



Influence of Drainage with High Levels of Water-Soluble Salts on the Environment in the Verhnekamskoe Potash Deposit, Russia

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Abstract

Saline drainage from slurry storage facilities can deteriorate the properties of clay barriers in the beds of embankment dams and slurry ponds and cause saline drainage to infiltrate into groundwater. The chemistry of slurry material, drainage, springs, surface water, and soils was studied near the slurry storage facility of the Verhnekamskoe potash mine (Russia). Our study showed that the Na–Cl type mine drainage water, with high amounts of nitrogen compounds, increased the salinity of the groundwater and surface water, and the river valley ecosystems. As a result of ion exchange and leaching, the soil, groundwater, and surface water have elevated levels of Ca^{2+} , Mg^{2+} , SO_4^{2-} , and Fe_{total} , and extremely high Na^+ and Cl^- values. Iron-rich precipitates and hydrogen sulfide tend to form down-gradient in the saline, water-logged seepage areas.

Keywords Slurry storage facility · Potash mining · Saline groundwater and surface water · Soil salinization · Iron-rich precipitates · Bare soil

Introduction

Most potash ores are extracted by underground mining. The beneficiation of these ores produces large volumes of waste materials (over 70% of the extracted ore) with high levels of water-soluble salts. Depending on the geological conditions and mining techniques, a potash mine produces solid halite waste, clay-salt slurry, and brines. The potash industry uses a wide variety of waste disposal methods in different countries, such as discharge of wastes into rivers and oceans, deep-well injection, or salt pile stacking (Rauche et al. 2001; United Nations 2001). In Russia, mining processes allow for the separate disposal of wastes. Halite wastes with over 90% NaCl content are typically placed in piles, while clay slimes and brines drain into storage facilities. The clay-salt slurry typically contains 35–40% water-soluble salts and 60–65% insoluble clay materials. Brines have a Na–Cl composition and more than 300 g/L of total dissolved solids (Bachurin and Baboshko 2008). The highly mobile water-soluble

salts can potentially contaminate both surface water and groundwater.

More than 30 million m^3 of clay-salt slurry are stored on the ground surface at the Verhnekamskoe potash deposit in Russia (Bachurin and Baboshko 2008), and the containment of brine in the slurry storage facility is a serious problem. The slurry storage facilities include: perimeter embankment dams that prevent slime and brine seepage from flowing outside the storage facility and settling pond; floating pumping stations to remove surplus brines from the storage facility and settling pond cells; and drainage ditches, slurry pipelines, and return flow lines for the reusable brines. Leakage of brines from dams and ponds is controlled by engineered barriers such as low-permeability clay-based seals or slurry barriers at the bed of the settling pond and dams. While materials such as geomembranes are very effective in preventing leakage from tailings cells (Sliusar et al. 2012), clay-based seals are generally used due to their lower cost.

There is evidence that the low effectiveness of some clay barriers is due to the interaction between brines and clay particles (Barbour and Yang 2011; Bel'tyukov 1996; Kolpashnikov et al. 2010; Maksimovich and Gorbunova 1989; Monyushko and Pakhomov 1985; Osipov 2012). Salinization on the surface of the clay-based seal increases the pore space between soil particles and increases soil permeability up to 75% (Bel'tyukov 1996).

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Salinization of surface water and groundwater in potash mining regions has been studied by many researchers (Arle and Wagner 2013; Baure et al. 2005; Bel'tyukov 1996; Kolpashnikov et al. 1979; Liu and Lekhov 2013; Lucas et al. 2010). In this study, we examined the direct and indirect consequences of brine filtration from slurry storage facilities on the chemistry of the surrounding surface water, groundwater, soil, and vegetation after 40 years of exploitation.

Materials and Methods

Study Area

The Verhnekamskoe potash deposit is one of the largest such deposits in the world, with an area of about 6.5×10^3 km². It is located on the left bank of the Kama River in Russia (Fig. 1). The ore contains 18–34% KCl. There are geological reserves of up to 96.4 billion tons of carnallite, up to 112.2 billion tons of sylvinit (sylvite), and up to 4.65 trillion tons of halite. Annual production of potassium-magnesium salts is about 40 million tons (Kudryshov 2006).

The Verhnekamskoe potash deposit has more than 500 m of solid evaporite strata with layers (from bottom to top) of underlying rock salt of 320–400 m, potash ore (70–100 m), and more rock salt (20 m). Sylvinit (with an average thickness of 17.5 m) and carnallite (with an average thickness of 54 m) zones comprise the potash deposit (Kudryshov 2001). The evaporite strata are underlain by 200–220 m of clay-anhydrite deposits and overlain with Ufimian strata of the lower Permian (Fig. 2). The Sheshminsky horizon of the Lower Permian (P₁ss) is represented by speckled deposits and is therefore referred to as “speckled strata”. The speckled strata is covered by Quaternary (Q) sediments.

The lens-shaped evaporite strata as a regional aquiclude dividing suprasalt (fresh, mineralized waters and brines) and subsalt (highly-mineralized brines) water. The brines come from the holes in some areas at the top of salt strata or near them; the degree of mineralization reaches 320 g/L (Kudryshov 2001). Active water exchange occurs in the upper part of the suprasalt strata. Water entering the speckled and Quaternary aquifers discharges to the surface as springs and has a Ca–HCO₃ or Ca–SO₄ composition. The speckled and Quaternary aquifers are particularly vulnerable to potash mining activities (Fetisova et al. 2016).

The Lyonva River is affected by groundwater salinization from two potash mines in the area (Fig. 1). One of them, located at the head of the river (Fig. 1), is responsible for high levels of contamination of river water in the upstream from the slurry storage. The TDS of the upper river water ranges from 3.4 to 12.9 g/L, with Cl[−] from 1.7 to 6.8 g/L. The study area is situated on the left bank of the middle part of the Lyonva River, which is the left bank tributary of the

Kama Reservoir (Fig. 1), which is used as a water drinking supply.

The slurry storage facility has been in operation since 1976. A clay-based seal was used to protect the groundwater aquifers from contamination. The large amount of precipitation (averages 650 mm annually), rugged topography, and cold (temperature averages 0 °C) climate promotes active migration of water-soluble salts.

Methods

The impact of a clay-salt slurry storage facility was studied during 2013–2016 as part of the environmental monitoring conducted in the southern part of the Verhnekamskoe potash deposit. The program included hydrochemical, soil, and biological monitoring of the terrestrial and aquatic ecosystems (Khayrulina 2016). Samples were collected of the water infiltrating through the dam of the slurry storage facility (10 samples) and the Lyonva River at 1 km (18 samples) and 6 km (13 samples) downstream from the slurry storage facility and 1 km upstream (11 samples) of it (Fig. 1). Water from two springs (11 samples) was collected in the Lyonva River valley (Fig. 1) to assess groundwater pollution and its role in surface waters and soil salinization. Samples of surface waters, springs, and infiltration were collected four times a year in polymer bottles during periods of low-water levels in December and July and high-water levels in May and October. To determine Fe_{total}, separate water samples were collected. HCl was added to achieve a final concentration of 0.2–0.3 mol/L of HCl in each bottle.

Four soil samples each were collected at a depth of 0–20 cm from the river valley and along the surface runoff channels (Fig. 1) in July–August annually. The soils were classified as alluvial grey humic gley (Klassifikatsiya pochv 2000). In seepage areas in the Lyonva River valley, soil samples were collected in 2015 at 0–3 cm (3 samples) and 3–30 cm (4 samples) depth. The soil is an abralite (stripped mineral soil of loamy and sandy loamy composition devoid of a humus layer) (Klassifikatsiya pochv 2000). At each soil sampling site, the species composition of the vegetation was described. Five slurry samples were collected from each of two layers, at depths of 0–15 cm and 15–60 (5 samples) cm.

Samples of surface water and groundwater and aqueous extracts of soil were analyzed for NO₂[−], NO₃[−], NH₄⁺, Cl[−], K⁺, SO₄^{2−}, Ca²⁺, Na⁺, and Mg²⁺ by using a capillary electrophoresis Kapel-104. The pH, HCO₃[−], and TDS of the aqueous extract were determined by titration. The soil and bottom sediment samples were pretreated by removal of the <0.01 mm clay fractions. Soil and sediment mineralogy was then determined using a Nikon 104 binocular microscope. The material of the slurry storage site was triturated and then analyzed by X-ray diffraction (XRD) using a D2 Phaser desktop diffractometer “Bruker”.

Fig. 1 Geographical location and hydrogeological map (after Kharitonov et al. 1999) of the study area



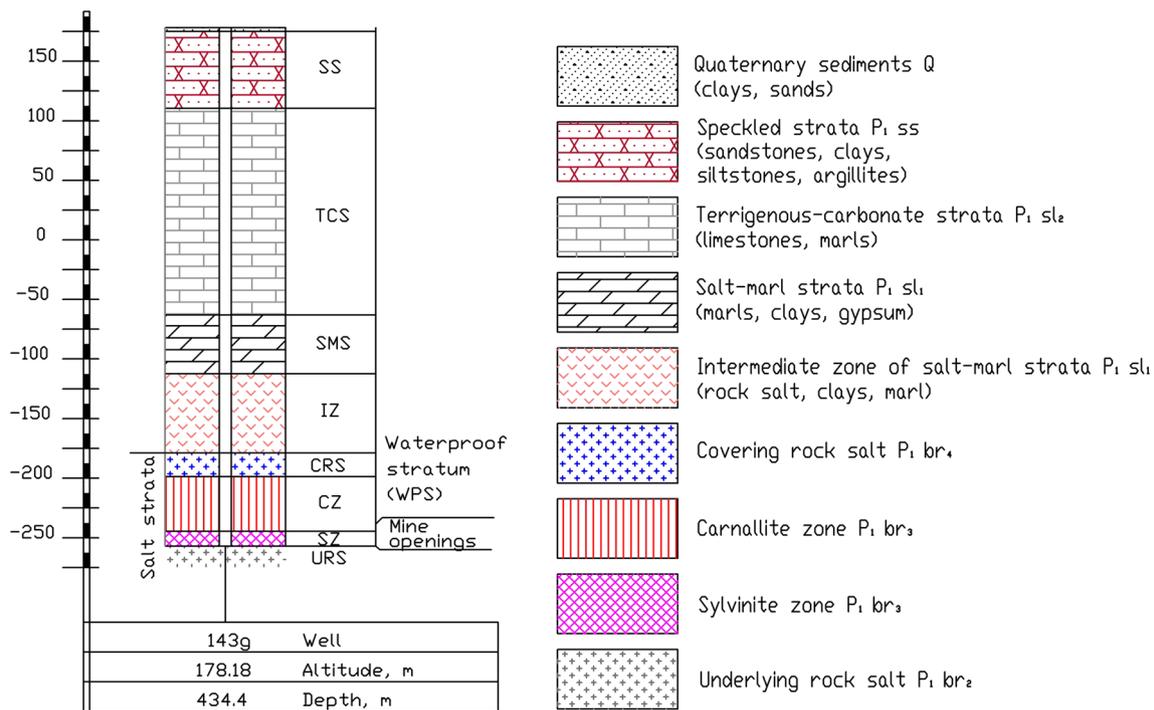


Fig. 2 Geological strip log of the study area (after Fetisov 2016)

The chemical composition of the surface water, groundwater, and soils were compared to unimpacted background concentrations (Khayrulina 2016) and the maximum allowable concentrations (MAC) (GN 2.1.5.1315-03 2003). Two types of ratios were calculated for the water samples. The Na/K ratio was used to identify close relationships to the mine wastes, while the Na/Cl ratio shows Na⁺ removal from groundwater by ion exchange processes.

Result and Discussion

Composition of the Fine Tailings in the Slurry Storage Area

The solid phase of the clay-salt suspension contains the insoluble residue of sylvinite ore, with an admixture of crushed sylvite and halite. The sulfates are usually anhydrite and gypsum, aluminosilicates are mostly feldspar, while the carbonate is dolomite. The processes of sulfatization and carbonatization occurring at the storage facility were accompanied by the widespread formation of gypsum crystals and finely powdered crystalline dolomite. The top layer of the storage facility consisted of 30% K-feldspar, 8.8–11.5% halite, 1.4–19.0% gypsum, and 12% dolomite (Table 1). These processes were accompanied by superimposed pyritization due to the change from oxidizing to reducing conditions

(Eh of −43.8). The pyrite content ranged from 1.3 to 1.8% (Table 1).

The aqueous extract of the slurry was dominated by Cl[−] (> 70 g/L), Na⁺ (33 g/L), K⁺ (19.5 g/L), SO₄^{2−} (19.6 g/L), Ca²⁺ (6.8 g/L), and Mg²⁺ (0.9 g/L) ions (Khayrulina 2016). The geochemical transformation of the slurry was accompanied by more intense discharge of contaminants into the environment with runoff, and increased infiltration through underlying rocks (Liu and Lekhov 2013). These processes were most active in humid environments.

The highly saline runoff into the hydrosphere occurred via seepage through the embankment dam and bed of the slurry storage area (Fig. 3). Saline water was discharged subaqueously into a river channel or as an ascending spring on the opposite side of the river because direct discharge was hindered by clay-rich deposits that line the valley slope in the vicinity of the slurry storage facility.

Surface Discharge Through the Dam

In the 40-year period of the facility's operation, water discharging along the valley slope by infiltration through the dam was stable and highly saline. The waters were predominantly of Na–Cl type with > 40 g/L TDS (Table 2). High concentrations of Cl[−], SO₄^{2−}, Na⁺, Mg²⁺, and K⁺ ions in the drainage water were due to the presence of water-soluble salts in the tailings facility (Table 1). High concentrations of nitrogen in the groundwater were caused by the presence

Table 1 Mineralogical composition of slurry material

Type of sample	No sample	Halite	Sylvin	Gypsum	Anhydrite	Dolomite	Calcite	Quartz	K-feldspar	Chlorite	Glist	Pyrite	Σ
Upper layer 0–15 cm	3.7/1	11.5	3.0	19.0	0.5	12.2	1.1	6.0	32.9	8.3	4.1	1.5	100
	3.7/2	8.8	2.3	7.4	7.3	12.0	1.2	7.2	35.2	9.3	7.6	1.7	100
	3.7/3	9.6	2.4	8.3	6.0	12.9	0.8	7.5	37.2	7.3	6.2	1.8	100
	3.9/1	14.2	2.9	1.1	21.2	9.2	1.0	7.2	29.6	5.2	6.5	2.0	100
	3.9/2	46.1	2.7	2.6	15.9	6.1	–	4.6	15.7	2.0	4.5	–	100
Lower layer 15–30 cm	3.8/1	5.5	1.6	21.7	0.9	14.6	2.6	8.3	31.4	5.6	6.6	1.3	100
	3.8/2	10.9	2.6	18.4	0.9	13.2	1.0	7.2	32.6	5.6	6.3	1.4	100
	3.8/3	8.5	2.8	22.9	0.9	11.7	3.2	7.3	31.2	5.3	4.9	1.4	100
	3.8/4	9.8	2.6	19.3	1.6	15.8	1.7	7.6	28.4	6.2	5.4	1.6	100
	3.8/5	8.9	2.6	18.4	0.5	12.6	1.9	6.8	33.5	6.6	6.7	1.5	100

of a wide range of heterocyclic compounds (Bachurin et al. 2014) in the tailings as components of flotation reagents. The Na/K ratio ranged between 2.1 and 3.0. The Na/Cl ratio ranged from 0.6 to 2.2, depending on the amount of atmospheric precipitation, but the average value was close to 1.0. High concentrations of Na⁺ and Cl⁻ in the drainage water were, in general, a result of halite dissolution and closely resembled the waters entering the groundwater.

The discharge of groundwater downstream from the tailings facility and the increase of the water table level after storage construction resulted in the formation of a salt marsh (Fig. 3) where the concentrations of water-soluble salts may reach 1% (Table 3). The vegetation of this salt marsh consisted mostly of halophytic plant species, such as reed (*Phragmites communis*) and broadleaf cattail (*Typha latifolia*), species, which are able to desalinate and purify water (Nazarmamedov 2007).

Underground Discharge

Effluents seeping through the bed of the slurry storage facility were discharged directly into the underlying Quaternary (Q) and speckled (P_{1ss}) aquifers or run off to nearby drains, forming a large saline plume between the storage facility and the river channel (Fig. 3). The brines could reach the nearest drain in several days after the start of filtration (Lyubimova et al. 2016). According to some reports, the infiltration to the speckled aquifer due to the high density of solutions (> 1 g/cm³) may account for up to 20% of the total runoff from the storage facility. Highly saline waters in the speckled aquifer (P_{1ss}) move to the main drain of the Perm region (Kama Reservoir) (Liu and Lekhov 2013).

A change in groundwater composition from CaHCO₃ to Na–Cl was observed for both springs near the slurry storage facility. The highest Cl⁻ concentrations were detected in the spring from the Quaternary deposits (up to 26.1 g L⁻¹). This aquifer was the one most affected by potash mining. The Na/K ratio (3.1 meq/L) was very similar to the drainage water while Na/Cl ratio (0.6 meq/L) showed the effects of ion exchange in the Quaternary aquifer. The speckled aquifer spring was characterized by lower concentrations of all chemical components except Fe_{total}, with Cl⁻ values above 3.2 g/L. The Na/Cl ratio of about 0.3 meq/L demonstrated more ion exchange processes.

Large variations in salinity in both springs during the period of observation (Table 2) can be explained by seasonal changes in the hydrodynamic regime. Infiltration through clayey, locally-dolomitic limestones and marls changed the Na/Cl ratio of the water relative from that of the drainage (Table 2), because leaching and ion exchange processes in the water–rock system became more intense in the presence of the highly saline anthropogenic Na–Cl groundwater than in the presence of freshwater (Kolpashnikov et al. 1979;

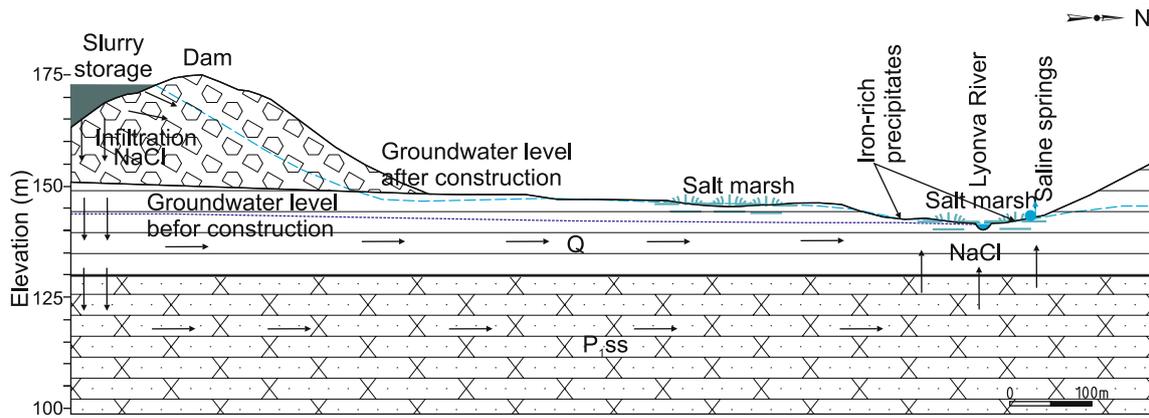


Fig. 3 Schematic cross-section of the Lyonva River showing the distribution of highly chloride waters

Lucas et al. 2010). As a result, in addition to chloride contamination, the groundwater had higher concentrations of Ca^{2+} , Mg^{2+} , and sulfate than the infiltration water (Fig. 4). In some samples, the Fe_{total} content of the saline groundwater reached 1.38 mg/L.

Water Chemistry of the Lyonva River

The discharge of contaminated groundwater as springs, as well as the areal, subaqueous, and surface discharges of highly saline water in the Lyonva River valley (Fig. 4) leads to salinization of the previously fresh water river and valley. As a result, the Lyonva River water has a Na–Cl composition (Table 2), neutral pH, and relatively high MAC levels for all components, including nitrogenous compounds. The Fe_{total} content is decreasing compared to the groundwater because of Fe^{2+} precipitation in oxygen settings of river water. In arid ecosystems, saline water is alkaline, but in the study area, the neutral pH of anthropogenic salinization of the Lyonva River is a result of the neutral drainage and the acidic soil solutions of the boreal coniferous forest. Despite the fact that the water chemistry of the Lyonva River is controlled by the presence of another potash mine located at the head of the river (Fig. 1), the highest concentrations of water-soluble salts are observed near the studied storage facility. The Cl^- content reached up to 15 g/L, Na^+ up to 6.4 g/L. Samples taken 6 km downstream of the slurry storage facility had lower contaminant concentrations and Na/Cl ratios due to dilution. The Na/K ratio is closer to the background level. It should be noted that the highest Na/K ratios were observed upstream of the slurry storage facility. This could have been due to more active involvement of K^+ in the biological cycle of aquatic ecosystems and, as a consequence, a sharp decrease in the K^+ compared to the Cl^- .

Salinization of the river and the presence of shallow groundwater of the Na–Cl type in the river valley has markedly increased concentrations of Cl^- , K^+ , SO_4^{2-} , and Na^+

in the river valley soils. The sum of toxic salts was equal to 1.5%, which corresponded to the “very high” degree (Bazilevich and Pankova 1968) of salinity (Table 3). The soil–water extract had much higher levels of Cl^- (400-fold), Na^+ (200-fold), and K^+ (sevenfold) than background soils.

In seepage areas, bare soils acquired reddish-yellow, iron-rich precipitates on their surface. Mineralogical analysis (Table 4) revealed that the insoluble part of the samples collected from the upper soil horizons (0–3 cm depth) had the highest content of iron minerals (84.9%) and ferruginated plants (20%). The lower soil horizon (3–30 cm depth) consisted of black gel-like phases with a high content of plant residues. High concentrations of sulfate in the saline waters and microbiological activities led to hydrogen sulfide in this horizon. The insoluble part of the samples contained up to 84% hydrogoethite, which was the result of iron oxidation during sample preparation. We suppose that hydrotroilite was the predominant iron-bearing mineral in this horizon. Other iron minerals (hematite and magnetite) were identified. The source of iron in the soils is the speckled rocks, slurry material, and soil minerals. Saline drainage and saline groundwater are more active than fresh groundwater leaching Fe-(hydr)oxide from the iron-rich speckled aquifer, slurry material, and soil minerals. The presence of dead trees in the bare seepage areas indicates that this process has developed relatively recently and could be the result of a rising water table or mining subsidence.

Conclusions

The interpretation of chemical and mineralogical data on slurry, saline spring, surface water, and soil samples collected at different distances from the slurry storage facility showed that the deterioration of the sealing properties of the materials at the bed of the tailings dam and storage

Table 2 Water chemistry in the vicinity of the slurry storage site

Components	Infiltration through the dam of slurry storage site	Saline spring (Q) in the Lyonva River valley	Saline spring (P _{1ss}) in the Lyonva River valley	Lyonva River 1 km from the slurry storage site downstream	Lyonva River 6 km from the slurry storage site downstream	Lyonva River 1 km from the slurry storage site upstream	MAC
pH	6.9 ^a	6.9	7.1	7.2	7.2	7.5	6.5–8.5
	6.34–7.2 ^b	6.8–7.0	7.0–7.1	6.8–7.7	6.8–7.6	7.1–7.8	
HCO ₃ ⁻ (mg/L)	340.5	152.6	129.0	137.0	116.5	183.0	-
	292.9–457.6	11.0–186.0	99.0–148.0	99.0–173.9	64.7–154.9	143.6–286.8	
SO ₄ ²⁻ (mg/L)	1834.8	373.5	106.4	600.3	486.3	203.1	100
	645.8–4189.7	191.0–597.9	83.6–121.7	73.0–1793.0	81.1–1511.0	26.4–840.5	
Cl ⁻ (mg/L)	33,380.0	14,992.3	3209.5	7931.4	6673.5	4464.6	300
	5540.0–66,725.0	6950.0–26,180.0	2368.0–5308.0	3320.0–15,290.0	2930.5–11,860.0	1717.7–6815.0	
NO ₂ ⁻ (mg/L)	6.1	<0.2	<0.2	3.3	2.5	<0.2	0,08
	0.34–10.28			0.1–12.3	0.2–7.6		
NO ₃ ⁻ (mg/L)	78.0	27.2	25.4	15.7	16.4	6.3	40
	15.0–126.2	0.2–65.0	10.8–62.0	2.8–32.4	6.9–32.4	1.3–26.3	
Ca ²⁺ (mg/L)	1528.6	1237.0	418.1	1178.6	1033.0	1104.2	180
	721.4–2713.0	552.0–2166.3	275.0–628.8	561.1–1593.0	601.2–1528.0	440.9–1947.0	
Mg ²⁺ (mg/L)	270.2	946.5	76.0	280.5	236.6	263.8	40
	145.8–727.0	117.0–5185.3	48.5–116.4	121.5–382.8	123.2–320.5	140.2–413.0	
Na ⁺ (mg/L)	16998.0	6395.1	1199.7	3082.8	2253.5	954.0	120
	7055.5–32142.0	2555.0–11005.0	866.0–1920.0	780.8–6422.0	963.5–5042.0	8.7–2576.0	
K ⁺ (mg/L)	10796.0	3232.9	489.0	1258.9	745.3	116.1	50
	5168.8–23688.5	1228.0–5856.4	339.0–894.3.0	158.0–4237.0	62.6–1580.0	4.2–600.0	
Fe _{Total} (mg/L)	0.5	0.6	0.8	0.8	0.8	0.5	0.1
	0.14–0.98	0.11–1.38	0.46–1.38	0.6–0.9	0.6–0.9	0.2–0.7	
NH ₄ ⁺ (mg/L)	53.0	16.2	<0.5	23.1	7.9	1.7	0,5
	5.0–193.0	15.3–17.0		0.56–93.5	0.7–20.1	0.4–5.2	
TDS (mg/L)	45,053.6	29,370.3	5945.0	12,888.0	12,109.0	7991.7	1000
	11,637.0–77,170.0	11,669.0–46,140.0	4570.0–9540.0	5293.7–21,840.3	5293.7–20,065.0	3490.0–12,900.0	
Na/K (meq/L)	2.7	3.1	4.3	4.7	8.2	20.2	13.3 ^c
	2.1–3.0	0.9–3.8	3.6–4.7	3.1–10.8	3.9–53.4	2.0–48.0	
Na/Cl (meq/L)	0.9	0.6	0.3	0.6	0.5	0.2	1.1 ^c
	0.6–2.2	0.4–1.2	0.3–0.4	0.3–1.1	0.4–0.6	0.001–0.39	
Number of samples	10	7	4	18	13	11	

MAC maximum allowable concentration

^a Average

^b Minimum and maximum values

^c Background concentrations (Khayrulina 2016)

Table 3 Range in contents of chemical elements in soils

Location	pH	Sum of toxic salts (%)	Cl ⁻ (mg/kg)	SO ₄ ²⁻ (mg/kg)	Na ⁺ (mg/kg)	K ⁺ (mg/kg)
Salt marsh below a dam of the slurry storage site	5.6	1.395	7220	375	3242	2204
Salt-affected valley	4–8	1.582	3390–10,163	16–66	753–2394	23–146
Background soils	4–6	0.011	15–19	6–25	5–8	7–30

Fig. 4 Piper diagram showing the element concentrations in the studied samples relative to background levels of elements in rivers and groundwater. Symbols are: black filled circle: drainages; red filled circle: Lyonva River water; blue filled circle: saline springs; red filled triangle: river water of unimpacted areas; blue filled triangle: fresh springs

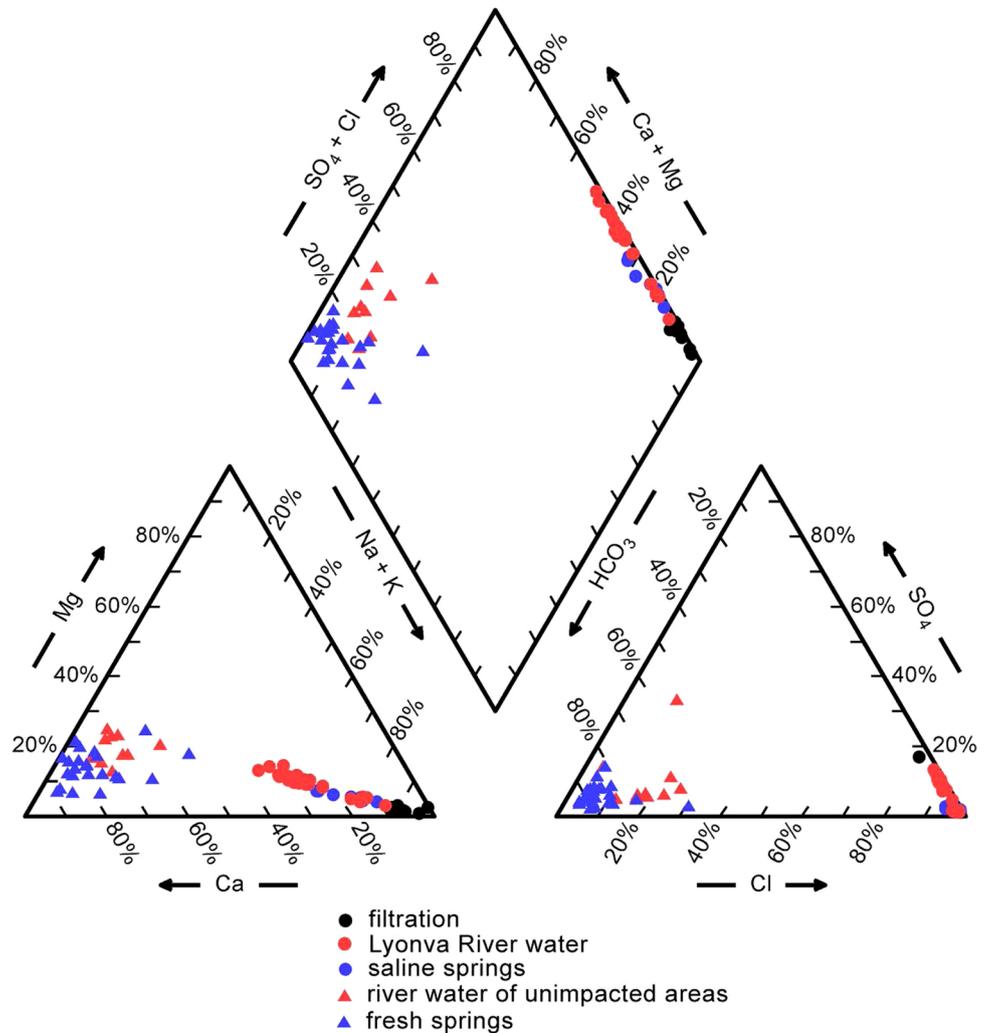


Table 4 Mineralogical composition of soils in seepage areas

Depth of sample	No sample	Quartz	Fe-bearing plant residual	Iron minerals	Hydrogottite	Hematite	Oxides of Mn	Other minerals
0–3 cm	4.1	0.1	10.0	84.9	–	–	–	5.0
	6.1	2.5	86.8	6.0	–	–	–	4.7
	8.1	1.0	20.0	73.9	–	–	–	5.1
	11.1	0.5	30.0	–	68.2	–	–	1.3
3–30 cm	4.2	57.6	9.0	25.0	–	–	–	8.4
	6.2	78.2	3.0	8.0	–	–	0.3	10.5
	8.2	5.0	5.0	–	84.8	–	–	5.2

–, not observed

facility has had a complex impact on the environment in the study area. The surface and underground discharge of Na–Cl waters with high concentrations of nitrogen compounds caused salinization of the surface water and groundwater and soils in the river valleys and along the surface runoff channels. Saline groundwater actively dissolved carbonate

and sulfate minerals, resulting in increased calcium, magnesium, and sulfate in the saline springs and Lyonva River. In addition, the percolation of saline groundwater through the speckled strata led to Fe²⁺ enrichment of the groundwater and resulted in precipitation of Fe_{total} on the soil surface due to the oxidizing conditions.

The groundwater salinization also caused a sharp increase in the Cl^- , K^+ , SO_4^{2-} , Na^+ content of the valley soils. In seepage areas, saltwater migration and waterlogging has resulted in the formation of salt marshes; areas of bare soil were characterized by elevated hydrogen sulfide concentrations and accumulation of iron-rich precipitates.

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