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COMPREHENSIVE RADIOECOLOGICAL MONITORING OF FRESHWATER ECOSYSTEMS IN THE VICINITY OF ROOPPUR NPP (PEOPLE'S REPUBLIC OF BANGLADESH)[*]

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The paper presents experience of developing and maintaining a system of radioecological monitoring of freshwater ecosystems in the vicinity of Rooppur Nuclear Power Plant (Bangladesh). Components of freshwater ecosystems in the zone of NPP impact are both very informative for determining the environmental state and very important for conducting economic activities. Therefore, the issue of assessing and predicting quality of freshwater ecosystems in the vicinity of NPP is relevant for ensuring radiation and environmental safety. During the studies, we developed a detailed monitoring program; selected observation points for the state of surface water and groundwater at different distances from Rooppur NPP; determined monitoring objects (water, bottom sediments, higher aquatic vegetation, and fish), list of parameters to be studied, observation regulation, methods, and regulatory and technical support. Among the indicators controlled we considered the following ones: physicochemical properties of water and bottom sediments; radionuclide content of components of freshwater ecosystems including natural (^{40}K, ^{226}Ra, and ^{232}Th) and technogenic (^{90}Sr, ^{137}Cs, and ^{3}H) radionuclides; and content of 19 heavy metals, as well as chemical pollutants. Monitoring studies were conducted in 2014–2017, considering climatic peculiarities of the region at different periods of the year. Radionuclides in environmental objects were determined by spectrometry and radiochemistry; heavy metals – by atomic absorption and plasma emission analysis methods. It was established that higher aquatic vegetation in the Padma River is found not in all seasons. In December, it was almost absent. The maximum species diversity was registered in June. Differences between surface water and groundwater in the vicinity of Rooppur NPP were distinguished for several physical and chemical characteristics. Values of drinking water total mineralization and hardness were higher than that of surface water by 2–3 times. This is due to Padma River water composition, the basis of which is meltwater and rainwater. Organic pollutants content in surface water and groundwater was below detection limits or at minimum ones (benzopyrene – less than 0.01 $\mu g \cdot L^{-1}$; phenols – 1.3–3.5 $\mu g \cdot L^{-1}$; and petroleum products – 0.01–0.043 $mg \cdot L^{-1}$). Activity concentration of ^{137}Cs in Padma River water did not exceed 0.18 $Bq \cdot L^{-1}$ (with a mean of 0.07 $Bq \cdot L^{-1}$) during the observation period. The content of ^{90}Sr was 0.02–0.12 $Bq \cdot L^{-1}$, and the concentration of ^{3}H varied in the range of 0.8–2.1 $Bq \cdot L^{-1}$. Mean specific activity of ^{90}Sr in bottom sediments was 0.5–1.8 $Bq \cdot kg^{-1}$, and ^{137}Cs – 0.8–2.1 $Bq \cdot kg^{-1}$. Specific activity of ^{3}H in bottom sediments was less than 3 $Bq \cdot kg^{-1}$, except for 3 samples in 2017 (12–30 $Bq \cdot kg^{-1}$), which was most likely due to a local pollution. Specific activity of ^{90}Sr in higher aquatic vegetation

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was 0.4–3.9 Bq·kg^{-1}, and ^{137}Cs – 0.4–1.0 Bq·kg^{-1}. In drinking water, activity concentrations of radionuclides were as follows: ^{137}Cs – 0.03–0.27 Bq·L^{-1}; ^{90}Sr – 0.01–0.16 Bq·L^{-1}; ^{3}H – 0.4–1.2 Bq·L^{-1}. Specific activity of ^{90}Sr in fish was 0.02–1.6 Bq·kg^{-1}.The content of ^{137}Cs in fish was 0.26–0.3 Bq·kg^{-1}. Analysis of monitoring data on heavy metal levels in components of freshwater ecosystems in the vicinity of Rooppur NPP showed that for a number of elements their increased concentrations were recorded, most of which belong to monsoon season. In Padma River surface water, a repeating increase in As, Cd, Mn, and Al concentrations was noted, and in bottom sediments – an increase in As, Cd, Ni, Co, and Zn content, which was associated with anthropogenic impact and increasing runoff of pollutants during monsoon rains. Repeatedly increased As and Mn concentrations were noted in drinking water of Rooppur NPP 30-km zone. In separate samples, there was an increase in Fe and Al content. This might be due to both natural peculiarities of the region (relatively high As content in aquifers) and the state of water supply systems. Obtained results and developed network of radioecological monitoring of freshwater ecosystems would make it possible to register a change in the situation and to identify impact of Rooppur NPP operation on human population and the environment.

Keywords: Bangladesh, Rooppur NPP, water resources, freshwater ecosystems, Padma River, drinking water, radioecological monitoring, radionuclides, heavy metals, chemical pollution

Based on the agreement signed between the Russian Federation and the People's Republic of Bangladesh in 2011, Rosatom State Corporation began in 2017 the construction of Rooppur Nuclear Power Plant (hereinafter NPP) with two VVER-1200 power units. NPP project is being implemented within the framework of the Bangladesh Nuclear Power Action Plan in accordance with recommendations and under the control of the International Atomic Energy Agency [24]. Rooppur NPP site is located on the northern bank of the Padma River (Ganges), 20 km east of the city of Pabna, 160 km northwest of Dhaka (Bangladesh capital), and 300 km along Padma and Meghna rivers to Bay of Bengal in the Indian Ocean. The Padma is one of the deepest and longest rivers in Southern Asia. River basin area is 1060 thousand km^2. Average amount of water carried by the river into the Bay of Bengal is estimated at 12 thousand m^3 per sec. All this indicates the importance of Padma's impact on the ecology of the Bay of Bengal and the Indian Ocean in general.

Radioactivity poses a potential hazard to humans and biota, including freshwater and marine organisms, when using nuclear power. It is possible to assess and minimize potential negative NPP impact on living organisms only on the basis of regular observations of the environment in the vicinity of NPP: by developing a system of radioecological monitoring. Such system is aimed to a greater extent at ensuring the radiation safety of humans and biota, *i. e.* has two components: sanitary, related with health protection of facility personnel and population, and environmental ones. Meanwhile, other types of hazard (chemical pollution, heat generation, electromagnetic radiation, noise level, etc.) are also subjects to control.

NPP life cycle lasts for more than 50 years from construction to decommissioning. That is why the development of radioecological monitoring system at NPP starts at the stage of designing: when preparing documents on investment justification and environmental impact assessment within the framework of engineering and ecological surveys [1 ; 2 ; 30]. Radiation and environmental monitoring prior to NPP construction makes it possible to assess the state of all ecosystems, as well as dose commitments on humans and biota at background level (so-called zero level). This stage is of great importance since it creates an informational basis for further analysis of NPP impact on the environment and humans during facility construction and operation. When assessing such an impact, it is necessary to take into account technogenic pollution of the environment from operating industrial enterprises in the vicinity of NPP during its construction. Composition and number of radionuclides, entering terrestrial and freshwater ecosystems from NPP due to its emissions and discharges, are strictly regulated; however, these contaminants can eventually enter a human body through food chains and direct contact with the environment. Thus, knowledge of the ways of spreading both technogenic and natural radionuclides is important for ensuring population radiation safety [34].

Being a densely populated country (1.2 thousand people per km^2), Bangladesh strongly depends on existence of water resources, their regional and seasonal availability, and quality of surface water and groundwater. These factors are greatly impacted by monsoon climate peculiarities and country's physiography. The eastern part of Bangladesh receives about 3 thousand mm of precipitation annually, while the western part receives only half of this amount. About 80 % of precipitation occurs in 5 rainy months during monsoon. A large volume of water (about 70 %) is used by population for irrigation. Besides agriculture, water is used in household and municipal water supply, industry, fishing, and shipping. Water use in the country largely depends on groundwater reserves (irrigation area is 7.5 million hectares, and 65–70 % of it is provided by groundwater). Dhaka Water Supply and Sewerage Authority produces 2.1 million liters of water per day for 12.5 million citizens of Bangladesh's capital, with 87.7 % of water volume provided by groundwater and the remainder – by surface water. Bangladesh groundwater system is threatened by the presence of natural arsenic in water of several regions, salinization of shallow aquifers in coastal zones, and decrease in groundwater levels due to irrational water abstraction [30].

Water regime in Padma River basin, being the main source of cooling for reactors of Rooppur NPP under construction, is not the same during the rainy season and outside it. For example, in Farakka River basin, average annual flow rate of the Padma River is 12.1 thousand m^3 per sec, and flow volume is 382.1 thousand m^3. From June to October, average flow rate is 24.5 thousand m^3 per sec, and from January to May – only 2.2 thousand m^3 per sec. Of total annual flow volume, 80 % occur on monsoon period [35]. The studies of various authors of fish catch dynamics in middle and lower flows of the Padma River differ in the data; this is due to ichthyofauna migration being associated, in particular, with river water regime. Components of freshwater ecosystems in Rooppur NPP area are both one of the most informative for determining environmental state and one of the most important for conducting economic activity. Therefore, the problem of assessing and predicting their quality is urgent. So, radiation and environmental monitoring of freshwater ecosystems is an obligatory element of a complex assessment of NPP impact on the environment.

The aim of this work is to present the experience in developing and maintaining a system of radiation and environmental monitoring of freshwater ecosystems in the vicinity of Rooppur NPP (People's Republic of Bangladesh).

MATERIAL AND METHODS

At the first stage of research, a detailed program of radiation and environmental monitoring of freshwater ecosystems in Rooppur NPP impact zone was developed in accordance with the requirements [1 ; 2]. The basis of this program is complexity of observations, consistency of their timing with characteristic hydrological and hydrobiological phases, and determination of indicators of water quality, composition of bottom sediments, and hydrobiocenosis state, as well as ensuring necessary accuracy and reproducibility of the results. Observation points for surface water and groundwater state were selected taking into account the results of the reconnaissance survey of water ecosystems in Rooppur NPP area (2014) and the analysis of stock data on physical, geographical, and morphometric characteristics of water bodies, on radionuclides and heavy metals contamination of surface water, bottom sediments, and water organisms, and on sanitary and hygienic indicators of drinking water quality.

The object of surface water study was Padma River area and other watercourses within 30-km zone of Rooppur NPP impact. These water bodies were considered as reference ones, *i. e.* the most affected by a possible negative NPP impact. To determine radionuclides and heavy metals content in components of freshwater ecosystems, a network of sampling points for water, bottom sediments, higher aquatic vegetation, and ichthyofauna was established. Sampling points included observation sites located within a radius of 30 km from Rooppur NPP. The allocated territory was conditionally divided into three zones with varying degrees of spatial provision. Most often, observation sites were set up in the area with a radius of 5 km from the NPP. Fewer observation sites were chosen in the area with a radius up to 10 km, taking into account existing anthropogenic sources of pollutants. Background sites (for the NPP) were set up along the edges of 30-km zone. The samples of components of freshwater ecosystems taken above Rooppur NPP characterize conditional background state of the water body. Samples taken in the lower sites make it possible to evaluate nature and degree of changes in river water composition under the impact of NPP runoff and wastewater. Sampling points were located taking into account coastline geomorphology at a distance of 3–5 m from both banks and on the midstream with geographic reference of the terrain coordinates. Taking into account the changes in river bed during the year (due to different hydrological regime) and in time, the sampling points were subject to some adjustment. Sampling points of bottom sediments, higher aquatic vegetation, and surface water coincided so that we had an opportunity to comprehensively compare the content of pollutant studied in components of freshwater ecosystems.

Thus, 11 sites were installed on the Padma River, from which components of freshwater ecosystems were sampled: site I – 25.5 km northwest of NPP platform (background values fixing); II – 11 km northwest above the platform; III – 5.5 km northwest above the platform; IV – 3 km northwest above the platform; V – 2.2 km west above the platform; VI – 0.5 km west of the platform; VII – 4.5 km south-southeast below the platform; VIII – 10 km south-southeast below the platform; IX – 14.5 km southeast below the platform; X – 20.5 km southeast below the platform; and site XI – 26.5 km southeast below the platform (Fig. 1).

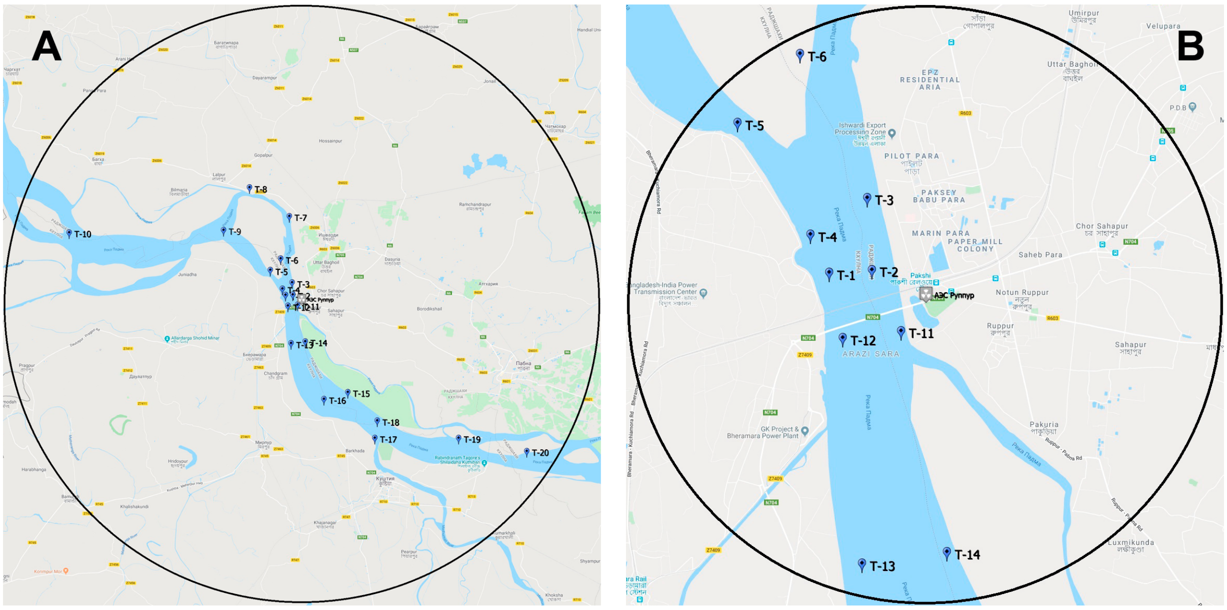

Fig. 1. Schematic map of radioecological monitoring network of freshwater ecosystems in the vicinity of Rooppur NPP: A – 30-km zone; B – 5-km zone (T indicates control point)

Water was sampled using a Niskin bottle. The suspension was separated using a device with filters for particles larger than 0.5 μm. Suspended matter and filtrate samples were analyzed separately. Volume of water samples for the analysis of gamma-radiation radionuclides and tritium, as well as for radiochemical analyses of radionuclides and heavy metals, was determined by the applied methods of sample preparation and measurements. Bottom sediments sampling was carried out with a benthic box corer DCh-0.025; weight of one sample (air-dry weight) was not less than 0.3 kg. Ichthyofauna and higher aquatic vegetation samples were taken with species description. Air-dry weight of higher aquatic vegetation samples was at least 0.2 kg, and that of ichthyofauna was 0.5–3.0 kg (wet weight). Samples of groundwater, used by local population for drinking and household needs, were taken in settlements of 30-km zone of Rooppur NPP impact at various distances and directions from the power plant from water columns, bore-holes, water pipes, and wells (Fig. 2).

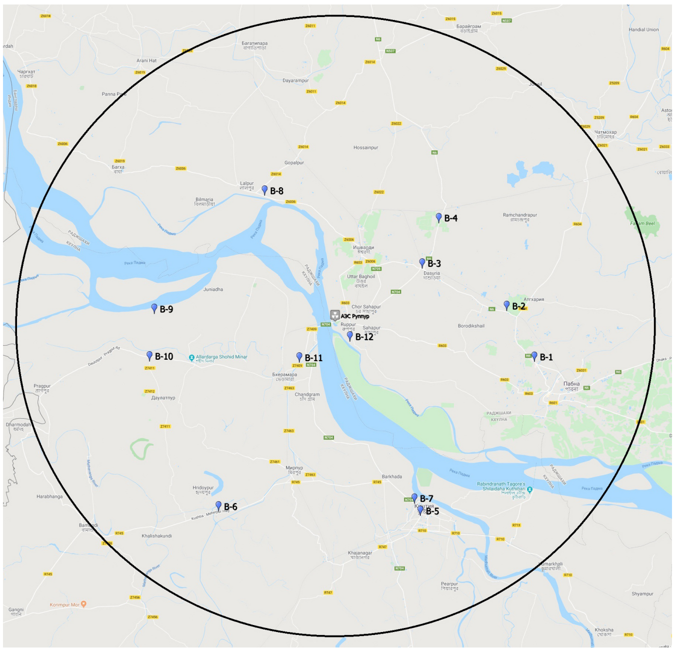

Fig. 2. Schematic map of radioecological monitoring network of groundwater (drinking water) in the vicinity of Rooppur NPP

Significant seasonal differences in climatic characteristics (monsoon rains from May to September; dry period from December to March) notably affect the regime of freshwater ecosystems in the vicinity of Rooppur NPP. Thus, during monsoons, Padma River water level rises 6–8 m, and in winter it drops to a minimum. Therefore, sampling of components of freshwater ecosystems in Rooppur NPP area was carried out in different periods of the year: August (2014), April (2015), December (2016), and June (2017). If the depth at water sampling point on the Padma River was more than 5 m, surface and bottom water samples were taken (Table 1).

Higher aquatic vegetation was detected not in every sampling period. Thus, it was virtually absent in December. The maximum species diversity was recorded in June. Ichthyofauna samples were taken only in 2016–2017 due to the fact that in the early years of the development of radioecological monitoring network in Rooppur NPP area, the emphasis in research was placed on assessing population diets with food obtained from terrestrial (agricultural) ecosystems.

Table 1. Number of samples of components of freshwater ecosystems taken in the vicinity of Rooppur NPP in 2014–2017

Component of freshwater ecosystem	Sampling period			
	21–28 August 2014	03–09 April 2015	02–07 December 2016	04–09 June 2017
Padma River surface water	22	20	20	23
Padma River bottom sediments	20	20	20	20
Padma River higher aquatic vegetation	3	4	1	19
Padma River fish	–	–	6	14
Groundwater (drinking water)	3	–	6	3

Sampling of components of freshwater ecosystems, their preparation for measurements, and measurements themselves were carried out following the developed regulations (Table 2) according to the certified methods in the accredited laboratories of Russian Institute of Radiology and Agroecology: for radionuclides – in the radiation control testing laboratory (accreditation certificate RA.RU.21AD81); for heavy metals and physical and chemical indicators – in the testing laboratory (accreditation certificate RA.RU.513078).

Table 2. Regulations of radioecological monitoring of freshwater ecosystems in the vicinity of Rooppur NPP

Component of freshwater ecosystem	Sampling frequency	Pollutants detected		
		Radionuclides	Heavy metals	Organic substances
Surface water, groundwater	Every season (4 times a year)	^{40}K, ^{226}Ra, ^{232}Th, ^{3}H, ^{90}Sr, ^{137}Cs	As, Hg, Cd, Ni, Co, Sr, Zn, Cu, Cr, Mn, Fe, Al	benzopyrene, phenols, petroleum products, organochlorine pesticides, polychlorinated biphenyls
Bottom sediments	Once a year		As, Hg, Cd, Ni, Co, Zn, Cu, Cr, Mn, Pb, Fe, Al	–
Higher aquatic vegetation	Once a year	^{3}H, ^{90}Sr, ^{137}Cs	As, Hg, Cd, Ni, Co, Zn, Cu, Cr, Mn, Pb, Fe, Al, Sr, Se, Mo, Sb, V, Li, Cs	
Fish	Once a year			

To assess radionuclide content in environmental objects, we used: low-background gamma spectrometer with a DKDK-100V detector; spectrometric alpha- and beta-radiometer Quantulus 1220; alpha- and beta- liquid scintillation counter Tri-Carb 4810TR; gamma-radiation energy spectrometer GAMMA-1P for two measuring paths with semiconductor detectors made of ultrapure germanium (EG&G ORTEC, USA); multichannel analyzer Desktop InSpector 1270 based on a semiconductor detector made of ultrapure germanium (Canberra Industries, Inc., USA); and gamma-radiation energy spectrometer Accuspec with a semiconductor detector made of ultrapure germanium based on an integral cryostat (Canberra Industries, Inc., USA). The relative measurement error of radionuclide activity was 6–35 % depending on the instrument and method used.

Heavy metals in environmental objects were determined by atomic absorption and plasma emission analysis methods. An axial atomic emission spectrometer (optical) with samples atomization in inductively coupled plasma Liberty II (Varian, Australia – USA) and a KVANT.Z.ETA-1 spectrometer with GRG-3 attachment were used for measurements. To prepare samples for measurement, both dry and wet ashing methods were used with a microwave system MARS-5 (CEM, USA).

Organic pollutants were determined by fluorometric method on a Fluorat-02 liquid analyzer according to methods, standards, and environmental regulations as follows: benzopyrene – ISO 28540-2011; phenols – PND F 14.1:2:4.182-02 (2010 edition); and petroleum products – PND F 14.1:2:4.128-98 (2012 edition).

Quality assessment of components of freshwater ecosystems was carried out by comparing measurement results with the data of regulations in the field of radiation and environmental safety, as well as with clarke content of toxicants or with regional background being established according to literature data.

RESULTS AND DISCUSSION

During surface water and groundwater sampling in the vicinity of Rooppur NPP, physical and chemical indicators were determined by a multiparameter water quality assessment instrument U-52 (Table 3).

Table 3. Physical and chemical indicators of surface water and groundwater in the vicinity of Rooppur NPP at sampling time (numerator is the mean; denominator is min.–max.)

Indicator	Sampling period			
	August 2014	April 2015	December 2016	June 2017
Surface water				
Temperature, °C	27.9 27.0–29.0	28.8 27.9–30.1	24.2 23.4–24.8	29.8 29.0–31.0
Hydrogen indicator (pH)	7.5 7.2–8.2	8.5 7.2–9.5	8.1 7.4–8.5	8.1 7.8–8.5
Redox potential, mV	No data	148.8 63.0–247.0	158.1 111.0–237.0	No data
Electrical conductivity, μS·cm^{-1}	0.37 0.31–0.40	0.31 0.26–0.43	0.31 0.30–0.34	0.30 0.28–0.31
Turbidity, FTU	335.5 279.6–426.9	92.7 14.8–294.8	92.6 66.0–143.0	No data
Dissolved oxygen, mg·L^{-1}	No data	13.0 6.4–13.8	11.1 7.1–12.5	12.0 11.1–13.4
Suspended matter, mg·L^{-1}	No data	31.1 5.0–80.0	42.5 0.4–109.0	13.1 2.2–77.4
Total mineralization (dry residue), mg·L^{-1}	131.0 112.0–150.0	177.9 158.0–249.0	195.3 11.4–395.0	160.9 108.0–198.0
Total hardness, mmol·L^{-1}	4.1 3.4–5.0	5.2 4.4–7.4	5.5 5.0–5.8	4.0 3.8–4.4
Groundwater (drinking water)				
Hydrogen indicator (pH)	7.1 6.9–7.2	No sampling	7.3 7.1–7.9	7.2 6.9–7.4
Suspended matter, mg·L^{-1}	62.7 33.3–92.0		No data	32.4 5.8–78.2
Total mineralization (dry residue), mg·L^{-1}	396.0 337.0–454.0		382.3 175.0–498.0	375.5 258.0–466.0
Total hardness, mmol·L^{-1}	12.63 7.8–15.3		17.8 14.8–18.9	10.8 8.1–13.9

The average water temperature in the Padma River varied from April to August within +28…+30 °C. It was minimal in December: +24 °C. Hydrogen indicator (pH) of surface water was on average 7.5–8.5. Redox potential of Padma River water was 149–158 mV. Specific electrical conductivity of water samples was at the level of 0.30–0.37 $\mu S \cdot cm^{-1}$. Average turbidity of the Padma River during the low rainfall period was 92–93 FTU; it increased up to 335 FTU during monsoon period (August) due to high soil runoff into the river with rainwater. Dissolved oxygen content in surface water varied within 11–13 $mg \cdot L^{-1}$. Suspended matter in water samples was in the range of 13–43 $mg \cdot L^{-1}$, and total mineralization (dry residue) was 130–195 $mg \cdot L^{-1}$. Total water hardness of the Padma River varied from 4.0 to 5.5 $mmol \cdot L^{-1}$.

Hydrogen indicator (pH) of groundwater was slightly lower than that of surface water: 7.1–7.3. Amount of suspended matter in groundwater was higher than that in surface water. It averaged 32–63 $mg \cdot L^{-1}$, which was most likely due to the state of water supply system in the vicinity under study. Total mineralization in groundwater varied within 375–395 $mg \cdot L^{-1}$, and total hardness – within 11–18 $mmol \cdot L^{-1}$, being 2–3 times higher than similar characteristics of surface water. This is due to the composition of Padma River surface water, the basis of which is meltwater and rainwater.

In water samples studied in the vicinity of Rooppur NPP, organic pollutants content was quite low. In 2014–2017, benzopyrene in water samples from the observation area was less than 0.01 $\mu g \cdot L^{-1}$. Phenols concentration varied in the range of 1.3–3.5 $\mu g \cdot L^{-1}$, and that of petroleum products was 0.01–0.043 $mg \cdot L^{-1}$. Organochlorine pesticides and polychlorinated biphenyls content in water samples was below detection limits.

When analyzing cation-anion composition of bottom sediments, it was noted that the samples did not contain carbonate ion, which is determined in water extract at pH = 8.4. In the results obtained, the maximum pH value was 8.2 (with a mean of 7.8). Therefore, only the bicarbonate ion was determined (Table 4).

Table 4. Cation-anion composition of bottom sediments of the Padma River (numerator is the mean; denominator is min.–max.)

Cations, mL-eq per 100 g		Anions, mL-eq per 100 g	
Ca^+	9.7 0.7–43.3	Cl^-	1.0 0.5–2.1
Mg^+	3.6 0.3–14.9	NO^{3-}	3.2 1.3–4.4
Na^+	1.1 0.1–2.9	Bicarbonate ion	0.4 0.04–0.6
K^+	0.4 0.02–2.5	F^-, μg per kg	7.4 5.8–9.7
NH_4^+	0.02 0.01–0.04	I^-, μg per kg	25.9 5–71

Granulometric composition of bottom sediments in different years of monitoring was quite stable and was characterized by: sand – 77.9 % (with a wide variability within 7.7–97.1 %); dust – 19.0 % (with a spread of values within 2.9–71.0 %); and clay – 3.1% (data range of 0.1–27.1 %). Very low ammonium content in bottom sediments was due to both absence of organic matter and minimum content of clay minerals. Ability of bottom sediments to fix ammonium is manifested in the presence of clay with a three-layer crystal lattice, especially vermiculite. Nitrates are not included in poorly soluble compounds composition and are not absorbed by negatively charged colloids of bottom sediments. Since the samples of light granulometric composition of bottom sediments analyzed were very poor in organic matter, nitrate content was also very low.

During field researches in 2014–2017, species composition of water and coastal flora in Rooppur NPP 30-km zone, including the Padma River and water bodies outside its impact, was determined. A total of 79 taxa were identified; this was not much, given the potential diversity of regional flora [17]. Macrophytes were represented by 5 species from 3 families of macroscopic algae, 1 species of fern, and 73 species of vascular plants from 63 genera and 35 families. For aquatic and coastal flora, the following families were leading in terms of taxa number: Poaceae (13 taxa), Leguminosae (5), Polygonaceae (5), Cyperaceae (4), Potamogetonaceae (4), and Asteraceae (3). In the families Amaranthaceae, Araceae, Hydrocharitaceae, Lemnaceae, Najadaceae, Pontederiaceae, Rubiaceae, Scrophulariaceae, Typhaceae, and Verbenaceae, two species were found in each; in the rest – one in each. A similar set of leading families is generally characteristic of riverside and waterlogged habitats in the region [23]. In the spectrum of life forms of aquatic and coastal flora, herbaceous annuals and perennials are absolutely dominant (51 and 43 %, respectively). Shares of the rest life forms were in the range of 1–3 %. This ratio is natural, given instability of river water regime, regular erosion of coastal zone, and high anthropogenic load on Padma River freshwater ecosystem [21]. Annuals, completing their life cycle prior to monsoon period, and rhizome perennials get the advantage here. Zones of different distance from NPP do not differ much in terms of vegetation cover characteristics since they have practically identical ecological habitat conditions characterized by severe coastline erosion, which greatly limits the set of species and communities. When planning monitoring for assessing the state of aquatic and coastal vegetation of the Padma River, it should be taken into account that spring and summer are the most appropriate periods for research: for the most complete identification of species and coenotic diversity.

Radionuclides inflow into surface water prior to the start of NPP operation occurs due to precipitation. Radioactive substances, entering water bodies, are rapidly redistributed and usually accumulated in bottom sediments, benthos, aquatic flora, and ichthyofauna. Analysis of natural and technogenic radionuclide content in components of freshwater ecosystem of the Padma River showed that it was quite low and corresponded in general to the global radiation background both before NPP construction (2014–2015) and after its start (2016–2017). The volumetric activity in Padma River water of the main radiologically significant ^{137}Cs during the entire observation period did not exceed 0.18 $Bq{\cdot}L^{-1}$ (with a mean of 0.07 $Bq{\cdot}L^{-1}$) (Table 5). The content of ^{90}Sr in surface water was on average at the level of 0.02–0.12 $Bq{\cdot}L^{-1}$.

Tritium (^{3}H) is one of the most mobile radionuclides being found mainly in water; therefore, under natural conditions, it can be transported by water flow over long distances. According to the research data of 2014–2017, values of the volumetric activity of tritium in Padma River water in the observation area of Rooppur NPP were in the range of 0.8–2.1 $Bq{\cdot}L^{-1}$. The global ^{3}H natural background in water is taken to be (2.2 ± 0.7) $Bq{\cdot}L^{-1}$; the technogenic background – 5 $Bq{\cdot}L^{-1}$. Thus, tritium content in surface water near Rooppur NPP is in the range below the global average value; ^{3}H content is 3 orders of magnitude lower than intervention level (7600 $Bq{\cdot}L^{-1}$ according to Radiation Safety Standards NRB-99/2009). Similar picture was observed for ^{90}Sr and ^{137}Cs. According to NRB-99/2009, intervention levels for the content of these technogenic radionuclides in water

Table 5. Radionuclide content in components of freshwater ecosystem of the Padma River in the vicinity of Rooppur NPP, Bq·kg^{-1} (Bq·L^{-1}) (numerator is the mean; denominator is min.–max.)

Sampling period	^{40}K	^{226}Ra	^{232}Th	^{90}Sr	^{137}Cs	^{3}H
Surface water						
2014	< 1.5	< 0.5	< 0.5	0.12 0.01–0.39	0.07 0.02–0.18	1.03 0.8–1.29
2015	< 1.1	< 0.4	< 0.4	0.03 0.01–0.05	< 0.05	1.15 0.77–2.05
2016	1.05 0.48–1.77	0.16 0.1–0.31	0.18 0.1–0.3	0.06 0.01–0.21	< 0.07	< 3
2017	2.54 1.19–6.99	< 0.2	< 0.4	0.02 0.01–0.04	0.07 0.03–0.11	< 3
Bottom sediments						
2014	735 570–820	48.5 42–51	59.5 44–71	1.79 1.5–2.19	2.1 0.5–4.2	< 3
2015	582 369–721	47.1 14.9–121	71.2 34.5–136	0.96 0.36–1.98	1.46 0.6–3.2	< 3
2016	494 340–710	43.2 21.4–82	66.8 24.7–137	1.54 0.09–3.53	0.75 0.25–1.4	< 3
2017	569 350–852	61.4 24.8–122	96.6 21.5–211	0.45 0.2–0.99	1.26 0.5–2.83	20.3 12.2–30.8
Higher aquatic vegetation						
2014	No data	No data	No data	3.19 2.51–3.54	2.23 1.8–2.6	< 3
2015	621 253–1090	21.9 19.2–24.6	49.9 31.5–68.3	1.58 0.91–2.18	1.1	< 3
2016	134.5	< 1.2	< 1.4	9.7	< 0.3	< 3
2017	742.6 347–1431	21.8 8.7–41.7	38.3 17.1–70.3	1.91 0.38–3.89	0.73 0.4–1.0	< 3

are as follows: ^{90}Sr – 4.9 Bq·L^{-1}; ^{137}Cs – 11 Bq·L^{-1}. The monitoring results showed that the volumetric activity of technogenic radionuclides in water of Padma River area studied is 40 times lower than intervention level for ^{90}Sr and 60 times – for ^{137}Cs. In the work [29] on the determination of radioactivity levels on Rooppur NPP site and in its vicinity, carried out by Bangladesh Atomic Energy Commission specialists in 2009, the results of measuring the content of natural radionuclides ^{238}U, ^{232}Th, and ^{40}K in water samples were presented. Their volumetric activities varied in the range of 0.11–0.21 Bq·L^{-1} for ^{238}U; 0.13–0.30 Bq·L^{-1} – for ^{232}Th; and 0.30–0.47 Bq·L^{-1} – for ^{40}K. Our research (2014–2017) showed the absence of significant changes in background content of natural radionuclides in Padma River water (Table 5).

The analysis of the results of measurements of natural radionuclide content in bottom sediments samples of the Padma River in the vicinity of Rooppur NPP showed that during the entire observation period (2014–2017) no increased level of their specific activity was detected. The maximum values were as follows: ^{40}K – 852 Bq·kg^{-1}; ^{226}Ra – 122 Bq·kg^{-1}; and ^{232}Th – 211 Bq·kg^{-1} (Table 5). Technogenic radionuclide content was also not high. Mean specific activity of ^{90}Sr in bottom sediments samples varied in the range of 0.5–1.8 Bq·kg^{-1}, and ^{137}Cs – 0.8–2.1 Bq·kg^{-1}. Specific activity of tritium in bottom sediments samples was less than 3 Bq·kg^{-1}, except for three samples (T-8, T-9, and T-10) taken upstream of the Padma River from Rooppur NPP at a distance of 15–20 km in 2017. These three samples showed increased tritium values: 12–30 Bq·kg^{-1}. They were taken in shallow water areas. Most likely in this area in January – May 2017, pollutants, containing this radionuclide in small concentrations, were discharged, and they have settled in bottom sediments. Since no increased tritium concentrations were detected in bottom sediments samples in December 2016, a possible discharge occurred in 2017 before June. Tritium concentrations identified in bottom sediments are not abnormally high. At the same time, this fact requires additional study to determine a possible pollution source. No research of radionuclide content in sediments of the Padma River in Rooppur NPP construction area has previously been carried out, but in 2016 a work on natural radionuclide content in sediments of the Brahmaputra River, which is similar to the Padma River in location and size, was published [26]. According to these studies, mean ^{232}Th and ^{40}K content in bottom sediments was (113 ± 5) and (1002 ± 43) Bq·kg^{-1} of dry weight, respectively; these values are comparable with our results obtained. The content of natural and technogenic radionuclides in aquatic vegetation is extremely low. According to the most representative sample of 2017 including 19 samples, specific activity of ^{90}Sr in aquatic vegetation varied within 0.4–3.9 Bq·kg^{-1}, and ^{137}Cs – within 0.4–1.0 Bq·kg^{-1} of wet weight.

When assessing the state of freshwater ecosystems from the point of view of radiation safety, it is important to analyze radionuclide content in components of population diet (drinking water and fish) from NPP area and to compare the data obtained with international and Russian standards governing annual enter of radioactive substances into a human body. Thus, in drinking water, the volumetric activity of standardized radionuclides varied in the ranges as follows: ^{137}Cs – 0.03–0.27 Bq·L^{-1} (40 times less than intervention level according to NRB-99/2009); ^{90}Sr – 0.01–0.16 Bq·L^{-1} (30 times less); ^{3}H – 0.4–1.2 Bq·L^{-1} (more than 6 thousand times less than intervention level) (Table 6).

For ^{226}Ra and ^{232}Th, the difference with intervention levels according to NRB-99/2009 was 2–3 times. Studies on radionuclide content in drinking water in the vicinity of Rooppur NPP were carried out in 1998 [14]. In Kushtia and Rajshahi area at that time, ^{232}Th content in drinking water was at the level of 0.25–0.27 Bq·L^{-1}, and ^{40}K – 7.95–8.52 Bq·L^{-1}. The results obtained during the radioecological monitoring (2014–2017) for ^{232}Th correlate well with the data of that work, and for ^{40}K they are a little bit lower.

In 2016–2017, fish from the Padma River in the vicinity of Rooppur NPP was sampled to assess radionuclide content. In 2017, the sample was quite representative: 14 samples of different species. The standardization of human radiation safety when eating fish is provided by both international and Russian regulations for the most radiologically significant radionuclides: ^{90}Sr and ^{137}Cs (Table 6). During the observation period, specific activity of ^{90}Sr in fish varied from 0.02 to 1.6 Bq·kg^{-1}, which is more than 60 times lower than in Russian and international standards. The content of ^{137}Cs was in the range of 0.26–0.3 Bq·kg^{-1}, which is more than 400 times lower than in Russian standards and more than 3 thousand times – in international ones. In general, it can be concluded that radionuclide content in drinking water and fish in the vicinity of Rooppur NPP does not exceed the values specified by requirements of international and Russian sanitary and hygienic standards for these types of population diet.

Table 6. Radionuclide content in drinking water and fish in the vicinity of Rooppur NPP, Bq·kg^{-1} (Bq·L^{-1}) (numerator is the mean; denominator is min.–max.)

Sampling period	^{40}K	^{226}Ra	^{232}Th	^{90}Sr	^{137}Cs	^{3}H
Groundwater (drinking water)						
2014	< 1.3	< 0.2	< 0.11	$\frac{0.07}{0.02–0.16}$	$\frac{0.05}{0.03–0.08}$	$\frac{0.92}{0.42–1.18}$
2016	$\frac{0.9}{0.6–1.1}$	$\frac{0.28}{0.11–0.71}$	$\frac{0.24}{0.2–0.33}$	$\frac{0.03}{0.01–0.07}$	0.27	< 3
2017	1.02	< 0.2	< 0.11	$\frac{0.042}{0.041–0.043}$	$\frac{0.05}{0.03–0.06}$	< 3
Standard[1]	–	0.49	0.60	4.9	11	7600
Fish						
2016	$\frac{110}{103–120}$	< 1.2	< 1.2	$\frac{0.6}{0.03–1.55}$	< 0.4	–
2017	$\frac{95}{78–124}$	< 1.4	< 2.4	$\frac{0.13}{0.02–0.24}$	$\frac{0.28}{0.26–0.30}$	–
Standard[2]	–	–	–	100	1000	–
Standard[3]	–	–	–	100*	130*	–

Note:
[1] SanPiN 2.6.1.2523-09 Radiation Safety Standards (NRB-99/2009);
[2] Codex Alimentarius. General Standard for Contaminants and Toxins in Food and Feed;
[3] SanPiN 2.3.2.1078-01 Hygiene Requirements for Safety and Nutritional Value of Food Products (as amended on 06.07.2011);
* excluding dried fish.

The second direction of monitoring studies was the assessment of heavy metals content in components of freshwater ecosystems in the vicinity of Rooppur NPP. Analysis of the data of 4-year observations of water pollution levels in the Padma River showed that for some heavy metals there are increased concentrations in different seasons of the year, and most of them are confined to August (2014) being monsoon period. Thus, arsenic belonging to the I hazard class enters surface water naturally from rocks and sediments as a result of related biogeochemical and hydrological processes, some of which are currently impacted by human activities [16]. This process intensifies during monsoon season. The limit of As content in water, recommended by the World Health Organization (hereinafter WHO) [18], the US Environmental Protection Agency [4], and Russian regulations, is 10 µg·L^{-1}. Taking into account WHO recommendations and Russian threshold limit values (hereinafter TLV), it can be concluded that an excess of standards for As in Padma River water occurred only in 2014. In other periods, arsenic content in surface water was at the level of 0.9–3.6 µg·L^{-1} (with a mean of 2.6). Mercury was not measured in 2014. In other years, Hg concentration in Padma River water was much lower than specified by Russian standards (Table 7).

The maximum permissible level of cadmium (the II hazard class) in drinking water, established by WHO, is 3 µg·L^{-1} [18]; Russian TLV is 1 µg·L^{-1}. Monitoring results showed that only in 2014 there was an excess of WHO permissible level and Russian TLV by 3–9 times in water for Cd (as in case with As). According to [10], cadmium content in water samples was very low (≤ 1 µg·L^{-1}, trace concentration), which is close to the results of our studies in other periods of the year. These Cd levels are considered safe for irrigation [32]. Similar low cadmium concentrations were registered in water samples from other Bangladesh rivers: Buriganga, Turag, and Shitalakshya [7 ; 19].

Table 7. Heavy metals gross content in surface water of the Padma River in the vicinity of Rooppur NPP, μg·L^{-1} (numerator is the mean; denominator is min.–max.)

Element	Sampling period				TLV*	TLV**
	2014	2015	2016	2017		
The I hazard class						
As	59.0 10.04–170.11	0.96 0.42–2.53	2.19 1.27–3.84	3.58 2.93–5.56	10	–
Hg	–	$5.9\cdot10^{-3}$ $3.7\cdot10^{-3}$–$1.5\cdot10^{-2}$	$1.03\cdot10^{-2}$ $6\cdot10^{-3}$–$2.3\cdot10^{-2}$	$9.35\cdot10^{-4}$ $1.1\cdot10^{-5}$–$2.8\cdot10^{-3}$	0.5	–
The II hazard class						
Cd	8.97 0.1–34.7	0.08 0.001–0.21	0.08 0.01–0.18	0.6 0.2–1.2	1	–
Ni	5.84 1.29–8.97	1.67 0.19–6.47	4.05 1.26–8.23	19.5 7.2–42.4	20	10
Co	3.6 3.0–4.2	0.2 0.1–0.5	2.6 1.6–3.9	1.5 0.3–2.8	100	–
Sr	103.8 71.0–165.0	48.3 9.3–67.0	135.5 102.2–154.6	–	7000	–
The III hazard class						
Zn	15.7 10.3–18.8	0.9 0.1–3.7	17.4 6.0–75.9	8.9 4.5–15.5	1000	10
Cu	6.5 1.1–13.4	0.4 0.06–1.25	3.3 1.4–7.9	7.7 2.7–18.5	1000	1
Cr	2.6 1.0–4.8	0.5 0.04–0.97	2.8 1.6–9.1	3.97 1.0–7.4	50	20
Mn	180.2 16.0–386.7	1.7 0.1–12.4	51.9 27.9–84.9	22.8 7.4–97.9	100	10
Fe	102.0 11.3–280.9	27.2 0.99–250.1	223.3 119.1–831.4	198.7 95.1–355.1	300	100
Al	151.8 113.3–382.3	28.9 0.2–244.4	252.4 52.0–595.2	211.1 128.9–358.9	200	–

Note:

* GN 2.1.5.1315-03 Threshold Limit Values (TLV) of Chemicals in the Water of Water Bodies of Domestic, Drinking, and Cultural-Domestic Water Use: Hygiene Standards;

** Water Quality Standards for Water Bodies of Fishery Importance, Including Standards for Threshold Limit Values (TLV) of Harmful Substances in the Waters of Water Bodies of Fishery Value. Approved on 13.12.2016 by order No. 552 of the Ministry of Agriculture of the Russian Federation.

Mean content of nickel (the II hazard class) in Padma River water for 4 years of monitoring varied within 1.7–19.5 μg·L^{-1}, and this does not exceed TLV for domestic, drinking, and cultural-domestic water use (Table 7). In 2017, Ni values in water were higher than Russian standards for fishery water use, but they were safe if using water for irrigation, according to the Food and Agriculture Organization of the United Nations (hereinafter FAO) recommendations (200 μg·L^{-1}) [32]. Other studies in Bangladesh show that nickel concentration in water samples from the Buriganga River varies from 7.2 to 10.3 μg·L^{-1} [7], which corresponds to levels, determined during monitoring in the vicinity of Rooppur NPP. In [19], heavy metals were studied in Karatoa River waters, and it was noted that Ni concentration was in the range of 9.3–66.0 μg·L^{-1}, which was slightly higher than the values obtained for Padma River area. For cobalt and strontium also belonging to the II hazard class, no excess of standards in Padma River water was detected over the entire observation period.

Zinc content (the III hazard class) in Padma River water was minimal (0.94 $\mu g \cdot L^{-1}$) in 2015 being significantly lower than values of other years (Table 7). However, maximum Zn concentrations recorded in the samples were much lower than the permissible level for irrigation (2000 $\mu g \cdot L^{-1}$) [37] and Russian standards (1000 $\mu g \cdot L^{-1}$). The results of studies on the Turag River presented in [10] show that water samples contained zinc in the range of 60–300 $\mu g \cdot L^{-1}$ (with a mean of 100 $\mu g \cdot L^{-1}$). Zn concentration in Buriganga River water samples [27] varied within 220–260 $\mu g \cdot L^{-1}$. These values are higher than monitoring data in the Padma River in the vicinity of Rooppur NPP. In [20], Balu River waters were studied, and zinc content varied from 8.39 to 76.86 $\mu g \cdot L^{-1}$, which is comparable with our results.

The maximum copper concentration in Padma River waters averaged 7.7 $\mu g \cdot L^{-1}$ in 2017 (Table 7). According to other studies, Cu content in Turag River water samples varied from ≤ 1 to 90 $\mu g \cdot L^{-1}$ (with a mean of 46 $\mu g \cdot L^{-1}$) [10]. As noted in [12], copper concentration in the samples from the same river varied within 10–70 $\mu g \cdot L^{-1}$ being higher than the results obtained during the monitoring of Rooppur NPP area. Cu content in Dhalesvari River water samples ranged from 98.4 to 188.1 $\mu g \cdot L^{-1}$ [6], which was also higher than in Padma River water.

Chromium content in Padma River water samples was quite stable over 4 years of monitoring (Table 7). Only in April 2015, a slight decrease in Cr concentration was noted, possibly due to peculiarities of river hydrological regime since in this period of the year water level there is much lower than during monsoon. Studies by other authors [10] show that chromium content in the waters of Bangladesh rivers exceeded the permissible levels and ranged from 0.23 to 0.47 $mg \cdot L^{-1}$ (with a mean of 0.32). Such Cr levels exceed TLV by an order of magnitude. Chromium pollution of river water was probably due to runoff from leather and textile enterprises. Similar results are presented in [7 ; 19]: among the content of heavy metals in water samples from urban rivers Buriganga, Turag, and Shitalakshya, the highest concentrations were that of Cr.

Manganese concentration in Padma River waters varied from 0.1 to 386.7 $\mu g \cdot L^{-1}$ during 4 years of monitoring (Table 7). In 2014, mean content of this heavy metal (180 $\mu g \cdot L^{-1}$) was higher than in other years of observation (1.7–51.9 $\mu g \cdot L^{-1}$), which was most likely associated with monsoon period. The maximum permissible level of Mn concentration in drinking water, established by WHO, is 500 $\mu g \cdot L^{-1}$, and by Bangladesh Centre for Advanced Studies – 100 $\mu g \cdot L^{-1}$ [18 ; 37]. In all years of this study, except for 2014, manganese levels in Padma River water were several times lower than those recommended by WHO and Bangladesh Centre for Advanced Studies. According to [28], in 2010 in the vicinity of Mohanpur, Mn content in surface water varied from 0.9 to 2.86 $\mu g \cdot L^{-1}$, which is on average an order of magnitude lower than monitoring results of 2014–2017. In [10], manganese concentration in river water was registered at the level of 350–920 $\mu g \cdot L^{-1}$ (mean value was 530 $\mu g \cdot L^{-1}$). Probably, Mn appeared in polluted river waters from discharges by chemical and textile enterprises. These values exceed the permissible levels of manganese content when using water for irrigation (200 $\mu g \cdot L^{-1}$ according to the recommendations [32]). Mn concentrations registered in [20] in most of Balu River water samples (28.3–730.8 $\mu g \cdot L^{-1}$) were comparable with the data of this study. It is shown in [39] that manganese content in Karatoa River water samples varied from trace concentrations to 320 $\mu g \cdot L^{-1}$; this corresponds to the level of values obtained by us for surface water in the vicinity of Rooppur NPP.

Iron content in Padma River waters according to monitoring data of 2014–2017 (Table 7) averaged 0.03–0.2 $mg \cdot L^{-1}$ (with a maximum of 0.8 $mg \cdot L^{-1}$) and did not exceed TLV for domestic, drinking, and cultural-domestic use (0.3 $mg \cdot L^{-1}$). However, Fe concentration in water was higher than TLV values for fishery use (0.1 mg·L^{-1}), except for 2015. It is shown in [10] that iron content in water samples from some Bangladesh rivers varied from 0.8 to 14.8 mg·L^{-1} (with a mean of 4.6 mg·L^{-1}). In a number of samples from this study, Fe concentration was above the acceptable limit (5.00 mg·L^{-1}) [37]. Iron contamination of river water might result from discharges by pharmaceutical, leather, and textile enterprises. In was noted in the study [5] that Fe content in Turag River water was in the range of 0.78–6.33 mg·L^{-1}, which was much higher than monitoring results of 2014–2017 of Padma River water.

Analysis of the data on aluminum content in Padma River water for the entire observation period showed that almost half of the samples are characterized with an excess of Al concentration in comparison with TLV (Table 7). The highest value reached 595 μg·L^{-1}, which is 3 times higher than TLV. Sources of aluminum intake into river system were also discharges by numerous industrial enterprises neglecting the environmental safety of production technologies.

Due to the absence of regulations governing TLV of heavy metals in bottom sediments, the method of comparing the values obtained with the officially established TLV of chemicals in soil was used (Hygiene Standards GN 2.1.7.2041-06 and GN 2.1.7.2511-09). Content of all heavy metals in bottom sediments in 2014 turned out to be higher than the values registered in other years of monitoring, which is most likely associated with a large soil runoff into the Padma River during monsoon period (Table 8).

Table 8. Heavy metals gross content in bottom sediments of the Padma River in the vicinity of Rooppur NPP, mg·kg^{-1} (dry weight) (numerator is the mean; denominator is min.–max.)

Element	Sampling period				TLV*	APC**
	2014	2015	2016	2017		
As	73.3 46.2–91.6	1.2 0.9–1.7	0.5 0.2–1.1	3.3 2.2–6.0	2.0	2.0
Hg	$1.24\cdot10^{-2}$ $6.3\cdot10^{-3}$–$2.1\cdot10^{-2}$	$8.24\cdot10^{-3}$ $4.4\cdot10^{-3}$–$1.2\cdot10^{-2}$	$7.4\cdot10^{-3}$ $3.2\cdot10^{-3}$–$1.3\cdot10^{-2}$	$5.99\cdot10^{-3}$ $7\cdot10^{-4}$–$1.8\cdot10^{-2}$	2.1	–
Cd	2.7 1.7–3.3	1.3 0.6–2.5	0.22 0.04–0.9	0.21 0.02–1.6	–	0.5
Ni	29.4 24.2–34.0	17.1 5.3–35.1	10.7 4.4–32.4	17.8 5.6–39.0	–	20.0
Co	20.6 15.7–23.3	3.9 1.7–6.9	8.8 4.8–16.4	8.9 4.1–15.9	–	–
Zn	73.3 45.1–88.8	21.2 7.8–52.3	77.3 20.7–190.0	200.7 27.2–582.8	–	55.0
Cu	23.4 17.8–27.1	9.5 1.5–20.2	6.9 2.4–29.3	6.1 0.7–19.0	–	33.0
Cr	–	9.8 3.8–18.3	25.4 16.2–55.3	23.9 11.5–51.8	–	–
Mn	602.5 505.0–701.0	411.7 140.0–935.0	388.9 150.0–902.0	406.2 163.0–928.0	1500	–

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Element	Sampling period				TLV*	APC**
	2014	2015	2016	2017		
Pb	25.4 21.5–28.4	3.6 0.3–7.5	17.3 12.8–22.6	16.4 11.4–48.5	32.0	32.0
Fe	$3.2\cdot10^4$ $2.6\cdot10^4$–$3.5\cdot10^4$	$1.7\cdot10^4$ $7.2\cdot10^3$–$3.5\cdot10^4$	$1.8\cdot10^4$ $1.0\cdot10^4$–$3.5\cdot10^4$	$2.0\cdot10^4$ $1.0\cdot10^4$–$3.7\cdot10^4$	–	–
Al	$4.8\cdot10^4$ $3.7\cdot10^4$–$6.6\cdot10^4$	$9.9\cdot10^3$ $3.2\cdot10^3$–$2.1\cdot10^4$	$3.8\cdot10^4$ $3.1\cdot10^4$–$5.4\cdot10^4$	$4.3\cdot10^4$ $3.3\cdot10^4$–$6.3\cdot10^4$	–	–

Note:

* GN 2.1.7.2041-06 Threshold Limit Values (TLV) of Chemicals in the Soil: Hygiene Standards;

** GN 2.1.7.2511-09 Approximate Permissible Concentrations (APC) of Chemicals in the Soil: Hygiene Standards.

For example, mean As concentrations in 2014 exceeded its TLV in the soil by more than 35 times and correlated with the data on its content in Padma River surface water. High As concentration in bottom sediments may also be associated with anthropogenic activity: operating of enterprises producing arsenic-containing fertilizers and pesticides [8]; wood processing using copper arsenate [33]; leather production [13].

Mean Cd concentration in bottom sediments in 2014 and 2015 was 2.7 and 1.3 mg·kg^{-1}, respectively, exceeding approximate permissible concentration (hereinafter APC) by 1.5–2.5 times. In subsequent years, it declined to acceptable levels.

The results obtained when determining lead concentration in bottom sediments (3.6–25.4 mg·kg^{-1}) were lower than the data presented in [9], where mean Pb content during summer and winter periods was 38.33 and 49.04 mg·kg^{-1}, respectively. High lead concentrations in bottom sediments could be associated with the impact of point-source and nonpoint-source pollution near the area under study: use of leaded gasoline and oil; industrial wastewater; and operating of steel plants and enterprises producing chemicals, electronics, cables, oils, tires, and cement [38].

Zn content in bottom sediments in all years, except for 2015, also exceeded APC.

Heavy metals content in higher aquatic vegetation of the Padma River varied in different years of monitoring (Table 9). In December 2016, relatively low concentrations were noted, which could be explained by the season of significant slowdown in plants vegetative activity.

Table 9. Heavy metals content in higher aquatic vegetation of the Padma River in the vicinity of Rooppur NPP, mg·kg^{-1} (dry weight) (numerator is the mean; denominator is min.–max.)

Element	Sampling period			
	2014	2015	2016	2017
As	1.6 1.1–2.1	1.8 0.5–2.7	0.04	0.9 0.1–2.6
Hg	$1.1\cdot10^{-2}$ $9.1\cdot10^{-3}$–$1.2\cdot10^{-2}$	$1.4\cdot10^{-2}$ $9.6\cdot10^{-3}$–$1.8\cdot10^{-2}$	$1.4\cdot10^{-2}$	$5.9\cdot10^{-4}$ $2\cdot10^{-4}$–$2\cdot10^{-3}$
Cd	0.2 0.2–0.3	0.8 0.1–1.2	0.02	0.2 0.01–0.4

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Element	Sampling period			
	2014	2015	2016	2017
Ni	3.3 1.2–7.2	8.2 0.7–12.3	0.13	4.2 0.2–16.7
Co	0.4 0.2–0.8	1.1 0.1–1.8	0.04	1.3 0.04–7.0
Zn	16.3 13.2–19.9	15.3 10.5–22.9	9.7	10.6 1.9–33.1
Cu	17.1 15.6–18.5	11.2 0.96–19.3	0.7	5.1 1.2–12.4
Cr	2.2 1.3–3.8	4.7 0.7–6.2	1.3	2.5 0.6–10.3
Mn	171.7 122.0–200.0	954.5 213.0–1492.0	42.6	259.5 15.8–770.0
Pb	1.8 1.4–2.1	1.8 0.1–3.1	0.7	2.1 0.01–15.3
Fe	1153.7 391–2523	6194 210–9026	1209	2999.3 163–15010
Al	1668.3 457.0–3547.0	7210.5 185.0–11458.0	48.1	1862.7 36.5–9918
Sr	40.3 34.5–49.3	54.2 3.6–95.1	3.2	55.6 8.8–102
Se	2.6 1.8–4.0	13.8 2.6–22.2	1.58	22.1 2.3–61.0
Mo	1.1 0.8–1.5	0.9 0.7–1.2	0.14	1.2 0.1–3.5
Sb	0.4 0.2–0.5	–	0.11	1.5 0.2–7.4
V	1.5 0.8–2.6	7.6 0.2–10.7	0.19	4.1 0.1–21.4
Li	–	6.7 0.2–10.1	0.16	2.6 0.2–15.2
Cs	–	0.31 0.03–0.5	0.52	0.5 0.2–1.9

In [28], As concentration in groundwater varied from 2.08 to 3.16 µg·L^{-1} at different sampling sites, which corresponds to our monitoring data of 2016–2017.

It was pointed out in [36] that Cd levels (the II hazard class) in groundwater in a number of Bangladesh regions vary from 6 to 13 µg·L^{-1}, *i. e.* exceed the limits established by Bangladesh, WHO, and USA standards (5, 3, and 5 µg·L^{-1}, respectively). Values of cadmium concentrations in drinking water of Rooppur NPP 30-km zone, obtained during the monitoring, do not exceed international standards; however, in some samples, Cd content was higher than Russian TLV (Table 10).

Table 10. Heavy metals gross content in drinking water of the Padma River in the vicinity of Rooppur NPP, µg·L^{-1} (numerator is the mean; denominator is min.–max.)

Element	Sampling period			TLV*
	2014	2016	2017	
The I hazard class				
As	$\frac{80.5}{14.2\text{–}136.6}$	$\frac{3.5}{0.96\text{–}8.1}$	$\frac{4.4}{0.5\text{–}13.3}$	10
Hg	–	$\frac{9.7\cdot10^{-3}}{5\cdot10^{-3}\text{–}1.3\cdot10^{-2}}$	$\frac{1.2\cdot10^{-2}}{1.9\cdot10^{-3}\text{–}3.02\cdot10^{-2}}$	0.5
The II hazard class				
Cd	$\frac{0.2}{0.1\text{–}0.4}$	$\frac{0.1}{0.02\text{–}0.3}$	$\frac{0.8}{0.2\text{–}1.5}$	1
Ni	1.01	$\frac{1.74}{0.3\text{–}3.8}$	$\frac{14.7}{11.3\text{–}18.7}$	20
Co	< 3	$\frac{0.74}{0.4\text{–}1.2}$	$\frac{1.95}{0.9\text{–}2.7}$	100
Sr	$\frac{197.7}{39.0\text{–}355.0}$	$\frac{338.1}{294.9\text{–}383.4}$	–	7000
The III hazard class				
Zn	< 30	$\frac{8.9}{3.7\text{–}23.8}$	$\frac{10.3}{4.0\text{–}16.5}$	1000
Cu	< 1	$\frac{2.02}{0.1\text{–}9.0}$	$\frac{2.9}{1.1\text{–}6.2}$	1000
Cr	$\frac{2.1}{1.8\text{–}2.4}$	$\frac{0.96}{0.64\text{–}1.43}$	$\frac{2.8}{2.3\text{–}3.5}$	50
Mn	$\frac{225.5}{52.1\text{–}398.9}$	$\frac{484.9}{197.8\text{–}1036.3}$	$\frac{492.3}{374.5\text{–}579.7}$	100
Fe	$\frac{35.9}{3.2\text{–}68.6}$	$\frac{251.1}{63.7\text{–}594.9}$	$\frac{136.9}{23.9\text{–}291.7}$	300
Al	$\frac{50.6}{5.8\text{–}95.4}$	$\frac{190.3}{73.9\text{–}336.8}$	$\frac{120.6}{85.3\text{–}147.0}$	200

Note:
* GN 2.1.5.1315-03 Threshold Limit Values (TLV) of Chemicals in the Water of Water Bodies of Domestic, Drinking, and Cultural-Domestic Water Use: Hygiene Standards.

Manganese concentration (the III hazard class) in groundwater of Rooppur NPP area during the entire observation period varied from 52 to 1036 µg·L^{-1}. The maximum permissible level of Mn content in drinking water is 0.1 µg·L^{-1} (according to Bangladesh, Russian, and WHO standards [18 ; 37]). Consequently, in all drinking water samples of 2016–2017, manganese concentration exceeded the upper limit established by international and Russian standards. Studies carried out in [28] showed that Mn content in groundwater in the Mohanpur region was in the range of 0.72–3.66 µg·L^{-1} (mean of 1.83 µg·L^{-1}), which was significantly lower than in Rooppur NPP 30-km zone. Exceeding standards for manganese was most likely associated with the poor condition of the water supply system of artesian wells in NPP construction area.

Concentrations of other heavy metals did not significantly exceed international and national standards.

Heavy metals content in fish of the Padma River, recorded during monitoring in 2016–2017, was lower than Russian TLV (Table 11) and partially comparable with the results of studies on the Buriganga River [25].

Table 11. Heavy metals content in fish of the Padma River in the vicinity of Rooppur NPP, $mg \cdot kg^{-1}$ (numerator is the mean; denominator is min.–max.)

Element	Sampling period	
	2016	2017
As (1.0[*])	0.011 0.005–0.02	0.012 0.001–0.03
Hg (0.3)	0.011 0.004–0.019	$6.98 \cdot 10^{-3}$ $6 \cdot 10^{-5}$–$1.99 \cdot 10^{-2}$
Cd (0.2)	0.011 0.003–0.032	0.02 0.002–0.075
Pb (1.0)	0.3 0.15–0.55	0.22 0.03–0.6
Ni	0.94 0.4–1.6	0.7 0.2–1.3
Co	0.03 0.01–0.07	0.04 0.006–0.11
Zn	7.71 3.77–10.7	7.3 4.4–16.2
Cu	1.42 0.16–3.12	1.2 0.03–4.5
Cr	1.6 0.8–2.2	0.4 0.1–0.6
Mn	0.5 0.12–1.02	0.4 0.07–1.03
Fe	8.8 2.9–13.1	14.1 7.5–28.3
Al	4.8 3.6–5.9	3.6 1.6–8.7
Sr	1.3 0.7–1.9	2.4 0.7–4.7
Se	1.13 0.12–2.24	1.96 0.8–3.5
Mo	0.15 0.08–0.35	0.4 0.13–1.01
Sb	0.6 0.2–1.3	0.9 0.23–2.23
V	0.15 0.05–0.3	0.26 0.06–0.5
Li	0.03 0.006–0.12	0.008 0.002–0.018
Cs	0.11 0.01–0.24	0.1 0.02–0.4

Note:

[*] SanPiN 2.3.2.1078-01 Hygiene Requirements for Safety and Nutritional Value of Food Products (as amended on 06.07.2011).

In this work, Cr, Mn, Ni, Cu, Zn, and Pb content in some samples exceeded TLV in fish recommended by FAO/WHO. Results of monitoring in Rooppur NPP area showed that in some fish samples Mn concentration was slightly higher than FAO standard [31], and Sb concentration in several samples exceeded FAO/WHO recommendations [15]. These metals do not pose a carcinogenic hazard, but their combined effects can negatively affect human health.

Conclusion. Based on radiation and environmental monitoring of freshwater ecosystems in Rooppur NPP 30-km zone (2014–2017), it can be concluded that the ecological situation in this area is generally favorable. It is determined by both the climatic peculiarities of the region and anthropogenic impact.

It is shown that organic pollutants content in surface water and groundwater is below detection limits or at minimum ones (benzopyrene – less than 0.01 $\mu g \cdot L^{-1}$; phenols – 1.3–3.5 $\mu g \cdot L^{-1}$; and petroleum products – 0.01–0.043 $mg \cdot L^{-1}$). The volumetric activity of ^{137}Cs in Padma River waters during the entire observation period did not exceed 0.18 $Bq \cdot L^{-1}$ (with a mean of 0.07 $Bq \cdot L^{-1}$). The content of ^{90}Sr was in the range of 0.02–0.12 $Bq \cdot L^{-1}$, and that of ^{3}H – in the range of 0.8–2.1 $Bq \cdot L^{-1}$. Mean specific activity of ^{90}Sr in bottom sediments varied from 0.5 to 1.8 $Bq \cdot kg^{-1}$, and ^{137}Cs – from 0.8 to 2.1 $Bq \cdot kg^{-1}$. Specific activity of ^{3}H in bottom sediments was less than 3 $Bq \cdot kg^{-1}$, except for three samples in 2017 (12–30 $Bq \cdot kg^{-1}$), which is most likely due to a local pollution. Specific activity of ^{90}Sr in higher aquatic vegetation was at the level of 0.4–3.9 $Bq \cdot kg^{-1}$, and ^{137}Cs – of 0.4–1.0 $Bq \cdot kg^{-1}$. In drinking water, the volumetric activity of standardized radionuclides varied in the ranges as follows: ^{137}Cs – 0.03–0.27 $Bq \cdot L^{-1}$; ^{90}Sr – 0.01–0.16 $Bq \cdot L^{-1}$; ^{3}H – 0.4–1.2 $Bq \cdot L^{-1}$. Specific activity of ^{90}Sr in fish varied from 0.02 to 1.6 $Bq \cdot kg^{-1}$. The content of ^{137}Cs in fish was in the range of 0.26–0.3 $Bq \cdot kg^{-1}$.

The situation in the area studied on pollution of freshwater ecosystems with heavy metals is somewhat worse, which is caused by the discharge of toxicants by industrial enterprises. As content in Padma River water is at the level of 0.9–3.6 (with a mean of 2.6 $\mu g \cdot L^{-1}$). Ni concentration varies within 1.7–19.5 $\mu g \cdot L^{-1}$. The maximum Cu content in Padma River waters during the observation period reached 7.7 $\mu g \cdot L^{-1}$. Mn concentration varied in the range of 1.7–51.9 $\mu g \cdot L^{-1}$. Fe content in surface water averaged 0.03–0.2 $mg \cdot L^{-1}$ (with a maximum of 0.8 $mg \cdot L^{-1}$). Analysis of the data on Al content in Padma River water showed that in almost half of the samples, its concentration was higher than threshold limit value, and the highest value reached 595 $\mu g \cdot L^{-1}$, which exceeds TLV by 3 times. Mean As concentration in bottom sediments exceeded its TLV in soil by more than 35 times and correlated with the data on its content in Padma River surface water. Mean Cd concentration in bottom sediments was 1.3–2.7 $mg \cdot kg^{-1}$, which exceeded soil approximate permissible concentrations by 1.5–2.5 times. Pb content in bottom sediments was 3.6–25.4 $mg \cdot kg^{-1}$. During some years of monitoring, an excess in As content in drinking water in the vicinity of Rooppur NPP was registered. Mn concentration in groundwater of this area during the entire observation period varied from 52 to 1036 $\mu g \cdot L^{-1}$. In all drinking water samples of 2016–2017, Mn content exceeded the upper limit established by international and Russian standards.

Monitoring network established will make it possible to register changes in the situation in the zone of Rooppur NPP impact, as well as to identify the impact of power plant operation on the environment, including the Bay of Bengal in the Indian Ocean. The results obtained during the radioecological studies of components of freshwater ecosystems will make it possible to estimate dose commitments on humans and hydrobionts due to technogenic-altered background in the region.

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КОМПЛЕКСНЫЙ РАДИАЦИОННО-ЭКОЛОГИЧЕСКИЙ МОНИТОРИНГ ВОДНЫХ ЭКОСИСТЕМ В РЕГИОНЕ РАЗМЕЩЕНИЯ АЭС «РУППУР» (НАРОДНАЯ РЕСПУБЛИКА БАНГЛАДЕШ)[*]

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Представлен опыт создания и ведения системы радиационно-экологического мониторинга водных экосистем в регионе АЭС «Руппур» (Бангладеш). Компоненты водных экосистем в зоне влияния АЭС являются как наиболее информативными для определения состояния окружающей среды, так и важными с точки зрения ведения хозяйственной деятельности. Именно поэтому оценка и прогнозирование качества водных экосистем в районе АЭС — актуальная проблема для обеспечения радиационной и экологической безопасности. Разработана детализированная программа мониторинга; выбраны пункты наблюдения за состоянием поверхностных и подземных вод на разном расстоянии от АЭС «Руппур»; определены объекты мониторинга (вода, донные отложения, высшая водная растительность, рыба), перечень исследуемых параметров, регламент наблюдений, а также методы и нормативно-техническое обеспечение. В числе контролируемых показателей рассмотрены: физико-химические характеристики воды и донных отложений; радионуклидный состав компонентов водных экосистем, включающий природные (^{40}K, ^{226}Ra, ^{232}Th) и техногенные (^{90}Sr, ^{137}Cs, ^{3}H) радионуклиды; содержание 19 тяжёлых металлов, а также химических загрязнителей. Мониторинговые исследования проведены в 2014–2017 гг. на фоновом уровне и на этапе строительства АЭС «Руппур» с учётом климатических особенностей региона в различные периоды года. Радионуклиды в объектах окружающей среды определены методами спектрометрии и радиохимии, тяжёлые металлы — атомно-абсорбционным и плазменно-эмиссионным методами анализа. Установлено, что высшая водная растительность в реке Падма (Ганг) встречается не во все сезоны. В декабре она фактически отсутствует; максимальное видовое разнообразие отмечено в июне. Выделены различия между поверхностными и подземными водами в регионе АЭС «Руппур» по ряду физико-химических характеристик. Показатели общей минерализации и жёсткости в питьевой воде выше, чем в поверхностной, в 2–3 раза, что обусловлено составом вод р. Падма, основа которых — талые воды ледников гор и дождевая вода. Содержание в поверхностных и подземных водах органических загрязнителей ниже или на уровне порога их обнаружения приборами (бензпирен — менее 0,01 мкг·л$^{-1}$; фенолы — 1,3–3,5 мкг·л$^{-1}$; нефтепродукты — 0,01–0,043 мг·л$^{-1}$). Объёмная активность в водах р. Падма ^{137}Cs за весь период наблюдений не превышала 0,18 Бк·л$^{-1}$ при среднем значении 0,07 Бк·л$^{-1}$. Содержание ^{90}Sr было в диапазоне 0,02–0,12 Бк·л$^{-1}$, а ^{3}H — в пределах 0,8–2,1 Бк·л$^{-1}$. Средняя удельная активность ^{90}Sr в донных отложениях варьировала в диапазоне 0,5–1,8 Бк·кг$^{-1}$, а ^{137}Cs — 0,8–2,1 Бк·кг$^{-1}$. Удельная активность ^{3}H в донных отложениях составляла менее 3 Бк·кг$^{-1}$, за исключением трёх проб в 2017 г. (12–30 Бк·кг$^{-1}$), что обусловлено, по всей видимости, локальным загрязнением. Удельная активность ^{90}Sr в высшей водной растительности была на уровне 0,4–3,9 Бк·кг$^{-1}$, а ^{137}Cs — 0,4–1,0 Бк·кг$^{-1}$. В питьевой воде объёмная активность нормируемых радионуклидов колебалась в следующих диапазонах: ^{137}Cs — 0,03–0,27 Бк·л$^{-1}$, что в 40 раз ниже уровня вмешательства по НРБ-99/2009; ^{90}Sr — 0,01–0,16 Бк·л$^{-1}$ (в 30 раз ниже норматива); ^{3}H — 0,4–1,2 Бк·л$^{-1}$ (более чем в 6 тыс. раз ниже уровня вмешательства). Удельная активность ^{90}Sr в рыбе варьировалась в диапазоне 0,02–1,6 Бк·кг$^{-1}$, что в 60 раз ниже российских и международных стандартов. Содержание ^{137}Cs

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в рыбе было в пределах 0,26–0,3 Бк·кг$^{-1}$, что в 400 раз ниже российских нормативов и более чем в 3 тыс. раз — международных. Анализ данных наблюдений за уровнями загрязнения тяжёлыми металлами компонентов водных экосистем в регионе АЭС «Руппур» показал, что по ряду элементов зарегистрированы их повышенные концентрации, бóльшая часть которых относится к сезону муссонов. Так, в поверхностных водах р. Падма отмечено периодическое увеличение содержания As, Cd, Mn, Al, а в донных отложениях — As, Cd, Ni, Co, Zn, что связано с антропогенным влиянием и с усиленным стоком загрязняющих веществ в период муссонных дождей. В питьевой воде 30-километровой зоны АЭС «Руппур» зафиксированы периодические повышенные концентрации As и Mn, а в отдельных пробах — Fe и Al, что может быть обусловлено как природными особенностями региона (относительно высокое содержание As в водоносных горизонтах), так и состоянием систем водоснабжения. Заложенная сеть радиационно-экологического мониторинга водных экосистем позволяет регистрировать изменение ситуации в регионе размещения АЭС «Руппур» и выявлять влияние работы атомной электростанции на человека и окружающую среду.

Ключевые слова: Бангладеш, АЭС «Руппур», водные ресурсы, пресноводные экосистемы, река Падма, питьевая вода, радиоэкологический мониторинг, радионуклиды, тяжёлые металлы, химическое загрязнение