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Radiological and Environmental Effects in Ignalina Nuclear Power Plant Cooling Pond – Lake Druksiai: From Plant put in Operation to Shut Down Period of Time

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1. Introduction

Ignalina Nuclear Power Plant (INPP) is situated in the Northeastern part of Lithuania close to the borders with Latvia and Belarus at a Lake Druksiai utilized as cooling pond (Fig. 1). The two RBMK-1500 reactor units, Unit 1 and Unit 2, were put into operation in December 1983 and August 1987, respectively. Like Chernobyl NPP, the INPP was equipped by RBMK type reactors, i.e. channel-type, graphite moderated pressure tube boiling water nuclear reactors. The RBMK reactors belong to the thermal neutron reactor category each of a design capacity of 1500 MW(e). Unit 1 was shut down on December 31, 2004 and Unit 2 on December 31, 2009 (http://www.iae.lt).

Lake Druksiai is the largest lake in Lithuania and has its eastern margin in Belarus, where the lake is called Drisvyaty. The total volume of water is about 369 × 10^6 m^3 (water level altitude of 141.6 m). The total area of the lake, including nine islands, is 49 km^2 (6.7 km^2 in Belarus, 42.3 km^2 in Lithuania). The greatest depth of the lake is 33.3 m and the average is 7.6 m. The length of the lake is 14.3 km, the maximum width 5.3 km and the perimeter 60.5 km. Drainage area of the lake is only 613 km^2.

The water regime of Lake Druksiai is formed by interaction of natural and anthropogenic factors. The main natural factors are the climatic conditions of the region which determine the amount of precipitations onto the surface of the water reservoir and natural evaporation from the lake surface and watershed. The anthropogenic factors, which are mainly related with INPP operation, are water discharges by the hydro-engineering complex. The yearly amount of water discharged from INPP is 9 times the volume of the lake and 27 times the natural annual influx of water to the lake.

The aim of this study was to evaluate radiological and environmental effects of radioactive, chemical and thermal pollution in cooling pond of INPP (Lake Druksiai). Main efforts were given to assess the presumptive radioactive impact on the lake non-human biota, with special emphasize on macrophytes and fish communities. Macrophytes were selected as

appropriate biological indicators of changes in radioecological situation which comprise one of the largest biomass and able to intensive accumulate radioactive and other substances.

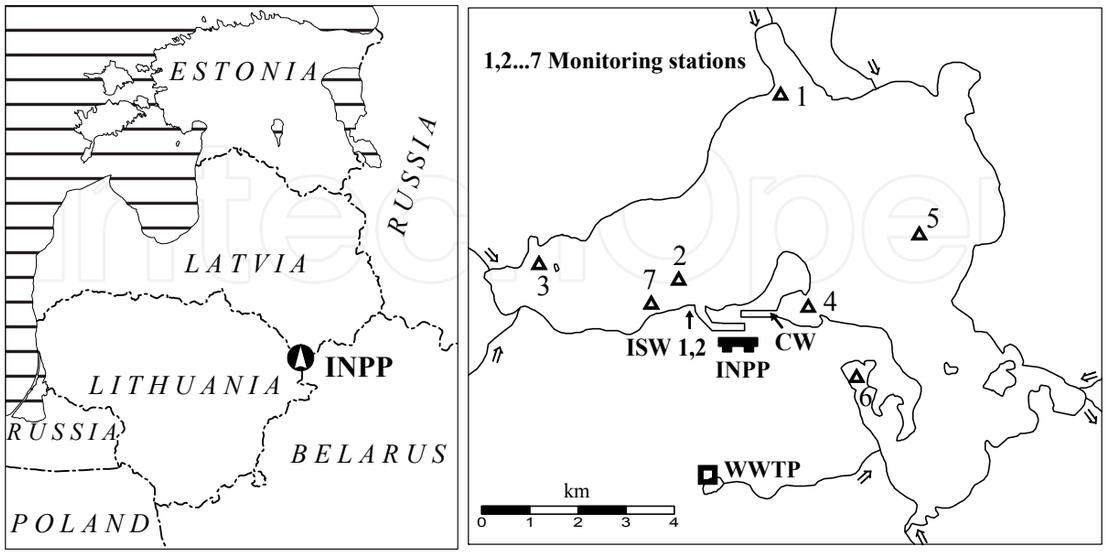


Fig. 1. The location of INPP (left) and permanent sampling (monitoring) stations, industrial storm water (ISW 1.2), cooling water (CW) and waste water treatment plant (WWTP) channels in Lake Druksiai (right)

The need for a systematic approach to the radiological assessment of non-human biota is now accepted by a number of international and national bodies (US DOE, 2002; ICRP, 2008). This requires the development and testing of an integrated approach where decision making can be guided by scientific judgments. The assessment of nuclear sites in context of comparison of non-human biota exposure due to discharged anthropogenic radionuclides with that due to background radiation is required and presented in this study.

2. Materials and methods

2.1 Lithuanian State research and academic institutions INPP environment investigations

The purpose of the environment investigation programmes (Lithuanian State Scientific Research Programme, 1998) was to detect INPP impacts, as they occur, to estimate their magnitude and ensure that they are the consequence of a well identified activity. The INPP environment investigation programs include all environmental exposure pathways that may exhibit long term concentration effects, such as in the case of the Lake Druksiai sediments. This investigation allows also the assessment of the effectiveness and mitigation of remedial measures and includes the follow-up of impacts and their verification against predictions. Samples of lake water, bottom sediments and non-human biota were collected and measured from the very beginning of INPP operation up to shut down period of time.

2.2 Anthropogenic radioactive pollution and natural-background radionuclides

The first stage in the distribution of radionuclides in freshwater ecosystem is quick and intense processes of accumulation of radionuclides in the bottom sediments. That stipulates the rather rapid decrease of the amounts of radionuclides in water. Therefore, data of

radionuclide activity concentrations in the water are insufficient in the assessment of the pollution of the freshwater ecosystem by radionuclides. Bottom sediments reflect the long-term pollution of Lake Druksiai by anthropogenic radionuclides.

This investigation amongst others presents the comparison of freshwater macrophytes and fish exposure due to discharged anthropogenic radionuclides (^{54}Mn, ^{60}Co, ^{90}Sr, $^{134;137}$Cs) with that due to semi-natural and background radionuclides (^{3}H, ^{14}C, ^{40}K, ^{210}Pb, ^{210}Po, ^{238}U, ^{226}Ra, ^{232}Th) mostly based on bottom sediments activity data accumulated during Lake Druksiai radiogeochemical mapping and other measurements, as presented in Fig. 2-4.

An assumption in the calculations was that the spatial distribution of investigated radionuclides in the INPP cooling-pond bottom sediments was uniformly distributed. However, the largest amounts of activated corrosion product radionuclides (^{54}Mn and ^{90}Co) coming from the INPP enter the lake with cooling waters (CW) and industrial stormwater discharge (ISW-1,2) outflows. The specific activity of activated corrosion products remains generally low in much of the lake and is concentrated especially close to the outflows (Fig. 3).

Frequency histograms depicting activity concentrations of some primary anthropogenic and naturally-occurring radionuclides in Lake Druksiai sediments are presented in Fig. 4.

Long-term radioecological investigations of Lake Druksiai showed that during the period of 1988–2008 the highest values of ^{137}Cs, ^{90}Sr, ^{60}Co and ^{54}Mn activity concentration in bottom sediments was estimated in 1988–1993 when both Units of INPP were operating. The tendency of decrease of the activity concentration of these most important radionuclides in the bottom sediments was observed from the beginning of 1996 (Fig. 5).

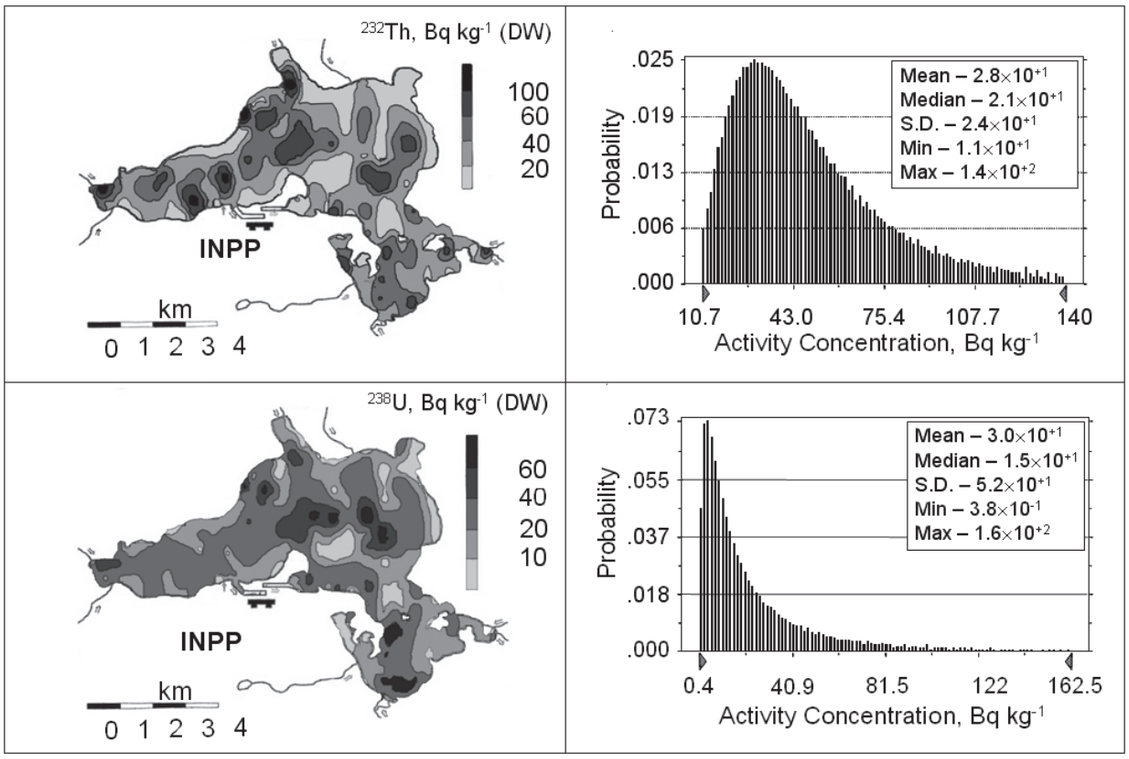


Fig. 2. The maps of spatial distributions (left) and frequency histograms (right) depicting activity concentrations of naturally-occurring background ^{232}Th and ^{238}U in Lake Druksiai sediments

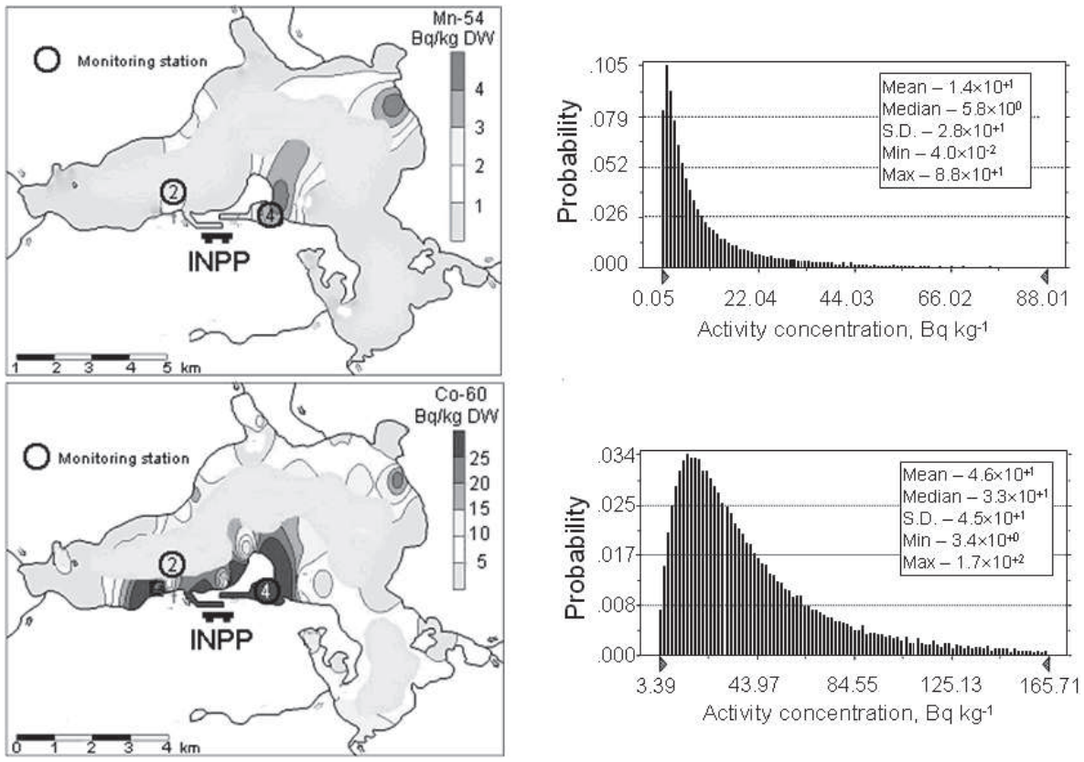


Fig. 3. The spatial pattern of activated corrosion products ^{54}Mn and ^{90}Co in bottom sediments (left) and frequency histograms (right) of Lake Druksiai. The highest activity concentrations corresponded the ISW-1,2 and CW sampling points

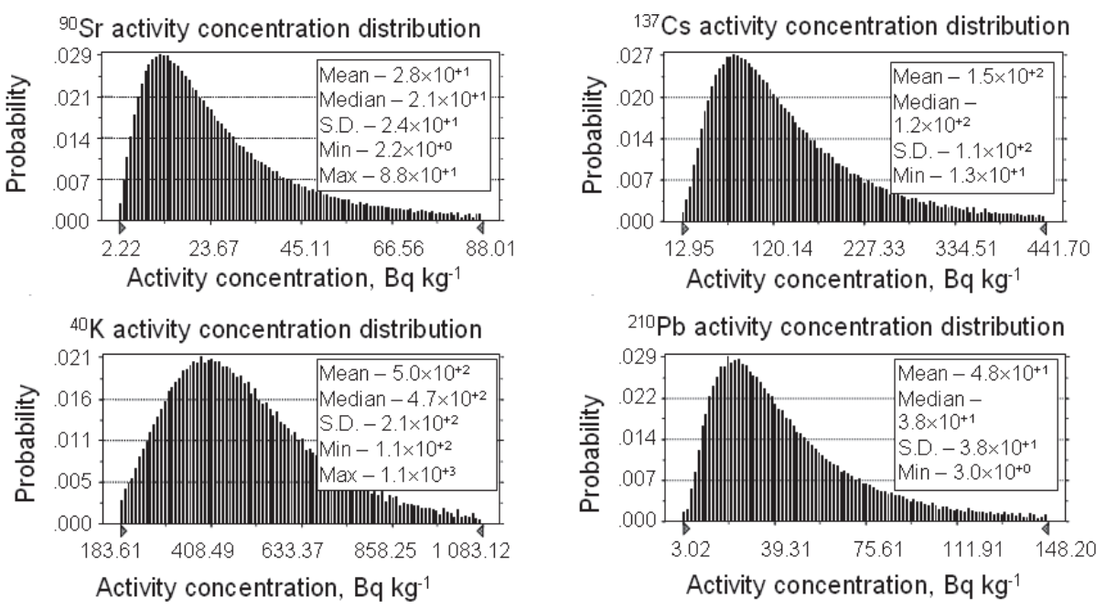


Fig. 4. Frequency histograms depicting activity concentrations of some anthropogenic and naturally occurring radionuclides in Lake Druksiai bottom sediment

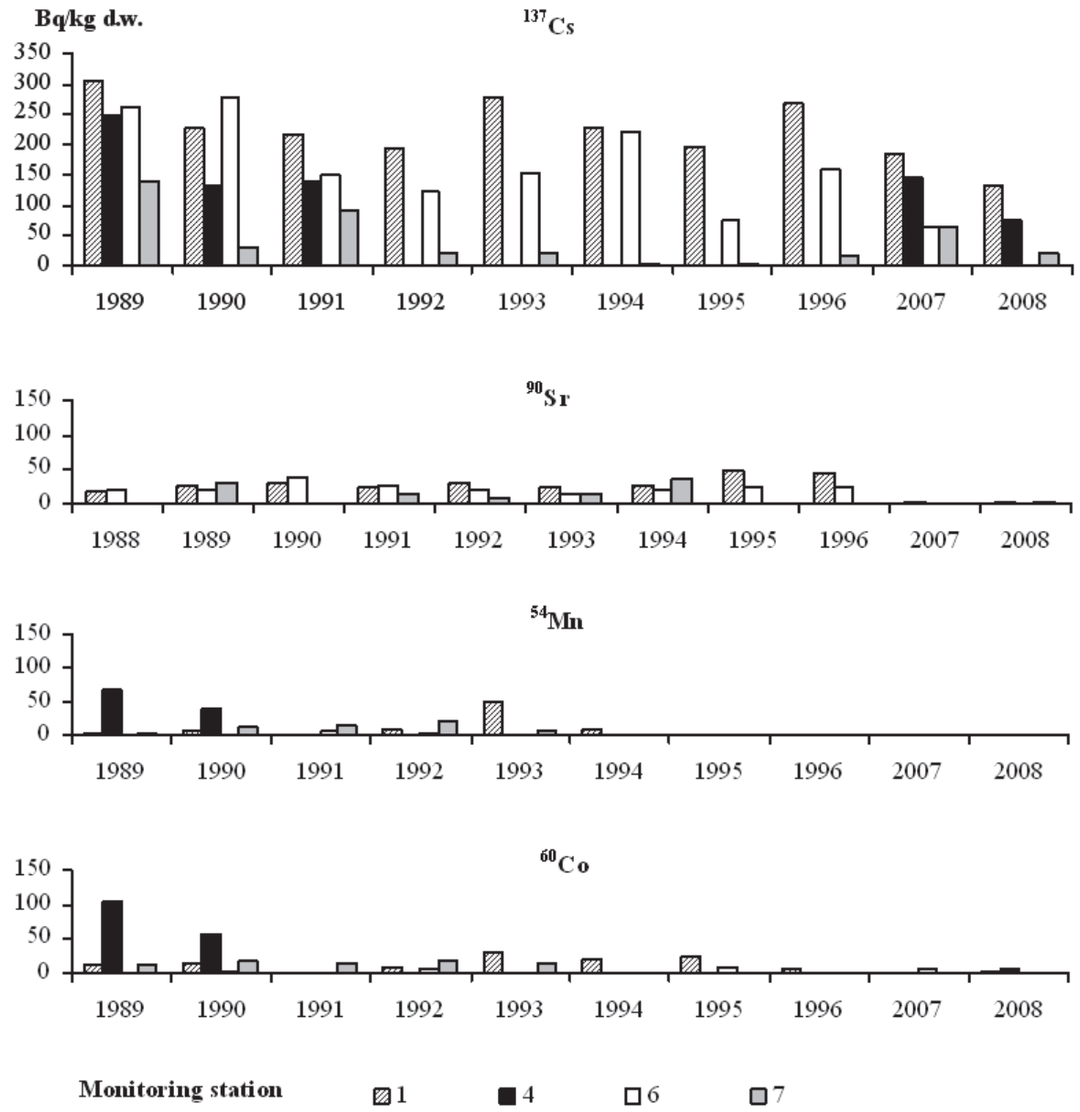


Fig. 5. Time-depended activity concentration of anthropogenic radionuclides in bottom sediment of Lake Druksiai

Traces of ^{3}H and ^{14}C originating from the INPP are found in the surface water (Fig. 6). For the period of 1980-2008 the highest ^{3}H activity concentration in Lake Druksiai was in 2003 year and reached 24 Bq/l. During this period ^{3}H activity concentration in the background water bodies was 2-3 Bq/l, so approximately 20 Bq/l was originated from INPP releases. ^{14}C activity concentration in background water bodies in Lithuania well fits with the international data for Northern Hemisphere. The excess of ^{14}C originated from thermonuclear weapon tests declines almost to the ^{14}C level of cosmogenic origin for all studied surface water bodies in Lithuania. From period of 1992-1993 in the atmosphere and in the surface water all over the world predominates ^{14}C of cosmogenic origin. Almost for all period of ^{14}C observation in surface water influence of INPP has been hardly estimated. Only from 2002 the ^{14}C excess in water influenced by INPP was observed. Very insignificant

fraction of ^{14}C originated from INPP in surface water bodies can be observed in channels and in Lake Druksiai. In 2005 ^{14}C activity in water from outlet channel compared to background level has increased about 30%. But in 2007 ^{14}C activity already did not differ from background level (Mazeika, 2010).

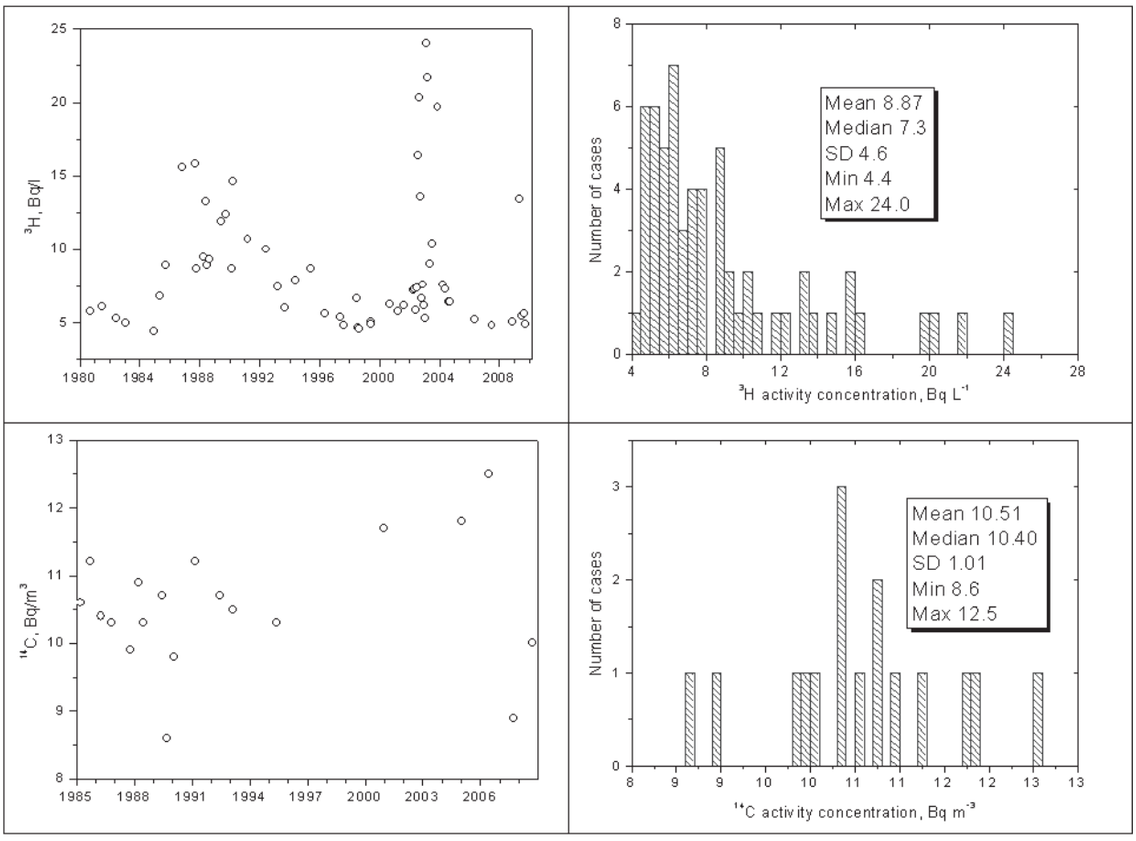


Fig. 6. Time-dependent activity concentrations of ^3H and ^{14}C in Lake Druksiai water (left) and frequency histograms (right)

2.2 Chemical and thermal pollution

The Lake Druksiai was impacted not only by radionuclide pollutions, but also by chemical and thermal pollution. Ignalina NPP discharges into the Lake Druksiai various waste water, which are mainly multicomponent mixtures of chemicals substances (biogenic elements, diluted weak organic acids, heavy metals, petrolic hydrocarbons and so on (Joksas, 1998)).

The main pollution source of Lake Druksiai is the treated waste water used for household needs in settlements, Visaginas town and INPP industrial storm water sewers. The wastewater treatment plant is designed for biological treatment and complementary cleaning with sand filters. The treated waste water is discharged into Lake Druksiai through the tertiary treatment pond. However, these facilities can nowadays be considered as a secondary source of organic pollution since the settled biomass or superior plants have not been removed and the accumulation of the produced biomass leads to a secondary eutrophication process. Around 5.5×10^6–8.5×10^6 m^3 of water enters Lake Druksiai annually from the wastewater treatment plant.

Actually the household waste water discharges from Visaginas town and the INPP are major contributors of nutrients into the lake. (Fig. 7). Up to 1000 tons of organic carbon, 700 tons of nitrogen and 50 tons of phosphorus has been entering the lake annually with maximum values before the year 1991 (Mazeika et al., 2006).

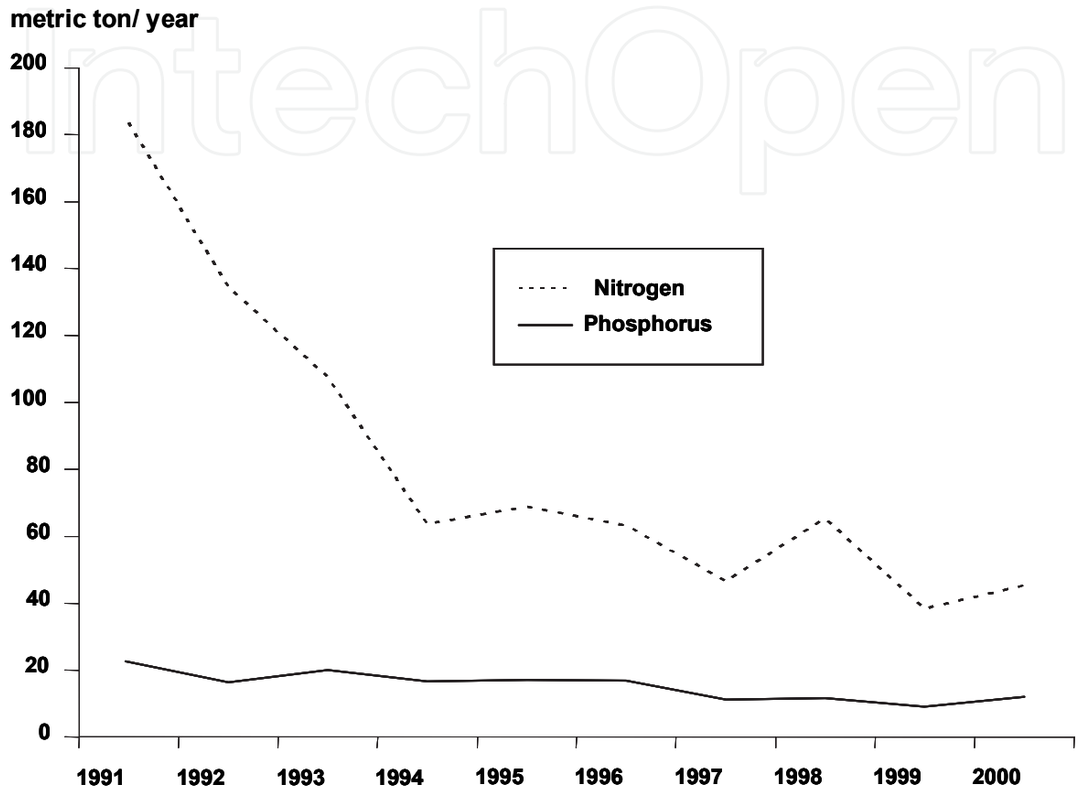


Fig. 7. Nitrogen and phosphorus load into Lake Druksiai

It was evaluated that mean annual concentrations of nitrogen and phosphorus in treated effluents even after the pond of additional purification at that time were 37.7 mg N/l and 3.5 mg P/l accordingly. These figures considerably decreased in the last few decades due to improvement of the purification facility of household effluent. Still this source supplies 55% of nitrogen and 80 % of phosphorus of total annual amount to the lake (Table 1) (Mazeika et al., 2006).

A slightly increasing tendency of total dissolved salts in the water has been observed recently. Waters of Lake Druksiai are dominantly bicarbonate-calcium with medium total dissolved solids (TDS) content. Evaporation from the surface of a lake was expected to become the most important push to increase the concentration of salts in the remaining water. However, it did not have a noticeable effect during several decades of operation of the INPP mainly due to the decrease of HCO^{3-} and Ca^{2+} concentration despite the fact (Table 2) that the content of chlorides, sodium, potassium, sulphates, magnesium increased (Salickaite-Bunikiene & Kirkutyte, 2003; Paskauskas et al., 2009).

Sources	N_t, metric tons year $^{-1}$	P_t, metric tons year $^{-1}$
Domestic and urban runoff	85.53	15.291
stormwater drainage of INPP site *1,2*	1.663	0.244
stormwater drainage of INPP site *3*	0.335	0.081
treated household effluents of INPP and Visaginas	81.625	14.720
stormwater drainage of Visaginas town *2*	0.617	0.046
stormwater drainage of Visaginas town *1*	0.416	0.04
stormwater drainage of site of spent nuclear fuel storage facility	0.870	0.16
Natural runoff	62.02	3.88
Total input	147.54	19.17
Prorva river (output)	98	14.11

Table 1. Long-term balance (1991-2000) of total nitrogen (N_t) and total phosphorus (P_t) load to Lake Druksiai

Parameters	Periods				
	1979–1983	1984–1988	1989–1993	1994–1997	2001–2006
Cl^-,mg/l	8.8	9.9	10.7	9.8	12.9
SO_4^{2-}, mg/l	8.9	12.6	18.6	19.3	18.0
HCO_3^-, mg/l	160.5	150.4	157.6	159.4	169.5
Ca^{2+}, mg/l	39.3	35.8	36.8	35.8	37.9
Mg^{2+}, mg/l	10.0	10.9	12.9	13.8	15.9
Na^+, mg/l	4.6	6.3	7.0	6.9	7.5
K^+, mg/l	1.8	2.7	3.0	2.9	3.2
TDS, mg/l	233.9	228.6	246.6	247.9	264.3

Table 2. Average long-term main ion concentrations and TDS values in Lake Druksiai

Direct contamination on Lake Druksiai emanate from the industrial areas and the town via storm water release systems, supplying the lake ecosystem with many contaminants and inhibitors of biological processes. However, the concentration of copper, lead, chrome, cadmium and nickel has not exceeded the allowable values for the water quality (Marciulioniene et al. 1998)

Concentrations of heavy metals (HM) in the waste water of the INPP and Lake Druksiai during the INPP operation time was higher in comparison with concentrations measured before the plant had been launched. Maximal concentrations of HM (soluble and suspended forms) discharged into the lake from the ISW-1,2 and WWTP channels (Table 3). The largest amount of Fe, Mn and Co got into the lake and migrated together with suspended particles. The main part of these metals deposited in the bottom sediments (Table 4) and the other part of them were involved into biological processes.

Sampling station No.	Year	Cd	Cr	Cu	Ni	Mn	Zn	Pb
		μg/l						
1	1996	–	0.2	3.7	1.3	15.1	4.5	0.25
	1997	–	0.05	4.8	1.1	2.0	6.0	1.4
	1999	<0.1	<0.2	4.6	0.57	1.0	0.2	0.3
2	1996	–	0.7	4.1	0.6	15.1	2.9	0.3
	1997	–	0.01	3.7	<1	0.6	<2.0	<1
	1999	<0.1	0.3	6.0	0.22	38.0	1.8	3.1
6	1996	–	0.7	3.9	1.4	29.6	4.0	0.3
	1997	–	<0.01	3.3	1.0	0.7	1.0	<1
	1999	<0.1	0.6	6.4	0.58	125.0	29.0	2.9

Table 3. Average midsummer heavy metals concentrations in water of Lake Druskiai

It has been estimated that heavy metal contaminated sediments (from intermediate to high level of contamination) cover 27.5 % of the lake bottom sediment area, slightly polluted area covers 41%, and non-polluted area covers about 32% (Joksas et al., 1998). Pollution with oil products was identified in 3.9 % of the bottom sediment area but major part of this has a natural origin since the natural hydrocarbons dominate. Concentration of hydrocarbons in the water was not high and varied from 2 to 44 μg/l. Their concentration in the surface layer of bottom sediments was from 1.12 to 127 mg/kg dry weight (DW) (Joksas et al., 1998).

Sampling station No.	Pb	Cd	Cr	Zn	Cu
	mg/kg, DW				
1	39.8	1.4	8.4	80.0	74.0
4	10.4	0.2	3.3	23.1	111.3
6	21.8	0.7	5.8	46.0	55.1
7	1.8	0.1	0.8	4.6	4.9

Table 4. Heavy metals concentrations in bottom sediments of Lake Druskiai

Thermal aspects together with chemical and radioactive pollution must be taken into account considered ecological risk. Lake Druksiai has been used as the source of cooling water already since 1983 when first unit was put into operation. When passing through the cooling system of the INPP, the quality of cooling water does not normally change in any other way than that the temperature raises approximately 9–11 °C. Heated water discharge led to changes in the hydrological conditions of the lake: the surface temperatures increased, the natural vertical thermal stratification altered and evaporation rates increased. The increased temperature of the lake and the subsequent decrease of the cold water volume (Fig. 8) did not only stimulate the acceleration of eutrophication of the lake but also changed the prevailing conditions unfavorably for stenothermal cryophilic species. In Druksiai water temperature at 10 m depth has risen by 4°C and at 30 m depth by nearly 2°C (Balkuviene & Parnaraviciute, 1994).

Due to the complex (thermal and chemical) anthropogenic impact the following ecological zones, as presented in Table 5, have developed in Lake Druksiai:

- Zone A: The most eutrophicated south-eastern part of the lake, where the main source of eutrophication is the household effluents of the INPP and Visaginas town with an elevated amount of nutrients (N, P). Increased amount of plankton as well as enhanced activity of production-decomposition processes are observed in this area.
- Zone B: The cooling water outflow zone is the area of the greatest thermal impact, where water temperature in many cases exceeds 28 °C. The lowest abundance and variety of most planktonic organisms (phytoplankton and zooplankton) as well as lower rates of primary production and more intensive decomposition processes of organic matter are observed in this area;
- Zone C: The rest of the lake, including the deep and mediate deep zones, where the various impact factors affect the ecosystem occasionally, depending on the INPP operation, wind direction, waves, etc.

In conclusion, eutrophication, the increase of salts content and warming of the lake water, interact to influence the habitats and ecosystems of the lake. Despite these changes in the lake ecosystem, the parameters examined still meet the requirements and range within the guide values.

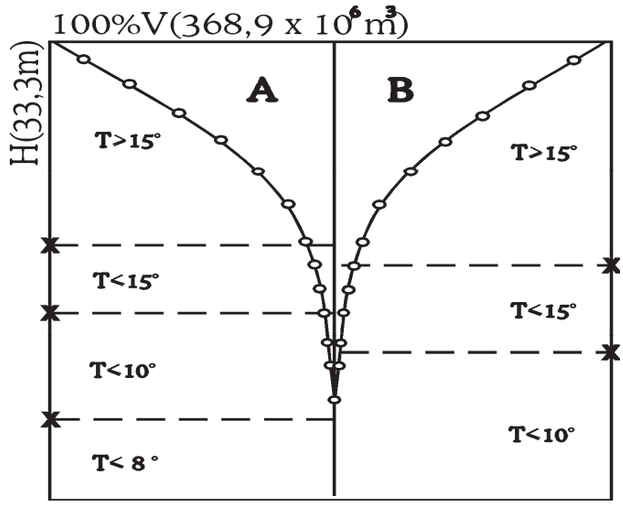


Fig. 8. The distribution of thermal zones during summer stratification in Lake Druksiai, 1977–1983 – A and 1984–1997 – B (Balkuviene & Parnaraviciute, 1994)

Parameter	Zone A	Zone B	Zone C
Secchi depth, m	1.0–2.8	3.0–3.9	1.2–6.5
Chlorophyll a, µg/l	6.6–113.5	0.88–16.5	0.99–70.0
Zooplankton biomass, mg/m^3	2 046–7 180	431–1 863	596–1 153
Phytoplankton primary production, mg C/m^3 d^{-1}	330–2 800	44–440	2–1 500
$C_{org.}$ total in bottom sediments, %	11.7–12.4	3.5–3.7	7.6–12.6
Organic matter mineralization in bottom sediments, mg C/m^2 d^{-1}	1 127–1 590	915–939	513–720

Table 5. Fluctuation range of some parameters in different zones of Lake Druksiai

3. Radioactive pollution and non-human biota exposure

Concerning dose calculations to non-human biota the data of radiological investigations and radionuclide transport pathway must be taken into account.
Radionuclide transfer modeling in various ecosystems using differential equations and transfer factors is desirable. For radiation doses to freshwater biota evaluation ERICA assessment tool (Environmental Risk of Ionizing Contaminants Assessment and Menagement – http://project.facilia.se/erica/) and site specific LIETDOS-BIO code (Nedveckaite et al., 2010) has been used.

3.1 ERICA biota exposure dose rates assessment approach

The ERICA project (the European Community 6th Framework programme at a European level) was carried out between 2004 and 2007. The final outcome of the project is the delivery of the ERICA Integrated Approach. The use of Integrated Approach is facilitated by ERICA Tool which is a software code that keeps records and communicates with a number of purpose-built databases.
The Community research in radiation protection underpins European policy and has already contributed to the high level of environmental protection. To put assessment of nuclear sites into context a comparison of biota exposure due to discharged anthropogenic radionuclides with that of background radionuclides is required. This investigation presents the comparison of freshwater Lake Druksiai reference biota (the reference organisms are the default organisms included in the ERICA code Tool) exposure due to discharged anthropogenic radionuclides with that due to natural background radionuclides using ERICA approaches. The data presented enlarge knowledge about the concentrations of radionuclide in European freshwater ecosystems in order to understand the exposure dose rates of freshwater organisms due to major discharged radionuclides and natural series contributors.

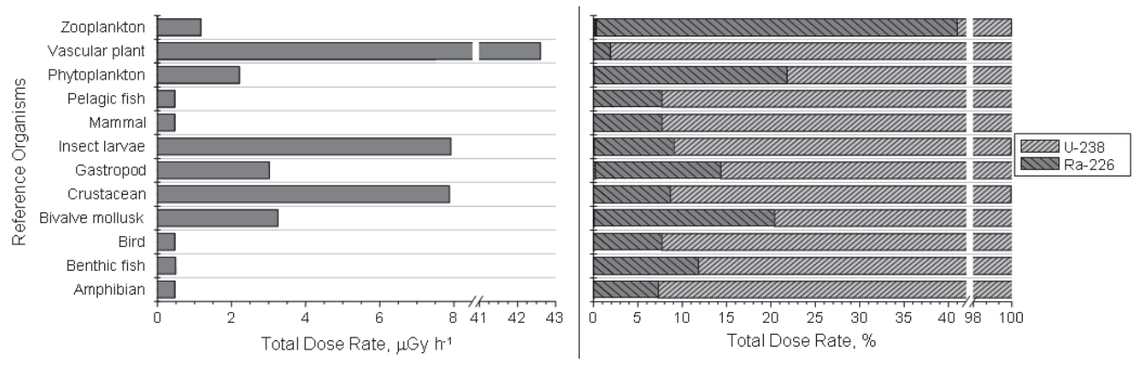


Fig. 9. The comparison of dose rates to freshwater reference organisms from natural background radionuclides (left) and the corresponding percentage due to separate radionuclides (right) in Lake Druksiai. The percentage of ^{210}Pb and ^{232}Th are less than 1%

In the case of INPP cooling pond Lake Druksiai the estimated exposure of freshwater ecosystem reference organisms is determined mostly by natural background radionuclides and arises from internally incorporated alpha emitters, with ^{210}Po, ^{226}Ra and ^{238}U being the major contributors (Fig. 9). The contribution of anthropogenic radionuclides exposure composes about 5% of this dose rates (Fig. 10). The exposure of reference organisms due to

the natural background exposure stands out above anthropogenic discharged radionuclides exposure.

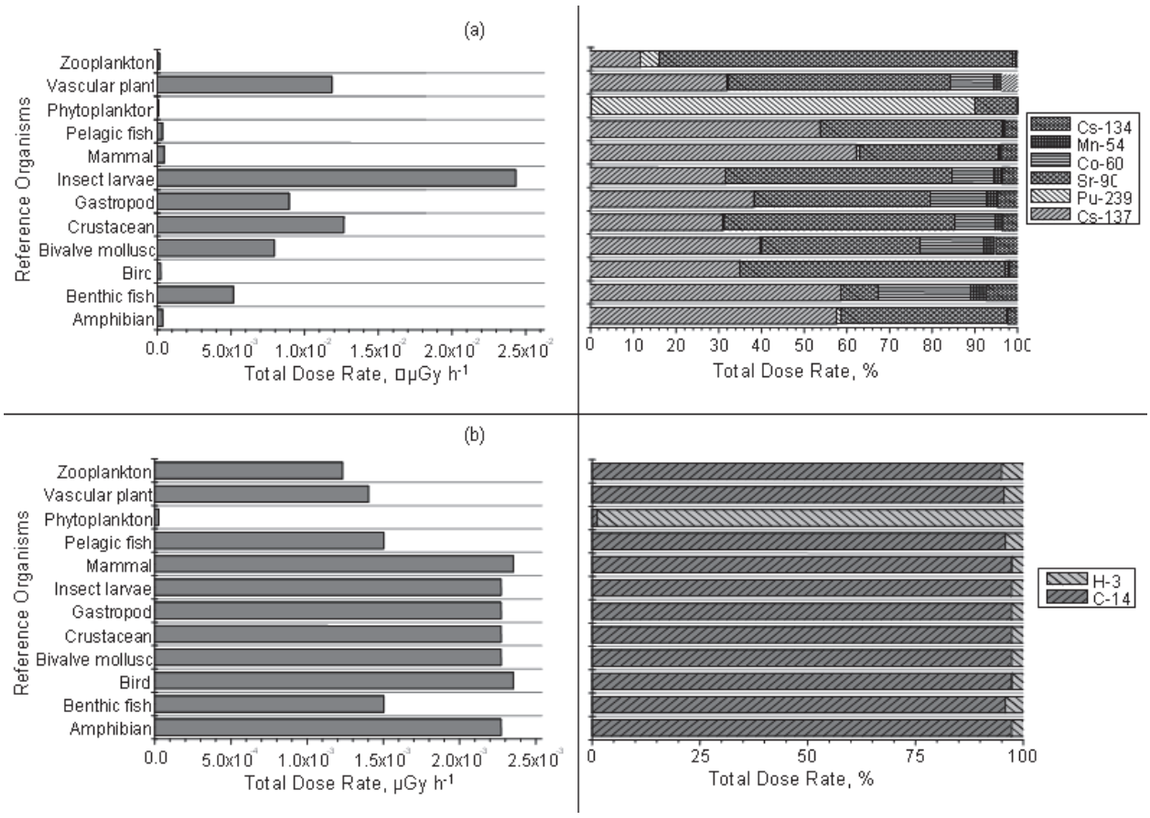


Fig. 10. The comparison of total dose rates derived by freshwater reference organisms inhabiting Lake Druksiai from anthropogenic (a) and natural-anthropogenic (b) radionuclides (left) and the corresponding percentage due to separate radionuclides (right)

3.2 Site-specific LIETDOS-BIO computer code designed for non-human biota exposure assessment approach

The site-specific LIETDOS-BIO assessment approach to non-human biota exposure protection from ionizing radiation is being developed to address contamination issues associated with nuclear power production and radioactive waste repository in Lithuania. LIETDOS-BIO model and computer code for biota exposure dose rate calculation was validated during IAEA EMRAS (Environmental Modeling for Radiation Safety) Working Group designated for model validation for biota dose assessment (Vives-i-Batlle et al., 2007; Beresford et al., 2008a; Beresford et al., 2008b; Beresford et al., 2009; Yankovich et al., 2010). The user is the Centre of Physical Science and Technology and Nature Research Centre.

LIETDOS-BIO code was designed to be consistent with MCNPX (general purpose Monte Carlo radiation transport code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport) (MCNPX, 2002) as well as Crystal Ball software (www.oracle.com/crystalball/index.html) for uncertainty analyses.

3.2.1 Preparing MCNPX input file for dose conversion coefficients (DCC) calculations

The MCNPX code is widely used for radiation transport simulation with relatively high flexibility and is now applied to many fields including radiation safety management, health physics, medical physics and reactor design. Based on information about the organism geometry specification, description of materials, specification of the particle source, the type of answers desired (energy deposited in a given volume) LIETDOS-BIO automatically creates an input file (specially designed to LIETDOS-BIO) that is sub sequentially read by MCNPX and calculates dose conversion coefficients for non-human biota. Examples of geometry specification model for dose conversion coefficient of external exposure calculation by MCNPX code is presented in Fig. 11.

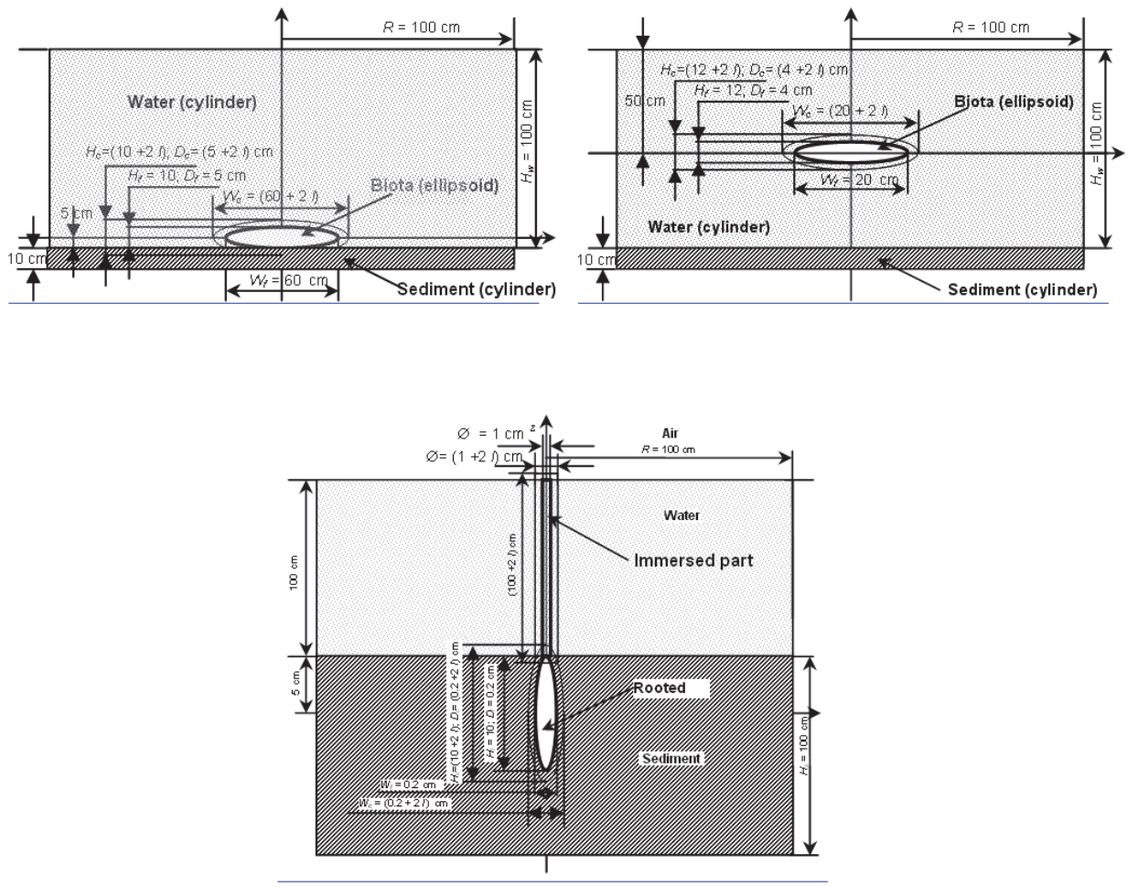


Fig. 11. Geometry specification model for non-human biota DCC of external exposure calculation by MCNPX code: organism on the bottom of water layer (left), organism in the middle of water layer (right), rooted submerged hydrophytes (below)

3.2.2 Method used for deriving uncertainty and accuracy estimates

Like any complex environmental problem, the evaluation of ionizing radiation impact is confounded by uncertainty. In radioecology stochastic calculations are used to an increasing extent. At all stages, from problem formulation up to exposure evaluation, the assessments

depend on models, scenarios, assumptions and extrapolations as well as technical uncertainties related to the data used. Uncertainties can be categorized as follows:

- Knowledge uncertainties defined as a lack of scientific knowledge about parameters and factors or models. It includes measurement errors as well as model misrepresentation and can be reduced through further study. It may be possible to represent some of these uncertainties by probability distributions.
- Variability is defined as a natural variability due to changes in a data set. Variability is easier to represent quantifiable through simple standard deviation or a frequency distribution or through probability density function.

To estimate the uncertainty of the endpoints of the exposure assessment, uncertainties in the inputs and parameters must be propagated through the model using Monte-Carlo analysis. Point estimates in a model equation are replaced with probability distributions, samples are randomly taken from each distribution, and the results are combined, usually in the form of a probability density function, in order to obtain 95% confidence interval. The uncertainties in LIETDOS-BIO model has been determined by Crystal Ball code statistical technique with 10 000 number of trials and the Latin Hypercube sampling method. An example of external dose rate evaluation is presented in Fig. 12. Sensitivity analysis is used to identify the relative quantitative contribution of uncertainty associated with each input and parameter value to the endpoint interested.

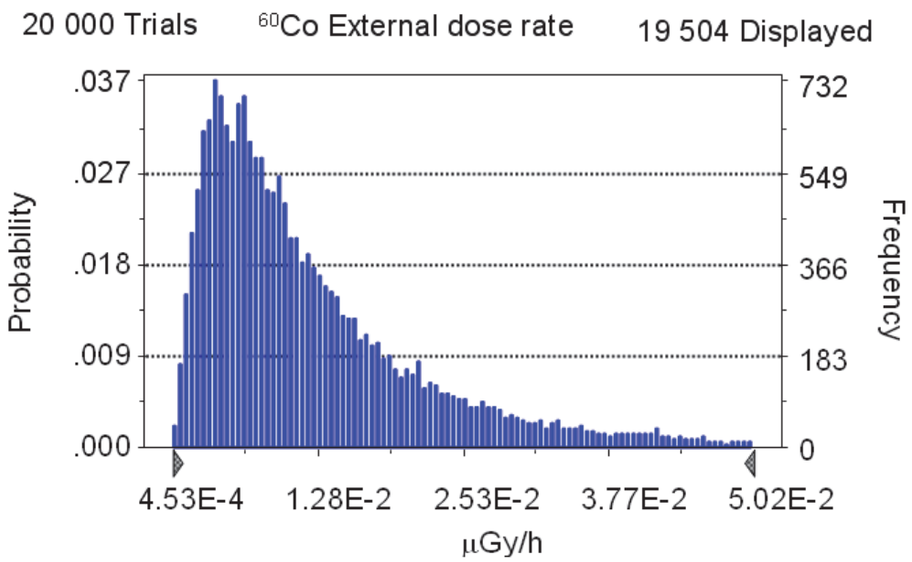


Fig. 12. An example of Druksiai Lake macrophytes external dose rate evaluation (Crystal Ball statistical techniques was used with 20 000 number of trials and Latin Hypercube sampling)

3.2.3 LIETDOS-BIO libraries and data bases

LIETDOS-BIO contains Nuclide library (ICRP, 1983) and site-specific parameters library (terrestrial and freshwater ecosystems). An example of site-specific freshwater ecosystem macrophytes ^{90}Sr concentration factor (CF) evaluation is presented in Fig. 13. Various species of macrophyte forming a greatest phytomass in water were investigated

(Marciulioniene et al., 1992). An amount of stable Sr and Ca as well as many biological and physical processes plays the main role among the factors determining ^{90}Sr concentration levels of the investigated species. The frequency of ^{90}Sr CF distribution based on 250 samples of 19 macrophyte species evaluation in Lithuanian lakes is presented in Fig. 13.
The examples of site-specific CF values, based on environmental monitoring of discharged radionuclide activity concentration in the submerged plants and water have been evaluated completing data gaps in freshwater environment. The concentration factors based on submerged hydrophyte and water activity measurements was estimated. Data presented in Table 6.

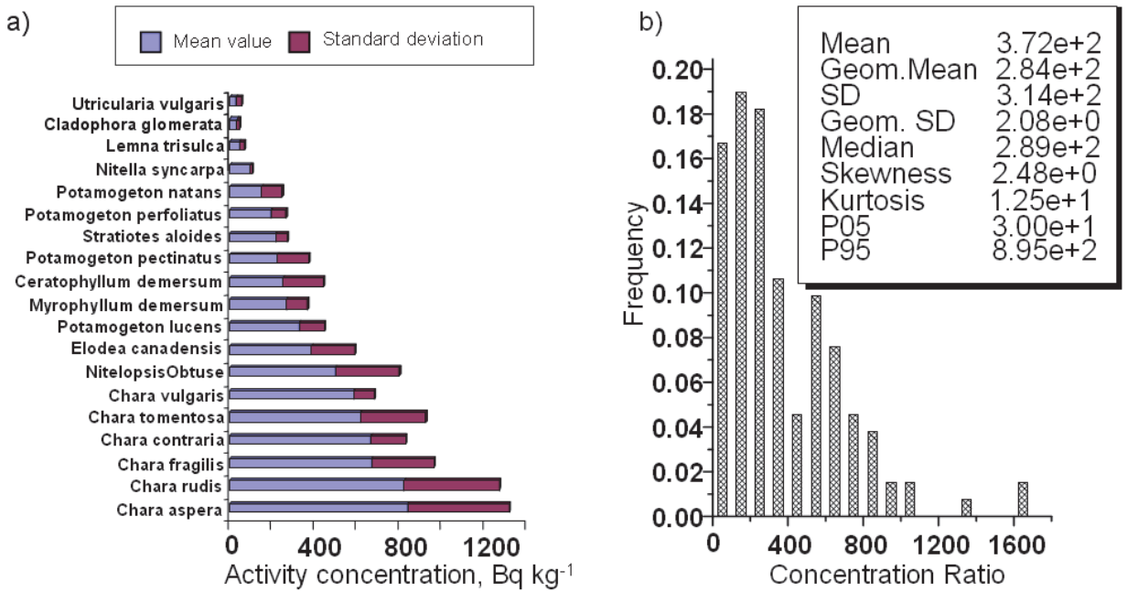


Fig. 13. Site-specific values of ^{90}Sr activity concentrations for different types of freshwater ecosystem macrophytes (a) and the distribution of corresponding CF values (b)

Parameters	Concentration factor, $m^3\ kg^{-1}$				
	^{40}K	^{54}Mn	^{60}Co	$^{90}Sr/^{90}Y$	$^{137}Cs/^{137m}Ba$
Mean	$1.5\times10^{+1}$	$1.2\times10^{+1}$	$8.6\times10^{+0}$	$2.0\times10^{+0}$	2.5×10^{-1}
Median	$1.0\times10^{+1}$	$2.3\times10^{+0}$	$3.6\times10^{+0}$	$1.1\times10^{+0}$	1.1×10^{-1}
Standard Deviation	$1.7\times10^{+1}$	$4.5\times10^{+1}$	$1.7\times10^{+1}$	$2.7\times10^{+0}$	4.8×10^{-1}
Range Minimum	1.4×10^{-1}	1.0×10^{-3}	8.0×10^{-3}	1.0×10^{-2}	1.0×10^{-3}
Range Maximum	$3.7\times10^{+2}$	$2.6\times10^{+3}$	$5.4\times10^{+3}$	$6.4\times10^{+1}$	$1.3\times10^{+1}$

Table 6. The submerged freshwater hydrophyte site-specific CF values

4. Exposure of biota in the INPP cooling pond Lake Druksiai

On the basis of the long-term studies of the radionuclides in biotic and abiotic components of Lake Druksiai (Marciulioniene et al., 1992; Lithuanian State scientific research programme, 1998) the potential impacts of radioactive pollution on lake non-human biota, with special emphasis on macrophytes were evaluated.

4.1 Submerged macrophytes exposure dose rates assessment

A decline in a hydrophyte population may indicate water quality problems. Such problems may be the result of chemical or thermal lake pollution, as well as exposure by radionuclide ionizing radiation. Internal and external exposures of submerged hydrophytes were estimated by means of LIETDOS-BIO code separately for above-sediment and rooted plant parts. Eighty-five samples of submerged macrophytes (*Myriophyllum spicatum, Ceratophyllum demersum, Nitellopsis obtusa*) have been measured to determine the activity concentrations of ^{54}Mn, ^{60}Co, ^{137}Cs, ^{90}Sr, ^{40}K, ^{210}Pb.

Based on the knowledge of radionuclide distribution within the freshwater environment a simplified compartmentalization of the ecosystems was used as a basis for selecting suitable target geometries (phantoms) for the macrophyte's above sediment and rooted parts dose rate calculations. The aquatic ecosystem has been considered as two compartments: bed sediment and water column (Fig. 11). It is reasonably safe to suggest that the above-sediment part of submerged rooted plants receive lower external radiation doses as compared with the external exposure of roots in sediments that is in a system which has been receiving radionuclides for a number of years. Consequently, the external and internal exposure of above-sediment and rooted parts of plant must be evaluated separately. An example of DCC values for rooted submerged hydrophyte's parts, calculated by means of LIETDOS-BIO code, are presented in Table 7.

Exposure	*DCC*, μGy/h per Bq/kg			
	^{54}Mn	^{60}Co	^{90}Sr/^{90}Y	^{137}Cs/^{137m}Ba
External	2.31E-04	7.63E-04	4.82E-04	2.77E-04
Exposure	*DCC*, μGy/h per Bq/kg (FW)			
	^{40}K	^{210}Pb	^{226}Ra	^{232}Th
External	2.41E-04	6.76E-07	2.58E-06	4.41E-08

Table 7. Submerged hydrophyte's rooted part weighted DCC for anthropogenic and background radionuclides (assuming weighting factor of 5 for α-radiation, both β-γ-radiation – 1)

Estimates of exposure were therefore made using two groups of model parameters:

- site-specific data when available - activity concentration in plants, bottom sediments and in most cases water (assuming site-specific equilibrium between two phases);
- generic parameters when site-specific data were lacking, for example CF values were generally needed for ^{232}Th and ^{238}U.

Some examples of submerged hydrophytes root external exposure dose rates evaluation due to discharged anthropogenic and natural background radionuclides are presented in Fig. 14. As presented in (Nedveckaite et al., 2007; Nedveckaite et al., 2011) the ionizing radiation exposure dose rates to submerged hydrophyte roots and above sediment parts due to the anthropogenic radionuclides (^{54}Mn, ^{60}Co, ^{137}Cs, ^{90}Sr) discharged into Lake Druksiai were 0.044 mGy h^{-1} and 0.004 mGy h^{-1}, respectively.

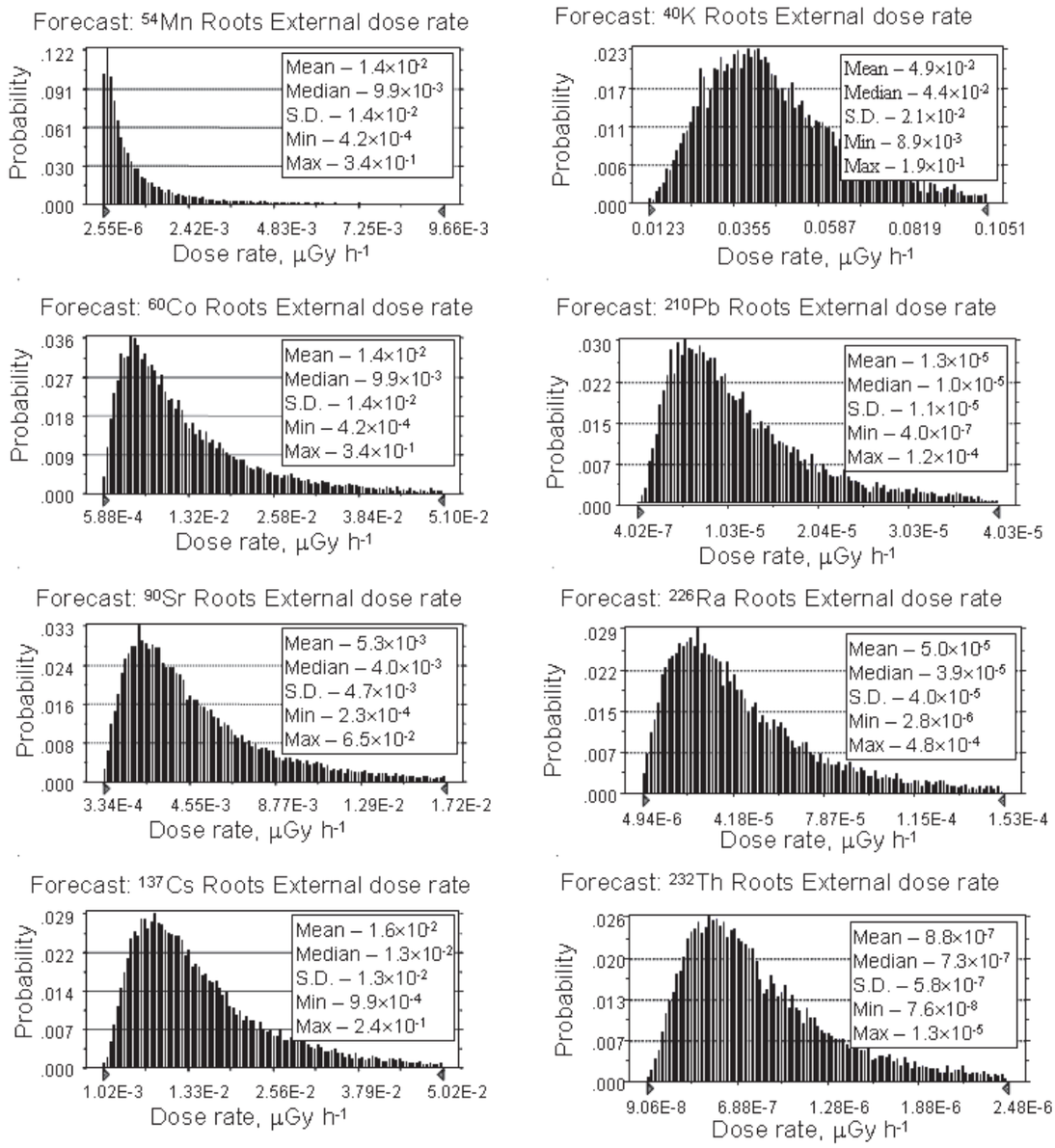


Fig. 14. The examples of submerged hydrophyte's root external exposure dose rates evaluation due to discharged anthropogenic and natural background radionuclides

5. The investigation of radiological, chemical and thermal pollution effects on the lake biota

5.1 Macrophytes

Aquatic plants make up a large biomass and intensively concentrate radionuclide's occurring in the environment in micro amounts by assimilating them both from water and bottom sediments. Therefore, to assess the radioecological state of a hydroecosystem, the plants (bioindicators) are used. Radionuclide activity concentrations in bioindicators are integrated in time (a month, a year or even longer period of time) as well as in space, whereas in the environment they demonstrate fast alteration due to environmental factors. Radionuclide activity concentrations in bioindicators can be established comparatively accurately, even in such cases, when their activity concentrations in other environmental components are under the minimal detectable level (Marciulioniene at al., 2011a). Activity concentration of radionuclides in macrophytes of Lake Druksiai during twenty years period of time is presented in Fig. 15.

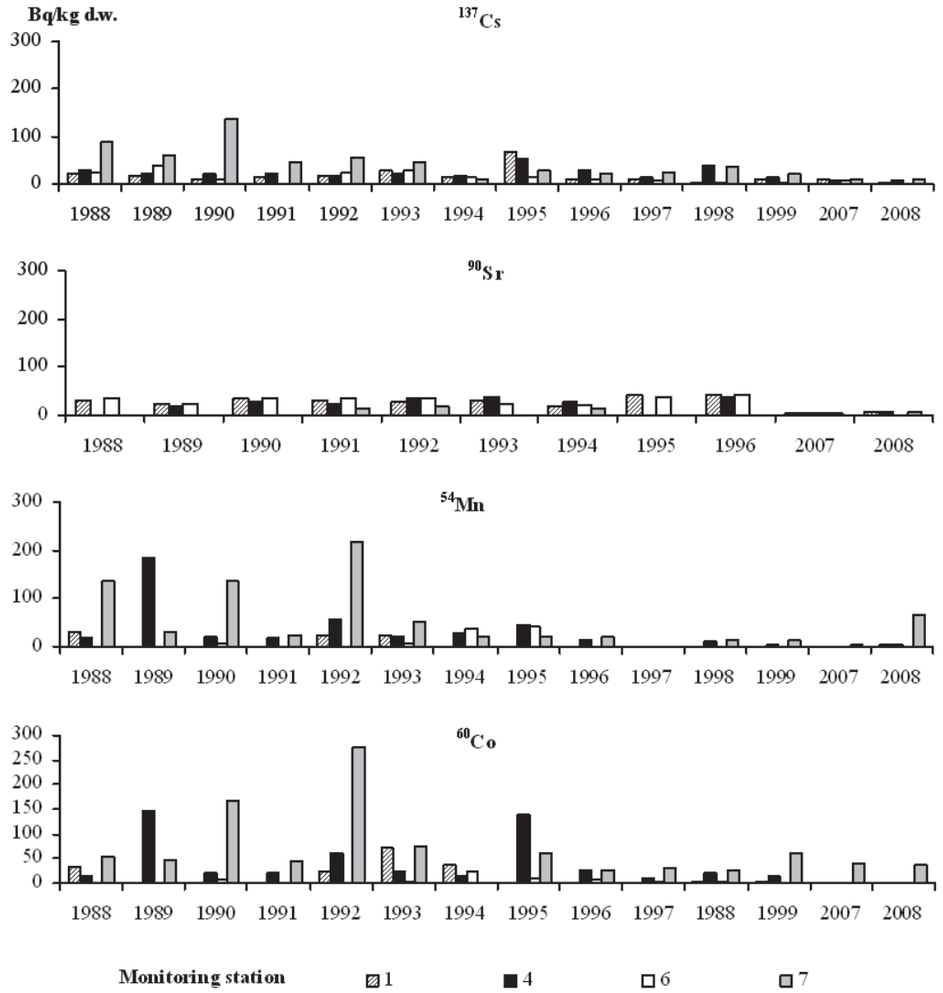


Fig. 15. Time-depended activity concentration of anthropogenic radionuclides in submerged macrophytes of Lake Druksiai

Macrophytes were collected in the stations of littoral zone at a depth less than 8 m. Ninety-five samples of different submerged macrophytes were measured to determine the radionuclide activity concentrations (Marciulioniene et al., 1992; Mazeika, 2002). In most cases co-located bottom sediment and water samples were also analyzed. It should be stressed that bottom sediment activity which contain radionuclides accumulated over a number of years determined the rooted submerged macrophyte exposure to a greater extent as compared with water activity.

5.1.1 Macrophytes and chemical pollution

Waste water polluted not only with radionuclides, but also with chemical contaminants (acid and alkali solutions, weak organic acids, heavy metals and etc.) were constantly discharged from WWTP and ISW-1,2 channels of INPP into Lake Druksiai, which accumulated in bottom sediments. A tendency of increasing toxicity of INPP WWTP channel discharge and bottom sediments as well as the water of ISW-1,2 channel discharges into Lake Druksiai zone and especially bottom sediments was observed. However, this waste water taking into account the degree of toxicity can be subsumed as low-toxicity waste water.

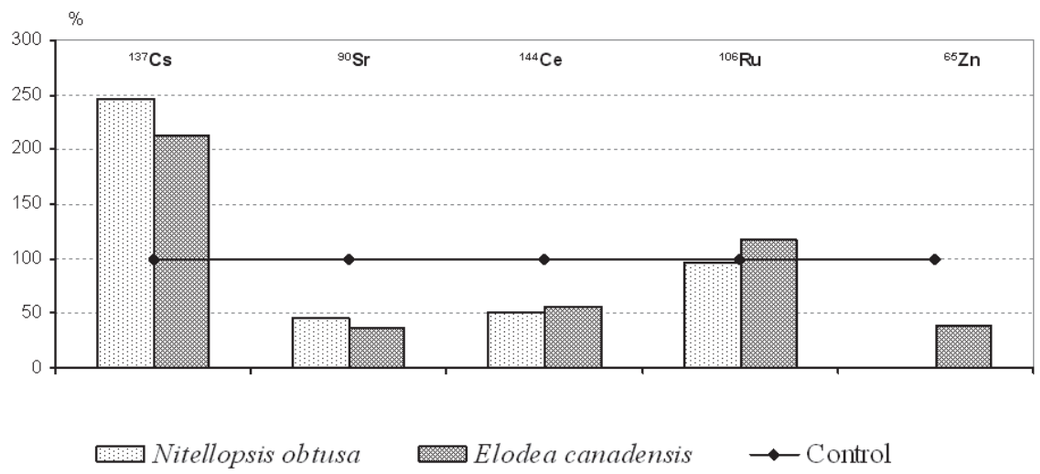


Fig. 16. Impact of INPP industrial storm water discharge channel on radionuclide accumulation (as compared with the control, %) in algae *Nitellopsis obtusa* and higher plant *Elodea canadensis*

The results of INPP industrial storm water discharge channel impact on radionuclide accumulation in algae *Nitellopsis obtusa* and higher plant *Elodea canadensis* are presented in Fig. 16.

5.1.2 Macrophytes and thermal pollution

It is known that stimulation of the growth of aquatic plants under high temperature of water is deviated from the normal functioning of plants. Hence, we may conclude that after the rapid development of the all species of plant of Lake Druksiai (1986–1989), the suppression of species, more sensitive to high temperature, had occurred. Temperature of water is one of the main factors which influence the physiological state of plant and it is strongly related

with the sensitivity of plants to chemical and radioactive matters. Accumulation of radionuclides in the *Nitellopsis obtusa* and *Elodea canadensis* under laboratory conditions showed that the increase in water temperature from 22 to 31°C influenced the accumulation levels of different radionuclides in the tested plant species differently (Fig. 17), accumulation level of ^{134}Ce increased signally.

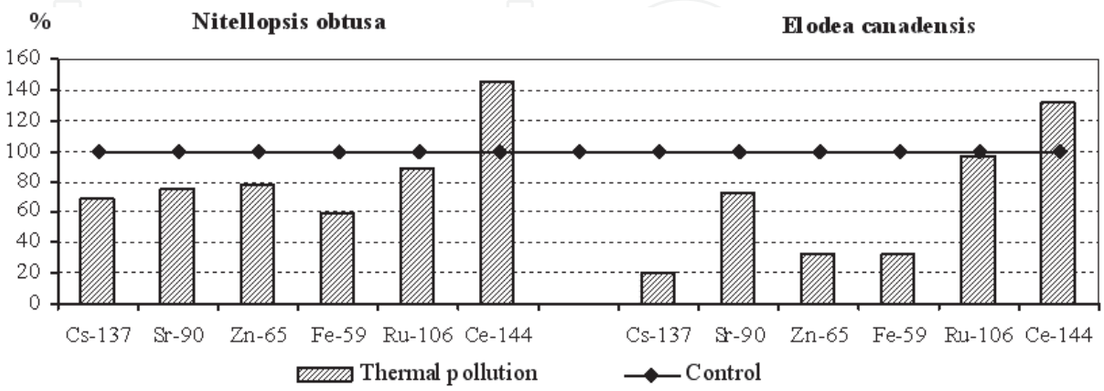


Fig. 17. Impact of thermal pollution (31°C) on radionuclide accumulation (as compared with the control at 22°C , %) in algae *Nitellopsis obtusa* and *Elodea canadensis*

It was found that impact of thermal and chemical pollution on accumulation of ^{137}Cs taking part in the metabolic processes in the aquatic plants may depend more on changes of the functional status of plant. Accumulation of microelement ^{60}Co and ^{54}Mn participating in metabolic processes of the aquatic plants under thermal impact may depend on both the functional status of the plant and changes of physical-chemical properties of these radionuclides.

5.1.3 Macrophytes and complex chemical, thermal and radioactive pollution

The main source of ^{60}Co and ^{54}Mn discharging into the lake was the waste water of the ISW-1,2 and CW channels (Fig. 3). The activity concentration of these radionuclide's in the bottom sediments from above mentioned channels were higher than that in Lake Druksiai. The decrease of the activity concentration of ^{60}Co and ^{54}Mn in the bottom sediments of the INPP's discharge channels and the lake was observed since 1994. Since 1996 the activity concentration of ^{54}Mn in the bottom sediments of the INPP's channels and the lake in the most cases was lower than minimal detection limit. It is necessary to stress that values of ^{137}Cs activity concentration in bottom sediments of Lake Druksiai were higher than that in hydrophytes. However, activity concentration of ^{60}Co and ^{54}Mn in bottom sediments were lower than that in hydrophytes (Table 8).

Presumably, high radionuclide activity concentrations in ISW-1,2 channel were induced due to planned maintenance of INPP. It should be indicated that the highest ^{60}Co and ^{54}Mn activity concentrations in macrophytes were established at the outlet of the channel, however, at its end, they markedly decreased: ^{60}Co by 5 times, ^{54}Mn by 43 times. ^{137}Cs and ^{134}Cs activity concentrations in plants differed insignificantly both at the outset of the channel and at its end.

Such differences in radionuclide accumulation in macrophytes can be explained by varying chemical and physical chemical characteristics of these radionuclide's, upon which not only

radionuclide accumulation in macrophytes, but also their dispersion in hydroecosystem depends. Although the investigated radionuclide activity concentrations in macrophytes sharply decreased in 2009 in comparison with 2008, however, they were higher than those in 2007 (Table 8).

Nuclides	*Ceratophyllum demersum*			*Myriophyllum spicatum*	
	2007	2008	2009	2008	2009
^{137}Cs	20±2**	392±47** 406±54***	22±1.2***	166±33* 271±20***	18±1.6* 13±1.1**
^{60}Co	34±2**	754±51** 634±50***	63±3.0***	2185±108* 463 ±23***	46±1.9* 37±1.6**
^{54}Mn	2±0.6**	2203±147** 1774±129***	75±3.0***	6428±372* 151±88***	44±2.3* 46±2.1**

<mdl – minimal detectable level; ISW-1,2 channel: outset – *, middle – **, end – ***

Table 8. Radionuclides activity concentration (Bq/kg) in macrophytes in INPP industrial storm water discharge channel (ISW-1,2) (2007–2009)

The macrophytes growing in this channel performed the role of cleaning (phytoremediation) of the channel waste water by accumulating large content of radionuclides. The flux of radionuclides discharged from this channel into the lake was low due to low water flow rate in ISW-1,2 channel and large water volume of lake what stipulated activity dilution.

5.2 Ichtiofauna

Lake Druksiai is important for commercial and free-time fisheries. In this connection the corresponding percentage contributions of different radionuclides to the various kinds of fish from key Lake Druksiai radionuclides has been investigated.

The factors that have an effect on the evolution of fish populations are: inputs of sedimentary substance (from the increase of the lake water level due to the construction of a dam and an active erosion of the lake banks), water temperature, in particular the optimum temperature for fish populations, the average biomass of phytoplankton, the average concentration of dissolved nitrogen and phosphorus.

The time-dependent changes in radionuclide activity concentrations in average annual specific activity of radionuclides in fishes are presented in Fig. 18. Corresponding fish muscle activity concentration distributions in Fig. 19.

As regards the fishery and corresponding committed effective human dose assessment as result of fish consumption, Lake Druksiai 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 performed using site-specific consumption data and the LIETDOS computer code demonstrate that adult human annual effective doses would be as small as a few μSv and are mostly attributable to the background radionuclides, for example, ^{40}K.

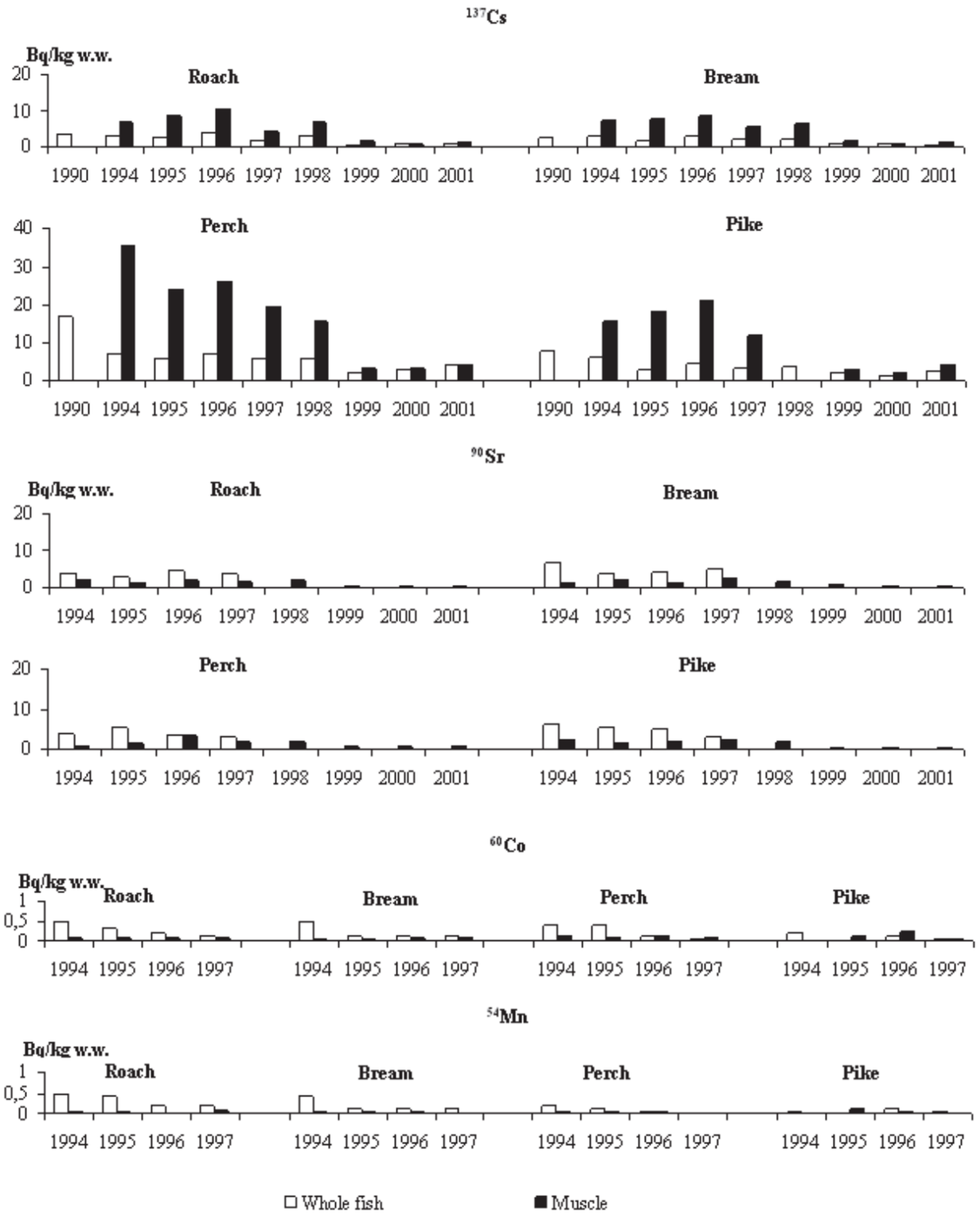


Fig. 18. Time dependent activity concentration of radionuclides in the whole fish and fish muscle from Lake Druksiai

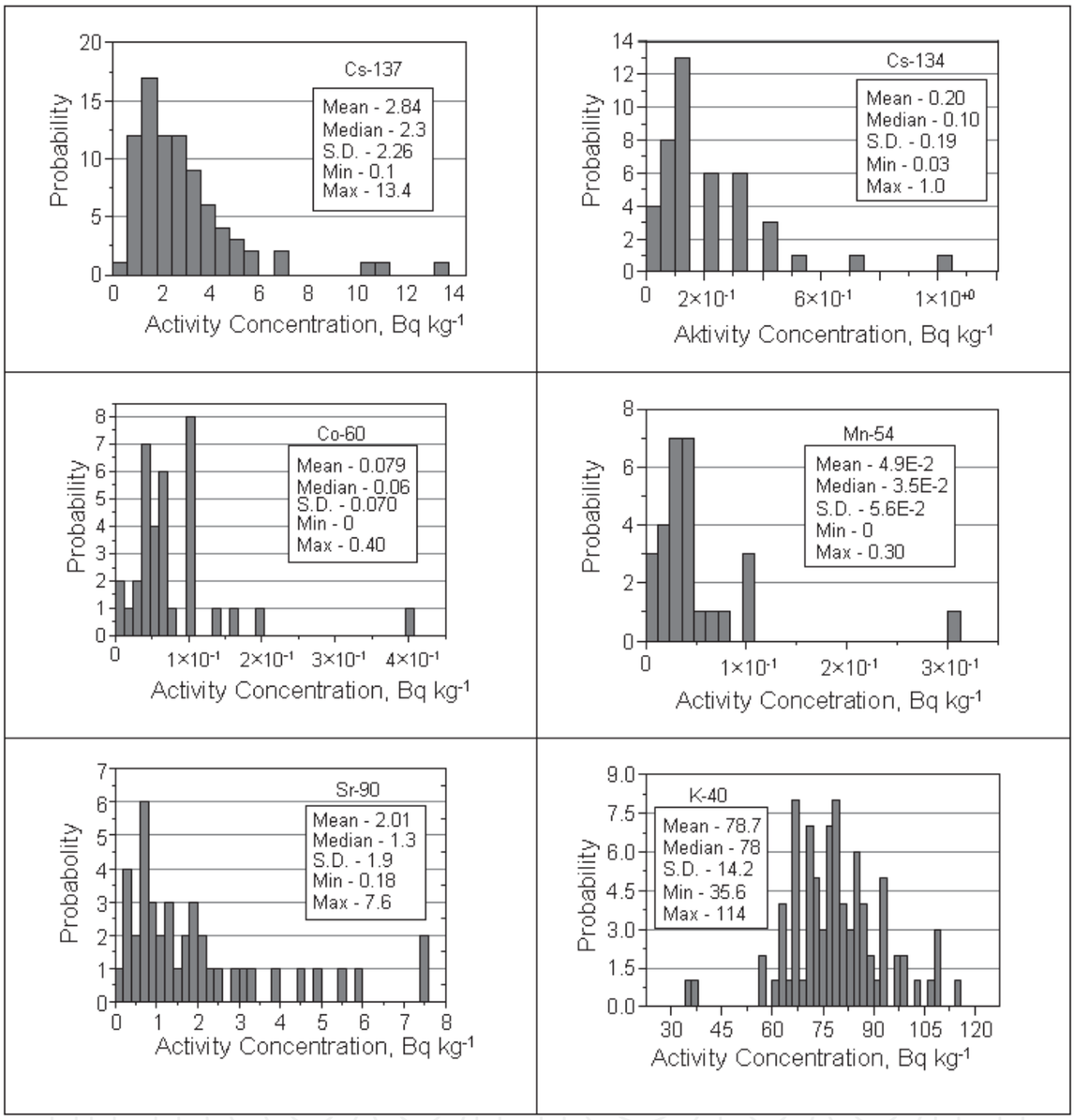


Fig. 19. Pelagic fish muscle activity concentration data (Marciulioniene et al., 1992) from key radionuclides discharged from the INPP into Lake Druksiai cooling pond and ^{40}K

5.3 Macrophytes and fish community changing

73 aquatic macrophyte species were recorded in Lake Druksiai. Among them eight *Charophyta*, two *Bryophyta*, one *Equisetophyta*, and 58 *Magnoliophyta* species. Before operation of the INPP Lake Druksiai was characterized as a typical mesotrofic lake of moderate depth with well developed submerged vegetation (dominant species *Chara rudis*, *C. filiformis*, *Nitellopsis obtusa*, *Potamogeton lucens*, *P. perfoliatus*) and fragmentally developed floating leaved and emerged vegetation (*Potamogeton natans*, *Phragmites australis*) (Marciulioniene et. al., 1992). Maximum depth limit for vegetation varied from 7 to 9 meters.

After 20 years of INPP operation significant changes were observed in all ecological zones of aquatic vegetation. *Charophyta* species have totally become extinct from the submerged plant zone of shallow areas near the INPP. The intensive development of filamentous green algae during a prolonged vegetation period and decrease of water transparency was an important reason for the decline of submerged vegetation. The areas occupied by helophyte communities (*Phragmites australis, Schoenoplectus lacustris*) increased significantly in shallow areas up to 2 m.

The fish species diversity in Lake Druksiai significantly decreased from 23–26 fish species to the current list of 14 species mostly due to total anthropogenic pressure and thermal load (Kesminas & Olechnoviciene, 2008). The changes occurred mainly after the first years of INPP operation, and then the successive changes slowed down. During the last years the lake fish community has changed insignificantly. There were also some adaptations among some species populations. *Vendace* (stenothermal fish) population partially adapted to the changed environmental conditions and its abundance in the recent years is quite high and constant. The survival and partial rehabilitation of *Vendace* indicates that some fish species may become acclimated to the disrupted thermal and eutrophic conditions in the lake (Ecosystem, 1992; Institute of Botany, 2008).

6. Conclusions and relevance

Considering the findings of this study, it can be assumed that changes in macrophyte species and fish communities diversity in Lake Druksiai could be induced by the total chemical, predominant thermal and very limited radioactive pollution as anthropogenic pressure which had a negative impact on some aquatic organisms.

The data presented enlarge knowledge about the concentration of radionuclides in European freshwater ecosystems in order to understand the internal and external exposure dose rates of macrophytes and fish communities due to major discharged radionuclides and natural series contributors. In the case of INPP cooling pond - Lake Druksiai the estimation of weighted internal exposure of macrophytes and fish is mostly determined by natural background radionuclides and arises from internally incorporated α-emitters with ^{238}U, ^{226}Ra and ^{210}Po being the major contributors. The total exposure due to anthropogenic discharged radionuclides is substantially lower as compared with the natural background exposure.

The INPP operational history and the routine radiation in environment monitoring data evidenced that INPP was operated safely and helpfully for the society from radiation protection point of view. However environmental changes in Lake Druksiai related mostly to the chemical, thermal and general urbanization pressure are unavoidable and acceptable from society side traces of electric power industry development.

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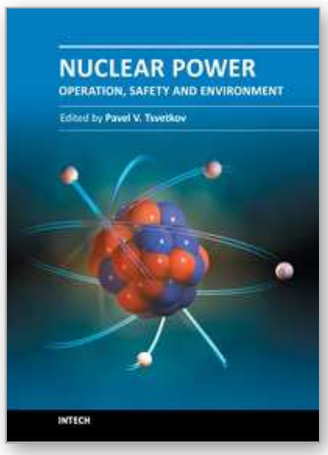
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Todayâ€™s nuclear reactors are safe and highly efficient energy systems that offer electricity and a multitude of co-generation energy products ranging from potable water to heat for industrial applications. At the same time, catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, design requirements and facilitated growing interests in advanced nuclear energy systems, next generation nuclear reactors, which are inherently capable to withstand natural disasters and avoid catastrophic consequences without any environmental impact. This book is one in a series of books on nuclear power published by InTech. Under the single-volume cover, we put together such topics as operation, safety, environment and radiation effects. The book is not offering a comprehensive coverage of the material in each area. Instead, selected themes are highlighted by authors of individual chapters representing contemporary interests worldwide. With all diversity of topics in 16 chapters, the integrated system analysis approach of nuclear power operation, safety and environment is the common thread. The goal of the book is to bring nuclear power to our readers as one of the promising energy sources that has a unique potential to meet energy demands with minimized environmental impact, near-zero carbon footprint, and competitive economics via robust potential applications. The book targets everyone as its potential readership groups - students, researchers and practitioners - who are interested to learn about nuclear power.

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