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Impact of radionuclide discharges from Temelín Nuclear Power Plant on the Vltava River (Czech Republic)

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1. Introduction

Temelín Nuclear Power Plant (Temelín plant) is located on the upper Vltava River in south Bohemia. The Vltava is an important resource of drinking water for Prague. Its water affects also quality of the Elbe River on the territory of both the Czech Republic and the Federal Republic of Germany.

Since 1989, possible impacts of the Temelín plant have been studied in a number of research projects. The first two projects (Hanslík, 1995, Hanslík, 1998) were sponsored by the Czech Ministry of the Environment and its main objectives were to examine pre-operational environmental conditions (a reference level) in terms of concentrations of radioactive and non-radioactive polluting substances in components of the environment, particularly in the hydrosphere, and to predict possible impacts of future operation of the Temelín plant. Special attention paid to the hydrosphere was associated with requirements for protection of water quality in the Vltava River. The observation and research activities continued during the period 1999-2008 within the framework of a project sponsored by Czech Power Company (Hanslík, 1999a, 2000, 2001a, 2002, 2003, 2004a, 2005a, 2006a, 2007, 2008). These studies subsequently continued in a project on Research and protection of hydrosphere – research of relationships and processes in water component of the environment focused on impacts of human pressures, the sustainable use and protection of the hydrosphere and legislative tools (MZP 0002071101 and SP/2e7/229/07 sponsored by the Czech Ministry of the Environment).

The main objectives of these projects were to assess the impacts of waste water discharged from the Temelín plant on the activities of tritium, radio caesium and strontium in hydrosphere, to compare these impacts with the residual contamination from the atmospheric tests of nuclear weapons and the Chernobyl accident in the last century and to evaluate long-term spatial and temporal trends in the activities of these radionuclides that have been monitored at sampling sites not affected and affected by the outflow of waste water from the Temelín plant.

Specific results of these projects have been reported in technical journals and international conferences (Hanslík et al., 1999b, Hanslík et al., 2001b, Hanslík et al., 2005b, Hanslík et al., 2009a-c, Ivanovová & Hanslík, 2009a-b). This Chapter reviews and summarises the main results of the projects.

2. Description of the study area

Beginning of the construction of the Temelín plant dates back to 1986. The plant is located in the basin of the upper Vltava River in south Bohemia (Fig. 1). It consists of two PWR reactors, each with capacity of 1000 MW_{el}. Pilot operation of the first reactor was launched in June 2002 and of the second one in April 2003. Since May 2003, the Temelín plant has been in full operation. The development of the output of the Temelín plant is illustrated in Fig. 2.

For the operation of the two reactors, the plant needs 1 200 l/s (annual mean) of technological water. It discharges 300 l/s (annual mean) of waste water, including the returning cooling water and purified waste water.

Two of the reservoirs (Hněvkovice and Kořensko), which have been constructed on the Vltava River, serve for water management purposes of the plant. Water for the plant is abstracted from Hněvkovice Reservoir (put into operation in 1991) and pumped into storage tanks with capacity of 2 x 15 000 m^3, from which it flows by gravity. The waste water is discharged into the Vltava River through turbines of hydroelectric power station located at Kořensko Dam.

Annual mean discharge (Q_a) at Kořensko Dam is 50 m^3/s and ensured ecological discharge (Q_{355}) is 9.45 m^3/s. This dam is located upstream from Orlík Reservoir, which is the first receiving water body of the waste waters from the Temelín plant. Its storage capacity is 720x106 m3, which is fed by water from three main tributaries of the reservoir, the Vltava, Lužnice and Otava Rivers, whose annual mean discharges are 30.6 m^3/s, 23.6 m^3/s and 23.5 m^3/s respectively.

The water from the Orlík Reservoir flows into the Elbe River through a cascade of other downstream reservoirs, Kamýk (12.9 x 10^6 m^3), Slapy (269.3 x 10^6 m^3), Štěchovice (10.4 x 10^6 m^3) and Vrané (11.1 x 10^6 m^3), built on the Vltava River.

The study area has been affected by contamination from the atmospheric tests of nuclear weapons and the Chernobyl accident in the last century.

3. Observation and data

The observations of changes in concentrations of radioactive and non-radioactive polluting substances were made for tributaries of the Orlík Reservoir, the Vltava, Lužnice and Otava Rivers, which are located upstream from the waste water outflow from the Temelín plant and represent therefore reference conditions ("reference sampling sites"), and in the Vltava River downstream from the outflow of waste water from the plant (Fig. 3) ("affected sampling sites").

The observation involved concentrations of the polluting substances in surface water, bottom sediments and fish species (Table 1).

Particular attention was paid to the time changes in the concentrations of anthropogenic radionuclides ^3H, ^{90}Sr, ^{134}Cs and ^{137}Cs in hydrosphere because these radionuclides, possibly present in the effluent returns from the Temelín plant, are identical to those remaining in the environment after the Chernobyl accident and atmospheric tests of nuclear weapons.
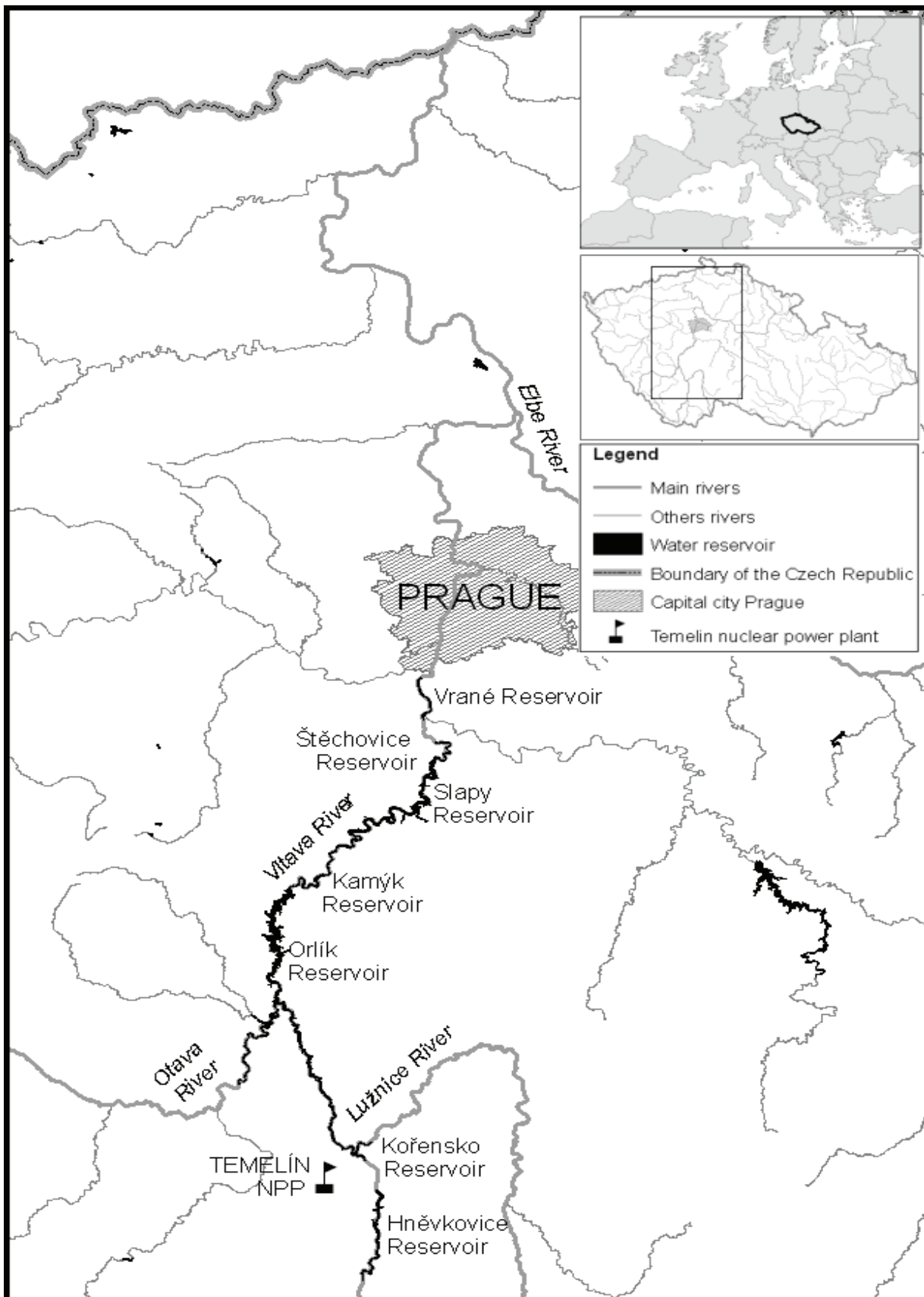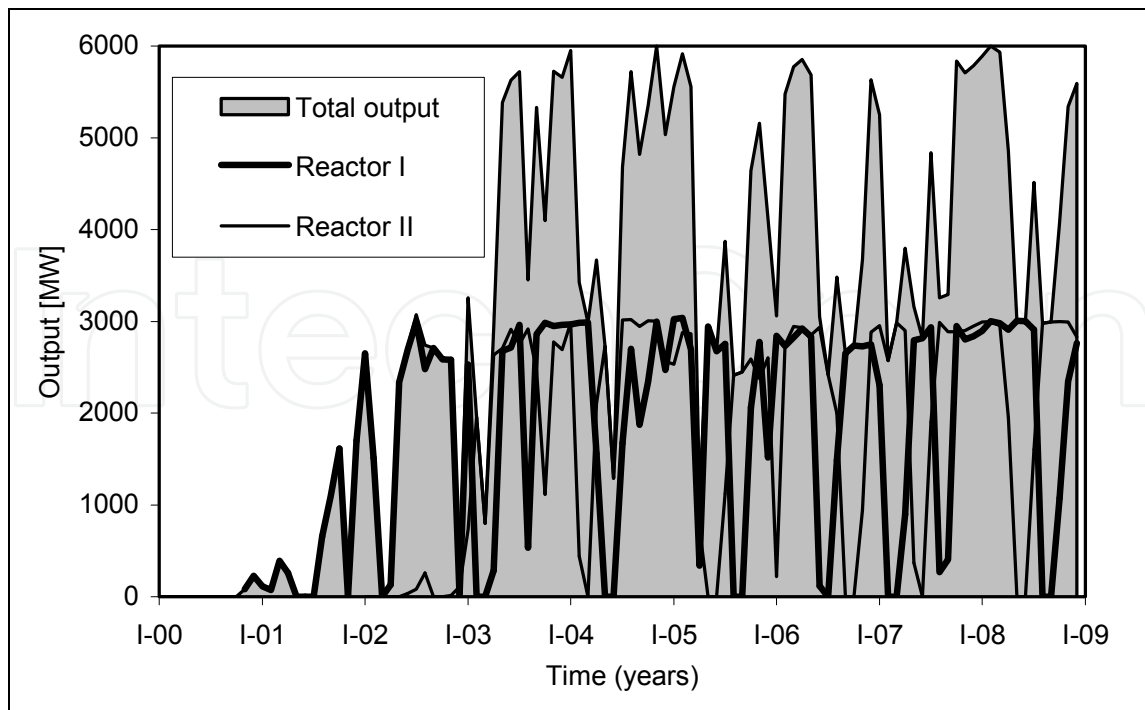
Fig. 1. The study area

Fig. 2. Development of the output of Temelín plant in the period 2001 – 2008

Component of the environment		Year of the observation beginning from 1990																		
		0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8
Surface water	³H ¹³⁷Cs	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	⁹⁰Sr				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	TSS	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Bottom sediment	¹³⁴Cs	x	x	x	x	x	x	x	x	x										
	¹³⁷Cs	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Biomass (Fish)	¹³⁷Cs				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Table 1. Observation periods of the polluting substances in components of the environment
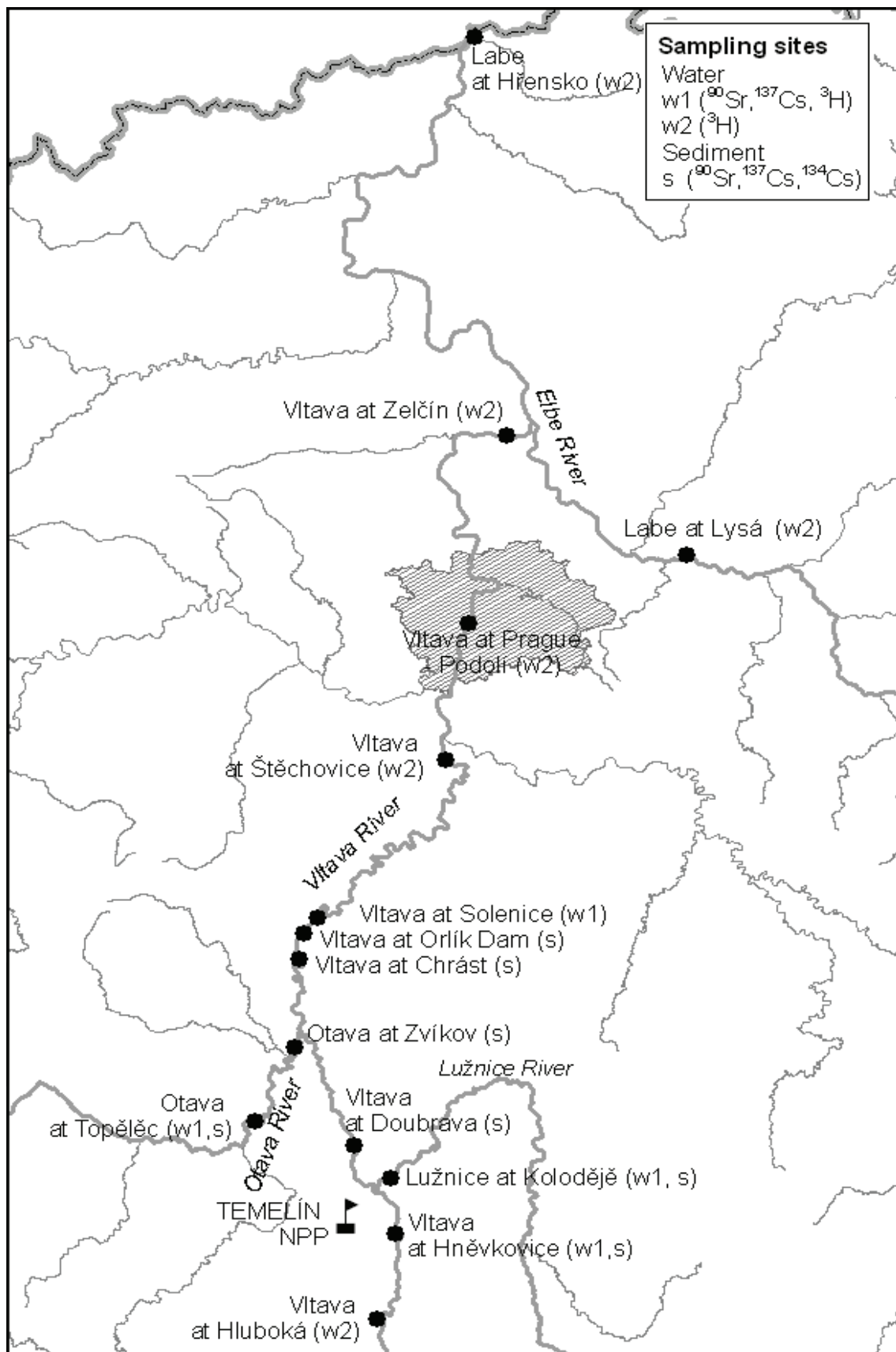
Fig. 3. Map showing sampling sites

4. Analytical methods

4.1. Radiological method

For sample collection and processing, the methods specified in ČSN EN 25667-1 (1994) and 2 (1994) Standards and ČSN EN ISO 5667-3 (1996), 4 (1994) and 6 (1994) were applied. Quality control practices of the T. G. Masaryk Water Research Institute (T.G.M. WRI) Radioecological Laboratory are performed according to the Standard ČSN EN ISO/IEC 17025 (2001). The laboratory takes part in national and international proficiency testing.

Large samples of water (50 l) were taken with frequency of four in a year. The samples were immediately stabilized with nitric acid to pH 1 and then, after transportation to the laboratory, condensed by vaporization. The vaporized samples were ignited (350 °C) and closed into Petri dishes. The radionuclides concentrations in water were determined in total solids (both in dissolved and suspended solids). Samples of water (1 l) for determination of ^3H and total suspended solids (TSS) were taken with frequency of four in a year.

Samples of bottom sediments were taken from the top layer (0 – 10 cm) by a diver at six sites involving the Vltava River tributaries and the Orlík Reservoir. The frequency of the sampling was one sample in a year. Granularity of the samples was generally less than 2 mm. For the analysis, the samples were dried at 105 °C and hermetically sealed in the measuring containers.

Samples of fish were also taken with annual frequency. These samples were dried.

The ^{134}Cs and ^{137}Cs concentrations were analysed according to Standard ČSN ISO 10 703 (1999) using gamma-spectrometry. A Canberra device was used. The measurement duration was set up in accordance with requested minimum detectable activity (MDA) of ^{137}Cs at the level of significance of $\alpha=\beta=0.05$. The MDA of ^{137}Cs in water for counting time of 2 days was 0,5 mBq/l. In the sediments, the MDA of 137Cs for counting time 8 h was approximately 0.5 Bq/kg. The results of ^{137}Cs activity in fish (dried samples) were converted to activity in wet weight. The MDA of ^{137}Cs in fish (wet weight) for counting time of 2 days was 0.1 Bq/kg.

^{90}Sr was determined in water by using a standard method after radiochemical separation (Čapková, 1993). Its activity was detected from the residuum after igniting via detection of yttrium 90 after radiochemical separation. Value of MDA of strontium 90 was 3 mBq/l. These methods were verified and recommended by the International Atomic Energy Agency (IAEA, 1996) in Vienna within the framework of its technical assistance organised in co-operation with the Ministry of the Environment of the CR and the State Office for Nuclear Safety.

The tritium concentrations were determined by using Quantulus 1220 and TriCarb low-level liquid scintillation spectrometers. The determination was performed according to ISO 9698 Standard (1996). The relative efficiency of tritium measurement was 26%. The MDA was set according the expected activities. For mixture of 8 ml of sample and 12 ml of scintillation solution and alternatively counting time of 800 minutes (samples from reference sampling sites) and 300 minutes (samples from affected sampling sites), the detection limit was 1.2 Bq/l and 2.2 Bq/l respectively at the level of significance of 0.05. Calibration was performed by using ^3H standard provided by Czech Metrological Institute.

In general, values below the MDA were included into the assessment and were substituted by 0.5 values of these limits. The measured values were used for calculation of annual average activities. Values of annual mean river discharges were provided by the Czech Hydrometeorological Institute.

4.2. Mathematical methods

The analytical data on the concentrations of radionuclides in water, sediments and biomass were assessed by using several mathematical methods, which are briefly described below.

The effective ecological half-lives were evaluated from the decrease in a radionuclide activity according to the equation (Smith & Beresford, 2005):

$$T_{eff} = \frac{\ln 2}{\lambda_{eff}} \tag{1}$$

where T_{eff} is   effective ecological half-life (y),
        λ_{eff} effective ecological decay constant of the radionuclide activity
                concentration (1/y).

Ecological half-lives were calculated by using an equation in the form (Smith & Beresford, 2005):

$$\frac{1}{T_{ecol}} = \frac{1}{T_{eff}} - \frac{1}{T_P} \tag{2}$$

where $\mathbf{T_{ecol}}$ is   ecological half- life (y),
        T_{eff} effective half- life (y),
        T_P physical half- life (y).

For a trend analyses, a kinetic equation of the first order was used in the form (an example for ^{137}Cs):

$$\ln c_{137Cs} = -\lambda_{eff} + q \tag{3}$$

where $c_{137Cs,j}$ is   annual average ^{137}Cs concentration in surface water (mBq/l) in   year j,
        λ_{eff} effective rate of decline in ^{137}Cs concentration (1/y), involving the
                physical decay constant (λ_p) and the ecological rate of the
                decrease (λ_{ecol}), $\lambda_{eff} = \lambda_p + \lambda_{ecol}$ (1/y),
        t   time of the monitoring in years,
        q   natural logarithm of activity at the beginning of the observation

The annual depositions of suspended solids in a reservoir were calculated from an equation in the form:

$$D_{S,j} = \left(\sum_{t=1}^{n} c_{S,j,t} Q_{j,t} t + c_{S,j,ia} Q_{j,ia} t - c_{S,j,o} Q_{j,o} t \right) x 10^{-3} \tag{4}$$

where $D_{S,j}$ is   deposition of suspended solids in a reservoir in individual
                years (j) (t/y),
        $c_{S,j,t}$ annual mean concentration of suspended solids (j) in
                tributaries (t) (kg/m³),
        $c_{S,j,ia}$ annual mean concentration of suspended solids (j) in the
                inflow from inter-basin area (ia) (kg/m³),
        $c_{S,j,o}$ annual mean concentration of suspended solids (j) in the
                outflow from a reservoir (kg/m³),
        $Q_{j,t}$ annual mean inflow (j) from tributaries (t) (m³/s),
        $Q_{j,ia}$ annual mean inflow (j) from the inter-basin area (m³/s),
        $Q_{j,o}$ annual mean outflow (j) from a reservoir (m³/s),

The deposition of suspended solids can was also calculated for individual years by the following formula and expressed in percentages:

$$D_{S,j} = \frac{\displaystyle\sum_{t=1}^{n} c_{S,j,t}Q_{j,t} + c_{S,j,ia}Q_{j,ia} - c_{S,j,o}Q_{j,o}}{\displaystyle\sum_{t=1}^{n} c_{S,j,t}Q_{j,t} + c_{S,j,ia}Q_{j,ia}} x100 \qquad (5)$$

where $D_{S,j}$ is   deposition of suspended solids in a reservoir in individual years (j) (%).

Similarly, based on the results of the ^{137}Cs activity monitoring in all substances in water (dissolved as well as undissolved solids), the deposition of ^{137}Cs can be determined by the formula:

$$D_{A,137Cs,j} = \left(\sum_{t=1}^{n} c_{137Cs,j,t}Q_{j,t}t + c_{137Cs,j,ia}Q_{j,ia}t - c_{137Cs,j,o}Q_{j,o}t \right) x10^{-9} \qquad (6)$$

where $D_{A,137Cs,j}$ is   deposition of ^{137}Cs in individual years (*j*) (GBq/y),

   $c_{137Cs,j,t}$ annual mean activity of ^{137}Cs (*j*) in tributaries (*t*) of a reservoir (Bq/m^3),

   $c_{137Cs,j,ia}$ annual mean activity of ^{137}Cs (*j*) the inflow from inter-basin area (*ia*) (Bq/m^3),

   $c_{137Cs,j,o}$ annual mean activity of ^{137}Cs (*j*) in the outflow from a reservoir in Bq/m^3.

Concentration factors (CF in l/kg) for fish samples were calculated according Smith & Beresford, (2005) (an example for ^{137}Cs and Orlík Reservoir):

$$CF = \frac{\overline{a}_{137Cs}}{\overline{c}_{137Cs}} \qquad (7)$$

where $\overline{a}_{137Cs}$ is annual average ^{137}Cs concentration in fish (wet weight) (Bq/kg),

   $\overline{c}_{137Cs}$ annual average ^{137}Cs concentration in water in tributaries of Orlík Reservoir (Bq/l).

Committed effective dose from tritium ingestion with drinking water (by adult) was calculated using the equation (IAEA, 2003):

$$E = h(a17)_{3H,ing} I_{3H,ing} \qquad (8)$$

where   E is   committed effective dose from intake of tritium by ingestion of drinking water (Sv/y),

   $h(a17)_{3H,ing}$ committed effective dose per ingested unit for tritium intake by the group of adults (age >17) (Sv/Bq),

   $I_{3H,ing}$ intake via ingestion of tritium during 1 year (Bq/y), calculated as: $I_{3H,ing} = c_jV$

   where c_j is   annual average tritium concentration in year *j* (Bq/l),

   V   consumption of drinking water by a member of the public (700 l/y).

5. Non-radioactive pollution from the Temelín plant

The results of the water quality monitoring show that non-radioactive substances discharged with waste water from the Temelín plant are highly influenced by the quality of the technological water extracted from the Vltava River at Hněvkovice. The Temelín contribution to dissolved solids includes mainly sulphate anions, added to the water as aluminium sulphate for the technological water treatment, and salts from the ion exchange filters. As an example of organic pollution, the biological oxygen demand (BOD$_5$) showed a significant decrease as compared to its values in supplied water, which is attributable to self-purification capacity of the cooling circuit, sedimentation of solid substances and other factors. A contribution of the biological waste water treatment plant to BOD$_5$ values is small. The Temelín plant reliably meets the limit values for discharged substances specified in the water management permit (Fechtnerová , 2002 - 2006).

6. Tritium

6.1. Tritium concentration

In conjunction with operation of nuclear power plants, high attention is paid to problems associated with the environment contamination by tritium. Tritium is emitted with waste waters from nuclear power plants into the environment and the discussions concerning tritium emissions are evoked by the fact that concentrations of tritium emitted into surface waters and other components of the environment exceed those of other radionuclides by several orders of magnitude.

The aims of the studies were to quantify tritium quantities discharged from Temelín plant into surface waters in the Vltava River basin and main tritium components stemming from natural processes and those originating from man activities (residual pollution from atmospheric tests on nuclear weapons in the last century and the atmospheric transfer from nuclear facilities worldwide). The intention was also to quantify tritium outflows into the Vltava River and to compare the results with data provided by Czech Power Works, joint stock company, which operates the Temelín plant.

6.2. Natural and artificial components of tritium background in the Vltava River basin

Tritium is permanently produced in upper layers of the atmosphere by nuclear reactions caused by cosmic radiation. The tritium reaction ^{14}N (n, ^3H) ^{12}C is evoked by fast neutrons generated by cosmic rays. The natural processes of tritium generation were studied by Libby (1946) and subsequently e.g. by Nir et al. (1966). According to results published in the literature, the world mean rate of tritium production consequently to cosmic radiation is 0.16 to 0.20 tritium nucleuses on one square centimetre of the land surface in one second. Value of 0.19 tritium nucleuses on one square centimetre in one second is relevant to the world tritium activity of 960 PBq (960×10^{15} Bq). Knowledge from satellite observation was used by Flamm et al. (1962), who derived that additional 0.4 tritium nucleuses on one square centimetre in one second, which exceeds that produced by cosmic radiation by a factor of two, originates from intensive solar activity. Tritium production by natural processes is estimated in the range from 150 to 200 PBq/y (NCRP, 1979). The tritium quantity of natural origin is constantly at a level of 2.6 EBq.

It is reported that mean tritium activity in the hydrosphere originating from natural processes is between 0.12 and 0.59 Bq/l. Results of the application of a seven-component model showed that tritium concentration in the air humidity is 0.61 Bq/l, in surface waters it is 0.38 Bq/l and in surface layers of oceans it is 0.06 Bq/l. It is reported that tritium concentration in human body is 0.46 Bq/l, which is relevant to annual dose of $1{,}2 \times 10^{-5}$ mSv/y. The dose of natural origin is therefore very small as compared to that originating from ionizing radiation, which is about 3 mSv/y (UNSCEAR, 1993).

For complete information on tritium sources and its occurrence in the environment, it is necessary to consider the fact that its concentrations are still affected by its main source in the past, the tests of nuclear weapons in the atmosphere. It has been estimated that till 1963, when the treaty on restriction of the tests of nuclear weapons was concluded (the Partial Test Ban Treaty), 114.7 EBq ($114{,}7 \times 10^{18}$ Bq) of tritium was emitted into the environment. The tritium activity remaining after the tests of the nuclear weapons was 43.3 EBq in 1980, 24.6 EBq in 1990 and 14.1 EBq in 2000 (NCRP, 1979). It can be derived from this data the remaining tritium activity in 2012 will still be 7.1 EBq. In 2030, the remaining tritium activity will be identical to that originating from natural processes, that is 2.6 EBq but this component presently still dominates.

For the studies of tritium activities in the Czech Republic, data from the period 1977 – 2008 were available from literature sources (Hanslík & Mansfeld, 1983) and from results of measurements made by staff of T.G.M. WRI (Hanslík et al., 1999b, Hanslík et al., 2006b, Ivanovova & Hanslík, 2009b).

The data from the whole period were used for calculation of effective ecological decay constant (λ_{eff}) and effective ecological tritium half-life. The data from "reference sampling sites" from the period 1990 – 2008, were used for more detailed analysis of the components of the water pollution by tritium.

The results showed that in the river reaches, which are not affected by waste water discharges from the Temelín plant, the mean tritium activity was 3.1 Bq/l at the beginning of the analysed period (1990) and 1.05 Bq/l at its end (2007). These results are in harmony with those of the observations performed by Palomo et al. (2007), who reported that tritium concentrations in samples taken in October 2005 and January 2006 in the vicinity of Asco Nuclear Power Plant (Spain) are in the range between less than 0.6 and 0.93 Bq/l.

For the analysis of the trends in tritium concentrations, the Equation 3 has a form as follows:

$$\ln c_{3HB,j} = -\lambda_{eff} + q \qquad (9)$$

where | $c_{3HB,j}$ | is annual average tritium concentration in surface water, representing the contamination from atmosphere tests of nuclear weapons, its generation by natural processes and the atmospheric transfer from nuclear facilities worldwide (background), based on the results of field measurements (Bq/l),
| λ_{eff} | effective ecological decay constant describing a decrease in concentrations of tritium (1/y),
| q | natural logarithm of tritium activity at the beginning of the observation.

Using the Equation 9, effective ecological tritium half-life T_{eff} = 8.1 years for the whole period (1977-2008) was calculated.

More detailed analysis of the period 1990 – 2008, showed that decreasing trend in the tritium activities was gradually lessening. For this period, the effective ecological half-life

was 12.3 years. This can be attributed to the facts that relatively small tritium activities originate also from a constant component, which is stemming from the cosmic radiation and from the atmospheric transfer from nuclear facilities worldwide. This component was considered also to be constant in the analysed period.

These factors were therefore eliminated in subsequent analysis by subtracting these components. For the modified approach (elimination of the components originating from cosmic radiation and the atmospheric transfer from nuclear facilities worldwide), the effective ecological half-life (T_{eff}) derived from the period 1990 – 2008 was 8.4 years, which is shorter than that derived by using the unmodified approach.

These results were compared with data published in the period after termination of atmospheric tests of nuclear weapons in 1963. According to Bennet (1973), mean tritium concentration in this year in 20 rivers in United States was 100 Bq/l. The decrease in tritium concentration observed in this period was faster as compared to the effective half-life T_{ef} = 8.1 years calculated in our study from the period 1977 – 2008. Bogen et al. (1979) reported that effective ecological half-life increased from 3 years in the period closely after termination of the tests of nuclear weapons to 5 years in about 1978. This can be explained by tritium migration into lower water levels in oceans, which is reflected in its decreasing concentration.

6.3. Impacts of the Temelín plant

Decision of Regional Authority (Permit on Water management, 2007) specifies a limit of 66 TBq/y tritium activity that can be discharged with waste waters from Temelín Nuclear Power Plant if 2 reactors of the plant are in operation. In harmony with the development of the operation, the tritium activity discharged from the plant has been increasing since 2001 (Fig. 4).

The mean annual tritium concentrations in the Vltava River consequently exhibited an increasing trend, which is attributable to gradual increase in the output of the plant associated with increasing discharged quantity of tritium. In 2001, the tritium concentrations in the Vltava River did not exceed maximum from the period before the operation of Temelín plant. In 2002, the tritium concentrations were affected by discharges from pilot operation of the plant but diluted by high river flows in this year. Low precipitation and therefore low flows in 2003 were reflected in the observed maximum concentration of 39 Bq/l (November 2003). The highest mean annual concentrations of tritium were subsequently observed in 2008.

The results of the monitoring of the tritium concentrations in the Vltava River below the outflow of waste waters from the Temelín plant show that the mean tritium concentrations are at a level below 3% of the pollution standard ($c_{average}$ = 700 Bq/l) specified in Guidance document to Resolution of the Czech Government No. 229/2007 Coll. The mean concentrations and also maximum concentrations did not exceed an indicative limit of 100 Bq/l specified in a Decree of the State Institute for Nuclear Safety No. 307/2002 and EC Council Directive on the quality of water intended for human consumption (98/83/EC).

The results of tritium monitoring in the Vltava River at Solenice, in reference locality on the Vltava River at Hluboká, and river flows were used for calculation of tritium outflows and there comparison with the data provided by the operator of the plant, Czech Power Works – Temelín NPP (Fechtnerová, 2002–2006, Lysáček, 2007-2009).
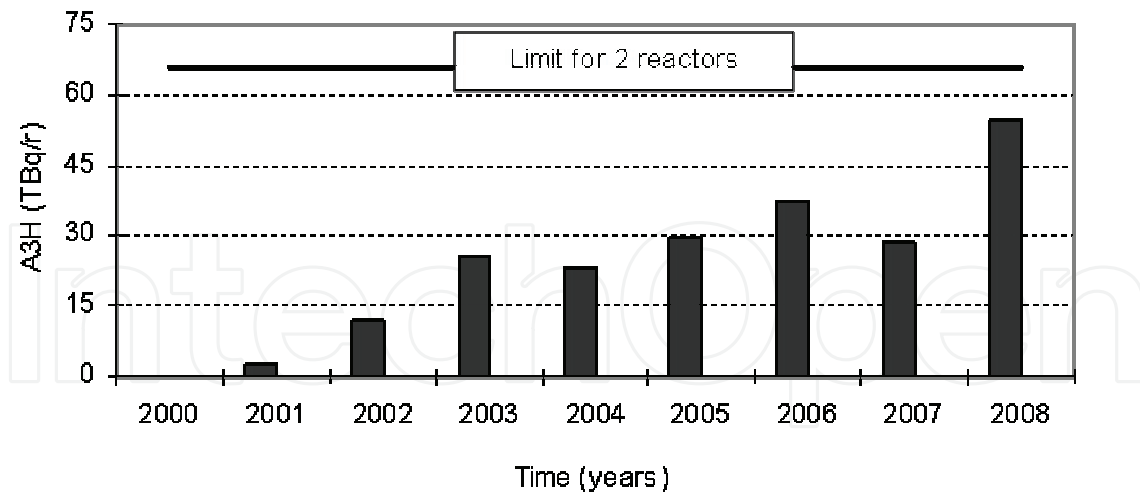
Fig. 4. Annul outflows of tritium discharged with waste water from Temelín Nuclear Power Plant in the period 2000 – 2008

The annual outflows of tritium activity ($A_{3Hcor.j}$ in Bq/y or TBq/y) in the Vltava River at Solenice (corrected by subtracting the background activity) were calculated as follows:

$$A_{3Hcor.,j} = c_{3hj}Q_j t - c_{3HBj}Q_j t \tag{10}$$

where c_{3Hj} is mean annual tritium concentration in year j (Bq/m^3),
            c_{3HBj} see Equation (9),
            Q_j mean annual river flow in year j (m^3/s),
            t   duration of a year in seconds.

The results of the calculation are summarized in Table 2, which shows that the tritium outflows (in the Vltava River at Solenice) calculated from the independent monitoring are until 2003 below the values derived from the data provided by the operator of the Temelín plant. The tritium outflows in 2002 were affected by extremely high river flows in this year. During 2003, which was dry, the tritium was accumulated in Orlík Reservoir consequently to low flows and therefore long delay time. For water storage in Orlík Reservoir of 720.10^6 m^3 and tritium concentration of 1000 Bq/m^3 (average background), the accumulated tritium quantity is 0.7 TBq. In 2004, a part of the accumulated tritium was discharged from the reservoir (Hanslík & Ivanovová, 2004b). In 2006 and 2007, the tritium outflows calculated from the monitoring exceeded those derived from Temelín data. The differences between the results are probably attributable to uneven tritium outflows from Temelín plant during a year and consequent shift of the tritium outflow from the reservoir between the years. If we take into account the fact that tritium outflow is calculated from 12 samples in a year and other uncertainties (accuracy of river flow data), we can conclude that the results are in good harmony.

Year	Results of monitoring in the Vltava at Solenice			Temelín NPP data
	Total outflow	Background	Total outflow - background	
	(TBq)			
2001	4.2	3.5	0.7	2.8
2002	15.6	6.0	9.6	11.9
2003	21.0	3.0	18.0	25.1
2004	33.9	3.5	30.4	23.0
2005	29.0	4.4	24.6	29.6
2006	55.4	4.9	50.5	37.3
2007	39.5	3.0	36.5	28.4
2008	46.8	2.5	44.3	54.3
Sum	245.5	30.8	214.7	216.4

Table 2. Annual tritium outflows calculated from the results of tritium monitoring in the Vltava River at Solenice and from data provided by the operator of Temelín Nuclear Power Plant

Continuous attention has been paid to the monitoring of tritium activities in the Vltava at Prague (Podolí), where water is abstracted for drinking water supply purposes. The tritium concentrations in the period 2002 – 2008 are together with the Vltava River flows in sampling days shown in Fig. 5. The results show that the tritium concentrations in the Vltava River at Podolí are affected by the operation of the reservoirs on the Vltava River, in addition to the effect of tritium dilution in the Vltava River reach (whose main tributaries are the Otava, Sázava and Berounka Rivers) downstream from the outflow of the waste water from the Temelín plant. This is substantiated by the relatively high tritium concentrations in January 2004, which were coupled with high outflows of the water from the Orlík Reservoir. The high tritium concentrations were caused by the fact that the tritium was accumulated in the reservoir during low flows in extremely dry period in the third and fourth quarters of 2003. A similar situation occurred again in the winter season at the end of 2004 and at the beginning of 2005 but the increase in the tritium concentration was lower than that in 2003.

7. Concentrations of ^{90}Sr, ^{134}Cs and ^{137}Cs

Decision of Regional Authority (Permit on Water management, 2007) specifies a limit 1 GBq/y for other activation and fission products (expressed as gross beta excluding tritium).

7.1. Concentrations of ^{137}Cs in water

Temporal changes of the ^{137}Cs concentrations in water samples taken from Orlík Reservoir and its tributaries were studied for two periods, 1990-1994 and 1995–2008.
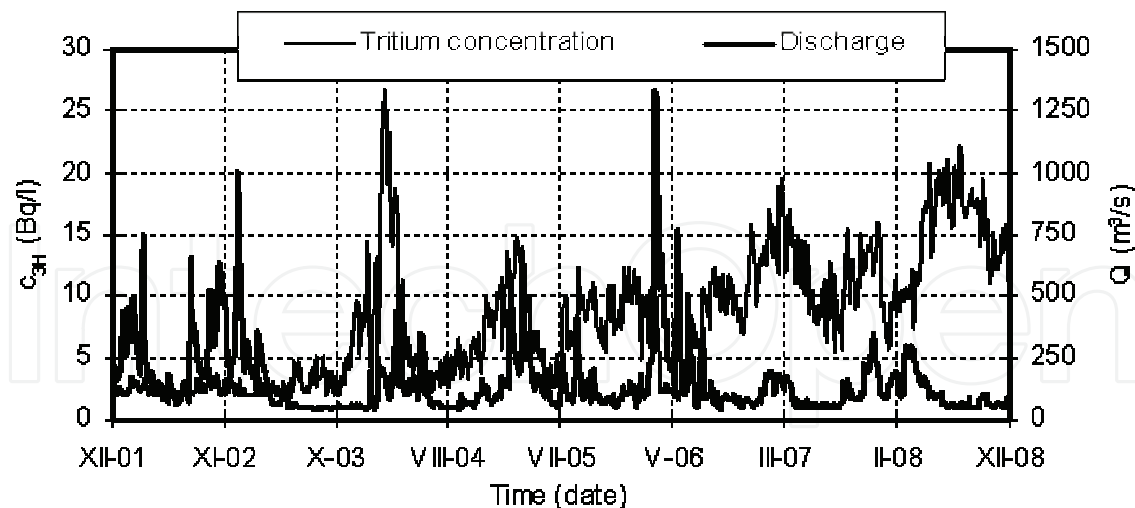
Fig. 5. Tritium concentrations (c_{3H}) and river flows (Q) in the Vltava River at Prague – Podolí in the period 2002 – 2008

The effective ecological half-lives (T_{eff}) in water in individual tributaries and outflow from Orlík Reservoir (Table 3) were evaluated in the range 1.1 – 2.2 y for the period 1990 – 1994 and 5.9 – 10.4 y for the period 1995 – 2008. The ecological half-lives (T_{ecol}) are in the range 1.2 – 2.4 y for the period 1990 – 1994 and 7.4 – 15.8 y for the period 1995 – 2008.

The results of studies showed that a decrease in the concentrations ^{137}Cs, which was observed before the plant operation, continued also during the subsequent period.

An example is shown in Fig. 6 for Vltava River at Hněvkovice (source of technological water) and the Vltava River at Solenice (downstream from the Temelín waste water outflow). In 2008, the average activity of ^{137}Cs in Hněvkovice was 0.8 mBq/l and 0.4 mBq/l in Solenice.

Period	1990 - 1994		1995 - 2008	
Tributaries of Orlík Reservoir	T_{eff} (y)	T_{ecol} (y)	T_{eff} (y)	T_{ecol} (y)
The Vltava River at Hněvkovice	1.5	1.6	7.5	10.1
The Lužnice River at Koloděje	2.2	2.4	10.4	15.8
The Otava River at Topělec	1.1	1.2	6.5	8.3
The outflow from Orlík Reservoir (the Vltava River at Solenice)	1.5	1.5	5.9	7.4

Table 3. The evaluated effective ecological half-lives and ecological half-lives of ^{137}Cs in water in the tributaries and outflow of the Orlík Reservoir in the periods 1990 – 1994 and 1995 – 2008

The results of the studies focused on the vicinity of the Temelín plant are in agreement with similar studies on changes in the water contamination after the Chernobyl accident. For example, Zibold et al. (2001) observed a faster decrease of ^{137}Cs concentration in the period 1986-1988, and the second slower phase in 1989-2000. Similarly, Smith & Beresford (2005) reported that the rate of decline of the ^{137}Cs concentration in the Pripyat River was decreasing in resent years. The effective half-lives of 1.2 years (dissolved phase) and 1.7 y

(particulate phase) in the period 1987 – 1991 increased to 3.4 y (dissolved phase) and 11.2 y (particulate phase) in the period 1995 –1998. This increase in T_{eff} has also been observed in Belarus, Ukraine and Finland (Smith & Beresford, 2005).
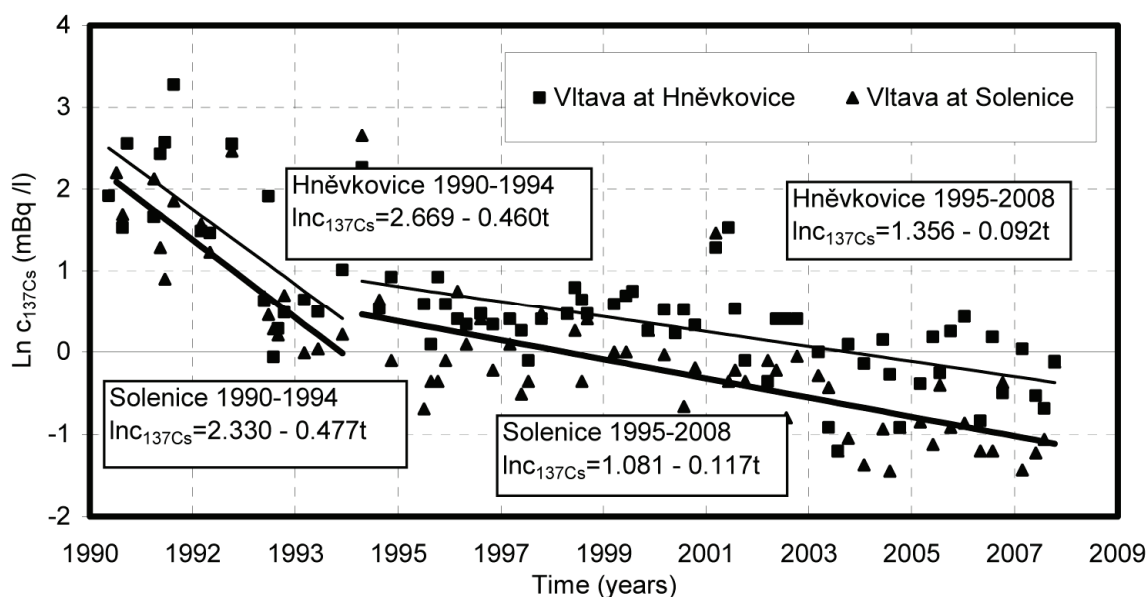

Fig. 6. Time changes of ^{137}Cs concentration (c_{137Cs}) in the Vltava River at Hněvkovice (source of technological water) and the Vltava River at Solenice (downstream from the Temelín waste water outflow) in the periods 1990-1994 and 1995-2008

7.2. Concentrations of ^{90}Sr in water

Temporal changes of the ^{90}Sr concentrations in water samples taken from Orlík Reservoir and its tributaries were studied for period 1993 – 2008.

The effective ecological half-lives (T_{eff}) in water in individual tributaries and outflow from Orlík Reservoir (Table 4) were evaluated in the range 6.8 – 12.4 y and the ecological half-lives (T_{ecol}) were in the range 9 – 21.8 y.

Period	1995 - 2008	
Tributaries of Orlík Reservoir	T_{eff} (y)	T_{ecol} (y)
The Vltava River at Hněvkovice	12.4	21.8
The Lužnice River at Koloděje	6.8	9.0
The Otava River at Topělec	8.3	11.6
The outflow from Orlík Reservoir (the Vltava River at Solenice)	8.5	12.0

Table 4. The evaluated effective ecological half-lives and ecological half-lives of ^{90}Sr in water in the tributaries and outflow of the Orlík Reservoir in the period 1993 – 2008

An example is shown in Fig. 7 for Vltava River at Hněvkovice and the Vltava River at Solenice. In 2008, the average activity of ^{90}Sr in Hněvkovice was 3.5 mBq/l and 2.5 mBq/l in Solenice.
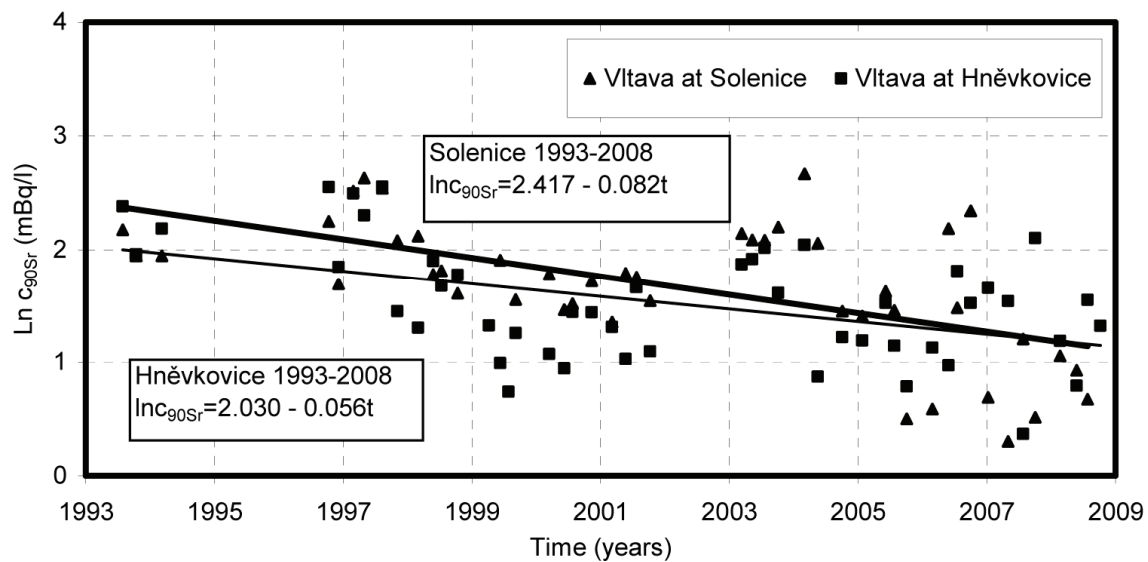
Fig. 7. Time changes of ^{90}Sr concentration (c_{90Sr}) in the Vltava River at Hněvkovice and the Vltava River at Solenice in the period 1993-2008

The concentrations of anthropogenic radionuclides ^{137}Cs and ^{90}Sr in the hydrosphere downstream from waste water discharge from the Temelín plant originate therefore mainly from the residual contamination from atmospheric tests of nuclear weapons and the Chernobyl accident. These activities show a decreasing trend in time. At present, the detected activities concentrations in surface water are near the detection limits.

7.3. Concentrations of radionuclides in sediments

The results of the analysis of sediments showed that the residual contamination from the atmospheric tests of nuclear weapons and the Chernobyl accident in the last century is dominant as compared to possible impacts of waste waters from the Temelín plant on sediment contamination. Apart from [134]Cs, ^{90}Sr and ^{137}Cs, the results of the monitoring did not substantiate sediment contamination by any other activation and fission products.

The concentrations of radiocesium in the individual river sites were different, which is attributable to inhomogeneous caesium deposition after the Chernobyl accident, different grain sizes of the sediments at the individual river sites, and different sediment transportation processes.

The activities of these radionuclides are decreasing in time. The rates of decline are similar for reference sampling sites and affected sampling sites river sites therefore the trends of decline were evaluated for average annual activities from all observed sites. The assessment of [134]Cs was stopped in 1998 because from this year all observed values were below the MDA. The effective half-life was 1.6 y for [134]Cs (for the period 1990-1998) and estimated ecological half-life was 7.8 y. For ^{137}Cs the effective half-life was 6.2 y for the period 1990-2008. The estimated ecological half-life was also 7.8 y.

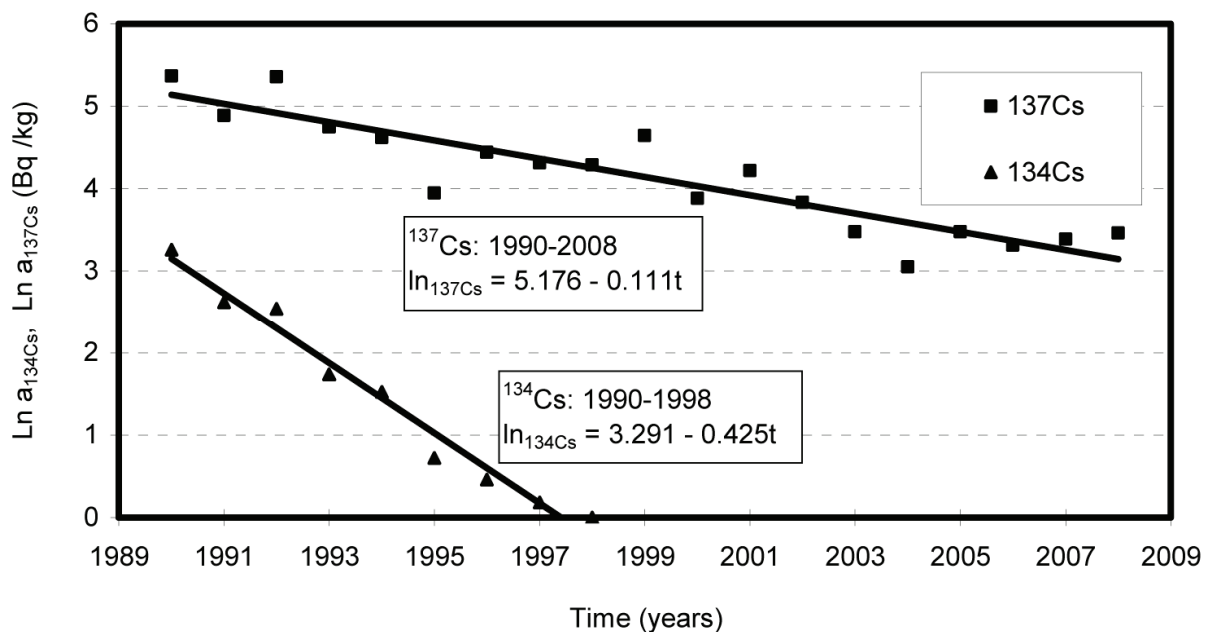Fig. 8 shows the decreasing trends in the ^{137}Cs and [134]Cs concentrations in sediments.

Fig. 8. Time changes of annual average concentrations of [134]Cs (a_{134Cs}) and [137]Cs (a_{137Cs}) in bottom sediments (dry matter) in Orlík Reservoir and its main tributaries in the periods 1990 – 1998 ([134]Cs) and 1990 – 2008 (^{137}Cs)

8. Depositions in Orlík Reservoir

Data on river flows and concentrations of suspended solids, ^{90}Sr and ^{137}Cs were used to assess possible impacts of the reservoir on monitored matters.

Annual mean concentrations of suspended solids in samples from Orlík Reservoir and its tributaries were used together with annual mean flows for derivation of a relationship between suspended solids deposition in Orlík Reservoir and annual mean flow (Fig. 9). Subsequently, it was derived that the annual deposition of suspended solids ranged between 71% – 95% (with the average value of 86 %) of the inflow of the suspended solids.

In mass unit, the annual mean deposition is 29 700 tons. The deposition of suspended matter in Orlík reservoir expressed in percentages did not show any time dependence.

The annual deposition of ^{137}Cs was derived between 36% and 76% (1.0 – 19.2 GBq) with the average value of 61%. The annual deposition was decreasing in time (Fig. 10) consequently to half life of 7.1 years (in the period 1990 – 2008). The temporal trend of the decrease is in harmony with observed trends in ^{137}Cs activity in water and bottom sediments in the study area (Hanslík et al., 2009c). The deposition of ^{137}Cs was greater in 2002 consequently to higher precipitation in this year as compared to that in the other years of the period 1996 – 2008. The mean percentage ^{137}Cs deposition was lower than that of the suspended solids. This result indicates that a part of ^{137}Cs concentration is dissolved in water and its deposited component is fixed on solid particles. This assumption is in harmony with the high level of distribution coefficient Kd for ^{137}Cs reported for the Constance lake and the Rhine River in the range $4.6 \times 10^4 - 2.7 \times 10^6$ l/kg (Smith & Beresford, 2005). The decrease in the deposition of ^{137}Cs in Orlík reservoir with the effective ecological
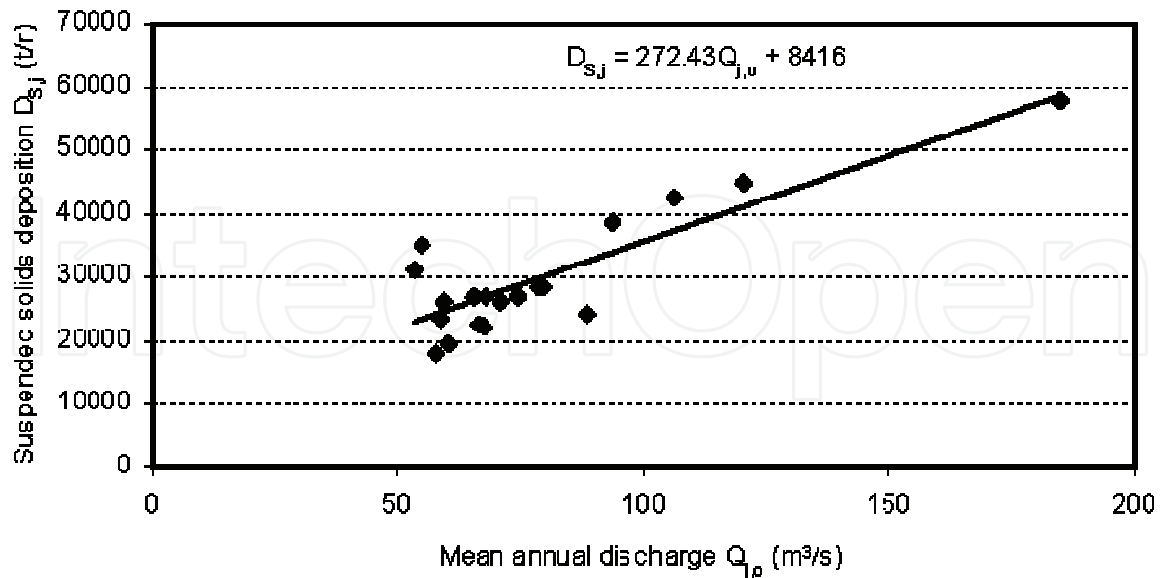
Fig. 9. Dependence of the suspended solids deposition in Orlík reservoir on the annual mean flow

half life of 7.1 years is in agreement with the half life of 6.2 years of the decrease in annual mean activity of ^{137}Cs in bottom sediments sampled during the period 1990 – 2008 from the reservoir and its tributaries.

The analysis of ^{90}Sr concentrations showed that the outflow from the reservoir exceeds that of the inflow from the tributaries and the inter-basin area. The percentage outflow of ^{90}Sr was detected in the range from -37% to 72% with the average value of 20%.

The outflow of ^{90}Sr from the reservoir corresponds with its higher mobility and lower values of Kd (750 – 1800 l/kg) published for the area surrounding Chernobyl Nuclear Power Plant (Smith & Beresford, 2005). The increased activity of ^{90}Sr at sampling sites that was detected from the monitoring after the extreme flood event in 2002 corresponds with the results obtained for the Dněpr Reservoirs, where significantly increased activity of ^{90}Sr was detected in water after the winter flood consequently to blockage of the river by ice floes (Vakulovsky et al., 1994).

It was also derived for ^{90}Sr that its residual pollution exceeds its contribution originating from wastewater discharges from Temelín Nuclear Power Plant. Annual discharges of ^{90}Sr in the period 2002 – 2008 were in the range < 0.0002 – < 0.003 GBq/y (Fechtnerová, 2003–2006, Lysáček, 2007-2009).

Annual activities of ^{90}Sr and ^{137}Cs discharged from the Temelín plant were significantly lower than the activities in the inflow and outflow from Orlík Reservoir. The concentrations of ^{90}Sr and ^{137}Cs originate from the atmospheric fall-out consequently to the atmospheric tests of nuclear weapons and Chernobyl accident in the last century.

The data on the outflows and depositions of ^{137}Cs and ^{90}Sr were compared with published results focused on the ratio of the mean activities of dissolved radioactive substances and suspended solids between the inflows and outflows from open European lakes and reservoirs in the period 1987 – 1994, that is after the Chernobyl accident (Smith & Beresford, 2005, Smith et al., 1997). In case of ^{137}Cs the detected ratio in the individual lakes ranged
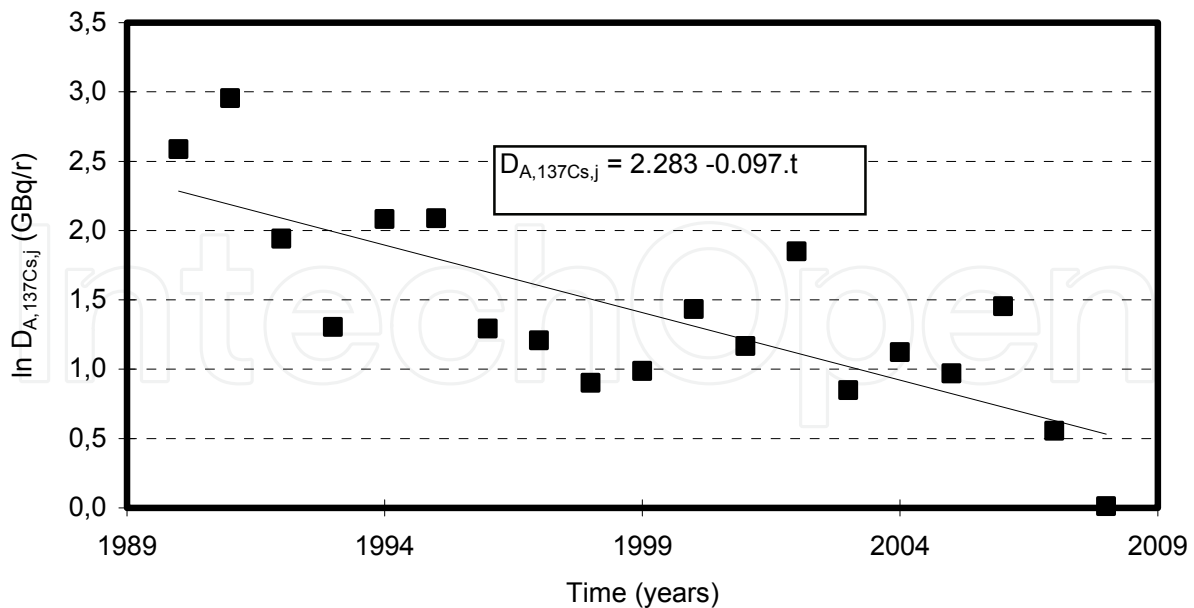
Fig. 10. Decrease in ^{137}Cs deposition in Orlík reservoir during 1990 – 2008

from 0.08 – 2.22, in case of ^{90}Sr the detected range was 0.66 – 1.44. For ^{90}Sr, the values of the ratio of its mean annual activity in the inflow and outflow from Orlík reservoir was 0.58 – 3.91 with the average value of 0.89 in the period 1996 – 2008, which was in accordance with the published results. The observed ratio of the annual mean activities of ^{137}Cs in the inflow and outflow from Orlík reservoir ranged from 1.56 to 4.11 with the average value of 2.76 in the period 1990 – 2008 and therefore this result exceeds significantly the published values (Smith & Beresford, 2005, Smith et al., 1997). The increased deposition of ^{137}Cs corresponds with the increased deposition of suspended solids in the range from 3.49 to 21.5 with the mean value of 9.00 derived for the identical period.

9. Bioaccumulation

A specific analysis was aimed at assessing ^{137}Cs concentrations in fish samples taken from Orlík Reservoir and its tributaries. Temporal changes of the ^{137}Cs concentrations were studied for two periods, 1986 – 1990 and 1994 – 2008. The results of the study were used for evaluation of ^{137}Cs temporal trends and evaluation of concentration factor and committed effective dose.

Temporal changes in ^{137}Cs concentrations in fish in Orlík Reservoir in the periods 1986 – 1990 and 1994 – 2008 are shown in Fig. 11.

Evaluated effective ecological half-lives (T_{eff}) for fish were 1.0 y for the period 1986 – 1990 and 6.1 y for the period 1994 – 2008 and ecological half-lives (T_{ecol}) were 1.1 y and 7.7 y respectively. Observed rates of decrease in ^{137}Cs concentrations in fish were approximately identical as in water. The evaluated rates of decrease in ^{137}Cs concentrations in fish are shorter than those published in literature. Brittain et al. (1991) reported that T_{eff} of ^{137}Cs in fish was 3.0 y for the period 1986 – 1989. The results from the period 1994 - 2008 confirm
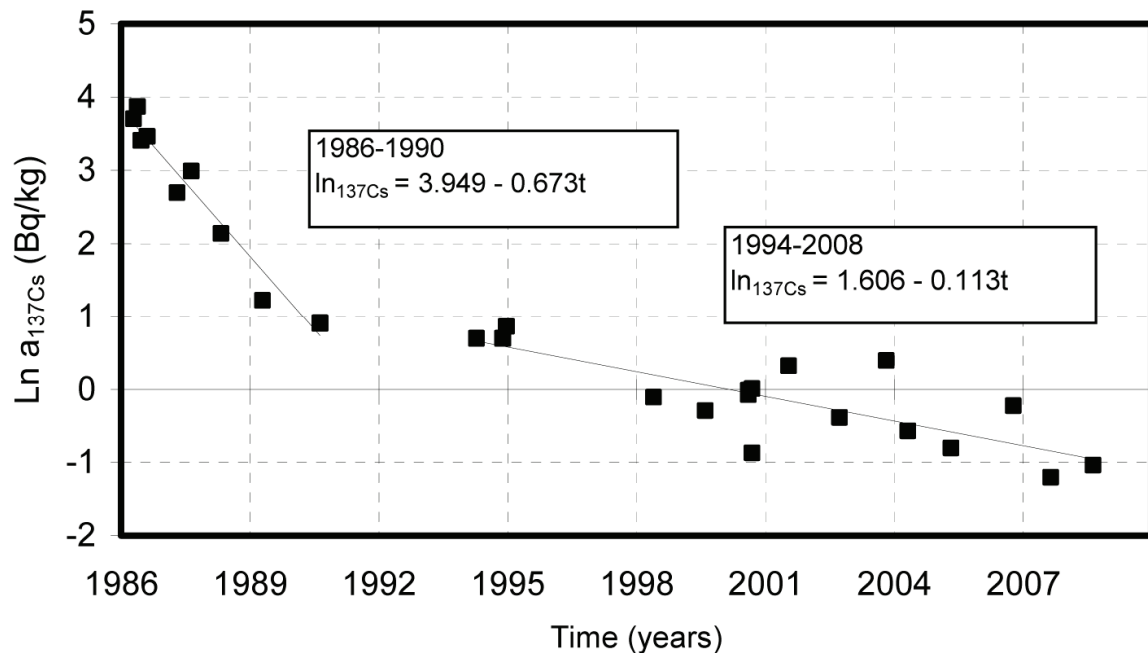
Fig. 11. Temporal changes of ^{137}Cs concentration (a_{137Cs}) in fish (wet weight) in Orlík Reservoir in the periods 1986 – 1990 a 1994 – 2008

that the rates of the decline in ^{137}Cs activity may decrease to values close to those determined by the physical decay half-life (Smith et al., 2000).

The results of the observation and analysis of ^{137}Cs concentration in fish were used for calculation of ^{137}Cs concentration factors in fish and radiation doses that could originate from fish ingestion (see Chapter on Radiation doses).

Fig. 12 shows results of the calculation of ^{137}Cs concentration factors in fish. The values of the concentration factors range from 92 to 671 l/kg, with the average value of 338 l/kg during the period 1990 – 2008.

These values are lower than those published by Smith et al. (2000) who reported the range between 82 – 14 424 l/kg with the average value 1912 l/kg. This could be attributed to the fact that the Czech study used ^{137}Cs activity in total solids in water (both in dissolved and non-dissolved solids), while Smith et al. (2000) used ^{137}Cs concentration in filtered water.

10. Radiation doses

The results from the above analyses were used for calculation of radiation doses that could originate from ingestion of fish (^{137}Cs) or water from the Vltava and Elbe Rivers (tritium).The committed effective dose from ^{137}Cs was derived from results of ^{137}Cs in fish via ingestion with 10 kg fish (by adult). Within the first few months after the Chernobyl accident it would be 4.9 µSv and since 2004 it is smaller than 0.1 µSv/y. Possible impact of radioactive waste waters from the Temelín plant was not substantiated.

Tritium concentrations were used for calculation of radiation doses from possible use of the water from the Vltava River at Solenice and the Elbe River at Hřensko for drinking water supply purposes. The calculated doses are given in Table 5. The average dose in the period
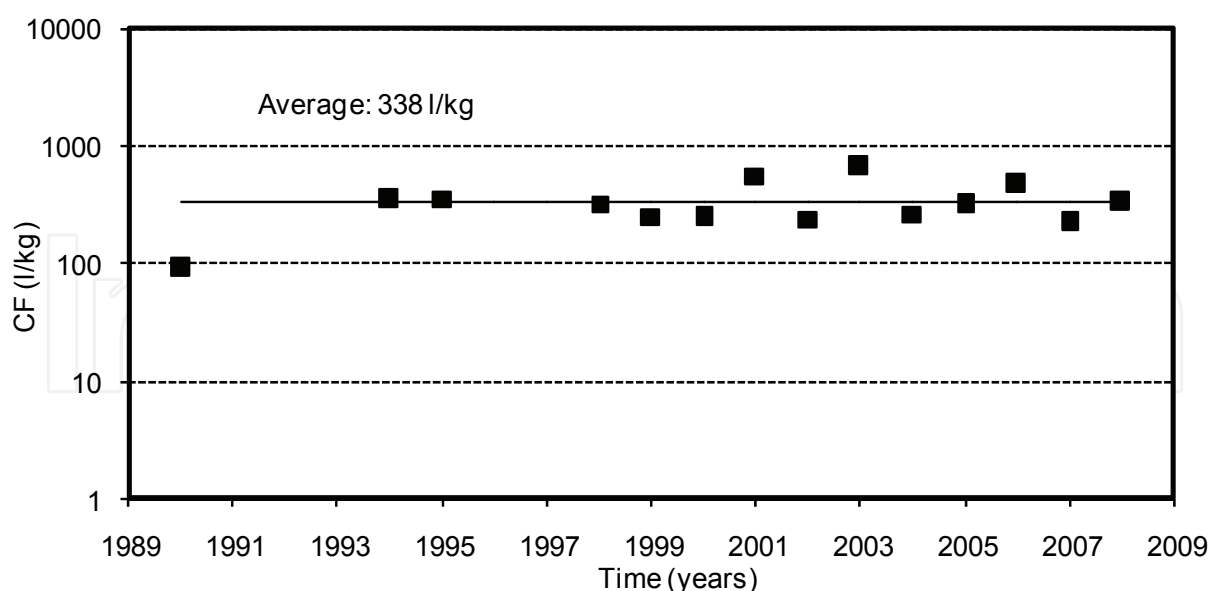
Fig. 12. ^{137}Cs concentrations factors in fish during the period 1990 – 2008

River site	Year	2001	2002	2003	2004	2005	2006	2007	2008
Vltava at Solenice	C_{3H} (Bq/l)	1.42	2.67	10.2	13.5	9.68	15.5	17.6	22.0
	E_{3H} (µSv/y)	0.018	0.034	0.128	0.170	0.122	0.195	0.222	0.277
Elbe at Hřensko	C_{3H} (Bq/l)	1.68	1.87	2.25	4.61	4.32	4.61	4.40	6.35
	E_{3H} (µSv/y)	0.021	0.024	0.028	0.058	0.054	0.058	0.055	0.080

Table 5. Annual average tritium concentrations (C_{3H}) in the Vltava at Solenice and the Elbe at Hřensko and committed effective doses (E_{3H}) due to tritium ingestion from water drinking by adults

2003 – 2008 was 0.186 µSv/y for the Vltava at Solenice and 0.056 µSv/y for the Elbe at Hřensko (the international boundary with the Federal Republic of Germany).

The calculated doses are below the limit specified in the permit issued by the State Agency for Nuclear Safety, which is 3 µSv/y for tritium and other activation and fission products. For a comparison, the calculated dose from the average ^{137}Cs concentration in the Vltava at Solenice calculated from the period 2001 – 2002 is 0.011 µSv/y. This dose has been mainly due to global fallout and the Chernobyl accident. The estimated radiation doses due to the operation of the Temelín plant are negligibly small.

11. Summary

The results of systematic monitoring of possible impacts of the Temelín plant on the hydrosphere show that the waste water discharges meet the limits specified in the permit on water management (Decision of Regional Authority - Permit on Water management, 2007) and in the Government Decree No. 61/2003 Coll. Concentrations of anthropogenic radionuclides in the hydrosphere downstream from the waste water outflow from the

Temelín plant are mainly due to the residual contamination from global fallout and the Chernobyl accident. Apart from tritium, the influence of the Temelín plant on the concentration of the activation and fission products in the hydrosphere has been negligible. Maximum annual released activity of activation and fission products excluding tritium was 0.46 GBq, which is still completely overlapped by the persisting impact of the deposition after the accident in Chernobyl NPP and atmospheric test of nuclear weapons in the last century.

Natural processes, residual contamination from atmospheric tests of nuclear weapons in the last century and discharges from nuclear facilities are the main sources of tritium concentrations in the environment. In terms of the tritium quantities, the residual contamination from the tests is dominating, however, this component is gradually diminishing consequently to the tritium radioactive decomposition. Effective half-life calculated for the period 1977 – 2008 was 8.1 years. For the period 1990 – 2008, the half-life was 12.3 years or 8.4 years if we subtract natural tritium component and tritium originating from the atmospheric transfer from nuclear facilities worldwide.

An increasing role is presently played by local tritium sources, specifically by outflows of waste waters from nuclear facilities. The results of tritium monitoring downstream from the outflow of waste waters from the Temelín plant showed that the annual tritium concentrations did not exceed an indicative limit of 100 Bq/l specified in a Decree of the State Institute for Nuclear Safety No. 307/2002.

Annual tritium outflows that have been derived from data from tritium monitoring in the Vltava River at Solenice are in harmony with the values derived from the data provided by the operator of the Temelín plant. These results therefore also substantiate the fact that the pollution data from the independent monitoring can affectively be used for verification of the pollution outflows from the Temelín plant.

For two time periods (1990-1994 and 1995–2008), the concentrations of ^{137}Cs were analysed in surface water and fish and for one period (1990-2008) in sediments. The effective ecological half-lives in water in individual tributaries and outflow from Orlík Reservoir were evaluated in the range 1.1 – 2.2 years for the period 1990 – 1994 and 5.9 – 10.4 years for the period 1995 – 2008. The results showed that in the first period (close to the accident in Chernobyl) the concentrations of ^{137}Cs were rapidly decreasing while slow decline was detected for the second period (after 1995). For ^{137}Cs in sediments the effective half-life was 6.2 years for the period 1990-2008 Evaluated effective ecological half-lives for fish were 1.0 y for the period 1986 – 1990 and 6.1 years for the period 1994 – 2008. Concentrations of ^{137}Cs in water and fish were decreasing approximately with the same rate. Temporal changes of the ^{90}Sr concentrations in water samples taken from Orlík Reservoir and its tributaries were studied for period 1993 – 2008. The effective ecological half-lives in water in individual tributaries and outflow from Orlík Reservoir were evaluated in the range 6.8 – 12.4 y.

Temporal changes of the ^{134}Cs and ^{137}Cs concentrations in sediments were studied for period 1990 – 1998 and 1990 – 2008 respectively. The assessment of ^{134}Cs was stopped in 1998 because from this year all observed values were below the MDA. The effective half-life was 1.6 y for ^{134}Cs (for the period 1990-1998). For ^{137}Cs the effective half-life was 6.2 y for the period 1990-2008.

Data on river flows and concentrations of suspended solids, ^{90}Sr and ^{137}Cs were used to assess possible impacts of the reservoir on monitored matters. It was derived that the annual deposition of suspended solids ranged between 71% – 95% (with the average value of 86 %) of the inflow of the suspended solids. The annual deposition of ^{137}Cs was derived

between 36% and 76% with the average value of 61 %. The annual deposition of ^{137}Cs was decreasing in time consequently to half life of 7.1 years (in the period 1990 – 2008). The analysis of ^{90}Sr concentrations showed that the outflow from the reservoir exceeds that of the inflow from the tributaries and the inter-basin area. The percentage outflow of ^{90}Sr was detected in the range from -37% to 72% with the average value of 20%.

During the period 1990 – 2008, the ^{137}Cs concentration factor calculated from fish samples ranged from 92 to 671 l/kg with the average value of 338 l/kg. Committed effective dose by ^{137}Cs via ingestion of 10 kg fish (by adult) within the first few months after the Chernobyl accident was 4.9 µSv and since 2004 it is smaller than 0.1 µSv/y.

In surface water, river bottom sediments and also fish samples from the Temelín vicinity, the ^{137}Cs and ^{90}Sr concentrations show a decreasing trend, including the samples taken downstream from the waste water outflow from the Temelín plant.

Acnknowledgement

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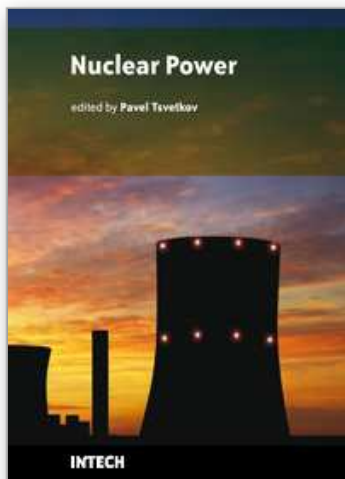
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The world of the twenty first century is an energy consuming society. Due to increasing population and living standards, each year the world requires more energy and new efficient systems for delivering it. Furthermore, the new systems must be inherently safe and environmentally benign. These realities of today's world are among the reasons that lead to serious interest in deploying nuclear power as a sustainable energy source. Today'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. The goal of the book is to show the current state-of-the-art in the covered technical areas as well as to demonstrate how general engineering principles and methods can be applied to nuclear power systems.