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Radiation impact assessment on wildlife from an uranium mine area

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ABSTRACT

Uranium mining and milling activities are one of the major causes of radioactive contamination of the environment. Radionuclides, especially uranium decay-chain products, are released from plant wastes into the soil and water and consequently into vegetation where they may accumulate. Transfer of radionuclides thus represents a radiological risk to humans and non-human organisms due to accumulation of radionuclides in target tissues and the consequent ionising radiation. The uranium mine at Žirovski vrh in Slovenia, which operated from 1985 to 1990, processed about 600,000 t of U-ore. Operational wastes were deposited at the Boršt and Jazbec sites. According to several studies, an environmental radiological risk to biota could be observed at sites exposed to radioactive contamination. A modelling approach can be used to estimate the risk in such areas. The ERICA tool is one of the more widely used models, developed to assess the environmental risk from ionising radiation to wildlife. In the present study, the ERICA Tool was applied for the assessment of the radiation impact on wildlife in the Žirovski vrh influential area. ERICA reference organisms, native plants and aquatic organisms were included in the assessment to screen the risk to different organisms. Total dose rate to organisms were up to 3.49, 33.0 and 2.58 $\mu Gy\, h^{-1}$ for *Juncus effusus*, lichens and *Austropotamobius torrentium*, respectively. Dose rates to other organisms are also presented and discussed.

1. Introduction

Uranium mining and milling activities in Slovenia were in full operation from 1985 to 1990 at Žirovski vrh, when altogether 600,000 t of uranium ore were excavated. Operational wastes, such as U-mill tailings (UMT) were deposited at the Boršt site, and red mud with spoil and lower grade ores at the Jazbec site (Križman et al., 1995). Emission of natural radionuclides to nearby habitats has occurred due to the flow of tailings and mine waters into local streams. After the mine closure, mine waters and U-mill tailings remained the major emission source of ^{238}U and ^{226}Ra. U-mill tailings also remained the major emission source of ^{210}Pb (Smodiš et al., 2009). Due to these phenomenon, constant surveillance monitoring was applied from the beginning of mine operation. According to several studies, a potential environmental radiological risk to wildlife can be observed at sites with nuclear activities (Geras'kin et al., 2008). Enhanced levels of ^{238}U, ^{226}Ra and ^{210}Pb in biota in the vicinity of the waste deposits at Žirovski vrh were already reported by Jeran et al. (1995). Due to long-term discharge of uranium decay-chain products to the local streams, a biota risk assessment should be performed as the potential radiological risk to native wildlife is evident; a modelling approach can be used for such a purpose. International interest in wildlife dose assessment has recently expanded to protect wildlife at sites exposed to radioactive contamination. Ionising radiation could result in significant mortality, as well as reproduction, morbidity and mutation effects at species where the screening value is exceeded (Andersson et al., 2008). Screening value is a dose rate assumed to be environmentally safe. Recently, many models (e.g., RESRAD-BIOTA, ERICA Tool, ECOMOD, AECL, LIETDOS-BIO, DosDiMEco) have been developed for the dose and risk assessment of biota resulting from exposure to ionising radiation (Beresford et al., 2008). The ERICA Tool is one of the models more often used by different European nuclear safety authorities and research institutions. The ERICA Tool is a software programme that allows the calculation of dose rates to and whole body activity concentrations in biota for terrestrial, marine and freshwater environments (Brown et al., 2008). The assessment process in the tool is organised into three separate tiers. The Tier 1 assessment is a highly conservative tier where minimum data are required for input. It was designed to be simple and can be used by non-specialist users. The Tier 2 assessment is a less conseravtive tier and is more site specific where a variety of CR values, Kd values and other default parameters can be used while this can not be done in the Tier 1. The Tier 3 is probabilistic risk assessment and not a screening tier. The user can estimate the probability and magnitude of the environmental effects that are likely to occur. The tool provides a database of default radionuclides, concentration ratios (CR), radioecological parameters and a database of dose conversion coefficients (DCCs) to enable dose rate calculations from the

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input data (Beresford et al., 2007). In dose rate calculations, DCC (μGy h^{-1} per Bq kg^{-1} fresh weight) are used in combination with default radiation weighting factors, which are 10 for alpha, 3 for low energy beta and 1 for other beta/gamma emitters. Also, radioactive daughter nuclides are included in the DCC calculation if their half-lifes are shorter than 10 days. DCCs for biota are compared to DCCs for humans (nSV per Bq) which are different due to another dosimetric approach. In human dosimetry, the radiation weighting factors are focused on stohastic effects while in biota dosimetry, deterministic effects such as morbidity, mortality, reduced reproductive success and mutations are considered. Human DCC are thus not applicable in biota dose and risk assessment (Ulanovsky et al., 2008).

In the present study, the ERICA Tool was applied for assessment of the radiation impact on terrestrial and freshwater biota from the uranium mine area. The estimated absorbed dose rates due to ^{238}U, ^{226}Ra and ^{230}Th for terrestrial and from ^{238}U, ^{226}Ra and ^{210}Pb for freshwater biota were calculated and are discussed.

2. Materials and methods

2.1. Characterisation of the environments assessed

The Uranium mine at Žirovski vrh is located in the north-west part of Slovenia in a subalpine region with relatively high rainfall and a relatively densely populated area. The area (Fig. 1) has two disposal sites which contribute to the emission of radionuclides to the nearby terrestrial and freshwater environments. The soil in the vicinity of the Boršt tailings pile was permanently flooded by tailings seepage waters and was contaminated with natural radionuclides. Local streams such as the Brebovščica and Todraščica brooks were also exposed to radionuclide contamination due to discharge of tailings and mine waters to these aquatic environments.

2.2. Assessment methodology for biota

The ERICA Tool was applied to assess the environmental impact of current and past releases of radionuclides on terrestrial and freshwater biota. The assessment was based on the radionuclides ^{238}U, ^{226}Ra and ^{230}Th for the terrestrial environment and ^{238}U, ^{226}Ra and ^{210}Pb for the aquatic environment as data for some other critical radionuclides was lacking. The exposed sites were around 50 and 500 m away from wastes for the terrestrial and the freshwater environments, respectively. Native plants (*Juncus effusus*, *Caltha palustris* and *Molinia arundinacea*), freshwater organisms (*Salmo trutta*, *Barbus barbus*, *Chondrostoma nasus*, *Cottus gobio* and *Austropotamobius torrentium*) and ERICA reference organisms (RAPs) were included in the assessment to screen the risk for different organisms. In the assessment, the Tier 2 was used to make the assessment more relevant to the site considered. A default uncertainty factor of three at Tier 2 was used in the model to account for uncertainties in the assessment method (Oughton et al., 2008). The measured activity concentrations of plants, soil, water and sediments were used as input data for the assessment (Tables 1 and 2). The plant and soil samples were taken in the year 2009, while measurements results of the long-term monitoring program were used for the water and sediment samples.

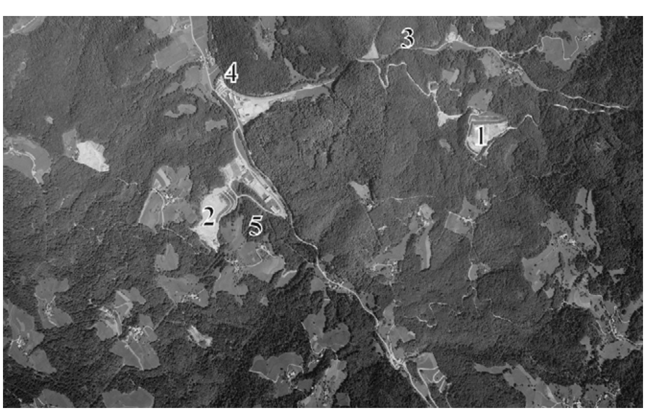

Fig. 1. Aerial picture of the uranium mine area at the Žirovski vrh: Boršt tailings pile (1) and its terrestrial environment (2); red mud with spoil and lower grade ore at the Jazbec site (3); Todraščica stream (4); Brebovščica stream (5); the mine entrance (6).

Table 1
Activity concentrations in plants (Bq kg^{-1} fresh mass) (measurement uncertainty, k = 2) and in soil (Bq kg^{-1} dry mass) (standard deviation, n = 3) near the Boršt tailings pile.

	^{238}U	^{226}Ra	^{230}Th
Juncus effusus	2.4 ± 0.2	22.0 ± 2.2	1.2 ± 0.12
Caltha palustris	0.4 ± 0.1	3.2 ± 0.3	1.0 ± 0.1
Molinia arundinacea	1.2 ± 0.2	16.3 ± 1.1	0.45 ± 0.08
Soil	536 ± 270	1054 ± 788	445 ± 282

Screening values proposed by U.S. Department of Energy (DOE)/International Atomic Energy Agency (IAEA), International Commission on Radiological Protection (ICRP) and ERICA/PROTECT for terrestrial and aquatic organisms were used to make the comparison with the estimated dose rates. Risk was defined as a risk quotient (RQ) which is the ratio between the estimated total dose rate and the screening dose rate. If the RQ value is more than one than a more refined exposure assessment has to be done. In this case it is recommended to perform a probabilistic assessment (Beresford et al., 2007). Concentration ratios for aquatic biota (Table 3) were calculated using the monitoring and literature data (Carvalho et al., 2007; Štrok and Smodiš, 2011) or taken from the IAEA handbook on wildlife transfer (IAEA, 2011). Concentration ratios for the reference organisms were taken from the ERICA database (Beresford et al., 2008).

3. Results and dicussion

3.1. Dose rates to terrestrial organisms

3.1.1. Internal dose rates

Internal dose rates to RAPs were in the range from 1.0E−1 to 3.08E1 μGy h^{-1} for ^{226}Ra, from 1.37E−3 to 9.13E−1 μGy h^{-1} for ^{238}U and from 1.47E−3 to 1.25E0 μGy h^{-1} for ^{230}Th. Internal dose rates to plants were in the range from 4.43E−1 to 3.05E0 μGy h^{-1} for ^{226}Ra, from 9.66E−3 to 5.80E−2 μGy h^{-1} for ^{238}U and from 1.21E−2 to 3.23E−2 μGy h^{-1} for ^{230}Th. Internal dose rates are graphically presented for the RAPs (Fig. 2).

Internal dose rates were the highest for lichens and invertebrates which is related to the species CR value and the higher contribution of ^{226}Ra.

3.1.2. External dose rates

External dose rates to RAPs were in the range from 2.11E−5 to 9.60E−1 μGy h^{-1} for ^{226}Ra, from 2.47E−10 to 6.97E−5 for ^{238}U and from 8.03E−10 to 9.37E−5 for ^{230}Th. External dose rates to plants were 3.53E−1 μGy h^{-1} for ^{226}Ra, 5.49E−2 μGy h^{-1} for ^{238}U and 6.28E−5 μGy h^{-1} for ^{230}Th. External dose rates are graphically presented for the RAPs (Fig. 3).

External dose rates were the highest for soil invertebrates and rat which are the most exposed group of organisms due to their presence in the soil. External dose rates were mainly from ^{226}Ra contribution as ^{226}Ra is also a gamma emitting radionuclide.

Table 2
Activity concentrations in water [Bq L^{-1}] and in sediment [Bq kg^{-1} dry mass] for Todraščica and Brebovščica streams, for the period from 1986 to 2009.

Mean annual values	Water [range]			Sediments [range]		
	^{238}U	^{226}Ra	^{210}Pb	^{238}U	^{226}Ra	^{210}Pb
Todraščica	0.032–0.124	0.005–0.047	0.002–0.025	63–255	116–897	110–586
Brebovščica	0.156–0.312	0.005–0.024	0.002–0.022	62–255	77–344	77–251

Table 3
CR values for aquatic biota.

	^{238}U	^{226}Ra	^{210}Pb
Salmo sp.	30 (Carvalho et al., 2007)	191 [monitoring]	84 [monitoring]
Barbus sp.	18 (Carvalho et al., 2007)	150 (Carvalho et al., 2007)	158 (Štrok and Smodiš, 2011)
Chondrostoma sp.	55 (Carvalho et al., 2007)	320 (Carvalho et al., 2007)	158 (Štrok and Smodiš, 2011)
Cottus sp.	75 (IAEA, 2011)	310 (IAEA, 2011)	180(IAEA, 2011)
Austropotamobius sp.	200 (IAEA, 2011)	270 (IAEA, 2011)	39(IAEA, 2011)

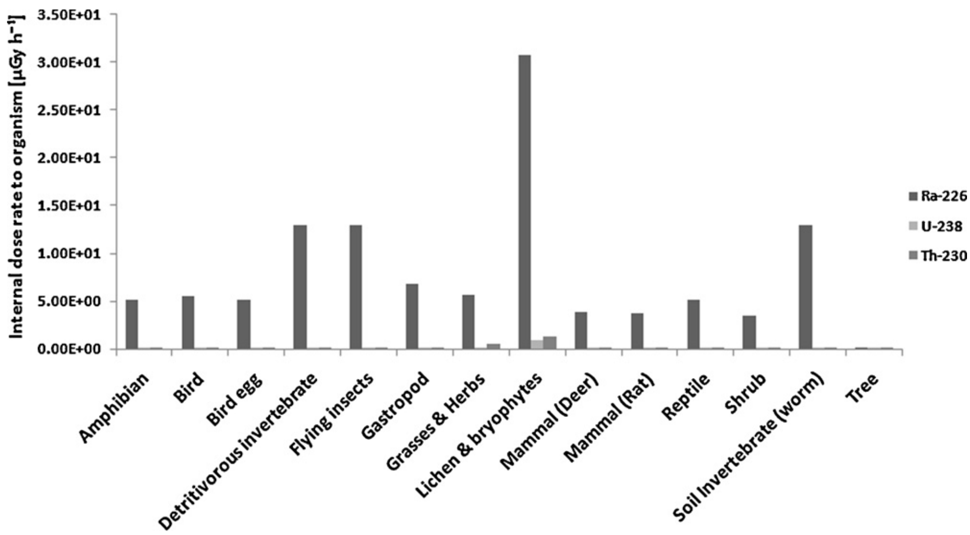

Fig. 2. Internal dose rates to RAPs.

3.1.3. Total dose rates

Total dose rates to organisms were in the range from 4.85E−1 to 3.30E1 μGy h^{-1} for RAPs and from 8.34E−1 to 3.49E0 μGy h^{-1} for plants. Dose rates to RAPs and plants are graphically presented in Figs. 4 and 5.

Among plants, rush received the highest dose rate which is evidently greater at the contamionated site than at the control site, but still far below the screening values. Similar situation was observed for terrestrial RAPs where detritivorous invertebrates, flying insects, lichens and soil invertebrates received the highest

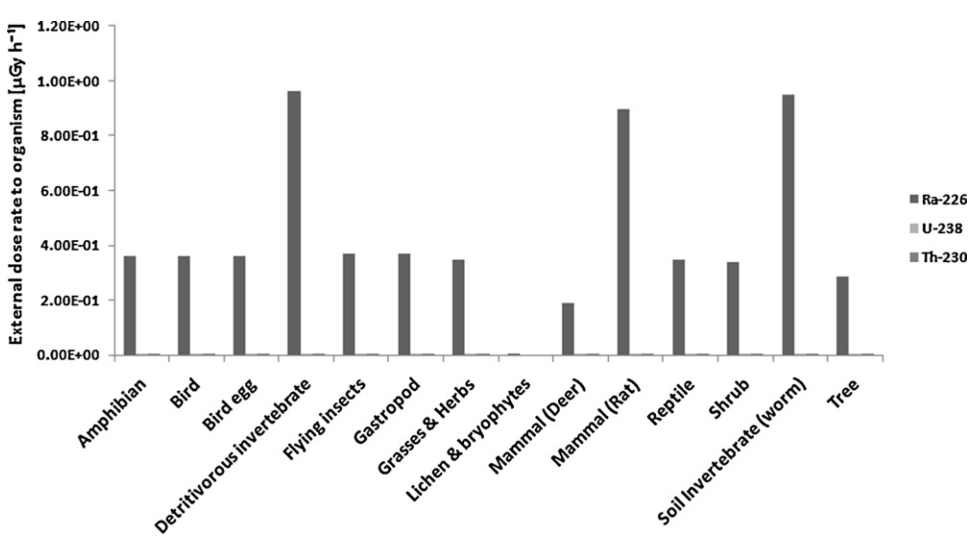

Fig. 3. External dose rates to RAPs.

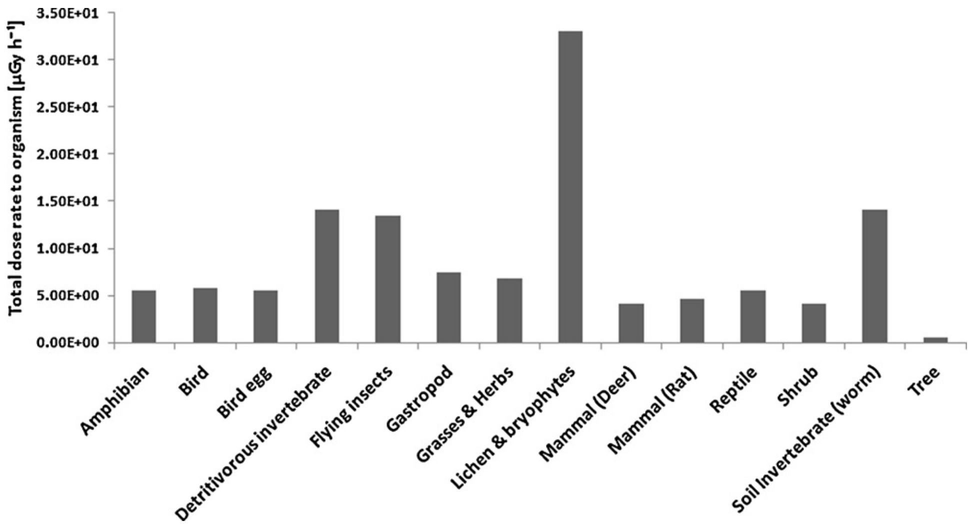

Fig. 4. Total dose rates to RAPs.

total dose rates. Dose rates to invertebrates are higher compared to vertebrates but are of minor concern due to their lower radiosensitivity.

3.1.4. Contribution of particular radionuclides to total dose rates in terrestrial biota

According to site contamination, ^{226}Ra contributed most to the dose received by the reference biota, as shown by the contribution of particular radionuclides to the total dose rate (Fig. 6). As observed from the results, ^{226}Ra contributed from 80 to 99% of total dose rate received by the reference biota. The results are in agreement with the previous site-related studies showing ^{226}Ra to be an important contaminant of biota (Černe et al., 2010; Jeran et al., 1995).

3.2. Dose rates to aquatic biota

Total dose rates are presented for the period from 1986 to 2009 while the year 1988 is used for the presentation of internal and external dose rates due to higher contamination levels in streams for that year.

3.2.1. Internal dose rates

Internal dose rates to biota were in the range from 3.85E−1 to 8.22E−1 µGy h^{-1} for ^{226}Ra, from 1.03E−1 to 1.15E0 µGy h^{-1} for ^{238}U and from 3.27E−5 to 1.49E−4 µGy h^{-1} for ^{210}Pb for the Brebovščica stream and from 9.85E−1 to 2.10E0 µGy h^{-1} for ^{226}Ra, from 2.97E−2 to 3.29E−1 µGy h^{-1} for ^{238}U and from 6.54E−5 to 2.98E−4 for ^{210}Pb for the Todraščica stream (Fig. 7).

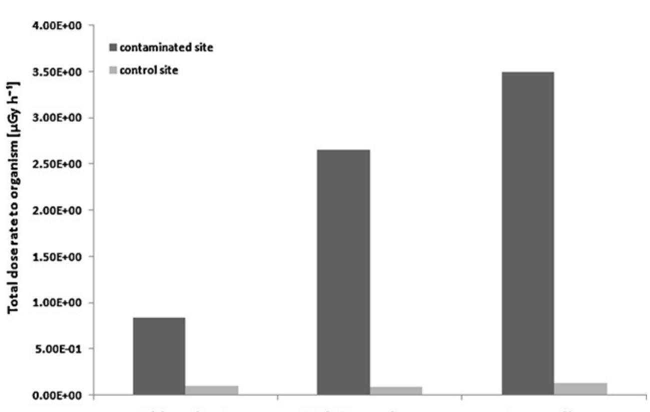

Fig. 5. Total dose rates to plants.

Internal dose rates were the highest for biota in the Todraščica stream due to higher activity concentration of alpha-emitting radionuclides in water. The species related CR value and the higher DCCs for alpha-emitters resulted in higher internal dose rates received by the *A. torrentium*.

3.2.2. External dose rates

External dose rates to biota were in the range from 1.08E−1 to 1.79E−1 µGy h^{-1} for ^{226}Ra, from 8.27E−6 to 4.02E−5 µGy h^{-1} for ^{238}U and from 1.08E−4 to 5.83E−4 µGy h^{-1} for ^{210}Pb for the Brebovščica stream and from 2.83E−1 to 4.67E−1 µGy h^{-1} for ^{226}Ra, from 5.25E−6 to 2.55E−5 µGy h^{-1} for ^{238}U and from 3.02E−4 to 1.63E−3 µGy h^{-1} for ^{210}Pb for the Todraščica stream (Fig. 8).

^{226}Ra contributed the most to the external exposure of aquatic biota due to higher gamma energy compared to ^{210}Pb. The external exposure was the highest for benthic organisms like *A. torrentium* and *C. gobio* in both streams. Todraščica stream resulted in higher external exposure compared to Brebovščica stream due to higher activity concentration of ^{226}Ra in sediments of the Todraščica stream.

3.2.3. Total dose rates

The assessment performed for the period from 1986 to 2009 shows an evident reduction of dose rates received by biota after mine closure in 1990. The estimated total dose rates were in the range from 1.64E−1 to 2.58E0 µGy h^{-1} for biota in the Todraščica stream and from 1.98E−1 to 2.26E0 µGy h^{-1} for biota in the Brebovščica stream as shown in Fig. 9.

Total dose rates to biota were the highest during mine operation (1986–1990) and declined after the mine closure (1990 and afterwards). Dose rates to biota were higher in the Todraščica stream due to the lower stream discharge rate and constant discharge of radionuclides from the nearby tailings deposit. *A. torrentium* was exposed to evidently higher dose rates compared to other species in both streams.

3.2.4. Contribution of particular radionuclides to total dose rates in freshwater biota

Total dose rates to freshwater biota arose mainly from ^{226}Ra and ^{238}U. The contribution of ^{210}Pb was negligible due to predominance of alpha emitters which induce higher internal dose rates and consequently total dose rates. The results shown in Figs. 10 and 11

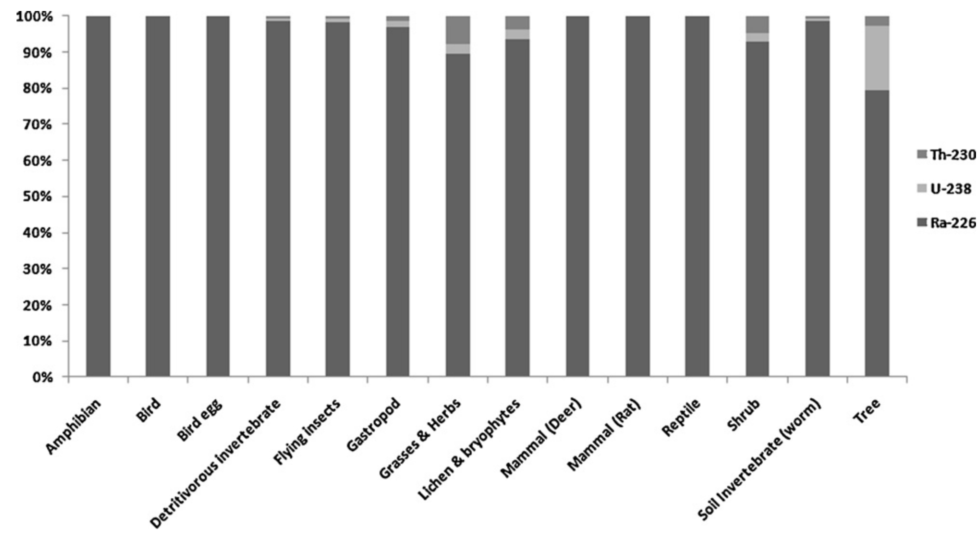

Fig. 6. Contribution of particular radionuclides to total dose rates received by RAPs.

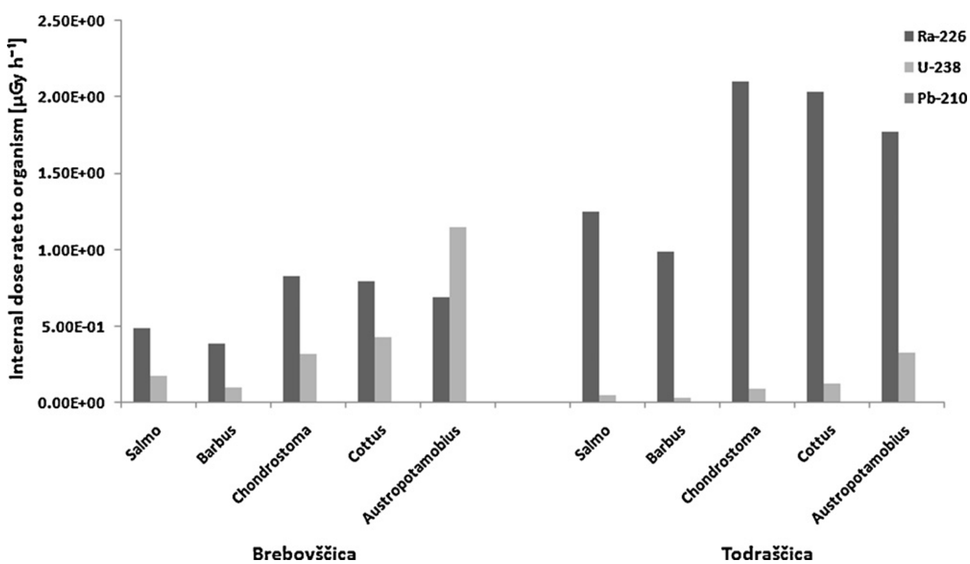

Fig. 7. Internal dose rates to aquatic biota for the year 1988.

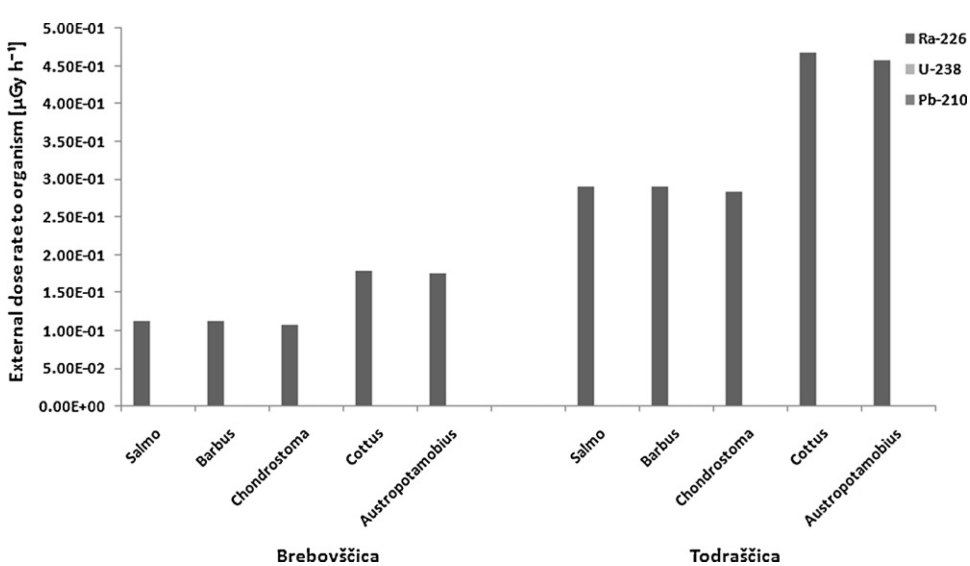

Fig. 8. External dose rates to aquatic biota for the year 1988.

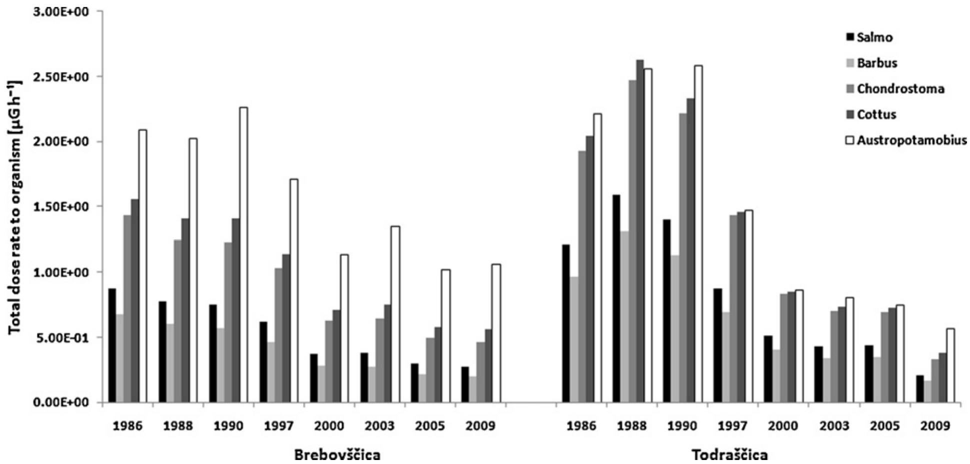

Fig. 9. Total dose rates to aquatic biota for the period from 1986 to 2009.

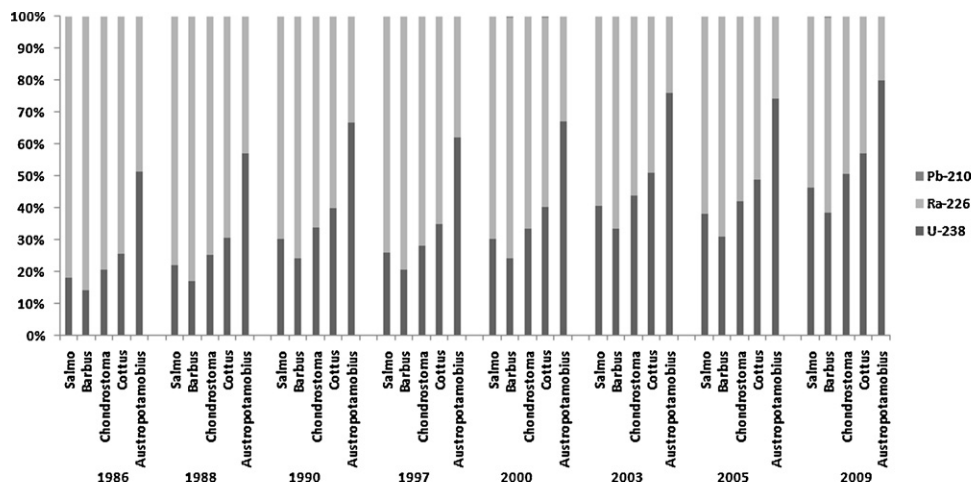

Fig. 10. Contribution of particular radionuclides to total dose rates received by native biota in the Brebovščica stream.

indicate tendency to reduction of ^{266}Ra dose rate contribution from the beginning of mine operation (1986) to the final mine remediation (2009). From the long-term monitoring results the main dose rate contribution from ^{238}U to biota in the Brebovščica stream and from ^{226}Ra to biota in the Todraščica stream could be expected.

3.3. Evaluation of environmental risk

According to the recommendations (Andersson et al., 2008; Howard et al., 2010) no risk to the terrestrial RAPs was found as no organism exceeded the screening values proposed by neither

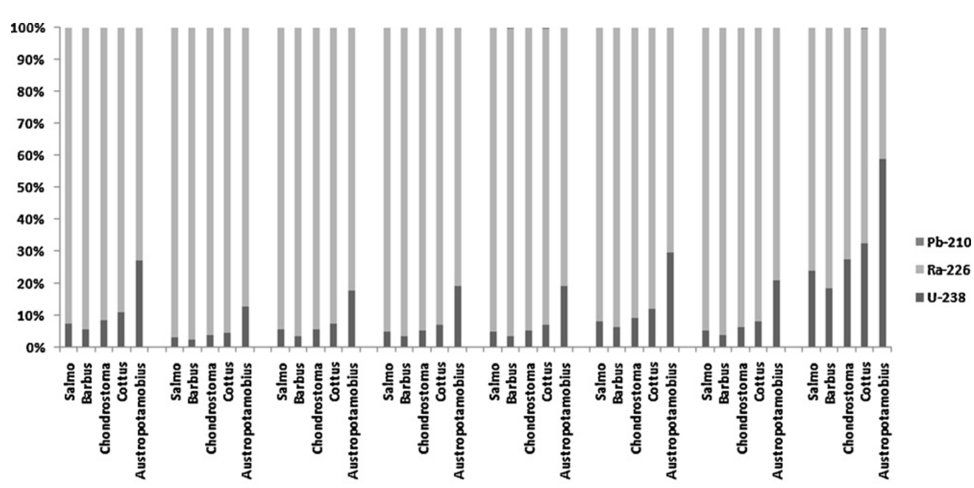

Fig. 11. Contribution of particular radionuclides to total dose rates received by native biota in the Todraščica stream.

Table 4
Comparison of maximum obtained dose rates (μGy h^{-1}) with recommended screening values.

	Max. total dose rate	IAEA/DOE	ICRP	ERICA
Detritivorous invertebrate	14.1	40	400–4000	10
Soil invertebrate (worm)	14.1	40	400–4000	10
Lichen&bryophytes	33	40	400–4000	10
Flying insects	13.5	40	400–4000	10
Juncus effusus	3.49	400	40–400	10
Austropotamobius torrentium	2.58	400	40–400	10

ICRP nor DOE/IAEA. The same was observed for the aquatic biota (Table 4).

4. Conclusions

The ERICA based assessment showed that no risk was found for terrestrial and aquatic organisms from the Žirovski vrh influential area. The highest total dose rates were assessed for lichens and *A. torrentium* due to higher internal dose rates related to ^{226}Ra contribution. The emission of natural radionuclides into the soil and local streams does not pose threat to wildlife in the vicinity of the former uranium mine. However, the fact that the ERICA Tool does not account for the movement of aquatic organisms and does not assess the exposure of terrestrial biota to ^{222}Rn inhalation, should be noted for further refinements of the software. It can also be concluded that low risk to wildlife at the Žirovski vrh area is also the result of good planning of production process and the proper management of mine remediation operations, which was confirmed by the relatively low contamination levels observed within the regular monitoring programme.

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