Features of the Formation of Strontium Pollution of Drinking Groundwater and Associated Health Risks in the North-West of Russia

Alexander I. Malov

Supplementary Materials

S1. Statistical distribution of strontium concentration values in drinking groundwater in the North-West of Russia

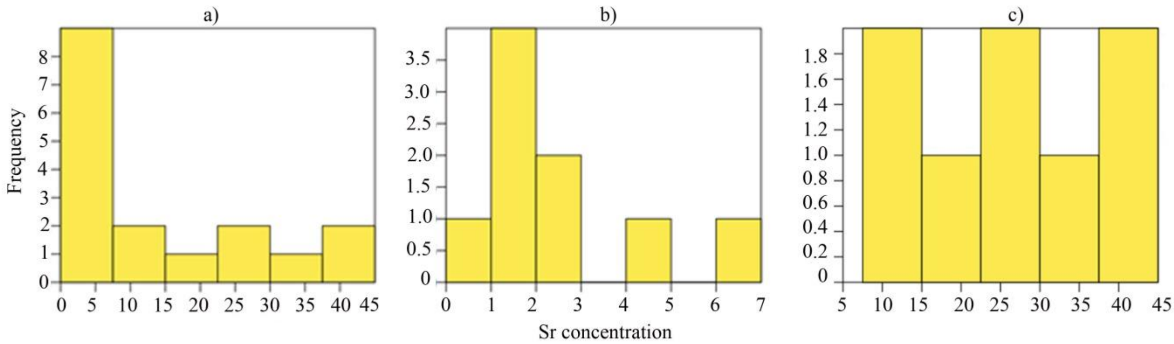

Figure S1. Histograms a) all 17 samples, b) 9 samples with strontium contents less than 7 mg/l, c) 8 samples with strontium contents more than 7 mg/l.

Table S1. Summary statistics on strontium concentration values.

Parameter	Number of samples	Average	Std. Dev.	Min	Max	Median
Sr	17	13.19	14.1	0.76	40.0	6.6
	9	2.55	1.90	0.76	6.60	
	8	25.15	11.89	8.20	40.0	

Table S2. Test of Normality Shapiro-Wilk

Parameter	Number of samples	Statistics	Significance value
Sr	17	0.81	0
	9	0.84	0.06
	8	0.94	0.59

S2. Summary statistics on compositions of drinking groundwater in the North-West of Russia

Parameter	Number of samples	Average	Std. Dev.	Min	Max
Sr>7mg/L	8	25.15	11.89	8.20	40.0
Na^+		60.42	50.70	18.90	170.00
Ca^{2+}		63.85	14.29	48.30	85.40
Mg^{2+}		26.21	6.82	16.80	37.20
K^+		5.11	2.59	3.61	11.10
Cl^-		51.86	46.00	17.70	158.00
SO_4^{2-}		61.54	42.81	8.30	123.00
HCO_3^-		382.00	78.40	265.00	489.00
TDS		676.25	202.60	410.00	979.00
pH		7.67	0.34	7.06	8.03
Eh		-11.13	112.00	-121.00	155.00
O_2		3.41	2.69	0	8.00
Altitude		11.25	4.68	6.00	22.00
$SI_{calcite}$		0.22	0.24	-0.24	0.44
$SI_{dolomite}$		0.54	0.54	-0.59	0.98
$SI_{strontionite}$		1.83	0.26	1.32	2.14
SI_{gipsum}		-2.09	0.41	-2.78	-1.61
$SI_{celestite}$		-1.94	0.47	-2.76	-1.35
^{14}C		47.48	9.22	29.53	59.23
$\delta^{13}C$		-10.42	1.57	-13.30	-8.60
Age		2151.38	1372.07	73.00	4662.00
U		0.08	0.07	0.01	0.23
$^{234}U/^{238}U$		1.96	0.97	1.12	3.94

Parameter	Number of samples	Average	Std. Dev.	Min	Max
Sr<7mg/L	9	2.55	1.90	0.76	6.60
Na^+		46.37	17.66	19.80	72.40
Ca^{2+}		88.07	20.39	61.30	111.00
Mg^{2+}		17.83	7.38	7.90	29.80
K^+		3.97	0.37	3.49	4.62
Cl^-		20.26	10.26	10.60	37.20
SO_4^{2-}		21.67	18.99	4.40	56.50
HCO_3^-		434.78	65.15	330.00	512.00
TDS		636.56	112.42	469.00	780.00
pH		7.72	0.16	7.45	7.90
Eh		-7.78	68.59	-103.00	73.00
O_2		2.84	1.33	0.60	5.60
Altitude		15.67	5,45	11.00	28.00
$SI_{calcite}$		0.49	0.11	0.27	0.64
$SI_{dolomite}$		0.76	0.40	-0.03	1.33
$SI_{strontionite}$		0.93	0.40	0.30	1.52
SI_{gipsum}		-2.42	0.45	-2.88	-1.75
$SI_{celestite}$		-3.44	0.38	-3.92	-2.88
^{14}C		62.17	7.75	50.15	74.47
$\delta^{13}C$		-13.60	2.12	-15.80	-9.10
Age		1991.6	1523.8	73.00	4540.0
U		0.69	0.68	0.03	1.89
$^{234}U/^{238}U$		2.13	0.86	1.23	3.48

S3. Correlation matrices on compositions of drinking groundwater in the North-West of Russia

	Sr	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	HCO_3^-	TDS	pH	Eh	O_2	Altitude	$SI_{calcite}$	$SI_{dolomite}$	$SI_{strontionite}$	SI_{gipsum}	$SI_{celestite}$	^{14}C	$\delta^{13}C$	Age	U	$^{234}U/^{238}U$
Sr>7 mg/L	1	0.68 0.06	0.40 0.32	0.84[a] 0.01	0.55 0.16	0.62 0.10	0.71[b] 0.05	0.83 0.01	0.90 0	-0.67 0.07	-0.58 0.13	-0.32 0.43	-0.33 0.43	-0.59 0.12	-0.43 0.29	0.26 0.54	0.70 0.06	0.8 0.01	-0.27 0.52	0.19 0.66	0.14 0.73	-0.21 0.61	0.80 0.03
Na^+		1	0.03 0.94	0.62 0.11	0.96 0	0.92 0	0.82 0.01	0.36 0.38	0.85 0.01	-0.38 0.36	-0.35 0.39	-0.40 0.32	-0.08 0.86	-0.39 0.34	-0.24 0.57	0.27 0.52	0.60 0.12	0.71 0.05	-0.60 0.12	0.23 0.59	0.64 0.09	-0.47 0.24	0.90 0.01
Ca^{2+}			1	0.28 0.50	0.09 0.84	0.17 0.69	0.27 0.52	0.70 0.05	0.48 0.23	-0.82 0.01	-0.45 0.26	-0.13 0.76	-0.04 0.92	-0.68 0.06	-0.72 0.04	-0.61 0.11	0.43 0.28	0.33 0.43	0.55 0.16	-0.36 0.38	-0.38 0.36	-0.03 0.04	0.05 0.91
Mg^{2+}				1	0.60 0.12	0.67 0.07	0.57 0.14	0.55 0.16	0.75 0.03	-0.31 0.46	-0.38 0.36	0.08 0.85	0.05 0.90	-0.16 0.71	0.02 0.97	0.52 0.19	0.49 0.22	0.64 0.09	-0.42 0.30	0.44 0.27	0.24 0.57	-0.19 0.65	0.91 0
K^+					1	0.97 0	0.76 0.03	0.21 0.62	0.77 0.02	-0.29 0.48	-0.20 0.64	-0.25 0.55	0.04 0.92	-0.27 0.52	-0.15 0.72	0.22 0.61	0.53 0.18	0.58 0.13	-0.61 0.11	0.21 0.62	0.71 0.05	0.42 0.29	0.87 0.01
Cl^-						1	0.66 0.07	0.26 0.53	0.78 0.02	-0.32 0.43	-0.25 0.55	-0.26 0.53	-0.01 0.98	-0.26 0.54	-0.14 0.75	0.25 0.56	0.44 0.28	0.52 0.18	-0.58 0.13	0.36 0.38	0.57 0.14	-0.54 0.17	0.93 0
SO_4^{2-}							1	0.57 0.14	0.88 0	-0.58 0.13	-0.38 0.35	-0.29 0.49	-0.06 0.90	-0.62 0.10	-0.49 0.21	0.02 0.95	0.92 0	0.93 0	-0.32 0.45	-0.27 0.52	0.59 0.13	0 1	0.71 0.07
HCO_3^-								1	0.78 0.02	-0.89 0	-0.77 0.03	-0.42 0.31	-0.24 0.56	-0.83 0.01	-0.74 0.04	-0.19 0.65	0.68 0.06	0.75 0.03	0.27 0.52	-0.16 0.71	-0.27 0.52	-0.13 0.76	0.39 0.38
TDS									1	-0.75 0.03	-0.61 0.11	-0.41 0.31	-0.15 0.73	-0.70 0.05	-0.56 0.15	0.04 0.92	0.80 0.02	0.89 0	-0.24 0.56	0.02 0.96	0.31 0.46	-0.31 0.44	0.81 0.03
pH										1	0.65 0.08	0.51 0.20	0.17 0.69	0.97 0	0.94 0	0.53 0.18	-0.70 0.05	-0.67 0.07	-0.35 0.40	0.39 0.34	0.18 0.67	0.17 0.69	-0.25 0.59
Eh											1	0.71 0.05	0.36 0.38	0.59 0.12	0.51 0.20	0.05 0.91	-0.29 0.48	-0.44 0.28	-0.40 0.32	-0.06 0.90	0.43 0.29	0.37 0.37	-0.32 0.48
O_2												1	0.63 0.09	0.58 0.14	0.54 0.16	0.14 0.73	-0.12 0.77	-0.27 0.52	-0.23 0.58	0.05 0.91	0.18 0.67	0.40 0.32	-0.15 0.75
Altitude													1	0.18 0.66	0.14 0.74	-0.29 0.48	0.05 0.91	-0.18 0.67	-0.11 0.80	-0.05 0.91	0.17 0.69	-0.18 0.68	-0.11 0.82
$SI_{calcite}$														1	0.98 0	0.57 0.14	-0.74 0.04	-0.70 0.06	-0.31 0.46	0.50 0.20	0.09 0.83	0.12 0.77	-0.17 0.72
$SI_{dolomite}$															1	0.72 0.04	0.64 0.09	-0.55 0.16	-0.44 0.28	0.60 0.11	0.17 0.68	0.08 0.86	0.02 0.97
$SI_{strontionite}$																1	-0.18 0.66	0.07 0.86	-0.64 0.09	0.71 0.05	0.30 0.47	-0.02 0.97	0.58 0.17
SI_{gipsum}																	1	0.94 0	-0.16 0.70	-0.46 0.25	0.44 0.28	0.16 0.71	0.52 0.23
$SI_{celestite}$																		1	-0.27 0.52	-0.22 0.59	0.41 0.32	0.06 0.90	0.70 0.08
^{14}C																			1	-0.50 0.21	-0.81 0.01	0.21 0.62	-0.66 0.11
$\delta^{13}C$																				1	-0.03 0.94	-0.61 0.11	0.51 0.24
Age																					1	0.08 84	0.53 0.22
U																						1	-0.68 0.10
$^{234}U/^{238}U$																							1

[a] - significance value $p \leq 0.01$

[b] - significance value $p \leq 0.05$

	Sr	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	HCO_3^-	TDS	pH	Eh	O_2	Altitude	$SI_{calcite}$	$SI_{dolomite}$	$SI_{strontionite}$	SI_{gipsum}	$SI_{celestite}$	^{14}C	$\delta^{13}C$	Age	U	$^{234}U/^{238}U$
Sr<7 mg/L	1	0.30 0.43	-0.16 0.68	0.57 0.11	0.08 0.83	0.30 0.43	-0.36 0.34	0.44 0.23	0.30 0.43	0.31 0.42	-0.51 0.16	0.34 0.36	0.07 0.85	0.56 0.12	0.58 0.10	0.89 0	-0.37 0.32	0.35 0.36	-0.28 0.46	-0.54 0.13	0.72 0.03	-0.29 0.45	0.80 0.01
Na^+		1	0.64 0.06	-0.20 0.61	0.64 0.07	0.67 0.05	0.30 0.44	0.86 0	0.90 0	-0.40 0.29	0.06 0.87	0.37 0.32	0.35 0.36	0.49 0.18	-0.01 0.98	0.29 0.44	0.29 0.45	0.52 0.15	0.26 0.49	-0.42 0.26	0.24 0.53	0.54 0.13	-0.27 0.49
Ca^{2+}			1	-0.54 0.13	0.76 0.02	0.56 0.12	0.71 0.03	0.71 0.03	0.84 0.01	-0.88 0	0.66 0.05	0.04 0.93	-0.27 0.48	-0.01 0.97	-0.56 0.12	-0.30 0.43	0.70 0.04	0.52 0.15	0.76 0.02	-0.32 0.40	-0.18 0.63	0.78 0.01	-0.53 0.15
Mg^{2+}				1	-0.13 0.73	0.14 0.73	-0.54 0.14	-0.08 0.83	-0.19 0.62	0.61 0.08	-0.62 0.07	-0.12 0.76	0.14 0.72	0.43 0.25	0.87 0	0.63 0.07	-0.45 0.22	0.01 0.98	-0.40 0.28	0.02 0.97	0.38 0.31	-0.73 0.03	0.72 0.03
K^+					1	0.53 0.15	0.43 0.25	0.68 0.04	0.75 0.02	-0.77 0.02	0.42 0.26	-0.30 0.44	0.09 0.82	0 0.99	-0.26 0.50	-0.13 0.74	0.40 0.29	0.34 0.37	0.74 0.02	-0.24 0.54	-0.23 0.56	0.35 0.36	-0.31 0.41
Cl^-						1	0.49 0.18	0.54 0.13	0.73 0.03	-0.38 0.31	0.32 0.41	0.34 0.37	-0.14 0.71	0.26 0.51	0.03 0.95	0.18 0.65	0.58 0.10	0.81 0.01	0.44 0.24	-0.34 0.37	0.13 0.74	0.30 0.43	-0.04 0.93
SO_4^{2-}							1	0.20 0.61	0.48 0.20	-0.82 0.01	0.68 0.04	-0.16 0.68	-0.39 0.30	-0.51 0.16	-0.77 0.02	-0.58 0.10	0.97 0	0.69 0.04	0.76 0.02	-0.24 0.54	-0.28 0.46	0.38 0.31	-0.42 0.26
HCO_3^-								1	0.94 0	-0.41 0.27	0.01 0.98	0.24 0.53	0.13 0.74	0.60 0.09	0.07 0.86	0.41 0.27	0.18 0.64	0.48 0.19	0.28 0.46	-0.56 0.12	0.38 0.32	0.51 0.16	0.06 0.88
TDS									1	-0.60 0.09	0.24 0.54	0.23 0.55	0.01 0.98	0.40 0.28	-0.13 0.74	0.21 0.59	0.48 0.20	0.67 0.05	0.49 0.18	-0.54 0.14	0.23 0.55	0.58 0.10	-0.19 0.62
pH										1	-0.80 0.01	0.26 0.49	0.30 0.44	0.45 0.22	0.80 0.01	0.58 0.10	-0.76 0.02	-0.42 0.26	-0.92 0	0.22 0.57	0.42 0.26	-0.56 0.12	0.54 0.13
Eh											1	-0.04 0.92	-0.48 0.19	-0.58 0.11	-0.80 0.01	-0.76 0.02	0.72 0.03	0.22 0.58	0.83 0.01	-0.01 0.98	-0.56 0.12	0.59 0.10	-0.62 0.07
O_2												1	-0.08 0.84	0.50 0.17	0.18 0.64	0.44 0.23	-0.10 0.81	0.22 0.57	-0.34 0.36	-0.21 0.58	0.39 0.30	0.47 0.20	0.07 0.86
Altitude													1	0.35 0.36	0.38 0.31	0.22 0.56	-0.40 0.29	-0.34 0.38	-0.25 0.52	-0.07 0.87	0.25 0.52	-0.21 0.58	-0.19 0.03
$SI_{calcite}$														1	0.76 0.02	0.81 0.01	-0.42 0.25	0.06 0.87	-0.48 0.20	-0.27 0.49	0.65 0.06	0.13 0.74	0.26 0.50
$SI_{dolomite}$															1	0.81 0.01	-0.68 0.04	-0.17 0.66	-0.67 0.05	0.02 0.97	0.53 0.14	-0.49 0.18	0.59 0.09
$SI_{strontionite}$																1	-0.57 0.11	0.15 0.69	-0.61 0.08	-0.32 0.41	0.74 0.02	-0.26 0.51	0.73 0.03
SI_{gipsum}																	1	0.71 0.03	0.77 0.02	-0.25 0.51	-0.24 0.54	0.39 0.29	-0.45 0.23
$SI_{celestite}$																		1	0.41 0.27	-0.57 0.11	0.32 0.40	0.16 0.69	0.18 0.65
^{14}C																			1	-0.31 0.42	-0.34 0.38	0.36 0.34	-0.48 0.19
$\delta^{13}C$																				1	-0.77 0.02	-0.07 0.86	-0.23 0.55
Age																					1	-0.22 0.56	0.55 0.12
U																						1	-0.66 0.05
$^{234}U/^{238}U$																							1

S4. Estimation of exposure and human health risk

Data on the carcinogenicity of strontium are very limited, and there is insufficient information to assess its carcinogenic potential due to the lack of adequate studies on long-term chronic exposure.

The assessment of non-carcinogenic risk to human health from contact with groundwater was carried out in accordance with the procedure described by the US Environmental Protection Agency (USEPA-2014; USEPA, 2004; USEPA, 2002). A deterministic approach was used for two routes of exposure (ingestion and water through the skin) to two subpopulations (adults and children). It is important to emphasize that strontium is not volatile, thus inhalation exposure is not likely, and therefore inhalation was not included in the risk assessment models in this study.

Average daily doses (ADI_{ing} and DAD)

The average daily intake for ingestion (ADIing in mg/kg per day) and dermal (dermal absorbed dose - DAD in mg/kg per day) were calculated according to equations (S1) and (S2) (USEPA, 2004, Zimoch and Lobos, 2015, Zhang et al., 2018). Calculations were made for adults and children separately.

$$ADI_{ing} = (Cw \times IR \times EF \times ED)/(BW \times AT) \quad (S1)$$

$$DAD = (DA_{event} \times EV \times SA \times EF \times ED \times CF)/(BW \times AT) \quad (S2)$$

where Cw is Sr concentration in groundwater (mg/L); IR – Ingestion rate of water (L/day), EF – Exposure frequency (day/year); ED – exposure duration (year); BW – body weight (kg); AT – averaging time (day), AT = ED x 365 (day); DA_{event} – absorbed dose per event (0.001mg/cm^2.event), $DA_{event} = Cw \times Kp \times t_{event}$; Kp – dermal permeability coefficient of compound in water (cm h^{-1}); t_{event} – event duration (h/event) час/событие; EV – event frequency (events/day); SA – skin surface area available for contact (cm^2), and CF is the unit conversion factor (=0.001).

Non-cancer risk assessment

Estimated ADI_{ing} and DAD values were compared with toxicity analysis data to characterize non-carcinogenic risk. Assessment of non-carcinogenic risk is usually done by calculating a hazard quotient (HQ) for threshold contaminants. A threshold pollutant exhibits non-carcinogenic effects beyond a certain exposure level (i.e. reference dose, RfD). Strontium is considered a threshold pollutant and HQ is calculated as the ratio of the average daily intake of Sr with (ADD_{ing} and DAD в mg/kg.day) with the respective reference doses (RfD_{ing} and RfD_{derm} в mg/kg.day) (USEPA, 2002; USEPA, 2004; Gerba, 2019; Ondayo et al., 2023):

$$HQ_{ing} = ADI_{ing}/RfD_{ing} \quad (S3)$$

$$HQ_{derm} = DAD/RfD_{derm} \quad (S4)$$

Based on the threshold value of RfD, it is possible to assess the existing adverse effects on human health. An RfD value higher than ADI or DAD indicates that there will be no adverse health effects. HQ values below 1 indicate low or no adverse health effects, while HQ values above 1 indicate likely adverse health effects (Gerba, 2019; Ondayo et al., 2023).

To assess the overall non-carcinogenic health risk from combined ingestion and dermal exposure, calculated HQ values from ingestion and dermal exposure (using equations (S3) and (S4)) were summed and expressed as the Hazard Index (HI) (USEPA, 2004; Gerba, 2019):

$$HI = HQ_{ing} + HQ_{derm} \quad (S5)$$

Values lower than 1 indicate no significant non-cancer health risk. Values of HI greater than 1 depict existing likelihood of non-cancer health effects occurring and the probability increases as the values rise (USEPA, 2004; Ondayo et al., 2023).

Selection of Health Reference Level (HRL), Body weight (Bw), Reference dose (Rf) and Averaging time (AT) values

According to U.S. EPA, 2014, the HRL is defined as a concentration against which to compare the occurrence data from public water system (PWSs) to determine if strontium occurs with a frequency and at levels of public health concern. The HRL for strontium is based on the Reference Dose (RfD). The RfD is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. The HRL for Strontium is based on the RfD of 0.3 mg/kg/day determined to be protective against a decreased rate of calcification in bone, especially during the periods of active growth from conception through adolescence. Age-specific exposure factors have been used in the HRL derivation in order to adjust for the increased risk associated with early life exposures. The HRL is calculated as follows:

Child specific HRL = (RfD/∑(DWI/BW x F)) x RSC

HRL = (0.3 mg/kg/day / 0.040 L/kg/day) x 0.2 = 1.5 mg/L.

where:

RfD = 0.3 mg/kg/day

DWI/BW = Drinking Water Intake Body Weight Ratio (DWI/BW) expressed as liters per kg body weight (L/kg/day)(90th percentile, consumers only) for each age-specific period for the first 18 years, the average postnatal duration for bone growth in humans.

F = The fraction of the 18 year exposure duration for each age-specific period.

RSC = Relative Source Contribution, or the level of exposure believed to result from drinking water when compared to other sources (e.g., food, ambient air). In all cases a 20 percent RSC is used for HRL derivation because it is the lowest and most conservative RSC used in the derivation of an MCLG for drinking water.

RfD	=	0.3 mg/kg/day
DWI/BW	=	Drinking Water Intake Body Weight Ratio (DWI/BW) expressed as liters per kg body weight (L/kg/day)(90th percentile, consumers only) for each age-specific period for the first 18 years, the average postnatal duration for bone growth in humans.
F	=	The fraction of the 18 year exposure duration for each age-specific period.
RSC	=	Relative Source Contribution, or the level of exposure believed to result from drinking water when compared to other sources (e.g., food, ambient air). In all cases a 20 percent RSC is used for HRL derivation because it is the lowest and most conservative RSC used in the derivation of an MCLG for drinking water.

That is, for a child of about nine years of age, you can take DWI/BW = 0.040 (L/kg/day), which corresponds to his consumption of 1.25 liters per day with a weight of 30 kg.

For an adult, the age of 18–20 years was chosen, when it becomes irrelevant to reduce the rate of calcification in the bones, due to the end of the period of active growth. Accordingly, with its weight of 70 kg and consumption of 2 liters of water per day, DWI/BWR = 0.029 (L/kg/day). Maximum allowable concentration according to SanRaR 2.1.4.1074-01, 7 mg/L corresponds to RfD 1 mg/kg/day:

HRL = (1 mg/kg/day / 0.029 L/kg/day) x 0.2 = 7 mg/L.

At the same time, an assessment of the risk of water consumption by the adult population was also performed at RfD 0.6 mg/kg/day (Zhang, 2018).

Descriptions of all parameters and their values used in the deterministic risk assessment are presented in Table S3.

Table S3: Parameters and values used for deterministic exposure calculations.

Parameters	Symbol	Units	Value	References
Element concentration in water	Cw	mg L^{-1}	This study	This study
Health Reference Level (Adults)	HRL A	mg L^{-1}	7,000	SanRaR 2.1.4.1074-01
Health Reference Level (Children)	HRL C	mg L^{-1}	1,500	USEPA, 2014
Ingestion rate of water (Adults)	IR A	L day^{-1}	2	Supplementary Materials
Ingestion rate of water (Children)	IR C	L day^{-1}	1.25	Zhang, 2018
Exposure frequency	EF	day $year^{-1}$	350	Gerba, 2019; Means, 1989
Exposure duration (Adults)	ED A	year	19	Supplementary Materials
Exposure duration (Children)	ED C	year	9	Supplementary Materials
Dermal permeability coefficient of compound in water	K_p	cm $hour^{-1}$	0.001	USEPA-2004
Event duration	t_{event}	hour $event^{-1}$	0.58	USEPA-2004
Event frequency	EV	event day^{-1}	1	USEPA, 2014
Skin surface area available for contact (Adults)	SA A	cm^2	18,000	USEPA, 2004
Skin surface area available for contact (Children)	SA C	cm^2	6,600	USEPA, 2004
Body weight (Adults)	BW A	kg	70	Supplementary Materials
Body weight (Children)	BW C	kg	30	Supplementary Materials
Averaging time – non carcinogen (Adults)	AT A	day	6935	Supplementary Materials
Averaging time – non carcinogen (Children)	AT C	day	3285	Supplementary Materials
Reference dose – ingestion (for Sr) (Adults)	RfD_{ing} A	mg kg^{-1} day^{-1}	1; 0,6	Supplementary Materials; Zhang, 2018 USEPA. RSLs
Reference dose – ingestion (for Sr) (Children)	RfD_{ing} C	mg kg^{-1} day^{-1}	0.3	USEPA, 2014
Reference dose – dermal (for Sr)	RfD_{derm}	mg kg^{-1} day^{-1}	0.12	USEPA, 2002; Zhang, 2018

References

Gerba, C.P., 2019. Risk assessment. Environmental and pollution science (3rd ed., pp. 541–563). Elsevier. https://doi.org/10.1016/B978-0-12-814719-1.00029-X

Means, B., 1989. Risk-assessment guidance for superfund. Volume 1. Human health evaluation manual. Part A. Interim report (Final) (No. PB-90–155581/XAB; EPA-540/1–89/002). Environmental Protection Agency, Washington, DC (USA). Office of Solid Waste and Emergency Response. Retrieved January 18, 2022, from https://www.osti.gov/biblio/7037757

Ondayo, M.A., Watts, M.J., Hamilton, E.M., Mitchell, C., Mankelow, J., Osano, O., 2023. Artisanal gold mining in Kakamega and Vihiga counties, Kenya: potential human exposure and health risk.

Environ Geochem Health https://doi.org/10.1007/s10653-023-01647-z

SanRaR 2.1.4.1074-01. Sanitary and epidemiological rules and regulations "Drinking water. Hygienic requirements for water quality of centralized drinking water supply systems. Quality control", approved by the Chief State Sanitary Doctor of the Russian Federation on September 26, 2001 (in Russian)

USEPA, 2002. Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites. OSWER 9355.4-24. U.S. Environmental Protection Agency, Washington, D.C.

USEPA, 2004. Risk Assessment Guidance for Superfund. Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment). Final. EPA/540/R/99/005. U.S. Environmental Protection Agency, Washington, D.C.

USEPA, 2014. Health Effects Support Document for Strontium. EPA 820-P-14-0012014. Washington, 2014. www.epa.gov/safewater/ccl/pdf/Strontium.pdf

USEPA. Regional Screening Levels (RSLs). Calculator.
Available online: https://epa-prgs.ornl.gov/cgi-bin/chemicals/csl_search (accessed on 2023-08-03).

Zimoch, I., Łobos, E., 2015. Evaluation of health risk caused by chloroform in drinking water. Desalin. Water Treat. 57 (3), 1027–1033.

Zhang, H., Zhou, X., Wang, L., Wang, W., Xu, J., 2018. Concentrations and potential health risks of strontium in drinking water from Xi'an, Northwest China. Ecotoxicology and Environmental Safety. 164, 181-188 https://doi.org/10.1016/j.ecoenv.2018.08.017

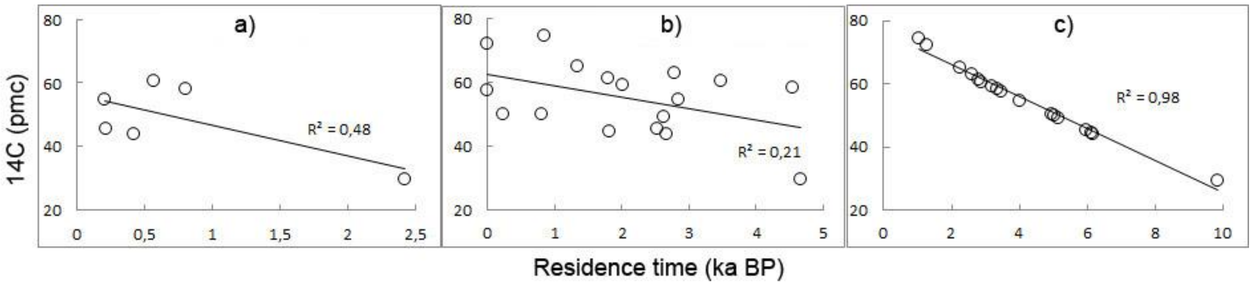

Figure S2. Plots of the radiocarbon/residence time in the fresh groundwater Pearson model (a), Ferronsky model (b), and Vogel model (c)

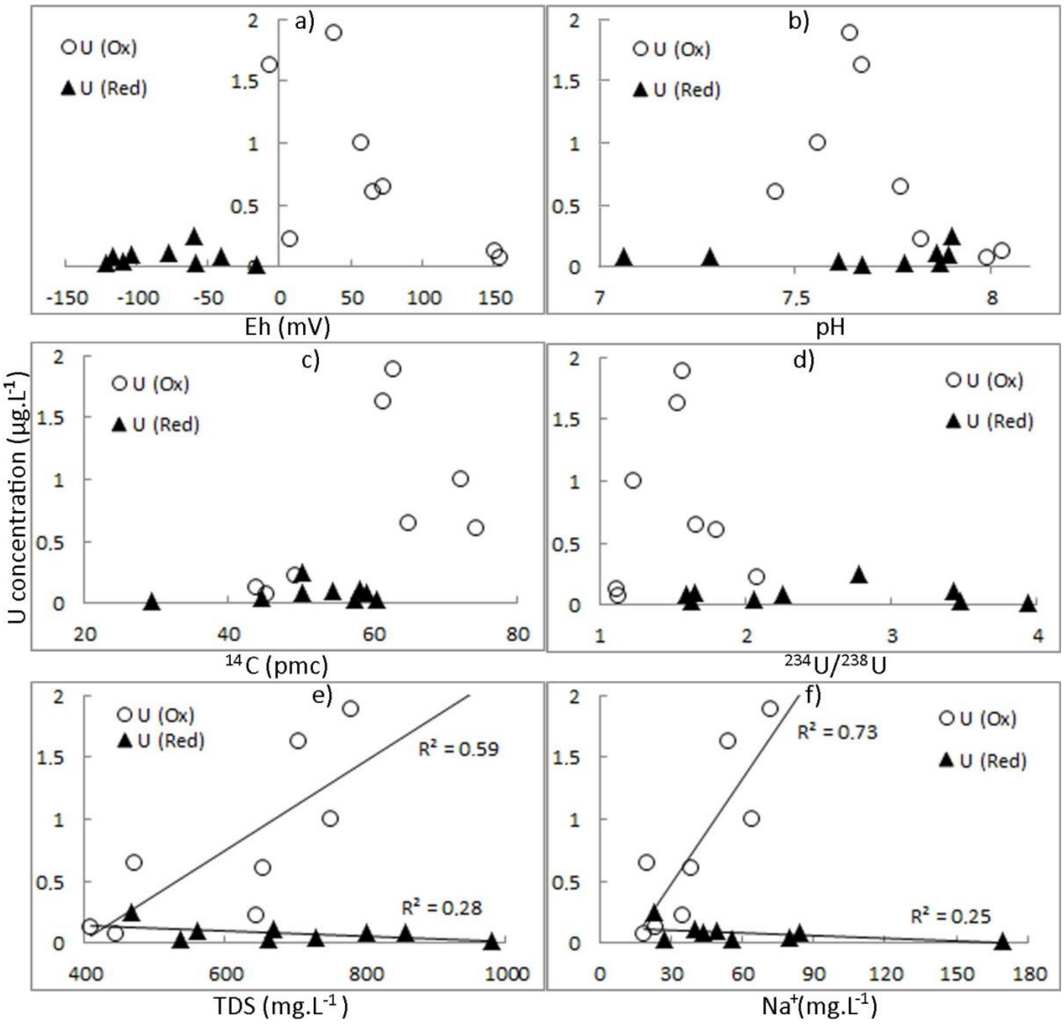

Figure S3. Plots of the U concentration in the fresh groundwater vs Eh (a), pH (b), ^{14}C (c), $^{234}U/^{238}U$ (d), TDS (e), Na^{2+} (f). (Ox) - oxidizing conditions in the aquifer, (Red) - reducing conditions in the aquifer

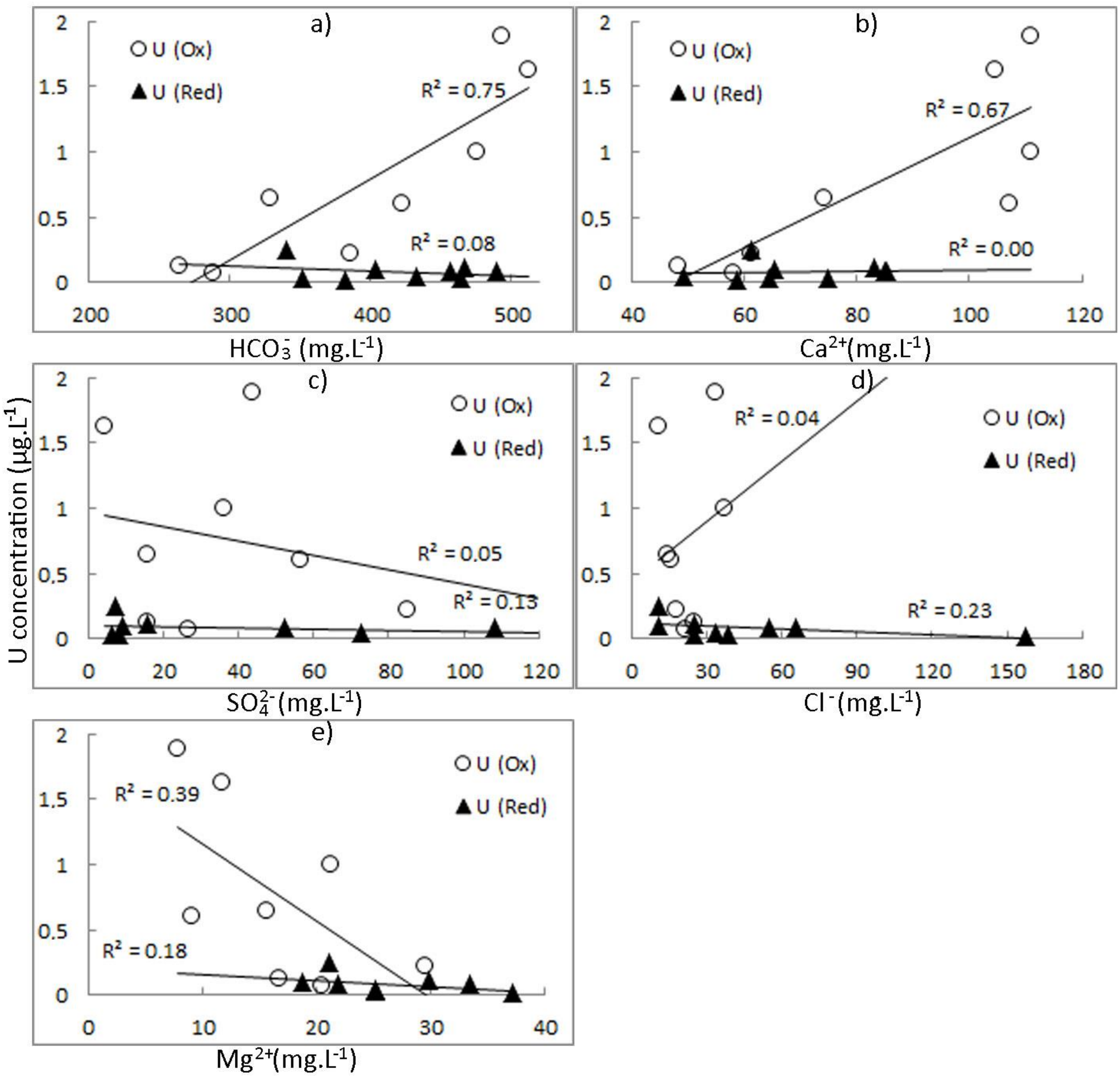

Figure S4. Plots of the U concentration in the fresh groundwater vs HCO_3^- (a), Ca^{2+} (b), SO_4^{2-} (c), Cl^- (d), Mg^{2+} (e). (Ox) - oxidizing conditions in the aquifer, (Red) - reducing conditions in the aquifer