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APPLICATION OF PROBABILISTIC METHODS FOR IONIZING RADIATION DOSE ASSESSMENT

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1. INTRODUCTION

Radionuclide penetration into the environment as well as the human and biota (flora and fauna) radiation protection are a topical problem in all chains of the nuclear power engineering cycle. Radiation protection is the entirety of scientific and practical actions determined by special specifications, the objective of which is to constrain the human exposure and the environment radioactive contamination to as low as possible, society-permissible levels consistent with those validated by standards. Up to the present time great attention was paid to the human radiation protection: the impact of ionizing radiation was investigated and normative acts regulating the human exposure at international and national levels were validated. In recent years both the European Union and a great many of other international and national organizations pay ever-increasing attention to the biota radiation protection of the environment and different ecosystems (terrestrial, freshwater and marine) [1]. It should be noted that in the assessment of human and biota exposure probabilistic methods (correlation analysis, determination of sensitivity of parameters, etc.) are finding increasing use as well as the assessment uncertainties of exposure by ionizing radiation at all stages of the nuclear power plant maintenance, termination of its operation and radioactive waste storage are considered.

In this work probable uncertainties of the human exposure assessment by applying probabilistic methods were evaluated by considering the radionuclide water pathway migration from the Maišiagala near-surface radioactive waste repository based on the long-term observation data [2]. The results were compared with the radiation protection criteria established in the Republic of Lithuania: the annual effective limited dose of population in maintaining and terminating the activity of nuclear power engineering objects, which include this repository as well, is 0.2 mSv per year [3].

Uncertainties of biota exposure were considered by evaluating the radioecological state of the state enterprise Ignalina Nuclear Power Plant (INPP) cooling pond, i.e. Lake Drūkšiai, in forecasting the biologic impact of the radionuclide ionizing radiation on flora and fauna during the INPP operation and after termination of its exploitation as well as after installation of a hypothetic radioactive waste disposal facility at the 1.5 km distance from the lake. The biota exposure assessment was performed referring to the data of radioecological investigations of Lake Drūkšiai carried out in 1989-2008 [4-5].

Topicality of the work

The objectives of assessment of the impact on humans and the environment in the Republic of Lithuania are determined in the law of economic activity (including nuclear power engineering objects) [6], the main provisions on the human and environment radiation protection of which are the following:

- to determine, characterize and evaluate a probable direct and indirect impact of the planned economic activity on the human health and the environment (on fauna and flora among them);
- to reduce the negative impact of the planned economic activity on the human health and the environment components or to avoid this impact;
- to determine whether the planned economic activity after evaluating its character and impact on the environment is permissible at the selected site.

Radionuclide penetration into the environment is a relevant problem in all chains of the nuclear power engineering cycle. For the assessment of the probable impact of ionizing radiation on the human health, it is necessary to evaluate the present and possible exposure taking into consideration the parameter variation and uncertainties by determining average, maximum exposure values and 95^{th} percentiles.

The assessment of biota exposure of Lake Drūkšiai, INPP cooling pond, as well as comparison of background and anthropogenic exposure and determination of risk factors will allow drawing a conclusion about peculiarities of biota exposure of this freshwater ecosystem and evaluating a possibility of further development of fishery and other uses, including the development of nuclear power engineering.

The main aim of the doctoral dissertation

The aim of this work is to determine, characterize and assess the probable impact of ionizing radiation on the public health and environment (including flora and fauna) in the environment of nuclear power engineering objects (in case of the Maišiagala radioactive waste disposal facility – by evaluating a possible impact on humans and in case of Ignalina NPP cooling pond Lake Drūkšiai – by evaluating a possible impact on freshwater ecosystem biota) as well as to determine whether this activity after evaluating its character and impact on the environment meets the standards valid in the Republic of

Lithuania or in the European Union and is permissible at a selected site at present or in the future.

The main tasks:

1. To evaluate the migration of radionuclides from the radioactive waste repository (based on the observation data of the Maišiagala repository environment presented in reports and publications in 1989-2010 [2]) by applying probabilistic methods as well as to determine potentially important radionuclides and the impact of migration pathways of separate radionuclides on the annual effective dose values of human exposure.
2. To perform sensitivity analysis of parameters of the mathematical model meeting local conditions of radionuclides migration; to evaluate the influence of separate model parameters and uncertainties on the assessment of the annual effective dose of human exposure by ionizing radiation.
3. To investigate exposure of reference biota of freshwater ecosystem (based on radioecologic investigation data of Lake Drūkšiai provided in reports and publications in 1989-2008 [4-5]) using probabilistic methods, to determine potentially important radionuclides, to evaluate risk factors and other factors determining exposure of reference biota.
4. To assess human and reference biota exposure in the environment of nuclear power engineering objects taking into consideration the radiation protection criteria established or recommended in the Republic of Lithuania and the European Union.

Scientific novelty

1. Radionuclides potentially important from the radiation protection point of view migrating from the investigated repository have been determined and the percentile contribution of exposure ways (drinking-water, nutrition) to the annual effective dose value has been evaluated. By applying correlation and sensitivity analysis, potentially significant model parameters and their partial rank correlation coefficients determining the radionuclide migration outside engineering barriers in three-dimensional space from the radiation protection point of view have been determined.

2. For the first time by applying probabilistic methods, the exposure of reference organisms of freshwater ecosystem INPP cooling pond, Lake Drūkšiai, by ionizing radiation of background and anthropogenic radionuclides has been evaluated.
3. It has been determined that after installation of additional protective barriers, in the environment of the Maišiagala repository the annual effective human exposure dose is significantly lower compared to the limited dose value, and 95^{th} percentile does not reach the limited dose value of 1 mSv per year established in the hygiene standards.
4. It has been established that the probable and conservative risk factors of Lake Drūkšiai biota exposure dose rates due to the impact of anthropogenic origin radionuclide ionizing radiation do not exceed the regulated level proposed in the European Union.

Practical importance of the dissertation

Referring to the long-term observation data of radionuclide migration in the environment of the Maišiagala repository and by applying probabilistic methods, a significant human exposure decrease has been determined after installation of additional protective barriers. It has been determined that the Ignalina NPP cooling pond, Lake Drūkšiai, from the point of view of biota radiation protection (background exposure significantly exceeds the anthropogenic one, conservative risk factors make up about 10% of the screening value proposed in the European Union) could be used for the further development of nuclear power engineering taking into account a possible impact of temperature, chemical contamination and other factors. The annual effective dose of human exposure due to consumption of fish from the INPP cooling pond, Lake Drūkšiai, is of the order of some μSv. Based on these data it can be stated that amateur fishing in Lake Drūkšiai from the human radiation protection point of view is possible.

Defended statements of the dissertation

1. In the considered cases the sensitivity analysis of parameters of the mathematical model meeting local conditions of water pathway migration of radionuclides has shown that the main parameters determining the exposure value are the horizontal lateral dispersivity of saturated zone, the leach rate of radionuclide penetration into the environment, hydraulic gradient of saturated zone and the precipitation amount.

2. Taking into consideration nourishment chain peculiarities the analysis of the obtained data has shown that out of all radionuclides taken for storage in case of the Maišiagala repository ^{3}H, ^{14}C and ^{36}Cl are regarded as dangerous, while in case of a hypothetic Stabatiškės repository – ^{14}C, ^{36}Cl, ^{129}I, ^{99}Tc, during later period – ^{237}Np.

3. The dose rate of reference organisms in Lake Drūkšiai freshwater ecosystem biota due to INPP discharges and radionuclide water pathway migration from a hypothetic radioactive waste disposal facility shows that the biota exposure dose rate due to background radionuclides significantly exceeds the impact of ionizing radiation of anthropogenic origin radionuclides, the probable and conservative exposure risk factors make up about 10 % of the screening value recommended in the European Union.

4. It has been established that out of all radionuclides in Lake Drūkšiai bottom sediments from the point of view of the total biota exposure ^{60}Co and ^{137}Cs can be regarded as dangerous, and the internal exposure dose rate value in separate cases is determined by ^{90}Sr and ^{54}Mn activity concentration in bottom sediments.

5. Out of reference organisms benthonic organisms (*Bivalvia mollusca, Crustacea, Gastropoda, Insectum larvae*) and *Tacheophytes* experience the largest exposure due to anthropogenic radionuclides in Lake Drūkšiai.

6. The annual internal effective dose of adults due to consumption of pelagic fish of the INPP cooling pond, Lake Drūkšiai, is of the order of some μSv and is the most dependent on the radionuclide ^{40}K.

2. HUMAN DOSE ASSESSMENT IN THE VICINITY OF THE RADIOACTIVE WASTE REPOSITORY BASED ON PROBABILISTIC UNCERTAINTY ANALYSIS

The primary design goal of the radioactive waste disposal facility is to provide the protection of human health and environment in the long term after the facility is closed and until the time when the associated radiological hazard will reach an insignificant level. Radioactive waste needs to be safety managed in a regulated manner, compatible with internationally and nationally agreed principals and standards. For events at the repository in the post-closure phase the appropriate fraction, termed the dose constraint, determined by the National regulatory body is 0.2 mSv per year [3].

The storage of radioactive waste (Fig. 1) formed in industry, medicine and scientific investigations in a near-surface special Maišiagala radioactive waste repository was started in 1963. Waste was transported not only from Lithuania but also from neighboring Kaliningrad and Gardin regions till 1988. The ferroconcrete vault partly filled with waste was sealed up and sanded in 1989, and newly-generated radioactive waste was directed at the disposal facility of the INPP. Though a comparatively small amount of radioactive waste (only about 120 m^3) is stored, but it has not been sorted out: the long-lived high-level radioactive waste is placed together with the short-lived low-level radioactive waste. The total activity concentration of long-lived alpha radionuclides (Pu and Ra isotopes) reaches 3 kBq/g and exceeds the set limit.

Due to high mobility of hydrogen atoms, tritium is the first radionuclide released from the radioactive waste repository. This is also confirmed by the monitoring data of the environment of this radioactive waste repository. The largest tritium migration from the repository to the groundwater, when the activity concentration of tritium exceeded 10 kBq/l, was determined in the region of boreholes 4, 41 and 42 (Fig. 1). A significant decrease in 2006 can be related to the reconstruction of protective engineering barriers.

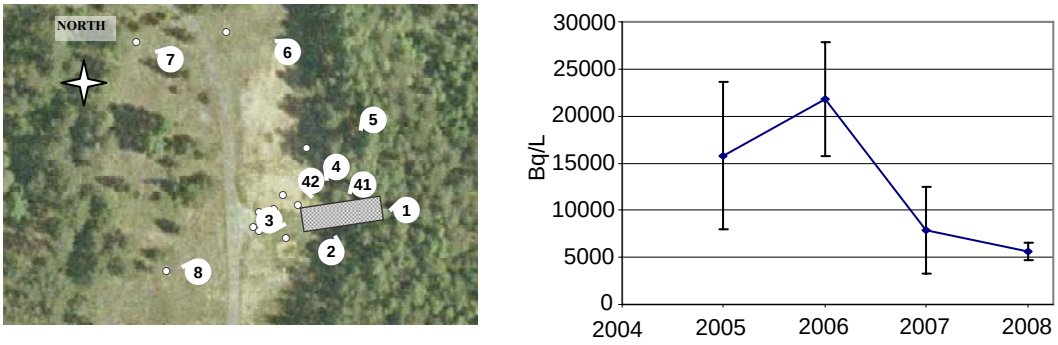


Fig. 1. Location of the near-surface radioactive waste repository together with monitoring boreholes (left) and tritium activity concentration time-dependent fluctuations in water of borehole 4 [2] (right).

The aim of this work is to assess the changes of radionuclide migration from the radioactive waste repository through the water pathway and human exposure due to the reconstruction of protective engineering barriers by applying the deterministic and stochastic approximations taking into account the radiation protection criteria established in the Republic of Lithuania**.**

The migration of radionuclides to the environment and consequent human exposure may occur in connection with slow degradation of repository barriers due to natural

processes. The further transfer through underground water is presently the main route for radionuclides to migrate from the repository to the environment. The monitoring locations as presented in Fig.1 (10 installed observation boreholes) allow detecting any significant migration of contaminants to groundwater, provision monitoring of ambient radiation levels and human dose assessment.

2.1. HUMAN DOSE ASSESSMENT METHODOLOGY

2.1.1. RESRAD-OFFSITE computer code and site-specific parameter values

RESRAD-OFFSITE model and code [8] have been developed in U.S. Department of Energy, Argonne National Laboratory. The RESRAD-OFFSITE model of the radionuclide migration via the water pathway assesses the radionuclide penetration into the unsaturated zone by infiltration through the repository engineering and natural barriers as well as their further transfer to the aquifer through the water embedded in soil pores. In the case when only single-measure (longitudinal) hydrodynamic dispersion in the unsaturated zone and the aquifer is assessed not taking into account a possible decrease of the radionuclide activity concentration in water due to lateral and vertical dispersion, the human exposure is assessed in a conservative way. The computer program RESRAD-OFFSITE makes it possible to assess the groundwater migration in the three-dimensional space taking into account longitudinal, lateral and vertical dispersion.

Radionuclides migrate in the aquifer through the groundwater in the prevailing direction due to advection-dispersion processes. Eventually, radionuclides reach the biosphere, where having penetrated into the drinking-water well or bore become a potential source of human exposure. In the RESRAD-OFFSITE code, simulations of 109 parameter collections, in most cases and their distributions, have been used. Successive RESRAD-OFFSITE human exposure pathways were considered: 1) direct exposure from contamination in soil, 2) inhalation exposure can occur from inhalation of airborne radionuclides, 3) ingestion pathways consist of ingestion of plant food, meat and milk from local farming.

Accumulation in plants is computed by using:

$$p_i(t) = rtf_i s_i^o(t) . \quad (1)$$

Here $p_i(t)$ is the activity concentration of contaminant *i* in plants, rtf_i is the root uptake factor of contaminant *i* for plants, $s_i^o(t)$ is the activity concentration of contaminant *i* in off-site soil.

Transfer and accumulation of contaminants in meat and milk due to ingestion of contaminated plants, incidental ingestion of soil with plant feed, and consumption of contaminated livestock water are considered. These are computed by using:

$$m_i(t) = imf_i \; [q_{ing}^p \, p_i(t) + q_{ing}^s s_i^o(t) + f_a \, f_{cd}(t) \;\; q_{ing}^s \;\; s_i(t) + q_{ing}^w \;\; w_i^{ls}(t)] \,. \qquad (2)$$

Here imf_i is the daily intake to equilibrium/slaughter concentration in the meat/milk factor, q_{ing}^p is the quantity of plant feed ingested per day, $p_i(t)$ is the activity concentration of contaminant *i* in plants, q_{ing}^s is the quantity of soil ingested with the plant feed per day, $s_i^o(t)$ is the activity concentration of contaminant *i* in off-site soil, $s_i(t)$ is the activity concentration of contaminant *i* in on-site soil, q_{ing}^w is the quantity of water consumed per day, $w_i^{ls}(t)$ is the activity concentration of contaminant *i* in livestock water, f_a is the fraction of the agricultural area that lies directly above the primary contamination.

The dose conversion factor values used for dose assessment are taken from ICRP publication 72.

2.1.2. Probabilistic uncertainty and sensitivity analysis of parameters

For evaluation of uncertainties in decision making the RESRAD-OFFSITE computer code was used to estimate the radiological consequences to the receptor. It calculates radiological doses based on predicted radionuclide concentrations in the environment.

In order to assess the contribution of separate parameters to the exposure dose the computer program RESRAD-OFFSITE provides the possibility of investigating uncertainties and sensitivity of the model results using the regresion analysis. The contribution of more than 100 model parameters to the exposure dose was evaluated. As several statistical methods of the sensitivity analysis are known, it is useful not only to choose a proper method but also to compare the obtained results with those obtained by other methods. In this case a partial rank coefficient of correlation, the standardized rank

regression coefficient, a partial correlation coefficient and the standardized regression coefficient were determined.

The presented values of stochastic variables show that the main parameters describing the radionuclide dispersion causing the exposure dose are related to the aquifer lateral dispersion, the hydraulic gradient and hydraulic permeability, the precipitation amount, the radionuclide activity concentration and the constant of penetration into the environment. The presented uncertainty data determine the limits of the annual effective dose variation. The main determined parameters along with the values of stochastic variables in the case of ^{3}H are presented in Table 1.

Table 1. Values of main parameters probability variables determining the exposure dose in case of ^{3}H (distance from the well to the Maišiagala repository – 500 m).

Description of probabilistic variables	PRCC	SRRC	PCC	SRC
Horizontal lateral dispersivity of saturated zone to well	-0.97	-0.79	-0.61	-0.48
Leach rate of ^{3}H	0.91	0.41	0.57	0.42
Hydraulic gradient of saturated zone to well	-0.73	-0.20	-0.32	-0.20
Concentration of ^{3}H	0.72	0.19	0.35	0.22
Hydraulic conductivity of saturated zone	-0.59	-0.13	-0.34	-0.21
Thickness of contaminated zone	0.56	0.12	0.21	0.13
Precipitation amount	0.44	0.09	0.14	0.09

Here PRCC is the partial rank correlation coefficient, SRRC is the standardized rank regression coefficient, PCC is the partial correlation coefficient, SRC is the standardized regression coefficient.

The RESRAD-OFFSITE code performs probabilistic analysis to study the influence of the main site-specific physical, hydrological, meteorological, human consumption and farming parameters with corresponding distributions. Examples are presented in Fig. 2 and Fig. 3.

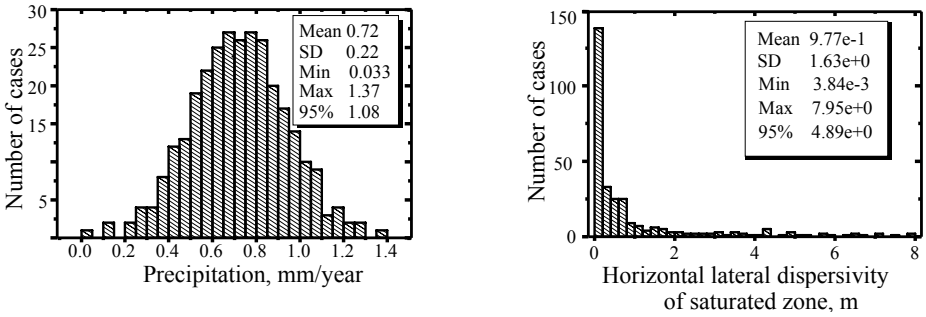


Fig 2. Examples of site-specific meteorological and hydrological parameters identified by means of RESRAD-OFFSITE probabilistic simulation in the case of dose assessment.

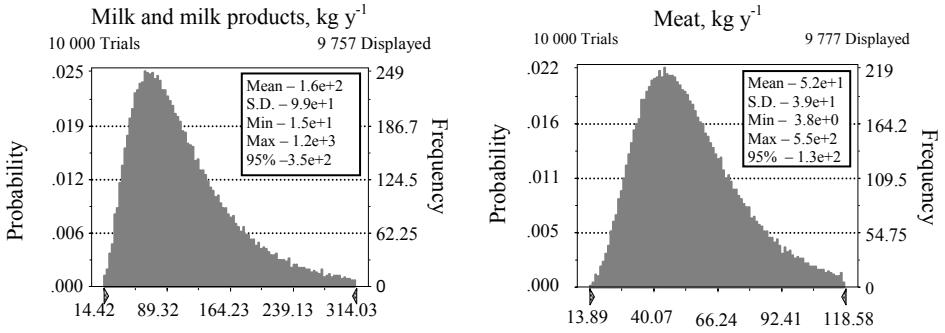


Fig 3. Examples of site-specific human food consumption rate distributions.

2.2. HUMAN DOSE ASSESSMENT RESULTS AND DISCUSSIONS

2.2.1. Radionuclide release scenarios

When assessing the radionuclide migration and forecasting the human exposure in the environment of repositories the scenarios can be created and chosen in some different ways. For the assessment of human exposure out of the scenarios presented in the IAEA document [9] the scenario of the radionuclide leaching from the repository after the closure of facility has been adopted. Successive RESRAD-OFFSITE human exposure pathways were considered in this work: direct exposure from contamination in soil, ingestion of plant food, meat and milk from local farming. The water the individual drinks and uses can be drawn from a well located at a different distance.

In this work a very conservative scenario of drinking-water (also used for farming) from the largest contamination well and two scenarios of possible development of the repository (scenario A – naturally degrading repository barriers and scenario B – new protective engineering barriers of the repository) were analyzed.

2.2.1a. Conservative drinking-water scenario

Referring to the presented experimental data the annual effective exposure dose of adult and children was evaluated by applying the most conservative scenario of groundwater from borehole 4 (Fig. 1), when water is used for drinking and farming. In the exposure dose assessment special attention was paid to the parameters of annual site-specific main food products and drinking-water consumption. In this work the assessment of the annual effective dose variation, when the drinking-water source is at the 100 m, 500 m and 2.5 km distance from the closed radioactive waste repository, taking into account site-specific parameter values, has been performed. The results of assessment of radionuclide migration through the water pathway by the RESRAD-

OFFSITE computer code have shown that out of all stored radionuclides at the present time ^{3}H, ^{14}C and ^{36}Cl are regarded as dangerous from the radiation protection point of view. The time-dependent variation of the annual effective dose due to migration of these radionuclides through the water pathway is presented in Fig. 4.

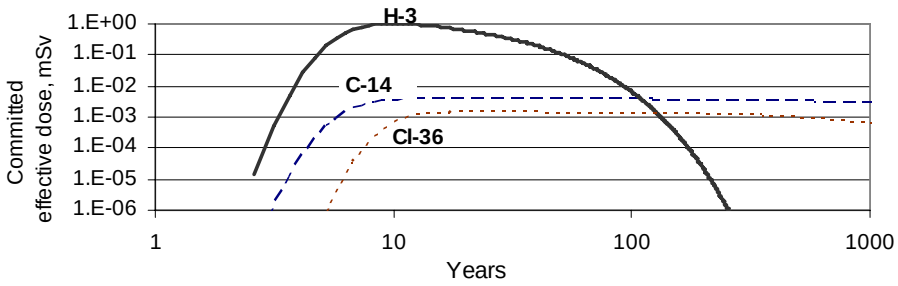


Fig 4**.** RESRAD-OFFSITE code simulated variation of the annual effective dose due to radionuclide migration through the water pathway when the water source (water used for drinking and farming) is at the distance of 500 m from the repository.

The contribution of separate exposure pathways to the annual effective doses in the case of ^{3}H, ^{14}C and ^{36}Cl is presented in Fig. 5 and Fig. 6.

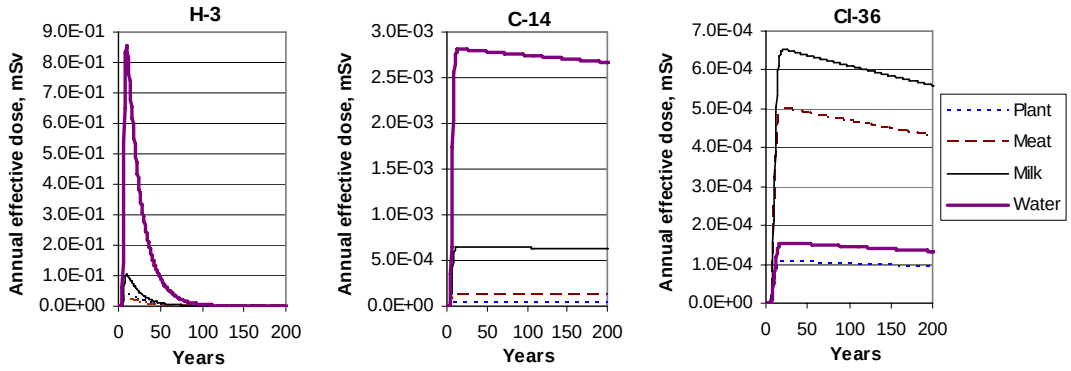


Fig 5**.** The time-dependent contribution of separate exposure pathways to the human annual effective doses in the case of ^{3}H, ^{14}C and ^{36}Cl.

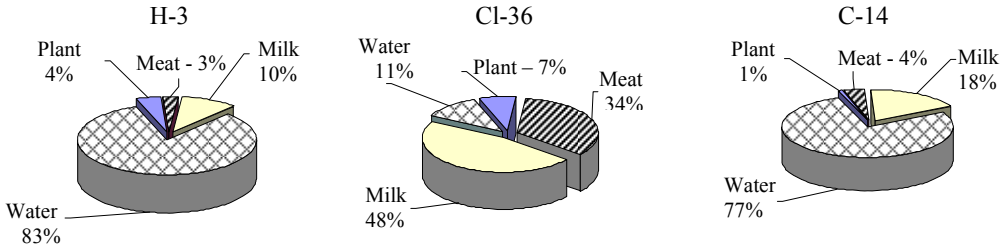


Fig. 6. The peculiarities of simulated human exposure by means of ^{3}H, ^{14}C and ^{36}Cl different pathways using water for drinking and farming from borehole 4 (Fig. 1).

The peculiarities of simulated human exposure by means of ^{3}H, ^{14}C and ^{36}Cl pathways demonstrate that in the case of ^{3}H and ^{14}C the dominant human exposure pathway is water contamination, in the case of ^{36}Cl – additionally milk and other food contamination.

2.2.1b. Human dose assessment scenarios based on probabilistic uncertainty estimation

Under the EU PHARE project the French companies THALES and ANDRA having much experience in radioactive waste management together with the Lithuanian Energy Institute and the Institute of Physics determined the technical state of the repository, analyzed the monitoring results and evaluated its safety [10]. One of the most significant results of the project is construction of additional protective engineering barriers: the system of two layers of very low permeability high density polyethylene (HDPE) membranes, the durability of which is not shorter than 30 years, was constructed on the ferroconcrete vault of the radioactive waste.

In this work the human dose assessment and evaluation of uncertainties in decision making were investigated in the case of Scenario A and Scenario B.

Scenario A - naturally degrading engineering barriers. Due to the natural aging of engineering barriers and their degradation the processes of radionuclide penetration into the environment from the repository through the water pathway were assessed.

Scenario B – reconstruction of protective engineering barriers. According to the project additional protective barriers were constructed over the radioactive waste vault in 2006. With the constant control and renewal of the membrane system an assumption is made about the unchanging radionuclide penetration into the environment through the engineering barriers till the end of the active institutional superintendence period.

RESRAD-OFFSITE site-specific analysis of committed effective doses together with upper and lower limits of uncertainty in the case of scenario A and scenario B are presented in Table 2. These data testify that the committed effective dose for members of the public in the case of repository radiological safety improvements (new capping system after the waste repository reconstruction) does not exceed a dose constraint of 0.2mSv per year [2] and maximal possible values do not exceed the national dose limit of 1 mSv per year for members of the public from all sources. Uncertainty analysis

presented in Table 2 demonstrates a possible variability of radiation protection criteria in decision making.

Table 2. Variation of main annual committed effective dose assessments by applying the stochastic approximation of radionuclide pathway in the environment and leaching through the repository barriers (scenarios A and B) when the drinking-water wells are at the distance of 500 m from the repository.

Radionuclide	Scenario A, annual committed effective dose, mSv				Scenario B, annual committed effective dose, mSv			
	Min	Max	Average	St. deviation	Min	Max	Average	St. deviation
	50 years after the repository closure							
^{3}H	5.34E-03	2.22E+00	2.02E-01	2.23E-01	3.77E-03	9.02E-01	8.89E-02	9.51E-02
^{14}C	3.22E-04	5.03E-02	6.38E-03	6.99E-03	1.29E-04	2.02E-02	2.80E-03	2.80E-03
^{36}Cl	1.21E-07	2.54E-02	2.62E-03	2.80E-03	4.57E-05	1.04E-02	1.08E-03	1.15E-03
Sum	7.57E-03	2.26E+00	2.11E-01	2.30E-01	4.67E-03	9.19E-01	9.28E-02	9.77E-02
	100 years after the repository closure							
^{3}H	5.56E-04	1.16E-01	1.22E-02	1.27E-02	2.26E-04	5.08E-02	5.17E-03	5.45E-03
^{14}C	3.19E-04	4.87E-02	6.85E-03	6.81E-03	1.28E-04	1.98E-02	2.76E-03	2.75E-03
^{36}Cl	1.08E-04	2.20E-02	2.44E-03	2.53E-03	4.50E-05	9.67E-03	1.04E-03	1.09E-03
Sum	1.67E-03	1.94E-01	2.70E-02	2.55E-02	5.68E-04	6.80E-02	8.96E-03	8.29E-03

It is evident that the reconstruction of protective engineering barriers of the closed radioactive waste repository in summer 2006 has significantly reduced the human exposure, which was assessed by applying a very conservative scenario of water consumption from the largest pollution well. Based on the monitoring data of 2007-2008 [2] and the exposure assessment it can be stated that at present the effective exposure dose is significantly lower compared with the dose constraint established in the Republic of Lithuania [3].

3. METHODOLOGY OF LAKE DRŪKŠIAI, INPP COOLING POND, BIOTA DOSE ASSESSMENT BASED ON PROBABILISTIC UNCERTAINTY ANALYSIS

The only nuclear power plant in Lithuania, the Ignalina NPP, is situated in the north-east of the country on the bank of Lake Drūkšiai, the largest Lithuanian water-body (Fig. 7). Lake Drūkšiai provided cooling water for the INPP. The two RBMK-1500 reactor units, Unit 1 and Unit 2, were put into operation in December 1983 and August 1987, respectively. Unit 1 was shut down on 31 December, 2004 and Unit 2 on 31 December, 2009.

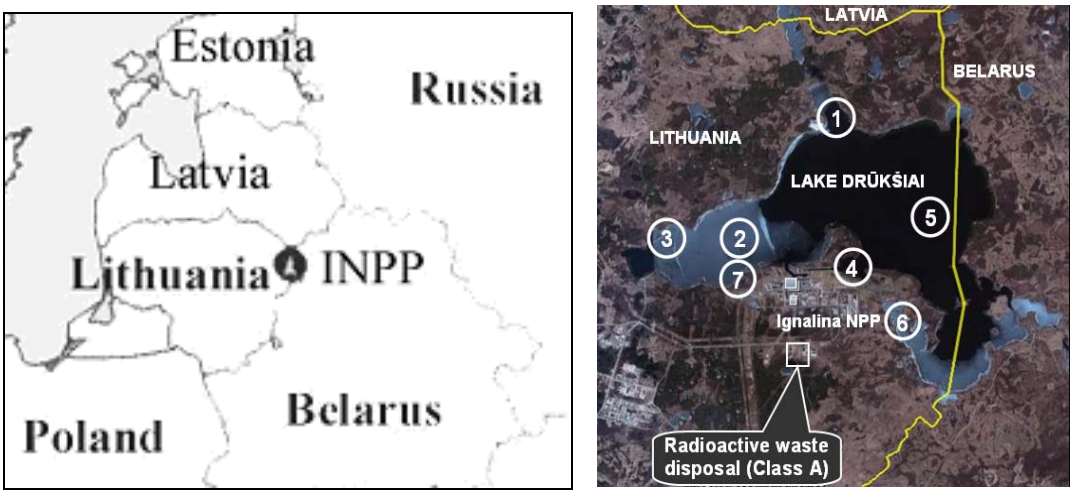


Fig. 7. The location of INPP (left) and sampling points in cooling pond, Lake Drūkšiai, (right) together with the hypothetical low level, near-surface, radioactive waste disposal facility.

The main task of this work is to estimate the radiological dose to freshwater non-human biota using the ERICA code [11], along with long-term data from the INPP Environment Monitoring Program [4-5]. This investigation also presents a comparison of the exposure of freshwater biota to natural background radionuclides relative to anthropogenic radionuclides discharged to Lake Drūkšiai.

3.1. BIOTA DOSE ASSESSMENT METHODOLOGY

3.1.1. ERICA computer code and risk quotient evaluation

ERICA Integrated Approach and ERICA Tool [11], which is a software program with supporting databases and special attention to the risk assessment, were used in this investigation. ERICA Integrated Approach is based on the approach of reference organisms, which are the default organisms included in the ERICA Tool. The exposure and risk assessment of Lake Drūkšiai freshwater ecosystem non-human biota reference organisms are based on previously collected activity concentrations of anthropogenic and background radionuclide measurement data [4-5].

The assessment and management of environmental risks from ionizing radiation are the second main output of the ERICA Integrated Approach and ERICA Tool. In terms of analysis of species sensitivity to radiation a universal screening dose rate criterion of 10 μGy/h incremental dose rate in the European Union is suggested for the assessment procedure being confident that environmental risks are negligible.

Risk quotient (the ratio of assessed value and screening value) characterization is the estimation of the probability and magnitude of adverse effects in biota, together with identification of uncertainties for the purpose of prioritizing risks as a basis for further actions.

The assessment element is organized in three separate Tiers, where satisfying certain criteria in Tiers 1 and 2 allow the user to exit the assessment process being confident that the effects on non-human biota are low or negligible, and that the situation requires no further actions.

Tier 1 estimates Risk Quotient (*RQ*) for radionuclide „n“ value taking into account values of Environmental Media Concentration Limits (*EMCL*):

$$RQ_n = \frac{M_n}{EMCL_n} \ , \tag{3}$$

Where M_n is the measured activity concentration in medium *M* in Bq/kg in sediments.

In the case $RQ < 1$, it can be assured that there is a very low probability that the assessed dose rate to any organism exceeds the incremental screening dose rates. In the case $RQ \geq 1$, ERICA Tier 2 assessment is necessary.

In **Tier 2** the estimated total dose rates for each reference organism included in the assessment are compared with the dose rate screening value. This produces a risk quotient for each radionuclide selected for inclusion in the assessment. The risk quotient is defined by:

$$\sum RQ_i = \frac{D_{sum}}{D_{\lim}} . \tag{4}$$

Here D_{sum} is the estimated total dose rate (μGy/h) for each reference organism; D_{lim} is the screening dose rate (10 μGy h^{-1}).

If the conservative *RQ* value is below 1 for all organisms, then the assessment does not exceed the screening value and the ERICA Tool will recommend the user to exit the Tier 3 assessment. In Lake Drūkšiai, IAE cooling basin, it is not necessary to use ERICA Tool Tier 3, as presented in Table 5.

3.1.2. Probabilistic uncertainty and sensitivity evaluation of site-specific parameter

The results of Lake Drūkšiai sediment survey to measure background activity concentrations of ^{232}Th and ^{238}U are presented in Fig. 8 histograms depicting the corresponding sediment activity distributions.

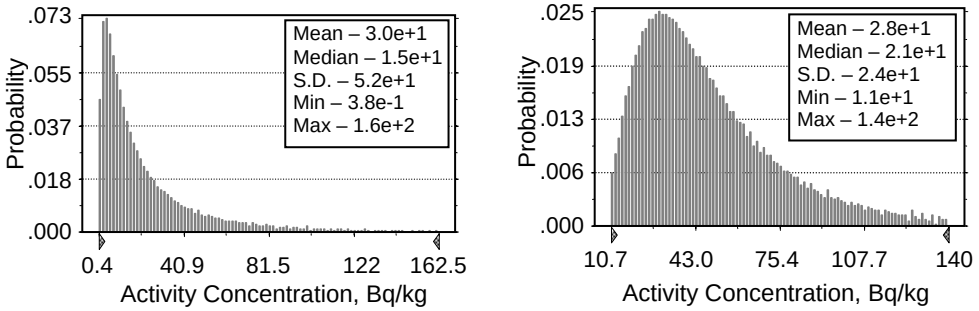


Fig. 8. The frequency distributions of ^{238}U (left) and ^{232}Th (right) in bottom sediments of Lake Drūkšiai [4-5].

There is a large range of anthropogenic radionuclides, which may need to be considered in non-human biota exposure assessments. The major investigated components of anthropogenic radionuclides discharged by INPP are ^{54}Mn, ^{60}Co, ^{137}Cs and ^{90}Sr. Examples of anthropogenic radionuclide frequency distributions in bottom sediments of Lake Drūkšiai are presented in Fig. 9.

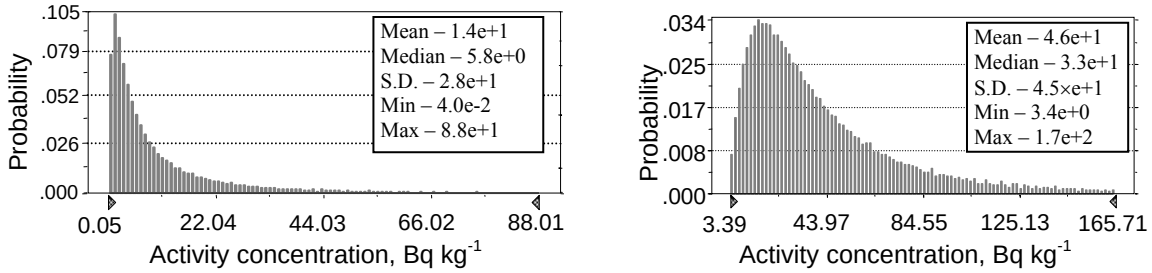


Fig. 9. The frequency distributions of corrosion products ^{54}Mn and ^{90}Co in bottom sediments of Lake Drūkšiai.

A statistical summary of the activity concentrations of background and anthropogenic radionuclides that were discharged into Lake Drūkšiai from the INPP in bottom sediments is presented in Table 3.

Table 3. Statistical summary of activity concentrations of background and anthropogenic radionuclides in the bottom sediments of Lake Drūkšiai based on data from the INPP environment monitoring program conducted during 1983 – 2006.

Nuclide	Mean	S.D.	Distribution	Min	Max	Reference
Background radionuclides						
^{238}U	30	22	TR	3.8	160	[4]
^{232}Th	28	24	LN	11	140	
^{40}K	500	210	LN	110	1100	
Anthropogenic radionuclides						
^{54}Mn	14	28	TR	0.04	88	[5]
^{60}Co	46	45	LN	3.4	170	
^{90}Sr	28	24	LN	2.2	88	
^{134}Cs	1.7	1.0	TR	0.26	7.8	
^{137}Cs	150	120	LN	13	440	
^{239}Pu	0.012	0.012	LN	0.008	0.014	

*LN- Lognormal; TR- Triangular

The models for calculation of dose rates implemented in the ERICA Tool allow performing sensitivity analyses using simple correlation coefficients between the inputs/parameters and the endpoints. In the present version of the tool, two correlation coefficients are computed every time a probabilistic simulation is carried out: the Pearson Correlation Coefficient (PCC) and the Spearman Rank Correlation Coefficient (SRCC). The PCC assumes a linear relationship between variables whereas the SRCC does not. Tool Sensitivity analysis is used to apportion the relative effect of the uncertain inputs and parameters on the variation and uncertainty of the simulation endpoints. Based on data of Lake Drūkšiai sediment anthropogenic radionuclide activity concentrations (1983 – 2006) and ERICA sensitivity analysis tool the anthropogenic sediment activity concentration impact on total dose rate values of mostly exposed reference organisms has been evaluated (Table 4).

Table 4. The results of sensitivity analysis based on Lake Drūkšiai sediment anthropogenic radionuclide activity concentrations (input data) and total dose rate values of most exposed reference organisms (output data).

	^{60}Co	^{137}Cs	^{54}Mn	^{90}Sr	^{239}Pu
PCC					
Tracheophyta	8.06E-01	5.96E-01	1.90E-01	1.36E-01	3.05E-02
Insectum larvae	8.02E-01	6.01E-01	2.24E-01	1.42E-01	2.97E-02
Gastropoda	8.36E-01	5.62E-01	2.33E-01	8.62E-02	3.03E-02
Crustacea	7.95E-01	6.08E-01	2.23E-01	1.49E-01	2.99E-02
Bivalvia mollusca	8.52E-01	5.36E-01	2.50E-01	7.15E-02	2.97E-02
SRCC					
Tracheophyta	7.37E-01	6.02E-01	2.26E-01	1.49E-01	4.28E-02
Insectum larvae	7.33E-01	6.06E-01	2.24E-01	1.54E-01	4.20E-02
Gastropoda	7.69E-01	5.75E-01	2.33E-01	9.93E-02	4.18E-02
Crustacea	7.26E-01	6.11E-01	2.23E-01	1.62E-01	4.23E-02
Bivalvia mollusca	7.87E-01	5.53E-01	2.50E-01	8.35E-02	4.07E-02

Based on presented data it is obvious that total dose rates of reference organisms are mostly dependent on ^{60}Co and ^{137}Cs- radionuclide sediment activity concentration values

3.1.3. Hypothetical low-level waste disposal facility and Lake Drūkšiai radionuclide activity concentration changes

After the closure of the INPP, additional waste generated during the decommissioning phase will need to be handled in compliance with the requirements of International Atomic Energy Agency governing solid radioactive waste management [12]. Therefore, a low-level, near-surface radioactive waste disposal facility (Fig. 7) is being proposed at a distance of about 1.5 km from Lake Drūkšiai to dispose the low-level radioactive waste.

The RESRAD-OFFSITE code was used to calculate the amount of radionuclides flowing into the surface water body (Lake Drūkšiai) using a mass balance approach to determine the activity concentrations in the surface water. The scenarios of leaching into Lake Drūkšiai include the infiltration flow rate through the facility, depending on the time and evolution of the facility engineering barriers and considering three possible states, as follows:

- intact over 50 years of control and at the infiltration rate of 5 mm/year;
- constant rate of degradation over the 50 to 300 year period of time at the infiltration rate of 50 mm/year;
- complete degradation over more than 300 years at the infiltration rate of 200 mm/year.

Based on this assessment, the potential long-term radiological hazard presented by the waste has been evaluated. The time-dependent radionuclide activity concentration changes in Lake Drūkšiai water are presented in Fig. 10.

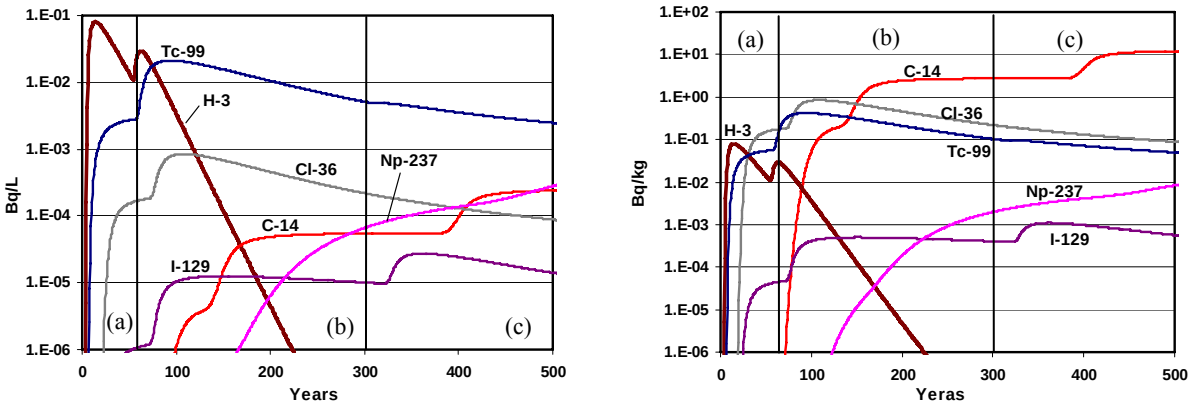


Fig. 10. Time-dependent changes in Lake Drūkšiai water radionuclide activity concentrations (a) and average annual specific activity of radionuclides in fish (b) for each of the three hypothetical infiltration scenarios: (a) infiltration rate – 5 mm/year, (b) infiltration rate – 50 mm/year, (c) – 200 mm/year.

3.2. BIOTA DOSE ASSESSMENT RESULTS AND DISCUSSION

3.2.1. Radiological exposure to non-human biota in Lake Drūkšiai

ERICA model predictions of total dose rates to reference organisms (Fig. 11-13) in Lake Drūkšiai are based on the summarized data from the environment monitoring program conducted between 1983 and 2006.

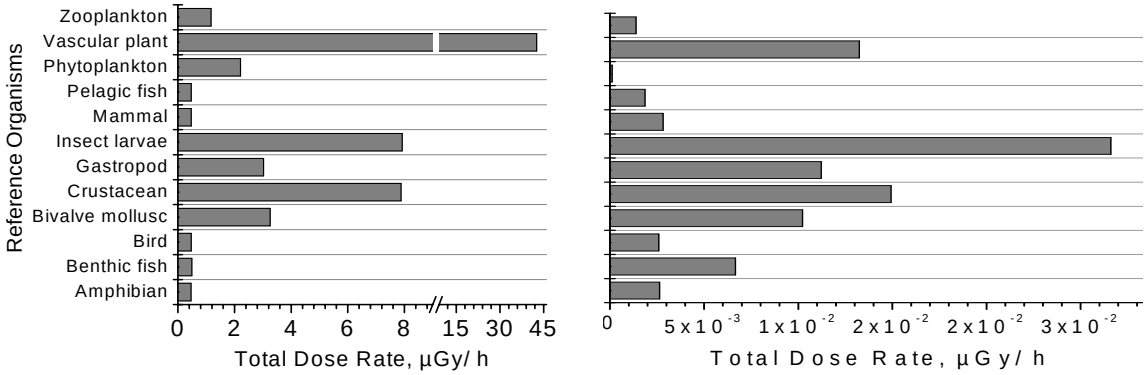
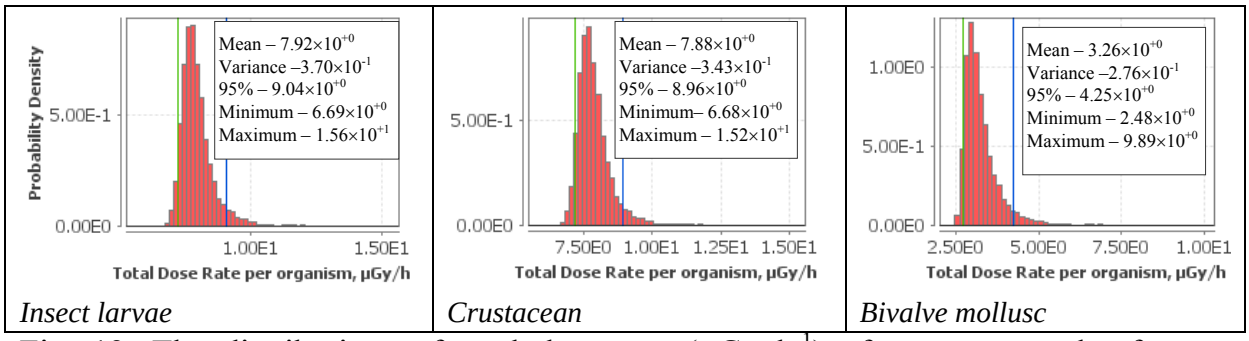
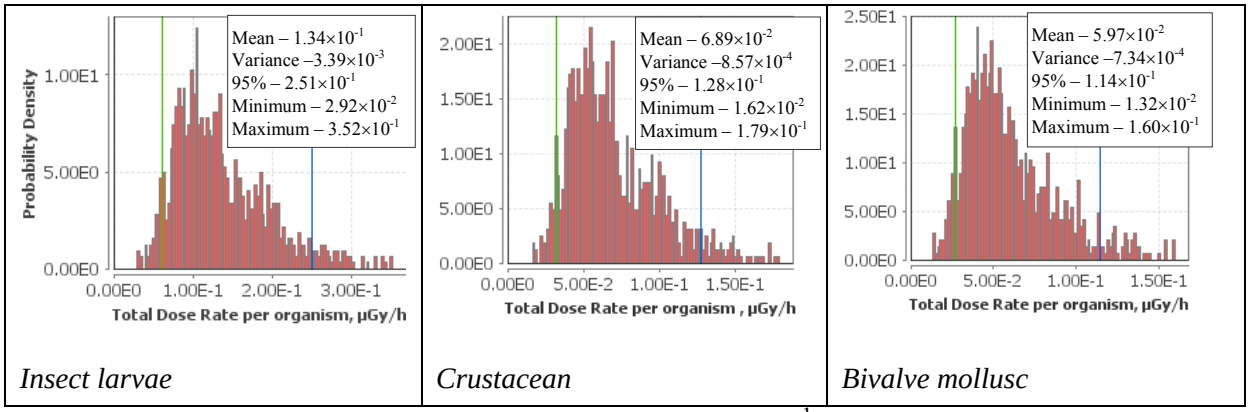


Fig. 11. The comparison of total dose rates to reference organisms from background radionuclides (left) and anthropogenic radionuclides (right) in Lake Drūkšiai.



Insect larvae *Crustacean* *Bivalve mollusc*

Fig. 12. The distributions of total dose rate (µGy h^{-1}) of most exposed reference organisms due to background radionuclides in Lake Drūkšiai.



Insect larvae *Crustacean* *Bivalve mollusc*

Fig. 13. The distributions of total dose rate (µGy h^{-1}) of most exposed reference organisms due to anthropogenic radionuclides in Lake Drūkšiai.

The exposure dose rate of reference organisms in Lake Drūkšiai due to the ionizing radiation impact of background radionuclides is higher than that due to anthropogenic ones. Out of all the investigated reference organisms, the largest exposure dose rate was determined for benthonic organisms (*Bivalvia mollusca, Crustacea, Gastropoda, Insectum larvae*). It should be noted that among them other reference organisms vascular plants undergo the largest exposure.

3.2.2. Background and anthropogenic radiological exposure to benthic fish in Lake Drūkšiai

Relying on data presented in [5], up to now Lake Drūkšiai continues to be a high-productivity water body with intensive angling. In this connection the corresponding percentage contributions of different radionuclides to the estimated internal and external dose rates to the reference organism pelagic fish from key Lake Drūkšiai radionuclides are provided in Fig. 14.

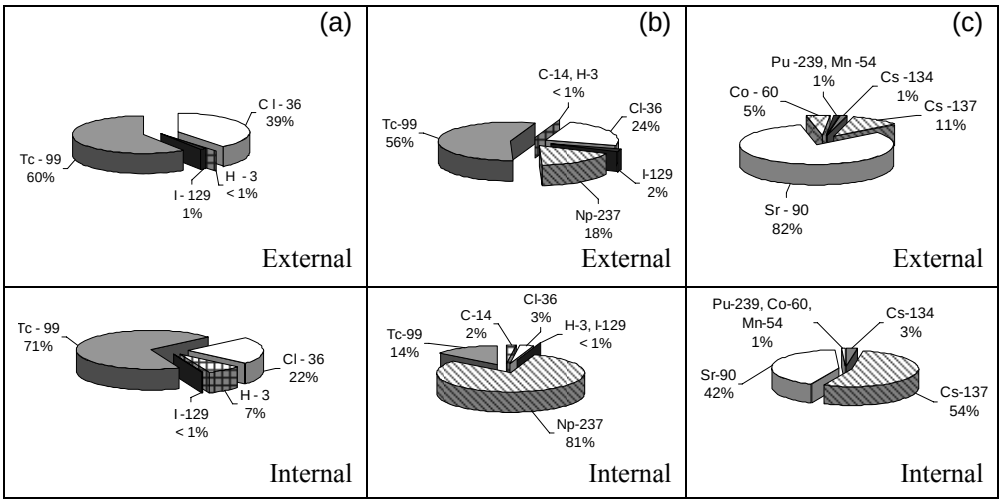


Fig. 14**.** The percentage of internal and external dose rates to the reference organism pelagic fish from key radionuclides discharged into Lake Drūkšiai from the INPP (a) and hypothetical near-surface low level radioactive waste disposal facility: (b) - intact time 50 years, (c) - intact time longer than 300 years.

As regards the fishery and corresponding committed effective human dose assessment as a result of fish consumption, Lake Drūkšiai continues to be a high-productivity water body with intensive angling and possible commercial fishing. The distributions of ingestion doses as a result of fish consumption from the key radionuclides, discharged from INPP (Fig. 15) demonstrate that annual doses would be as small as some $\mu Sv\ y^{-1}$.

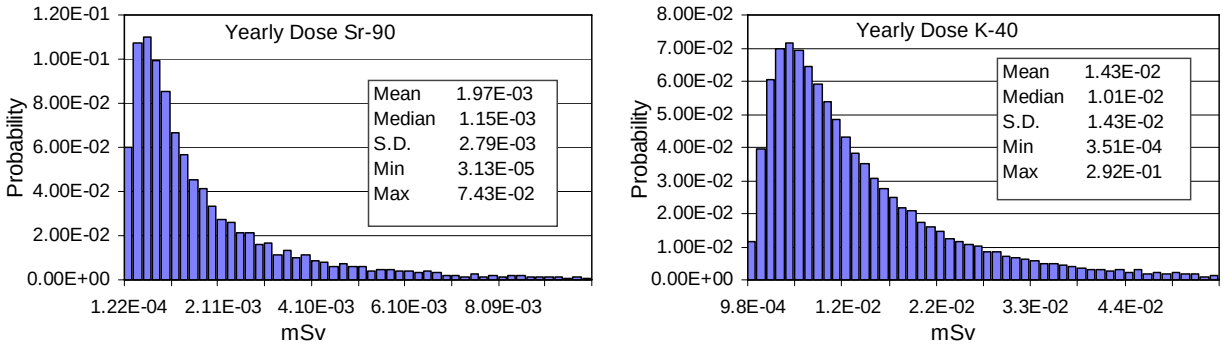


Figure 15. The radionuclide dependent distributions of adult human annual committed effective doses as a result of Lake Drūkšiai pelagic fish consumption based on probabilistic uncertainty estimation.

These results demonstrate that the total predicted human annual effective doses expected to be received due to consumption of Lake Drūkšiai pelagic fish are mostly attributable to the background radionuclide ^{40}K.

3.2.3. Hypothetical near-surface low-level waste disposal facility releases to Lake Drūkšiai and radiological exposure of reference organisms

The most important nuclides to be evaluated with respect to radionuclide migration and release to Lake Drūkšiai and the subsequent radiological exposure to reference organisms over the 100-year period of institutional control include ^{3}H, ^{99}Tc, ^{36}Cl (as prevailing during the first period of time up to 100 years) and ^{237}Np later. Total dose rates predicted by ERICA Tool which would be hypothetically received by reference organisms in Lake Drūkšiai due to the main released radionuclides are presented in Fig. 16.

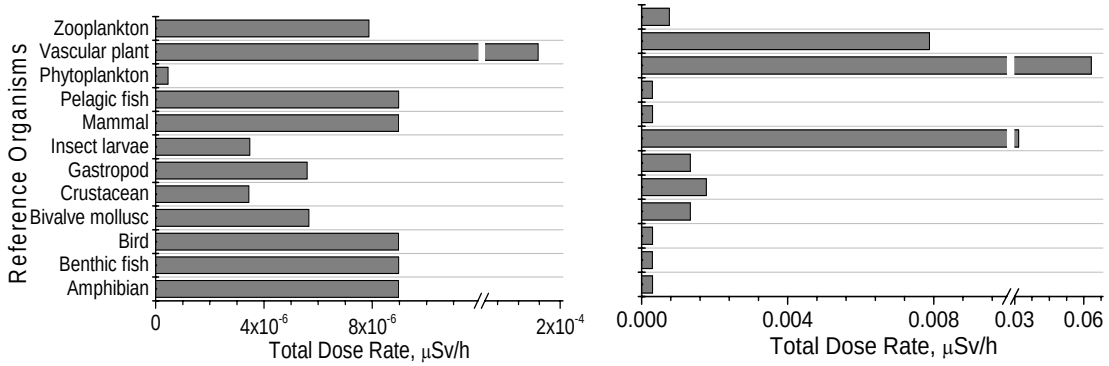


Fig. 16. The total dose rates hypothetically received by Lake Drūkšiai reference organisms due to radionuclides released from low level waste disposal facility: in the case of 50-year period and infiltration rate of 5 mm/year (left) and 300-year period with infiltration rate of 200 mm/year (right).

3.4. THE SUMMARY OF LAKE DRŪKŠIAI REFERENCE ORGANISM DOSE RATE AND RISK QUOTIENT ASSESSMENT BASED ON ENVIRONMENTAL MONITORING DATA

The data presented enlarge the knowledge about the concentration of radionuclides in European freshwater ecosystems in order to understand the internal and external exposure dose rates to reference non-human organisms from background radioactivity relative to anthropogenic contributions (Fig. 17).

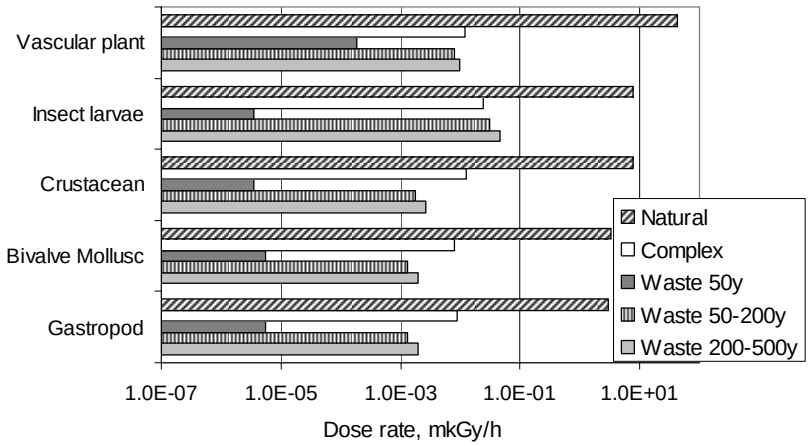


Figure 17**.** The comparison of dose rates to freshwater biota reference organisms from background, complex anthropogenic radionuclides from INPP and time-dependent radionuclides hypothetically to be discharged to Lake Drūkšiai from the low-level, near-surface radioactive waste disposal facility.

The presented data demonstrate that total dose rates to Lake Drūkšiai reference organisms exposed to anthropogenic radionuclides discharged from the INPP and the hypothetical low-level radioactive waste disposal facility are substantially lower than those expected from the natural background radioactivity.

Risk characterization is the final phase of the ecological risk assessment and is the culmination of planning, problem formulation, and analysis of predicted or observed adverse ecological effects related to the assessment endpoint. Conclusions presented in the risk characterization should provide clear information to risk managers to be useful for environmental decision making. Risk quotient (the ratio of assessed value and screening value) characterization is the estimation of the probability and magnitude of adverse effects in biota, together with identification of uncertainties for the purpose of prioritizing risks as a basis for further actions. Risk quotient assessment of Lake Drūkšiai reference organisms based on monitoring data [4-5] is presented in Table 5.

Table 5. Dose rates of Lake Drūkšiai most exposed reference organisms due to anthropogenic radionuclide ionizing radiation together with the expected and conservative risk quotient value assessment based on environmental monitoring data.

Organism	Total Dose Rate, μGy h^{-1}	Screening value, μGy h^{-1}	Risk Quotient (expected value)	Risk Quotient (conservative value)
Bivalvia mollusca	0.062724	10	0.006272	0.018817
Crustacea	0.072106	10	0.007211	0.021632
Gastropoda	0.065233	10	0.006523	0.019571
Insectum larvae	0.142446	10	0.014245	0.042734
Traheophyta	0.070464	10	0.007046	0.021139

The presented data testify that the expected and conservative risk quotient values of Lake Drūkšiai biota reference organisms comprise no more than 10% of the European Union recommended 10 μGy/h incremental dose rate suggested for the assessment procedure being confident that environmental risks are negligible. It should be stressed likewise that the total predicted doses expected to be received by Lake Drūkšiai reference organisms are mostly attributable to background radionuclides. Based on the presented data, it can be concluded that the radiological protection of non-human biota in Lake Drūkšiai, the Ignalina NPP cooling pond, is both feasible and acceptable, thus, supporting the viability of the progression of nuclear power engineering in Lithuania. The Ignalina NPP operational history and the routine radiation in environment monitoring data evidenced that INPP was operated safely and helpfully for the society from the biota radiation protection point of view. However, environmental changes in Lake Drūkšiai related mostly to the chemical, thermal and general urbanization pressure are unavoidable and acceptable from the society point of view for electric power industry development.

4. CONCLUSIONS

1. Based on the evaluation results of human exposure by applying the probabilistic uncertainty analysis methods introduced in the RESRAD-OFFSITE program and taking into consideration the selected scenarios and parameter uncertainties, it has been determined that in the environment of the Maišiagala repository after installation of additional protective barriers, the annual effective human exposure dose is significantly lower as compared to the annual limited dose of 0.2 μSv determined in the environment

of nuclear power engineering objects and 95th percentile does not exceed the exposure of 1 mSv per year regulated in the main human radiation protection standards in the Republic of Lithuania.

2. In case of the near-surface Maišiagala repository of radioactive waste, after evaluation of the radionuclide migration and human exposure uncertainties by applying the correlation and regression analysis introduced in the RESRAD-OFFSITE program it has been determined that the saturated zone horizontal lateral dispersivity, the hydraulic gradient and hydraulic conductivity of saturated zone, the precipitation amount and water consumption have the largest impact on the human annual effective doses.

3. The analysis of the obtained data has shown that out of all radionuclides taken for storage in the environment of the Maišiagala repository ^{3}H and ^{14}C are regarded as dangerous (the largest exposure is related to drinking-water) together with ^{36}Cl (the largest exposure due to consumption of local food).

4. The exposure dose rate of reference organisms of Lake Drūkšiai, the INPP cooling pond, biota (evaluated using the ERICA code) due to INPP discharges and water pathway radionuclide migration from a hypothetic Stabatiškės radioactive waste disposal facility shows that the dose rate due to the impact of ionizing radiation of anthropogenic radionuclides does not exceed the screening value of 10 μGy/hour recommended in the European Union.

5. Among reference biota organisms, the benthonic organisms (*Insectum larvae, Crustacea, Bivalvia mollusca, Gastropoda*) and vascular hydrophytes (*Tracheophytes*) of Lake Drūkšiai experience the largest exposure.

6. The analysis of the obtained data has shown that out of all radionuclides in Lake Drūkšiai bottom sediments after termination of the Ignalina NPP operation, from the biota total exposure point of view ^{60}Co and ^{137}Cs are regarded as dangerous, and the internal exposure dose rate value is also mostly caused by ^{90}Sr activity concentration in bottom sediments.

7. The internal annual effective exposure dose of adults due to consumption of fish from the INPP cooling pond, Lake Drūkšiai, is of the order of several *μSv*. Based on these data it can be stated that from the point of view of human radiation protection amateur fishing in Lake Drūkšiai is possible.

8. It has been determined that the Ignalina NPP cooling pond, Lake Drūkšiai, in case of necessity and from the point of view of biota radiation protection (natural background exposure significantly exceeds the anthropogenic one, and conservative risk factors make up about 10 % of the regulated limited value of risk factors proposed in the European Union) can be used for further development of nuclear power engineering taking into account a possible impact of temperature, chemical contamination and other factors.

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REZIUMĖ

Iki pastarojo laikotarpio daugiausiai dėmesio buvo skirta žmogaus radiacinei saugai: tiriamas jonizuojančiosios spinduliuotės poveikis, įteisinti norminiai aktai reglamentuojantys žmonių apšvitą tarptautiniame ir nacionaliniame lygiuose. Šiuo metu tiek Europos Sąjungos, tiek ir daugelis kitų tarptautinių ir nacionalinių organizacijų vis daugiau dėmesio skiria aplinkos ir skirtingų ekosistemų (sausumos, gėlavandenės ir jūrinės) biotos radiacinei saugai. Rio Deklaracijoje 1992 m. išdėstytos pagrindinės aplinkos radiacinės saugos nuostatos, apibrėžta koncepcija, kad aplinkos radiacinė sauga turi būti įteisinta ir nagrinėjama atskirai nuo žmonių radiacinės saugos.

Lietuvoje nėra norminių aktų, reglamentuojančių biotos apšvitą. Bet šiuo metu Europos Sąjungoje rekomenduojama didžiausia galima biotos apšvitos dozės galia - 10 μGy/h.

Šio darbo tikslas – nustatyti, apibūdinti ir įvertinti galimą jonizuojančiosios spinduliuotės poveikį visuomenės sveikatai ir aplinkai (tame tarpe gyvūnijai ir augalijai) branduolinės energetikos objektų aplinkoje (Maišiagalos radioaktyviųjų atliekų saugyklos atveju - vertinant galimą poveikį žmogui, ir Ignalinos AE (IAE) aušintuvo Drūkšių ežero atveju - vertinant galimą poveikį gėlavandenės ekosistemos biotai), taikant tikimybinius metodus; nustatyti, ar ši veikla, įvertinus jos pobūdi ir poveikį aplinkai, atitinka Lietuvos Respublikoje arba Europos Sąjungoje galiojančius standartus, yra leistina pasirinktoje vietoje dabartiniu laikotarpiu arba ateityje.

Darbe buvo taikomos 2 pagrindinės programos: RESRAD-OFFSITE ir ERICA. Minėtų kompiuterinių programų pasirinkimas nėra atsitiktinis. RESRAD-OFFSITE ir ERICA programos suteikia galimybę naudoti tyrimui pasirinktos vietovės vietines sąlygas atitinkančias parametrų verčių išbarstymą. Biotos ir žmonių apšvitos dozės galiai įvertinti programos naudoja tikimybinę (koreliacinę, regresinę, jautrio ir kt.) analizę. Vietoj gautų išvesties rezultato (apšvitos dozės) pavienių skaičių kaip deterministiniame skaičiavime, gauname verčių rinkinį (verčių skaičius atitinka iteracijų skaičių). Žmonių ir biotos apšvita, kuri yra už 95% pasikliautinumo ribos, yra svarbi, nes 5% žmonių arba biotos gali gauti didesnę apšvitos dozę, negu likusieji 95%.

Šiame darbe, galimi žmonių apšvitos nustatymo neapibrėžtumai, taikant tikimybinius metodus, buvo vertinami nagrinėjant radionuklidų sklaidą vandens keliu iš Maišiagalos paviršinės radioaktyviųjų atliekų saugyklos, remiantis 1989-2010 m. ataskaitose ir publikacijose paskelbtais Maišiagalos saugyklos aplinkos stebėsenos duomenimis. Buvo įvertinta dėl radionuklidų sklaidos vandens keliu metinės efektinės dozės galios kaita, naudojant du scenarijus: A scenarijus – iki naujų apsauginių barjerų įrengimo, B scenarijus – įrengus naujus apsauginius barjerus 2006 metais.

Biotos apšvitos neapibrėžtumai buvo nagrinėti vertinant IAE aušinimo baseino, tai yra Drūkšių ežero, radioekologinę būklę, prognozuojant radionuklidų jonizuojančiosios spinduliuotės biologinį poveikį florai ir faunai elektrinei veikiant ir nutraukus jos eksploatavimą bei įrengus hipotetinį radioaktyviųjų atliekų (Stabatiškės) kapinyną 1,5 km atstumu nuo ežero. Biotos apšvitos vertinimas buvo atliktas remiantis 1989-2008 m.m. Drūkšių ežero radioekologinių tyrimų duomenimis. Drūkšių ežero, IAE aušinimo baseino, biotos apšvitos vertinimas, gamtinės ir antropogeninės kilmės apšvitos palyginimas bei rizikos faktorių nustatymas leis padaryti išvadą apie šios gėlavandenės ekosistemos biotos apšvitos ypatumus. Įvertinta galimybė toliau ežerą taikyti žuvininkystei bei kitoms reikmėms, tame tarpe ir branduolinės energetikos vystymui.

Darbo naujumas:
Nustatyti sklaidos iš nagrinėtų saugyklų ir kapinynų potencialiai radiacinės saugos požiūriu reikšmingi radionuklidai (6), įvertintas apšvitos kelių (geriamasis vanduo, mityba) procentinis indėlis metinės efektinės dozės dydžiui. Pritaikius koreliacinę ir jautrio analizę, nustatyti inžinierinių barjerų radionuklidų sklaidą trimatėje erdvėje lemiantys radiacinės saugos požiūriu potencialiai reikšmingi modelio parametrai. Pirmą kartą, taikant tikimybinius metodus, įvertinta gėlavandenės ekosistemos IAE aušinimo baseino Drūkšių ežero standartizuotųjų organizmų apšvita gamtinių ir antropogeninių radionuklidų jonizuojančiąja spinduliuote. Nustatyta, kad, įrengus papildomus apsauginius barjerus, Maišiagalos saugyklos aplinkoje metinė efektinė gyventojų apšvitos dozė yra žymiai mažesnė lyginant su apribotosios dozės dydžiu, 95 procentilis nesiekia higienos normose patvirtintos 1 mSv per metus apribotosios dozės dydžio. Nustatyta, kad Drūkšių ežero biotos apšvitos dozės galia dėl antropogeninės kilmės radionuklidų jonizuojančiosios spinduliuotės poveikio, laukiamasis ir konservatyvusis apšvitos rizikos faktoriai neviršija Europos Sąjungoje siūlomo reglamentuojamojo lygio.

Nustatyta, kad IAE aušintuvas - Drūkšių ežeras biotos radiacinės saugos požiūriu galėtų būti naudotinas tolimesniam branduolinės energetikos vystymui, įvertinus galimas cheminę ir šiluminę taršą.

Žmonių apšvitos metinė efektinė dozė dėl suvartotos maistui IAE aušintuvo Drūkšių ežero žuvies yra kelių *μSv* eilės. Remiantis šiais duomenimis galima teigti, kad žmonių radiacinės saugos požiūriu Drūkšių ežere mėgėjiška žuvininkystė yra galima.

Remiantis žmonių apšvitos vertinimo rezultatais, taikant RESRAD-OFFSITE programoje įdiegtus tikimybinės analizės metodus, galima teigti, kad Maišiagalos saugyklos aplinkoje, įrengus papildomus apsauginius barjerus, gyventojų metinė efektinė apšvitos dozė yra žymiai mažesnė lyginant su branduolinių objektų aplinkoje nustatytuoju metiniu 0,2 μSv apribotosios dozės dydžiu, 95 procentilis neviršija Lietuvos Respublikoje pagrindinėse radiacinės saugos normose gyventojams reglamentuotos 1mSv metams apšvitos.

Paviršinės Maišiagalos radioaktyviųjų atliekų saugyklos atveju, įvertinus radionuklidų sklaidos vandens keliu ir žmonių apšvitos neapibrėžtumus, taikant RESRAD-OFFSITE programoje įdiegtą koreliacinę ir regresinę analizę, nustatyta, kad didžiausią įtaką gyventojų metinių efektinių apšvitos dozių vertinimui turi vandeningojo horizonto skersinė dispersija, vandeningojo horizonto hidraulinis gradientas ir hidraulinis laidumas, kritulių kiekis ir vandens vartojimas.

Iš visų saugojimui patikėtų radionuklidų Maišiagalos saugyklos aplinkoje pavojingais laikytini ^{3}H ir ^{14}C (didžiausia apšvita sietina su geriamuoju vandeniu) ir ^{36}Cl (didžiausia apšvita - dėl vietinės kilmės maisto produktų vartojimo).

Ignalinos AE aušintuvo Drūkšių ežero gėlavandenės ekosistemos biotos standartizuotųjų organizmų apšvitos dozės galia dėl IAE nuotekų ir radionuklidų sklaidos vandens keliu iš hipotetinio Stabatiškės radioaktyviųjų atliekų kapinyno, įvertinta taikant ERICA programą, rodo, kad apšvitos dozės galia dėl antropogeninės kilmės radionuklidų jonizuojančiosios spinduliuotės poveikio neviršija Europos Sąjungoje siūlomo reglamentuojamo 10 μGy/val. dozės galios lygio. Hipotetinio Stabatiškės kapinyno atveju, pavojingais radionuklidais laikytini: ^{14}C, ^{36}Cl, ^{129}I, ^{99}Tc, vėliau – ^{237}Np.

Standartizuotųjų biotos organizmų tarpe didžiausią apšvitą patiria Drūkšių ežero priedugnės zonos bentosiniai organizmai (I*nsectum larvae, Crustacea, Bivalvia mollusca, Gastropoda*) ir gysliniai hidrofitai (T*racheophytes*). Iš visų Drūkšių ežero dugno nuosėdų radionuklidų, nutraukus IAE darbą, biotos suminės apšvitos požiūriu pavojingais laikytini ^{60}Co ir ^{137}Cs, vidinės apšvitos dozės galios dydį lemia ir Sr-90 aktyvumo koncentracija dugno nuosėdose.

Radionuklidų patekimas į aplinką yra aktuali problema visose branduolinės energetikos ciklo grandyse. Siekiant įvertinti galimą jonizuojančiosios spinduliuotės poveikį gyventojų sveikatai, būtina įvertinti esamą bei galimą apšvitą, atsižvelgiant į parametrų kaitą ir neapibrėžtumus, nustatant vidutines, maksimalias apšvitos vertes bei 95 procentilius.