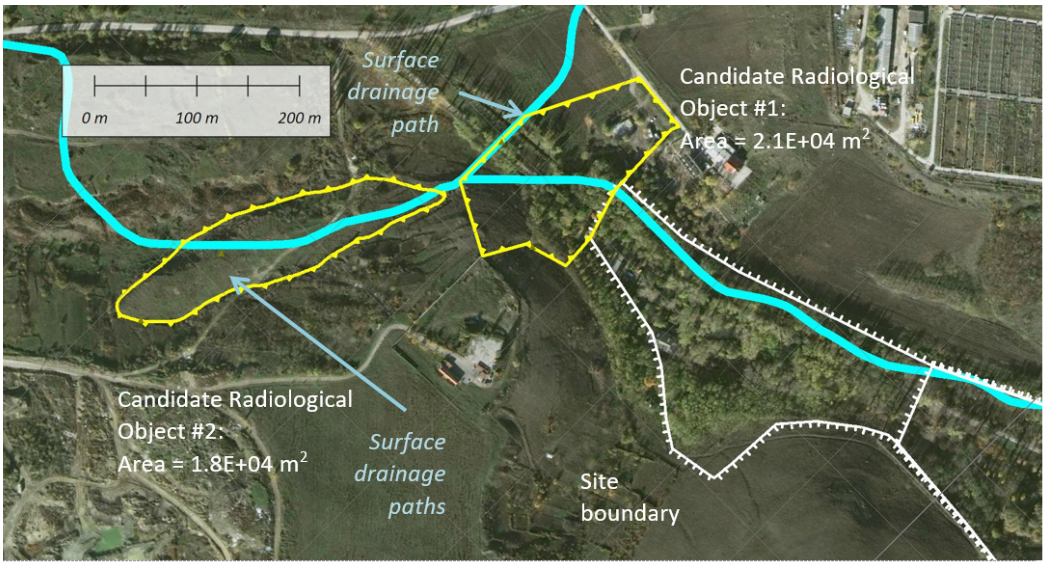
contaminants in the model, i.e., the active compartments in the compartmental model.

iii. The existing model from the ISAM report is audited against the revised model description in Fig. 24b.

The key features of the procedure are described below.

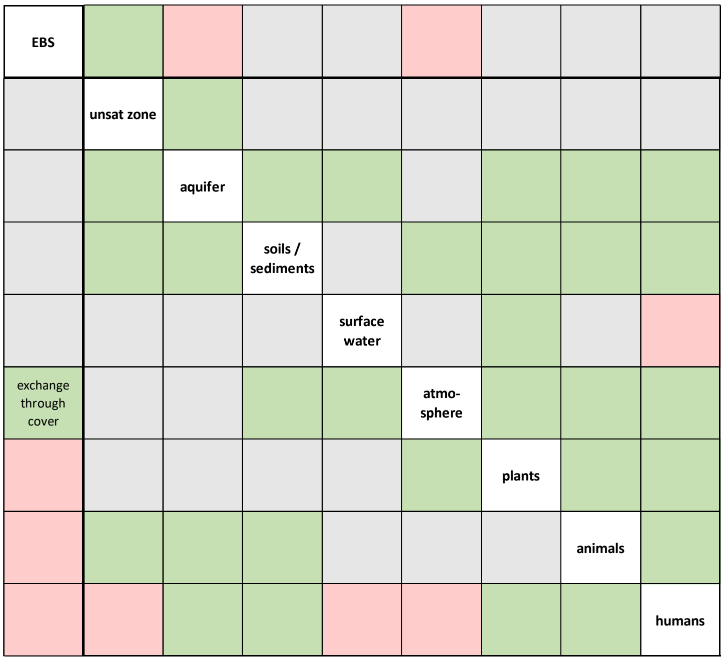


(a) 3D-map



(b) 2D map

Fig. 23 Candidate areas for potential radiological objects. With reference to the orthophoto two areas are identified downslope from the site boundary.



(a) ISAM interaction matrix for the biosphere sub-model (IAEA, 2004a, Fig B.6, revised)

(b) Revised site specific IM, describing *radionuclide transfers* used for model definition.

Key to compartments

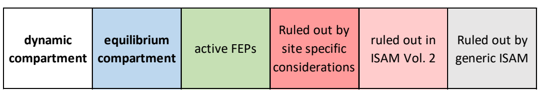


Fig. 24 Initial ISAM interaction matrix compared to the revised version modified to take into account site-specific details and model simplifications in the dose model. Leading diagonal elements become entities in the mathematical model.

Definition of the biosphere dose model

In developing the implemented form of the biosphere dose model the nature of the leading diagonal elements is an issue. A distinction can be made between *dynamic* components for which the time evolution of the radionuclides content is required and *equilibrium* components, the content of which depend on a linear combination of the content of the dynamic components. Taking the compartmental model approach in Eq. (2), this means identifying those *compartments* in the model interaction matrix that can be approximated by $\frac{dN_i}{dt} = 0$. The progressive simplification of the interaction matrix as the mathematical model is developed involves the justified removal and amalgamation of the leading diagonal elements. This is a more formal expression of the ISAM-recommended procedure for defining models given above.

The main difference between the two interaction matrices in Fig. 24 is that the number of LDEs is reduced. The surface water component of the ISAM model is not required in this site context for the well case since the drainage stream is small and transient. Focus is therefore on the overall accumulation of water in the total catchment. The atmosphere component can be neglected because of the expected low concentrations in the air above the biosphere object. Doses from dust inhalation can be described by suspended dust in equilibrium with the rooting zone soil compartment. For C-14 and the gaseous and non-reactive Kr-85 this is a potentially non-conservative assumption but it follows the ISAM model implementation.

The repository and geosphere transport path are consolidated into the upper two elements and these constitute a distinct sub-model that transfers activity into the aquifer in the biosphere sub-model. The disaggregation of the soil model into two layers allows for losses from the rooting zone to be evaluated with the possible accumulation at the lower layer also calculated. There is no water flux from the lower soil to the rooting zone because the moisture content of the lower soil (unsaturated material) is too lower to facilitate capillary rise to any significant degree. The transfer is therefore set to zero.

Losses from the biosphere sub-system are accounted for by the inclusion of a sink and the rest of the LDEs represent distinct spatial volumes such that the two soil layers are identified, one the rooting zone soil where the crops grow and the lower (unsaturated) soil through which water flows following deposition at the soil surface (rainfall and irrigation less evapotranspiration). Details of the hydrology in the model depend on the understanding of the site from the topographic analysis and the description of the local stratigraphy.

In terms of the physical structure of the soils and aquifer, the local slopes and soil thicknesses mean that there is little chance of interaction between the aquifer and lower soil, so that infiltrating water fluxes pass downwards and return to the aquifer.

The biosphere model therefore comprises two dynamic compartments for which the first order linear differential equations need to be solved plus the sink compartment. The remaining three LDEs – plants, animals and humans are all treated as equilibrium compartments. Humans are the end-point of the calculation in the sense that they are the recipient of the calculated dose. The interactions expressed in the ISAM matrix (Fig. 24a) represents a more generalised interaction whereas the mathematical model matrix (Fig. 24b) describes the exposure pathways.

Plants are in equilibrium with the content of the rooting zone soil and with intercepted well water used for irrigation. Animals consume plants and drink water from the local source as well as small quantities of soil during grazing. They too are therefore in equilibrium with soil and well water.

The dose model is complete when the off-diagonal elements are parameterised. The details of the current model are set out below.

Mathematical expressions in the dose model

The issue of dilution in the aquifer is a well known problem. The total flow in the aquifer can be obtained by the annual net precipitation captured but this gives only a basic interpretation of the hydrologic conditions in the water bearing strata below the site. As seen from Fig. 23 the local catchment for the site is in a watershed that is not likely to receive inflow to the aquifer in the model here from upstream as this will be defined by the larger (and deeper) regional groundwater circulation. The maximum dilution can be assumed to be the total captured net precipitation, $Q_{aquifer}$:

$$Q_{aquifer} = (PPT - ETP)A_{catch} \qquad \text{Eq. (29)}$$

where the catchment area, A_{catch} is 1.1×10^6 m^2 (Table 6 and Fig. 22), precipitation (PPT) and evapotranspiration (ETP), respectively, 0.573 and 0.460 m year^{-1}, which means the total water in catchment for dilution is 1.24×10^5 m^3 year^{-1}.

While the biosphere dose object area is 2.1 hectare whereas the irrigation abstraction for the site is d_{irri} = 0.3 m year^{-1} so that the total irrigation rate is 6.3×10^3 m^3 year^{-1}, the irrigation abstraction is therefore only 5% of the total flow in the aquifer. If we use the total water flow in the catchment as the well capacity in Eq. (9) we get a maximum dilution as a bounding case. If we assume the well capacity is equal to the irrigation rate we get a most pessimistic case i.e., no dilution. In reality, the well capacity is thus between this no dilution and maximum dilution. In this assessment the well capacity is assumed as 6 500 m^3/y (slightly higher than the irrigation rate).

There are three transfer processes that are used to determine the dynamic content of the rooting zone soil, lower soil and sink compartments plus the loss from the vault to the sink defined as part of the vault model. The biosphere-specific transfer processes are:

- **Transfer from rooting zone soil to lower soil**
  The percolation of water entering the top of the soil column as precipitation or irrigation drives the transfer, taking the net precipitation into account:

$$\lambda_{soil-lowerSoil} = \frac{d_{irri} + PPT - ETP}{s_{soil}\varepsilon_{soil}R_{soil}Th_{soil}} \quad \text{Eq. (30)}$$

  Where ε_{soil} is the porosity of the soil layer [-], s_{soil} is the water filled fraction of the porosity [-], R_{soil} is the retardation factor in the soil (cf. Eq. (4)) [-], and Th_{soil} is the thickness of the soil layer [m].

  This expression is also a major part of λ_{eff} in Eq. (12) to obtain the simple approximation of soil concentration in the biosphere. A comparison of the results obtained from the simple approximation and the dynamic developed in this section will be given in section 5.1.1.

- **Transfer from lower soil to sink**
  The transfer from the lower zone is directed to the sink compartment. In this way the lower soil acts as a sink for the biosphere sub-model with loss from the modelled system directed from there to the sink:

$$\lambda_{lower\ soil-sink} = \frac{d_{irri} + PPT - ETP}{s_{lowerSoil}\varepsilon_{lowerSoil}R_{soil}Th_{lowerSoil}} \quad \text{Eq. (31)}$$

  Where $\varepsilon_{lowsoil}$ is the porosity of the low soil layer [-], $s_{lowsoil}$ is the water filled fraction of the porosity of the low soil layer [-].

  Driven by the water flux entering the top of the soil column, the expression takes the same form as for the rooting zone – lower soil transfer, with the parameters characterising the lower soil used.

- **Transfer from aquifer sink**
  The loss from the aquifer to the external sink is shown in Fig 24b as a transfer from the aquifer component but mathematically is corresponds to the loss from the outflow of the final geosphere compartment in the vault model because the aquifer is treated as an equilibrium compartment. The expression is therefore the same as that given by Eq. (5).

  Concentrations in the well water, rooting zone soil are solved in the compartment model as time series. These are combined to calculate the concentrations in water, soil, and foodstuffs that the human population encounter.

  The soil concentration [Bq kg^{-1} dw soil] is given by

$$C_{soil} = \frac{1}{(1-\varepsilon_{soil})\rho_{soil}} \frac{amount_{soil}}{Th_{soil}A_{root}} \qquad \text{Eq. (32)}$$

where ρ_{soil}, [kg m^{-3}] is the dry mass density of the soil material and $amount_{soil}$, [Bq] is the activity content of the soil compartment as a function of time.

In the previous report (Xu and Kłos, 2019) the irrigation interception process, whereby radionuclides in irrigation water are intercepted by the leaves of the irrigated plants was neglected for the simplicity. The effect of irrigation interception process on the calculated ingestion dose is investigated in this report.

As with the soil compartments it would be possible to disaggregate the plant component of the leading diagonal of the matrix in Fig 24b in a way that more completely expressed the interactions between irrigation water, plant leaves, edible portions and soil and taking $\frac{dplant}{dt} = 0$ to represent the content of the plant at harvest. The result of the process can then be reaggregated system with the result that the expression for the activity concentration, Bq kg^{-1} fw plant, of the plant is given by

$$C_{crop} = TF_{crop}C_{soil} + \mu_{crop}d_{irri}\frac{1+f_{trans}}{Y_{crop}\lambda_{weather}}C_{well} \qquad \text{Eq. (33)}$$

where TF_{crop} is the soil to plant concentration factor for the crop [Bq/kg fresh weight per Bq/kg dry soil] same as in the Eq. (16), μ_{crop} is the interception factor describing the fraction of irrigated water [-], f_{trans} is a nuclide dependent translocation factor [-] (shown in Table A-7) describing the fraction of radionuclide transferred to the edible portions of the crop, Y_{crop} is the yield of the crop and $\lambda_{weather}$ is a weathering loss rate [year^{-1}] to account for the removal of activity from the external surface of the plant.

Eq. (33) is a simplified form of the expression used in the ISAM modelling (IAEA, 2004b). The conservative boundary conditions expressed in Fig 24b allow processes to be ruled out, however. Food processing losses are neglected, retaining activity on the consumed plant material. Weathering of external deposits implicitly returns activity to the soil. Plants, animals and humans being in equilibrium with soil so that senescence and excrescence losses are similarly conserved within the modelled system. To study the effect of adding this irrigation interception process on the ingestion dose we insert this expression into Eq. (16) and Eq. (17).

Results from the dynamic modelling show that the interception process typically contributes less than 5% of the root uptake contribution to plant concentration and that this plays little impact on the overall doses calculated. However, the interception process has been included in the simulations in the following section. The ISAM models (IAEA, 2004b) include this mechanism and it is used here for completeness although it provides only a minor addition to the activity content of the crops.

4.4 Data compilation

Radionuclide and element dependent data are given in the Appendix. Data used in evaluation of the alternative scenarios are covered by the data used for the human intrusion scenarios. Therefore, they are not given explicitly here again. The data obtained from the site investigation are noted as site data. The rest of data used in simulations are adapted from ISAM reports (IAEA 2004a, b) and IAEA TECDOC-1380 (IAEA 2003b). Since most of the data are adopted from the ISAM test cases this simplifies the procedure of data complication. Nevertheless, the sensitivity analysis is performed to identify the key parameters that are to be considered in the next iteration of the assessment.

4.4.1. Data used in evaluation of design scenario

Except for the source terms, radionuclide and element dependent data all the parameter values used in the calculation of the design scenario are given below:

Radionuclide transport:

- Infiltration = 0.573 [m/y] (site data, 10% of infiltration at the initial state and linearly increasing to 100% at 500 years)
- the surface area of the disposal facility = 75 [m^2] (site data)
- the volume of the disposal facility = 225 [m^3] (site data)
- the thickness of the concrete wall 0.35 [m] (site data)
- the density of the concrete 2300 [kg/m^3]
- the porosity of the concrete wall 0.15 [-]
- the density of the waste 1000 [kg/m^3] (assumed)
- the effective porosity in the medium = 0.4 [-] (site data)
- the degree of saturation of the medium = 0.2 [-]
- the bulk density of the medium (unsaturated) = 1910 [kg/m^3] (site data)
- the thickness of unsaturated zone to the aquifer = 1 [m] (assumed based on the site data)
- the total distance to the well = 300 [m] (site data)
- the effective porosity of the medium (aquifer) = 0.4 [-] (site data, an uniform distribution is assumed in the probabilistic calculation, max. 0.4 [-] and min. 0.2 [-])
- the bulk density of the medium (aquifer) = 2000 [kg/m^3] (site data)
- the hydraulic conductivity = 0.35 [m/d] (an average value of the site data, see section 3.2.1, an uniform distribution is assumed in the probabilistic calculation, max. 0.5 [m/d] and min. 0.2 [m/d])

- the hydraulic gradient = 0.1 [-] (site data, see section 3.2.1)
- the well capacity = 6 500 [m3/y] (a log-triangle ular distribution is assumed in the probabilistic calculation, max. 1.24×105 [m3/y] and min. 6.3×103 [m3/y])
- the area of the biosphere object = 2.1×10^4 [m^2] (site data, see section 4.3)
- the area of the catchment associated with biosphere object = 1.1×10^6 [m^2] (see section 4.3)
- precipitation = 0.573 [m/y] (site data, see section 3.2.2)
- evapotranspiration = 0.46 [m/y] (assumed as 80% of the precipitation)

Human behaviour:
- average adult breathing rate = 1 [m^3/h]
- intake rate of drinking water = 0.73 [m^3/y]
- the suspended particle concentration in the river water = 0.01 [kg/m3]
- consumption rate of grain = 148 [kg/y]
- consumption rate of root vegetables = 235 [kg/y]
- consumption rate of green vegetables = 62 [kg/y]
- consumption rate of cow milk = 330 [kg/y]
- consumption rate of cow meat = 95 [kg/y]
- dust concentration during ploughing activities = 10^{-6} [kg/m^3]
- occupancy factor for ploughing activities = 0.034 [-]

Plants:
- irrigation rate per crop = 0.3 [m/y] (site data, an uniform distribution is assumed in the probabilistic calculation, max. 0.4 [m/d] and min. 0.25 [-])
- the interception factor describing the fraction of irrigated water=0.3 [-]
- the yield of the crop = 1 [kg dw/y]
- the weathering loss rate = 18 [1/y]

Cattle:
- daily water consumption = 0.06 [m^3/day]
- daily soil consumption = 0.6 [kg/day]
- daily pasture intake (wet) = 55 [kg/day]
- average milk production = 5500 [kg/y]

Soil:
- thickness = 0.25 [m]
- kinematic porosity = 0.3 [-]
- dry bulk density = 1800 [kg/m^3]

Atmosphere:
- dust concentration during non-ploughing activities = 2×10^{-8} [kg/m^3]

4.4.2. Data used in evaluation of human intrusion scenarios

Bathtubbing scenario

Except for the source terms, radionuclide and element dependent data all the parameter values used in the calculation of the bathtubbing scenario are given below:

- water overflow to the garden during one year (OF) = 0.1 m
- the volume of the disposal unit = 225 [m^3]
- the moisture content of the disposal unit = 0.7 [-]
- for external exposure, a shielding factor (*sf*) of 0.1 for indoor activities is assumed.
- breathing rate indoor = 0.75 [m^3/h]
- breathing rate outdoor = 1 [m^3/h]
- time spent indoor = 6575 [h/y]
- time spent outdoor = 2191 [h/y]
- consumption rate of root vegetables = 118 [kg/y]
- consumption rate of green vegetables = 31 [kg/y]
- inadvertent soil ingestion rate = 3×10^{-2} [kg/y]
- soil thickness = 0.25 [m]
- soil dry bulk density = 1800 [kg/m^3]
- indoor dust level = 1×10^{-8} [kg/m^3]
- outdoor dust level = 2×10^{-8} [kg/m^3]

On-site residence scenario
Except for the source terms, radionuclide and element dependent data all the parameter values used in the calculation of the on-site residence scenario are given below:

- dilution factor is 0.3
- the volume of the waste = 75 [m^3]
- the density of the waste = 1000 [kg/m^3]
- for external exposure, a shielding factor of 0.1 for indoor activities is assumed.
- breathing rate indoor = 0.75 [m^3/h]
- breathing rate outdoor = 1 [m^3/h]
- time spent indoor = 6575 [h/y]
- time spent outdoor = 2192 [h/y]
- root vegetables consumption rate = 118 [kg/y]
- green vegetables consumption rate = 31 [kg/y]
- inadvertent soil ingestion rate = 3×10^{-2} [kg/y]
- indoor dust level = 1×10^{-8} [kg/m^3]
- outdoor dust level = 2×10^{-8} [kg/m^3]

Road construction scenario
Except for the source terms, radionuclide and element dependent data all the parameter values used in the calculation of road construction scenario are given below:

- dilution factor = 0.3
- the volume of the waste = 75 [m^3]
- the density of the waste = 1000 [kg/m^3]
- inadvertent soil ingestion rate = 3×10^{-2} [kg/y]

- exposure duration = 88 [h]
- Breathing rate of the intruder = 1.2 [m^3/h]
- Inadvertent soil ingestion rate of the intruder = 3.4×10^{-5} [kg/h]
- Dust level experienced by the intruder = 1×10^{-6} [kg/m^3]

5. Results of the analyses

The models described in the previous chapter were implemented in Ecolego, which is a modelling software explicitly made for compartmental transport modelling (Ecolego 2018). This chapter presents the results from various scenarios and calculation cases. Generally, a period of 100,000 years is simulated starting from the closure of the disposal facility, which is assumed as 2015 because the estimated inventory is for that year.

5.1 Results from the design scenario

5.1.1. Comparison of the simple expression and the dynamic model

As noted in section 4.2.1 Eq. (12) is a simple expression to approximate activity concentrations in the soil, which was used in the earlier report (Xu and Kłos, 2019). This simple approximation is updated by a dynamical biosphere model described in section 4.3.2. This means that the virtual compartment “soil” in Fig. 17 is replaced by the dynamic biosphere model described in the previous section. Fig. 25 shows the comparison of calculated total doses for the well case from both the simple approximation expression and the dynamic biosphere developed in section 4.3.2. As can be seen the simple expression gives a good approximation of the total dose compared to the dynamic model. The simple expression overestimates the total dose slightly at earlier times and gives almost identical result as the dynamic model in the later times. Nevertheless, it can be considered to be a good approximation in the earlier stages of the assessment. Hereafter, all the calculations for the well case are performed by the dynamic biosphere model.

5.1.2. Deterministic calculation results

In the deterministic calculations of the well case for the design scenario, so called “best estimated” parameter values are used in the calculations. The maximum dose for the well case is about 0.02 mSv/a at around 1 000 years after the closure (see Fig. 26). The dominating radionuclide is C-14. The first peak is about 15 years after the closure. The dominating radionuclide is Cl-36. The third peak of the doses are caused by Pu-239 and its daughter radionuclides. Fig. 27 shows time series of annual effective doses across exposure pathways. As can be seen the ingestion dose dominates and coincides with the maximum dose.

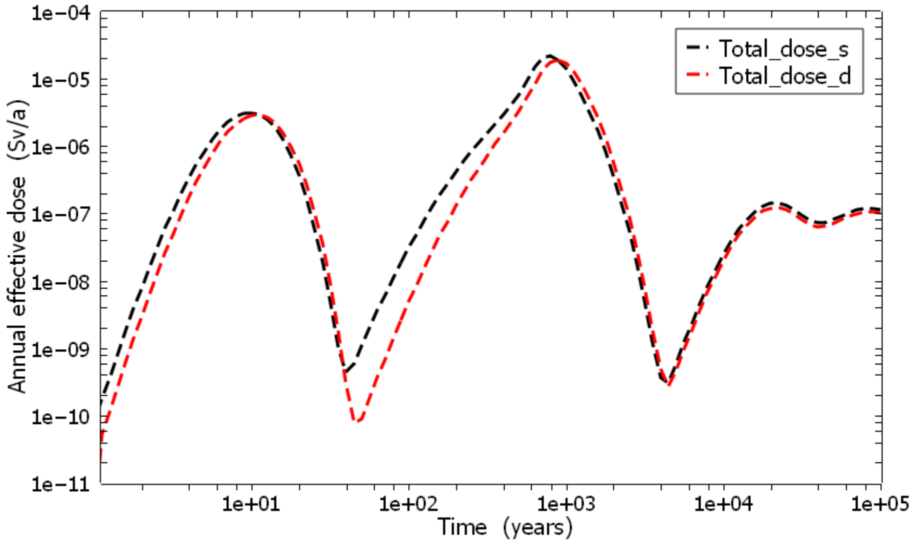


Fig. 25 Comparison of calculated total doses between the simple expression and the dynamic biosphere model for the well case. The dashed red line denotes the result obtained from the simple expression and the dashed black line denotes the result obtained from the dynamic model.

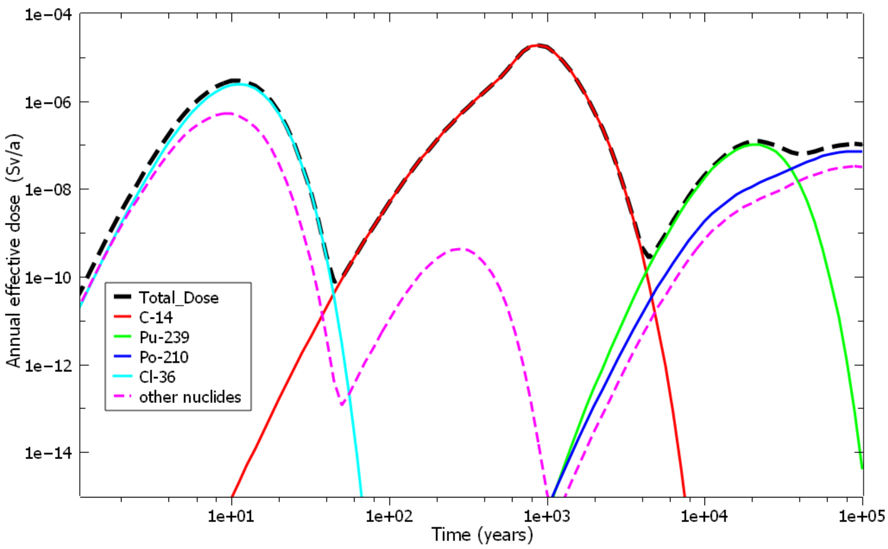


Fig. 26 Effective doses to the most exposed group for releases from the disposal facility in the well case of the design scenario after the closure.

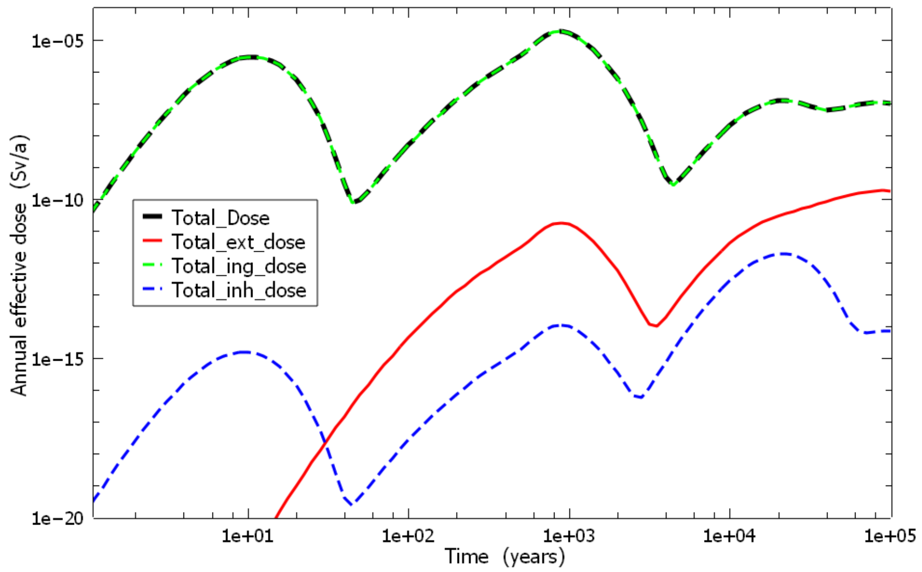


Fig. 27 Effective doses to the most exposed group for releases from the disposal facility in the well case of the design scenario and contributions from the individual exposure pathways.

5.1.3. Probabilistic calculations and sensitivity analysis

The parameters used in simulations are usually divided into three categories: i) time-independent parameters considered to be certain, ii) time-independent parameters with uncertain values, and iii) time-dependent parameters (Avila et al., 2010). Parameters that fall into the first category are those that represent habits and properties of the exposed individuals, such as inhalation rates, water ingestion rates food ingestion rates and dose coefficients. These parameters were assigned constant values adopted from IAEA ISAM reports (IAEA 2004a, b) and IAEA TECDOC-1380 (IAEA 2003b). Other time-independent parameters were considered to fall into the second category and the effect of their uncertainty on the calculated total dose was studied by performing probabilistic simulations. These parameters are distribution coefficients and parameters used in determining transfer rates shown in Fig. 17. The distribution coefficients with assigned probabilistic distribution functions are given in Appendix. Four parameters connected to the transfer rates are studied. These parameters are:

- well capacity,
- water velocity in the aquifer,
- effective porosity in the aquifer, and
- irrigation rate.

Sensitivity analysis was also carried out using results from the probabilistic simulations. Fig. 28 shows the time series of different statistics of the total doses from probabilistic simulations for above mentioned parameter values by using Latin Hypercube sampling method with 3000 iterations. The range from the 3th to the 97th percentile is about three and a half orders of magnitude during the period when peak dose occurs. The maximum mean dose is about 0.025 mSv/a, with the 97th percentile of dose at 0.17 mSv/a. The large spread of the calculated doses with three and a half orders of magnitude is due to the wide range of K_d values assigned in the probabilistic simulations. These were chosen to allow sensitivity to K_d values to be investigated. Ranges for site-specific data would likely be less than that implemented here.

The aim of the sensitivity analysis is to rank the model parameters by their relative effect on the calculated total doses. Sensitivity analyses were performed using Standardised Rank Regression Coefficients (SRRC) with the sample sets generated from probabilistic simulations. The SRRC are a measure of the importance of different parameters for a given output, in this case the influence on total dose is the focus. The higher the SRRC for a parameter, the higher effect on the output. A positive SRRC value indicates that the input and the output move in the same direction, whereas a negative SRRC value indicates that they move in opposite directions.

The total dose time series has three peaks (see Fig. 26). Tornado plots with the values of SRRC show the effect of different model parameters on the local peak doses at three time points, around 15, 1 000, 20 000 years after closure, respectively (see Fig. 29). A SRRC analysis of the total dose at three time points on the input parameters yields in descending order as follows:

- at time point 15 years – K_d_soil (Cl-36), velocity in aquifer, porosity in aquifer, well capacity
- as time point 1 000 years - K_d_aquifer (C-14), K_d_soil (C-14), well capacity, porosity in aquifer, velocity in aquiufer, irrigation rate
- at time point 20 000 years - K_d _aquifer (Ra-226), K_d_aquifer (Po-210), well capacity, K_d_aquifer (Th-230), velocity in aquifer, K_d_aquifer (Pu-239).

As can be seen parameter sensitivity varies with the time owning to the peak doses associated with dominated radionuclides. The most sensitive parameters at three time points are K_d values related to the corresponding dominated radionuclides. Soil K_d values are positively correlated to the calculated doses. While K_d values in aquifer are negatively correlated to the calculated doses. This is because for certainty radionuclide the more adsorbed in aquifer the less releases to surface environment. This may also explain why a large range of K_d values leads to a wide distribution of calculated doses.

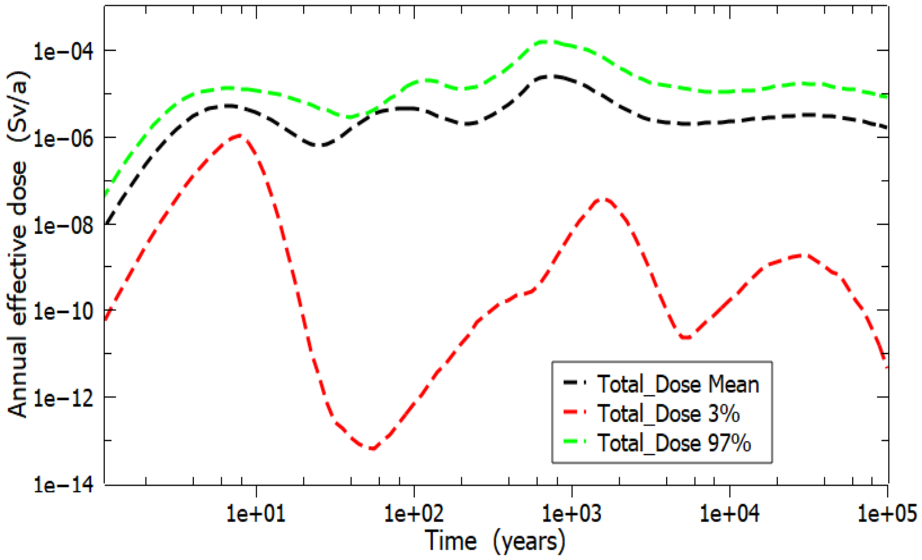


Fig. 28 The time series of different statistics of the total doses from probabilistic simulations, in which the mean, median, 3 percentile and 97 percentile are shown.

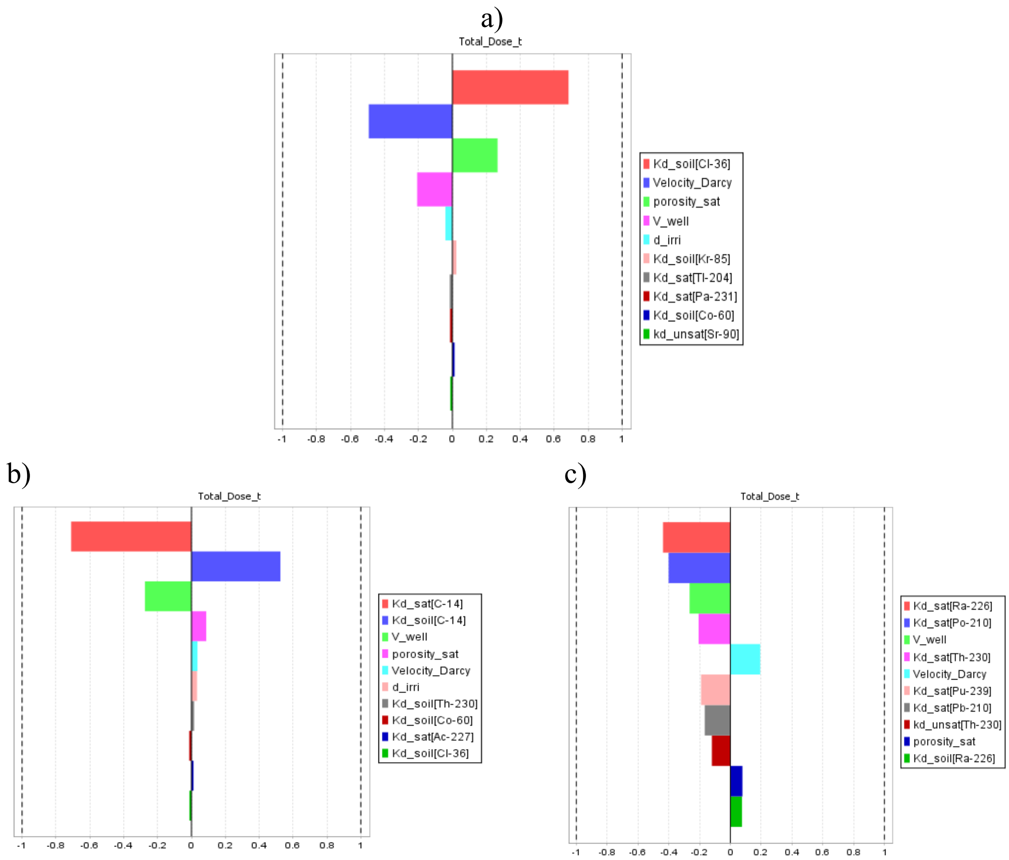


Fig. 29 Tornado charts of presenting SRRC values of local peaks of the total doses at three time points obtained from probabilistic simulations, in which a) at 15 years, b) at 1 000 years and c) at 20 000 years.

The common sensitive parameter at all three time points is the parameter well capacity, V_{well} in Eq. (9), which is negatively correlated to the total dose. This result is to be expected because this parameter is directly related to the effect of groundwater dilution, i.e., the higher dilution the lower total dose is. More discussions about this will be given in the following section.

5.1.4. Results of the "What if" case

For the well case of the design scenario it includes a further pessimistic assumption case, i.e., there is no engineered barrier (concrete wall is completely degraded at the initial state). This is so called "What if" case to illustrate the robustness of various natural and engineered barriers. Simulation was done by setting the retardation factor R in Eq. (3) to 1 and keeping the infiltration rate constant at 0.573 [m/y].

Fig 30 shows the calculated total dose of this "What if" case compared with the base case. As can be seen the maximum dose is 0.05 mSv/a which is doubled that of the base case. The peak dose arrives much earlier than that of the base case, around 300 years after closure instead of 1 000 years for the base case. It is interpreted as the effect of no concrete barrier. However, it seems that the concrete barrier does not affect the peak dose so much. This might be explained that the concrete barrier is already treated as partly degraded at the initial state in the base case.

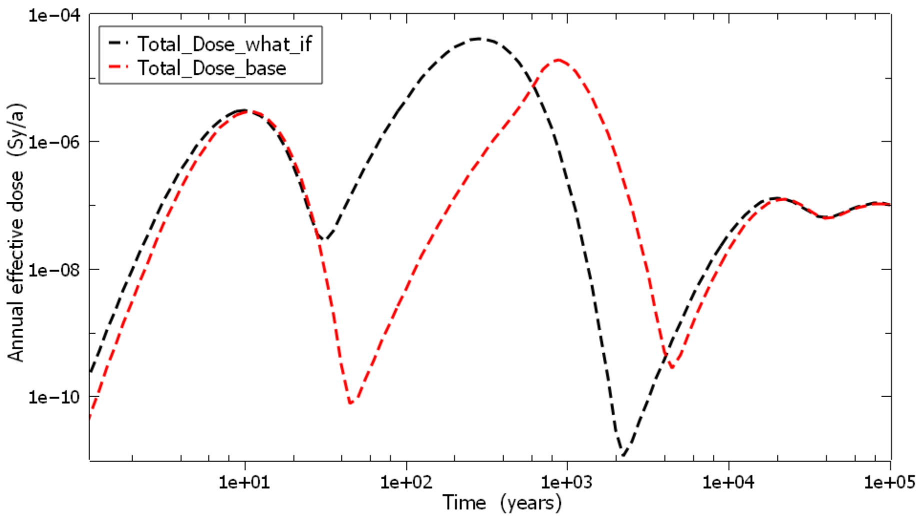


Fig. 30 Comparison of calculated results between the well case with a totally degraded concrete wall at the initial state (black dashed line) and the base well case with partly degraded concrete wall at the initial state (red dashed line).

5.2 Results from the human intrusion scenarios

As mentioned in section 4.1.3 three human intrusion scenarios were selected to assess the disturbed evolution of the disposal facility: the bathtubbing scenario (SCE4); the on-site residence scenario (SCE6); and the road construction scenario (SCE7). The earliest time for these scenarios to happen has been set to the end of institutional control 300 years after the closure. The results are presented below.

5.2.1. The bathtubbing scenario

The bathtubbing scenario anticipates that the existence of a cover and the partly degraded nature of the disposal facility limits the site exploitation, thus reduces the transfer pathways. It is only considered that the water resulting from a leakage accumulation (bath-tub effect) could contaminate a residence system by overflow.

Fig. 31 shows the results for the total dose for this scenario and main radionuclides contributed to the doses. The maximum total dose is about 1 mSv/a and the main radionuclide contributed to the doses is C-14.

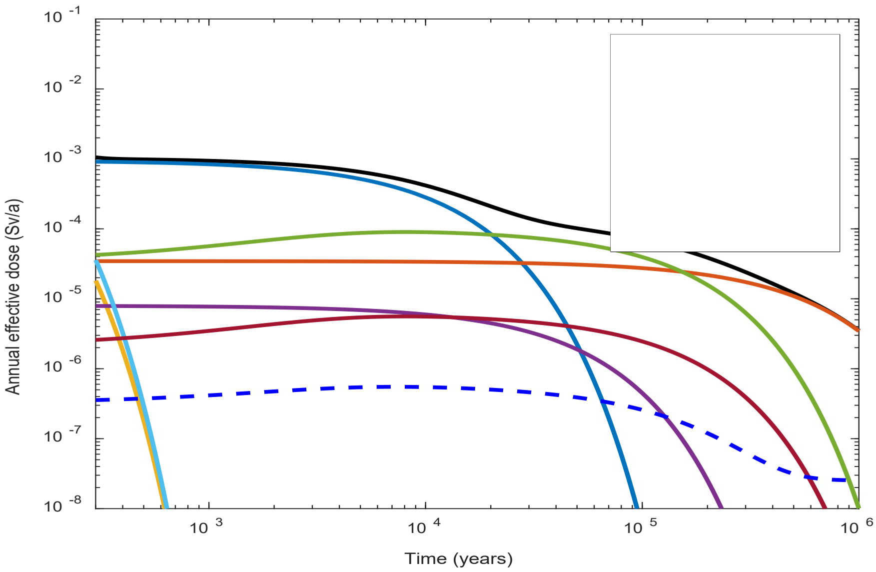


Fig. 31 Total annual effective dose for the bathtubbing scenario.

5.2.2. The on-site residence scenario

The On-site residence scenario assumes that the engineered barriers of the disposal facility as well as the waste are totally degraded. The exposed residents in this scenario are supposed to live in a house that had been built directly on top of the facility. Due to this distribution of waste material, the soil around the house is expected to be contaminated which is equal to the specific activity of the waste divided by a dilution factor. Residents grow vegetables in the garden for their own consumption.

Fig. 32 a) shows the results for the total dose for this scenario and main radionuclides contributed to the doses. The maximum total dose is about 130 mSv/a. The results show that human intrusion activities after the institutional control can lead to radiological exposure above the level of 1 mSv/a for up to 100,000 years. The main radionuclides contributed to the doses are Pu-239 and its daughter nuclides, Ra-226, Po-210 and Pb-210. Fig 32 b) shows the results for the total dose for this scenario and total doses for the individual exposure pathways considered for the scenario. As can be seen the consumption of vegetables grown on the garden is the main contribution to the total dose (see model description, section 4.2.2).

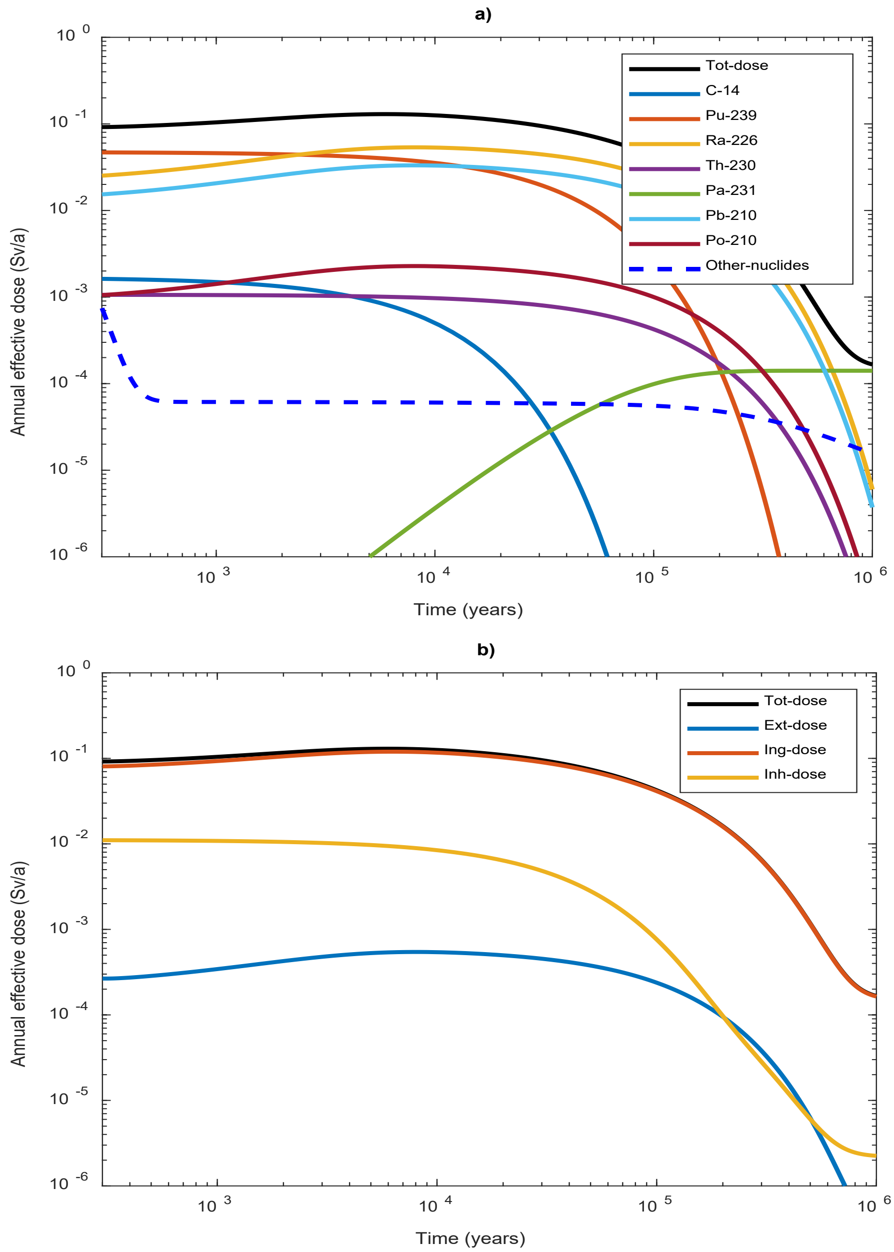


Fig. 32 Total annual effective dose for the on-site residence scenario, the results of the main radionuclides contributed to the doses (figure a)) and total doses for different exposure pathways (figure b)).

5.2.3. The road construction scenario

The road construction scenario expects that the engineered barriers of the disposal facility as well as the waste are totally degraded. A road construction is directly across the disposal facility. The situation is considered as very unlikely to occur but, were it to do so, potentially to important radiological impact could arise.

Fig. 33 shows the calculated doses for the intruders for this scenario. The maximum total dose is about 13 mSv/a, with doses dominated by Pu-239 at time up to 100 kyear.

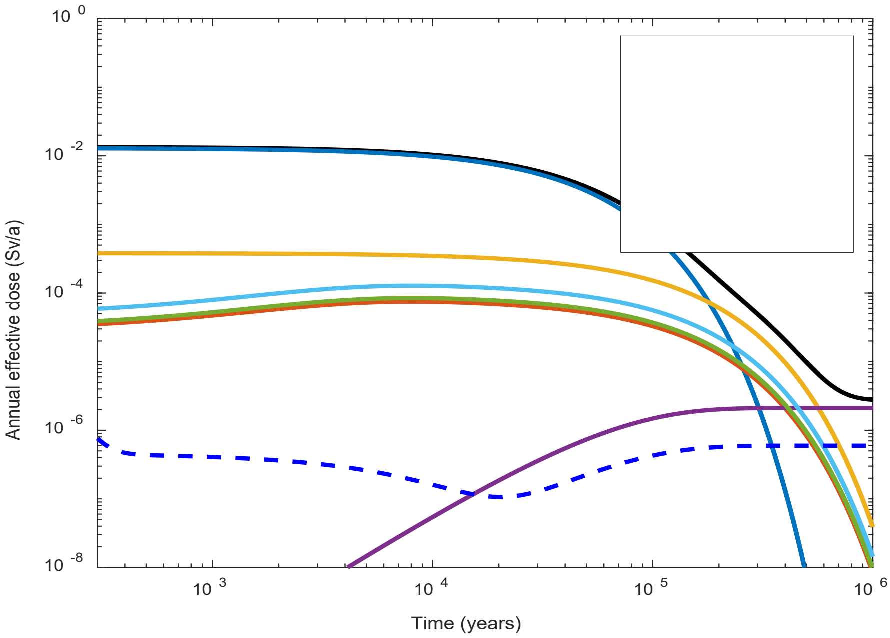


Fig. 33 Total annual dose for the road construction scenario.

5.3 Results from the alternative scenarios

As mentioned in section 4.1.2 two alternative scenarios were selected to assess the deviation of the reference evolution for the long-term safety of the disposal facility: the flooding scenario and landslides scenario. The frequency that the flooding will occur is derived in section 4.1.2 with Eq. (1). The consequences of this event occurring before that time should be considered may be expressed for discrete events as (Bergström et al., 2008):

$$Dose\ (T) = \sum_{t=0}^{T} P(t) \cdot D(T,t) \qquad \text{Eq. (34)}$$

where $Dose\ (T)$ is the effective annual dose at time T considered [Sv/a], $p(t)$ is the frequency of the occurrence at time t [-] (Eq. (1)), $D(T,t)$ is the annual dose at time T associated with an event at time t [Sv/a], which is calculated by Eq. (19) - Eq. (20).

Fig. 34 shows the calculated effective annual dose due to flooding event with the frequency considered during the whole assessment period. The maximum total dose is 1.56 mSv/a occurring at around 30 years after the closure. However, this is only a theoretical estimation. In reality 30 years after the closure is still under the institutional control period and measures can be taken if such a flooding event occurs. The purpose of the alternative scenario analysis is to illustrate that possible rare events to violation of the safety function.

As mentioned in section 4.2.3 the result of the on-site residence scenario can cover the landslides scenario. Therefore, no separate calculation was performed for this scenario.

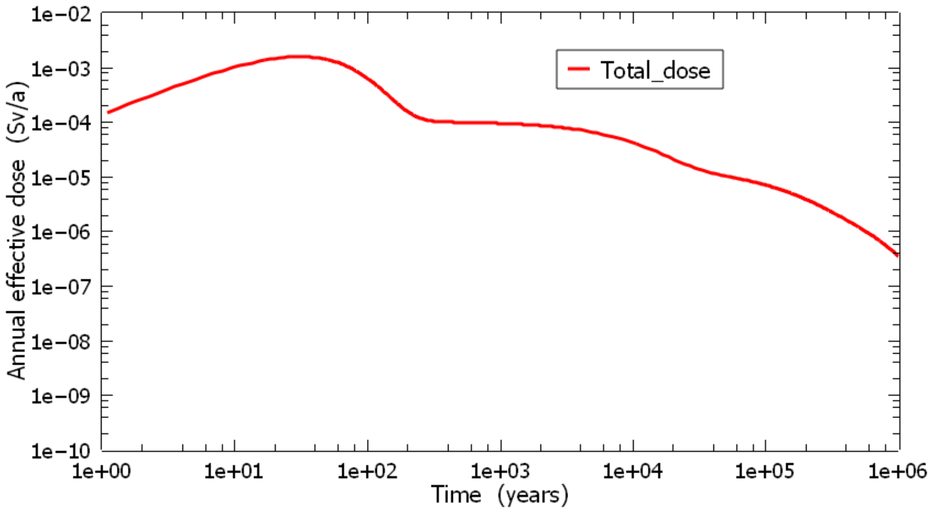


Fig. 34 Total effective annual dose for releases from the disposal facility due to the flooding event of the alternative scenario.

5.4 Results of the assessment for non-human biota

In SSG-29 (IAEA 2014) it states "*Radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations; that is, the generations that produce the waste have to seek and apply safe, practicable and environmentally acceptable solutions for its long term management*", however, IAEA's guidance does not state any numerical criteria or require any specific approach to be used in order to show compliance, but the accompanying guidelines point out that the risk assessment may be done utilising the framework presented by ICRP.

The potential effects on non-human biota from exposure to released radionuclides were assessed. The maximum values of the radionuclide concentrations in soil over simulation times were obtained. These values were then divided by the corresponding Environmental Media Concentration Limits (EMCL), which have been derived in the ERICA project[2] (SKB 2006). The resulting values are the so-called Risk Quotients (RQ), which are used for screening purposes of the graded approach proposed in ERICA for assessment of potential risks to non-human biota. According to the ERICA screening method, if the RQs are below one, then it can be assured that risks to biota are insignificant and no further assessments are required. If the RQ are above one, then more detailed assessments are required.

The soil concentration obtained from the deterministic calculations for the well case are presented in Table 7, which shows that for all radionuclides the activity concentrations in the soil compared with the corresponding EMCL values are below 1. This means that no further assessment is needed.

Table 7 Comparison of predicted maximum values of the radionuclide concentrations in soil with the Environmental Media Concentration Limits (EMCL) for the well case of the design scenario.

Radionuclide	Conc. soil Bq/kg DW	EMCL Bq/kg	RQ
Ac-227	1.5E-06	N/A	N/A
C-14	2.1E+01	8.5E+01	2.5E-01
Cl-36	2.2E-01	2.9E+03	7.6E-05
Co-60	3.3E-15	N/A	N/A
Cs-137	3.5E-15	7.6E+02	4.7E-18
H-3	4.6E-01	N/A	N/A
Kr-85	2.1E-01	N/A	N/A
Ni-63	1.0E-16	1.2E+06	8.4E-23
Pa-231	1.5E-06	N/A	N/A
Pb-210	2.2E-03	N/A	N/A
Po-210	2.2E-03	N/A	N/A
Pu-239	1.7E-01	1.1E+03	1.5E-04
Ra-226	2.0E-03	4.2E+00	4.9E-04
Sr-90	1.7E-05	1.3E+02	1.3E-07
Th-230	3.6E-04	1.6E+03	2.3E-07
Tl-204	9.7E-40	N/A	N/A
U-235	1.6E-07	1.8E+03	8.7E-11

[2] Environmental Risk from Ionising Contaminants: Assessment and Management. EC-EURATOM 6 Framework Programme (2002–2006). Project Contract FI6R-CT-2004-508847.

6. Discussions and conclusions

Based on the procedures defined by the IAEA's standards and best practices the ISAM and BIOMASS methodologies are adapted for this risk assessment. We make maximum use of site-specific descriptive detail when deriving parameter values for the physical components of the assessment model. Rather than using a stylised biosphere object, the area of land considered in the evaluation of dose is embedded in the local surface drainage system, identified from the landscape context using a DEM and GIS methods. The area for dose calculation is identified as the biosphere object that is closest to the disposal site boundary (conservatively minimising spatial dilution) and the size of the object is chosen to be large enough to supply the dietary needs of at least a small family group, maximising use of local resources. The assessment philosophy is therefore cautious.

The generation of scenarios has been conducted according to ISAM approach (shown in Fig. 14), which contains various state of the disposal and human behaviour components for a generic RADON-type facility. Considering of the specific conditions of Chişinău disposal facility seven scenarios/calculation cases were selected for this assessment. For the design scenario (SCE1) a well exposure pathway case is defined as the base case and a "What if" case as the variant case to illustrate the robustness of the engineered barrier. Two alternative scenarios were selected to assess the deviation of the reference evolution for the long-term safety of the disposal facility: the flooding scenario and the landslides scenario. Three human intrusion scenarios were selected to assess the disturbed evolution of the disposal facility: the bathtubbing scenario (SCE4); the on-site residence scenario (SCE6); and the road construction scenario (SCE7).

This report is an update of the previous report (Xu and Kłos, 2019). In this work, a dynamic biosphere model was developed based on the site specific data and compared with the simple approximation used in the previous report. The comparison shows that the simple approximation, Eq. (12) to describe the activity concentrations in soil can be a good approximation at earlier stages of the assessment.

Fully probabilistic uncertainty and sensitivity analyses have been performed to explore the effects of parameter uncertainties and the most important parameters determining calculated doses. The key parameters identified through sensitivity analysis are K_d values and well capacity. Well capacity is related to the issue of dilution in the aquifer, which is a well-known problem in this type of radiological assessment. In this updated report a physically based model to describe activity concentrations in the well water is suggested based on the ISAM model. The approach taken in defining the values for this model can provide practical bounds for the parameterisation of well dilution, directly linked to water balance in the model components based on the identification of the local catchment area. If well capacity is assumed equal to the irrigation rate a most pessimistic, minimal-dilution case is defined.

The most important pessimistic assumptions and parameter values used in the assessment are as the following:

- no retardation of radionuclides in the waste material itself and the engineered barrier (concrete wall that is partly degraded at the initial sate)
- maximum infiltration rate and no engineered barrier (a concrete wall that is totally degraded at the initial state) as “What if” case
- the shortest possible transport distances of releases from the disposal facility to a well
- the hydraulic gradient follows surface inclination

The calculated peak doses and time at which the peak is observed from seven scenarios/calculation cases are summarised in Table 8.

With these pessimistic assumptions, estimated doses from the calculation cases of the design scenario, i.e., for the well case and the “what-if ” cases are lower than the IAEA’s dose criteria. However, estimated doses for the on-site residence scenario after the end of the institutional control period are higher than IAEA’s criteria. The results show that human intrusion activities after the institutional control period could lead to radiological exposure above the level of 1 mSv/a for up to 100,000 years. The long-lived radionuclide Pu-239 dominates doses for the on-site residence scenario. Of course, the very conservative assumptions used in the modelling of the on-site residence scenario should be noted. Nevertheless, measures should be taken to address this issue if the waste were to remain at its present place of disposal.

Potential effects on non-human biota from exposure to released radionuclides have also been addressed. Radionuclide concentrations in soil obtained from the deterministic calculations for the well case have been compared with the corresponding Environmental Media Concentration Limits (EMCL). The EMCL levels are never exceeded in any of the calculations so that no further assessment is required.

Table 8 Peak annual dose and time after the closure at which the peak is observed from seven scenarios/calculation cases

Scenarios		**Descriptions**	**Peak dose [mSv/a]**	**Years**	**IAEA criteria [mSv/a]**
Design scenario	SCE1	Well case (Deterministic)	0.02	1 000	0.3
		(Mean)	0.025	1 000	0.3
		(97^{th} percentile)	0.17	1 000	0.3
		“What if” case	0.05	300	0.3
Alternative scenario		Flooding	1.6	30	0.3
		Landslides	130*	-	0.3
Human intrusion scenario	SCE4	Bathtubbing	1	300	20
	SCE6	On-site residence	130	300	20
	SCE7	Road construction	13	300	20

*Calculated dose was not taken into account the frequency of occurrences.

This assessment has the primary function of assessing potential radiological impacts thereby identifying where better local information might reduce conservatism and lead to a more realistic expression of the assessment of radiological impact.

The disposal facility is located on the upstream area of Chişinău, which might, in hindsight, not have been an optimal choice of the site for a radioactive waste disposal.

As a final point it should be noted that this is a relatively simple application of the ISAM methodology which includes aspects of the updated BIOMASS methodology to develop mathematical models of the biosphere component of the assessment model chain and to derive relevant site-specific details. The model used is suitable for an early-stage assessment of the potential hazards of the site and can be used to inform decisions about continued licensing and operation or, as needs be, remediation. The results from the assessment here indicate that C-14 is a significant radionuclide in the inventory and the doses calculated have used the standard form from the ISAM model description. This treats C-14 using a standard transport and dose model that is common to other radionuclides. It is known, however, that C-14 shows behaviour that is not well represented by such models since the soil-atmosphere-plant continuum is not directly considered. For future developments the possibility of alternate model for C-14 dose assessment might be considered.

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Appendix: Radionuclide and element dependent data

Non-sampled data

The following sets of data are parameters as non-varying in the probabilistic uncertainty and sensitivity studies.

Table A-1 The activity inventory of the disposal facility [Bq]

Radionuclide	Inventory disposed [Bq]
C-14	4.86E+10
Cl-36	3.70E+07
Co-60	4.96E+10
Cs-137	3.41E+11
H-3	4.91E+08
Kr-85	2.41E+09
Ni-63	3.07E+04
Po-210	0.00E+00
Pu-239	2.41E+11
Ra-226	3.05E+09
Sr-90	6.48E+10
Th-230	8.51E+09
Tl-204	5.79E+05

Table A-2 Radionuclide and decay chains considered in the assessment

Radionuclide	Daughters	Radionuclide	Daughters
Ac-227	-	Sr-90	-
C-14	-	Tl-204	-
Cl-36	-	Ra-226	-
Co-60	-	Pb-210	-
Cs-137	-	Po-210	-
H-3	-	Th-230	Ra-226 →Pb-210 → Po-210
Kr-85	-	U-235	-
Ni-63	-	Pu-239	U-235→Pa-231→Ac-227
Pa-231	-		

Table A-3 Dose coefficient for ingestion, inhalation and external irradiation (data from IAEA DOC-1380)

Radionuclide	DF_intag [Sv/Bq]	DF_inh [Sv/Bq]	DF_ext [Sy/h per Bq/kg]
Ac-227	1.2E-06	5.7E-04	6.0E-11
C-14	5.8E-10	5.8E-09	0.0E+00
Cl-36*	9.3E-10	7.3E-09	0.0E+00
Co-60	3.5E-09	3.1E-08	5.5E-10
Cs-137	1.3E-08	3.9E-08	1.2E-10
H-3	1.8E-11	2.6E-10	0.0E+00
Kr-85**	1.8E-11	7.30E-09	0.00E+00
Ni-63	1.5E-10	1.3E-09	0.0E+00
Pa-231	7.1E-07	1.4E-04	6.1E-12
Pb-210	6.9E-07	5.7E-06	2.5E-13
Po-210	1.2E-06	4.3E-06	1.9E-15
Pu-239*	2.30E-07	4.60E-05	2.30E-14
Ra-226	2.8E-07	9.5E-06	5.7E-10
Sr-90	3.1E-08	1.6E-07	2.1E-12
Th-230	2.1E-07	1.0E-04	2.4E-14
Tl-204	1.2E-09	3.9E-10	8.1E-14
U-235	4.7E-08	8.5E-06	1.9E-11

*adapted from TR-99-14 (Bergström et. al., 1999), **estimated

Table A-4 Transfer coefficients to cows meat [days/kg fresh weight] and milk [days/l] (data from IAEA TECDOC-1380)

Element	TF_beef	TF_milk	Element	TF_beef	TF_milk
Ac	1.60E-04	4.00E-07	Pb	4.00E-04	3.00E-04
C	1.20E-01	1.00E-02	Po	5.00E-03	3.40E-04
Cl*	2.00E-02	1.70E-02	Pu	1.00E-05	1.10E-06
Co	1.00E-02	3.00E-04	Ra	9.00E-04	1.30E-03
Cs	5.00E-02	7.90E-03	Sr	8.00E-03	2.80E-03
H	2.90E-02	1.50E-02	Th	2.70E-03	5.00E-06
Kr**	2.90E-02	1.50E-02	Tl	4.00E-04	3.00E-04
Ni	5.00E-03	1.60E-02	U	3.00E-04	4.00E-04
Pa	5.00E-05	5.00E-06			

*adopted from TR-99-14 (Bergström et. al., 1999), **estimated

Table A-5 Soil to plant concentration factors [Bq/kg fresh weight per Bq/kg dry soil] for crops, root vegetables, green vegetables, and pasture. (IAEA TECDEC-1380, Table IV.8)

Element	TF_crop	TF_root	TF_veg	TF_pasture
Ac	1,00E-03	1,00E-03	1,00E-03	1,00E-03
C	10E-01	1,00E-01	1,00E-01	1,00E-01
Cl*	3,00E+01	6,00E+00	3,00E+00	3,00E+01
Co	3,0E-02	3,0E-02	3,0E-02	6.0E-03
Cs	2,00E-02	3,00E-02	3,00E-02	3,00E-02
H	5,00E+00	5,00E+00	5,00E+00	5,00E+00
Kr**	5,00E+00	5,00E+00	5,00E+00	5,00E+00
Ni	5,00E-02	3,00E-02	3,00E-02	2,00E-02
Pa	4,00E-02	4,00E-02	4,00E-02	4,00E-02
Pb	1,00E-02	1,00E-02	1,00E-02	1,00E-02
Po	2,00E-04	2,00E-04	2,00E-04	2,00E-04
Pu	1,00E-03	1,00E-03	1,00E-04	1,00E-03
Ra	4,00E-02	4,00E-02	4,00E-02	4,00E-02
Sr	8,00E-02	9,00E-02	3,00E+00	3,00E+00
Th	5,00E-04	5,00E-04	5,00E-04	5,00E-04
Tl	1,00E-02	1,00E-02	1,00E-02	1,00E-02
U	1,00E-04	1,00E-03	1,00E-03	1,00E-03

*adopted from TR-99-14 (Bergström et. al., 1999), **estimated

Table A-6 Near field distribution coefficient (data from ISAM report Vol. II IAEA 2004b)

Element	K_d_vault_non_deg [m^3/kg]	K_d_vault_deg [m^3/kg]
Ac	1E+0	2E-1
C	2E+0	2E-1
Cl**	0E+0	0E+0
Co	1E-1*	0E+0**
Cs	2E-2	2E-2
H	0E+0	0E+0
Kr**	0E+0	0E+0
Ni	1E-1	1E-2
Pa	5E+0	1E-1
Pb	5E-1	5E-2
Po	0E+0	0E+0
Pu	5E+0	1E+0
Ra	5E-2	5E-2
Sr	1E-3	1E-3
Th	5E+0	1E+0
Tl	2E+0*	1E-1**
U	2E+0	1E-1

*adopted from IAEA TECDOC-1380, **values are estimated

Table A-7 Translocation factor (IAEA, 2004b).

Nuclide	translocation factor f_{trans}	Nuclide	translocation factor f_{trans}
H-3	2.30E-02	Tl-204	4.50E-01
C-14	5.80E-01	Pb-210	2.20E-01
Cl-36*	6.10E-01	Po-210	2.20E-01
Co-60	1.90E-01	Ra-226	1.80E-01
Kr-85	1.00E-03	Ac-227	4.50E-01
Ni-63	3.70E-01	Th-230	3.80E-02
Sr-90	2.00E-01	Pa-231	4.50E-01
Cs-137	1.90E-01	U-235	3.60E-01
		Pu239	3.60E-01

* taken from the I-129 value, from the ISAM database.

Sampled parameters

Distribution coefficients are important and uncertain parameters. They control the mobility of chemical species in the various geologic media. The database used for this example application is based on the lists of k_d-values in IAEA TECDOC-1380. However, only a central, representative value is quoted and so the shape of the distribution and the spread is not specified. k_ds are generally seen to be log-normally distributed, for example the dataset employed in SKB's SR-Site assessment (Nordén *et al*. 2010), which quotes geometric mean (GM) and geometric standard deviation (GSD) as the numerical parameters defining the probability distribution functions.

In this study, the central values are taken to be the geometric mean and a geometric standard deviation of 4 is adopted for all radionuclides. This is consistent with the typical GSD values and provides a range of values that lie within two orders of magnitude on either side of the GM value. This provides a suitable basis for the sensitivity study and gives a plausible range for the uncertainty analysis.

Table A-8 Element specific distribution coefficient (K_d) for unsaturated mediums (IAEA TECDEC-1380), the distribution function is assumed in this study.

Element	K_d_clay, GM [m^3/kg]	PDF	GSD
Ac	7.6E+0	lognormal	4.0
C	1.0E-3	lognormal	4.0
Cl	0	-	
Co	5.0E-1	lognormal	4.0
Cs	2.0E+0	lognormal	4.0
H	0	-	
Kr**	0	-	
Ni	6.0E-1	lognormal	4.0
Pa	7.6E+0	lognormal	4.0
Pb	5.0E-1	lognormal	4.0
Po	3.0E+0	lognormal	4.0
Pu	7.6E+0	lognormal	4.0
Ra	9.0E+0	lognormal	4.0
Sr	1.0E-1	lognormal	4.0
Th	6.0E+0	lognormal	4.0
Tl	6.0E+0**	lognormal	4.0
U	4.6E-2	lognormal	4.0

*adopted from TR-99-14, **values are estimated

Table A-9 Element specific distribution coefficient (K_d) for saturated mediums (IAEA TECDEC-1380), the distribution function is assumed in this study.

Element	K_d_geo, GM [m^3/kg]	PDF	GSD
Ac	3.4E-1	lognormal	4.0
C	5.0E-3	lognormal	4.0
Cl	0	-	
Co	1.5E-2	lognormal	4.0
Cs	3.0E-1	lognormal	4.0
H	0	-	
Kr**	0	-	
Ni	4.0E-1	lognormal	4.0
Pa	3.4E-1	lognormal	4.0
Pb	3.0E-1	lognormal	4.0
Po	1.5E-1	lognormal	4.0
Pu	3.4E-1	lognormal	4.0
Ra	5.0E-1	lognormal	4.0
Sr	1.5E-2	lognormal	4.0
Th	3.0E+0	lognormal	4.0
Tl	3.0E+0**	lognormal	4.0
U	5.6E-1	lognormal	4.0

Table A-10 Element specific distribution coefficient (K_d) for soil media (IAEA TECDEC-1380), the distribution function is assumed in this study.

Element	K_d_soil, GM [m^3/kg]	PDF	GSD
Ac	4.5E-1	lognormal	4.0
C	1E-1	lognormal	4.0
Cl	1.0E-3*	lognormal	4.0
Co	6.0E-2	lognormal	4.0
Cs	2.7E-1	lognormal	4.0
H	1E-4	lognormal	4.0
Kr**	1E-4	lognormal	4.0
Ni	4E-1	lognormal	4.0
Pa	5.4E-1	lognormal	4.0
Pb	2.7E-1	lognormal	4.0
Po	1.5E-1	lognormal	4.0
Pu	5.4E-1	lognormal	4.0
Ra	4.9E-1	lognormal	4.0
Sr	1.3e-2	lognormal	4.0
Th	3.0E+0	lognormal	4.0
Tl	2.7E-1	lognormal	4.0
U	3.3E-2	lognormal	4.0

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