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# Radiological risk assessment for the “Radon” type surface disposal facility in Chisinau, Moldova

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This report concerns a study which has been conducted for the Swedish Radiation Safety Authority, SSM. The conclusions and viewpoints presented in the report are those of the author/authors and do not necessarily coincide with those of the SSM


## Abstract

The long-term conditions and potential radiological consequences of the legacy radioactive waste stored in the RADON-type disposal facility outside Chisinau is of concern for the central government authorities of the Republic of Moldova. A radiological risk assessment of "zero alternative scenario" for the RADON-type of near-surface disposal facility has been conducted. 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.

Based on the current state of the art, the procedures defined by IAEA's standards and best practices the ISAM methodology and IAEA's BIOMASS methodology are adapted in this risk assessment. We use the site specific information as much as possible to derive the parameter values used in the assessment. Instead of using a stylised biosphere object the relevant biosphere object and associated catchment areas were identified based on the site specific DEM (digital elevation model) using GIS tools. As to the relevant biosphere object we mean that the identified biosphere object is close to the disposal site boundary so as to avoid excessive spatial dilution and the size of the object is large enough to supply the dietary needs of at least a small family group.

The generation of scenarios has been conducted according to ISAM approach, which contains various state of the disposal and human behavior components for a generic RADON-type facility. A limited number of deterministic sensitivity analysis was performed to explore the model uncertainty and parameter uncertainty. 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 degraded at the initial sate)
- the shortest possible transport distances of releases from the disposal facility to a well or a stream
- the hydraulic gradient follows surface inclination
- no sorption to waste mass in the flooding scenario

With pessimistic assumptions, the estimated doses from the calculation cases of the design scenario, i.e. for the well case and the stream case are lower than the IAEA's criteria. Estimated doses for the on-site resi-

dence scenario after institutional control are higher than IAEA's criteria. 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. Long lived radionuclide Pu-239 dominates the doses for the on-site residence scenario. Of course, the very conservative assumptions used in the modelling of the on-site residence scenario can be discussed. Nevertheless, measures should be taken for this matter if the waste is at its present place of disposal.

The potential effects on non-human biota from exposure to released radionuclides were assessed. The stream case of the design scenario was considered. The maximum values of the radionuclide concentrations in fresh water and in soil were compared with Environmental Media Concentration Limits (EMCL). If the ratio between the maximum values and EMCL is less than one no further assessments are required. For most of radionuclide concentrations calculated from the stream case are below one except C-14 and Pu-239 in freshwater.

Scenarios with high calculational consequences are obviously of interest though not necessarily because they are a true expression of radiological hazard. This first iteration 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 the radiological impact.

The disposal facility is located on the upstream area of Chisinau, which might be not an optimal choice of the site for a radioactive waste disposal.

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# Content

# 1. Introduction

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 Chisinau (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.

Swedidh Radiation Safety Authority (SSM) suported a collaborative project during 2017-2018 that aims at 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 inventory have been completed and documeted 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 Chisinau” as well as “Hydrogeological and geotechnical conditions of radioactive waste deposit from Uzinelor 210 str. mum. Chisinau, 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 “zero alternative scenario” for the RADON-type of near-surface 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.

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 harmonized assessment methodology (see Fig. 1), the ISAM project methodology (IAEA 2004a,b), 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, development and justification of scenarios, iii) formulation and implementation of models and iv) analysis of results and building confidence. However, given the resource constraints illustration of the application of the methodology is limited, for instance, for the RADON Test Case, which prevented detailed study of the system and collection of many site specific data that would be available in a real assessment.

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).

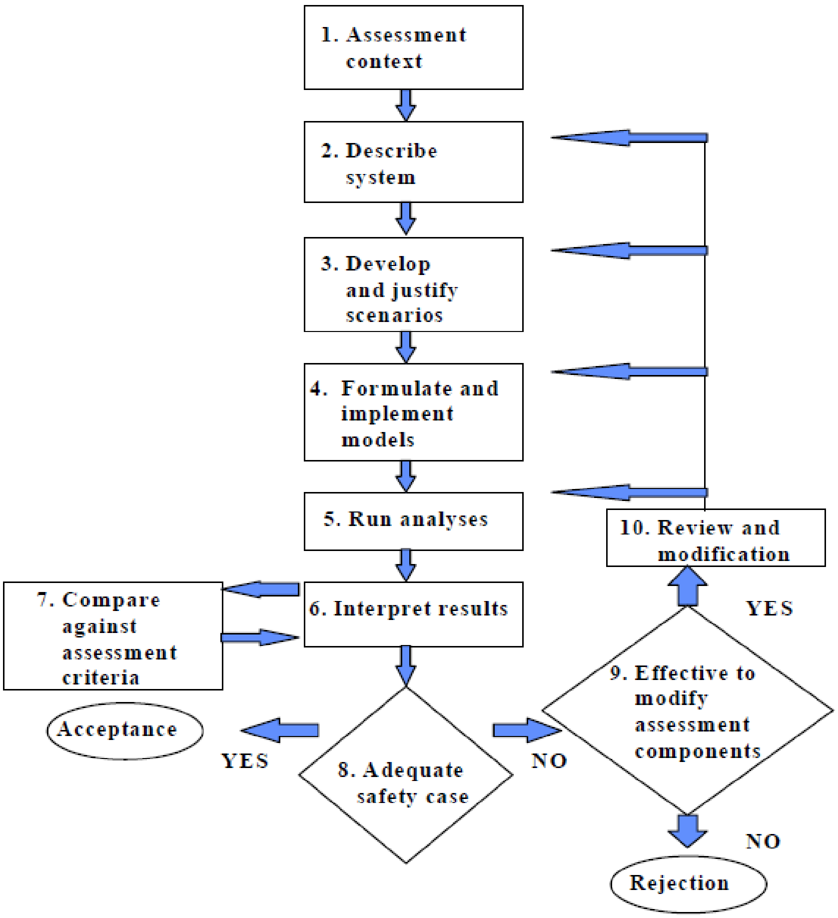



**Fig. 1** The ISAM project methodology (IAEA 2004a)

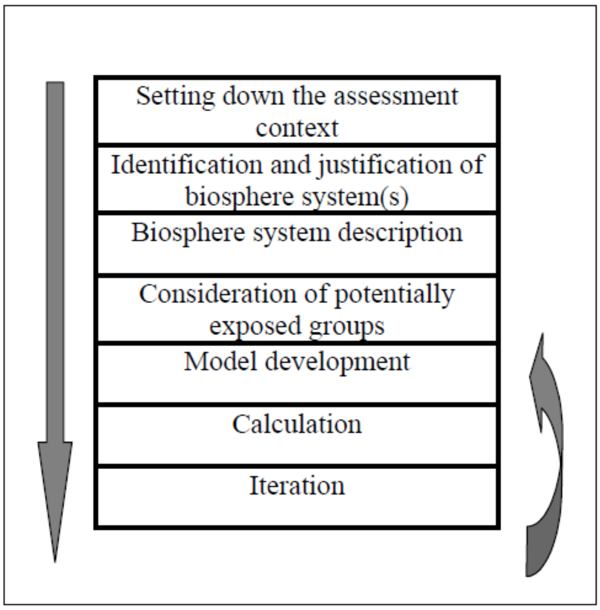



**Fig. 2** The BIOMASS methodology (IAEA 2003a)

# 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 Chisinau (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 managemewnt in Moldova is under development. For the time being, there are no legal requirements for undertaking risk assessments for near-surface disposal facilities in Moldova. 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 4.2).

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, like the 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 radioactivity 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.

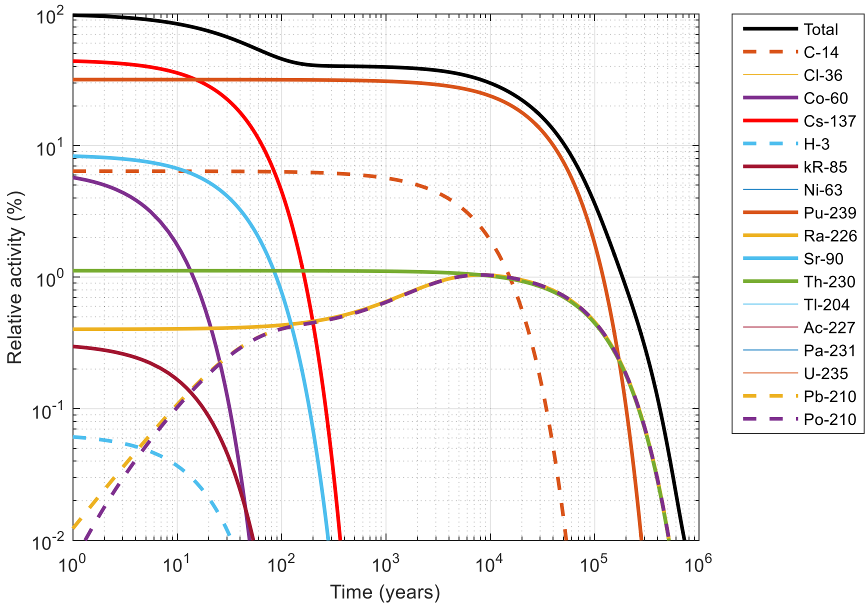



**Fig. 3** Percentage contribution to the total activity as a function of time.

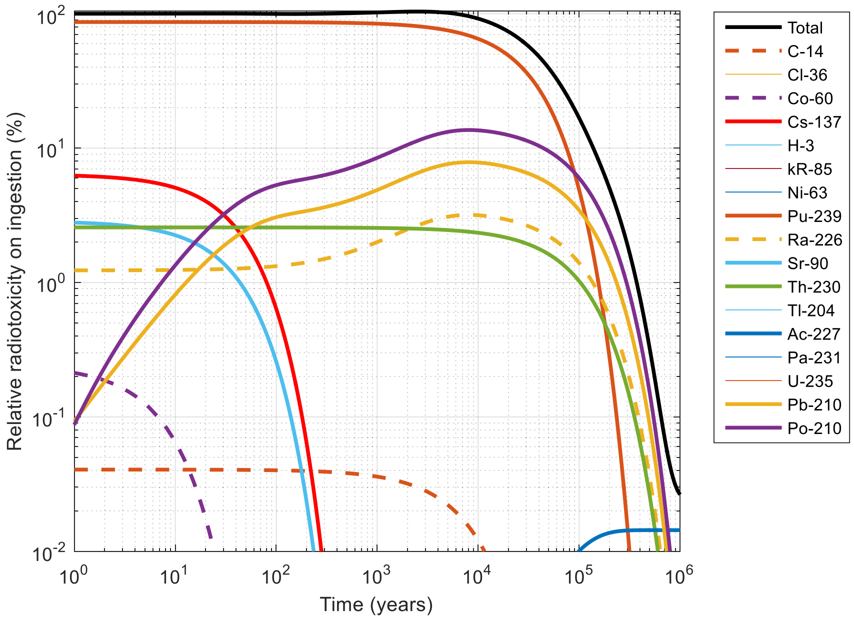



**Fig. 4** Percentage contribution to total radioactivity as a function of time.

# 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 are covered by prefabricated reinforced concrete panels (width about 80 cm, height about 24 cm). The panels were placed on the concrete crown (about 8 cm height) of Vaults. The gaps of about 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 × 1400mm, 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 could be estimated respectively 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 about 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 about 75 $m^3$.

Four vaults do not provide satisfactorily isolation (see Fig. 7). According to the operator's narration the elevated groundwater table was observed inside the vault IV during the late '90s (Site Report, p. 95). As mentioned previously, 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.

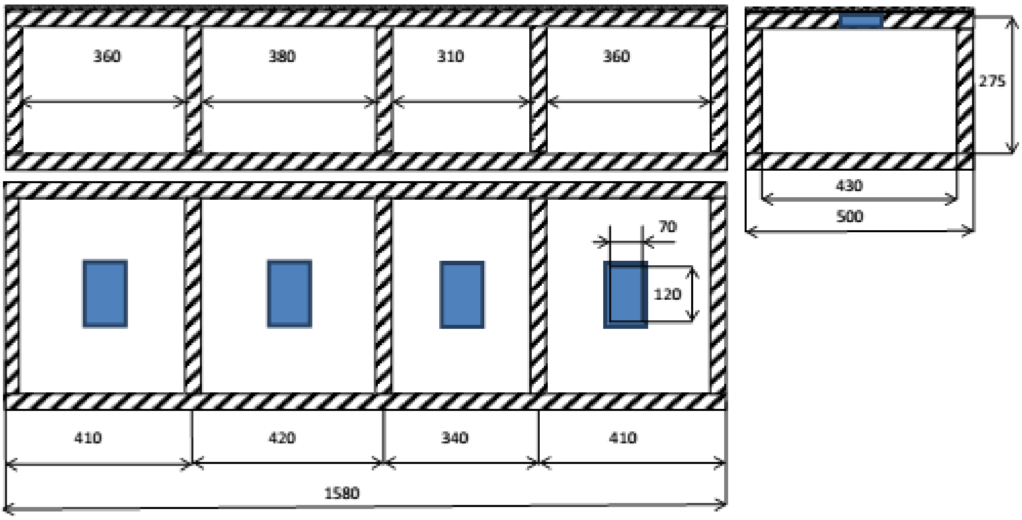


**Fig. 5** Vault layout and cross section.

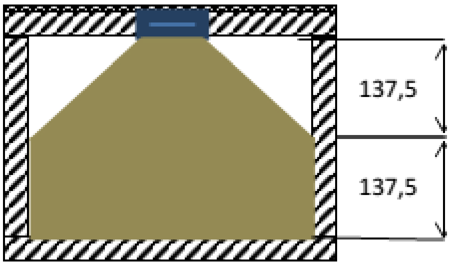


**Fig. 6** Schematics of waste position in the vault.


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

The activities of the isotopes are summarized 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 Chisinau municipality, and the territory adjacent to the facility falls within the limits of the city, Chisinau on 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

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

**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.

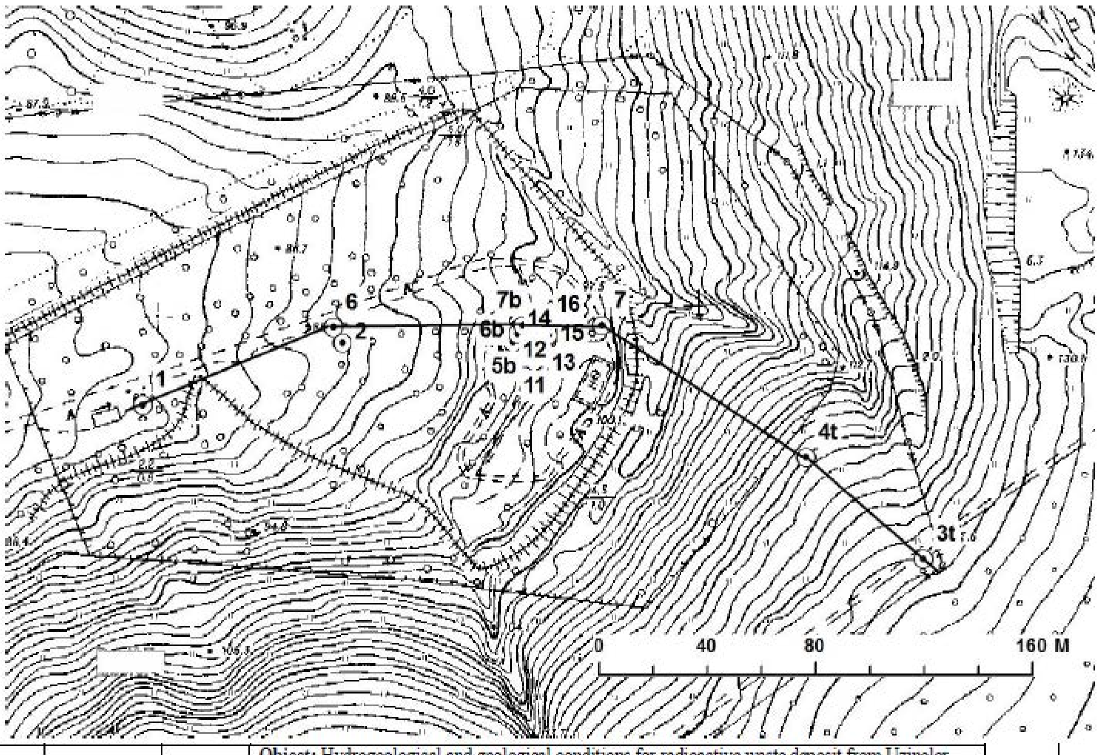
The upper part of geological section is characterized by small thickness of Quaternary loam and Neogene sandy-clay formation. These rocks are covered by agriculture (layer 1) and artificial (layer 2) soils. Quaternary loam (layer 3) has no subsidence properties. Neogene formation represented by sandy loam (layers 4, 7) layered with clay and clay layered with sands (layers 5, 6). Upper part of clays, which is located at slope with intense inclination, is 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 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 of the degree of the fracturing and stratification.

The groundwater is situated on the different levels: from 1.5 to 11.0 m (altitude 81.0 – 88.6 m above the sea level, WGS84). The raising of groundwater level is indicated after its appearance to 1.3 – 1.8 m. The appearance of the shallow groundwater layer is possible in the wet season, which is not a favourable factor for the slope stability. The principal water bearing rocks are sandy loam, which are in fluid consistence (liquid state according to Atterberg limits) in water saturated zone. 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 |
|---|---|---|---|---|---|
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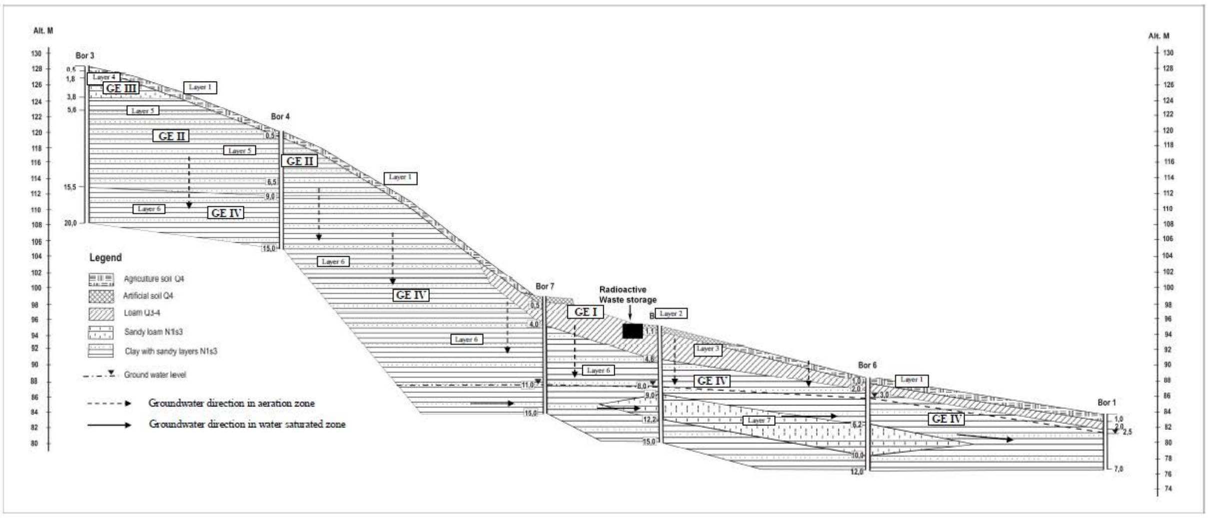
**Fig. 9** Map of actural materia.




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 was 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 contains the spatial distribution of monthly, seasonal and annual average values. Fig. 11 shows linear trends in the evolution of mean air temperature ($^{o}$C/year - left side), and precipitation (mm/year - right side) for two instrumental observation time spans at Chisinau Meteorological Station (Site Report).

The climate of the Republic of Moldova is moderate-continental and is characterized 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.

For future climate, projections of climate scenarios for the Republic of Moldova suggest that what is considered as 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).

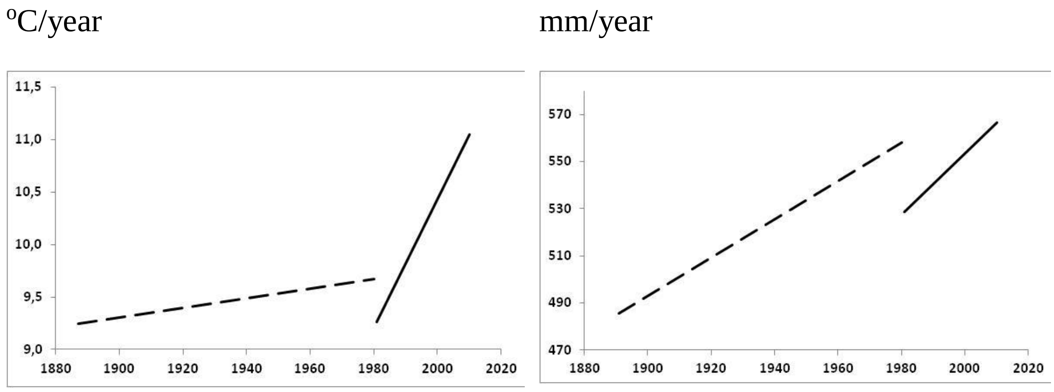



**Fig. 11** Linear trends in the evolution of mean air temperature (°C/year - left side), and precipitation (mm/year - right side) for two instrumental observation time spans at Chisinau Meteorological Station (dashed line: 1887-1980 and continuous line: 1981-2010)

### 3.2.3. Land use

The general characterization of land use on the site is shown in Table 2. The obtained data shows the dominance of the infrastructure land, 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. 10a.

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. 10b 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 characterization of non-agricultural use

| Use | Nr. of objects | Surface, Ha | % of total object surface |
|---|---|---|---|
| agricultural | 108 | 219.163 | 38.1 |
| nonagricultural | 100 | 109.912 | 19.1 |
| Infrastructure | 123 | 245.973 | 42.8 |
| **TOTAL** | **331** | **575.05** | **100** |

**Table 3** General characterization of agricultural use

| Category of use | Nr. 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** |

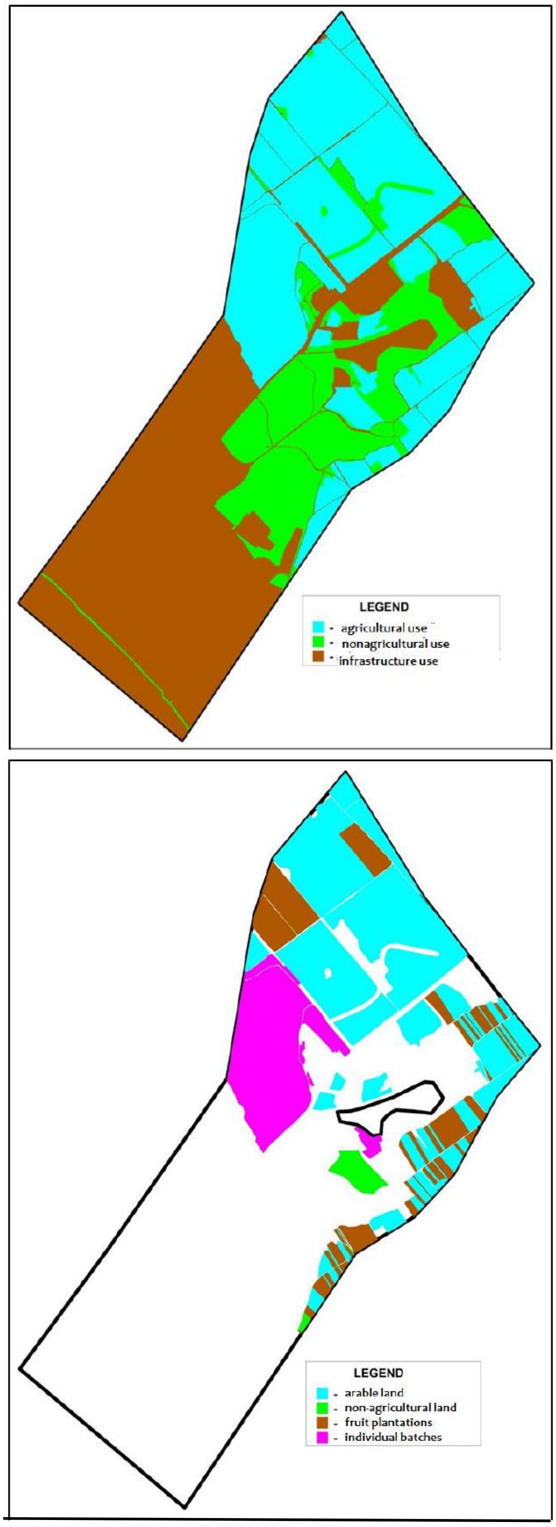



**Fig. 12** Land map a) by usage mode; b) by agricultural categories

# 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

In SSG-23 (IAEA, 2012), it 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.*"

In ISAM project a systematic assessment framework has been developed 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 taken 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 summarized as the following:

- Screen the ISAM FEPs list on the basis of the assessment context and system description;
- Develop and agree a simplified Base 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 FEPs list, especially focusing on the external FEPs.
- Identify a limited number of scenarios due to inadvertent intrusion of disposal facilities after the institutional control

An example of a formal approach to developing a set of generic post-closure scenarios is illustrated in Fig. 13.

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

Combing the approach illustrated in Fig. 13, 14 and the site specific conditions we are able to select scenarios for this 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 downstream of the disposal facility. Identification of the farm system is given in section 4.2. 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 variant calculation cases can be defined, a well exposure pathway and a stream exposure pathway.

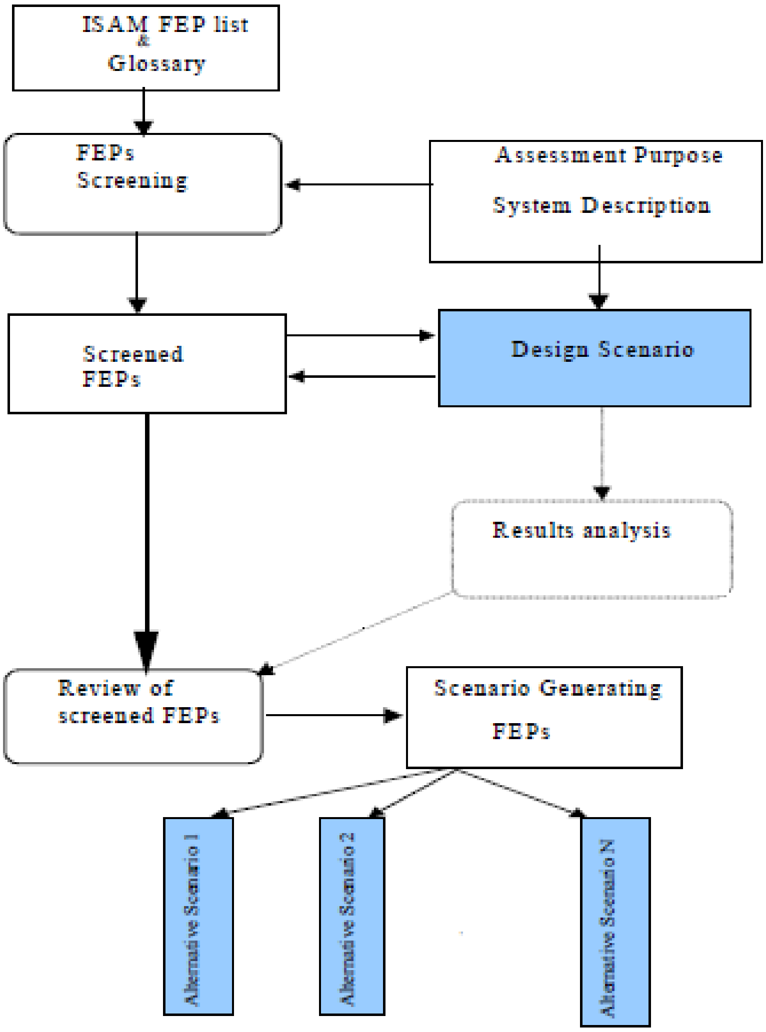



**Fig. 13** The RADON Test Case Scenario Generating Approach (IAEA 2004, Volume I).

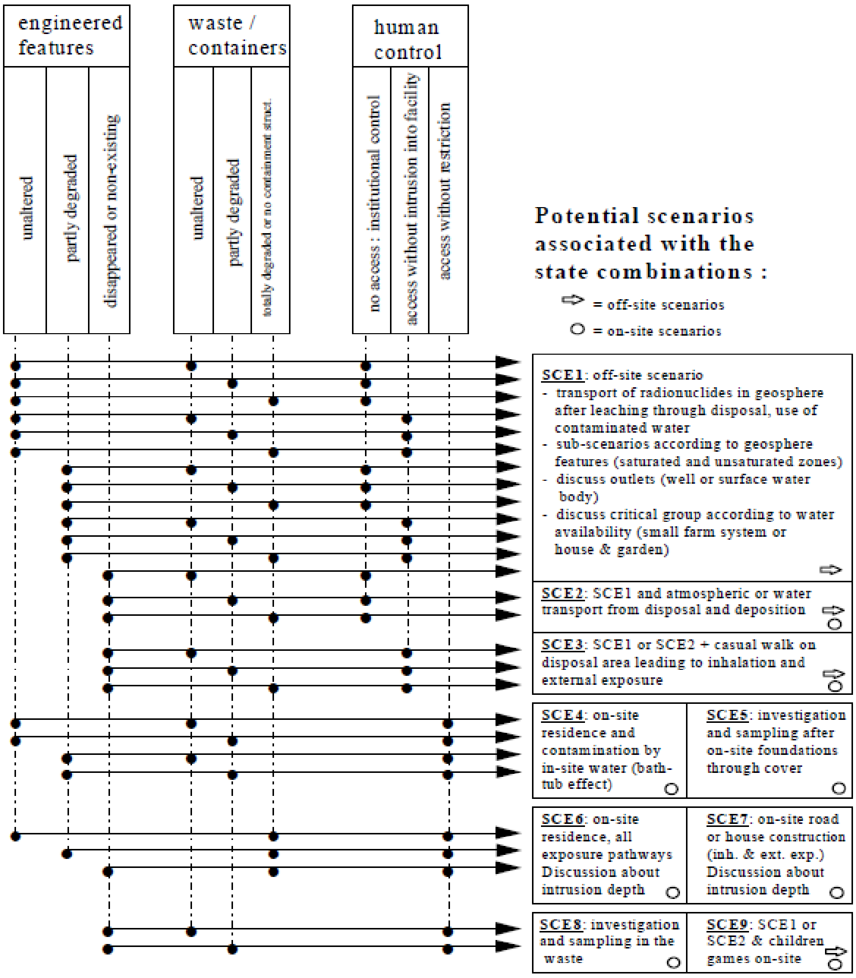



**Fig. 14** Generation of a Set of Scenarios (SCE) According to Various States of the Disposal and Human Behaviour Components (IAEA 2004a)

### 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*". The 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.*"

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

### 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) the 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 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. 15), 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.

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., (2018).

Fig. 16 shows identified catchments and streams on the map of the site. The disposal facility is within a single catchment of area 1140907 $m^2$ (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 1453830 $m^2$ (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 the streams. The water balance of the object can be conservatively derived from the red and green areas, areas are listed in Table 4. The distance between the disposal facility to the nearest stream is about 50 m.

[1] Copyright © 2019 Blue Marble Geographics

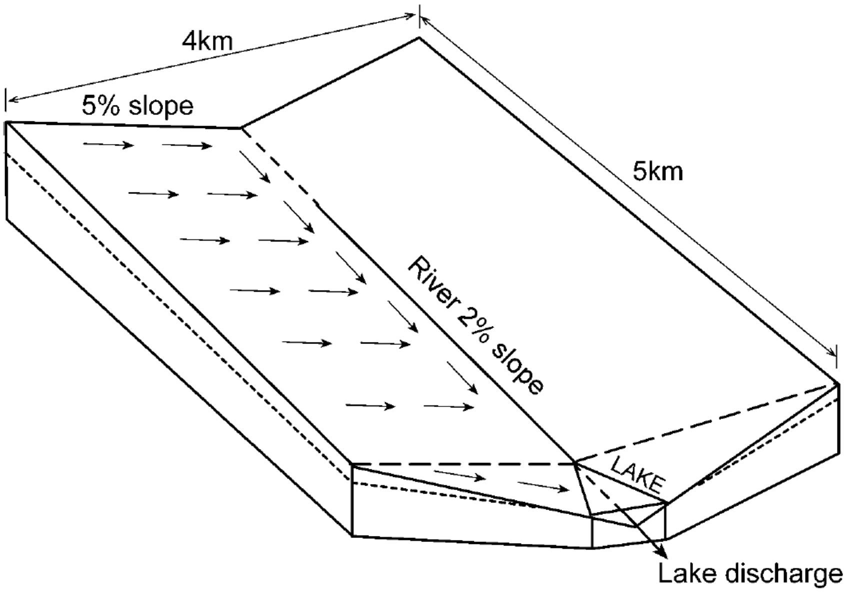



**Fig. 15** Site-generic interpretation of a stylized landscape dose objects. Illustration of the ERB2b catchment, (IAEA 2003a, Figure C11.3).

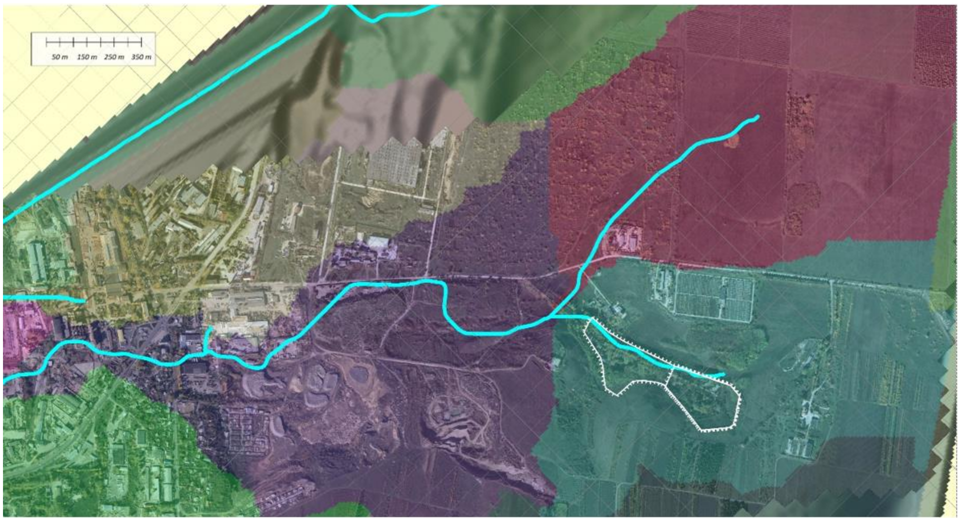


**Fig. 16** Catchments and streams around the disposal site

**Table 4** Areas of subcatchments in the map in Fig. 15.

| 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 |

When identifying the candidate areas for the *radiological objects* the requirement is to determine locations in the landscape where the highest concentrations of radionuclides remobilised from the disposal facilty 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 and the map
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 the flowing surface and groundwater. 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 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 $2 \times 10^4$ to $10^5$ $m^2$.
3. Account should be taken of the confluence of drainage systems from different water sheds

The two candidate objects are indicated in Fig. 17. The first object is closest to the site boundary an is situated on the land adjacent to the drainage stream that runs through the waste site itself and is along the stream 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 stream. The areas of the two objects are, respectively, 2.1E+04 $m^2$ and 1.8E+04 $m^2$.

According to the landuse map (Fig. 12) the area of object 1 is currently agricultural land with woodland along the stream location. 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.

## 4.3 Conceptual and Mathematical models

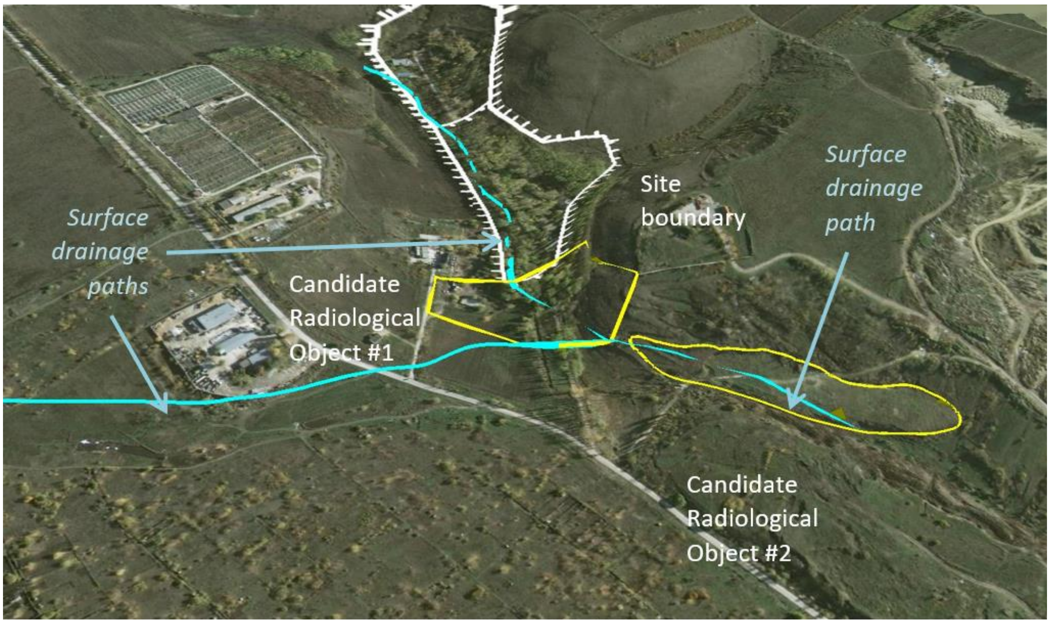
### 4.3.1. Modelling of design scenario

The conceptual model for the design scenario is shown in Fig. 18. A time period for concrete degradation is assumed as 500 years (IAEA 2003b). 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 leakages 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.

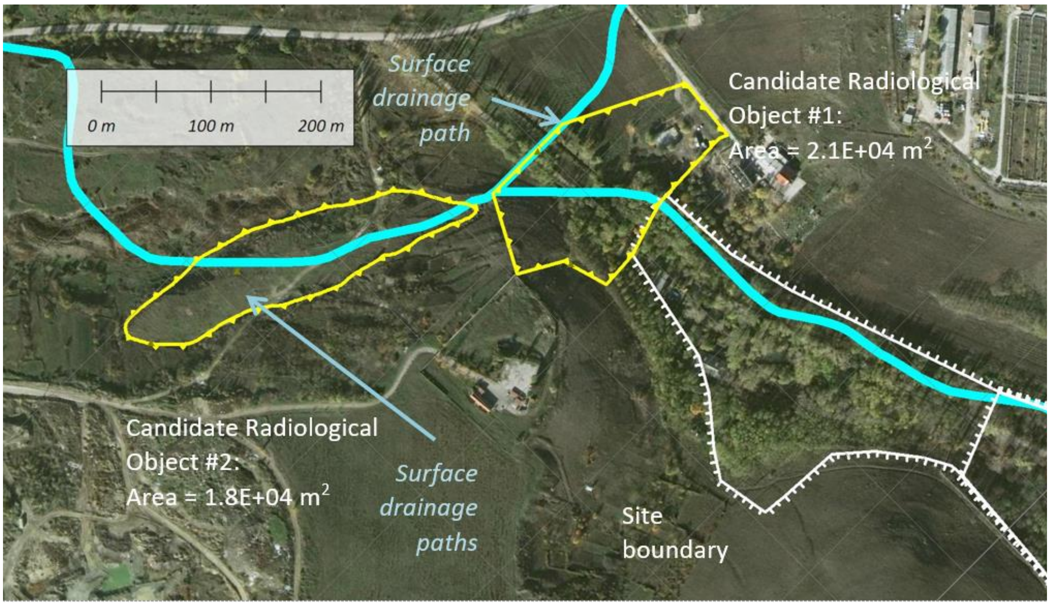
Two variant calculation cases of SCE1 were defined, a well case and a stream case. The first calculation case was assumed that infiltrating water down to the aquifer migrates along groundwater into a well (see Fig. 19). The second calculation case was assumed that the clay later overlying the aquifer was continuous and so a perched aquifer was assumed to be present above the clay since the layer 3 below the surface layer (layer 2) has more dense property (see Fig. 10). It was assumed that infiltrating water migrates along this perched aquifer, rather than infiltrating down into the aquifer, and discharging into the stream (see Fig. 20). Release mechanisms, transport media and exposure mechanisms for these two calculation cases are identified in Table 5.

In the ISAM approach transport in the biosphere is not modelled dynamically (IAEA 2004a). 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. For example, 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.

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).




(a) 3D-map




(b) 2D map

**Fig. 17** Candidate areas for potential radiological objects. With reference to the orthophoto two areas are identified downslope from the site boundary.

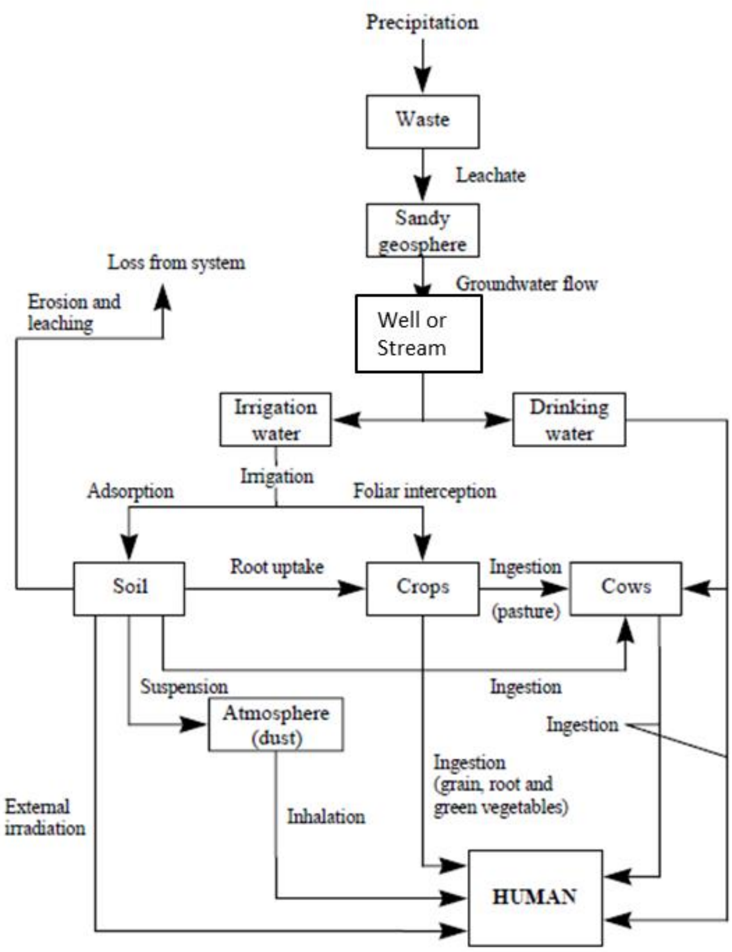



**Fig. 18** Conceptual model for the design scenario (IAEA 2004, Volume I).

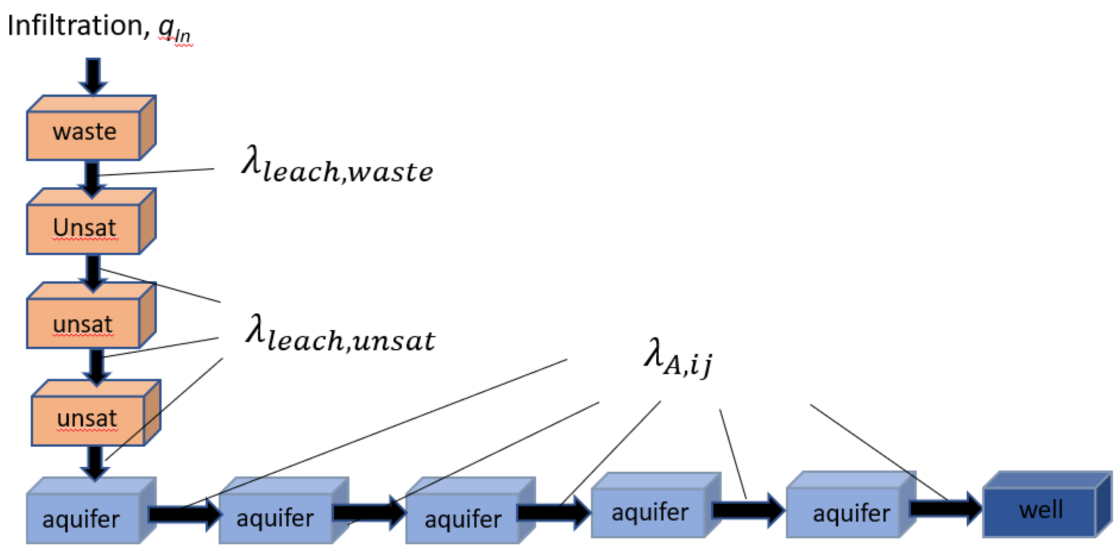



**Fig. 19** Constructed compartmental model of radionuclide transport for the calculation case of well exposure pathway of SCE1.

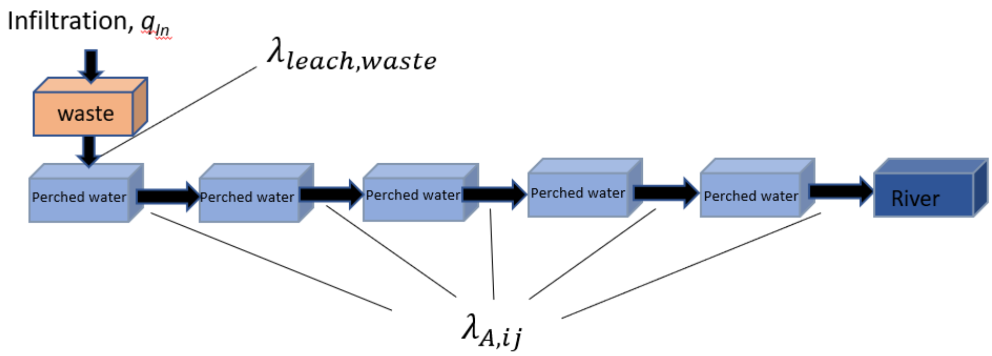



**Fig. 20** Constructed compartmental model of radionuclide transport for the calculation case of river exposure pathway of SCE1

**Table 5** Release mechanisms, transport media and exposure mechanisms for these two calculation cases of design scenario, SCE1

| **Scenario (calculation cases)** | **Contaminant Release Mechanisms** | **Contaminant Release Media** | **Contaminant Transport Media** | **Contaminant Transport Mechanisms** | **Human Exposure Mechanisms** |
|---|---|---|---|---|---|
| SCE1: Leaching (well exposure pathway) | Leaching | Leachate | Solute in groundwater<br>Well (irrigation, drinking)<br>Soil<br>Crops<br>Cows<br>Atmosphere (dust) | Advection<br>Dispersion<br>Water abstraction for irrigation and drinking water<br>Root uptake<br>Adsorption<br>Ingestion of water, pasture and soil by cows<br>Leaching<br>Erosion | Ingestion of water, crops, and animal produce<br>Inhalation of dust<br>External irradiation from soil |
| SCE1: Leaching (river water pathway) | Leaching | Leachate | Solute in perched water<br>River (irrigation, drinking)<br>Soil<br>Crops<br>Animals (cows and fish)<br>Atmosphere (dust) | Advection<br>Dispersion<br>Water abstraction for irrigation and drinking water<br>Root uptake<br>Adsorption<br>Ingestion of water, pasture and soil by cows<br>Leaching<br>Erosion<br>River flow | Ingestion of water, crops, and animal produce<br>Inhalation of dust<br>External irradiation from soil |

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 in-growth of the radionuclide. For the $i^{th}$ compartment, the ODE of a compartment ($k$) has the following general form:

$$\frac{dN_i}{dt} = \left[\sum_{j \neq i} \lambda_{ji} N_j + \lambda_N M_i + S_i(t)\right] - \left[\sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i\right] \qquad \text{Eq. (1)}$$

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., $\lambda_N$ is the decay constant for radionuclide $N$ (in 1/y); and
$\lambda_{ji}$ , $\lambda_{ij}$ 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:

$$\lambda_{leach,waste} = \frac{Q_{in}}{\mathrm{V}} \qquad \text{Eq. (2)}$$

where $Q_{in}$ is the infiltration flow rate [m$^3$/y], which is a product of infiltration $q_{in}$ [m/y] and the surface area of the disposal facility $A_{facility}$ [m$^2$] ; $V$ is the volume of the disposal facility [m$^3$].

Here, we assume that there is no retardation of radionuclides in the waste material itself and the engineered barrier (concrete wall that is degraded at the initial state), which is a pessimistic assumption.

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

| | |
|---|---|
| $\lambda_{leach,unsat} = \frac{q_{in}}{\theta \varepsilon \mathrm{DR}}$ | Eq. (3) |

where $q_{in}$ is infiltration [m/y], $\theta$ is the effective 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:

$$R = 1 + \frac{\rho_{unsat} K_d}{\varepsilon \theta} \qquad \text{Eq. (4)}$$

where $\rho_{unsat}$ 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. 19 and 20, five compartments are used in the modelling. The transfer coefficient $\lambda_{A,ij}$ is expressed as

$$\lambda_{A,ij} = \frac{q}{L/n\,\theta_w R_w} \quad \text{Eq. (5)}$$

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

$$q = -\mathrm{K}\frac{\partial \mathrm{H}}{\partial x} \quad \text{Eq. (6)}$$

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

Once the radionuclide discharge fluxes to either the well or stream are determined the activity concentrations for well water $C_{well}$ or stream water $C_{river}$ can be determined:

$$C_{well} = \frac{Amount_w}{\theta_w V_w R_w} \quad \text{Eq. (7)}$$

where $Amount_w$ is the amount of the radionuclide in the well (flux discharged to the well) [Bq]; $V_w$ is the volume of the compartment representing the well [m$^3$].

$$C_{river} = \frac{Amount_w}{(Prec - ET)Area_{catchment}} \quad \text{Eq. (8)}$$

Where $Prec$ is precipitation [m/y]; $ET$ is evapotranspiration [m/y]; $Area_{catchment}$ is the area of the catchment [m$^2$].

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):

$$Dose = Dose_{inh} + Dose_{ext} + Dose_{ing} \quad \text{Eq. (9)}$$

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:

$$Dose_{inh} = A_{soil} \cdot b_r \cdot 8766 \cdot \left[dust_{act}\%_{occup} + dust_{norm}\left(1 - \%_{occup}\right)\right]DF_{inh} \qquad \text{Eq. (10)}$$

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 as:

$$A_{soil} = C_{water}\frac{irr}{\rho_{soil} \cdot Th_{soil}} \qquad \text{Eq. (11)}$$

where $irr$ is the irrigation rate [m/y]; $\rho_{soil}$ is the soil dry bulk density [$kg/m^3$]; $Th_{soil}$ is the soil thickness [m]; $C_{water}$ is the radionuclide concentration in the water [$Bq/m^3$], which can be well water or stream water (see Eq. 7 and 8) depending on the calculation cases.

The dose due to external exposure is expressed as

$$Dose_{ext} = A_{soil} \cdot 8766 \cdot DF_{ext} \qquad \text{Eq. (12)}$$

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

The dose due to ingestion is expressed as:

$$Dose_{ing} = Dose_{ing\_water} + Dose_{ing\_crop} + Dose_{ing\_animal} \qquad \text{Eq. (13)}$$

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

$$Dose_{ing\_water} = Ing_{wat} \cdot C_{water}\frac{1}{1 + Kd_w \cdot part} \cdot DF_{ing} \qquad \text{Eq. (14)}$$

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.

$$Dose_{ing\_crop} = \sum_{root,green,grain}\left[Ing_{crop}\left(A_{soil} \cdot TF_{crop}\right)DF_{ing}\right] \qquad \text{Eq. (15)}$$

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

$$Dose_{ing\_animal} = \sum_{beef,milk} \left[ Ing_{animal} \left( q_{water} C_{water} + q_{soil} A_{soil} + q_{pasture} A_{soil} TF_{pasture} \right) \times TF_{animal} DF_{ing} \right] \quad \text{Eq. (16)}$$

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].

### 4.3.2. 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. 21 – 23. Release mechanisms, transport media and exposure mechanisms for these three scenarios are identified in Table 6.

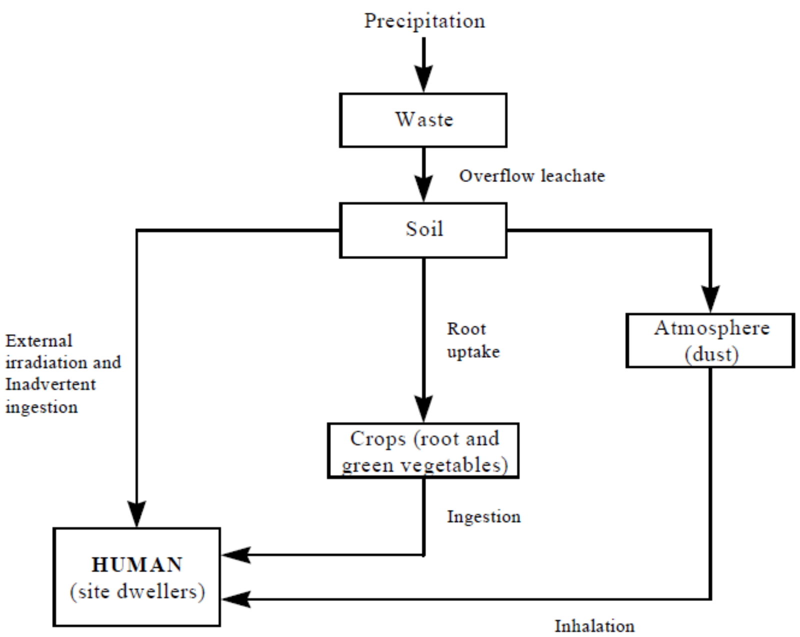



**Fig. 21** Simplified representation of the conceptual model for the Post-closure Bathtubbing Scenario (IAEA 2003b)

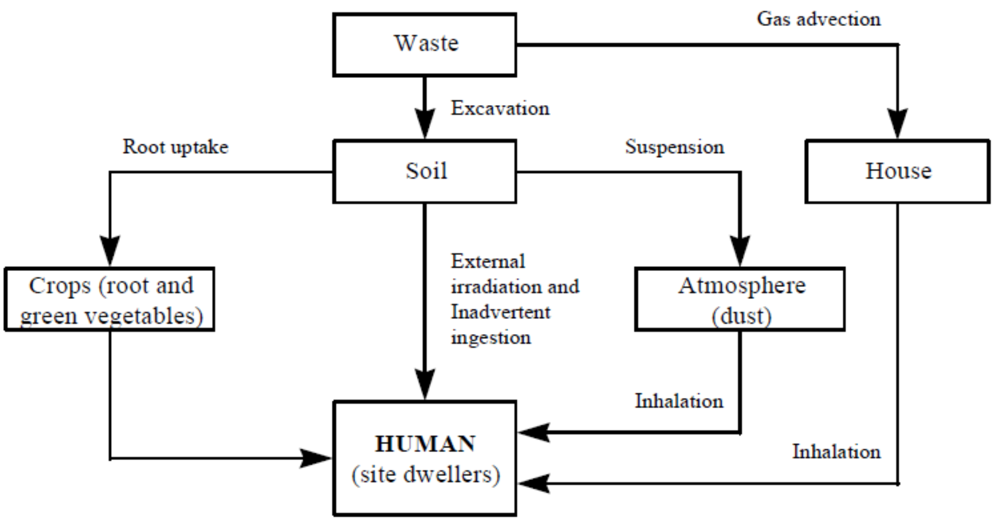



**Fig. 22** Simplified representation of the conceptual model the Post-closure On-site Residence Scenario SCE6 (IAEA 2003b)

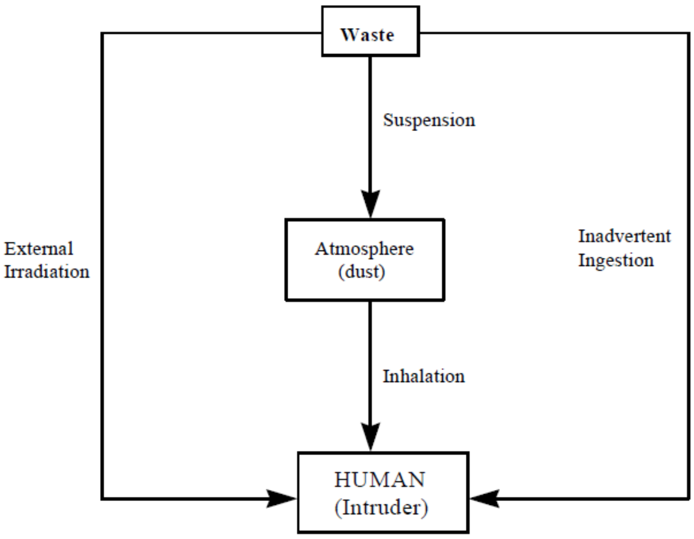



**Fig. 23** Simplified representation of the conceptual model the Post-closure Road Construction Scenario SCE7 (IAEA 2003b)

**Table 6** 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<br>Soil<br>Atmosphere (dust)<br>Crops | Overflow of leachate<br>Suspension<br>Root uptake<br>Adsorption | Ingestion of crops<br>Inadvertent ingestion of soil<br>Inhalation of dust<br>External irradiation from soil |
| SCE6: On-site residence | Excavation<br>Gas generation | Excavated waste<br>Gas | House<br>Gas<br>Soil<br>Atmosphere (dust)<br>Crops | Gas advection<br>Root uptake<br>Adsorption<br>Suspension | Ingestion of crops<br>Inadvertent ingestion of soil<br>Inhalation of dust and gas<br>External irradiation from soil |
| SCE7: Road construction | Excavation | Dust | Atmosphere (dust) | Suspension | Inadvertent ingestion of contaminated material and waste<br>Inhalation of dust<br>External irradiation from contaminated material and waste |

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:

$$C_{disp}(t) = e^{-\lambda t}\frac{A_{mi}}{V_{dispunit}(\omega_{ed} + \rho_{bd}Kd_d)} \qquad \text{Eq. (17)}$$

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$^3$]; $\omega_{cd}$ is the moisture content of the disposal unit [-]; $\rho_{bd}$ 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 ($Dose_{ing}$).

$$Dose_{ext} = \frac{OF}{\rho_{soil}\cdot Th_{soil}}C_{disp}(sf\cdot t_{in} + t_{out})DF_{ext} \qquad \text{Eq. (18)}$$

where $OF$ is the water overflow to the garden during one year [m]; $\rho_{soil}$ 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].

$$Dose_{inh} = \frac{OF}{\rho_{soil}\cdot Th_{soil}}C_{disp}(dust_{in}br_{in}t_{in} + dust_{out}br_{out}t_{out})DF_{inh} \qquad \text{Eq. (19)}$$

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].

$$Dose_{ing} = \frac{OF}{\rho_{soil}\cdot Th_{soil}}C_{disp}\left(TF_{vegt}Q_{vegt} + Q_{soil}\right)DF_{ing} \qquad \text{Eq. (20)}$$

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:

$$A_{res} = A_m e^{-\lambda t_1} \cdot dil \qquad \text{Eq. (21)}$$

where $A_m$ is the initial concentration of the radionuclide disposed waste [Bq/kg]; $\lambda$ 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 ($\lambda_{eff}$)); $t_1$ 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 ($Dose_{ing}$).

$$Dose_{ext} = A_m(sf \cdot t_{in} + t_{out})DF_{ext} \qquad \text{Eq. (22)}$$

$$Dose_{inh} = A_m(dust_{in}br_{in}t_{in} + dust_{out}br_{out}t_{out})DF_{inh} \qquad \text{Eq. (23)}$$

$$Dose_{ing} = A_m\left(TF_{vegt}Q_{vegt} + Q_{soil}\right)DF_{ing} \qquad \text{Eq. (24)}$$

*Road construction scenario (SCE7)*

The analytical solution of the activity concentration to which the intruder is similar to the Eq. (21) and is expressed as $A_{int}$ [Bq/kg of waste], which is given by

$$A_{int} = A_m e^{-\lambda t_1} \cdot dil \qquad \text{Eq. (21)}$$

where $A_m$ is the initial concentration of the radionuclide disposed [Bq/kg of waste]; $\lambda$ is the radioactive decay constant [y] (if required other mechanisms contributing to
diminishing the radioactivity could also be incorporated in an effective decay term ($\lambda_{eff}$)); $t_1$ 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]):

$$Dose = A_{int}\left(Q_{soil}DF_{ing} + DF_{ext} + b_r \cdot dust \cdot DF_{inh}\right)t_2 \qquad \text{Eq. (22)}$$

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].

### 4.3.3. 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 similar to the model used for the bathtubbing scenario (Eq. (17)) except for no retardation considered in the vault. It is assumed that a sudden increasing of infiltration with a flooding event the retardation effect might be reduced significantly. Therefore the concentration of radionuclides in the overflowing leachate $C_{disp}$ [Bq/m$^3$] used in evaluation of the flooding scenario is expressed as:

$$C_{disp}(t) = e^{-\lambda t} \frac{A_{mi}}{V_{dispunit}\omega_{ed}} \qquad \text{Eq. (23)}$$

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$^3$]; $\omega_{cd}$ is the moisture content of the disposal unit [-].

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 4.3.2).

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

## 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 main source of the data are adapted from ISAM reports (IAEA 2004a,b) and IAEA technical document 1380 (IAEA 2003b) as well as data from the site investigation (section 3.2, 4.2).

### 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] (10% of infiltration at the initial state and linearly increasing to 100% at 500 years)
- the surface area of the disposal facility = 75 [m$^2$]
- the volume of the disposal facility = 225 [m$^3$]

- the effective porosity in the medium = 0.4 [-] (see section 3.2.1)
- the degree of saturation of the medium = 0.2 [-]
- the bulk density of the medium (unsaturated) = 1910 [kg/$m^3$]
- the distance between surface and the aquifer = 1.5 [m]
- the total distance to the well = 300 [m]
- the total distance to the stream = 50 [m]
- the porosity of the medium (aquifer) = 0.4 [-]
- he bulk density of the medium (aquifer) = 2000 [kg/$m^3$]
- the hydraulic conductivity of the sandy clay soil layer = 0.5 [m/y] (used for the stream case, see section 3.2.1)
- the hydraulic conductivity of the fine sand layer = 0.35 [m/y] (used for the well case, see section 3.2.1)
- the hydraulic gradient = 0.1 [-] (assumed as the same as surface inclination about 6 degrees, see section 3.2.1)
- the volume of the compartment representing the well = 8300 [$m^3$]
- the area of the biosphere object = $2.1\times10^4$ [$m^2$] (see section 4.2)
- the area of the catchment associated with biosphere object = $1.1\times10^6$ [$m^2$] (see section 4.2)
- precipitation = 0.573 [m/y] (see section 3.2.2)
- evapotranspiration = 0.46 [m/y] (assumed as 80% of the precipitation)

Human behavior:
- 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]

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 = $2\times10^{-8}$ [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 = $3\times10^{-2}$ [kg/y]
- soil thickness = 0.25 [m]
- soil dry bulk density = 1800 [kg/$m^3$]
- indoor dust level = $1\times10^{-8}$ [kg/$m^3$]
- outdoor dust level = $2\times10^{-8}$ [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 = $3\times10^{-2}$ [kg/y]
- indoor dust level = $1\times10^{-8}$ [kg/$m^3$]
- outdoor dust level = $2\times10^{-8}$ [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 = $3\times10^{-2}$ [kg/y]
- exposure duration = 88 [h]
- Breathing rate of the intruder = 1.2 [$m^3/h$]
- Inadvertent soil ingestion rate of the intruder = $3.4\times10^{-5}$ [kg/h]
- Dust level experienced by the intruder = $1\times10^{-6}$ [$kg/m^3$]

# 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

The assessment of the design scenario comprises two variants, the well case and the stream case. In the design scenario it was assumed that the concrete wall was degraded already at the initial state, i.e., 10% of total infiltration at the beginning of the simulation. An overview of the main results obtained for the design scenario is presented below.

In the deterministic calculation for the well case of the design scenario, the maximum dose is about 0.04 mSv/a at around 15 years after the closure (see Fig. 24). The dominating radionuclide is Co-60. The second peak is about 250 years after the closure. The dominating radionuclide is C-14. The third peak of the doses are caused by Pu-239 and its daughter radionuclides. Fig. 25 shows time series of annual effective doses across exposure pathways. As can be seen the ingestion dose dominates and coincides with the maximum dose.

A deterministic sensitivity analysis was performed by assuming the concrete wall was totally degraded, i.e., the 100 % infiltration at the initial state. Fig 26 shows the calculated total dose based on this assumption compared with the base case. As can be seen the maximum dose is 0.28 mSv/a which is significantly higher than that of the base case. However, it is still under the criteria (IAEA 2011).

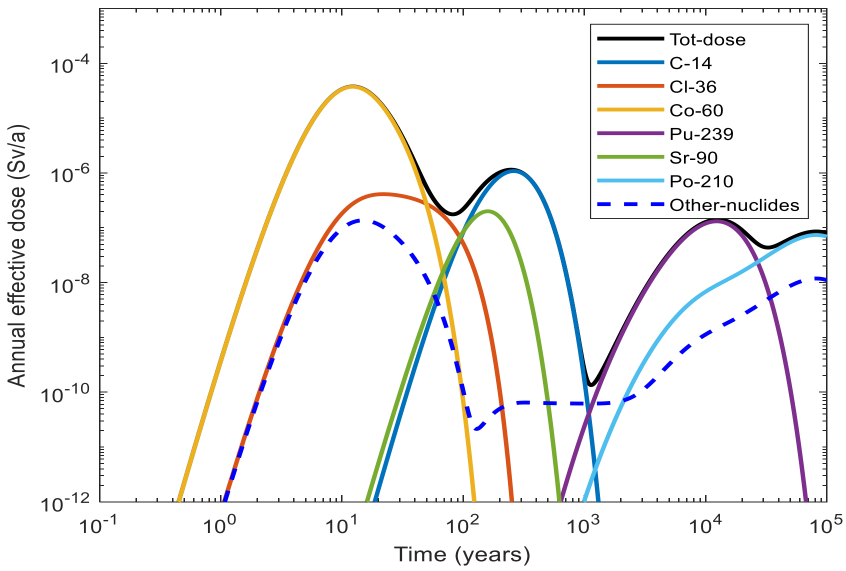



**Fig. 24** Effective doses to the most exposed group for releases from the disposal facility in the well case of the design scenario after the closure.

For the stream case the calculated maximum dose is about 0.07 mSv/a at around 3000 years after the closure. The dominated radionuclide is Pu-239 (see Fig. 27). The first peak dose is mainly caused by Cl-36 one year after the closure. The second peak is about 50 years after the closure caused by Sr-90.

Since the assumption of no any retardation of waste itself and the engineered barrier for the design scenario was already pessimistic no further probabilistic and sensitivity analyses were conducted.

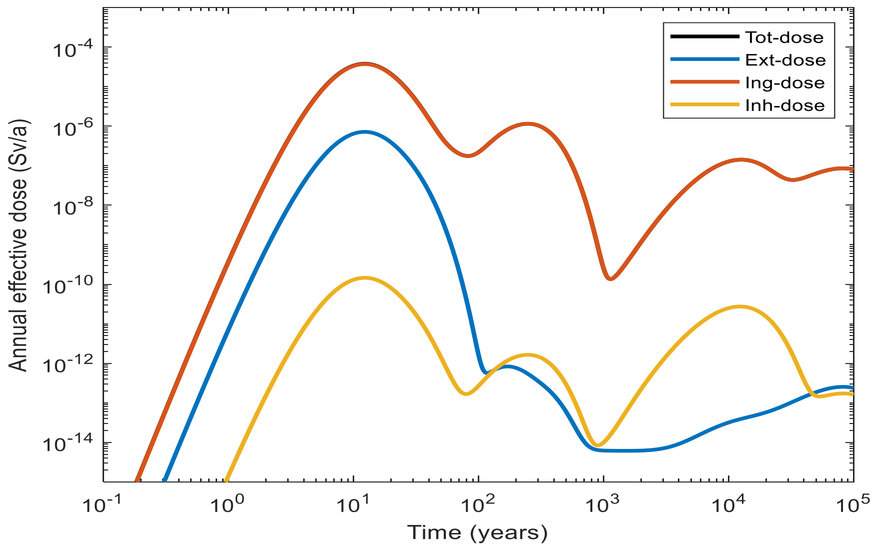



**Fig. 25** Effective doses to the most exposed group for releases from the disposal facility in the well case of the design scenario and contributions from the individual exposure pathways.

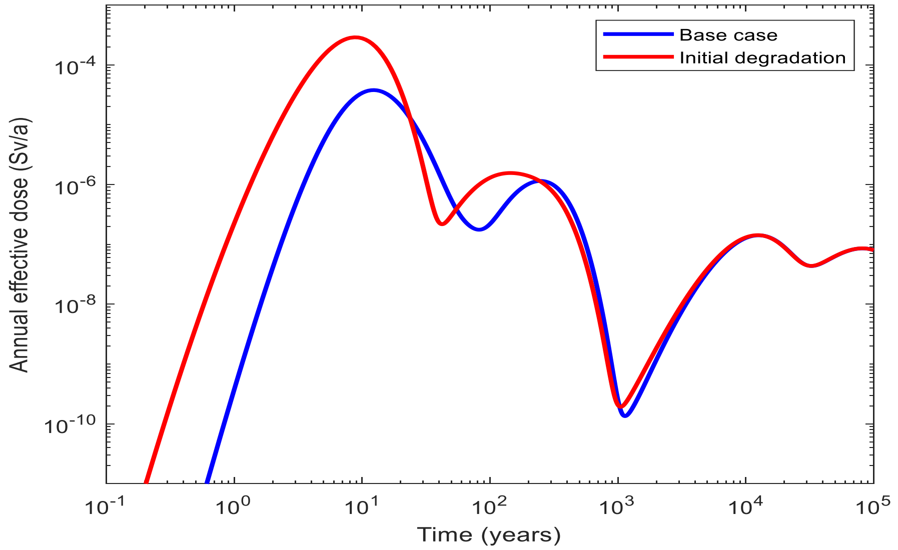



**Fig. 26** Comparison of calculated results between the well case with a totally degraded concrete wall at the initial state (red line) and the base well case with partly degraded concrete wall at the initial state (blue line).

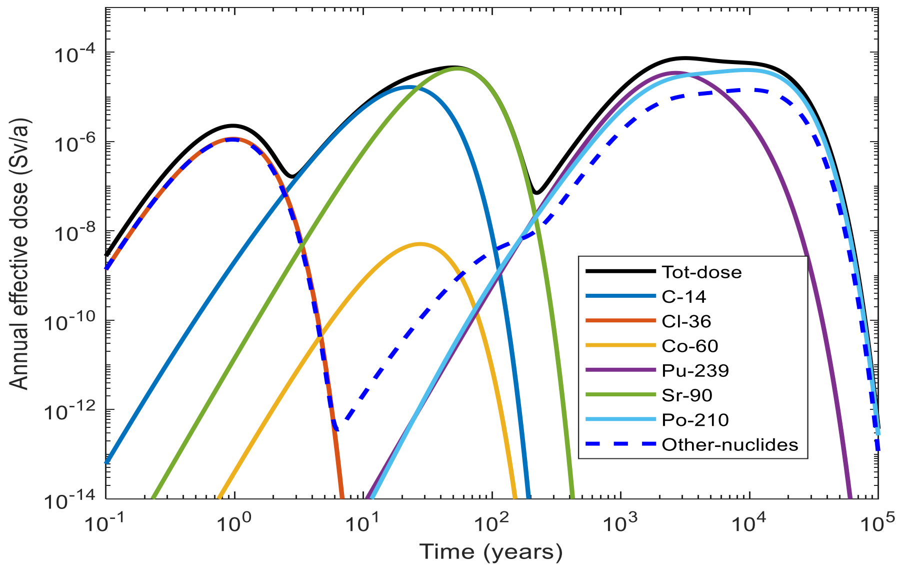



**Fig. 27** Effective doses to the most exposed group for releases from the disposal facility in the stream case of the design scenario after the closure.

## 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 expects that the existence of a cover and the partly degraded nature of the disposal facility limits the site exploitation and thus reduce 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. 28 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.

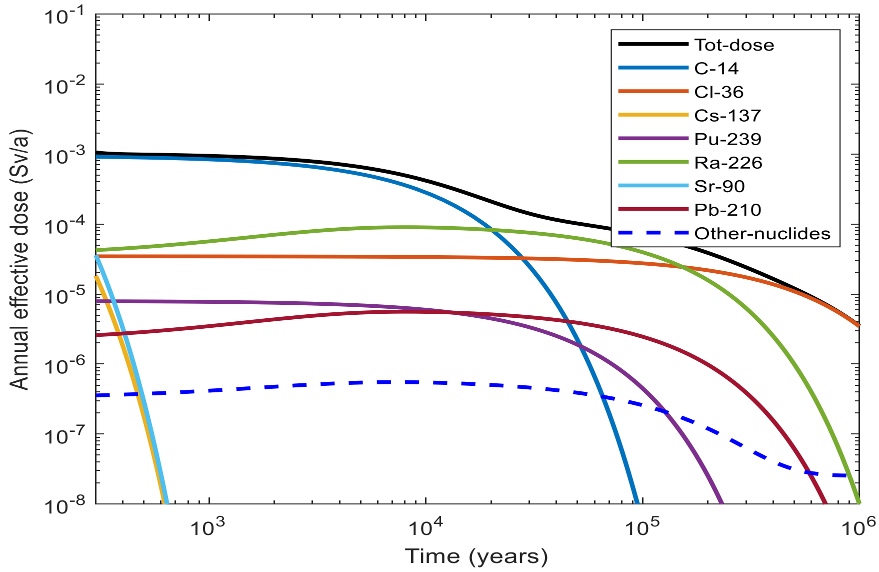



**Fig. 28** Total annual effective dose for the bathtubbing scenario.

## 5.2.2. The on-site residence scenario

The On-site residence scenario expects 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. 29 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 29 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 4.3.2).

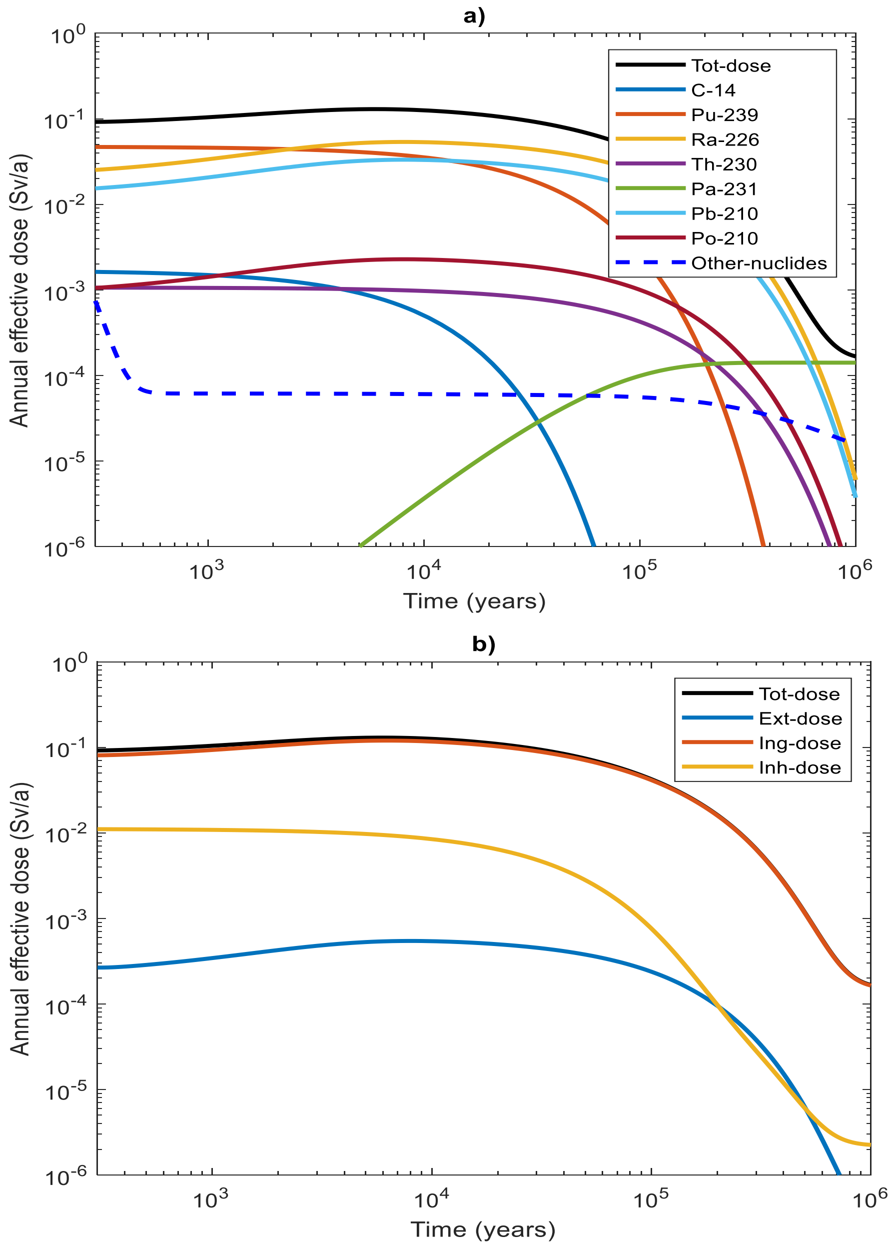



**Fig. 29** Total annual effective dose for the on-site residence scenario, the results of the main radionuclides contributed to the doses (figure a)) and total doses for different exposure pathways (figure b)).

### 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 leading potentially to important radiological impacts.

Fig. 30 shows the calculated doses for the intruders for this scenario. The maximum total dose is about 13 mSv/a and the main radionuclide contributed to the doses is Pu-239.

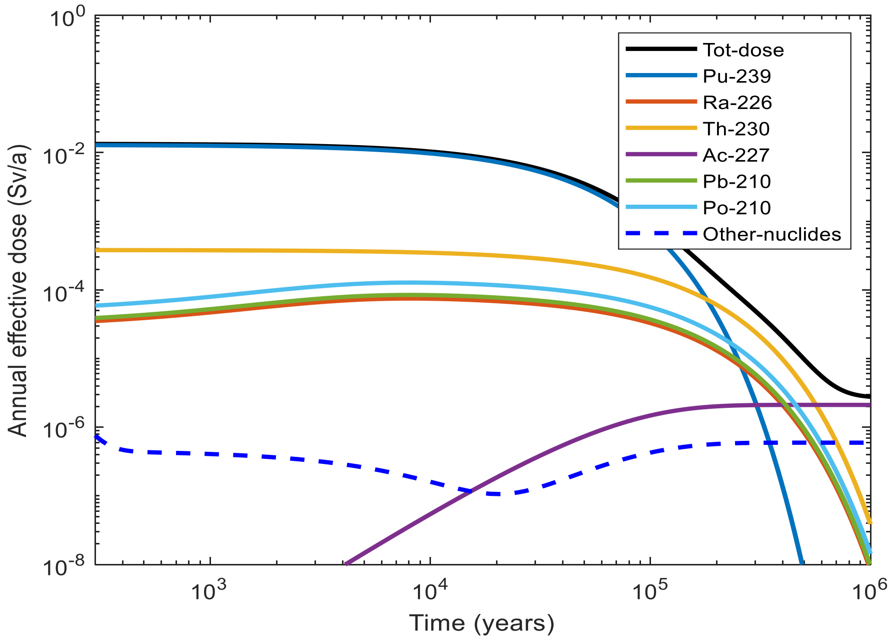



**Fig. 30** Total annual dose for the road construction scenario.

## 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.

For the flooding scenario a modified ISAM model was to assess the radiological impacts with the assumption of no retardation considered in the vault (see Eq. (23) in section 4.3.3). Since the time for the event of flooding to occur is unknown the simulations were performed by assuming that the event occurred at 50, 300 and 2500 years after the closure. As can be seen from Fig. 31 the simulated results fall in the same curve. This is because the assumption of initial conditions for the disposal facility is the same except for the decay of the inventory. Fig. 32 shows the results of the flooding scenario using ISAM bathtubbing model (Eq. (17)). As can be seen the calculated dose is about a factor 10 lower than that of the modified model.

As mentioned in section 4.3.3 the result of the on-site residence scenario can cover the landslides scenario. Therefore, no separate calculation was performed for this scenario. We did not assign probabilities to the alternative scenarios. Because the purpose of this assessment of “zero alternative scenario” for the RADON-type disposal facility is to provide a basis for decision making regarding the decommissioning of the legacy radioactive waste.

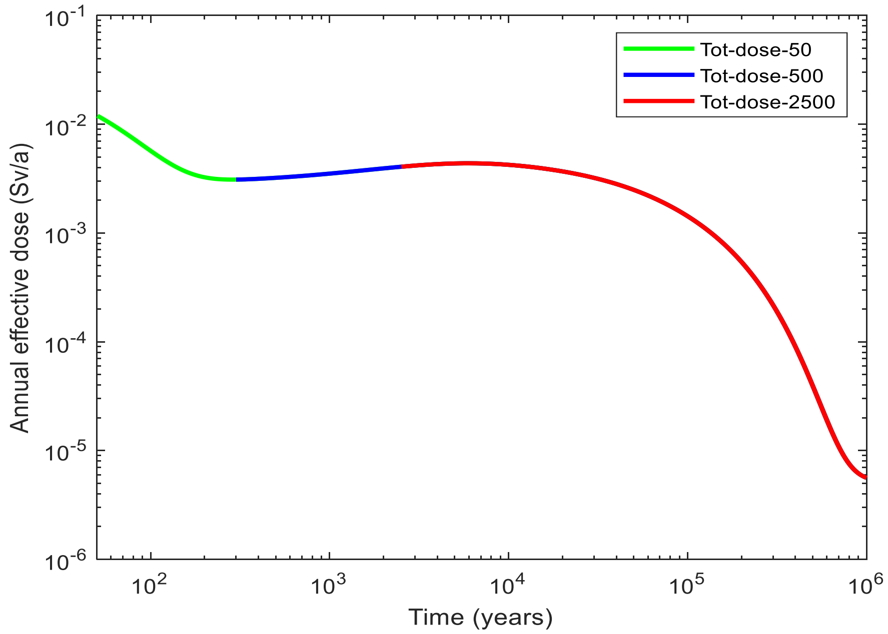



**Fig. 31** Total annual dose for the flooding scenario.

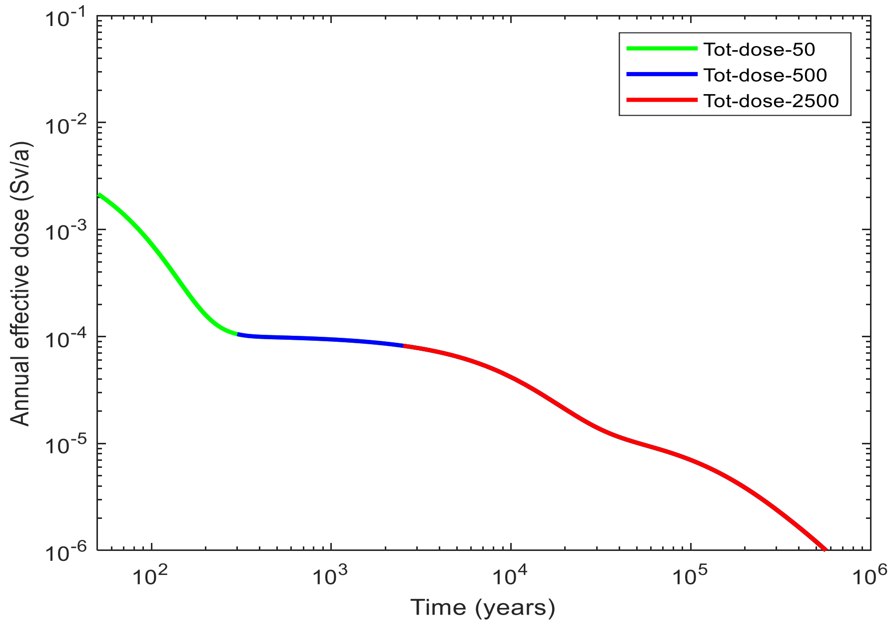



**Fig. 32** Total annual dose for the flooding scenario using ISAM bathtubbing model.

## 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 utilizing the framework presented by ICRP.

The potential effects on non-human biota from exposure to released radionuclides were assessed. The stream case of the design scenario was considered. The maximum values of the radionuclide concentrations in stream water and 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 results obtained for the stream case are presented in Tables 7 and 8, which show the maximum values of the environmental concentrations obtained, the EMCL used, and the calculated values of the RQs. The highest RQs in this case are observed for C-14 and Pu-239 in freshwater concentration, which are 2 and 15, respectively. This means more detailed assessments are needed. However, given the resource constrains no further assessment was conducted in this assignment. Bear in mind this assessment is the first iteration according to ISAM methodology.

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

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

| **Radionuclide** | **Conc. water Bq/m$^3$** | **EMCL Bq/m$^3$** | **RQ** |
|---|---|---|---|
| Ac-227 | 7.13E-05 | N/A | N/A |
| C-14 | 1.35E+04 | 6.7E+03 | 2.0E+00 |
| Cl-36 | 2.61E+02 | 2.4E+07 | 1.1E-05 |
| Co-60 | 1.97E+00 | N/A | N/A |
| Cs-137 | 2.90E-01 | 2.5E+03 | 1.2E-04 |
| H-3 | 3.29E+03 | N/A | N/A |
| Kr-85 | 1.60E+04 | N/A | N/A |
| Ni-63 | 1.99E-07 | 4.4E+04 | 4.5E-12 |
| Pa-231 | 7.57E-05 | N/A | N/A |
| Pb-210 | 2.17E+01 | N/A | N/A |
| Po-210 | 4.33E+01 | N/A | N/A |
| Pu-239 | 1.89E+02 | 1.3E+01 | 1.5E+01 |
| Ra-226 | 1.42E+01 | 2.3E+01 | 6.2E-01 |
| Sr-90 | 1.31E+03 | 1.4E+04 | 9.3E-02 |
| Th-230 | 2.97E+00 | 1.7E+01 | 1.8E-01 |
| Tl-204 | 3.32E-18 | N/A | N/A |
| U-235 | 1.05E-03 | 2.4E+02 | 4.4E-06 |

**Table 8** Comparison of predicted maximum values of the radionuclide concentrations in soil with the Environmental Media Concentration Limits (EMCL) for the river case of the design scenario.

| **Radionuclide** | **Conc. soil Bq/kg DW** | **EMCL Bq/kg** | **RQ** |
|---|---|---|---|
| Ac-227 | 4.36E-08 | N/A | N/A |
| C-14 | 7.49E+00 | 8.5E+01 | 8.8E-02 |
| Cl-36 | 1.45E-01 | 2.9E+03 | 5.01E-05 |
| Co-60 | 1.09E-03 | N/A | N/A |
| Cs-137 | 1.63E-04 | 7.6E+02 | 2.14E-07 |
| H-3 | 1.83E+00 | N/A | N/A |
| Kr-85 | 8.89E+00 | N/A | N/A |
| Ni-63 | 1.12E-10 | 1.2E+06 | 9.3E-17 |
| Pa-231 | 4.42E-08 | N/A | N/A |
| Pb-210 | 1.32E-02 | N/A | N/A |
| Po-210 | 2.65E-02 | N/A | N/A |
| Pu-239 | 2.10E-01 | 1.1E+03 | 1.9E-04 |
| Ra-226 | 7.93E-03 | 4.2E+00 | 1.9E-03 |
| Sr-90 | 7.34E-01 | 1.3E+02 | 5.6E-03 |
| Th-230 | 1.81E-03 | 1.6E+03 | 1.1E-06 |
| Tl-204 | 2.03E-21 | N/A | N/A |
| U-235 | 5.86E-07 | 1.8E+03 | 3.3E-10 |

# 6. Discussions and conclusions

Based on the current state of the art and the procedures defined by IAEA's standards and best practices the ISAM methodology (IAEA 2004a, b) and IAEA's BIOMASS methodology (IAEA 2003a) are adapted in this risk assessment. We use the site specific information as much as possible to derive the parameter values used in the assessment. For instance, instead of using a stylised biosphere object the relevant biosphere object and associated catchment areas were identified based on the site specific DEM using GIS tools. As to the relevant biosphere object we mean that the identified biosphere object is close to the disposal site boundary so as to avoid excessive spatial dilution and the size of the object is large enough to supply the dietary needs of at least a small family group.

The generation of scenarios has been conducted according to ISAM approach (shown in Fig. 14), which contains various state of the disposal and human behavior components for a generic RADON-type facility. Considering of the specific conditions of Chisinau disposal facility seven scenarios/calculation cases were selected for this assessment. For the design scenario (SCE1) two variant calculation cases were considered, a well exposure pathway case and a stream water exposure pathway case. 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. 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).

A limited number of deterministic sensitivity analysis was performed to explore the model uncertainty and parameter uncertainty. 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 degraded at the initial sate)
- the shortest possible transport distances of releases from the disposal facility to a well or a stream
- the hydraulic gradient follows surface inclination
- no sorption to waste mass in the flooding scenario

The calculated peak doses and time at which the peak is observed from seven scenarios/calculation cases are summarised in Table 9.

With pessimistic assumptions, the estimated doses from the calculation cases of the design scenario, i.e. for the well case and the stream case are lower than the IAEA's criteria. Estimated doses for the on-site residence scenario after institutional control are higher than IAEA's criteria. 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. Long lived radionuclide Pu-239 dominates the doses for the on-site residence scenario. Of course, the very conservative assumptions used in the modelling of the on-site residence scenario can be discussed. Nevertheless, measures should be taken for this matter if the waste is at its present place of disposal.

**Table 9** 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 | 0.04 | 15 | 0.3 |
| | SCE1 | River case | 0.07 | 3000 | 0.3 |
| Alternative scenario | | Flooding | 10* | 50 | 0.3 |
| | | Landslides | 130* | - | 0.3 |
| Human intrusion scenario | SCE4 | Bathtubbing | 1 | 300 | 20 |
| | SCE6 | On-sire residence | 130 | 300 | 20 |
| | SCE7 | Road construction | 13 | 300 | 20 |

*Doses would be expected to be much lower were the probabilities of the event to occurring to be considered.

The potential effects on non-human biota from exposure to released radionuclides were assessed. The stream case of the design scenario was considered. The maximum values of the radionuclide concentrations in fresh water and in soil were compared with Environmental Media Concentration Limits (EMCL). If the ratio between the maximum values and EMCL is less than one no further assessments are required. For most of radionuclide concentrations calculated from the stream case are below one except C-14 and Pu-239 in freshwater.

Bearing in mind that this assessment is the first iteration according to the ISAM methodology further iterations would develop the site understanding further so as to reduce uncertainties and the need for the conservative assumptions adopted here. Further assessments can be conducted if necessary, such as a detailed assessment for non-human biota and a more site specific assessment with new measurements to reduce parameter uncertainties.

Scenarios with high calculational consequences are obviously of interest though not necessarily because they are a true expression of radiological hazard. This first iteration 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 the radiological impact.

The disposal facility is located on the upstream area of Chisinau, which might be not an optimal choice of the site for a radioactive waste disposal.

Since in the ISAM approach radionuclide transport in the biosphere is not modelled dynamically further investigation by comparing the equilibrium approach used in the ISAM and dynamic approach used in the BIOMASS could be of interest.

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# Appendix: Radionuclide and element dependent data

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

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

**Table A-3** Dose coefficient for ingestion, inhalation and external irradiation

| Radionuclide | DF_intag [Sv/Bq] | DF_inh [Sv/Bq] | DF_ext [Sy/y per Bq/kg] |
|---|---|---|---|
| Ac-227 | 1.21E-06 | 5.70E-04 | 1.40E-12 |
| C-14 | 5.80E-10 | 5.80E-09 | 5.80E-17 |
| Cl-36 | 9.30E-10 | 7.30E-09 | 0.00E+00 |
| Co-60 | 3.40E-09 | 3.10E-08 | 8.50E-12 |
| Cs-137 | 1.30E-08 | 3.90E-08 | 2.00E-12 |
| H-3 | 1.80E-11 | 2.60E-10 | 0.00E+00 |
| Kr-85 | 1.80E-11 | 7.30E-09 | 0.00E+00 |
| Ni-63 | 1.50E-10 | 1.30E-09 | 0.00E+00 |
| Pa-231 | 7.10E-07 | 1.40E-04 | 1.50E-13 |
| Pb-210 | 6.91E-07 | 5.70E-06 | 1.30E-14 |
| Po-210 | 1.20E-06 | 4.30E-06 | 3.00E-17 |
| Pu-239 | 2.50E-07 | 1.20E-04 | 1.30E-15 |
| Ra-226 | 2.80E-07 | 9.50E-06 | 6.00E-12 |
| Sr-90 | 3.07E-08 | 1.60E-07 | 2.00E-14 |
| Th-230 | 2.10E-07 | 1.00E-04 | 2.50E-15 |
| Tl-204 | 4.50E-10 | 3.90E-10 | 5.30E-15 |
| U-235 | 4.73E-08 | 8.50E-06 | 6.00E-13 |

**Table A-4** Transfer coefficients to cows meat [days/kg fresh weight] and milk [days/l]

| Element | TF_beef | TF_milk |
|---|---|---|
| Ac | 1.60E-04 | 4.00E-07 |
| C | 1.20E-01 | 1.00E-02 |
| Cl | 1.70E-02 | 1.70E-02 |
| Co | 4.30E-04 | 1.10E-04 |
| Cs | 5.00E-02 | 7.90E-03 |
| H | 2.90E-02 | 1.50E-02 |
| Kr | 2.90E-02 | 1.50E-02 |
| Ni | 5.00E-03 | 1.60E-02 |
| Pa | 5.00E-05 | 5.00E-06 |
| Pb | 4.00E-04 | 3.00E-04 |
| Po | 5.00E-03 | 3.40E-04 |
| Pu | 1.00E-05 | 1.10E-06 |
| Ra | 9.00E-04 | 1.30E-03 |
| Sr | 8.00E-03 | 2.80E-03 |
| Th | 2.70E-03 | 5.00E-06 |
| Tl | 2.70E-03 | 5.00E-06 |
| U | 3.00E-04 | 4.00E-04 |

**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.

| Element | TF_crop | TF_root | TF_veg | TF_pasture |
|---|---|---|---|---|
| Ac | 2,50E-03 | 1,00E-03 | 1,00E-03 | 1,00E-03 |
| C | 5,50E+00 | 1,00E-01 | 1,00E-01 | 1,00E-01 |
| Cl | 3,00E+01 | 6,00E+00 | 3,00E+00 | 3,00E+00 |
| Co | 8,50E-03 | 1,10E-01 | 1,70E-01 | 4,50E-02 |
| Cs | 4,00E-02 | 3,00E-02 | 3,00E-02 | 3,00E-02 |
| H | 4,80E+00 | 5,00E+00 | 5,00E+00 | 5,00E+00 |
| Kr | 4,80E+00 | 5,00E+00 | 5,00E+00 | 5,00E+00 |
| Ni | 5,00E-02 | 3,00E-02 | 3,00E-02 | 2,00E-02 |
| Pa | 1,00E-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 | 3,00E-01 | 9,00E-02 | 3,00E+00 | 3,00E+00 |
| Th | 1,00E-03 | 5,00E-04 | 5,00E-04 | 5,00E-04 |
| Tl | 1,00E-03 | 5,00E-04 | 5,00E-04 | 5,00E-04 |
| U | 2,50E-02 | 1,00E-03 | 1,00E-03 | 1,00E-03 |

**Table A-6** Element specific distribution coefficient ($K_d$) for saturated and unsaturated mediums

| Element | $K_d$_sat [$m^3$/kg] | $K_d$_unsat [$m^3$/kg] | $K_d$_water [$m^3$/kg] |
|---|---|---|---|
| Ac | 0.34 | 0.34 | 10 |
| C | 0.005 | 0.005 | 0.1 |
| Cl | 0 | 0 | 0.1 |
| Co | 0.015 | 0 | 0.015 |
| Cs | 0.3 | 0.54 | 1 |
| H | 0 | 0 | 3E-5 |
| Kr | 0 | 0 | 3E-5 |
| Ni | 0.4 | 0.4 | 1 |
| Pa | 0.34 | 0.34 | 5 |
| Pb | 0.3 | 0.3 | 10 |
| Po | 0.15 | 0.15 | 10 |
| Pu | 0.34 | 0.34 | 100 |
| Ra | 0.5 | 0.5 | 0.5 |
| Sr | 0.015 | 0.0088 | 1 |
| Th | 3 | 3 | 10 |
| Tl | 3 | 3 | 10 |
| U | 0.56 | 0.0025 | 0.05 |

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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