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CHANGES IN MACROPHYTES AND FISH COMMUNITIES IN THE COOLER OF IGNALINA NUCLEAR POWER PLANT (1988–2008)

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Abstract. On the basis of long-term studies of the radionuclide and heavy metals accumulation and scatter in biotic and abiotic components of Drūkšiai Lake as well as of water and bottom sediments toxicity and genotoxicity, radioactive, chemical and thermal pollution potential impacts on macrophytes and fish communities of Drūkšiai Lake were evaluated. Before starting exploitation of Ignalina Nuclear Power Plant (INPP) 95 species of macrophytes were found in Drūkšiai Lake. Since the start-up of the second nuclear reactor of INPP (1987), significant alternations in macrophytes species composition and biomass in Drūkšiai Lake were especially observed to 1989. Resistant to the pollution macrophytes species began to dominate in the Lake. In 2007–2008 in the main part of the Lake, in which INPP sewage entered, only resistant to anthropogenic impacts macrophytes species were found. Fish species composition also has changed. The varietal diversity of the fish in the Lake significantly decreased from 23–26 (before INPP start-up) species to 14 ones. Considering the findings of our study, it can be assumed that changes in macrophytes species and fish varietal diversity in Drūkšiai Lake could be induced by total chemical, thermal and radioactive pollution, which had a negative impact on aquatic organisms. It can be predicted that new ecological conditions will appear in Drūkšiai Lake after INPP closing in 2009, notably after the changes of thermal water regime. However, the chemical and radioactive pollution in the Lake will be over a long period of INPP dismantling works. In addition, the great challenge for the ecosystem of Drūkšiai Lake will be a new nuclear power plant construction near the closed INPP.

Keywords: Drūkšiai Lake, Ignalina Nuclear Power Plant, radioactive, chemical and thermal pollution, water, bottom sediments, toxic and genotoxic effects, macrophytes, fish.

1. Introduction

Ignalina Nuclear Power Plant (INPP) is located near the Lithuanian border with Belarus and Latvia, at a large Drūkšiai Lake utilized as cooling pond. Like Chernobyl NPP, the INPP was equipped by RBMK-1500 type reactors, i.e. graphite moderated, channel-type, boiling water nuclear reactors (Sarauskiene 2002). Unit One and Unit Two were closed in 2005 and in 2009, respectively. In 2007 the INPP generated about 72.6% of all required electricity in Lithuania (Mažeika and Skuratovič 2009). Drūkšiai Lake is the biggest lake of Lithuania. It is located at an altitude 141.6 m above Baltic Sea level. The area of the Lake is 49 km^3, the greatest depth is 33.3 m, the average depth –7.5 m, the total water volume – 369×10^6 m^3. The catchments area of the lake constitutes of 613 km^2 (Jurgelevičienė *et al.* 1983).

The main pollution source of Drūkšiai Lake was the industrial waste water (WW) of the INPP, municipal waste water (after treatment) and storm water (untreated) from rainwater sewer of the INPP and Visaginas town. All these discharges were mainly multi-component mixtures of chemical substances such as biogenic elements (nitrogen and phosphorus), diluted weak organic acids, heavy metals, radionuclides, petrolic hydrocarbons, ect.) (Marčiulionienė *et al.* 1992; EIA Report 2009). During the INPP operating time the permitted levels of substances, which concentrations are under control were exceeded in very rare cases (EIA Report 2009).

Three different stages of ecological changes in Drūkšiai Lake, stipulated by anthropogenic impact, can be marked. The first stage began after the construction of the INPP started. The large amounts of nutrients entered the water together with terrigenic materials, activating the growth of autochthonous cryophylic algae and cyanobacteria and increasing the activity of primary producers (EIA Report 2009). The second stage of ecological changes began after the First Unit started operating in 1984. The heated water activated the processes, which continued to modify the structure and functional relations of organism communities. The diversity of plankton organisms and cold-water species decreased (EIA Report 2009). The third stage of the change of Drūkšiai Lake ecosystem started when the Unit Two was brought into operation in 1987, which was followed by a period of stable operation of the INPP (EIA Report 2009). New ecological conditions developed and stabilized in all ecosystem of the Lake.

Physical-chemical parameters of water and bottom sediments are very important characterizing the ecological state of aquatic ecosystem and the tendencies of its alterations. Formation of the communities of flora and fauna and their changes during vegetation period reveals the response of the organisms to the impact of environment. The hydrological and hydrochemical regime of the water basin, which are under anthropogenic impact shifts and to these shifts first of all respond species, which are sensitive to one or another environment factor.

Aquatic plants, forming the largest biomass, play the main role in the chemical substances accumulation in fresh water ecosystems. They are the main producents of organic matter and concentrate various substances in rather large amounts (Selbu 2009). The nutrition of the most of aquatic plants is running through the water, therefore, water is the main medium stipulated the accumulation of various toxicants in these plants. Aquatic plants are the first barrier stopped toxicants spreading in the water basin and they are the first link in toxicants migration throughout nutrition chain (Radioecology 1998). The main chain of toxicant migration in the aquatic ecosystem is the following: water – macrophytes – phytofags – predators.

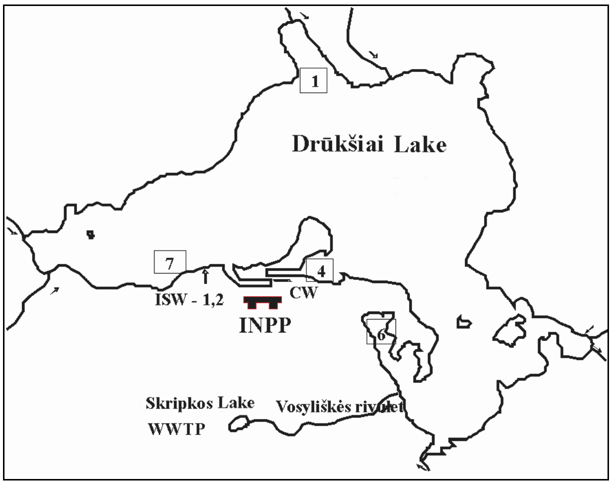
The aim of this study was to assess presumptive impact of thermal, chemical and radioactive pollution on macrophytes and fish communities of Drūkšiai Lake, in accordance with long-term investigations of the pollution of the lake ecosystem by radionuclides and heavy metals and investigations of the toxic and genotoxic effects of water and bottom sediments using biological tests.

2. Materials and methods

Samples of macrophytes, water and bottom sediments were collected at the monitoring stations (1, 4, 6, 7) of Drūkšiai Lake, in the INPP industrial storm water and process water discharge channel (ISW-1,2), in the cooling water discharge channel (CW), as well as in the channel of the INPP and Visaginas municipal waste water treatment plant (WWTP) and in the route of the WW of the WWTP into Drūkšiai Lake in 1988–2004 and 2007–2008 (Fig. 1).

Radionuclide activity concentration in the dry macrophytes and wet fish biomass was estimated by the nuclear spectroscopy methods (Lukšienė *et al.* 2006; Butkus and Konstantinova 2003). Activity concentration of radionuclides in bottom sediments macrophytes and fish was measured in all years showed in graphs of Figs. 2–6, however, the values of activity concentration in some cases were lower than minimal detectable level.

^{137}Cs, ^{60}Co and ^{54}Mn activity concentration in the macrophytes, fish and bottom sediment samples was estimated by γ-spectroscopy method (Gudelis *et al.* 2000). The samples were measured using a high purity germanium detector, with relative efficiency of 30% and energy resolution of 1.72 keV at 1333 keV. The radiochemical methods (Pimpl 1996; Suomela *et al.* 1993) were used for determination of ^{90}Sr activity concentration in the samples. ^{90}Sr activity concentration determination in our laboratory was based on the measurement of ^{90}Y by low background radiometer UMF–1500 M, with counting efficiency of approximately 17%. From 2002, the determination of ^{90}Sr in equilibrium with ^{90}Y was carried out by monitoring the Cerenkov radiation of beta particles (2.27 MeV) from ^{90}Y in a liquid scintillation spectrometer Tricarb 3170TR/SL; efficiency of measurement was approximately 39%. The values of radionuclide activity concentrations in the study are presented on the dry weight basis. The data were expressed as mean ± standard error of the mean that did not exceed 10–15%.



Monitoring stations of Drūkšiai Lake:
St. 1 – the furthest from the INPP; **St. 4** – about 200 m from cooling water discharge channel; **St. 6** – at the zone of impact of waste water of Visaginas municipal WWTP; **St. 7** – at the discharge zone of waste water of industrial storm water and process water discharge channel;

Ignalina NPP waste water channel:
CW – cooling water channel; **ISW-1,2** – channel of industrial-storm water and process water discharge; **WWTP** – INPP and Visaginas municipal waste water treatment plant.

Fig. 1. Scheme of the discharge channels of the Ignalina NPP and monitoring stations of Drūkšiai Lake

Toxicity and genotoxicity tests of the water and bottom sediments were carried out based on the biological tests widely used in the world (EPA 1996a, b; OECD 2003): *Spirodela polyrrhiza* L. (Schleid.) (common duckweed); *Lepidium sativum* L. (garden-cress) (Magone 1989; Montvydienė and Marčiulionienė 2004); *Tradescantia* clone 02 (spiderwort) (Marčiulionienė *et al.* 2004) and *Oncorhynchus mykiss* Walbaum (rainbow trout) (LST ISO 1994). The level of toxicity of water and bottom sediments to *S. polyrrhiza* and *L. sativum* was assessed following the method suggested by Wang (1992), and genotoxic level to *Tradescantia*, following the method suggested by Marčiulionienė *et al.* (1996).

Statistical analysis was performed using *Statgraphics plus for Windows Version 2.1.* (Statistical Graphics Corp., USA) or *GraphPAD InStat* (USA). The data were expressed as mean ± standard error of the mean (M±SE). Differences between measured characteristics were tested by Student's *t*-test with $p \leq 0.001$ or $p < 0.05$.

3. Results and discussion

Until the beginning of the INPP operation Drūkšiai Lake belonged to the group of mesotrophic water bodies with traits of oligotrophicity (Bunikis *et al.* 1987; Balevičienė and Zinkevičienė 1997; Salickaitė-Bunikienė *et al.* 1997). Generally, during the first years after the launch of the INPP (1984–1988), the trophic status of the Lake remains almost unchanged (Salickaitė-Bunikienė *et al.* 1997). Later, when the continuous pollution of Drūkšiai Lake with cooling and waste water proceeded, most of the main parameters of water quality changed, and the Lake turned into a eutrophic water body during very short period of time (Salickaitė-Bunikienė *et al.* 1997; Bernotas 2002; Salickaitė-Bunikienė and Kirkutytė 2003).

3.1. Thermal pollution

80 m^3/s of water from Drūkšiai Lake was used to cool one NPP Unit. The heat load comprises 0.06 kW/m^2 for each Unit under full operating capacity (Sarauskienė 2002). The water was heated by 10–12 °C (compared with input water temperature); the water temperature in the output channels cooled down by 2–3 °C (Janukėnienė and Jakubauskas 1992). The distribution of the temperature fields of surface water depended on the amount of heat discharged to the Lake and metrological conditions (Janukėnienė and Jakubauskas 1992). The natural highest surface temperature of the Lake fluctuated from 20.4 to 25.5 °C (Gailiušis and Virbickas 1995). During the operation time of both Units the discharged effluents raised the average monthly surface temperature of the Lake by 3–4 °C (Sarauskienė 2002). In summer time when natural temperature of surface water exceeded 20 °C the temperature of cooling water discharged from the INPP to the Lake could exceed 28 °C, which is harmful to biota (Drižius *et al.* 1997). The thermal impact of the INPP was obviously localized, and even if it decreased moving away from overheated water discharge place, covered a large of the Lake (Sarauskienė 2002).

3.2. Chemical pollution

Data obtained until the beginning of the INPP operation (1979–1983) showed that mineralization of Drūkšiai Lake water was 233.9 mg/L, an average concentration of the phosphatic phosphorus reached only 0.002 mg/L, and the rate of total nitrogen (N_t) and total phosphorus (P_t) was 21:1 (Bunikis *et al.* 1987). In 1994–1997 the average concentration of P_t exceeded the concentration, which was measured before the INPP operation had been started in 2.4 times and the concentration of phosphatic phosphorus – in 9 times (Salickaite-Bunikiene *et al.* 1997). In 1993 the average rate of the N_t and P_t annual concentrations in the Lake water was very close to the typical rate of eutrophic lakes and in 1995 it became equal to the this rate, e.g. 10:1 (Salickaitė-Bunikienė and Kirkutytė 2003).

Before the INPP operation was started, waters of the Drūkšiai Lake were dominantly bicarbonate-calcium. During the period of 1979–2006 concentration of HCO_3^- and Ca^{2+} ions in these waters varied in narrow limits (EIA Report 2009). Increasing of sedimentation of terrigenic material and organic substances increased the concentration of dissolved organic material (Salickaitė-Bunikienė *et al.* 1997). The increase of particulate organic matter has been observed in the bottom sediments of the Lake. In addition, due to high activity of micro-organisms a decrease of dissolved oxygen content was also observed (EIA Report 2009).

About 80% of the all amount of oil products was discharged into the Lake from the INPP (Jokšas *et al.* 1997). 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 d.w. About 4% of the Lake area had been polluted by hydrocarbons (Jokšas *et al.* 1997).

Concentrations of heavy metals (HM) in the waste water of the INPP and Drūkšiai Lake during the INPP operation time was higher in comparison with concentrations measured before the Plant had been launched (Marčiulionienė *et al.* 1995). During 1993–2007 concentrations of HM in these waters varied in rather wide limits (Montvydienė 2002a; EIA Report 2009). However, in the most cases the concentrations of HM in the water of Drūkšiai Lake have not exceeded the allowable values of water quality (EPA Annual report 2003). Maximal concentrations of HM (soluble and suspended forms) discharged into the Lake from the ISW-1,2 and WWTP channels (Jokšas *et al.* 1997). 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 and the other part of them were involved into biological processes. In other hand, the largest amount of Cu, Ni, Zn, Pb and Cr in the most cases were found out in soluble phase (Jokšas *et al.* 1997). Cd, Pb and Zn prevailed among HM in the bottom sediments of the Lake (EIA Report 2009). According to the pollution level of bottom sediments by HM, the average and strong polluted area covers 27% of all Lake's bottom sediments area, slightly polluted area covers 41%, and non-polluted area covers about 32% (Jokšas *et al.* 1997).

3.3. Radioactive pollution

According to the data of Mažeika and Skuratovič (2009) in the period of 2000–2006 the average annual value of the activity (Bq/year) of ^{137}Cs, ^{90}Sr, ^{60}Co and ^{54}Mn discharged from the INPP into Drūkšiai Lake were $2.91 \cdot 10^8$, $1.42 \cdot 10^8$, $7.16 \cdot 10^7$ and $1.02 \cdot 10^7$, respectively. In 2008 the volume activity of ^{60}Co in the water of ISW-1,2 and CW channels was lower than minimal detectible level (MDL); activity of ^{137}Cs in the water of CW channel was lower than mdl, in the water of ISW-1,2 channel it was 1.4 Bq/m^3 and volume activity of ^{90}Sr in water of the ISW-1,2 and CW channels was 2.1 and 11.5 Bq/m^3, respectively (Mažeika and Skuratovič 2009).

The first stage in the distribution of radionuclides in fresh water ecosystem is quick and intense processes of accumulation of radionuclides in the bottom sediments and hydrophytes. That stipulates the rather rapid decrease of the amounts of radionuclides in water. Therefore, data of radionuclides activity concentration in the water are insufficient in the assessment of the pollution of the fresh water ecosystem by radionuclides. Bottom sediments reflect the long-term pollution of Drūkšiai Lake by radionuclides (especially by ^{137}Cs, ^{60}Co and ^{54}Mn) in the best way, because bottom sediments actively accumulate radionuclides (Marčiulionienė *et al.* 1992).

In 1988 the activity concentration of ^{60}Co and ^{54}Mn was measured only in the bottom sediments of the 4th and 5th monitoring stations of Drūkšiai Lake which are directly impacted by the cooling water from the INPP (Figs 1, 2). However, in 1990 these radionuclides were measured in the bottom sediments of all tested monitoring stations. The main source of ^{60}Co and ^{54}Mn discharged into the Lake was the waste water of the ISW-1,2 and CW channels. The activity concentration of these radionuclides in the bottom sediments from above mentioned channels were higher than that from Drūkšiai Lake (Figs 1, 3). 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 mdl (Figs 1, 3).

The values of the activity concentration of ^{137}Cs and ^{90}Sr in the bottom sediments of the Lake ranged in rather wide limits in 1988–1996 (Fig. 2). The tendency of the decrease of the activity concentration of mentioned above radionuclides was not observed in this period. In addition, the ^{134}Cs was measured in the bottom sediments of the Lake at this time of investigations. Activity concentration of ^{137}Cs and ^{90}Sr in bottom sediments of the CW and ISW-1,2 channels was significantly lower than that in bottom sediments of Drūkšiai Lake. On the contrary, activity concentration of ^{60}Co and ^{54}Mn in bottom sediments of these channels in many cases was significantly higher than that in the bottom sediments of the Lake (Figs 2, 3). In the most cases the activity concentration of ^{60}Co and ^{54}Mn in the bottom sediments of the CW channel and 4th monitoring station of the Lake directly impacted by cooling water was higher than that in the bottom sediments of the ISW-1,2 channel and 7th monitoring station, which is directly impacted by waste water from this channel. That may be affected by the different amounts of ^{60}Co and ^{54}Mn released into Drūkšiai Lake from these channels and by the impact of cooling water on the accumulation of these radionuclides in the bottom sediments of CW channel. In other hand, chemical substances found in the water of the ISW-1,2 channel can decrease accumulation of the radionuclides of corrosion origin in the bottom sediments and hydrophytes, because chemical substances can change physical-chemical form of radionuclides and their distribution in the various components of hydroecosystem (Marčiulionienė 1994).

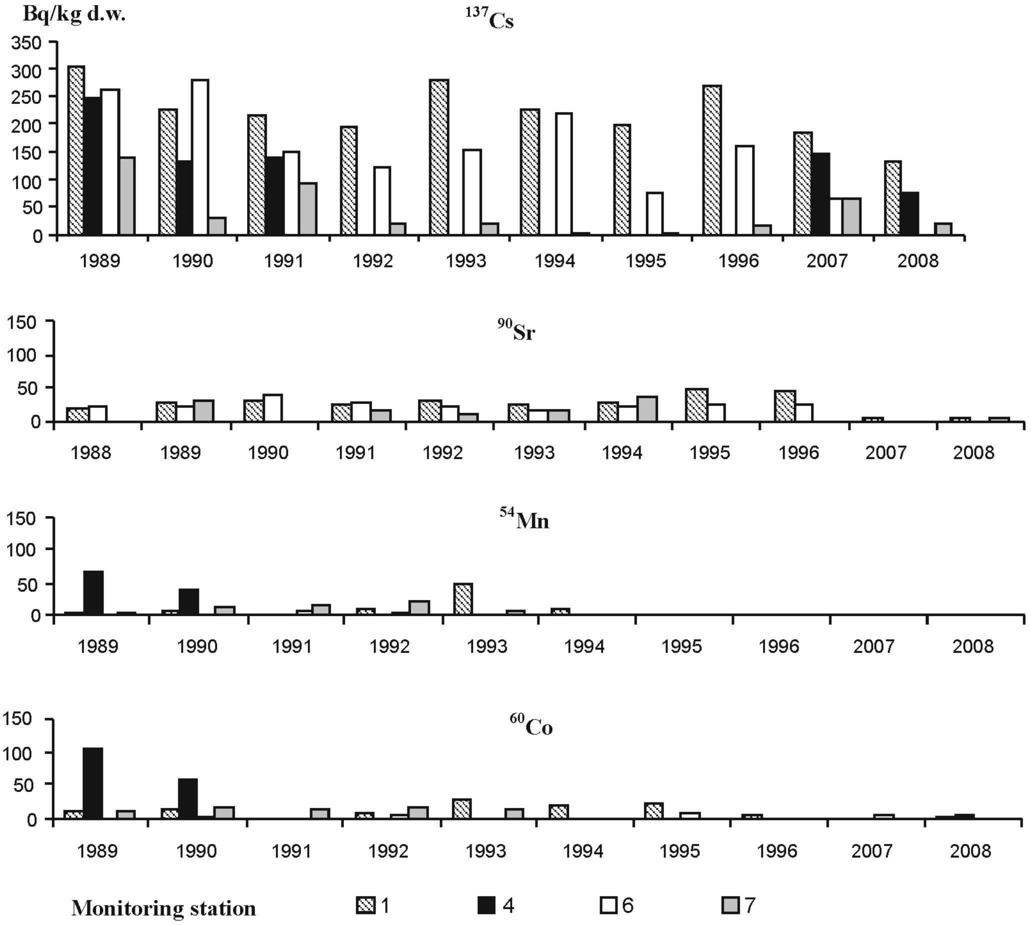


Fig. 2. Activity concentration of radionuclides in bottom sediment of Drūkšiai Lake

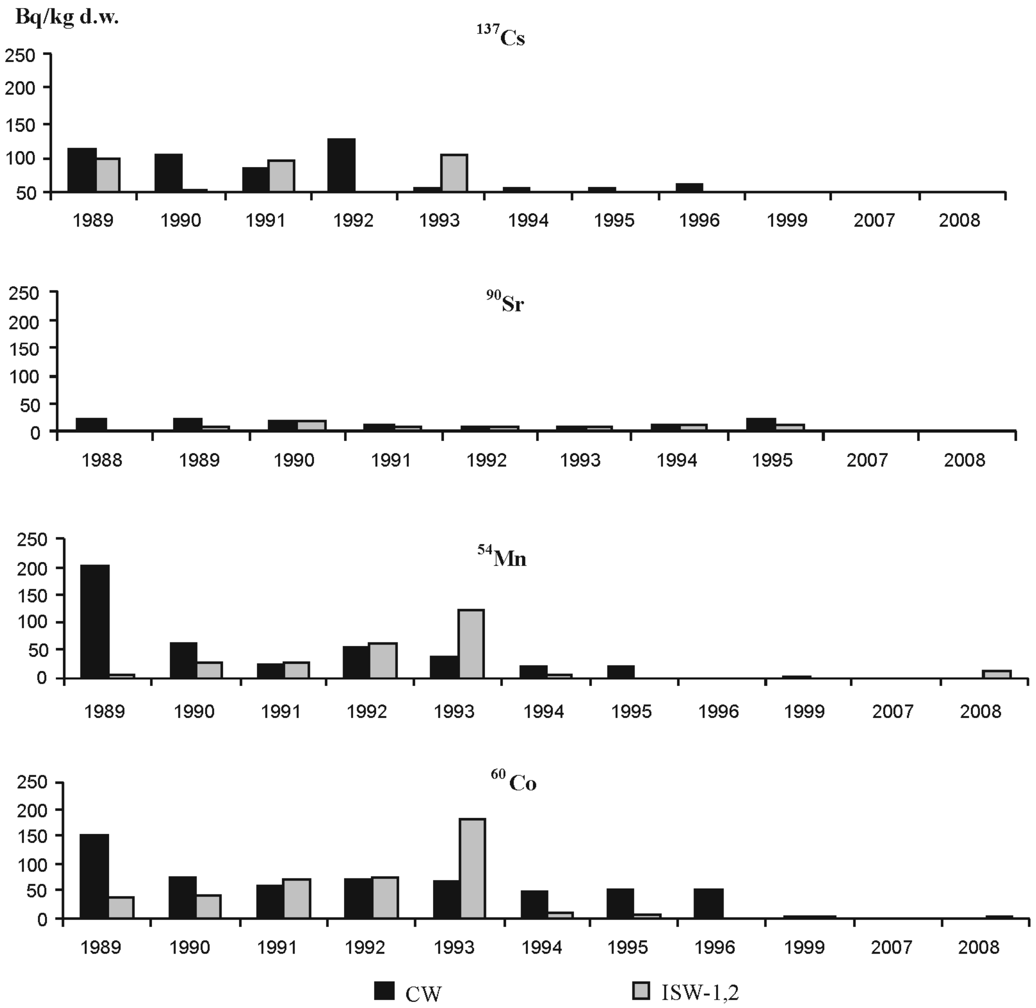


Fig. 3. Activity concentration of radionuclides in bottom sediment of the waste water discharge channels of the Ignalina NPP

For the radioecological investigations about 14 species of macrophytes were collected in the various biotops of Drūkšiai Lake in the period of 1988–1997. However, only 2 species of macrophytes (*Ceratophyllum demersum, Myriophyllum spicatum* and *Potamogeton sp.*) and 1 filamentary algae (*Cladophora* sp.) were found in sufficient amounts in the central part of Lake in 2007–2008.

The highest activity concentration of ^{60}Co and ^{54}Mn was measured in the macrophytes from the 4th and 7th monitoring stations directly impacted by WW from the CW and ISW-1,2 channels in the period 1988–1997 (Fig. 4). Since 1996 the tendency of the decrease of the activity concentration of ^{60}Co and ^{54}Mn in the macrophytes from the INPP's WW channels and the Lake was observed. In the most cases the average values of ^{60}Co and ^{54}Mn activity concentration in the macrophytes from the INPP's channels and from the lake monitoring stations directly impacted by the waste water of these channels differed slightly. However, in 2008 the measured activity concentration of ^{54}Mn and ^{60}Co in the macrophytes from the ISW-1,2 channel was very high – 2639 and 309 Bq/kg d. w., respectively. At time of macrophytes samples collection the INPP was stopped for routine repair. So, high activity concentration of ^{60}Co and ^{54}Mn could be related with these repair works. Consequently, the activity concentration of radionuclides of the INPP's origin can significantly increase after the Plant decommissioning and beginning of dismantling works.

Average values of the activity concentration of ^{137}Cs in the macrophytes were several times lower than that in the bottom sediments during 1988–1996 (Figs 2, 5). The highest values of this radionuclide activity concentration in the macrophytes of the Lake were observed in the period 1989–1995 (Fig. 5). Activity concentration of ^{134}Cs in the macrophytes from the INPP's WW channels and Drūkšiai Lake was detected only in rare cases. The average values of the activity concentration of ^{90}Sr in the macrophytes from the Lake were higher than that in macrophytes from the INPP's WW channels (Figs 4, 5).

Activity concentration of ^{60}Co and ^{54}Mn in whole roach, bream, perch and pike from Drūkšiai Lake is shown in Fig. 6. The largest amounts of these radionuclides accumulated in gills, digestive tract and gonads (Marčiulionienė and Petkevičiutė 1997). In 1987 the values of the activity concentration of ^{137}Cs in the predatory fish (perch and pike) were significantly higher than that in cyprinid fish (roach and bream) (Marčiulionienė and Petkevičiutė 1997).

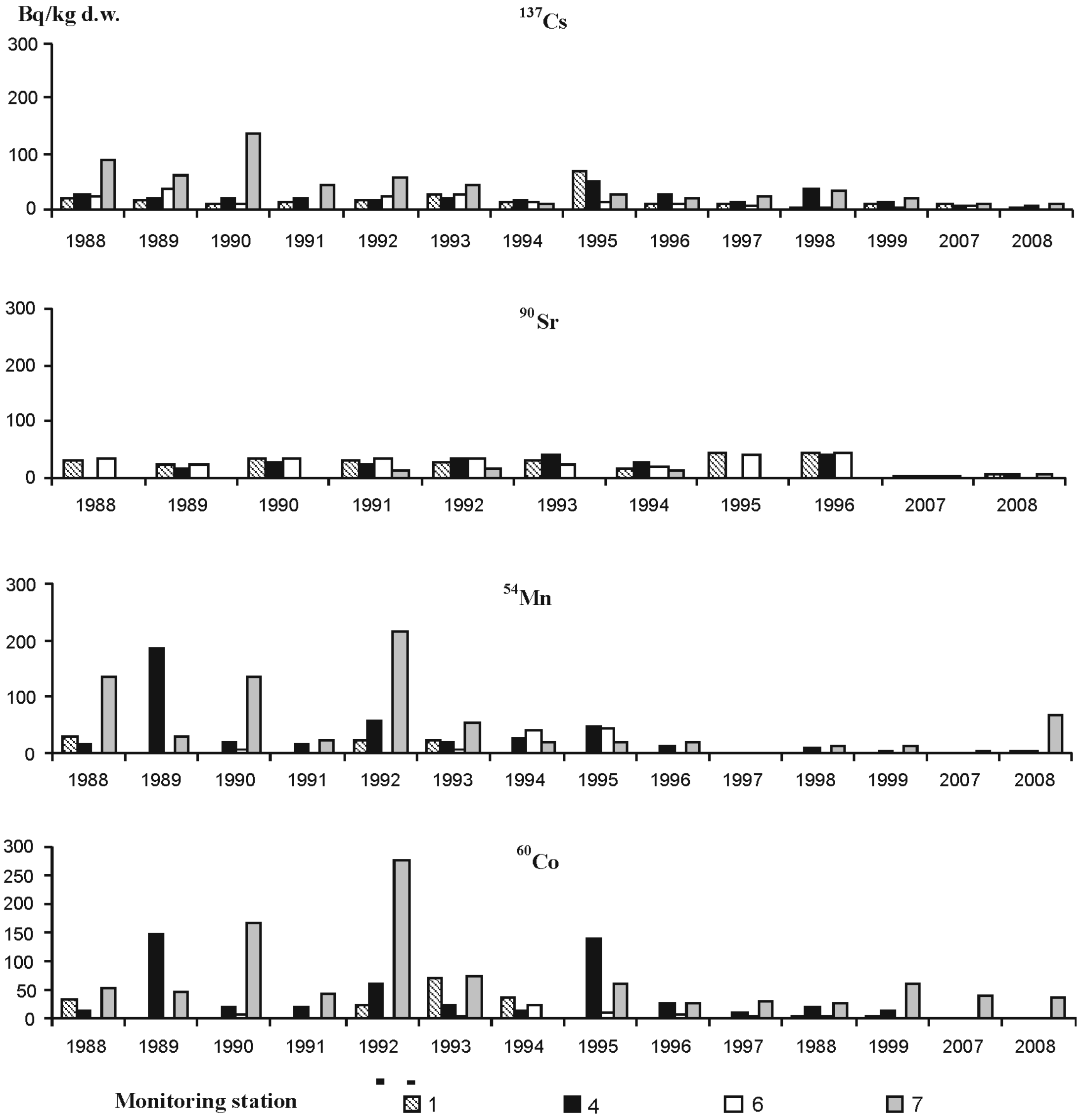


Fig. 4. Activity concentration of radionuclides in macrophytes of Drūkšiai Lake

In 1994 and 2000 activity concentration of this radionuclide in tested fish decreased (Fig. 6). ^{137}Cs activity concentration in the muscle was significantly higher than that in the whole fish (Fig. 6). ^{90}Sr activity concentration in whole fish did not depend on dietary approach. Activity concentration of this radionuclide in the fish muscle was lower than that in whole fish (Fig. 7). ^{137}Cs in the soft tissue of fish distributed rather evenly. This radionuclide can accumulate more intensively only in fish gonads (Marčiulionienė and Petkevičiutė 1997). ^{90}Sr accumulated in the fish bones, digestive tract and gonads in the largest amounts (Dušauskienė-Duž and Gudelienė 2003). Gonads are very sensitive to the impact of ionizing radiation, therefore, they become a target of ^{60}Co, ^{54}Mn, ^{90}Sr, and partly of ^{137}Cs (Dušauskienė-Duž and Marčiulionienė 2002).

Radiological data show that these radionuclides ^{137}Cs and ^{90}Sr are at higher activity concentrations in fish from Drūkšiai Lake. The average activity concentration of ^{90}Sr in the bones of fish from this Lake was 6.54 ± 1.30 Bq/kg, and in the muscles it ranged from 0.29 ± 0.06 to 1.6 ± 0.4 Bq/kg. This area (Drūkšiai Lake) was contaminated after the accident at the Chernobyl NPP. Some radionuclides emmited from the Ignalina NPP to the Lake, and this could be the reason for more contaminated fish as well. The activity concentration of ^{90}Sr in the bones of predatory fish is 3.7 times higher than in their muscles. The highest activity concentration of ^{90}Sr in the bone samples was measured in perch from Drūkšiai Lake (4.50 ± 1.04 Bq/kg). Accumulation of ^{90}Sr in the muscles of roach varied within 0.5 to 1.0 Bq/kg. For perch, activity concentration was mainly the same in all samples from three lakes (0.1–0.3 Bq/kg), but the activity concentration of ^{90}Sr in the samples of predatory fish from Drūkšiai Lake was 1.2 Bq/kg, and in bone samples of predatory fish it was half as low as in peaceful fish (3.2 and 5.7 Bq/kg, respectively). Radioecological monitoring of lakes should be continued, especially of Drūkšiai Lake during the decommissioning of the Ignalina NPP where this Lake is used for cooling, and release to the Lake is possible, considering that this territory was contaminated after the Chernobyl accident also (Čepanko *et al.* 2007, 2006).

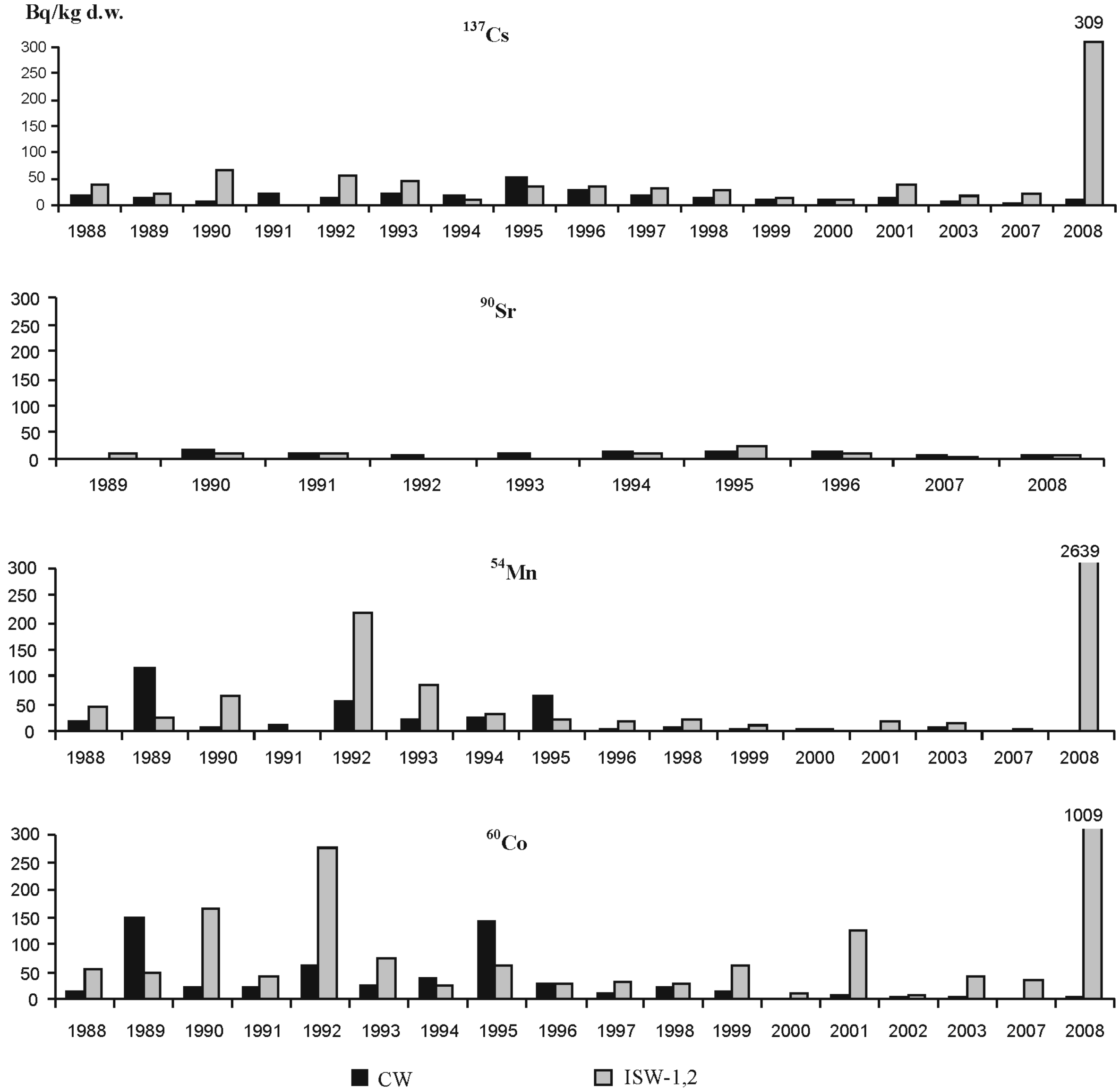


Fig. 5. Activity concentration of radionuclides in macrophytes of wastewater discharge channels of the Ignalina NPP

3.4. Assessment of the toxicity of water and bottom sediments of Drūkšiai Lake using biological tests

There are not much data on the toxic impact of discharges of NPPs on biological tests (Marčiulionienė *et al.* 1992, 1996; Montvydienė 2002; Montvydienė *et al.* 2008), because the main focus of the attention in the most investigations is devoted to the emission of radionuclides from the power plant, their accumulation and distribution among abiotic and biotic components of ecosystem and to the effects caused by low doses of radiation on humans and non-human species (Geras'kin *et al.* 2008).

The impact of WW of the INPP on plants' test-organisms in 1988–2000 and 2007–2008 according to toxicity and genotoxicity scale differed slightly. In most cases, these WW caused weak toxic impact or were non-toxic for *S. polyrrhiza* and *L. sativum*, for *Tradescantia* they were medium or strongly genotoxic. The WW of the ISW-1,2 channel was the most toxic to the tested plants. However, WW (after treatment) of the WWTP and water of Skripkos Lake and Vosyliškės rivulet were more toxic to the tested plants than WW of ISW-1,2 and CW channels. Water of Drūkšiai Lake for *S. polyrrhiza* was mostly non-toxic, for *L. sativum* slightly toxic or non-toxic, and for *Tradescantia* water of the 6th and the 7th monitoring stations was medium, and of the 1st station slightly or medium genotoxic.

According to the impact on *S. polyrrhiza* and *L. sativum* the WW of the INPP may be attributing to WW of low toxicity, however, toxic substances released into the Lake with this WW, in spite of water flow, can accumulate in the bottom sediments of the INPP's channels and Drūkšiai Lake. In the period 1996–2000 and 2007–2008 seed germination of *L. sativum* in the bottom sediments of the INPP's WW channels and Drūkšiai Lake in the most cases did not differ significantly from the control ($p < 0.05$). Toxic impact of bottom sediments of the INPP's channels in the most cases was weak toxic or non-toxic and in rare cases

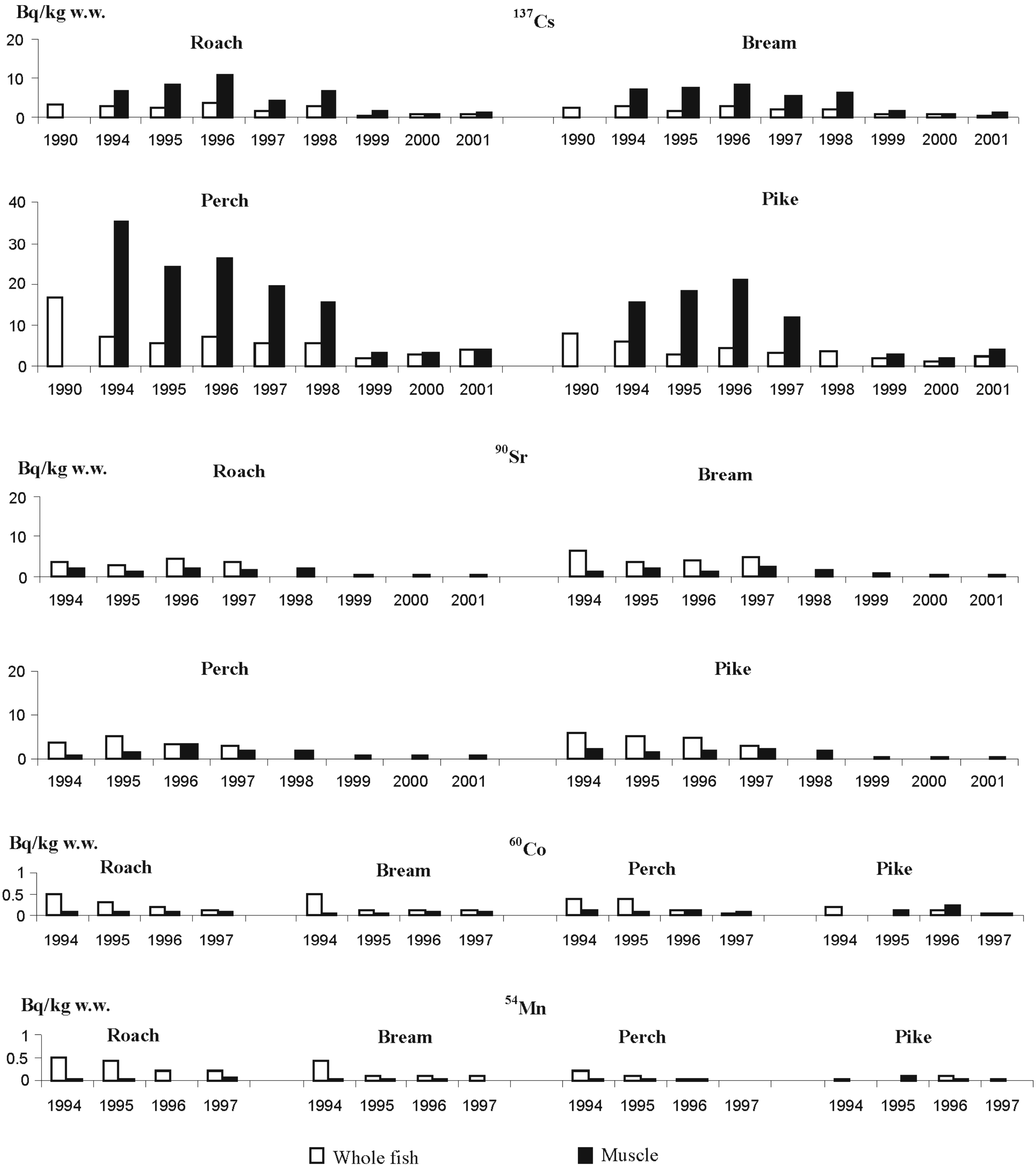


Fig. 6. Activity concentration of radionuclides in the whole fish and fish muscle from Drūkšiai Lake

moderate or strong toxic. For *Tradescantia* the genotoxicity of tested bottom sediments ranged from medium to strong. Such fluctuation of the toxicity of tested bottom sediments to plants may be stipulated by the amounts of toxic substances discharged from the INPP, water flow rate and sorption characteristics of bottom sediments.

Significant seasonal changes on the impact of the tested samples of water and bottom sediments of the INPP discharge channels and Drūkšiai Lake on the growth of tested plants were not observed (Montvydienė 2002).

Ecotoxicological cartography performed in 1995 showed that radioactive and non-radioactive substances in INPP discharges may accumulate in the bottom sediment of the Lake and form areas with the increased level of toxicity. These areas coincide with the borders of an area exposed to the highest level of geochemical contamination (Montvydienė *et al.* 2008).

After regression analysis of data obtained in 1996–2000 and 2007–2008, a tendency of increased toxicity to *L. sativum* of water and bottom sediments of CW channel and the 7-th monitoring station of Drūkšiai Lake have been detected (Montvydienė 2009). Impact of water and bottom sediments of other INPP channels and monitoring stations of the Lake to *L. sativum* has changed little (Montvydienė 2009). This demonstrates that even in case of shutdown of the Unit One, a great amount of chemical substances that reduce growth of *L. sativum* is constantly penetrating with the INPP discharges into Drūkšiai Lake.

Activity of radionuclides in macrophytes and bottom sediments of Drūkšiai Lake after shutdown of the Unit One decreased; however, at the initial stage of the INPP operation, total ^{137}Cs, ^{90}Sr, ^{134}Cs, ^{60}Co and ^{54}Mn activity of the INPP origin in bottom sediments together with thermal and chemical pollution could have caused occurrence of somatic mutations in the stamen hair (SH) system of *Tradescantia*, revealing impact of contemporary environment to the future generations. Since radioactive pollution acts in conjunction with chemical and thermal pollution, therefore, it is very difficult to forecast the summary impact of these pollutions on the future generations of various organisms of the Lake. Most usual radioactive and chemical pollution of Drūkšiai Lake was detected in the period from 1988 to 1993, and the most evident genetic changes in biological tests were recorded in 1993 (Montvydienė 2002). It was found that water and bottom sediments of INPP's channels and Drūkšiai Lake usually caused colorless and morphological, and only rarely (and only till 1993), pink mutations in *Tradescantia* SH system (Montvydienė 2002). Pink mutations as it is thought generally occur due to impact of radiation (Osipova and Shevchenko 1984; Ichikawa 1992; Marčiulionienė *et al.* 1996). It showed that genotoxicity of water and bottom sediments of the INPP's channels and Drūkšiai Lake was caused more not by ionizing radiation, but by the impact of the mixture of non-radioactive and radioactive substances presented in the WW of the INPP. Additionally, at the period of 1988–1993 giant plants were detected in the INPP's channels and in the Lake zones directly impacted by WW from the INPP (especially in the thermal pollution zone). It is common known that ability of giant plants to reproduce themselves is decreased (Shevchenko and Pomeranceva 1985). So, it may be stated that genetic changes of organisms caused by thermal, chemical and radioactive pollution could be one of the reasons that caused changes of ecosystems of Drūkšiai Lake, which resulted in degradation of these communities due to extinction of species in them (Stankevičiūtė 2007; Kesminas and Olechnovičienė 2008).

Perennial (1986–1995) of the INPP WW and Drūkšiai Lake water biotesting data showed that the most toxic to fish (*O. mykiss*) in early ontogenesis (embryos, larvae) was WW of the ISW-1,2 channel. The water of CW channel and water of 4th, 6th, and 7th monitoring stations of Drūkšiai Lake was less toxic. The water of the 1st monitoring station was non-toxic. In the WW of the ISW-1,2 and CW channels has been observed the deterioration of physiological state of *O. mykiss* embryos and hatched larvae: changes in the heart and respiratory rates, decreased the average body mass. The major toxic effects of the studied test-organisms were occurred in May and in July, the lowest – in October (Marčiulionienė *et al.* 1995, 1996; Kazlauskienė and Čepulienė 1998).

In 2007 the long-term toxicity of the INPP WW and Drūkšiai Lake waters on the *O. mykiss* in early ontogenesis (embryos, larvae) was assessed and compared with the biotesting results obtained in 1996. During the tests the mortality, growth and physiological parameters were recorded. It was determined (in 2007) that the water of the 1st and 6th monitoring stations of Drūkšiai Lake, the WW of the ISW-1,2 and CW channels were toxic to *O. mykiss* embryos and larvae. The water of 4th station was found to be less toxic and the water of 7th station was non-toxic. The comparison of the results obtained in 1996 and the results determined in 2007 demonstrated that the effect of cooling water of INPP and the waters of 1st and 6th monitoring stations on the larval mortality increased 1.5–2 times. The toxicity of water of the 1st station on physiological parameters of larval of this fish increased, too. Meanwhile, the toxicity of the water of the ISW-1,2 and CW channels and waters of tested monitoring station of Drūkšiai Lake on growth rate of *O. mykiss* larvae was lower or similar to that obtained in 1996 (Kazlauskienė 2009). The results of the 1996 toxicity studies of the water of the INPP's channels and Drūkšiai Lake, and the data obtained in 2007 demonstrated that such toxicity of the Lake water is increasing for the continuously re-entering of INPP toxic substances into those waters (Kazlauskienė 2009).

3.5. Macrophytes and fish communities changes in Drūkšiai Lake

Aquatic plants – macrophytes and phytoplankton – are the main producents of the primary production of the organic matter and, therefore, they influence the development of other hydrobionts. Composition of macrophytes species and the development of vegetation zones are the one of the main criterion which describes the trophic state of water basin (Balevičienė and Balevičius 2006).

The botanical investigations in Drūkšiai Lake site, in the valley of river Drūkšos, and in littoral of Drūkšiai Lake were performed in 1979–1983, in 1993–1997, and in 2006–2007 (Stankevičiūtė 2007). At the vicinity of the INPP the 9 habitats from EU Habitat Directive Annex I and 8 plant species from the Lithuanian Red Book were identified. Drūkšiai Lake belongs to the habitat 3140 (hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.) (Stankevičiūtė 2007).

Before the launch of the INPP (in 1979–1983), Drūkšiai Lake was described as a mesotrophic lake with the belt-type-fragmentary overgrowth (Balevičienė and Zinkevičienė 1997). It was found that helophytes made up various size fragments of the communities, the vegetation of *Chara* sp. prevailed in the zone of limneids; the communities of potameids were developed very fragmentary, and communities of nimpheids were observed only in some shallow eutrophicated bays (Balevičienė and Zinkevičienė 1997). At this period of the botanical investigation 96 species of aquatic plants were found in this Lake, while in the period of 1996–1997 only 69 species of plants were detected (Balevičienė and Zinkevičienė 1997). In 1996 the significant changes were observed in vegetation of the Lake zones directly impacted by anthropogenic pollution: the belts of *Phragmitetum australis* and *Scirpetum lacustris* were whole and in 100–200 m wide. *Schoenoplectus lacustris* and *Phragmites australis* occupied the habitats suited for *Characeae* and rare species (*Alisma gramineum* and *Zannichellia palustris*); in the areas enclosed of waves the decayed plants concentrated; and the processes of water logging of the falls of rivers were observed (Balevičienė and Zinkevičienė 1997). In addition, the distinct impact of filamentary algae on the development of other plants in the belts of potameids and limneids was estimated. Balevičienė and Zinkevičienė (1997) forecasted the loss of *Chara* sp. and other minor aquatic plants in the Lake, the spreading of the helophytes in shoreline and in the shallow zones (up to 2 m) of the Lake in the nearest future. This prognosis came true (EIA Report 2009). So, nowadays the state of Drūkšiai Lake as the 3140 type habitat is worsened markedly.

The species diversity in Drūkšiai Lake significantly decreased from 23–26 fish species (before launching the INPP) to the current list of 14 species. The Lake is no longer home for the Lake smelt, catfish and some introduced species such as the whitefish and pikeperch. The littoral of the Lake does not hold river fish species such as the bullhead, dace, ide or gudgeon, a recent dweller of the littoral. The numbers and distribution of the tench and introduced warm-water species such as the German carp and common carp increased; catches of the grass carp and silver carp are also recorded. As to the fish community structure, Drūkšiai Lake is undergoing a change of dominant species. The fish community is basically composed of three eurythermal species: silver bream (32.9%), perch (30.1%) and roach (21.7%). Recently the abundance of silver breams has particularly increased, whereas the numbers of the roach and bream decreased. The populations of stenothermal species decreased to the critical level: the Lake smelt is not caught at all and the vendace accounts for merely ca. 3% of the total number of fish. By biomass, the Lake is dominated by roach (38.7%), followed by several species with insignificant variations in biomass: perch (15.7%), bream (14.0%), tench (12.1%) and silver bream (9.5%) (Kesminas, Olechnovičienė 2008).

4. Conclusions

On the basis of the long-term studies of the radionuclide and heavy metal accumulation and scatter in biotic and abiotic components of Lake Drūkšiai as well as water and bottom sediments toxicity and genotoxicity radioactive, chemical and thermal pollution potential impacts on macrophytes and fish communities of Drūkšiai Lake were evaluated.

Before starting exploitation of Ignalina Nuclear Power Plant (INPP) 95 species of macrophytes were found in Drūkšiai Lake. Since a start-up of the second nuclear reactor of INPP (1987), significant alternations in macrophytes species composition and biomass were notably observed to 1989. Resistant to the pollution macrophytes species began to dominate in the Lake. In 2007–2008 in the main part of the Lake, which INPP sewage entered, only resistant to anthropogenic impacts macrophytes species were found. Fish species composition also has changed. The varietal diversity of the fish in the Lake significantly decreased from 23–26 (before INPP start-up) species to 14 ones.

Considerable changes in macrophytes and fish species compositions in the Drūkšiai Lake could be induced by various effects:

- enlarged radionuclide activity in macrophytes and fish, and an increase in the concentration of heavy metals in the water of the Lake, especially till 1993;
- the growth stimulation of macrophytes, which was evaluated in heated water area of the Lake till 1994–1995. Therefore, the stress state of the plants could affect their disappearance;
- enlarged genotoxic effect of water and bottom sediments on test-organisms, which was observed in 1993–1998. This observation was confirmed by large mutagenic and lethal lesions in the stamens cellular system of *Tradescantia.* The cell gigantism in the stamens cellular system of *Tradescantia* showed that lesions could occur at early stage of development of cellular system;
- enlarged toxic effect of water and bottom sediments of the Drūkšiai Lake, which was observed in 1993–1998, and INPP sewage discharged into the Drūkšiai Lake areas, water and bottom sediments toxicity were upward trended also in 1996–2007;
- enlarged lake water and bottom sediments pollution by contaminants such as heavy metals, radionuclide's etc. after ecological conditions as well as hydrologic and hydrochemic regime changed can return into water and be accumulated in flora and fauna of the Lake.

Considering the findings of our study, it can be assumed that changes in macrophytes species and fish varietal diversity in Drūkšiai Lake could be induced by total chemical, thermal and radioactive pollution, which had a negative impact on aquatic organisms. It can be predicted that the new ecological conditions will appear in Drūkšiai Lake after INPP closing in 2009, notably after the changes of thermal water regime. However, the chemical and radioactive pollution in the Lake will be over a long period of INPP dismantling works. In addition, the great challenge for ecosystem of Drūkšiai Lake will be a new nuclear power plant construction near the closed INPP.

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MAKROFITŲ IR ŽUVŲ RŪŠINĖ KAITA DRŪKŠIŲ EŽERE – IGNALINOS ATOMINĖS ELEKTRINĖS AUŠINIMO BASEINE (1988–2008).

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Santrauka

Remiantis radionuklidų bei sunkiųjų metalų akumuliacijos ir sklaidos Drūkšių ežero biotiniuose ir abiotiniuose sanduose bei ilgalaikiais vandens ir dugno nuosėdų toksiškumo bei genotoksiškumo tyrimais, buvo įvertintas galimas radioaktyviosios, cheminės ir šiluminės taršos poveikis Drūkšių ežero makrofitams ir žuvims. Prieš pradedant veikti Ignalinos atominei elektrinei (IAE) buvo rasta 95 makrofitų rūšys. 1987 m. pradėjus veikti Ignalinos atominės elektrinės (IAE) antrajam energoblokui, ypač iki 1989 m., nustatyta žymi makrofitų Drūkšių ežere rūšinės sudėties ir biomasės kaita. Ėmė vyrauti taršos poveikiui atsparios makrofitų rūšys. 2007–2008 m. pagrindinėje ežero dalyje, į kurią patenka IAE nuotekos, rasta tik atsparios antropogeninių veiksnių poveikiui makrofitų rūšys, pasikeitė ir žuvų rūšinė sudėtis. Ežere žymiai sumažėjo žuvų rūšinė įvairovė: nuo 23–26 (prieš IAE paleidimą) iki 14 žuvų rūšių. Apibendrinant duomenis galima teigti, kad Drūkšių ežero augalijos ir gyvūnijos pokyčiai galėjo būti indukuoti suminės – cheminės, šiluminės ir radioaktyviosios taršos. Galima prognozuoti, kad uždarius IAE (2009-12-31.) Drūkšių ežere susiformuos naujos ekologinės sąlygos, ypač – pasikeitus terminiam vandens režimui, tačiau dugno nuosėdų cheminė ir radioaktyvioji tarša išliks. Per ilgą IAE išmontavimo periodą tarša gali dar padidėti. Be to, didelis išbandymas Drūkšių ežerui bus šalia uždarytos IAE numatoma naujos AE statyba.

Reikšminiai žodžiai: Drūkšių ežeras, Ignalinos atominė elektrinė, radioaktyvioji, cheminė ir terminė tarša, vanduo, dugno nuosėdos, toksinis ir genotoksinis poveikis, makrofitai, žuvys.

ИЗМЕНЕНИЕ ВИДОВОГО СОСТАВА МАКРОФИТОВ И РЫБ В ОЗ. ДРУКШЯЙ – ВОДОЕМЕ-ОХЛАДИТЕЛЕ ИГНАЛИНСКОЙ АТОМНОЙ ЭЛЕКТРОСТАНЦИИ (1988–2008 гг.)

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Резюме

На основании многолетних данных, полученных при изучении аккумуляции и миграции радионуклидов и тяжелых металлов в биотических и абиотических компонентах озера Друкшяй, а также токсического и генотоксического действия воды и донных отложений на тесторганизмы, было оценено возможное действие теплового, химического и радиоактивного загрязнения на видовой состав макрофитов и рыб. До пуска Игналинской атомной электростанции (ИАЭС) в озере Друкшяй было установлено 95 видов макрофитов. В 1987 г. после пуска 2-го энергоблока ИАЭС, особенно до 1989 г., в оз. Друкшяй было отмечено изменение видового состава и биомассы макрофитов. В озере стали бурно развиваться более устойчивые к действию антропогенных факторов среды виды макрофитов. В 2007–2008 гг. в основной части озера, в которую поступают сточные воды ИАЭС, были найдены лишь те виды макрофитов, которые наиболее устойчивы к действию различных загрязнителей. В озере также отмечено изменение видового состава рыб. Из 23–26 видов, установленных до пуска ИАЭС, осталось лишь 14 видов рыб. На основании полученных данных можно предположить, что изменения, происходящие в видовом составе макрофитов в оз. Друкшяй, были индуцированы совместным действием химического, теплового и радиоактивного факторов среды, которые могли представлять особую опасность и для других видов гидробионтов. Можно прогнозировать, что после закрытия ИАЭС в 2009 г. в оз. Друкшяй будут формироваться новые экологические условия, особенно связанные с изменениями термического режима воды. Однако химическое и радиоактивное загрязнение озера будет существовать долгие годы во время демонтирования ИАЭС. Кроме того, рядом с ИАЭС намечается строительство новой АЭС, что будет новым вызовом для оз. Друкшяй.

Ключевые слова: озеро Друкшяй, ИАЭС, радиоактивное, химическое и термическое загрязнение, вода, донные осадки, токсическое и генотоксическое действие, макрофиты, рыбы.

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