https://www.sworldjournal.com/index.php/swj/article/view/swj06-07-113
DOI: 10.30888/2663-5712.2020-06-07-113

УДК 502.51-049.5

RADIATION CAPACITY OF FRESHWATER RESERVOIRS IN THE AREA OF THE SOUTH-UKRAINE NPP

РАДІАЦІЙНА ЄМНІСТЬ ПРІСНОВОДНИХ ВОДОЙМ У РАЙОНІ ЮЖНО-УКРАЇНСЬКОЇ АЕС

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Abstract. *The purpose of the work is to estimate the radiation capacity of reservoirs around the SU NPP for the use of this indicator in the environmental regulation of liquid discharges from the NPP. The method of estimating the radiation capacity of reservoirs [6] based on the construction of a chamber model of the ecosystem of a freshwater reservoir was used. When calculating the parameters of radionuclide transfer between the chambers, the data of radiometry of water samples and water components of reservoirs of the external dosimetry laboratory (EDL) of the SU NPP [1] and data of radionuclide content in water and bottom sediments of reservoirs were used [3]. Data on the content of radionuclides in the components of the freshwater ecosystem, which are given in [4], were also used.*

The results are to determine the characteristics (accumulation factors) of the migration processes of radionuclides (^{137}Cs, ^{90}Sr, ^{54}Mn, ^{108m}Ag, ^{110m}Ag, ^{103}Ru, ^{106}Ru, ^{57}Co, ^{60}Co) in the technological reservoirs of the SU NPP and radionuclides (^{137}Cs, ^{90}Sr) in the storage reservoirs, which are hydrodynamically related to these technological reservoirs and to assess the indicators of the state and reliability of the ecosystem (factor of radiation capacity) of the technological reservoirs and storage reservoirs.

Scientific novelty. The radiation capacity was determined and the factors of radiation capacity of water biota, bottom sediments for reservoirs of freshwater ecosystem, which are hydrologically connected with the technological reservoirs of the NPP, were assessed for the first time.

Keywords: *radiation capacity of reservoirs, bottom sediments, water biota, critical inflow, technological reservoirs of the NPP, ecosystem of freshwater reservoir.*

Introduction.

Due to the fact that the discharge of water is practically the only possibility for significant material masses to leave the NPP, and, as a result, there is a possibility of radioactive substances getting into surface and underground waters, it is necessary to investigate the radioecological state of freshwater ecosystems which are hydrologically connected with the technological reservoirs of the NPP.

Reservoirs can act as the main reservoir where radioactive substances accumulate [9-11]. In this case, aquatic ecosystems, on the one hand, are the highways through which the migration of radionuclides occurs, on the other hand they are a place of deposition of these pollutants [12].

At the NPP, water for cooling the reactor is taken from surface reservoirs, and after it passes through the cooling circuit and absorbs significant radionuclide activity, it is returned back. For this purpose, NPP cooling ponds are created, which can be a reservoir of accumulated radioactivity.

The main text.

The water system in the location area of the SU NPP is formed, on the one hand, by the Southern Bug River and storage reservoirs created in its channel, and, on the other hand, the Arbuzynka and Mertvovid rivers.

The technological reservoirs of the SU NPP are the cooling pond (the Tashlyk Storage Reservoir) and three ponds with biological treatment of industrial and municipal sewerage (IMS).

The surface area of the Tashlyk Reservoir at the normal production level (NPL) is 8.6 km^2, at the level of the base volume (BVL) – 5.3 km^2. The volume of water at NPL is $8.61 \cdot 10^7$ m^3, at BVL – $4.0 \cdot 10^7$ m^3. The average depth of the reservoir is 10 m. The maximum depth reaches 44.5 m.

The Oleksandrivka Reservoir has a complex purpose and is used for hydropower (ensuring the operation of the Oleksandrivka HPP and Tashlyk PSP), irrigation and drinking water supply. The storage reservoir is also used for fishing. The surface area is 13.1 km^2, the average depth is 9.07 m, the maximum depth is 20.36 m, the length is 19.35 km, the width is 0.677 km, and the coastline is 45.1 km.

Liquid discharges of the SU NPP after preliminary treatment are mixed with the discharges of industrial and municipal sewerage (IMS) of the NPP and Yuzhnoukrainsk, and through treatment facilities, which include biological retention basin ponds, since 1993 are discharged to the cooling pond, from which “blow-off” water is constantly discharged to the Southern Bug River. Simultaneously from the river, in the same mode, water losses in the cooling pond are replenished. Three biological treatment ponds have been created for biological treatment of IMS. The three bio-treatment ponds of IMS of the SU NPP are represented as a cascade of three interconnected reservoirs in which a gradual deposition of radioactivity is carried out naturally after mechanical and chemical treatment at the NPP treatment facilities.

The Taborivka Reservoir is an irrigation and economic facility. It is located near the city of Voznesensk. Its volume at NPL is equal to $6.35 \cdot 10^7$ mln m^3. Water surface area at NPL is $1.03 \cdot 10^7$ mln m^2. Working water volume is $4.9 \cdot 10^7$ mln m^3. The Trykraty Storage Reservoir is hydrologically connected with it and it is a channel reservoir of the Arbuzynka River (a tributary of the Mertvovid River), which flows in the location area of the bio-treatment ponds of IMS of the SU NPP, and to which the discharges of IMS were carried out until 1993.

The hydrodynamic relationship between these reservoirs is as follows. To desalinate the waters of the SU NPP cooling pond, it is blown off into the Southern Bug River with a volume of $2.8 \cdot 10^7$ m^3 a year. Filtration of water from the cooling pond in the Southern Bug River is $0.3 \cdot 10^7$ m^3 a year. At the same time, the Tashlyk Storage Reservoir is fed with clean water from the Southern Bug River with a water intake in the village of Oleksiyivka (above the location of the SU NPP), the volume of adding is $9.4 \cdot 10^5$ m^3 a year. Liquid discharges of industrial and municipal sewerage after treatment facilities and settling in three ponds of biotreatment, since 1993 have been pumped by pipeline from treatment facilities, and at a speed of 82.8 m^3 a day are discharged into the cooling pond. Until 1993, the discharge of these waters with a volume of 11 mln m^3 a year was carried out into the low-water (river runoff is 6 mln m^3 a year) Arbuzynka River. After this change in the discharge of liquid wastewater, drainage and natural filtration of water from bio-treatment ponds in the Arbuzynka River remained. Thus, the block diagram of the transfer of radioactivity to the freshwater ecosystem of the Southern Bug River in the SU NPP area can be represented in the form shown in Fig. 1.

Let us consider each chain of possible migration of radionuclides from the technological reservoirs of the SU NPP into the freshwater ecosystem of the Southern Bug river. According to the research materials [4] in the water of the cooling pond of the SU NPP at the beginning of its operation (1982 – 1988), such radionuclides were registered as: ^{137}Cs, ^{90}Sr, ^{54}Mn, ^{108m}Ag, ^{110m}Ag, ^{103}Ru, ^{106}Ru, ^{57}Co, ^{60}Co. Cobalt and silver radioisotopes were also registered in the water of the bio-treatment ponds of the treatment facilities of IMS of the SU NPP in the early 1990s. Some of these radionuclides were also registered in the water of the reservoirs hydrologically connected with the technological reservoirs of the SU NPP: the Oleksandrivka Storage Reservoir, the Trykraty Storage Reservoir, the Taborivka Storage Reservoir. In recent years, the highest levels of radioactivity were characteristic of ^{137}Cs, ^{3}H.

The migration processes of radionuclides, which were periodically or chronically present in the water of these reservoirs, were reflected in the presence of these radionuclides in other components (bottom silts, algae) of the ecosystems of reservoirs. The generalized calculation results concerning the coefficients of transition of radionuclides into the bottom deposits of reservoirs, into algae are presented in Table 1. The calculated average values of the corresponding coefficients for each radionuclide as for the reservoirs are also presented. When calculating the radionuclide accumulation factors by bottom deposits, we used the formula (1):

$$k^i_{bottom} = \frac{C^i_{bottom}(\frac{Bq}{kg})}{C^i_{water}(\frac{Bq}{l})}, \tag{1}$$

where k^i_{bottom} – is radionuclide i accumulation factor by bottom sediments of the reservoir from water, $\frac{Bq/kg}{Bq/l}$;

C^i_{bottom} – specific activity of radionuclide i in bottom sediments of the reservoir, $(\frac{Bq}{kg})$;

C^i_{water} – specific activity of radionuclide i in the water of the reservoir, $(\frac{Bq}{l})$.

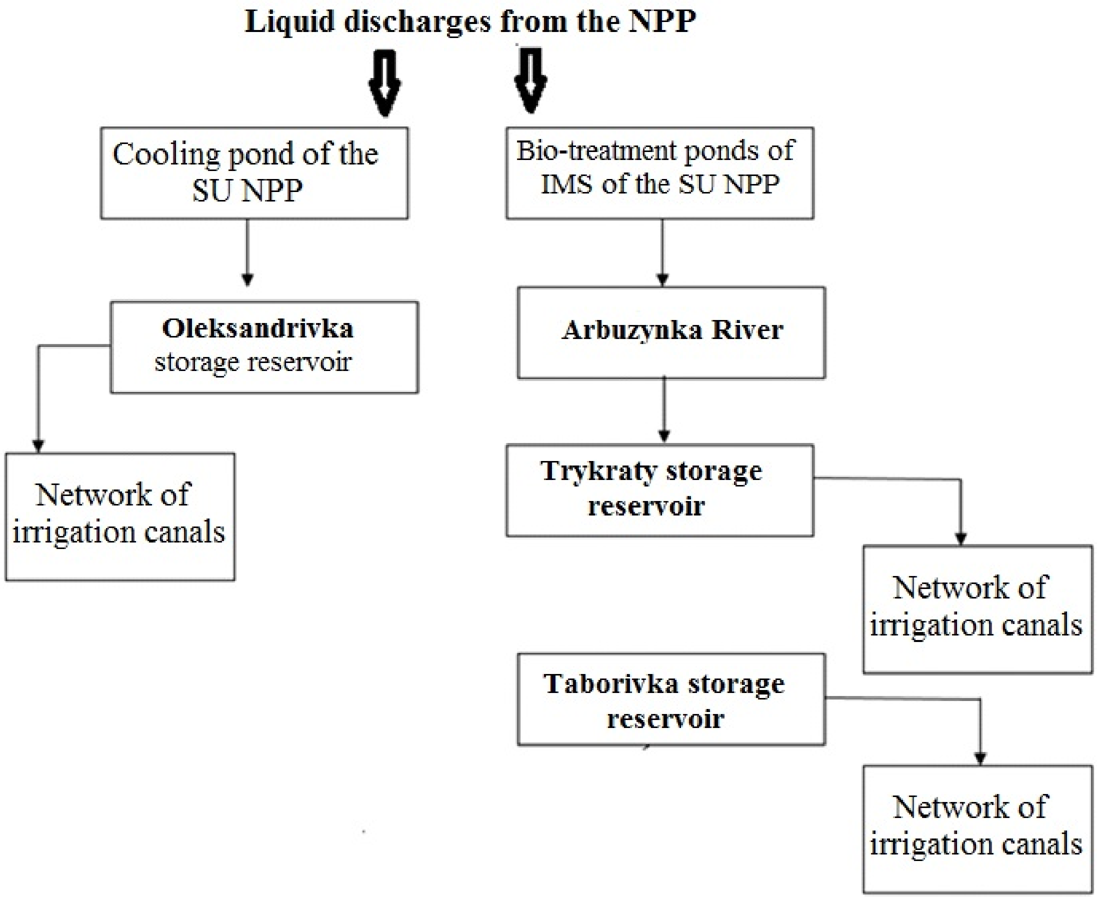

Figure 1 – Block diagram of options for possible migration of radionuclides from technological reservoirs of the SU NPP into the freshwater ecosystem of the Southern Bug River

When calculating the radionuclide accumulation factors by algae, we used the formula:

$$k^i_{algae} = \frac{C^i_{algae}(\frac{Bq}{kg})}{C^i_{water}(\frac{Bq}{l})}, \qquad (2)$$

where k^i_{algae} – radionuclide i accumulation factor by algae from the water of the reservoir, $\frac{Bq/kg}{Bq/l}$;

C^i_{algae} – specific activity of radionuclide i in algae of the reservoir, $(\frac{Bq}{kg})$;

C^i_{water} – specific activity of radionuclide i in the water of the reservoir, $(\frac{Bq}{l})$.

These results were estimated when calculating the radiation capacity and radiocapacity factors: the radiocapacity factor of the bottom sediments of the reservoir, the radiocapacity factor of the water biota of the reservoir, the total radiocapacity factor of these reservoirs (Table 2) according to the formulas [6]:

Table 1

Average values of radionuclide accumulation factors (k^i_{bottom}, k^i_{algae}) of reservoirs

Reservoir	Accumulation factor	^{137}Cs, ^{134}Cs	^{90}Sr	^{54}Mn	^{108m}Ag, ^{110m}Ag	^{103}Ru, ^{106}Ru	^{57}Co, ^{60}Co
Cooling pond	$k^i_{bottom}, \frac{Bq/kg}{Bq/l}$	700	150	250	580	430	420
	$k^i_{algae}, \frac{Bq/kg}{Bq/l}$	1200	1500	2500	3800	4300	4200
3rd bio-treatment pond of treatment facilities	$k^i_{bottom}, \frac{Bq/kg}{Bq/l}$	650	120	350	620	420	400
	$k^i_{algae}, \frac{Bq/kg}{Bq/l}$	1250	1200	3500	6200	5200	4000
Oleksandrivka Reservoir	$k^i_{bottom}, \frac{Bq/kg}{Bq/l}$	500	120	–	–	–	–
	$k^i_{algae}, \frac{Bq/kg}{Bq/l}$	980	120	–	–	–	–
Trykraty Reservoir	$k^i_{bottom}, \frac{Bq/kg}{Bq/l}$	580	70	–	–	–	–
	$k^i_{algae}, \frac{Bq/kg}{Bq/l}$	1100	70	–	–	–	–
Taborivka Reservoir	$k^i_{bottom}, \frac{Bq/kg}{Bq/l}$	570	70	–	–	–	–
	$k^i_{algae}, \frac{Bq/kg}{Bq/l}$	1100	70	–	–	–	–
Average as for reservoirs	$k^i_{bottom}, \frac{Bq/kg}{Bq/l}$	600	265	300	600	425	
	$k^i_{algae}, \frac{Bq/kg}{Bq/l}$	1126	592	3000	5000	5300	4100

$$A^i = C^i_{water} \times S \times (H + k^i_{bottom} \times h + k^i_{algae} \times P \times H),$$

$$F_{bottom}^{i} = \frac{k_{bottom}^{i} \times h}{H + k_{bottom}^{i} \times h}),$$

$$F_{algae}^{i} = \frac{P \times k_{algae}^{i} \times H}{(H + P \times k_{algae}^{i} \times H)}),$$

$$F^{i} = \frac{\left(k_{bottom}^{i} \times h + P \times k_{algae}^{i} \times H\right)}{\left(H + k_{bottom}^{i} \times h + P \times k_{algae}^{i} \times H\right)}$$

where S — surface area of the reservoir, m^2;

H – depth of the reservoir, m;

h – thickness of the effective layer of bottom sediments (the layer in which radionuclides accumulate, h = 0.1 m);

k_{bottom}^{i} – is radionuclide i accumulation factor by bottom sediments of the reservoir from water, $\frac{Bq/_{kg}}{Bq/_{l}}$;

k_{algae}^{i} – radionuclide i accumulation factor by algae from the water of the reservoir, $\frac{Bq/_{kg}}{Bq/_{l}}$.

Radiocapacity $A^{i}(Bq)$ is a fundamental property of ecosystems which determines the maximum amount of radionuclides (Bq) that can be kept stably by the biota of the ecosystem, without damaging (changing) its basic functions (growth, biomass growth of biota and habitat conditioning). Radiocapacity factor F^{i} determines the proportion of radionuclides which is retained in the biotic and abiotic components of the ecosystem.

As shown by the results presented in Table 2, the calculated values of the radiation capacity of the SU NPP technological reservoirs for radionuclides that the NPP discharges into the surface reservoirs ($^{137,134}Cs$, ^{90}Sr, ^{54}Mn, $^{108m,\,110m}Ag$, $^{103,106}Ru$, $^{57,60}Co$, ^{60}Co, ^{3}H), differed between the cooling pond and the third biotreatment pond of the SU NPP by three orders of magnitude, the range of values was $n \times 10^{8} - n \times 10^{11}$Bq. This is due to the difference in the volume of reservoirs and the difference in the radionuclide accumulation factors by the components of the reservoir ecosystem (higher accumulation factors were registered for the biotreatment pond of the treatment facilities of IMS of the SU NPP). Between surface storage reservoirs (Oleksandrivka, Taborivka, Trykraty) the difference in the value of radiation capacity (range of values $\mathrm{n} \times 10^{9} - \mathrm{n} \times 10^{16}$) is due to the difference only in the volume of reservoirs.

Table 2

The average values of the factors of radiation capacity of technological reservoirs in the area of the SU NPP for the period of its operation (1982-2018), obtained for each radionuclide

Reservoir	Indicator	^{137}Cs, ^{134}Cs	^{90}Sr	^{54}Mn	^{108m}Ag, ^{110m}Ag	^{103}Ru, ^{106}Ru	^{57}Co, ^{60}Co
Cooling pond	F^i_{bottom}	0.60	0.60	0.68	0.68	0.60	0.66
	F^i_{algae}	0.99	0.97	0.72	0.68	0.60	0.68
	F^i	0.71	0.62	0.72	0.68	0.60	0.68
3rd biotreatment pond	F^i_{bottom}	0.89	0.80	0.72	0.76	0.79	0.79
	F^i_{algae}	0.97	0.89	0.78	0.80	0.82	0.88
	F^i	0.97	0.78	0.80	0.82	0.88	0.78

The results of calculating the radiocapacity factors of individual components of the reservoir ecosystem showed that for all radionuclides the value of the radiocapacity factors of the biotic component of the reservoir F^i_{bottom}, which was represented by higher aquatic plants, is greater than the corresponding values for the radiocapacity factors of bottom sediments F^i_{algae}, which emphasizes the leading role of water biota in the retention of radioactivity within the ecosystem. The results of the calculation of radiocapacity factors F^i_{bottom}, F^i_{algae} for the cooling pond of the SU NPP deserve special attention: radiocapacity factors F^i_{bottom}were low for almost all radionuclides. This indicates that the bottom sediments of this reservoir are not characterized by a high ability to retain radionuclides.

Radiocapacity factors differed by reservoirs: the smallest values (0.68–0.71) were determined for the cooling pond. For another technological reservoir - the III rate of biotreatment of the treatment facilities of IMS of the SU NPP - the radiocapacity factor was quite high (0.89–0.97). For other reservoirs, the radiocapacity factors were at a sufficiently high level (0.89–0.98), which indicates the good ability of the ecosystems of these reservoirs to retain radionuclides, to accumulate and concentrate radionuclides, which have got into the biomass, without significant consequences for the ecosystem itself. The low values of the radiocapacity factor for the cooling pond of the SU NPP, and for all radionuclides, may indicate that the ecosystem of this reservoir is not characterized by high reliability, therefore it is necessary to take measures to increase the value of the radiocapacity factor. This, first of all, consists in establishing a higher yield of water biota in this pond, as well as in the selection of those particular aquatic plants which are characterized by higher radionuclide accumulation factors, and will act as biological deactivators of reservoirs.

Conclusions.

The average value of the volume of liquid discharges of the SU NPP into the nearby surface reservoirs for the period from 1987 to 2017 was 54163,48±11265,95 m^3 a year, the maximum value reached 171900 m3. The total activity of liquid discharges of radionuclides ($^{137,134}Cs$, ^{90}Sr, ^{54}Mn, $^{108m,110m}Ag$, $^{103,106}Ru$, $^{57,60}Co$, ^{60}Co) of the SU NPP into water bodies varied in the range of 100–840 MBq a year. The activity of liquid discharges for ^{3}H was in the range of 483–2535 GBq a year. That is, 3H discharges made up to 99% of the total activity of liquid discharges of radionuclides of the SU NPP into the nearby surface reservoirs. It is calculated that during 1994–2018, an average of 205.0±12.1 TBq of ^{3}H was removed from the Southern Bug River as a result of blow off, and 51±9 TBq of ^{3}H was removed as a result of filtration through underground horizons.

The values of radionuclide accumulation factors ($^{137,134}Cs$, ^{90}Sr, ^{54}Mn, $^{108m,110m}Ag$, $^{103,106}Ru$, $^{57,60}Co$, ^{60}Co) by bottom sediments and algae for two technological reservoirs of the SU NPP (cooling pond, 3rd biotreatment pond) and radionuclides (^{137}Cs, ^{134}Cs, ^{90}Sr) for three nearby surface reservoirs (Oleksandrivka, Trykraty, Taborivka) were calculated.

The average values of radionuclide accumulation factors by bottom sediments were: for ^{137}Cs, ^{134}Cs – 600±30 $\frac{Bq/kg}{Bq/l}$, for ^{90}Sr – 265±35 $\frac{Bq/kg}{Bq/l}$, for ^{54}Mn – 300±50 $\frac{Bq/kg}{Bq/l}$, for ^{108m}Ag, ^{110m}Ag – 600±20 $\frac{Bq/kg}{Bq/l}$, for ^{103}Ru, ^{106}Ru – 425±10 $\frac{Bq/kg}{Bq/l}$, for ^{57}Co, ^{60}Co – 410±10 $\frac{Bq/kg}{Bq/l}$.

The average values of radionuclide accumulation factors by algae were: for ^{137}Cs, ^{134}Cs – 1126±30 $\frac{Bq/kg}{Bq/l}$, for ^{90}Sr – 592±75 $\frac{Bq/kg}{Bq/l}$, for ^{54}Mn – 3000±300 $\frac{Bq/kg}{Bq/l}$, for ^{108m}Ag, ^{110m}Ag – 5000±1200 $\frac{Bq/kg}{Bq/l}$, for ^{103}Ru, ^{106}Ru – 5300±1000 $\frac{Bq/kg}{Bq/l}$, for ^{57}Co, ^{60}Co – 4100±1000 $\frac{Bq/kg}{Bq/l}$

The calculated values of the radiation capacity of the SU NPP technological reservoirs by radionuclides which the NPP discharges into surface reservoirs ($^{137,134}Cs$, ^{90}Sr, ^{54}Mn, $^{108m,110m}Ag$, $^{103,106}Ru$, $^{57,60}Co$, ^{60}Co, ^{3}H) differed between the cooling pond and the third biotreatment pond by three orders of magnitude, the range of values was $n \times 10^{8} \div n \times 10^{11}$ Bq, due to the difference in the volume of reservoirs and the difference in the radionuclide accumulation factors by the components of the reservoir ecosystem (higher accumulation factors were registered for the biotreatment pond of the treatment facilities of IMS of the SU NPP). Between surface storage reservoirs (Oleksandrivka, Taborivka, Trykraty) the difference in the value of radiation capacity (range of values $n \times 10^9 \div n \times 10^{16}$) is due to the difference only in the volume of reservoirs.

The calculated factors of the radiation capacity of the surveyed reservoirs differed by reservoirs: the smallest values (0.68–0.71) were determined for the cooling pond. The radiation capacity factor was high (0.89–0.97) for the III biotreatment pond of the treatment facilities of IMS of the SU NPP. For other reservoirs, the radiocapacity factors were at a sufficiently high level (0.89–0.98), which indicates the good ability of the ecosystems of these reservoirs to retain radionuclides, to accumulate and concentrate radionuclides, which have got into the biomass, without significant consequences for the ecosystem itself. The low values of the radiocapacity factor for the cooling pond of the SU NPP, and for all radionuclides, may indicate that the ecosystem of this reservoir is not characterized by high reliability, therefore it is necessary to take measures to increase the radiocapacity of the reservoir.

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Анотація. *Ціль роботи – оцінити радіоємність водойм навколо ЮУ АЕС для використання цього показника при екологічному нормуванні рідких скидів АЕС. Результати полягають у визначенні характеристик (коефіцієнтів накопичення) міграційних процесів радіонуклідів (^{137}Cs, ^{90}Sr, ^{54}Mn, ^{108m}Ag, ^{110m}Ag, ^{103}Ru, ^{106}Ru, ^{57}Co, ^{60}Co) у технологічних водоймах ЮУАЕС та радіонуклідів (^{137}Cs, ^{90}Sr) у водосховищах, які гідродинамічно пов’язані з цими технологічними водоймами та в оцінці показників стану і надійності екосистеми (фактора радіоємності) технологічних водойм і водосховищ. Вперше визначено радіоємність і оцінено фактори радіоємності водяної біоти, донних відкладень для водойм прісноводної екосистеми, які гідрологічно пов’язані з технологічними водоймами АЕС.*

Ключові слова: *радіаційна ємність водойм, донні відкладення, водяна біота, критичне надходження, технологічні водойми АЕС, екосистема прісноводної водойми.*

Стаття відправлена: 10.12.2020 г.