Distribution of Radioactive Materials in the Absheron Peninsula, Azerbaijan – 13567

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ABSTRACT

The Absheron Peninsula forms the extreme Eastern part of Azerbaijan and juts into the Caspian Sea. The region has a long history of oil and gas exploration, transport, and processing and includes a number of abandoned chemical plants that were used in the separation of iodine from formation waters. As a result of lax environmental standards during the Soviet era, the industrial activity has led to serious contamination from oils residues, heavy metals and naturally occurring radioactive materials (NORM). Radiometric surveys performed over a wide range of the Absheron Peninsula showed generally low NORM concentrations. However, radiation levels two to three orders of magnitude above background levels were detected at two abandoned iodine separation plants near the capital city, Baku. These elevated radiation levels are mainly due to Ra-226 and U-238 with lower contributions from Ra-228 and U-235.

INTRODUCTION

The Absheron Peninsula in Azerbaijan juts approximately 60 km into the Caspian Sea and has a maximum width of approximately 30 km, giving it an area of approximately 2100 km (Fig. 1). The peninsula has played a critical role in past conflicts, in particular in the two World Wars and continues to play an extremely important role in providing fossil fuels to Europe. Currently, 35 leading oil companies, representing 15 nationalities, are involved in exploration in 22 areas in this country. Although the history of oil and gas in this region can be traced back to the third and fourth century [1], the intensive oil extraction activities started in the late 1880s in response to the demands of the industrial revolution. Refineries and various chemical plants, including iodine isolation and purification plants, were established in the region. The intense industrial activities, the urgency to extract oil to meet the demand of the war effort, and less stringent environmental standards have left a legacy of contamination in the region. The invasion of the Soviet Union in 1990 followed by its dissolution in 1991 and the conflict with Armenia prevented earlier attempts at an environmental assessment and remediation of the contaminated regions.

Because of increased environmental awareness, the current Azeri government has initiated a number of projects to identify contaminated regions, to quantify the extent of contamination, and to develop and implement remedial action programs. Of particular importance to these initiatives is the presence of naturally occurring radioactive material (NORM), which are contaminants produced during oil extraction and refining processes. Preliminary investigations had shown U-235, U-238, Th-232, and K-40 levels that present unacceptable hazards to both the environment and the general public [2-5]. These projects are carried out with scientific and financial cooperation and support from a number of international organizations and funds [2, 6-8]. Within these programs, *Project Radio ecological survey of the soil of the territory of Baku City of the Absheron Peninsula* was coordinated by Baku State University. The main purpose of this project was to perform radiometric surveys of soil, surface water, and marshy areas in the vicinity of Baku to: (1) identify sources of harmful radiation; (2) determine radionuclide composition and radioecological parameters, including activity, energy of radiation of these sources; and (3) estimate radioecological impact of the extent of the contamination.

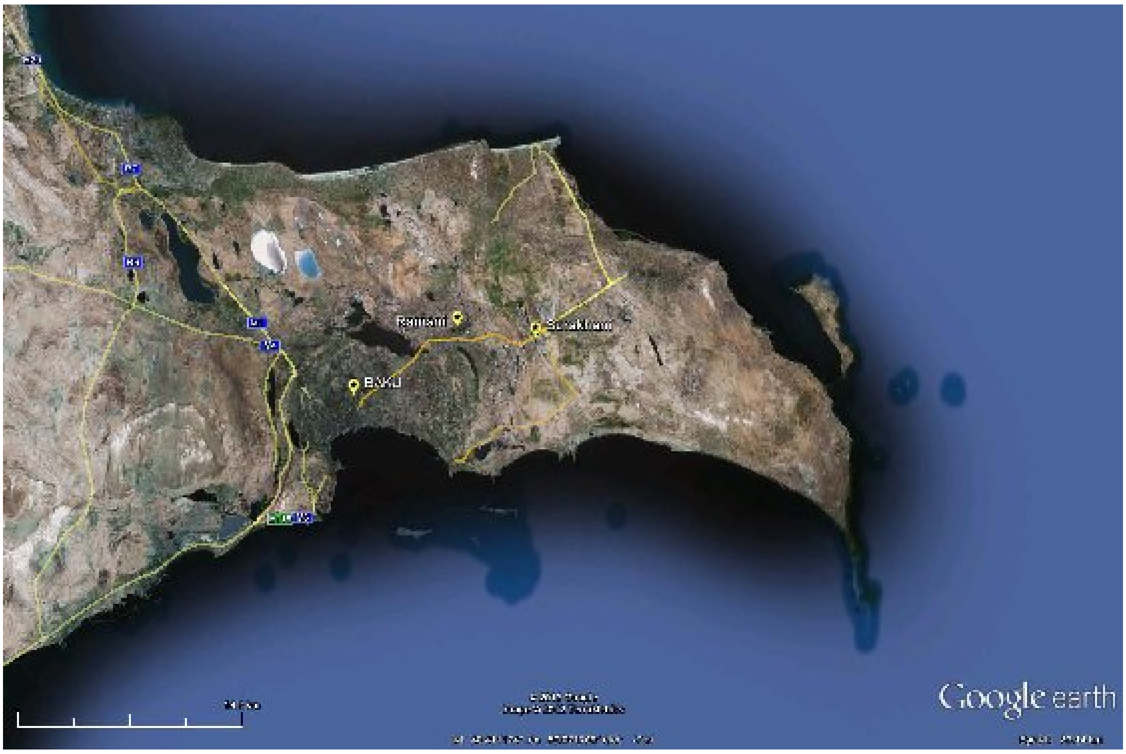

Fig. 1: Absheron Peninsula, showing the locations of the two main contaminated sites, Ramani and Surakhani relative to the capital of Azerbaijan, Baku

Tighter environmental controls have reduced the environmental impact of the oil industry but a legacy of less stringent environmental controls in the past remains in the form of considerable contamination of the soil and water in the region with naturally occurring radioactive materials (NORM) as well as with heavy metals and organic materials. The extracted oil is contaminated with saline groundwater and has to be separated from the groundwater in oil extraction plants. This groundwater contains trace concentrations of dissolved solids including alkali elements (sodium and potassium), alkaline earth elements (calcium, strontium and barium), halides including iodine, and NORM. Once the oil has been separated from the subsurface water, the water is disposed of in artificial lakes. Over time, NORMs accumulate in surface waters and soil, giving rise to local radiation levels as high as 1000 μR/h. The decay of uranium and thorium into radium and radon isotopes also presents a hazard to personnel who work on the oil extraction platforms. Preliminary investigations had earlier identified K-40, Ra-226, Ra-228, Th-232 and U-238 at elevated concentrations. Higher than normal K-40 concentrations are undoubtedly associated with halites in the groundwater. Elevated concentrations of heavy metals, including lead, have also been observed. The recovery of iodine for commercial purposes has exacerbated the environmental problem. The process to isolate iodine involves activated charcoal that was disposed of on the surface area around the iodine separation facilities. The sites are still contaminated and pose a health risk for those who live nearby. For example, although the sites are surrounded by security fences, local residents can be exposed to contaminants when they use materials from the sites for cooking or heating fuel in their homes.

TOPOGRAPHY

The topography of the Absheron Peninsula is generally flat with little topographic relief. As a result, there is very little runoff with no discernible rivers and any precipitation forms temporary water flows that drain into low-lying areas and either evaporates or migrates towards the Caspian Sea.

CLIMATE

The Absheron Peninsula is characterized by hot and dry summers and mild winters. Average January temperatures range between -1° C and 5° C and between 21° C and 27° C in July. Annual precipitation ranges from 150 to 220 mm, with most of the precipitation falling in the winter. The average humidity is affected by the Caspian Sea and ranges from 70 to 80%. Most of the precipitation occurs in the winter. Prevailing winds are from the NNW with average velocities of 5 to 6 m/s. Wind speed exceeds 15 m/s between 50 and 100 days per year [9]

EXPERIMENTAL

Procedure

Ten routes including two sites on the Absheron Peninsula were selected for dosimetric measurements (Fig. 1). The routes are mainly along established roads and the two sites are locations of past or current industrial activity and were selected on the basis of their economic and commercial importance to Azerbaijan but also because they provided relatively easy access to a wide area. The routes and sites are shown in Figure 1 and covered a total of 542 km. In addition, measurements were taken at three industrial sites, at two abandoned iodine separation plants at Ramani and Surakhani, approximately 15 km E of the centre of Baku and separated from each other by approximately 7 km, and at an oil field at Lokbatan, approximately 10 km SW of the centre of Baku. Dosimetric measurements were made using a scintillation gamma dosimeter (MKC-AT1125) equipped with a NaI(Tl) crystal (ATOMTEX, Minsk, Belarus). Readings were taken in triplicate at a distance of 50 cm from the surface and averaged. Radiation readings were also taken at a distance of 10 m from the perimeter of the sites. The coordinates of the locations were determined with an eTREX Legend CX GPS positioning device (Garmin, USA) with an accuracy of 0.1" or 5 m. This accuracy can be obtained using "differential GPS" that uses a second, stationary GPS receiver, the location of which is accurately known, as a reference [10]. All data were entered into an Excel spreadsheet. At some locations, radon was measured using a RRA-01M-01 radon radiometer with a detection limit of 20 Bq/m^3 (SPC "Doza" Ltd, Moscow, Russia)
Soil and sediment samples were taken from each corner and from the centre of selected 100 cm x 100 cm rectangular quadrats. The samples were thoroughly mixed, then dried for 5 hours at a temperature of 105°C. The dried samples were stored in hermetically sealed Marinelli beakers for one month to allow to allow Pb-214 and Ac-228, daughters of Ra-226 and Ra-228, respectively, to grow in and reach secular equilibrium. The samples were subsequently counted by gamma spectrometry using an ORTEC spectrometer with an HPGe detector.

Water samples were taken from individual operation oil wells. The water samples were evaporated and the resulting residues sealed in Marinelli beakers for 14 days to allow the daughters of Ra-226 and Ra-228 to grow in and reach close to 90% of secular equilibrium and then counted by gamma spectrometry.

RESULTS AND DISCUSSION

Radiometric Surveys

A summary of the results of the radiation dose measurements along the ten routes is shown in Table 1. The location of the routes are shown in Figure 1 and a bubble plot of all results are shown in Fig. 2. With the exception of the routes Qobustan - Lokbatan, Baku - Shemakha, Baku - Binagadi, and in the Azizbayov and Sarakhan regions, all readings were <10 μR/hr.

TABLE I. Summary of Dosimetric Measurements along Ten selected Routes

Route	Number on Map (Fig. 2)	Length (km)	Number of readings	Dose Rate (μR/h)			
				min	max	μ	σ
Qobustan - Lokbatan	1	101.0	694	1.7	187	5.7	2.5
Gurd Gapisi Region	2	24.6	136	2.2	7.8	3.8	1.3
Baku - Shemakha	3	36.9	247	2.5	14.5	5.1	1.3
Baku - Guba	4	79.2	366	2.7	5.8	4.2	0.6
Baku - Binagadi	5	35.3	308	2.5	15	3.7	1.1
Balakhani Region	6	41.5	430	2.5	8.8	3.8	0.7
Mashtaga Region	7	78.9	711	2.9	8.5	4.4	0.9
Azizbayov Region	8	75.0	574	2.4	37.5	7.5	4.9
Surakhani Region	9	70.0	570	31.0	825	74.8	85.5
Pirallaghi Island	10	23.4	110	2.0	4.7	3.1	0.6

The 101-km Qobustan - Lokbatan route is the longest route surveyed. A total of 671 dosimetric measurements were taken along its length for an average frequency of ~6.6 readings/km or ~150 m between adjacent measurements. This route, Highway M3, is located to the SW of Baku and follows the coast of the Caspian Sea from Baku towards Astara. The region contains drained marshes and areas polluted by domestic waste. Abandoned pipelines that previously were used for oil extraction, and waste building materials are discarded along this route. Since ancient times, this region has also been the location of many oil wells, some of which are still in operation.

Dosimetric measurements were taken along the highway as far as 2.5 km north of Qobustan. An additional 23 measurements were taken on oil refinery near Lokbatan, ~5 km SW of Baku. The mean and standard deviation of the measurements along the highway were 4.9 and 2.5 μR/h, indicating no appreciable contamination. Readings above background, defined for this study as 5.4 μR/h (see below under the discussion for the route Baku-Guba) were obtained for 182 locations, or 27% of the number of measurements, The highest measurement obtained was 20 μR/h. However, of the 23 readings taken at the industrial site near Lokbatan, 16, or 70% exceeded 5.4 μR/h with the highest measurements of 140 and 187 μR/h. High dose rates were generally associated with surface channels containing formation water from the oil deposits, with abandoned equipment and especially with the inside of discarded pipelines.

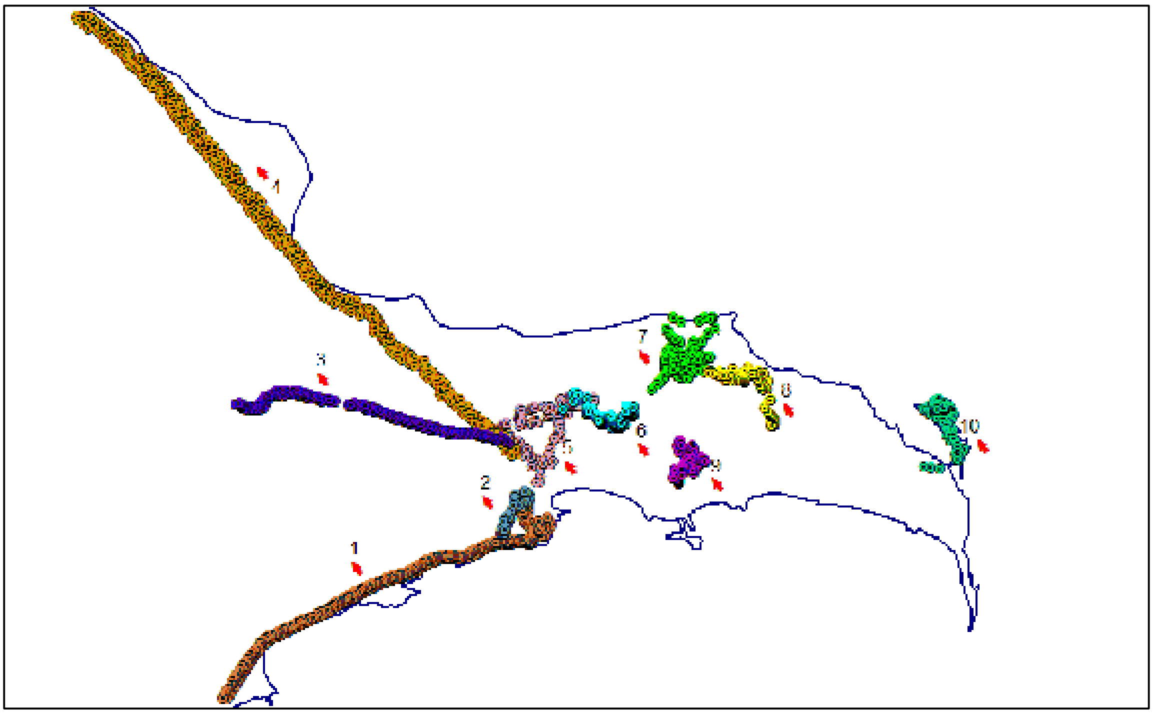

Fig. 2: Location of all 4146 Dose Measurements along the Ten Routes (see Table I for names of Route)

The route in the Gurd Gapisi region is also located SW of Baku but is slightly more inland and near the Sederek Trading Centre. A total of 136 measurements were taken along the 24.6 km route for an average frequency of 5.6 measurements.km or 180 m between adjacent measurements. Only 10% of the measurements were above background (5.4 µR/h) with the highest measurement of 7.8 µR/h.

The Baku-Shemakha route extends from the NW outskirts of Baku and follows the Shemakha highway for 36.9 km into an arid and sparsely populated territory. This is a major highway for international traffic. There are no oil wells in this region but there are swampy areas of volcanic origin. Of the 247 measurements taken, 81 exceeded 5.4 µR/h. This corresponds to 31% of the number of measurements. Four measurements fell between 10 and 15 µR/h.

The road along which the dosimetric measurements for the Baku-Guba route were taken, Highway M2, runs from Baku towards the NW and follows the Caspian Sea coast. The length of this route was 79.2 km and 366 measurements were taken, for a frequency of ~5/km or a an average distance of 210 m between points. This route showed the lowest radiation levels, with a mean of 4.2 µR/h, a standard deviation of 0.6 µR/h and a maximum reading of 5.8 µR/h. Only 10 out of the 366 measurements (3%) exceeded two standard deviations from the mean. The measurements obtained along this route were considered to reflect the natural background radiation for this study.

The region of the Absheron Peninsula surrounding the Baku-Binagadi route is characterized by a somewhat greater topographic relief than the other routes. This region also contains an active mud volcano, the closest of a number of these geological entities to Baku. In addition, there are several natural water reservoirs that are hydrologically isolated from the Caspian Sea. The level of some of these water reservoirs fluctuates considerably during the year with some of them drying up completely during the summer season. This region is densely populated and also contains a number of industrial sites. There is little vegetation. A total of 308 dosimetric measurements were taken along the 35.3-km route for a frequency of ~9/km and an average distance of 115 m between adjacent points. Only nine readings exceeded the background level of 5.4 μR/h. The highest reading of 15 μR/h was obtained ~1 km NE of Boyukshor Lake. In addition to the 308 dosimetric readings, three radon measurements. All readings were <20 Bq/m^3.

The oldest oil wells in the Absheron Peninsula are located along the 41.5-km long route in the Balakhani region. This region had also the highest density of oil extraction activity. Historic records indicate that oil seeped to the surface under natural conditions. In extraction of the oil in this region is accompanied by natural gas. Water reservoirs in this region are highly contaminated with oil and oil products: water surfaces are often covered by thick layers of oil. Water from these reservoirs tends to flow toward Boyukshor Lake but are prevented from entering the lake by artificial earthen barriers. In spite of this heavily contaminated region, results showed that only 10 out of 430 measurements (3%) exceeded background levels, with a highest reading of 8.8 μR/h. Readings were taken, on average, 97 m apart.

The 78.9-km long route in the Mashtaga region compasses the northern area of the Absheron Peninsula. This region is also a heavily populated district with suitable agricultural lands. There is little topographic relief and surface waters are limited to small ponds that are surrounded by marshy areas and beds of reeds. The surface waters have low total dissolved solids concentrations. Yet, the region is polluted by abandoned oil wells and refineries that have been replaced by other industrial and agricultural activity. Remedial activity is being undertaken to restore these lands for residential and agricultural use. A total of 711 measurements were taken along this route, both during the rainy and dry seasons. Again, as was the case for the route in the Balakhani region, surprisingly little excess radiation was observed, in spite of the industrial activity: only 73 readings (10%) were above background. The maximum measured dose rate was 8.5 μR/h.

A total of 574 dosimetric measurements were taken along the 75-km long route in the Azizbayov region, between a, for a frequency of ~8/km and 131 m between adjacent measurements. project. Approximately 30 readings, or 5%, exceeded 10 μR/h with the highest reading 37.5 μR/h.

The Pirallaghi Island route is located mainly on the island of that name, a low-lying ~8 km x ~2 km island connected to the Absheron Peninsula by a causeway. A large area of this island is devoted to oil extraction. Somewhat unexpectedly, the 110 dosimetric measurements along the 23.4-km route were very low, with a maximum readings of 4.7 μR/h.

Of all the regions in the Absheron Peninsula, the region bounded by the Surakhani - Shuvelyan route is considered to be the most highly polluted. Some of this pollution is due to the numerous oil wells and refineries but also to two iodine extraction facilities in Ramani and Surakhani. These facilities, now abandoned (Fig. 3), were used to extract iodine from formation water that was extracted with the oil from the subsurface. The recovery of iodine for commercial purposes has exacerbated the environmental problem. When iodine was isolated, it was absorbed on activated charcoal in the presence of an acidic solution, then oxidized with $KMnO_4$, Cl_2, NaClO, $NaClO_3$, $KClO_3$, H_2O_2 or $NaNO_2$ [5]. The activated charcoal, estimated to be close to 20,000 metric tons and contaminated with NORM, was disposed of on the surface area around the iodine separation facilities. The sites are still contaminated and pose a health risk for those who live nearby. For example, although the sites are surrounded by security fences, local

residents can be exposed to contaminants when they use materials from the sites for cooking or heating fuel.
The 70-km-long route in the Surakhani region included both the Ramani and Surakhani sites. In total, 570 dosimetric measurements were taken. All readings were well above background, with a mean and standard deviation of 74.8 μR/h and 85.5 μR/h, respectively and covering a range of 31 - 825 μR/h.

Fig. 3: Abandoned Iodine Separation Facility at Ramani
showing the Activated Charcoal in Front of the Building.

Gamma Spectrometric Results

The radionuclide concentrations of the activated coal samples from the Ramani and Surakhani sites were determined by gamma spectrometry and are shown in Table II.

The dose rate near the wastes was in the range of 38-163 μR/h, and 102-240 μR/h near the centre. At a distance of 10 m from the perimeter, the dose rate remained relatively high, i.e., 12-25 μR/h, compared to background readings of 5-8 μR/h. During these dose rate measurements, the activity of radon isotopes was below the limit of detection of the instrument (<20 Bq/m^3), presumably because of dilution in the atmosphere or dispersion by the wind. However, under confined conditions, radon emanation would be expected to lead to unacceptably high values; and thus unsafe working conditions. This point should be considered in plans for eventual disposal and handling of the activated charcoal, and also with respect to any unauthorized use of this material as fuel for heating or cooking.

Results obtained for water samples showed the presence of U-235, U-238, Ra-226, and Ra-228, including decay products. Ra-226 and Ra-228 concentrations in the groundwater associated with oil were less than

10 Bq/L, and that of K-40 was less than 30 Bq/L. The high radionuclide concentrations in the activated charcoal are attributed to the high sorptive capacity of this material. It should be noted that, with the exception of K-40, the concentration of NORM in unpolluted soils, taken near Baku State University and near the Heydar Aliyev International airport, are lower than 100 Bq/kg.

TABLE II. Radionuclide concentrations in activated charcoal samples from the Ramani and Surakhani sites

Sample Location (waste)	**Depth** (m)	**U-235** (Bqkg)	**U-238** (Bq/kg)	**Ra-226** (Bqkg)	**Ra-228** (Bqkg)	$\mathbf{A}_{eff}$ (Bqkg)
Ramani						
M7 (A)	0.0	167±5	3480±15	5019±19	811±11	6081±24
M12 (B)	0.0	84±2	1743±12	4111±19	680±11	5002±24
M25 (C)	0.0	284±6	5928±27	9452±30	576±11	10207±33
M25 (C)	0.6	174±5	3623±16	7120±25	445±16	7703±33
M41	0.0	3371±443	70360±9260	138250±3350	9573±125	150790±3353
Surakhani						
N12 (I)	0.0	82±2	1709±15	8003±41	2974±32	11899±59
N17 (II)	0.0	150±5	3129±19	8510±31	1252±18	10150±39
N23 (III)	0.0	170±6	3553±21	8984±30	963±19	10246±39
N23 (III)	0.3	179±6	3744±23	11876±46	979±31	13158±61
N23 (III)	0.6	164±5	3421±19	10176±47	718±32	11117±63
N24 (IV)	0.0	182±7	3797±22	10523±49	951±33	11769±65

Although the measured uranium concentration in the groundwater was also very low, uranium is expected to have been sorbed on the activated charcoal over the years, resulting in relatively high U-235 and U-238 concentrations. The absence of K-40 in the activated charcoal can be explained by the high solubility of the salts that it forms. Any sorbed potassium would have been leached from the charcoal by rainwater over the years.

To estimate the radiological health hazard of the activated charcoal, its activity was evaluated on the basis of Russian standards, which are applied to construction materials containing NORMs. This standard is based on the calculation of the effective activity, $A_{eff.}$ [11]. The values for A_{eff} and its standard deviation were calculated using the following equations:

$$A_{eff} = A_{Ra226} + 1.31 A_{Th232} + 0.085 A_{K40} \quad \text{(Eq. 1)}$$

$$\sigma_{A_{eff}} = \sqrt{\sigma^2_{A_{Ra226}} + 1.7\sigma^2_{A_{Th232}} + 0.007\sigma^2_{A_{K40}}} \quad \text{(Eq. 2)}$$

The classification of these waste categories are shown in Table III

TABLE III. Categories of industrial waste at the Ramani and Surakhani Sites

Waste Category	**Effective Activity (A_{eff})** Bq/kg	**Gamma Radiation Dose Rate** μR/h
I	A_{eff}≤1 500	≤70
II	1 500<A_{eff}≤10 000	70-440
III	A_{eff}>10 000	>440

Note: Gamma radiation dose rate was measured at a distance of 0.1 m from the surface of the waste

On the basis of these calculations, the activated charcoal at the Ramani site in general falls into Category II, with the exception of one highly contaminated sample that appears to be contaminated with some geological material. Most of the activated charcoal at the Surakhani site falls into Category II.
Results from the radiometric analysis of samples of soil, sediments (including a salt sample form the bottom of a dry lake), and unidentified deposits in discarded pipes at the Surakhani site are shown in Table IV. These results show that some of the discarded industrial material fits into Category II and that remediation is necessary.

TABLE IV: Gamma Spectrometric Analysis Results for Samples from the Surakhani Site

Sample	Dose Rate (μR/h)	Bq/kg			
		K-40	Ra-226	Ra-228	A_{eff}
Sediment in pipe	115	1000	3700	1900	6200
Sediment in pipe	210	1400	6500	1000	8000
Salt from dry lake	50	<100	60	20	100
Sediment from holding pond	10	100	30	10	50

Of the 12 locations selected, four exceeded a dose rate of 100 μR/h. Excellent correlation (R2 = 0.9988) was found between dose rate and [Ra-226]. Calculated A_{eff} values showed that, of the 12 samples, one exceeded a value of 10,000 Bq/kg, placing it in Category III and two samples fell into Category II.

A summary of the dose rate and results from the gamma spectrometric analysis of 25 surface soil samples taken along the Qobustan - Lokbatan route are shown in Table V. Concentrations of Cs-137 are negligible and indicate minimum environmental impact from anthropogenic contamination, either from Chronobyl or from nuclear power plants in Armenia.

Groundwater samples taken from 20 wells that access a single formation at a depth of approxinately 1200 m at the Surakhani site showed very low concentrations of K-40 (3.9 ± 5.8 Bq/l), Ra-226 (3.7 ± 2.3 Bq/l),and Ra-228 (2.7 ± 1.8 Bq/l).

TABLE V: Summary of Dose Rate and Soil Samples Data from the Qobustan - Lokbatan Route

Dose Rate	units	min	max	μ ± σ
	μR/h	2.5	187	30.6 ± 45.3
Cs-137	Bq/kg	2.2	7.3	5.3 ± 1.6
U-235	Bq/kg	1.2	210	29.1 ± 56.7
U-238	Bq/kg	26.0	4470	630 ± 1230
Ra-226	Bq/kg	12.7	7310	761 ± 1905
Ra-228	Bq/kg	18.5	1640	177 ± 377
K-40	Bq/kg	357	796	541 ± 118

Groundwater samples taken from 20 wells that access a single formation at a depth of approxinately 1200 m at the Surakhani site showed very low concentrations of K-40 (3.9 ± 5.8 Bq/l), Ra-226 (3.7 ± 2.3 Bq/l),and Ra-228 (2.7 ± 1.8 Bq/l).

Samples of groundwater taken from depths ranging between 900 and 3200 m showed no clear pttern in the relationship between depth and Ra-226 and Ra-228 concentration (Fig. 4). This is not surprising since these two isotopes have different precursors that are likely present in different concentrations. The lowest values were obtained from the Gimaki formation that is located at a depth beween 1420 and 2500 m.

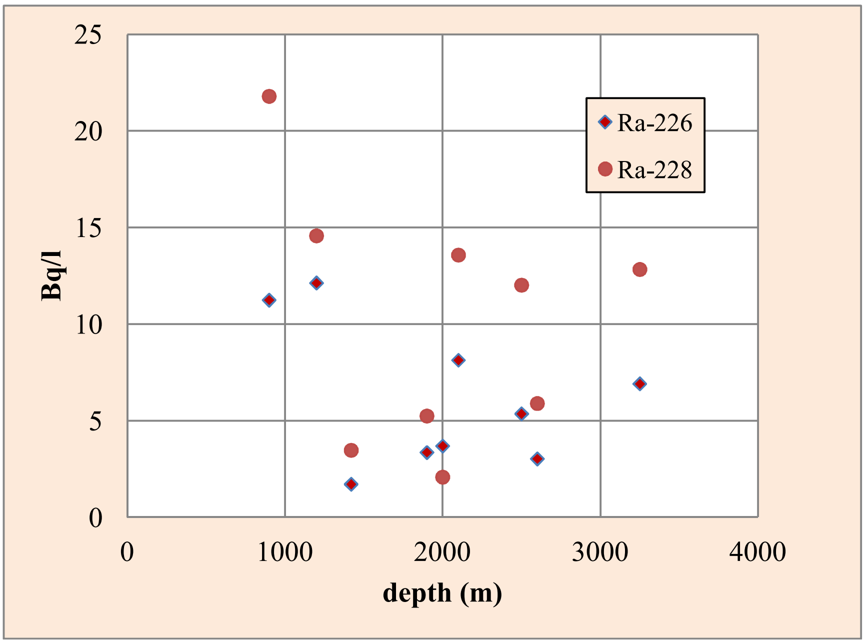

Fig 4: Ra-226 and Ra-228 concentrations as a function of depth

DATABASE DEVELOPMENT

During the course of this project, it became apparent that it would be advantageous to combine the considerable quantity of paper documents, in the form of geological and administrative information such as roads and structures, topographic data, and the electronically generated survey and radiochemical information generated in this study into an electronic database that is consistent with the UTM [Universal Transverse Mercator] International Coordinate System. This coordinate system divides the surface of the Earth into 60 vertical zones, each with a width of 6° and a maximum width of 800 km. The Absheron Peninsula is covered by Zone 39N with a central meridian at 51°E. ERDAS Imagine (Leica GeoSystems and Mapping, USA), a remote sensing application with raster graphic editor was used to generate digitized images and maps. The GIS software program ArcView (Esri USA) was selected for this project. All GPS information that had been generated in the form xx° yy' zz" was converted into decimal data. Radiation survey measurements were entered into the database with their coordinate values. Fig. 5 is an ArcView "screenshot" showing the Ramani site obtained from Google Earth with the radiation levels (in μR/h) superimposed at the measurement locations. Similar composite figures have been generated combining radiometric data and topographic information and radiometric data and road maps.

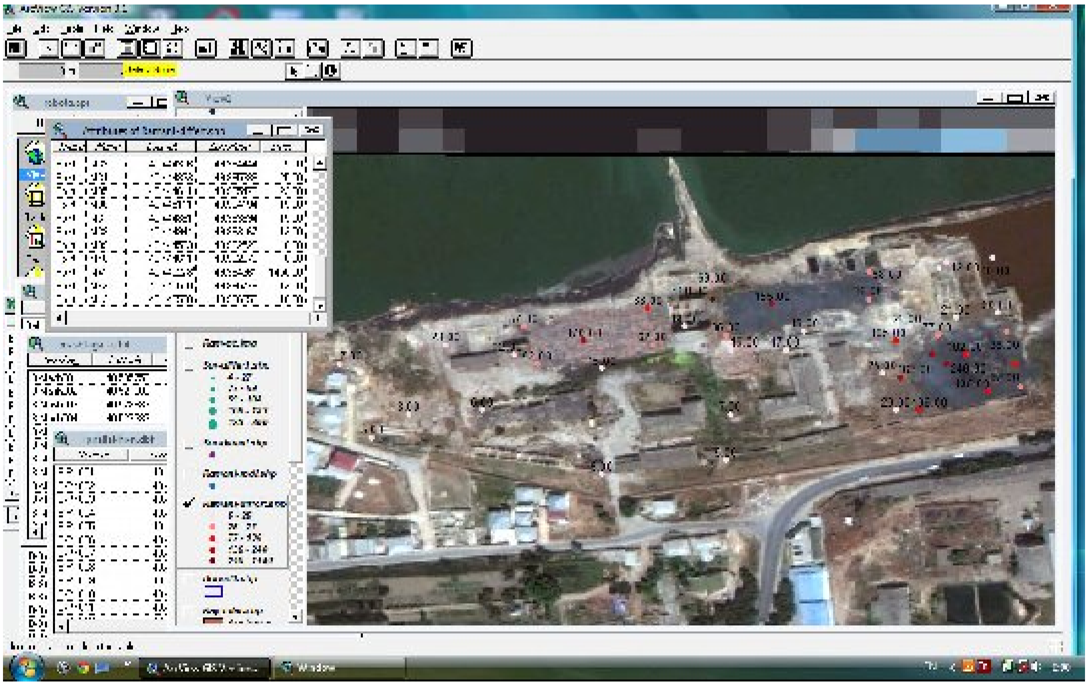

Fig. 5: Computer screenshot of ArcView showing a composite of Google Earth and dosimetric readings of the Ramani Site and the data files used to generate the image

ASSESSMENT AND RECOMMENDATIONS

The results from the dosimetric measurements and the gamma spectrometry of the activated charcoal, soil, sediments, and water samples suggest that, in general, the contamination by NORM is limited to the industrial sites at Lokbatan, Ramani, and Surakhani. Very little evidence of the contamination from anthropogenic radionuclides such as Cs-137 was found. This is encouraging as remediation is only required to be performed in relatively small areas. Remediation is facilitated by the climatic and topographic conditions on the Absheron Peninsula: the combination of an arid climate and little topographic relief suggests that contaminant transport by flowing groundwater is expected to be limited. With the exception of the contaminated activated charcoal at the Ramani and Surakhani sites, radiation levels to the general public can be reduce considerably by applying a layer of soil to the surface of the sites and planting vegetation to prevent wind erosion. In addition, the layer of soil will act as a barrier to the movement of radon gas. The radon isotope of interest, Rn-222, has a half life of 3.8 d and is likely to decay before it diffuses through the layer of soil to the surface. Some consideration should be given to a continued monitoring of the vegetation to determine if it plays a role in phytoremediation. The presence of NORM in the vegetation would be an indicator that some members of the uranium and thorium decay chain are remobilized in the subsurface and can be taken up by the root system of the planted vegetation. Any appreciable radionuclide concentrations in the plants could provide a process to remove the radionuclides from the environment by harvesting the vegetation and incinerating the plants under controlled conditions and incorporating the radionuclides into a leach-resistant waste form for eventual long-term geological storage or disposal.

The activated charcoal is more problematic and should be transported to a central site and disposed of in a engineered facility, possibly similar to that proposed for similar material in neighbouring Turkmenistan [12]. Another option would be to oxidize the activated charcoal under controlled conditions and capture the NORM in the form of fly ash that could then be immobilized in concrete for subsequent disposal. This would reduce the volume of waste considerably and reduce transportation costs but would also generate large amounts of greenhouse gases.

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ACKNOWLEDGMENTS

This three-year project was initiated on 2009 February 01 and was funded by the Government of Canada as part of the G8 Global Partnership Program through the Department of Foreign Affairs and International Trade (DFAIT), Ottawa and was administered by the Science and Technology Center in Ukraine (STCU), Kyiv.

The authors express their sincere gratitude to the Canadian Government for support of this project under the auspices of the Global Partnership Program and to the Rector of Baku State University, Academician A. Magerramov. Assistance from Adalat Hasanov (STCU) and from Dr Naida Chamilova (DFAIT) is gratefully acknowledged. Dr Margaret McKenna, currently at the University of Ottawa, is acknowledged for her initiative in bringing the Azeri and Canadian researchers together and for her support throughout this project.