SIMULATION OF ^{226}RA RADIONUCLIDES TRANSFER THROUGH THE SATURATED ZONE OF THE BAITA BIHOR NATIONAL RADIOACTIVE WASTE REPOSITORY, BIHOR COUNTY

Daniela Livia PARASCHIVOIU, Alexandru DANCHIV***

Abstract: *The paper presents the simulation of ^{226}Ra radionuclides transfer through the saturated zone of the site of Baita Bihor National Radioactive Waste Repository (NRWR), through a conceptual model of double porosity media. The effect of a continuous radioactive source located in repository was simulated. The radionuclides transfer simulation was carried out using the Toth model, the piezometric head is equal with the water level from the rivers. The area of radioactive influence of the repository, at the surface and at depth, was established.*
Key words: *Toth model, radionuclides transfer simulation, saturated zone, concentration distribution.*

1. Introduction

The scope of this paper is the simulation of ^{226}Ra radionuclide transfer trough the fully saturated rock layers, using conservative values, and the delimitation of the influence area of the repository both at the surface and in depth.

Baita Bihor National Radioactive Waste Repository (NRWR) is located in Bihor Mountains, in a former uranium mine (Galleries 50, and 53), 2 km E from the mining village of Baita Plai, Bihor County.

2. Geological conditions

Baita Bihor Repository is located within an area of complex geological and structural setting, which is the result of multiple tectonic episodes, magmatic intrusions, and hydrothermal activity.

Watson et al., 2006 described the following geological and structural characteristics of Baita Bihor Repository:

- The area was the subject of multiple episodes of over-thrusting of the older rocks over the younger ones.
- The area is characterized by a fault system, striking NNW-SSE, and minor reverse faults.
- In the vicinity of the repository, the magmatic activity is associated with a faulting process. Diabase, and diorite dykes were found within the meta-sediments.
- The extensive mineralization in this area it is largely associated with hydrothermal alteration resulting from the magmatic activity.
- The repository galleries lie within meta-sandstone, mica schist, and crystalline meta-carbonate rocks (marble and skarn).
- The meta-carbonate produced a karst drainage system in the area to the NW of the repository.
- The valleys downstream of Baita Sat/Nucet are covered with Neogene and Quaternary alluvial deposits, typical of areas downstream of an active orogen.

3. Hydrological conditions

Baita Bihor NRWR is located in the upper part of the Crisul Negru hydrological basin.

The main tributary of the Crisul Negru River, in NRWR area, is Crisul Baita, whose main tributary is Valea Baita River.

The repository is located between Paraul Mic Creek (with permanent flow in the lower part of its course) to SE and Lupului Creek (with intermittent flow). A second creek (Stancii Creek) drains the central part of the Baita open pit mine.

4. Hydrogeological conditions

According to the Management Plan of the Romanian National Water Administration 2009 – 2015, the water catchment area of NRWR belongs to Vascau ROCR05 groundwater body, Codru – Moma Mountains.

Vascau ROCR05 groundwater body, Codru – Moma Mountains, is characterized by a karst – fissural aquifer, quartered in Triassic limestone and dolomite (*Romanian National Water Administration, 2009*).

The hydrogeology of the area is dominated by the presence of the hydro – karst system, with a dendritic catchment pattern. The NRWR area is included in Crisul Baita karst system, which is located in the upper hydrological basin of the valley with the same name. The topography of the NRWR area is rough, as a result of intense tectonic

* *Eng. Ph.D.stud. University of Bucharest, Romania*
** *Prof.eng. Ph.D University of Bucharest, Romania*

processes. (*Oraseanu et al., 1991; Oraseanu, 1996).*

The carbonate outcrops have no permanent surface flow of water. The small streams flowing on the non-carbonate slopes infiltrate in the karst system when they reach over the carbonate surface (*Oraseanu et al., 1991, Oraseanu, 1996).*

4.1 Lithological characteristics

The Baita Bihor NRWR galleries were carved in the Permian strata of Arieseni Nappe (*Watson et al., 2006*). The uppermost rocks, intercepted by the repository galleries, are metamorphosed sandstones and phyllites, intruded by mainly diabase dykes. In the repository area, the metamorphosed sandstone is, in general, layered granular rocks with intrinsic porosity and lower permeability.

Metasomatic and albitisation processes are frequent, which caused alterations on foliation and joints.

4.2 Structural settings

The NRWR repository area is bounded by Lupului Fault System (LFS) toward NW and toward SE by the Central Fault System (CFS). Both fault systems have dip angles of 50 - 80°. Along LFS the tectonic contact between diabase, to NW, and meta-sandstone, at SE, is visible. The Central Fault System separates, at the surface, the meta-sandstone and the black phyllite outcrops (*Watson et al., 2006)*.

The rocks of the repository area are highly fractured, with minor displacement. The discontinuities in the rocks have been classified by *Watson et al.*, 2006 in three groups:

- **S0** – the original bedding planes, which can play a major role in the movement of the groundwater;
- **S1** – metamorphic foliation, which is almost coincident with the bedding;
- **S2** – the main faulting/fracturing system.

Most of the fissures and fractures from repository galleries belong to the group (**S2**) which according with the prevalent direction of fracture was divided into four systems:

<u>F1 System</u> – associated with LFS;

<u>F2 System</u> – oriented NE - SW which is less important;

<u>F3 System</u> – This system has a low frequency, but has an important hydrogeological significance. In the repository area this system is represented by a fault oriented NNW – SSE, which is transverse to the galleries.

<u>F4 System</u> – oriented NW – SE represents the main tectonic stress direction in the repository galleries. This system (together with its supporting micro faults and fractures) occurs in almost all repository galleries.

Watson et al., 2006 noted that the main directions of regional faulting and fracturing system observed at the surface are similar with the one identified underground, which influences the water infiltration-drainage pattern.

The aquifer system in the NRWR can be compared with a double porosity system, composed of a micro-fractured matrix, with lower permeability, crossed by high permeability faults.

Taking into account the observations from above was considered a generic model composed of a fracture which is in direct contact with the porous matrix (micro-fissured) and intersects the repository.

5. Conceptual model

The areal extent of the model was highly influenced by the hydrological and hydrogeological conditions. Thus, taking into account the general flow direction of the groundwater and the geological characteristics, the area surrounding the waste repository, from Baita Sat and Baita Plai vicinity was included in the modeled domain.

Using Toth model (*Toth et al., 2010*) it was established that the piezometric head is equal with the water level from the rivers, imposed in the nodes corresponding to the rivers only in the upper part of the modeled surface.

It was considered that the rivers have only a drainage role. This condition was achieved by forcing the maximum values of recharge, from the rivers, to be zero. In this way the model considered just the nodes with negative flow values of drainage.

Toth model is a spatial model which allows analysis of the groundwater movement in depth, and the water discharge in drainage centers located away from the source.

According to Toth et al., 2010 the piezometric surface is a replication of the topography of the recharge zone, mainly from rainfall.

The first conceptual models developed for the NRWR have been realized by Watson S. P. et al., 2006.

Saturated zone model presented in this paper differs from previous models in three important aspects:

- It is based on a conceptual model of gravitational flow: the aquifer is an unconfined one and piezometric surface will result from the boundary conditions and the recharge; secondary basins are thus a consequence of the conditions imposed;

- Are introduced regional and local systems faults;
- The boundary conditions in mass transport are given by the source terms, performed by Dr. Petre Ilie from Pitesti Nuclear Research Branch (Pitesti NRB), as a variation of concentration in time; the shape of concentration-time functions has been derived taking into account the possible disposal processes.

5.1 Boundary conditions

The boundary conditions of the studied area were established as follows:

- to the N – the natural limit on Crisul-Baita River;
- to the S – the natural limit on Crisul Negru River;
- to the V – mixed boundary conditions were imposed by the natural limit of Crisul Baita and Crisul Negru rivers, and a zero flux boundary.
- to the E – the natural limit of the hydrographic basin. The eastern limit is a zero flux boundary, imposed on the entire thickness of the model.

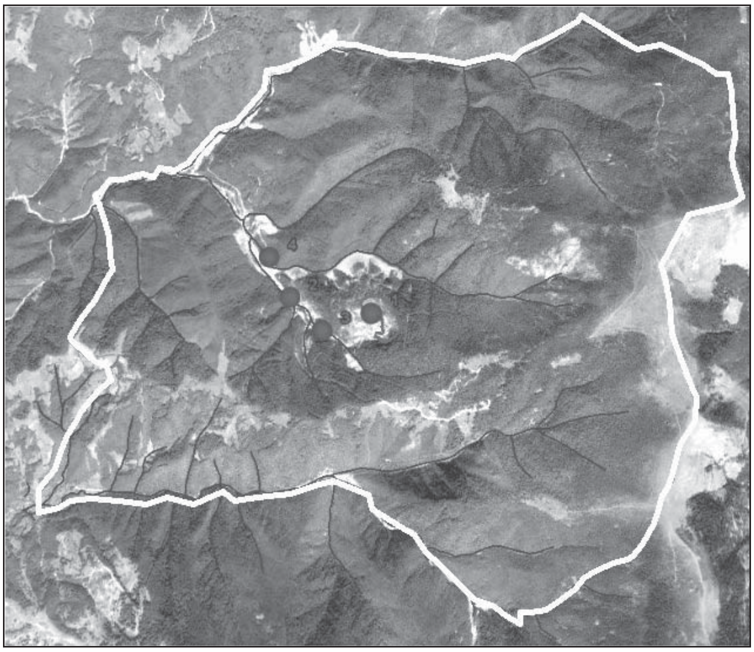

Fig. 1 *Areal extent of the model (natural limits), map modified from Google Earth* © software

5.2 Model conceptualization

Danchiv et al., 2007 stated that the model conceptualization must be seen from two perspectives, namely the conceptualization of the physical model, and the conceptualization of the hydrogeological model.

From a physical point of view, the conceptual model is represented by the double porosity media. In general, for the NRWR area this is a system with a lower permeability and some highly conductive distinct elements, represented by the local faulting system (LFS) and the regional fault (CFS) existing in the modeled area, which influence the flow significantly.

The hydrogeological conceptual model consists in the equivalence of the hydrographic and hydrogeological basins. As a result of this schematization flow pathways appear, corresponding to the drainage divide lines, pathways extended through the entire thickness of the hydrogeological basin.

Using these assumptions was established that the tridimensional model will consist of five layers with different thicknesses. The physical model will be that of a double porosity medium, in which the secondary porosity is given by the fracture system. This simulation was run using the FEFLOW ® software package.

The main parameters used to achieve the model are shown in Table 1.

5.3 Model description

Model digitization required the drawing of a polygonal network with 13 superelements, covering an area of 23.5 km^2, taking into account the geometry of the modeled area.

The upper surface of the model was then digitized into a network formed by 35.565 triangular prism interconnected through 24.564 nodes. The existing rivers of the NRWR area were digitized separately by approximate curves. Detailed digitization was done to the area surrounding the repository, and along the rivers Crisul Baita, Valea Calului, Paraul Mic, Poiana

Crisului, and Crisul Negru. Also, reference points for the model were established for calibration purposes. These points were the piezometric head levels measured at the entrance of the Gallery 11, at the entrance and at the end of Gallery 10, and at the interface of Poiana Crisului (Watson et al., 2006). Thus, the built-up macro-network was the support for the mathematical model. The local and regional fault systems were modeled using discrete elements, vertical planes, which cut throughout the entire thickness of the model.

Table 1 *Model parameters*

Parameter	Unit	Value
General parameters		
Superelement polygon network	no. polygons	13
Interconnected triangular prism network	no. prism	35.565
Layer 1 elevation	m	surface elevation
Layer 2 elevation	m	25
Layer 3 elevation	m	40
Layer 4 elevation	m	225
Layer 5 elevation	m	525
Porous matrix parameters		
Effective porosity	%	0,001
Conductivity	m/sec	10^{-7}
Longitudinal dispersivity	m	250
Transversal dispersivity	m	10
Molecular diffusion coefficient	m^2/sec	1,6 x 10^{-9}
Regional surface recharge	mm/year (mm/day)	27,37 (0,075)
Local surface recharge (repository vicinity)	mm/year (mm/day)	36,5 (0,100)
Fracture parameters		
Fractures opening	mm	1
Fractures conductivity	m/sec	0,816
Fractures longitudinal dispersivity	m	20
Fractures transversal dispersivity	m	0
Fractures molecular diffusion coefficient	m^2/sec	1,6 x 10^{-9}

The resulting model is delimited at the upper part by the topographic surface and at the lower part by a base plan. Five intermediate planes located at -25m, -40m, -225m and -525 m below the surface were inserted.

5.4 Estimation of hydraulic parameters of the model

The estimation of hydraulic parameters of the model was done according to the conceptual model, considering an unconfined aquifer system.

Given the large volume and area of the model, and the limited number of observation points, it was considered that the general flow characteristics were not influenced by local heterogeneities so that the whole aquifer was considered to be homogeneous and isotropic on almost the entire modeled volume. The repository area is an exception because of the mining activity which created supplementary fractures, thus higher values of hydraulic conductivity and infiltration flow rates are expected.

The free surface was determined through successive changes in the position of the upper surface in order to attain finally the condition of equality between the piezometric head and surface elevation in all the points of the model surface.

The model calibration involved the identification of the hydraulic conductivity of the rock matrix and identification of the specific recharge flow from the surface.

The model calibration was based on the estimated piezometric levels of some references points, obtained during a series of mining works performed by Watson et al., 2006.

The ranges of values of the estimated hydraulic heads are summarized in table 2.

Table 2 *The ranges of estimated values of hydraulic heads in reference points*

ID reference points	Stereographic coordinates		The range of hydraulic head [m]
	X	Y	
1	318928,7	555848,7	550-620
2	318124,1	555866,1	620-660
3	318495,5	555608,6	640-690
4	317845,8	556210,5	570-620

Using hydraulic conductivity and infiltration flow values of the NRWR, two distribution areas were taken into consideration.

- An area with regional values distributed on the entire modeled surface and in the all layers;
- And an area with local values, representing the area within the immediate vicinity of the repository, through the entire depth of the first layer.

The deep layers were included in the area with regional values of hydraulic conductivities and infiltration flows considering that their properties have not been affected by the mining activities.

Model calibration was done at regional scale in order to establish the order of magnitude for hydraulic conductivity and infiltration flow. These values have been subsequently adjusted until piezometric head with values close to those measured into the reference points were obtained.

The identification process considered two types of conceptual models:

- The model with a single porosity in which the hydraulic conductivity is due to primary porosity represented by microfractures in the rock system. At a regional scale the medium with a single porosity can be equivalent with porous medium;

- The model with a double porosity in which the regional and local fracture system was superimposed over the primary porosity, which can have preferential flow pathways.

5.5 Model calibration – a medium with simple porosity

The starting premise was that the medium within NRWR is equivalent with a homogeneous and isotropic aquifer, in almost all of its volume, characterized by unique, average values of hydraulic conductivity and infiltration flow. To analyze the effect of the primary porosity, three versions of the model calibration have been selected, which revealed piezometric head values close to the ones measured in the reference points.

When the matrix conductivity is 10^{-7} m/sec and the existing fracture systems of the modeled area are ignored, the distribution of piezometric heads is strongly influenced by the presence of the rivers, especially downstream of the confluence of Calului Valley and Paraul Mic. Upstream of confluence of Calului Valley and Paraul Mic the groundwater movement has an almost constant gradient, the water level is 300 – 350 m below surface.

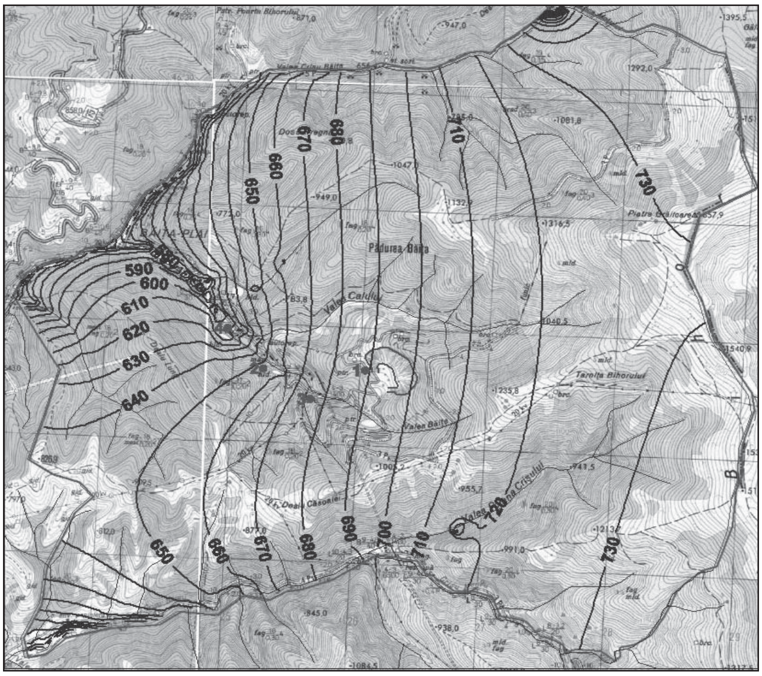

Fig.2 *Piezometric head distribution as a result of a model calibration for $K_{matrix} = 10^{-7}$ m/sec and W_{matrix} = 0,075 mm/day, Paraschivoiu et al., 2014 (map modified from MoND)*

5.6 Model calibration – medium with double porosity

The movement of groundwater through fracture system was modeled by considering the fractures as two parallel planes placed at a distance of 2b (the fracture opening). Darcy's law should remain valid for laminar flow conditions. The fracture permeability is proportional with the square of the fracture opening. Field measurements revealed an average fracture opening of about 1 mm which resulted in equivalent fracture conductivity ($K_{fracture}$) of 8,167 x 10^{-1} m/sec (0,861 m/sec). For the analysis of the effects of the secondary porosity, given by the major fracture system, four variants of the model were considered.

By contrast with the homogeneous medium, in which the matrix had the same hydraulic conductivity of 10^{-7} m/sec, the presence of the fracture system caused significant changes of hydrodynamic conditions (fig. 3).

Due to the presence of regional and local systems of fractures the global-equivalent conductivity of the aquifer is increased overall. Unlike the homogeneous medium simulation, in which similar conductivity values were used, the fractured medium leads to a decrease of about 75 m in the elevation of the water table, as a result of the increased hydraulic conductivity. The changes of the hydrodynamic conditions are reflected, mainly, in changes of the flow direction, the aquifer being drained outside of Baita River and its two adjacent rivers (Calului Valley and Paraul Mic). In the vicinity of these valleys the equipotential curves are almost parallel with rivers valleys (Figure 3), clearly indicating the flow direction into the valleys. If the discharge in the two adjacent valleys represents the cumulative effect of the rivers and of the local fracture system, the regional fracture in itself is a preferential flow path, leading to a secondary discharge to S of NRWR, into Crisul Negru River.

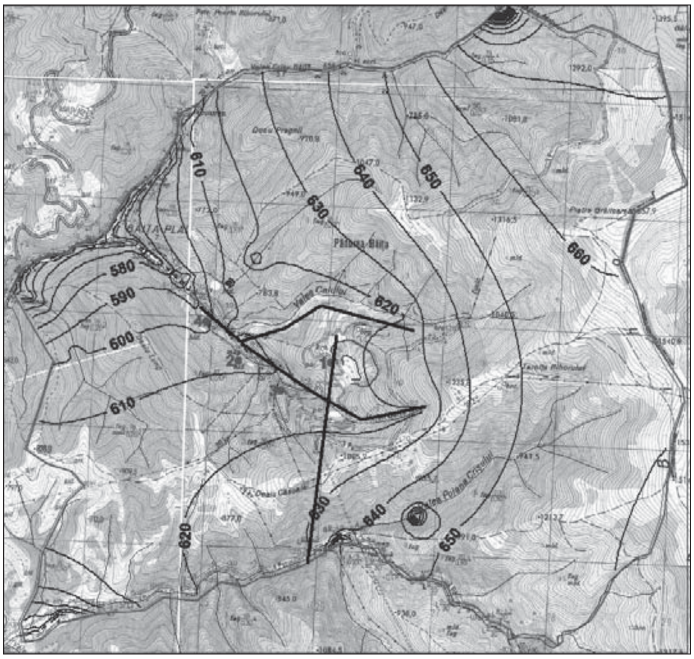

Fig. 3 *Piezometric head distribution resulting from a model calibration for $K_{matrix} = 10^{-7}$ m/sec, W_{matrix} = 0.075 mm/day and $K_{fracture}$ = 0.861 m/sec, Paraschivoiu et al., 2014 (map modified from MoND)*

Table 3 *Piezometric head values for the reference points, after model calibration*

ID	Unit	Hydraulic head interval	Isotropic medium			Local + regional fracture systems		
			Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
	mm/day		W = 0.075					
	m/sec		$K_m = 10^{-7}$	$K_m = 10^{-6}$	$K_m = 10^{-8}$	$K_m = 10^{-7}$	$K_m = 10^{-6}$	$K_m = 10^{-8}$
1	m	550-620	689	601	860	617	601	645
2	m	620-660	654	593	725	607	596	631
3	m	640-690	676	597	769	612	599	640
4	m	570-620	610	589	624	598	594	604

The results of model calibration, calculated for 6 representative scenarios are presented in Table 3.

The results show that the closest modeled values, of the piezometric head, to those measured were obtained when the local and regional fracture systems were considered as intersecting each other. If the fracture systems are neglected, and we have plausible values of conductivity and infiltration, the piezometric heads are higher, by approximately 65 m, 240 m then the measured values. The fractures increase the overall conductivity of the rock and hence the hydraulic gradient of the groundwater from the NRWR area. The hydrodynamic conditions are strongly influenced by the presence of a local fracture system. The local fracture system leads to the appearance of an arch in the distribution of piezometric heads within the NRWR area. The presence of a regional fracture system seems to have a lesser influence over the hydrodynamic regime of the NRWR.

The values of recharge and discharge flow rates, and non-closing flow rates, calculated for all six model calibration versions are presented in Table 4.

Table 4 *Recharge flow rates, discharge flow rates, and non-closing flow rates as resulted from the model*

	Unit	Unfractured medium			Local + regional fracture systems		
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
	mm/day	W = 0.075					
	m/sec	$K_m = 10^{-7}$	$K_m = 10^{-6}$	$K_m = 10^{-8}$	$K_m = 10^{-7}$	$K_m = 10^{-6}$	$K_m = 10^{-8}$
Recharge flow rates	m^3/day	$1.19x10^2$	$2.51x10^3$	4.17	$1.12x10^3$	$3.64x10^3$	$8.46x10^2$
Discharge flow rates	m^3/day	$-1.86x10^3$	$-4.24x10^3$	$-1.74x10^3$	$-2.87x10^3$	$-5.38x10^3$	$-2.59x10^3$
Non-closing flow rates	m^3/day	1.10	1.86x10	7.62	1.47	6.13	0

The presence of regional and local fracture systems, overall, increases the conductivity of the aquifer, thus increasing the discharge flow rates, when compared with homogeneous medium versions (Table 4).

Considering these values for $K_{matrix} = 10^{-7}$ m/sec; W_{matrix} = 0.075 mm/day (27.37 mm/year); $2b_{fracture} = 10^{-3}$ m (1 mm); $K_{fracture} = 8.167 \times 10^{-1}$ m/sec (0.861 m/sec) trial number four has the closest values to those measured.

The shape of the piezometric surface resulted from the model are justifying Toth's model by creating a secondary basin around the repository, where the piezometric curves are near parallel with the river valleys.

Using these results of the model, for the radionuclides transfer simulation through the saturated area, a medium with double porosity was chosen, in which the secondary porosity is represented by the local and regional fracture systems.

6. Simulation transfer of radionuclides in the saturated zone

A continuous release source was simulated to analyze the possible release and transfer of radionuclides in NRWR area, for both surface and depth contamination. The simulation was done starting with some conservative assumptions such as the rock layers are fully saturated and a ^{226}Ra radionuclide source, part of the long-lived radionuclides class was also considered.

The purpose of this simulation was to study the concentration distribution of radionuclides under the influence of the local geological and hydrogeological conditions.

The source term for ^{226}Ra isotope was calculated and presented as a variation of concentration in time (Bq/m^3), by Dr. Petre Ilie from the Authority for Nuclear Activities (ANA), Pitesti NRB, 2009.

The distribution of the concentration through the multi layered model was calculated for multiple time intervals, but only the representative time intervals for each intermediary surface were chosen.

Four observation points were established to track the distribution of radionuclide concentrations and to register the restitution curves (Figure 4).

The location of observation points are as follows: Point 1 – at the repository surface; Point 2 - on the Paraul Mic Valley, at the intersection of the local and regional fault systems; Point 3 – on the local fault, along the Paraul Mic Valley; Point 4 - at the confluence of Paraul Mic and Calului valleys.

Fig. 4 *Distribution of the observation points for simulation transfer of ^{226}Ra radionuclides, Paraschivoiu et al., 2014 (map modified from MoND)*

The main characteristics of restitution curves are summarized in the Table 5, where T_{max} and C_{max} represent the time period in which the maximum concentration value is reached in the observation point, respectively the maximum concentration registered in that point.

Table 5 *The maximum concentration of ^{226}Ra radionuclides in the observation points*

Point	Depth (m)	T_{max} (years)	C_{max} (Bq/m^3)
1	On the repository surface (the source)	50	4.1E+08
2	On Paraul Mic Valley, at the intersection of the local and regional fault systems	52	5.02E+06
3	On the local fault along Paraul Mic Valley	53	1.43E+07
4	At the confluence of Paraul Mic and Calului valleys	54	1.44E+07

From the values it can be observed that, at 25 m depth, the concentration for the observation points decreases by two orders of magnitude, respectively by one order of magnitude compared with the maximum concentrations recorded at the source. The shortest transfer time and the lowest concentration (52 years, 5.02E+06 Bq/m^3) was registered in the observation point number two, located at the contact of the local and regional fault systems. This was expected because in this area the transport is preferentially along the two fault systems.

The transfer time is longer (53 years) in the observation point number three, located on local fault along Paraul Mic Valley, because here the transport is influenced only by the local fault. In this point the ^{226}Ra isotopes concentration decreased by one order of magnitude to 1.43E+07 Bq/m^3.

For the observation point number four, situated at the confluence of Paraul Mic and Calului valleys, the farthest point from the source, the longest ^{226}Ra radionuclide transfer time was registered, 54 years. The ^{226}Ra isotopes concentration decreased by one order of magnitude, down to 1.44E+07 Bq/m^3, and it is almost equal with the concentration registered in the observation point number three.

In brief, it was observed that the Ra isotope transfer mainly occurs along the main hydraulic gradient, on an E-W direction, towards the drainage area located at the confluence of Calului and Paraul Mic valleys, also influenced by the fault systems.

^{226}Ra concentration distribution in NRWR area

Because the half-life of ^{226}Ra isotope is much longer than the residence time, two time intervals were chosen, 50 and 100 years from the moment of release of the radioactive particles. For each time period the concentration distribution of ^{226}Ra was calculated for the two intermediate surfaces, at -20m and -40m depth. The results are presented in Figures 5 – 8.

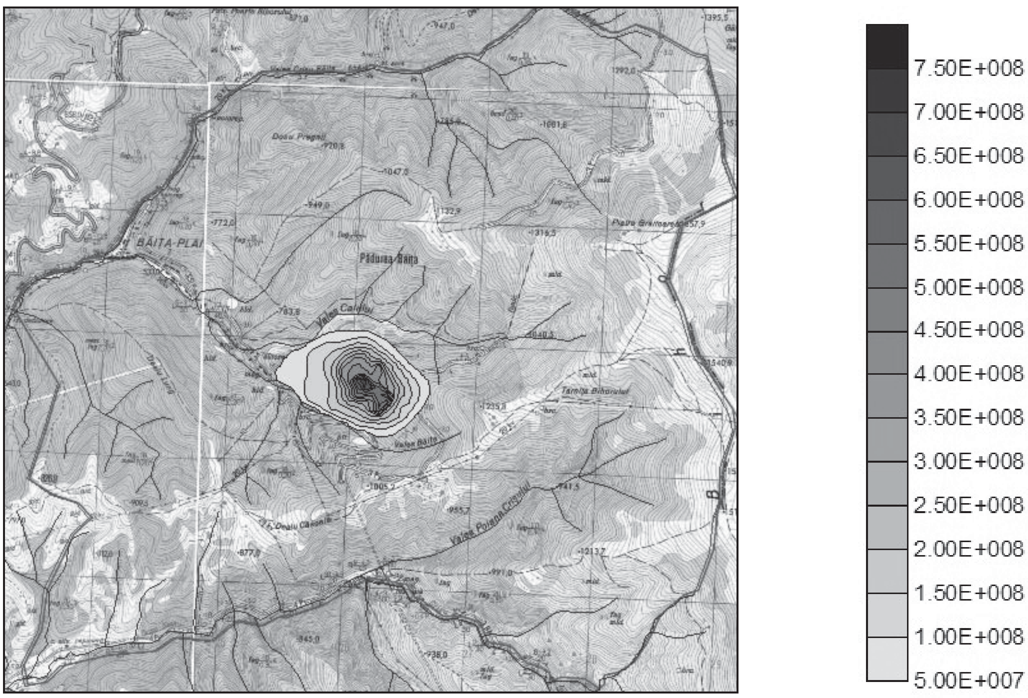

Fig. 5 *^{226}Ra isotopes concentration distribution (Bq/m^3) after 50 years from the release from the repository at -25m depth, Paraschivoiu D.L., et al., 2014 (map modified from MoND)*

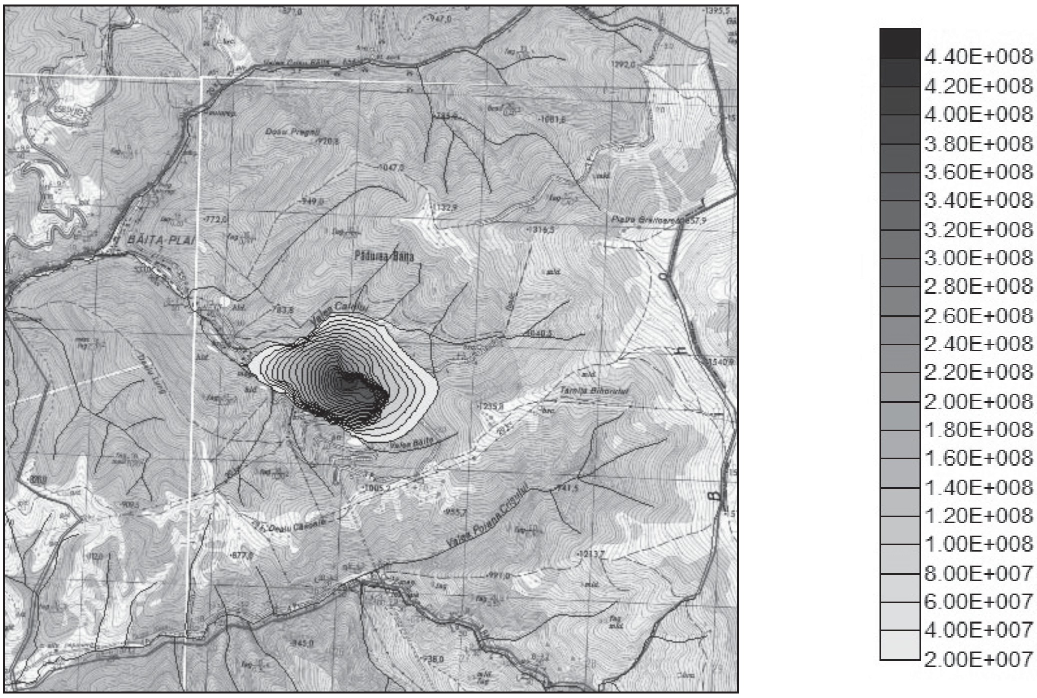

Fig. 6 *^{226}Ra isotopes concentration distribution (Bq/m^3) after 50 years from the release from the repository at -40m depth, Paraschivoiu D.L., et al., 2014 (map modified from MoND)*

At 50 years from the release time, Ra isotope concentration decrease by one order of magnitude from a concentration of 7.50E+008 Bq/m^3 registered at -25m depth (Figure 5) to a minimum concentration of 2.00E+007 Bq/m^3 registered at -40m depth (Figure 6).

Analyzing the areal extent of the contaminant plume at -25 m and -40 m depths after 50 years from the release from the repository, it can be observed that the plume is found between the two river valleys, Calului Valley and Paraul Mic. At -40 m depth, the contaminant plume starts to travel along the confluence of the two rivers.

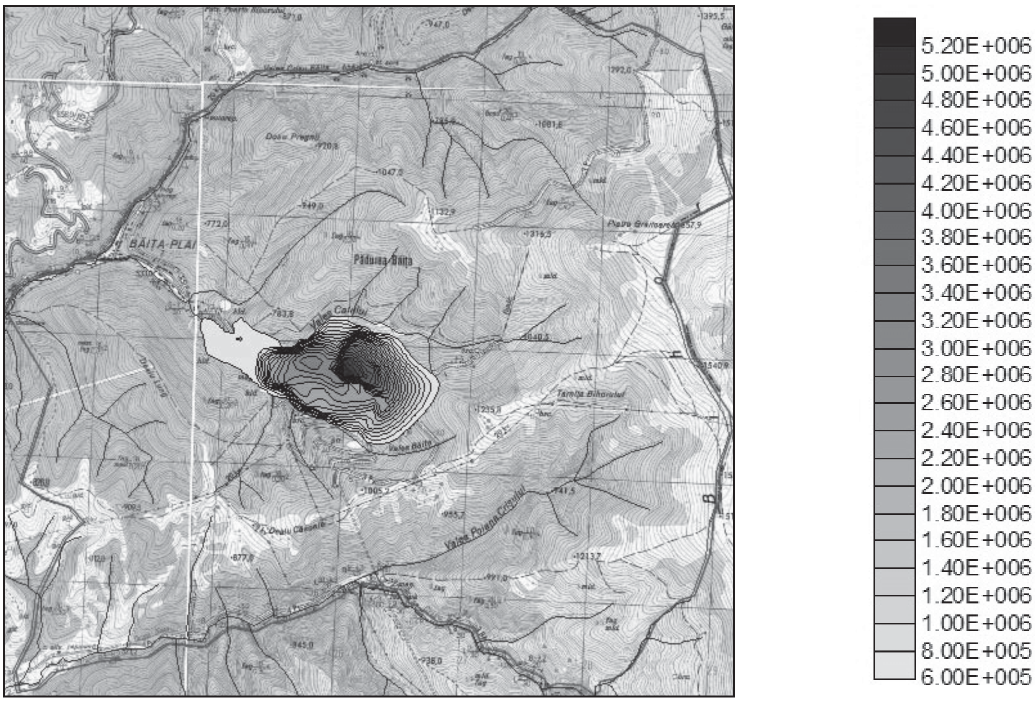

Fig. 7 *^{226}Ra isotopes concentration distribution (Bq/m^3) after 100 years from the release from the repository at -25m depth, Paraschivoiu et al., 2014 (map modified from MoND)*

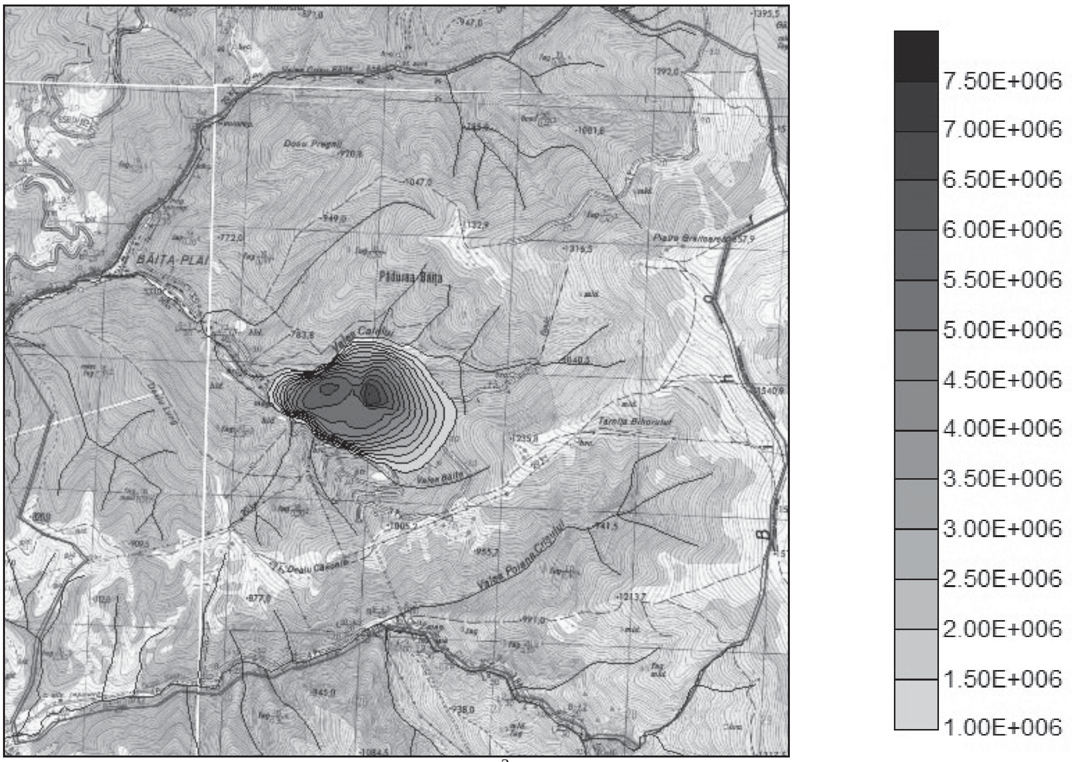

Fig. 8 *^{226}Ra isotopes concentration distribution (Bq/m^3) after 100 years from the release from the repository at -40m depth, Paraschivoiu et al., 2014 (map modified from MoND)*

After 100 years from the release moment, the Ra isotope concentration decreased by one order of magnitude, from a maximum concentration of 7.50E+006 Bq/m^3 (Figure 7) to a minimum concentration of 1.00E+006 Bq/m^3 (Figure 8) registered at -40m depth.

Analyzing the extent of the contaminant plume at -25 m depth it can be observed that, after 100 years, the contaminant plume mimics the shape of the area between the two rivers and starts to extend, slightly, above the confluence of Calului and Paraul Mic valleys.

At -40m depth, after 100 years, the contaminant plume remains within the Calului and Paraul Mic river system and has an areal extent almost identical with the one registered after 50 years.

7. Conclusion

The underground migration of the contaminant plume is well explained by the Toth model within the regional hydrological basin. Once entered into the ground the contaminant plume is distributed between the five virtual layers of the model. The contaminant from the upper layer is discharged in the closest drainage center, Calului and Paraul Mic valleys.

In case of an accidental release of Ra isotopes, the area with the highest contamination risk is at the confluence of Calului and Paraul Mic valleys and along the Crisul Baita creek. Taking into account that the surface waters have a high flow rate it is expected that the contaminant plume will reach the Baita Sat and Baita Plai localities. The transfer through the rock mass, however, reduces the concentration by one or two order of magnitude.

Considering that the radionuclides transfer is along the Crisul Baita creek, the influence area of NRWR must be extended to the West, thus, the mining village of Baita Plai is included in the area of influence of NRWR.

Since the mining activities from Baita Plai have stopped for 14 years (in one part of the mine) and for five years (in the remaining parts of the mine) and that the repository has implemented procedures regarding radioactive security, in accordance with national and international legislation, the risk of contamination with ^{226}Ra radionuclides as a result of the operation of NRWR, seems to be low. However, it is possible that a historical area of contamination may exist in the mine since this mine was operating from the early 1930's to extract uranium ore.

References

1. Authority for Nuclear Activities (ANA), Pitesti Nuclear Research Branch (Pitesti NRB),
Activity Report, Activity III.3 – Assessing the influence of engineered barriers used at NRWR through modeling of the potential radioactive leaks, 2009;

2. Danchiv A., Iurkiewicz A., Popa I.
Research of optimization radioactive waste disposal practices at the National Repository Baita Bihor (DNDR) to ensure radiation safety in accordance with national and international recommendations (Funding contract for implementation projects no. 71072/2007), University of Bucharest, Research Department of Geology and Environmental Geophysics, 2007;

3. Ministry of National Defense (MoND), Military Topographic Directorate
Topographic map L-34-70-D, scale 1:50.000;

4. Romanian National Water Administration "Apele Romane", Crisuri Water Catchment
Management Plan of Crisurile Hydrographic Area, 2009 – 2015, 2009;

5. Oraseanu I.
Contribution to the hydrogeology of the karst area of the Bihor - Vladeasa Mountains (Romania), Theoretical and Applied Karstology, 9, 185 - 214, 1996;

6. Oraseanu I., Gaspar E., Pop I. Tanase T.
Tracer experiments in the karst area of Bihor Mountains (Romania), Theoretical and Applied Karstology, 4, 159 - 172, 1991;

7. Toth Jozsef, Hazashi Masaki
The Theory of Basinal Gravity Flow of Groundwater and its Impacts on Hydrology in Japan, Journal of Groundwater Hydrology, Volume 52, No. 4, 2010;

8. Paraschivoiu D.L., Danchiv A.
Analysis of hydrodynamic conditions and radionuclides transport at the Baita Bihor National Radioactive Waste Repository, 2014;

9. Watson S. P., Matyasi S., Matyasi L., Vlas G., Nicolae R., Butler A. P., Little R. H., Bond A. E., Niculae O., Pantazi D., Paulley A., Robinson P. C., Thorne M. C. and Walke R. C.
Preliminary Safety Analysis Report for Baita Bihor Repository, Quintessa Report QRS-1255A-PSAR2, Version 1.0, Quintessa Limited, Henley-on-Thames, UK, 2006.