Research Article

Altitude - Dependent Distribution of Cesium-137 In The Environment: A Case Study of Aragats Massif, Armenia

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Abstract

The paper considers distribution of ^{137}Cs concentrations in soils and atmospheric dry depositions by altitudinal belts of the Aragats mountain massif (Armenia). Undisturbed soil samples were collected at altitudes from 1000 to 3200 m. For the determination of geochemical variability two soil sampling campaigns were undertaken. Atmospheric dry depositions were sampled from five stations at 1100-3200 m onto organic fiber filters between June and December 2016. ^{137}Cs activity was measured using an HPGe detector. Results indicated that ^{137}Cs activity in soils and atmospheric dry depositions decrease as the absolute altitude decreases. The 50-year effective dose from exposure to ^{137}Cs fallout varies with altitude from 0.007 to 1.42 mSv and does not exceed the maximum effective dose limit for the population of 1 mSv year^{-1}.

Introduction

Radioactive fallout in the terrestrial environment from nuclear weapons tests and accidental emissions from nuclear power plants (NPP) is the major source of radiocesium in the environment. The long-lived ^{137}Cs isotope of radioactive cesium is one of major dose-forming radionuclides resulting from uranium and plutonium fission. The total release of ^{137}Cs into the stratosphere from atmospheric nuclear testing was approximately 960×10^{15} Bq, and produced a fallout density of 3.42×10^3 Bqm^{-2} in the northern hemisphere, 0.86×10^3 Bqm^{-2} in the southern hemisphere, and 3.14×10^3 Bqm^{-2} average global [1]. As of 1985, mean fallout density of ^{137}Cs was estimated at 3.4×10^3 Bq m^{-2} in the former USSR [2].

Under normal operating conditions at NPPs, releases of radionuclides including ^{137}Cs, are insignificant [1,3]. Complex situations may emerge in the case of NPP accidents where radioactive materials are released. To the present, hundreds of accidents with varying degrees of severity have been documented. However, only some of these released significant amounts of radionuclides into the environment. The Chernobyl NPP accident of 1986 has been the worst to occur in the entire history of the nuclear energy [4]. The reactor destroyed in the accident released huge amounts of radionuclides 1.85×10^{18} Bq (RNGs excluded) to the environment. The activity of radioactive cesium released was estimated at 270×10^{15} Bq, some of which was distributed globally [5]. Approximately 40% of ejected radioactive cesium was deposited on the Former Soviet Territory, which became a primary dosimetry concern after radioactive iodine had decayed (in 2-3 months). The Chernobyl accident produced highly heterogenic radioactive contamination due to the prolonged release of radionuclides (for 10 days) and unstable weather conditions: atmospheric precipitation and changes in wind directions [6].

The Fukushima Daiichi NPP accident of March 11, 2011

provoked by the great East Japan earthquake and the tsunami also spread radioactive contamination on a global scale. Dispersion and deposition of radionuclides mostly occurred throughout the northern portion of the Pacific Ocean [7,8]. According to the IAEA's assessment, atmospheric releases from the Fukushima Daiichiaccident constituted approximately one tenth of those from the Chernobyl accident [5,8]. Other sources of smaller releases of ^{137}Cs to the environment are spent fuelre processing radio chemical plants and radioactive waste storage facilities [9].

Radioactive debris from a nuclear explosion are aerosols and airborne particulates produced from condensation of radioactive and nonradioactive products of the explosion. The solubility of aerosols and leach ability of radionuclides from particles is determined by the conditions of their formation, and once mobilized contribute to radionuclide migration in the environment and become available for bioaccumulation. The solubility of ^{137}Cs in atmospheric precipitation varies within wide limits from 9.3 to 83.4%, averaging 49% [10], depending on the conditions of formation for radioactive particles. The atmosphere serves as a primary reservoir for radionuclides released to the environment, where they are transported and eventually deposited onto the earth's surface. Typically, the micro aerosols formed in the debris cloud are absorbed by larger particles and are slowly deposited on the Earth's surface. This process is accelerated by atmospheric precipitation and aggregation of particles into the larger ones [11]. Radioactive cesium deposited on the earth surface, then can migrate in horizontal and vertical directions under the influence of environmental factors [12].

Mountain regions have a special role in radionuclide redistribution processes [6,13,14]. The territory of Armenian Highlands and present-day Armenia in particular play a key part in the processes of migration of long-lived fission products in the South Caucasus due to its geographical position and unique geographic features. Hypsometrically, as compared with the rest of the South Caucasian countries, Armeniais positioned at the highest elevation, mean altitude - 1830 ma.s.l., the highest benchmark 4090 m - Mt. Aragats. Numerous tributaries of trans boundary Rivers Kura-Araks originate within the Republic [15]. Armenia operates NPP (ANPP), spent nuclear fuel storage, medium- and low-activity waste storage facilities; neighboring states have also actively been developing nuclear technologies.

The territory is sensitive to the influence of transboundary transfer of radionuclides. After the Chernobyl accident, for example, radionuclides from Chernobyl were identified in different environmental compartments due to meteorology favorable to transport to, and fallout on Armenia's high mountain regions [16-19]. No radionuclides from the Fukushima Daiichi NPP accident have been detected in Armenia [20]. In this context, the first stage of radioecological monitoring implemented in Armenia was the assessment of radionuclide contents from atmospheric depositions, levels of accumulation in soils, and distribution by altitudinal belts. This particular research was done to study altitude-dependent distribution of ^{137}Cs in soils and dry atmospheric depositions. Observation stations were arranged on the southern slope of the Aragats mountain massif.

Materials and Methods

Description of Study Region

The Aragats mountain massif - a stratovolcano - dominates the west of Armenia. It has four peaks, the northern being the highest within present-day Armenia (4090 m. a.s.l.). Geological structure includes basalts, and esites, tracheandesites, tuffs and tuff breccias. As the altitude decreases, soil types regularly change from mountain meadow to meadow steppe and cinnamonic at the foot, and brown semi-desert within Ararat Valley. On the eastern and southeastern slopes bedrock outcrops with underdeveloped stony soil cover are observable. [21]. The types of native vegetation also change as the absolute altitude changes: from meadow and meadow steppe (alpine and subalpine meadow vegetation: forbs and grains) to steppe (with a dominance of grains) and semi-desert (ephemerwermuth) [21].

Sampling

Soil sampling was done repeatedly: in July and August 2016. Sampling stations are located starting from the Ararat Valley (1000 m a.s.l.) at a sampling interval of 200 m via the southern slope of the Aragats massif to Lake Kari (3200m a.s.l.) (Figure 1).
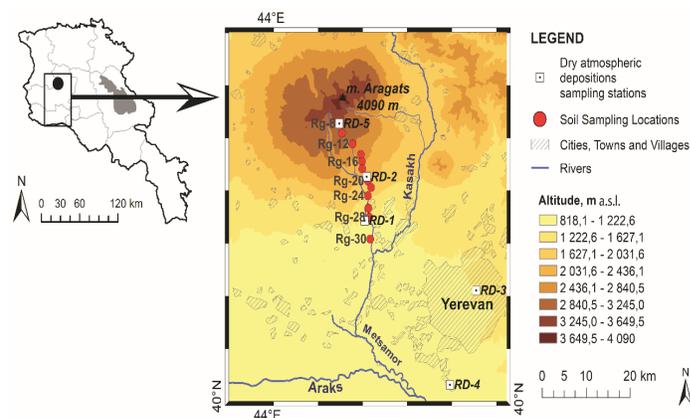
Figure 1: Soil sampling sites and dry atmospheric deposition sampling stations in Aragats massif and Ararat Valley.

Undisturbed topsoil samples were collected at 0-5 cm deep as a large share of atmospheric depositions containing heavy metals and radionuclides, is accumulated from the air in this layer [22]. When sampling, priority was given to locations minimally liable to wind and water erosion.

A standard operating procedure for soil sampling was developed in compliance with the IAEA technical document [23] and EPA guidelines [24]. Data regarding soil sampling locations and soil types are given in Table1. Dry depositions were sampled by a standard operating procedure developed in compliance with methods described by a number of publications [25-27]. Five dry deposition sampling stations are arranged at different heights of the Aragats massif and the Ararat Valley (Figure 1, Table 2). Plastic trays with an area of 2640 cm^2 and bottoms covered with organic fine fiber filter (Petryanov's filtering cloth) were installed at a height of 1.5-2 m above ground level. The filters were kept on stations for 24-30 days and then replaced by new ones.

Sample number	Sampling date	Latitude, longitude	Altitude, ma.s.l.	Soil type
Rg-30	29 Jul 2016 25 Aug 2016	40˚16'33.84"N 44˚16'16.68"E	1000	Semi-desert gray typically, grainy, partly carbonated and carburized
Rg-28	29 Jul 2016 25 Aug 2016	40˚18'50.88"N 44˚16'4.98"E	1200	Brown, grainy, carbonated, partly carburized
Rg-26	29 Jul 2016 25 Aug 2016	40˚19'46.82"N 44˚15'56.64"E	1400	Brown, grainy, carbonated, partly carburized
Rg-24	29 Jul 2016 25 Aug 2016	40˚21'4.80"N 44˚15'50.58"E	1600	Chernozem soil, carbonated
Rg-22	29 Jul 2016 25 Aug 2016 3 Oct 2016	40˚21'56.46"N 44˚16'21.42"E	1800	Chernozem soil, non-calcareous, deep-carbonated
Rg-20	29 Jul 2016 25 Aug 2016	40˚22'37.38"N 44˚15'50.28"E	2000	Chernozem soil, non-calcareous, deep carbonated
Rg-18	29 Jul 2016 25 Aug 2016	40˚23'52.26"N 44˚14'55.56"E	2200	Meadow-steppe typical residual saturated
Rg-16	29 Jul 2016 25 Aug 2016	40˚24'37.74"N 44˚14'52.14"E	2400	Mountain-meadow, saturated
Rg-14	29 Jul 2016 25 Aug 2016	40˚25'22.44"N 44˚14'40.68"E	2600	Mountain-meadow, saturated
Rg-12	29 Jul 2016 25 Aug 2016	40˚26'27.00"N 44˚13'18.52"E	2800	Mountain-meadow, soddy saturated
Rg-10	29 Jul 2016 25 Aug 2016	40˚27'34.26"N 44˚11'35.94"E	3000	Mountain-meadow, soddy saturated
Rg-8	28 Jun 2016 25 Aug 2016	40˚28'35.52"N 44˚11'9.42"E	3200	Mountain-meadow, soddy saturated

Table 1: Soil sampling sites and soil types.

Station number	Location	Latitude, longitude	Altitude, ma.s.l.	Duration of exposure, days
RD-5	Aragats massif, Lake Kari, Aragatsotn marz	40˚28'35.04"N 44˚11'9.02"E	3200	98
RD-2	Amberdmeteostation, Aragatsotn marz	40˚23'3.78"N 44˚15'38.46"E	2032	178
RD-1	Village of Aghdzk, Aragatsotn marz	40˚18'29.76"N 44˚15'21.84"E	1208	229
RD-3	Yerevan	40˚11'17.80"N 44˚33'20.91"E	1281	222
RD-4	Village of Mkhchyan, Ararat marz	40˚1'26.42"N 44˚29'12.58"E	854	228

Table 2: Location of dry deposition sampling stations and duration of exposure.

Samples Pretreatment and Analysis

Soil samples were air dried at a room temperature, disaggregated and sieved (>1 mm), then placed into plastic Marinelli beakers, sealed and labeled. Filters with collected atmospheric depositions were accumulated per station over the entire period of observation, dried at 100OC and then ashed in muffle furnace at 400OC.

The specific activities of radionuclides in atmospheric depositions and activity concentrations in soils were determined using a Canberra high-purity germanium γ-ray spectrometer with energy resolution of 1.8 keV FWHM for the 60Co γ-ray energy line at 1332 keV coupled with DSA-1000 multichannel analyzer (CANBERRA). Full energy and efficiency calibration procedures were performed prior to the measurements using a standard sources (CANBERRA) i.e.[137]Cs,[155]Eu and 22Na. Background radiation level were measured once a week. Spectrum acquisition time varied from 15000 seconds for soil, and 60000 seconds for filter ashes. After background subtracting in Genie 2000software, the activity concentration of ^{137}Cs was determined from photopeakat energy 661.5 keV. A relative measurement uncertainty for ^{137}Cs in soils was 6%, and in dry atmospheric depositions varied 25 to 30%.

Activity concentration of naturally occurring radionuclides [238]U, [232]Th and [40]K in soils were determined as well. 1460.0 keVgamma-rays were used for the determination of [40]K, while [238]U and [232]Th were calculated by taking the mean of photopeaks of their short-lived decay products:[238]U by [226]Ra at 186.0, [214]Pb at 351.9 and [214]Bi at 609.2 keV; [232]Th by [212]Pb at 239.0 and [212]Bi at 727.0 keV.

Assessment of Effective Dose from Exposure to Soil Contamination from Global [137]cs

The slopes of Aragats massif are rather densely populated and alpine and subalpine meadows utilized as seasonal pastures. Here one may enjoy national historic sites of Armenia, recreation zones, and lots of tourist routes running through the region. For this reason, this research included an assessment of potential dose to the population from [137]Cs. The effective dose from ^{137}Cs deposition over a 50-year long period was calculated by a formula suggested in an IAEA Technical Document [28].

$$E_{ext} = \sum_{i=1}^{n} C_{g,i} \times CF_i$$

where E_{ext} is effective dose from deposition for the period of concern (50 year), expressed in mSv; $C_{(g,i)}$is average deposition (ground) concentration of radionuclide i, expressed in kBq m^{-2}; CF_i is conversion factor - effective dose per unit deposition for radionuclide i (includes external dose and committed effective

dose from inhalation due to resuspension of contaminated ground particles for the period of concern), for ^{137}Cs equal to 0.13 mSvkBq^{-1} m^{-2} in 50-year period; n is number of radionuclides.

Estimation of Radiological Indices

With the purpose to collate activity concentration of ^{137}Cs and naturally occurring radio nuclides in soils Radium equivalent activity was calculated using the relation [29]:

$$RaEq = C_U + 1.43C_{Th} + 0.077C_K$$

Where C_U, C_{Th} and C_K are the activity concentration in Bqkg^{-1} of [238]U, [232]Th and [40]K respectively. In order to assess the potential radiological hazard External gamma radiation hazard index (H_{ex}) from natural sources of gamma rays in soils was calculated according to UNSCEAR [29]:

$$H_{ex} = \frac{C_u}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$$

External hazard index is dimensionless parameter;a unit represents hazard posed by activity concentration equal to 370 Bq kg^{-1} [238]U (or [226]Ra). In case of $H_{ex} \leq 1$, the external gamma radiation level is considered insignificant.

The annual effective dose equivalent (AEDE) from naturally occurring radionuclides in soils was calculated by using the following equation:

$$AEDE = D \times DCF \times OF \times T$$

where D is outdoor gamma absorbed dose rate (D) and was calculated from the concentrations of the radionuclides in soil: $D = 0.462C_U + 0.604C_{Th} + 0.0417C_K$; DCF is dose conversion factor (0.7 SvGy^{-1}), OF is outdoor occupancy factor (0.2), and T is the time (8760 h/y) [29].

Results and Discussion

Specific activity of ^{137}Cs in the studied mountain soils are given in Table 3. Data generated from the 1st and 2nd sampling campaigns point to high correlation of results (r=0.96 at p>0.01). Shapiro-Wilk test results (p-value equal 0.185 and 0.608 for the 1st and the 2nd sampling campaign respectively) showed that both samples follow lognormal distribution. The resulting p-value of paired sample t-test was 0.65 indicating that two samples are the representatives of the same population. Activity concentrations of natural radionuclide activities in soils measured in the context of this research (Table 4) suggest that in contrast to ^{137}Cs, [238]U and [232]Th exhibitsignificant geochemical variability withinsampling sites and no regularities of distribution by altitude. Activity concentrations of [40]K estimated in the 1st and 2nd sampling campaigns are correlated significantly (r=0.61 at p>0.05) and slightly decrease as the altitude

increases. Specific activity of ^{137}Cs in soils varies within wide limits from 495-528 Bq m^{-2} at 1000 ma.s.l. in Ararat Valley to 10500-11470 Bq m^{-2} in soils nearby Lake Kari at 3200 m. ^{137}Cs activity level in soils increases as the absolute height above sea level increases (Table 3). The dynamics of altitudinal dependence of ^{137}Cs concentration is sufficiently described by exponential function (Figure. 2).
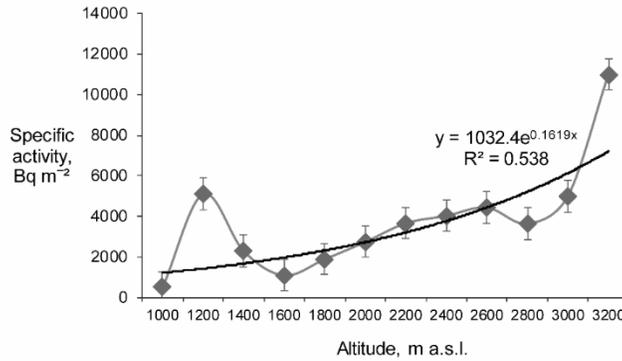
Figure 2: Specific activity of ^{137}Cs in soils by altitudes. Mean data for the 1st and 2nd sampling campaigns.

Sample number	Sampling date	Altitude, ma.s.l.	Activity concentration, Bq kg^{-1}	Specific activity, Bq m^{-2}
Rg-30	29 Jul 2016	1000	11	495
	25 Aug 2016		12	528
Rg-28	29 Jul 2016	1200	87	5510
	25 Aug 2016		115	4690
Rg-26	29 Jul 2016	1400	56	2520
	25 Aug 2016		47	2068
Rg-24	29 Jul 2016	1600	15	750
	25 Aug 2016		29	1450
Rg-22	29 Jul 2016	1800	42	1890
	25 Aug 2016		38	1900
Rg-20	29 Jul 2016	2000	64	3200
	25 Aug 2016		38	2289
Rg-18	29 Jul 2016	2200	91	3785
	25 Aug 2016		85	3541
Rg-16	29 Jul 2016	2400	88	4000
	25 Aug 2016		99	4059
Rg-14	29 Jul 2016	2600	85	4250
	25 Aug 2016		110	4620
Rg-12	29 Jul 2016	2800	97	3463
	25 Aug 2016		103	3814

| Rg-10 | 29 Jul 2016 | 3000 | 124 | 4588 |
	25 Aug 2016		123	5412
Rg-8	28 Jul 2016	3200	350	10500
	25 Aug 2016		310	11470

Table 3: Specific activity ^{137}Cs in studied mountain soils.

Sample number	Altitude, m a.s.l.	Activity concentration, Bq kg^{-1} and sampling dates					
		^{238}U		^{232}Th		^{40}K	
		29 Jul 2016	25 Aug 2016	29 Jul 2016	25 Aug 2016	29 Jul 2016	25 Aug 2016
Rg-30	1000	134	46	43	31.5	543	415
Rg-28	1200	77	110	38.5	37	420	408
Rg-26	1400	111	75	41	43	461	494
Rg-24	1600	103	70	42	45	510	481
Rg-22	1800	53	102	46	52	200	456
Rg-20	2000	96	58	60	38.5	260	222
Rg-18	2200	73	84	39.5	39.5	252	230
Rg-16	2400	84	53	33	54.5	256	312
Rg-14	2600	30.5	73	40	36.5	309	276
Rg-12	2800	84	64	39	42	266	263
Rg-10	3000	75	87	39.5	36	300	233
Rg-8	3200	77	23.5	32	54	123	300
Average concentrations of radionuclides in soils [25]		25		25		370	
Typical range [25]		10-50		7-50		100-700	

Table 4: Activity concentrations (Bq kg^{-1}) of natural radionuclides in studied mountain soils.

Relatively high contents of ^{137}Cs detected in Rg-28 and Rg-26 soils (1200 and 1400m a.s.l.) may presumably be determined by sorption ability of soils (brown, grainy, carbonated, and partly carburized).

The obtained data nicely correlate with earlier research results regarding the territory of the Ararat Valley [30] and the zone monitored by the ANPP [2,16,29]: over the last decade (2006-2016) ^{137}Cs activity in native landscape soils at 880-1100 m showed variations 300 to 429 Bq m^{-2} (Figure 3).
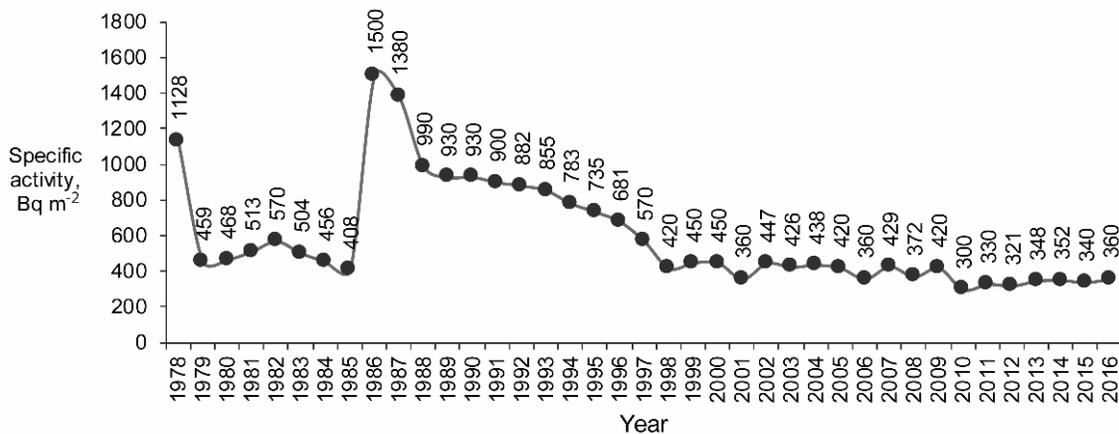
Figure 3: Specific activity of ^{137}Cs (Bq m^{-2}) in Ararat Valley soils within the zone monitored by the ANPP.

^{137}Cs activity in dry atmospheric depositions varies 1.06 to 2.37Bq m^{-2} per quarter (Table 5) and increases as the altitude increases. Correlation coefficient for the five concurrent soil samples and atmospheric deposition is rather high: r=0.86 at p>0.05 (Figure 4). According to monitoring data provided by the ANPP, ^{137}Cs activity in dry atmospheric depositions at a heigh to f 900 m within the environmental impact zone monitored by ANPP constituted 0.8 Bq m^{-2} per quarter for 2016.
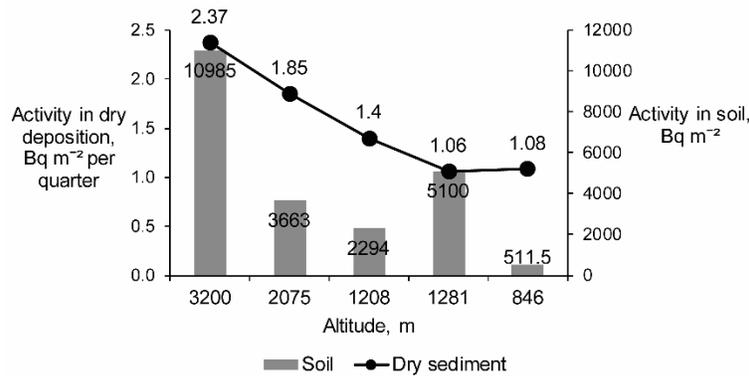

Figure 4: Specific activity of ^{137}Cs in dry atmospheric depositions (Bq m^{-2} per quarter) and soils (Bq m^{-2}) from concurrent sampling locations and sampling stations.

Sampling stations	RD-5	RD-2	RD-3	RD-1	RD-4
Altitude, ma.s.l.	3200	2032	1281	1208	846
Activity of ^{137}Cs, Bq m^{-2} per quarter	2.37	1.85	1.40	1.06	1.08

Table 5: Specific activity of ^{137}Cs in dry atmospheric depositions.

The estimated effective dose for 50 year period from ^{137}Cs accumulated by soil by altitude varies 0.07 to 1.43 mSv year^{-1} (Figure 5), which is far lower than a per capita dose limit established in Armenia 1 mSv/year [31]
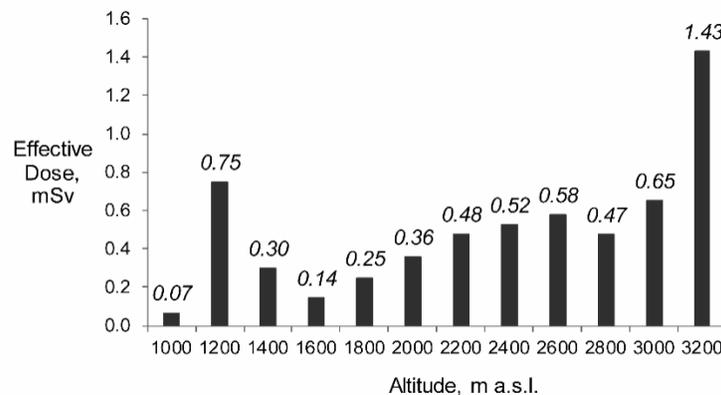
Figure 5: Effective dose for 50-year period from ^{137}Csin studied soils by altitude. Mean data for the 1st and 2nd sampling campaigns. National permissible annual effective dose - 1 mSv per year [31]

Radium equivalent activity in studied soils varied from 128.0 to 189.8 Bq kg^{-1} averaged to 162.2Bq kg^{-1} (Table 6) which are lower than the global average value reported by UNSCEAR [29]. Subsequently the external hazard index did not exceed 1. Annual effective dose equivalent from naturally occurring radionuclides in soils of Aragats varied from 0.07 to 0.11 averaged at 0.09 mSv year-1, which exceed the world average value estimated as 0.07 mSv year-1[29]. The values of Annual effective dose equivalent decreased as altitude increases which suggest the domination of naturally occurring radionuclides in radiological dose formation

by the 3000 m a.s.l., where settlements and seasonal pastures are situated. The share of ^{137}Cs increased dramatically above the mentioned altitude mark of 3000 ma.s.l. (Figure 5).

Samplenumber	Altitude, m a.s.l.	RaEq, Bq kg $^{-1}$	H_{ex}	D, nGy h^{-1}	AEDE, mSv year^{-1}
Rg-30	1000	180.2	0.49	84.1	0.10
Rg-28	1200	179.4	0.48	83.3	0.10
Rg-26	1400	189.8	0.51	88.2	0.11
Rg-24	1600	186.9	0.50	86.9	0.11
Rg-22	1800	172.8	0.47	79.1	0.10
Rg-20	2000	166.0	0.45	75.4	0.09
Rg-18	2200	153.5	0.41	70.2	0.09
Rg-16	2400	152.9	0.41	69.9	0.09
Rg-14	2600	129.0	0.35	59.2	0.07
Rg-12	2800	152.3	0.41	69.7	0.09
Rg-10	3000	155.5	0.42	71.3	0.09
Rg-8	3200	128.0	0.35	58.0	0.07
World average, according to [20]		370	not available	59	0.07

Table 6: Radium Equivalent activity, outdoor gamma dose rate in air and annual effective dose equivalent from naturally occurring radionuclides in soils of Aragats massif. Mean data for the 1st and 2nd sampling campaigns.

The dynamics of altitude-dependent ^{137}Cs concentration was determined on the initial intermediate stage of regular investigations of radionuclide migration throughout Armenia. This was the start of a program for a quantitative assessment of transboundary (global) migration of radionuclides. A comprehensive understanding of typical concentrations and migration pathways of radionuclides will make it possible to determine new occurrences of environmental contamination and identify the sources. So, early identification of risk associated with radioecological issues will largely contribute to development of an early warning system, mitigate risks to the population and environment, increase safety and promote sustainable development of regions.

Conclusion

In 2016 investigations were completed to assess the altitude-dependent distribution of ^{137}Cs in soils and dry atmospheric depositions in Aragats massif and Ararat Valley (Armenia). The specific activity of ^{137}Cs insoilsat 1000 mis 495-528 Bq m^{-2}, and at 3200 m is 10500-11470 Bq m^{-2}. The dynamics of altitudinal dependence of ^{137}Cs is described by an exponential function. There was no correlation observed for [137]Csversus natural radionuclides, which varies in distribution by altitude. Specific activities of ^{137}Cs in dry atmospheric depositions vary from 1.06 at 846 m

to 2.37Bqm^{-2} perquarterat 3200 m and increases as the altitude increases. Activities of ^{137}Cs in soil and dry atmospheric deposition correlate significantly.

The effective dose from ^{137}Cs-contaminated soils by altitudes over 50-year period varies from 0.07 to 1.43 mSv, which is far lower than a per capita dose limit established in Armenia. Annual effective dose equivalent from naturally occurring radionuclides in soils of Aragats exceeds the world average value for all studied soils. Thus, naturally occurring radionuclides are dominated in radiological dose and dose rate formation in Aragats massif however external radiation hazard index from primordial radionuclides is insignificant. This new understanding of radionuclide distribution from historic nuclear test and reactor accident fallout serves as essential information necessary to detect new inputs to the environment, and serves as the basis for an early warning system for radiation safety in Armenia. Additional ongoing studies are aimed at assessing stream flow transport of radionuclides, soil erosion, and radionuclide migration in food chains.

Acknowledgement

References

1. (1982) Ionizing Radiation: Sources and Biological Effects. UNSCESR, New York.

2. Moiseev AA (1985) Cesium-137. Environment. Men. Energoatomizdat, Moscow.

3. (2001) Generic models for use in assessing the impact of discharges of radioactive substances to the environment. Vienna.

4. Beresford NA, Fesenko S, Konoplev A, Skuterud L, Smith JT, et al. (2016) Thirty years after the Chernobyl accident: What lessons have we learnt?. J Environ Radioact 157: 77-89.

5. (1991) The International Chernobyl Project Technical Report. IAEA, Vienna.

6. Cort M De, Dubois G, Fridman SD, Germenchuk MG, Izrael YA, et al. (1998) Atlas of Caesium Deposition on Europe after the Chernobyl Accident. EC/IGCE, Roshydromet/Minchernobyl (UA)/Belhydromet, Brussels - Luxembourg.

7. Povinec PP, Hirose K, Aoyama M, Povinec PP, Hirose K, et al. (2013) Radionuclide Releases into the Environment. In: Fukushima Accident. Elsevier 103-130.

8. (2015) The Fukushima Daiichi Accident. IAEA, Vienna.

9. Ewing RC (2004) Environmental impact of the nuclear fuel cycle RODNEY. In: Giere R, Stille P (arg) Energy, Waste, and the Environment: a Geochemical Perspective. Geological Society of London, London 7-23.

10. Pavlotskaya FI (1973) Sostoyaniei formynakhozhdeniyaradioizotopov v global'nykhvypadeniyakh (State and species of radioisotopes in global fallout). Atomizdat, Moscow.

11. Bobovnikova TI, Makhon'ko KP, Siverina AA, Rabotnova FA, Gutareva VP, et al. (1992) Physical-chemical forms of radionuclides in atmospheric fallout, and their transformations in soil, after the accident at the Chernobyl atomic energy plant. At Energy 71: 932-936.

12. Smith JT, Beresford NA (2005) Radioactive fallout and environmental transfers. In: Chernobyl --- Catastrophe and Consequences. Springer Berlin Heidelberg, Berlin, Heidelberg 35-80.

13. Pourcelot L, Louvat D, Gauthier-Lafaye F, Stille P (2003) Formation of radioactivity enriched soils in mountain areas. J Environ Radioact 68: 215-233.

14. Le Roux G, Pourcelot L, Masson O, Duffa C, Vray F, et al. (2008) Aerosol deposition and origin in French mountains estimated with soil inventories of 210Pb and artificial radionuclides. Atmos Environ 42: 1517-1524.

15. Baghdasaryan AB, Abrahamyan SB, Aleksandryan GA (1971) Physical geography of Armenian SSR. Publishign House of AS ASSR, Yerevan.

16. Ananyan VL, Araratian LA (1990) Atmospheric precipitation, its chemical composition and radioactivity in the Armenian SSR. AS ArmSSR, Yerevan.

17. Avagyan RM, Haroutyunyan GH, Atoyan VA, Hovsepyan AV, Pyuskyulyan KI, et al. (2009) Investigation of spatial distribution of 137Cs in soil in area of location of the Armenian NPP. J Contemp Phys 44: 36-42.

18. Nalbandyan AG (2006) Investigations of radioactivity level variations in Armenia after the Chernobyl accident. In: International Conference '20 Years After Chernobyl: Strategy for Recovery and Sustainable Development of the Affected Regions' in Minsk, Republic of Belarus 19-21 April 2006.

19. Pyuskyulyan K, Atoyan V, Arakelyan V, Saghatelyan A (2008) The Net Effect of the Armenian Nuclear Power Plant on the Environment and Population Compared to the Background from Global Radioactive Fallout. In: Salbu B, Skipperud L (arg) Nuclear Risks in Central Asia, NATO Scien. Springer, Almaty, Kazakhstan, 125-131.

20. (2012) Convention on Nuclear Safety. National Report of Republic of Armenia. Yerevan.

21. Vardanyan M (2006) National Atlas of Armenia, Volume 1. Tigran Mets, Yerevan.

22. Shankar S, Shikha (2017) Management and Remediation of Problem Soils, Solid Waste and Soil Pollution. In: Singh RL (arg) Principles and Applications of Environmental Biotechnology for a Sustainable Future. Springer Singapore, Singapore 143-171.

23. (2004) Soil sampling for environmental contaminants. IAEA-TECDOC-1415. International Atomic Energy Agency, Vienna.

24. (2012) Sample Collection Procedures for Radiochemical Analytes in Environmental Matrices. EPA/600/R-12/566. US EPA: Office of Research and Development: National Homeland Security Research Center, Cincinnaty, Ohio.

25. Hirose K (2000) Dry and Wet Deposition Behaviors of Thorium Isotopes. J Aerosol Res 15: 256-263.

26. Krmar M, Wattanavatee K, Radnović D, Slivka J, Bhongsuwan T, et al. (2013) Airborne radionuclides in mosses collected at different latitudes. J Environ Radioact 117: 45-48.

27. Valmari T, Tarvainen M, Lehtinen J, Rosenberg R, Honkamaa T, et al. (2002) Analytical Methods for Wide Area Environmental Sampling (WAES) for Air Filters. Finnish support to IAEA. TummavuorenKirjapaino Oy, Vantaa.

28. (2000) Generic procedures for assessment and response during a radiological emergency. IAEA-TECDOC-1162. IAEA, Vienna.

29. UNSCEAR (2000) Sources and effects of ionizing radiation. United Nations, New York

30. Nalbandyan AG, Kyureghyan AA, Ananyan VL (2007) Hrazdan region's soil radioactivity monitoring (Armenia). In: Saghatelyan AK (arg) Mountian Areas: Ecological Problems of Cities. CENS NAS RA, Yerevan 54-56.

31. (2007) RA Govermental Regulation N 1489. On Approval of Radiation Safety Rules. Republic of Armenia.