Evaluation of aquatic routine radioactive releases from the Ignalina Nuclear Power Plant

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The Ignalina Nuclear Power Plant is located on the shore of Lake Drūkšiai and is cooled by water from this lake, which is characterized by a relatively slow water exchange. Run-off from this lake reaches the Gulf of Riga of the Baltic Sea through a long and complex pathway approximately 550 km long. In this work, radionuclide activities in the environment as well as annual individual effective doses over the main exposure pathways for fishermen (also their family members) groups related to different parts of the hydrological system were estimated on the basis of reported aquatic releases. For the observed minimum and maximum discharges from the Ignalina NPP, annual effective doses to adult fishermen of Lake Drūkšiai were calculated within the range 1.1×10^{-3}–0.02 mSv y^{-1} and to fishermen of the Daugava River (in the vicinity of the Daugavpils city) within 4.0×10^{-6}–1.6×10^{-4} mSv y^{-1}. This dose exceeds the exemption level insignificantly.

Key words: nuclear power plant, radionuclide, hydrological system, routine releases, compartment, dose assessment

INTRODUCTION

The Ignalina Nuclear Power Plant is located in the northeastern part of Lithuania near the borders of Belarus and Latvia. The plant is operating two graphite-moderated, channel-type boiling water RBMK-1500 reactors with a designed thermal power outputs of 4800 MW. The first unit was put into operation in December 1983, the second one began operating in August 1987.

For cooling the turbine condensers, the Ignalina NPP uses water from Lake Drūkšiai, the eastern part of which belongs to Belarus. Lake Drūkšiai is a flow-through lake with several small rivers, creeks and drains flowing in and one river, with a water regulation dam, flowing out. Lake Drūkšiai is characterized by a relatively slow water exchange. Run-off from the lake takes place in Belarus and begins with the Prorva River (Fig. 1).

According to international practice, in normal operation mode of the plant radioecological evaluation of atmospheric and aquatic releases to the environment is based on public individual doses. Dose assessment is done for critical group members. The principle of dose limitation requires that the sum of effective doses caused by all human activities that can increase the exposure of individuals to radiation shall not exceed the dose limit of 1 mSv annually. For separate nuclear facilities there is established a dose constraint which in the case of the Ignalina NPP is equal to 0.2 mSv/year. When different radionuclide release pathways correspond to the same or different critical groups, both major release pathways (atmospheric and aquatic) have half of the actual dose constraint value (= 0.1 mSv/year).

For the period 1984–1998, annual committed effective doses for critical group members were less than 0.001 mSv for the Ignalina NPP airborne releases and less than 0.05 mSv for aquatic releases (Nedveckaite et al., 2000). Relatively higher doses due to aquatic releases compared to airborne ones and the increased attention of neighboring countries to the radioecological state of the hydrological system related to the Ignalina NPP discharges stimulated a more detailed evaluation of radionuclide transport via the hydrological pathway and of the doses for a critical receptor related to various chains of the hydrological system.

In the present work, calculations of radionuclide transfer through lakes and rivers and the maximum annual effective doses for the critical group members were performed using a slightly modified PC CREAM (Consequences of Releases to the Environment Assessment Methodology) model (Simmonds et al., 1995). However, the PC CREAM 97 code does not include a lake module. Therefore, a simple box model for lakes was combined with the river PC CREAM model.

Validation of the calculations was done using Lake Drūkšiai radioecological monitoring data. However, only a few radionuclides such as ^{60}Co, ^{137}Cs, ^{90}Sr, ^{3}H and ^{14}C have been measured in the environment and could be used for the validation. Activity concentration of other radionuclides is below detection limits.

METHODS

A dynamic compartment analysis method was used to simulate the transfer of radionuclides in the aquatic environment. This method assumes instantaneous uniform mixing within each compartment, with the transfer between compartments being proportional to the inventory of radionuclides in the source compartment (Simmonds et al., 1995).

The differential equation which describes the variation of the activity A_i, in compartment i of the model is the following:

$$\frac{dA_i}{dt} = \sum_{j=1}^{n} k_{ji} A_j - \sum_{j=1}^{n} k_{ij} A_i - k_i A_i + Q_i \, , \tag{1}$$

where A_i and A_j are activities present at time t in compartments i and j (Bq);

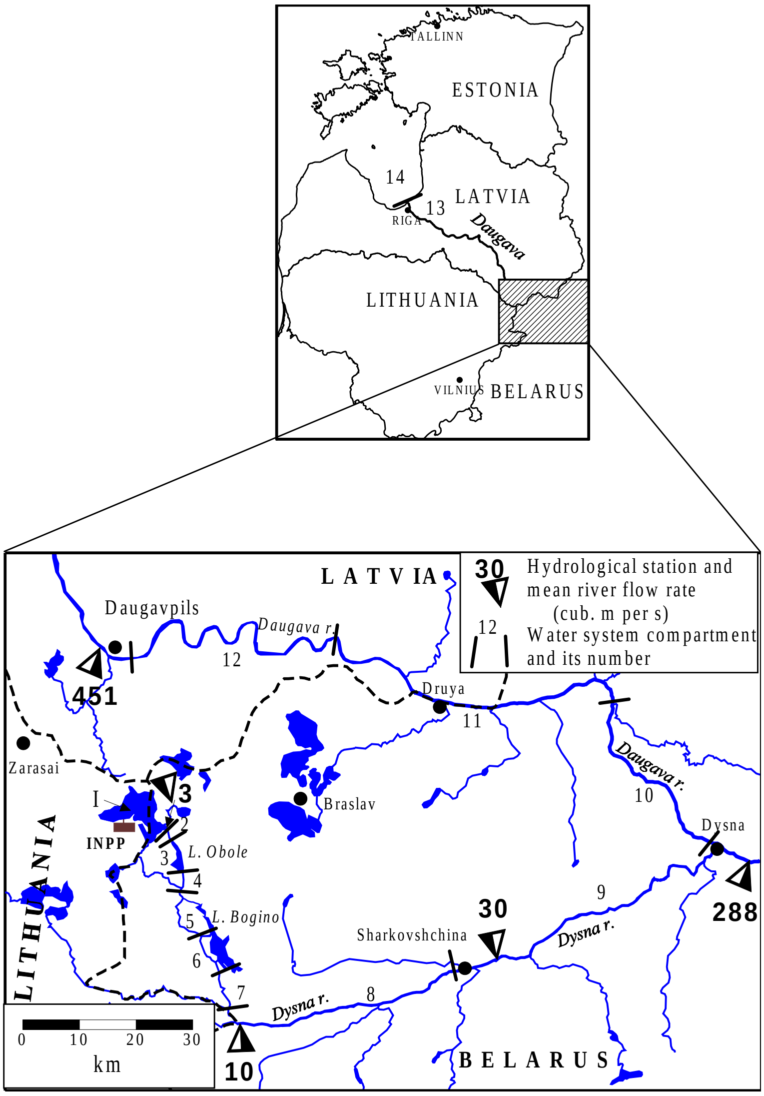

Fig. 1. The hydrological system of the Dysna and Daugava Rivers connecting Lake Drūkšiai and the Gulf of Riga of the Baltic Sea

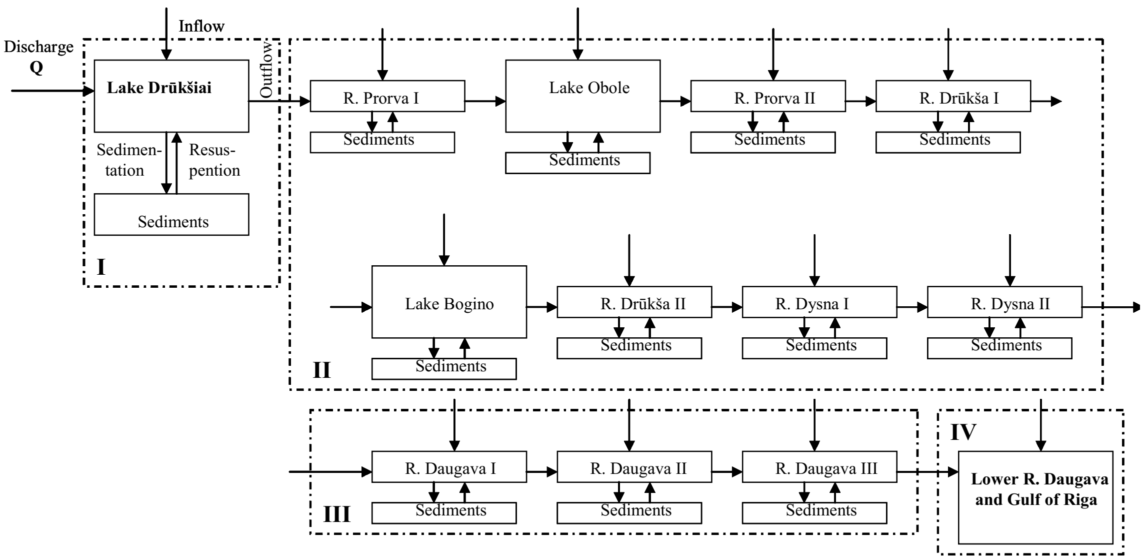

Fig. 2. Schematization of Lake Drūkšiai and related river system compartments

k_{ij} and k_{ji} are the rates of transfer between compartments i and j (s^{-1}); k_i is the effective transfer rate from compartment *i,* which takes account of radionuclide loss from the compartment without transfer to another, for example, by radioactive decay (λ, s^{-1}); Q_i -is a source of continuous input into compartment i or the discharge rate (Bq s^{-1}); n is the number of compartments in the system; i = 1, n; k_{ii} = 0.

Several modules were developed to characterize the hydrological system related to the Ignalina NPP discharges: module I – Lake Drūkšiai; module II – dynamic river model II; module III – dynamic river model III; module IV – simple dilution river (rest Daugava) and the Gulf of Riga models (Fig. 2).

Radionuclide activity concentrations associated with suspended sediments and with bed sediments as well as in filtered water were calculated for three operation durations (1, 5, 50 years) for each simulated compartment and then used to derive different irradiation parameters. The site-specific and generic radionuclide transfer parameter values were applied during calculation using PC CREAM 97 code. These were: freshwater sediment distribution coefficients K_d, sedimentation coefficients k' and concentration factors for freshwater fish (Simmonds et al., 1995); gamma energies and decay constants λ for each radionuclide (ICRP, 1983); beta doses for each radionuclide (US DoE, 1988); and the dose coefficient for intakes by ingestion (IAEA, 1996). For photon exposure recommended by NRC (NRC, 1977), reduction factors (0.3 for lake shoreline, 0.2 for river shoreline) were applied.

INPUT DATA AND ASSUMPTIONS

A major part of radionuclides from the INPP enters Lake Drūkšiai with technical (cooling) water. ^{137}Cs, ^{60}Co, ^{89}Sr, ^{90}Sr, ^{54}Mn, ^{95}Nb dominate in discharges. The contribution of the other outlets of discharges into the lake is less important. The annually released total activity changes in time and has a decreasing trend over the past several years. Improvements in the NPP operation, without additional reactor downtime, implemented over the past decade are mainly responsible for this trend. Two time points were selected from this trend for calculations: 1990, when maximum annual discharges took place: 2000, when a significantly reduced discharge rate was observed (Table 1).

To compare transfer extension of various radionuclides in a hydrological system, the unit discharge rate was used as well. Ten typical radionuclides with a more significant abundance in releases and in environmental objects were selected for calculations. For comparison of doses received in the environment of different hydrological pathway chains, only members of one critical group (fishermen) were investigated.

The main parameter values for radionuclide transport in rivers are presented in Table 2.

Main hydrological parameter values were obtained from the state hydrological networks of Lithuania, Belarus and Latvia. Mean river flow rates were evaluated as follows: the Prorva R. is 3 m^3 s^{-1} (observation in 1980–1983): the Dysna R. is 10 m^3 s^{-1} (observation in 1945–1960), the Dysna R. is 30 m^3 s^{-1} (observation in 1945–1981), the Daugava R. is 288 m^3 s^{-1} (observation in 1944–1988), the Daugava R. is 451 m^3 s^{-1} (observation in 1921–1980) (see Fig. 1).

For calculations of radionuclide activity in water in the lower reaches of the Daugava River and in the Gulf of Riga, the flow rate of 700 m^3 s^{-1} (compartment 13) and water volume of 1.1×10^{12} m^3 (compartment 14) respectively were adopted (the hydrological path from Daugavpils to the Gulf of Riga makes 250 km).

There are radionuclide-dependent site-specific parameter values (K_d, B_F) for some globally distributed radionuclides as ^{137}Cs and ^{90}Sr (Mažeika et al., 1999; Motiejūnas et al., 1999; Špirkauskaitė and Tarasiuk, 1997). The other parameter values are generic (Simmonds et al., 1995).

Table 1. **Input into Lake Drūkšiai activity (release rate) used in calculations**

Source term	Radionuclide									
	$^{3}H^{a}$	$^{14}C^{a}$	^{54}Mn	$^{59}Fe^{b}$	^{60}Co	^{90}Sr	$^{95}Nb^{b}$	$^{131}I^{b}$	$^{134}Cs^{b}$	^{137}Cs
Unit release (Bq y^{-1})	1×10^{12}	1×10^{12}	1×10^{12}	1×10^{12}	1×10^{12}	1×10^{12}	1×10^{12}	1×10^{12}	1×10^{12}	1×10^{12}
Actual release in 1990 (Bq y^{-1})	9.5×10^{11}	1.6×10^{8}	2.4×10^{9}	2.1×10^{8}	5.2×10^{10}	6.2×10^{8}	4.2×10^{8}	4.2×10^{8}	8.2×10^{8}	4.1×10^{9}
Actual release in 2000 (Bq y^{-1})	2.4×10^{11}	3.4×10^{7}	3.0×10^{5}	3.6×10^{7}	4.0×10^{7}	3.5×10^{8}	3.3×10^{6}	9.1×10^{8}	7.1×10^{7}	4.4×10^{8}

[a] Released activity of ^{3}H and ^{14}C was not measured but evaluated according to environmental data (Mažeika ir kt., 1998).
[b] Evaluated typical release rate in recent years, while the measured released activity in 2000 was reported to be zero.

Table 2. **River characteristics used in river dynamic models (II and III)**

Compartment	Velocity (m y^{-1})		Suspended	River			Accepted low river flow rate (m^3 s^{-1}) /mean flow rate ×~0.5/
	water	bed sediment	sediment load (t m^{-3})	width (m)	length (m)	mean depth (m)	
2 – R. Prorva I	3.8×10^6	3.8×10^3	3.0×10^5	14	1.75×10^3	1.3	2.1
3 – Lake Obole	1.0×10^5	1.0×10^2	5.0×10^{-5}	420	6.5×10^3	3	4
4 – R. Prorva II	1.1×10^7	1.1×10^4	4.0×10^{-5}	14	3.5×10^3	1.3	6
5 – R. Drūkša I	8.2×10^6	8.2×10^3	3.0×10^{-5}	21	9.0×10^3	1.3	7
6 – Lake Bogino	1.0×10^5	1.0×10^2	4.0×10^{-5}	510	1.5×10^4	4.9	8
7 – R. Drūkša II	8.2×10^6	8.2×10^3	3.0×10^{-5}	27	9.0×10^3	1.4	10
8 – R. Dysna I	1.1×10^7	1.1×10^4	4.0×10^{-5}	34	4.0×10^4	1.5	18
9 – R. Dysna II	1.5×10^7	1.5×10^4	5.0×10^{-5}	45	5.0×10^4	1.6	44
10 – R. Daugava I	1.5×10^7	1.5×10^4	5.0×10^{-5}	83	2.8×10^4	2.6	100
11 – R. Daugava II	1.9×10^7	1.8×10^4	6.0×10^{-5}	100	6.0×10^4	2.7	160
12 – R. Daugava III	2.2×10^7	2.2×10^4	6.0×10^{-5}	120	6.0×10^4	3	200

Exposure pathways for Lake Drūkšiai include ingestion of fish, inhalation of spray, external gamma and beta radiation from bank sediments and from fishing gear. Exposure pathways for river compartments include ingestion of fish, ingestion of drinking water (which is assumed to be filtered river water without water treatment processes) and external gamma and beta radiation from bank sediments.

RADIONUCLIDE ACTIVITY AND DOSE ESTIMATES BASED ON REPORTED RELEASE DATA

Radionuclide concentrations in lake and river compartments after 1, 5 and 50 years of operation at a continuous unit discharge rate of 10^{12} Bq y^{-1} were calculated to compare the behavior of radionuclides. For most of the radionuclides studied, equilibrium concentrations in the water are to be reached within 1–5 years. It takes a longer time to reach equilibrium in the bottom sediments. In the case of long-living ^{137}Cs and ^{90}Sr radionuclides it takes as much as 50 years. Activity variations depend mainly on bed sediment downstream transport. The calculated radionuclide concentrations in filtered water of all compartments following a continuos release into Lake Drūkšiai are presented in Fig. 3.

As the discharge rate for various radionuclides is the same, their averaged behavior in the hydrological system differs and is caused by physico-chemical peculiarities (solubility, decay rate, etc.), which can be integrally expressed by main transfer parameters (K_d, λ). ^{3}H, ^{14}C, ^{90}Sr and ^{131}I are the radionuclides most mobile in the hydrological system. Their activity concentrations in water at the beginning of the hydrological pathway (first river compartment is the Prorva R.) little decrease compared to the equilibrated activity in Lake Drūkšiai. Activity concentrations of low mobility or short-lived radionuclides (^{60}Co, ^{137}Cs) in the first river compartment decrease significantly – almost two times for ^{60}Co and 3 times for ^{137}Cs. This trend of radionuclide activity decrease with certain variations is more drastic going downstream, while dilution processes in rivers with a high flow rate and through-flow lakes with large water volume are active.

Similar calculations have been repeated for the years 1990 and 2000 with highest and lowest releases respectively. The bulk of ^{3}H and ^{14}C discharged into Lake Drūkšiai enter the Prorva R. The fraction of these radionuclides (especially of ^{3}H) chan-

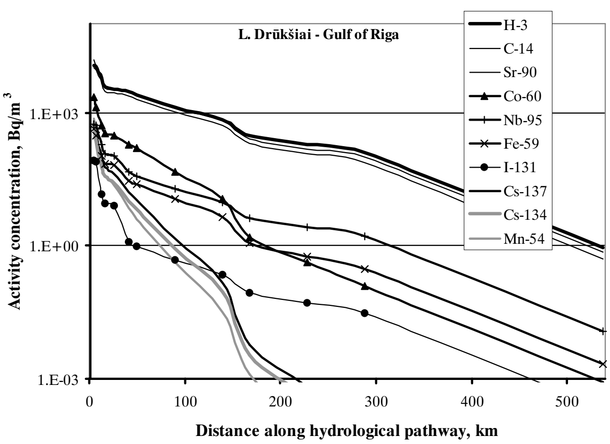

Fig. 3. Simulated radionuclide activity concentrations in filtered water of different compartments along the hydrological pathway for the unit release rate into Lake Drūkšiai 10^{12} Bq y^{-1} (integration time 50 years)

ges little downstream to the Gulf of Riga due to radioactive decay and a low sedimentation effect (sedimentation factor *k′* for ^{3}H is assumed to be zero). Approximately 90–76% of discharged ^{3}H and ^{14}C and 56% of ^{90}Sr flow into the Gulf of Riga. Only an extremely small amount of low mobility or short-living radionuclides such as ^{54}Mn, ^{60}Co, ^{131}I, ^{134}Cs, ^{137}Cs can reach the Gulf of Riga.

The radionuclide activity concentrations in the lake water calculated using discharges of the year 2000 are as follows: for ^{3}H is 2760 Bq m^{-3}, ^{14}C is 0.5 Bq m^{-3}, ^{60}Co is 0.1 Bq m^{-3}, ^{90}Sr is 3.9 Bq m^{-3}, ^{137}Cs is 0.5 Bq m^{-3}. Downstream along the hydrological pathway reaching approximately 280 km in length as far as Daugavpils the activity concentrations of each radionuclide in filtered water reduce significantly. The factor of reduction of radionuclide activity in filtrated water has the following values: 90 times for ^{3}H, 155 times for ^{14}C, 1.8×10^{4} times for ^{60}Co, 144 times for ^{90}Sr and 1.3×10^{7} times for ^{137}Cs.

In the next stage, an estimation of maximal individual doses due to the Ignalina NPP discharges was performed. According to the reported data, maximum aquatic releases have taken place in 1990 (see Table 1). For this year the maximum annual effective doses to fishermen of Lake Drūkšiai was less than 0.02 mSv and to fishermen of the Daugava River critical group (in the vicinity of the Daugavpils city) was about 1.6×10^{-4} mSv. The doses for different age groups (adults, children and infants) are presented in Fig. 4.

In 1990, the exposure dose for Lake Drūkšiai compartment was caused by ^{60}Co, ^{137}Cs, ^{134}Cs, ^{90}Sr mainly. Downstream the contribution of ^{60}Co is growing significantly due to sediment transport, while the total dose is decreasing.

According to the 2000 discharge data (see Table 1), the maximum annual effective dose to fishermen of Lake Drūkšiai critical group makes up to 1.1×10^{-3} mSv y^{-1} and to fishermen of the Daugava River in the vicinity of the Daugavpils city is less than 4.0×10^{-6} mSv y^{-1}. Total doses for different age groups (adults, children and infants) are presented in Fig. 5.

In Lake Drūkšiai compartment the dose is caused by ^{137}Cs, ^{90}Sr and ^{134}Cs. The contribution of ^{90}Sr is growing downstream and tends to prevail due to water transport, while the total dose decreases. The contribution of immobile radionuclides (for example, ^{60}Co) among the considered exposure pathways (fish consumption, water ingestion, spray inhalation, external gamma and beta radiation from shoreline sediments) to the irradiation reduces significantly along the hydrological stream.

The main exposure pathway for Lake Drūkšiai is ingestion of fish, however, for downstream compartments the contribution of fish ingestion decreases, while the importance of external gamma exposure increases significantly. Partial contribution of mobile radionuclides (for example, ^{3}H) to the dose along the hydrological pathway changes little. For the critical groups related to downstream river compartments, the main exposure pathway is water ingestion, while fish ingestion makes up to 10% of the dose.

The highest individual doses are evaluated for adult fishermen. In all cases the estimated total individual doses decrease from adults to infants. The highest individual dose received due to liquid radioactive effluents from the Ignalina NPP made about 2% of the dose limit. However, individual effective doses due to the operation of the Ignalina NPP exceed the doses caused by liquid discharges from nuclear power plants located on marine coast and having better dilution, for example, Finnish nuclear power plants (Klemola et al., 1998).

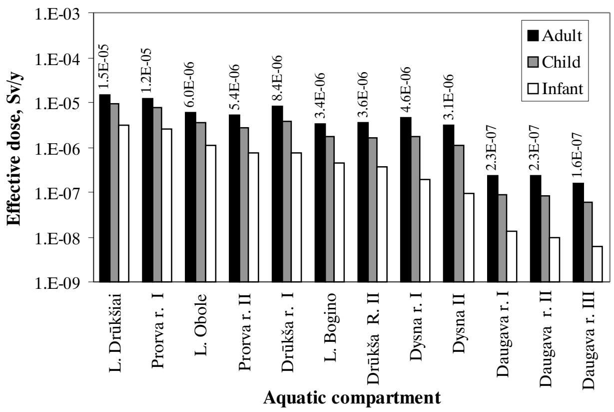

Fig. 4. Total individual effective doses to members of critical groups related to all chains of the hydrological system, predicted by aquatic releases of radionuclides from Ignalina NPP in 1990 (10^{-5} Sv/y – exemption level)

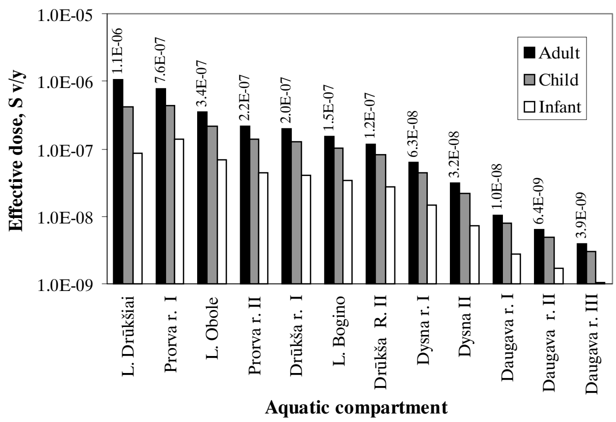

Fig. 5. Total individual effective doses to members of critical groups related to all chains of the hydrological system, predicted by aquatic releases of radionuclides from Ignalina NPP in 2000

Table 3. **Comparison of simulated and measured environmental data on radionuclide activity in Lake Drūkšiai**

Nuclide	Simulated values (for release rate of 2000 and 1990)			Measured activity range (in 1997–1999)			Comments
	Water (Bq m^{-3})	Bottom sediment[a] (Bq kg^{-1})	Fish (Bq kg^{-1})	Water (Bq m^{-3})	Bottom sediment[b] (Bq kg^{-1})	Fish (Bq kg^{-1})	
^{60}Co	0.1; 113	0.1	0.02; 32	<dl–0.5	<dl–0.7	0.1–0.7	Contributed only by Ignalina NPP releases
^{137}Cs	0.5; 4.4	0.05	0.8; 7.4	0.7–1.6	9.7	0.8–5	By Ignalina NPP releases contributed about 50% of ^{137}Cs in water and less than 1% in bottom sediments, transfer from catchment significant (global load ~1000 Bq m^{-2})
^{90}Sr	3.9; 6.5	2.0×10^{-3}	0.2; 0.3	18–24	4.7	1.5–18	By Ignalina NPP releases contributed about 10% of ^{90}Sr in water and less than 1% in bottom sediments, transfer from catchment significant (global load ~400 Bq m^{-2})
^{14}C	0.5; 2.4	1.4×10^{-3}	1.4; 6.6	120 ± 2 pmC	73 pmC	no data	1 pmC = 2.27 Bq per kg of C, global background 112 pmC, HCO_3^- in Lake Drūkšiai 150 mg l^{-1}, contributed by Ignalina NPP ^{14}C activity makes less than 7 pmC
^{3}H	2760; 10900	1.9×10^{-3}	1.9; 7.4	40 ± 4 TU	no data	no data	1 TU = 118 Bq m^{-3}, global background 16 TU, contributed by Ignalina NPP ^{3}H activity makes 24 TU

[a] Equilibrium activity corresponding to the release rate of 1990.
[b] Mean value from measurements of 240 samples.

COMPARISON OF THE ESTIMATED VALUES WITH MEASURED ENVIRONMENTAL DATA

For validation of the simulations it is necessary to compare the calculated data with the measured environmental data available for the region. There exists an extended set of monitoring and research data for Lake Drūkšiai, mainly on five most abundant artificial radionuclides (^{137}Cs, ^{90}Sr, ^{60}Co, ^{14}C and ^{3}H), meanwhile in simulations also ^{134}Cs, ^{131}I, ^{95}Nb, ^{59}Fe, ^{54}Mn whose activity concentration in the environmental object of the Ignalina NPP region often are below detection limits have been included. There are no or very few measured data for other aquatic compartments of the hydrological pathway. A comparison of simulated data and those measured during 1997–1999 is presented in Table 3.

The measured data are taken from relevant publications (Marčiulionienė, Petkevičiūtė, 1997; Mažeika ir kt., 1998; Mažeika ir kt., 2000; Nedveckaitė et al., 2000). Only simulated and measured data on ^{60}Co could be directly compared without corrections, because this radionuclide is from one source. Other radionuclides measured in the Lake Drūkšiai environment have contributions from several sources including nuclear weapons test, Chernobyl accident, cosmogenic sources as well as the Ignalina NPP. These contributions were already evaluated using a catchment-lake transfer approach [5].

In general, the simulation results do not contradict the environmental monitoring data available for different objects of Lake Drūkšiai and confirm the presented dose average estimates as well as those reported by the Ignalina NPP aquatic release data.

CONCLUSIONS

1. The calculated activity concentration values show a rather good agreement with the measured data.

2. Adsorption of radionuclides by sinking particles is the prevailing mechanism of radionuclide removal from the water, except ^{3}H, ^{14}C, ^{90}Sr and ^{131}I.

3. Adult fishermen are the group most heavily exposed to liquid radioactive effluents. The doses of irradiation of children from fishermen families are significantly lower.

4. The calculated individual committed dose due to the Ignalina NPP effluents is much less than the dose limit (less than 2% of the annual dose limit) and reduces significantly with the distance from the release point.

5. The cross-border transfer of the Ignalina NPP effluents via the hydrological pathway to Belarus and especially to Latvia is insignificant. Starting from Lake Obole compartment (Belarus) the committed dose is lower than the exemption level (0.010 mSv/a).

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VANDENS NUOTEKŲ SU RADIONUKLIDAIS IŠ IGNALINOS AE ĮVERTINIMAS, VEIKIANT ELEKTRINEI NORMALIU REŽIMU

S a n t r a u k a

Ignalinos AE pastatyta ant Drūkšių ežero kranto ir yra aušinama šio ežero vandeniu. Ežerui būdinga palyginus lėta vandens apykaita, paviršinis nuotėkis iš ežero ilgu (apie 550 km) ir sudėtingu hidrologiniu keliu pasiekia Baltijos jūros Rygos įlanką. Šiame darbe, remiantis išmetų su radionuklidais į Drūkšių ežerą apskaitos duomenimis bei panaudojant kompiuterinius modelius PC CREAM 97, įvairiuose aplinkos objektuose buvo suskaičiuoti radionuklidų aktyvumai, kuriuos galėjo lemti Ignalinos AE normali veikla. Taip pat buvo suskaičiuotos individualios efektinės dozės, kurias patiria kritinės grupės nariai (žvejai ir jų šeimos nariai) įvairiausiomis apšvitos trasomis. Buvo palyginta su skirtingais hidrologinės sistemos elementais susijusių kritinių grupių narių individuali apšvita. Remiantis registruotų išmetų į Drūkšių ežerą mažiausiais ir didžiausiais aktyvumų lygiais, nustatyta, jog suaugusių žvejų, susijusių su Drūkšių ežeru, apšvita kinta nuo 1,1 × 10^{-3} iki 0,02 mSv per metus, o analogiškos kritinės grupės, susijusios su Dauguvos upe (Daugpilio apylinkėse), apšvita kinta nuo 4,0 × 10^{-6} iki 1,6 × 10^{-4} mSv per metus. Skaičiavimų duomenys palyginti su eksperimentinių matavimų rezultatais ir iš esmės jiems neprieštarauja. Vandens keliu patiriamos dozės yra labai mažos ir tik kai kuriuose hidrologinės sistemos elementuose yra nereguliuojamos praktinės veiklos su jonizuojančios spinduliuotės šaltiniais lygio (10^{-5} Sv per metus) ar nežymiai didesnės už jį.

Raktažodžiai: atominė elektrinė, radionuklidai, hidrologinė sistema, išmetos, hidrologinės sistemos elementai, dozės nustatymas