Radionuclide migration in fresh water from nuclear power plant liquid effluent discharged: (Hypothetical case study)

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Abstract: Radionuclide migration in ecosystems including rivers is one of the major radioecology problems. Aquatic ecosystems can contribute to radionuclide migration at very long distances from intake or forming sources. This study provides new insights into field of radiological by studying the behavior of radionuclide transported in river, resulting of discharged effluent radionuclide from nuclear power plants (NPPs) during normal operation in the river, as hypothetical case study. It was demonstrated that, the concentration of radioactivity in the river at the same side of the NPPs, it's a higher than opposite side of river bank. In addition, we show that, the maximum concentration found at the point of discharged and clearly decreased with distance. In order to assessment of radiological hazard of ionizing radiation to non-human biota, ERICA toll software Tier 2 were used to calculate the Total Dose Rate per organism, the maximum value was found to the Insect larvae [2.094 µGy h⁻¹], this value was below the screening dose rate 10 µGy h⁻¹.

1. Introduction
During normal operation of nuclear power plants(NPPs), radioactive materials are produced as secondary product, appear in the aquatic environment due to liquid effluent discharges released from the cooling system of NPPs[1][2]. 80% of the NPPs are constructed adjacent to rivers in in France[3]. Protection of humans and non-human biota in environment is important especially in aquatic environment, therefore a key of importance that must be followed when thinking about building of NPPs[4].

Water is the source of life, the quality of water is directly related to humans and the health and survival of human[5]. Radioactive pollution is one of the three main factors in the quality of the aquatic environment in addition to bacterial and chemical pollution. Radionuclide it become an important indicator of water environmental quality standards so the levels of radionuclides are important for monitoring water quality.

As in figure (1) in aquatic environment the physical, chemical and biological processes playing a key role to the transportation and accumulation radionuclides in sediment[6]. Understood to control pollution of river systems from discharge of radionuclide into rivers, must bestudy,because is a major environmental problem, and the main cause of radiological hazard. The research of radionuclides liquid effluent discharges release in river, can provide helpful data about sources, transport mechanisms and the environmental significance of radionuclides in aquatic areas, in order to estimate
the radiation dose [7]. Past study has been carried out on the concentrations of natural radioactivity in the rivers, lakes, and coasts around the globe [8]. However, research concerning the radionuclides liquid effluent discharges release concentration in the water and sediment in the river is limited.

The aim of this paper is to explore the relation between radiological hazard in rivers and the factors impact on this hazard. Recent developments in the field of using nuclear technology have led to a renewed interest in the radiological hazards of radionuclides in environment. One of the greatest challenges in the aquatic environment is how to save from the radionuclide contamination, which is associated with increased risk of exposure to ionizing radiation.

![Figure 1. The primary mechanisms of radionuclides transport in river][6]

2. Material and method

2.1 Scenario description of radionuclides discharges into River

The IAEA SRS-19 models have been adapted to assess the radionuclide concentration based on the dispersion components of the SRS-19 models (river model) as input concentration values, for the assessment concentration of radionuclides in River due to discharge of the Nuclear Power Plant (NPP) during normal operation. The applied scenario for normal operation in table (2), was obtained from reported of the United State Nuclear Regulatory Commission (U.S.NRC) to radioactive effluent release from Arkansas one NPP in USA in 2018[9][1].

Table 1. Hypothetical River parameters corresponds to 30 year low annual mean flow

| Hypothetical River parameter | Parameters corresponds to 30 year low annual mean flow |
|------------------------------|-------------------------------------------------------|
| River width / B (m)          | 503                                                   |
| Depth / D(m)                 | 7.34                                                  |
| River flow rate / q_r (m^3/s)| 5 x10^3                                              |
|                              | 1.67x10^3                                            |

2.2 Estimation of concentration radionuclide in the river bank

The information of hypothetical river are listed in table (1) was optioned from the safety report series No.19 of International Atomic Energy Agency (SR-19). Under the non-tidal river condition and the
annual mean flow for 30 year was estimated. Concentration of radionuclides in fresh water \( C_w \) (Bq/L), and sediment \( C_s \) (Bq/Kg) of river can be calculated from analytical solution of governing equation.

Estimation of concentration radionuclide in river when the completed mixed of radionuclide over a river cross-section was achievable can be written by[10]:

\[
C_w = \frac{Q_i}{q_r} \exp \left( \frac{-X}{\lambda_i U} \right) P_r \quad (1)
\]

\( C_w \) is the total radionuclide concentration in water (Bq/m\(^3\)), \( Q_i \) is the average discharge rate for radionuclide i (Bq/s), \( q_r \) is the mean river flow rate (m\(^3\)/s), \( \lambda_i \) is the radioactive decay constant (s\(^{-1}\)), \( x \) is the distance between the discharge point and the receptor (m), \( U \) is the net river velocity (m/s).

\( P_r \) in equation (1) represented of the partial mixing correction factor due to increase of distance \( X \) i.e (\( X \) > \( L_z \))

\[
L_x = 7D \quad (2)
\]

\[
L_y = \frac{3B^2}{D} \quad (3)
\]

Where the \( L_x \) and \( L_y \) are the distances required to achieved the complete vertical and lateral mixing, which means the concentration of radionuclides decreased to one of half. At region after which complete vertical mixing

\[
P_r = \frac{1}{0.142} \exp \left( \frac{1.5DX}{B^2} \right) K_0 \left( \frac{1.5DX}{B^2} \right) \quad (4)
\]

Where \( D \) and \( K_0 \) are the depth of river and modified Bessel function respectively. When the distance of \( X \) its increased to (\( X \) > \( L_y \)) the value of \( P_r \) becomes unity and equation (1) can be writing without \( P_r \) term.

### Table 2. Radioactive Effluent Release from Arkansas Nuclear One in USA (2018).

| Radionuclide | Half-life | Liquid effluent rate (Bq/s) |
|--------------|-----------|-----------------------------|
| Co-60        | 5.27 a    | 10.71                       |
| Cs-137       | 2.6 a     | 9.48                        |
| Cs-134       | 8.04 d    | 5.76                        |
| I-131        | 30.0 d    | 0.02                        |

This data obtained from U.S.NRC [9]

(a)Units of years, (d) Units of days.

### 2.3 Absorbed dose rates of biota during normal operation of NPP

Using the ERICA toll software Tier 2 to calculated of the external and internal exposure, due to the short range of the emitted particles and their absorption in superficial tissues, alpha and low beta are neglected in case of external exposure[11]. Total dose rate for biota in aquatic ecosystems can be calculated on the basis of the dose conversion coefficients DCC methodology. In this study, total dose rates were calculated for the reference defined organism[12]by the following equation

\[
\sum D_{tot} = \sum (D_{ext} + D_{in}) \quad (5)
\]

Where \( D_{tot} \), \( D_{ext} \) and \( D_{in} \) are the total, external and internal absorbed dose respectively for non-human biota. Also the Risk Quotient assessment calculated from

\[
RQ_n = \frac{DR_n}{SDR_n} \quad (6)
\]

Where the \( RQ_n \), \( DR_n \) and \( SDR_n \) are the Risk Quotients, estimated total dose rate (\( \mu \text{Gy h}^{-1} \)) and screening dose rate( was used (10 \( \mu \text{Gy h}^{-1} \))) respectively.
3. Result and discussion

3.1 Concentration of radioactivity in Hypothetical River

For the effluent radionuclides discharged in Hypothetical River, one type of reactor to estimate the activity concentration in water and sediment. The activity concentration in water \(C_w\) and sediment \(C_s\) were listed in Table (3). It shows that, the activity concentration for water and sediment at the \(X < L_z\) (10 m from point of radionuclide discharged) higher than the concentration at \(X > L_z\) and these results is in agreement with these obtained by H. Vandenhove[13].

Table 3. The Activity concentration in water river [Bq m\(^{-3}\)] for the different distances from discharge effluent radionuclide at the same side bank of effluent discharged.

| Radionuclide | At \(x = 10\) m | At \(x = 50\)m | At \(x = 500\) m | At \(x = 1000\) m |
|--------------|-----------------|----------------|------------------|------------------|
| Co-60        | 10.710          | 0.079518       | 0.048            | 0.039            |
| Cs-137       | 9.480           | 0.0704         | 0.042            | 0.035            |
| Cs-134       | 5.760           | 0.0428         | 0.025            | 0.021            |
| I-131        | 0.020           | 0.0001         | 9 E-05           | 7.4E-05          |

At \(X < L_z\) the maximum value of \(C_w\) and \(C_s\) was found is 10.71 Bq/m\(^3\) and 1189.740 Bq kg\(^{-1}\) respectively, resulted from Co-60, and minimum value is 0.02 Bq/m\(^3\) and 2.860 Bq kg\(^{-1}\) form I-131.

When comparison between concentration of radionuclides in same side and opposite side river bank from NPP radionuclides discharged effluent specifically at \(X < L_z\), the concentration activity clearly decreased in opposite side its was showed, as can be seen in table (4) for water and table (6) for sediment. This result may be explained by the fact that, the width of Hypothetical river its greater than depth, so the distance required to achieve the complete lateral mixing \(L_y\) is greater than distance required to vertical mixing \(L_z\) according to equation (2) and (3). This finding broadly supports the work of other studies in this area linking concentration of radionuclides with the point of radionuclides discharged relies[10].

Table 4. Comparison between the Activity Concentration in Water River [Bq m\(^{-3}\)] in distances (\(X < L_z\)) from discharge of effluent radionuclide at the opposite and the same side bank of river.

| Radionuclide | Same side bank of river | Opposite side bank of river |
|--------------|-------------------------|-----------------------------|
| Co-60        | 10.710                  | 0.006                       |
| Cs-137       | 9.480                   | 0.005                       |
| Cs-134       | 5.760                   | 0.003                       |
| I-131        | 0.020                   | 1.2E-05                     |

The concentration activity observed its depends on the quantity of radioactivity discharged per one second (Bqs\(^{-1}\)), side of river bank and distance between the point of effluent radionuclides discharged to point of needed measurement, as mentioned in the introduction. Concentration of radionuclides was calculated to \(X > L_z\) of the radionuclide discharge at the same river bank, with assumed that, the completed vertical mixed was done. As shows in table (1), the concentration radionuclide in water for \(X > L_z\) was decreased with distance of \(X\) is increased. A possible explanation for this might be that in the water column that dissolved radionuclide concentration decreased due to the adsorbed in to sediments river.

The current study found that, generally the activity concentration in sediment it’s greater than activity concentration in water, due to non-uniform of the water velocity along the water column. At the surface it has a maximum value and is reduced with increasing depth as shown in figure (2)[14].
Table 5. The Activity Concentration in sediment [Bq kg$^{-1}$ d.w.] for the different distances discharge of effluent radionuclide at the same side bank of effluent discharged.

| Radionuclide | At x = 10 m        | At x = 50 m        | At x = 500 m       | At x = 1000 m       |
|--------------|---------------------|---------------------|---------------------|---------------------|
| Co-60        | 1189.740            | 8.833               | 5.358               | 4.404785            |
| Cs-137       | 1328.370            | 9.863               | 5.982               | 4.918025            |
| Cs-134       | 807.110             | 5.992               | 3.635               | 2.988137            |
| I-131        | 2.860               | 0.021               | 0.013               | 0.0105              |

Table 6. Comparison between the Activity Concentration in Activity Concentration in sediment [Bq kg$^{-1}$ d.w.] in distances (X<Lz) from discharge of effluent radionuclide at the opposite and the same side bank of river.

| Radionuclide | Same side bank of river | Opposite side bank of river |
|--------------|--------------------------|-----------------------------|
| Co-60        | 1189.740                 | 0.712                       |
| Cs-137       | 1328.370                 | 0.795                       |
| Cs-134       | 807.110                  | 0.483                       |
| I-131        | 2.860                    | 0.27E-2                     |

3.2 Absorbed dose in biota and Risk Quotient assessment

The total absorbed dose rate and Risk Quotient (RQ) of none-human biota assessment from exposure to contaminated river water and sediments was calculated used an default uncertainty factor (UF) selected equal to 3 will test for 5% probability of exceeding the dose screening value and listed in table (7) [12].

Figure 2. Profile the water velocity along the water column in river [14].

The maximum total absorbed dose rate in biota and QR was found 2.904 µGy h$^{-1}$ and 0.29 respectively for the Insect larvae, this result may be explained by the fact that in the river the Insect larvae occupancy factor (time spent in the sediment) equal one [15], compared to other non-biota less than one.

Table 7. Total Dose Rate per organism [µGy h$^{-1}$] and Risk Quotient [unitless], in distances (X<Lz) from discharge of effluent radionuclide at the opposite and the same side bank of river.

| Organism      | Total Dose Rate per organism [µGy h$^{-1}$] | Risk Quotient [unitless] |
|---------------|---------------------------------------------|--------------------------|
| Amphibian     | 0.009                                       | 0.9E-3                   |
| Benthic fish  | 1.285                                       | 0.128                    |
| Insect larvae | 2.904                                       | 0.290                    |
| Mollusc - bivalve | 1.383                                      | 0.138                    |
| Phytoplankton | 0.4E-3                                      | 0.47E-06                 |
| Reptile       | 1.271                                       | 0.1271                   |
| Vascular plant| 1.451                                       | 0.145                    |
Figure 3. Total Dose Rate per organism due to exposure in river

As shown in figure (3), the total absorbed dose for all references non-biota in river it’s below the screening level of the reference total absorbed dose 10 µGy h⁻¹[12].

4. Conclusions
It is important to estimate the concentration of radionuclides effluent discharge through rivers systems. The purpose of the current study was to estimation concentration of radionuclides in river and absorbed dose to non-human biota. The study contributes to our understanding the transfer and migration of radionuclides in ecosystem. This study has found that generally the activity concentration in sediment it’s greater than activity concentration in water.

The present study has been one of the first attempts to thoroughly examine of migration radionuclides in fresh water from liquid effluent emission from nuclear power plant as Hypothetical case study. It is unfortunate that, the study did not include the experimental data due to difficulty of experiment for this type of research. A further study could assess the long-term effects of radionuclides discharge effluent from NPPs in aquatic ecosystems in real case study for long time after discharged.

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References:
[1] S. Kamboj, “Nonhuman biota dose rate estimation from liquid effluent releases during normal operations of light water reactors using the LADTAP II computer code,” J. Environ. Radioact., vol. 196, no. April 2018, pp. 141–149, 2019.
[2] T. Y. Kong, S. Kim, Y. Lee, J. K. Son, and S. J. Maeng, “Radioactive effluents released from Korean nuclear power plants and the resulting radiation doses to members of the public,” Nucl. Eng. Technol., vol. 49, no. 8, pp. 1772–1777, 2017.
[3] S. Duchesne, P. Boyer, and K. Beaugelin-Seiller, “Sensitivity and uncertainty analysis of a model computing radionuclides transfers in fluvial ecosystems (CASTEAUR): Application to 137Cs accumulation in chubs,” Ecol. Modell., vol. 166, no. 3, pp. 257–276, 2003.
[4] T. L. Yankovich et al., “An international model validation exercise on radionuclide transfer and doses to freshwater biota,” J. Radiol. Prot., vol. 30, no. 2, pp. 299–340, 2010.
[5] T. Nakanishi and K. Sakuma, “Trend of 137Cs concentration in river water in the medium term and future following the Fukushima nuclear accident,” Chemosphere, vol. 215, pp. 272–279, 2019.
[6] W. S. Zhang, Y. X. Zhao, Y. H. Xu, Y. G. Wang, H. Peng, and G. H. Xu, “2-D numerical simulation of radionuclide transport in the lower Yangtze River,” J. Hydrodyn., vol. 24, no. 5, pp. 702–710, 2012.
[7] G. Suresh, V. Ramasamy, V. Meenakshisundaram, R. Venkatachalapathy, and V. Ponnu-
samy, “Influence of mineralogical and heavy metal composition on natural radionuclide
concentrations in the river sediments,” *Appl. Radiat. Isot.*, vol. 69, no. 10, pp. 1466–1474,
2011.

[8] J. Wang, J. Du, and Q. Bi, “Natural radioactivity assessment of surface sediments in the Yangtze
Estuary,” *Mar. Pollut. Bull.*, vol. 114, no. 1, pp. 602–608, 2017.

[9] T. L. Arnold, “Annual Radioactive Effluent Release Report,” *U. S. Nuclear Regulatory
Commission*, 2018. [Online]. Available: https://www.nrc.gov/docs/ML1911/ML19115A122.pdf.

[10] IAEA, “Safety Reports Series No. 19 Generic Models for Use in Assessing the,” 2001.

[11] K. W. Giwa, O. D. Osahon, F. R. Amodu, T. I. Tahiru, and F. O. Ogunsanwo, “Radiometric
analysis and spatial distribution of radionuclides with-in the terrestrial environment of South-
Western Nigeria using ERICA tool,” *Environ. Nanotechnology, Monit. Manag.*, vol. 10, no.
October, pp. 419–426, 2018.

[12] M. Sotiropoulou, H. Florou, and G. Kitis, “Calculating the radiological parameters used in non-
human biota dose assessment tools using ERICA Tool and site-specific data,” *Radiat.
Environ. Biophys.*, vol. 56, no. 4, pp. 443–451, 2017.

[13] H. Vandenhove et al., “Predicting the environmental risks of radioactive discharges from Belgian
nuclear power plants,” *J. Environ. Radioact.*, vol. 126, pp. 61–76, 2013.

[14] R. Periñeiz, *Modelling the dispersion of radionuclides in the marine environment: An
introduction*, 2005.

[15] H. ERICA, “ERICA Assessment Tool Help Function Document Contents,” no. June, pp. 1–123,
2016.