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Review

Environmental Aspects of Potash Mining: A Case Study of the Verkhnekamskoe Potash Deposit

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Abstract: Potash fertilizer production is one of the most important economic activities. Historically, potash mining has had a significant impact on the environment, often with catastrophic consequences. The purpose of this paper is to summarize the results of studies on the environmental impact of potash mining using the example of the Verkhnekamskoe potash deposit. The deposit is located in the central part of the Solikamsk depression in the Pre-Ural foredeep (Perm Krai, Russia). All the main features and problems of underground mining of water-soluble ores and potassium fertilizer production are considered using the example of one of the world's largest potash deposits. This paper looks into the specifics of the material composition of waste, its disposal, underground mining issues associated with the solubility of salts, and the risks of groundwater inflow into the mine workings, which causes flooding of mines. The results of all surveys show that potash mining affects the atmosphere, surface water, groundwater, soil, and vegetation. The most effective measure to reduce the adverse environmental impact of potash mining at the Verkhnekamskoe Deposit is hydraulic backfilling of mine chambers, which protects the underground mines from flooding, minimizes ground subsidence, and reduces the area of potash waste.

Keywords: potash; potash waste; solid and liquid waste; brine; environmental impact; freshwater salinization; chloride; waste management; subsidence; underground mining

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1. Introduction

Potassium is an essential macronutrient for plant growth and development. Along with nitrogen and phosphorus, it is one of the most important elements of plant mineral nutrition that increases biological productivity [1,2]. Modern agricultural production is heavily reliant on the quantity and quality of chemical fertilizers required to boost grain and horticultural yields in order to feed the majority of the world's population [3,4]. Potash production has increased by 9% in the last decade, owing to increased demand in Southeast Asia [5]. Global potash production expanded due to increased production in China, Canada, Russia, and Belarus. At the same time, the increase in potash production capacity in China is linked to the need to meet domestic demand [6]. Table 1 shows data on global potash production and reserves for 2020–2021 [7].

Potash deposits have been developed for over 150 years. The potash industry began its development in Germany [8,9]. Around the world, potash production depths vary between 300 m and 2000 m beneath the ground surface [10–13]. Underground mines use the traditional drill-and-blast technique and a mechanized method to mine potash ores at shallow depths (Verkhnekamskoe potash deposit of Solikamsk basin; Kłodawa salt mine of Zechstein basin) [14–16]. Solution mining with brine solvent methodology [17,18] is used when productive layers of potassium chloride are deeper.

Table 1. World potash mine production and reserves in thousand tons of K_2O equivalent [7].

	Mine Production		Reserves
	2011	**2021 ***	
Belarus	5500	8000	750,000
Brazil	454	210	2300
Canada	11,000	14,000	1,100,000
Chile	980	900	100,000
China	3700	6000	350,000
Germany	3010	2300	150,000
Israel	1960	2300	** Large
Jordan	1380	1600	** Large
Laos	-	300	75,000
Russia	6500	9000	400,000
Spain	420	400	68,000
United States	1000	480	220,000
Other countries	-	370	300,000
World total (rounded)	36,400	46,000	>3,500,000

* Estimated value; ** Israel and Jordan recover potash from the Dead Sea, which contains nearly 2 billion tons of potassium chloride.

The world's largest known deposits of potassium salts are located in Canada (Saskatchewan), Russia (Verkhnekamskoe potash deposit), and Belarus (Starobinskoe potash deposit) [19,20]. Large potash reserves are located in the United States, Germany, and China [21,22]. Potash deposits have been discovered in Central and Southeast Asia, South America, West and East Africa, and North America (previously undeveloped evaporite deposits) [23–25].

In Russia and Belarus, potash mining began during the Soviet era. The Verkhnekamskoe potash deposit (Solikamsk evaporite basin) was discovered in 1925, and the Starobinskoe deposit (Pripyat basin) was discovered in 1949 [26,27]. Great prospects for the exploration of the potash industry remain in post-Soviet countries such as Turkmenistan (the Garlyk deposit), Uzbekistan (the Tyubegatanskoe deposit), and Kazakhstan (the Zhilyanskoye potash-polyhalite deposit and the Satimola mining and potash deposit) [28–30].

Today, seven potash deposits in Russia contain chloride salts (Verkhnekamskoe, Nepskoe, Gremyachinskoe, Novo-Gremyachinskoe, Yakshinskoe, Zapadno-Petrikovskoe, and Vostochno-Petrikovskoe), and two deposits contain sulfate-chloride and sulfate salts (Nivenskoe and Severo-Krasnoborskoe) (Figure 1) [31,32]. Except for the Nepskoe deposit, which is located in the north of the Irkutsk Region, all deposits are located in the European part of the country.

Potash mining activities cause severe environmental damage to the surrounding environment area [33,34]. The environmental, social, and economic problems associated with active and abandoned mines include the salinization of lands and freshwater ecosystems, ground subsidence, and the occurrence of halophyte vegetation in potash mining areas [35,36]. The impact of potash mining causes a decrease in species richness along with a decrease in the salinity gradient in freshwater ecosystems [37,38]. The direct disposal of brine into the river with extremely high chloride concentrations (up to 6 g/L) from potash mines affected aquatic fauna and caused biological degradation [39–41].

This paper looks into the environmental aspects of potash mining using the Verkhnekamskoe potash deposit (Russia) as an example. The mining of potash ores at the Verkhnekamskoe deposit is a striking example that shows all of the major features and problems associated with the mining of water-soluble ores [42]. Environmental assessment of the territory of closed and operating mines of the Verkhnekamskoe potash deposit revealed that freshwater salinization and soil salinization are caused mainly by solid and liquid waste generated by mining and processing, as well as industrial sites [43,44]. Despite extensive research into the environmental impact of potash production, a fairly complete and up-to-date literature review on potash deposit environmental protection is still rare.

The goal of this study is to summarize and analyze the environmental impact of the potash industry based on recent studies.

Figure 1. Locations of potash deposits in Russia.

The current results were classified for the purpose of developing environmental management technologies in mining based on an analysis of more than 150 recent papers published in various fields over the last 20 years, including resource management, mineral processing and waste disposal technologies, information technology, transport research, and so on.

2. Characteristics of the Verkhnekamskoe Potash Deposit

The Verkhnekamskoe potash deposit is located in the Solikamsk depression, which is one of the largest negative tectonic structures in the Pre-Ural foredeep [45]. Potash mines are currently active in the northern part of Perm Krai (Russia), in Berezniki and Solikamsk. This deposit contains sylvinite (raw material for the production of potash fertilizers), carnallite rock (for the production of synthetic carnallite for the magnesium industry), and brines (raw material for the production of soda ash, energy, and so on) [46]. Potash ore mining at the Verkhnekamskoe deposit contributed greatly to the socioeconomic development of this region and the establishment of a chemical industry center in the Solikamsk-Berezniki industrial agglomeration [47].

The Verkhnekamskoe potash deposit is one of the largest in the world. This deposit has reserves of 96.4 billion tons of carnallite rock, 113.2 billion tons of sylvinites, and 4.65 trillion tons of rock salt [48]. In 1934, the Solikamsk potash plant became the first potash producer in the Soviet Union with the commissioning of an underground potash mine, which had an annual output of 3 million tons of sylvinite and 700 thousand tons of potassium chloride (95% KCl) [49]. Following the dissolution of the Soviet Union, the Verkhnekamskoe potash deposit was mined by three companies: Uralkali, EuroChem, and Acron [50]. At the Verkhnekamskoe deposit, potash ore is mined using conventional mechanized underground mining methods at 300–465 m depths [51].

Potash ore mining at the Verkhnekamskoe Potash Deposit is distributed over 11 mining sites approved by ROSNEDRA (the Federal Subsoil Resources Management Agency). In Russia, such sites are referred to as “license sites”, which have official mining permits from the agency. Four of the mining sites are located in the central part of the deposit (Solikamsky, Novo-Solikamsky, Polovodovsky, and Borovsky), and the remaining seven mining sites are in the southern part (Bereznikovsky, Duramansky, Balakhontsevsky, Bygelsko-Troitsky, Talitsky, Palashersky, and Ust-Yayvinsky) (Figure 2). There is also a small Yuzhno-Yurchuksky mining site in the southern part of the deposit (to the northwest of the Bygelsko-Troitsky site) [48,52]. Some of the active mines are located directly beneath the cities of Berezniki and Solikamsk (populations of 148 thousand and 106 thousand, respectively) [53]. There are six producing mines in Berezniki and Solikamsk, with two more mines under construction [54].

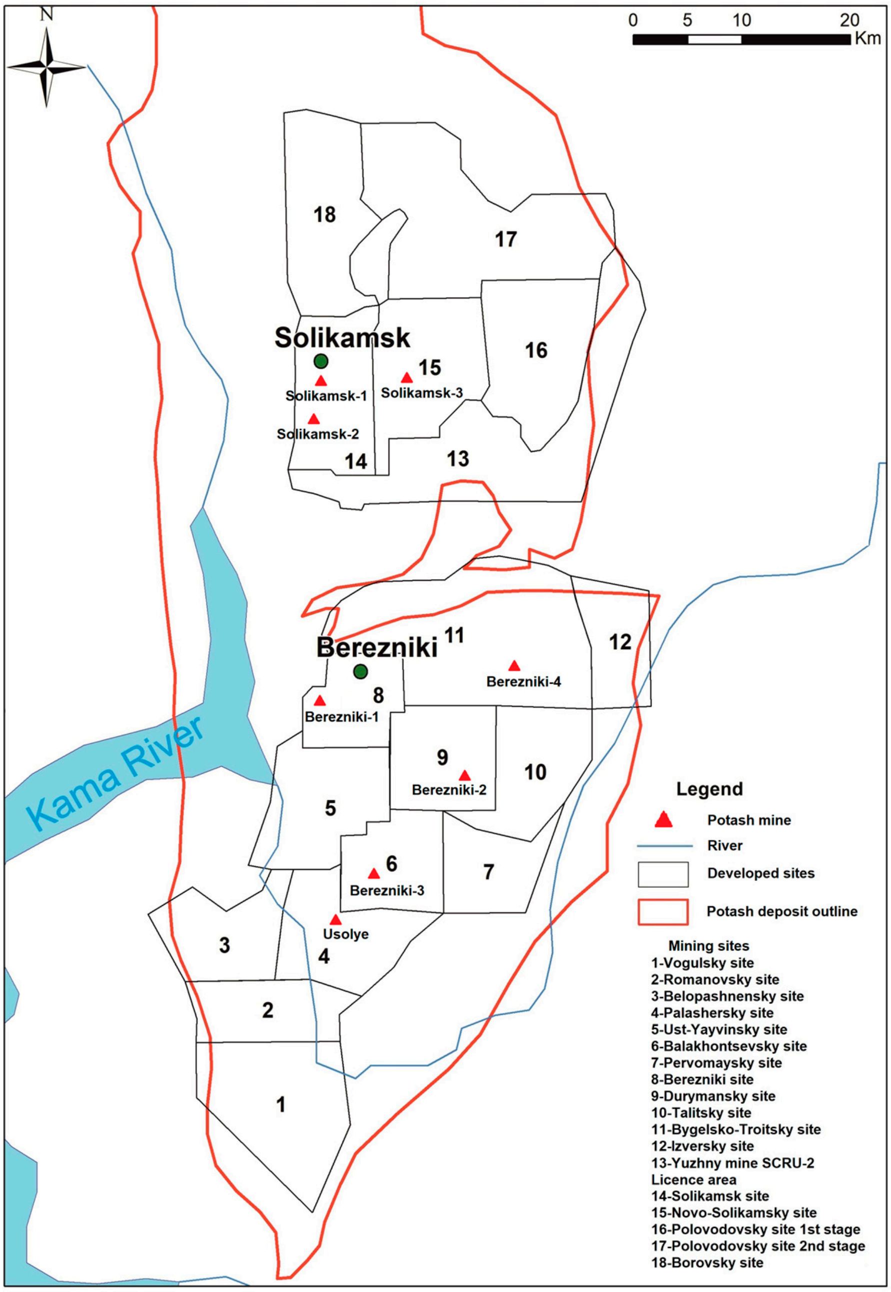


Figure 2. Map of the Verkhnekamskoe potash deposit.

The salt stratum of the Verkhnekamskoe potash deposit is shaped like a lens, has a thickness of up to 550 m, and covers an area of approximately 8.1 thousand km^2. It can be traced for 206 km in the meridional direction and up to 55 km in the latitudinal direction [55]. The salt stratum is composed of four salt layers from the Kungurian Stage (Lower Permian) [56]. The lowest underlying rock salt is composed of nearly monomineral halitites with scattered anhydrite and dolomite inclusions and rare clay and marl interlayers. Above that is a sylvinite zone with alternating layers of sylvinites and halitites, followed by a carnallite zone with intercalated carnallites and halitites. The uppermost overlying rock salt layer contains small amounts of dolomite, magnesite, anhydrite, and clay material [57]. Rocks of the Sheshma horizon (P_1šš), Upper Solikamsk horizon (P_1sl_1), and Lower Solikamsk horizon (P_1sl_2) of the Permian system are formed beneath Quaternary sediments in the study area (Figure 3) [46,58].

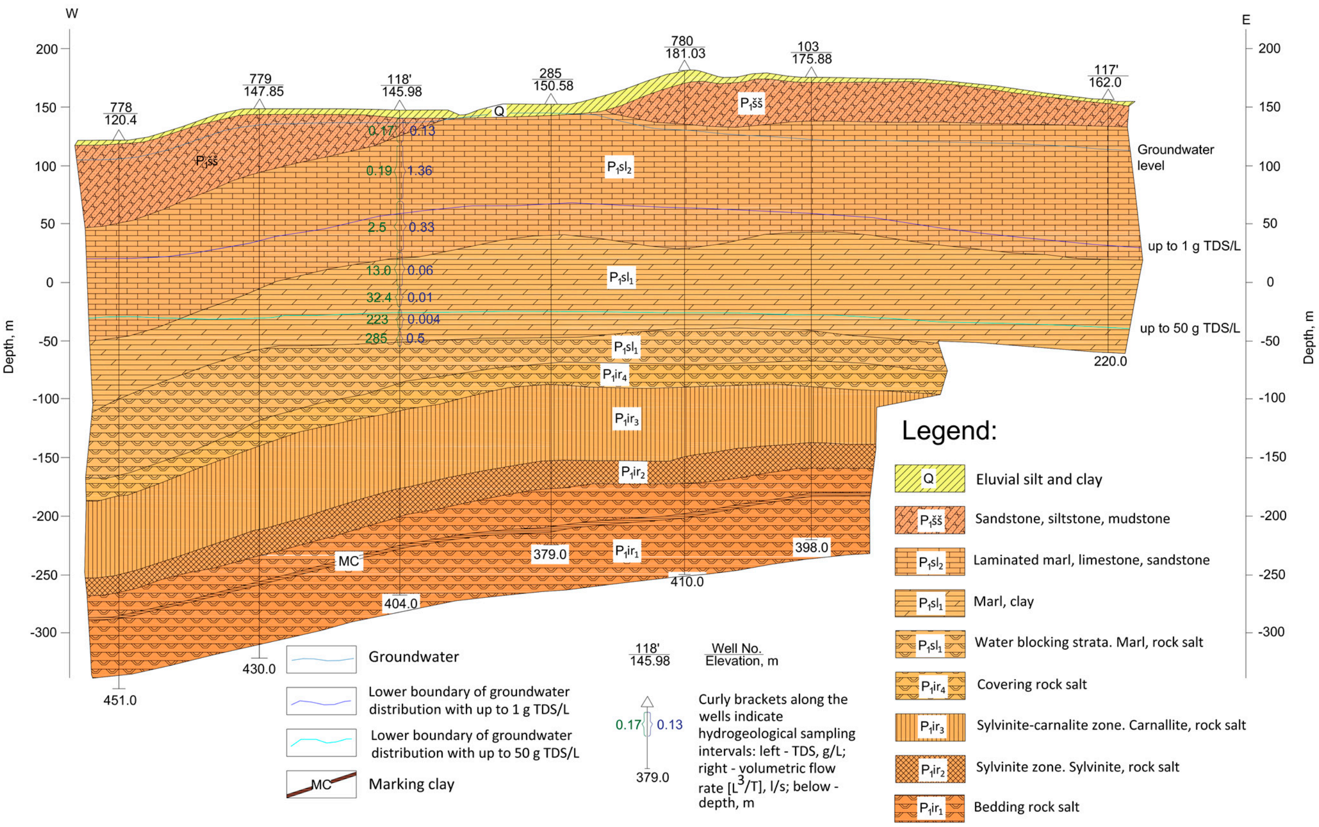


Figure 3. Geological setting of the central part of the Verkhnekamskoe potash deposit.

The potash-bearing complex in the Verkhnekamskoe deposit features only halite, sylvin, and carnallite. The content of standard $CaSO_4$ does not exceed 5.2; $CaCl_2$—0.6; and $MgSO_4$—0.2 wt % [57]. In addition to soluble sulfates and chlorides in all strata, the insoluble residue is present and distributed very unevenly both in the cross-section and in the rocks. The main minerals of insoluble residue are mainly dolomite, anhydrite, potassium feldspar, quartz, chlorite, and less frequently, illite, hematite, goethite, magnesite, gypsum, and plant detritus are present in subordinate amounts [59].

3. Potash Production Waste

The refining process at a potash mine involves several stages of separation: the ore is brought to the surface, crushed, ground, and slurried in a saturated brine of NaCl and KCl composition, and then insoluble minerals or insoluble residues are removed from the slurry using mechanical and chemical methods [60]. Potash ores contain high levels of fine water-insoluble minerals, which are referred to as “slurry” here (also, insoluble material in the waste potash ore is referred to as “slime” by various authors) [61].

The potash industry generates millions of tons of tailings (solid halite waste, clay–salt slurry, and saturated brines) [62,63]. Depending on the beneficiation method, the waste of water-soluble ores is separated into flotation and halurgic [64]. The waste generation per ton of the final product ranges from 0.99 to 4.97 tons of solid waste and 0.3 to 1.1 tons of liquid waste [65]. Potash production tailings account for approximately 75% of total production volume; the production of 1 kg of finished product generates 3 kg of waste [62,66]. Potash waste storage and disposal methods vary around the world (Table 2) and include waste disposal in potash tailings piles and tailings slurry (types of surface tailings storage facilities), underground waste storage, potash waste disposal into rivers and seas, and brine injection into deep wells [67–69]. Direct brine disposal into the River Werra (Germany) has resulted in chloride concentrations of up to 30 g/L [70]. To reduce anthropogenic salinization in the Llobregat River Basin, a 120-km long pipe was constructed to transport salt-saturated wastewater produced by potash mines in central Catalonia to the Mediterranean Sea [71]. Operation of such a long brine pipeline poses a risk of leaks and ruptures, resulting in salt-saturated inflows into rivers and adjacent lands.

Table 2. Potash production waste disposal.

Type of Waste	Disposal Method	Countries	References
Halite waste	Tailings pile	All potash mines	[72–74]
Clay-salt waste	Tailings slurry		
Brines	Tailings slurry	Verkhnekamskoe Deposit, Russia	[75]
	Rivers	Werra River, Germany	[76]
		Weser River, Germany	[38]
	Sea or an ocean	Boulby, England	[69]
		Sergipe, Brazil	[77]
		Catalonia, Spain	[78]
	Deep well injection for the waste brine disposal	Saskatchewan, Canada	[12]
		Northeast Thailand	[79]

The chemical composition of halite waste varies depending on the beneficiation method. The dominant component in halite waste after the halurgic method is NaCl (94.30 mass fraction, %), followed by $CaSO_4$, KCl, insoluble residue, $H_2O_{cryst.}$, $MgCl_2$, Br^- [64]. The chemistry of halite flotation waste of potash processing is the following: NaCl (87.78 mass fraction, %), followed by KCl, $CaSO_4$, $MgCl_2$, insoluble residue, $H_2O_{cryst.}$, Br^- [80]. Fine tailings (clay–salt slurry) and excess brine from potash production are stored in tailings slurry and brine ponds, respectively [81].

From 2011 to 2021, the amount of waste generated by potash mining and processing operations at the Verkhnekamskoe deposit increased steadily from 26 million tons to 41 million tons per year, with an average of 32 million tons. More than 270 million tons of solid waste (halite waste) and more than 30 million m^3 of liquid waste (clay–salt slurry) have already accumulated on the Verkhnekamskoe deposit's territory [82]. At the same time, over the 65-year operation of the Starobinskoe deposit (Belarus), 980 million tons of halite waste and 115 million tons of clay–salt slurry have been accumulated [83]. Since the start of mining at the Tyubegatanskoe potash deposit (Uzbekistan) in 2010, more than 6 million tons of potash waste have been accumulated, with the potash plant producing 1.2 million tons of sylvinite ore per year with 27% of KCl in the ore [84].

At the Verkhnekamskoe deposit, solid and liquid wastes from the Solikamsk and Berezniki potash mines were generated during ore processing (by flotation or halurgic methods) and disposed of in tailings pile and tailings slurry [85]. Mineral composition in the liquid waste after halurgic processing are the following: anhydrite (22 wt. %), potassium feldspar (18 wt. %), sylvin and quartz (16 wt. %), dolomite (14 wt. %), halite (11 wt. %), and insignificant content of pyrite and chlorite. Flotation liquid waste is practically the same as the halurgic method [86].

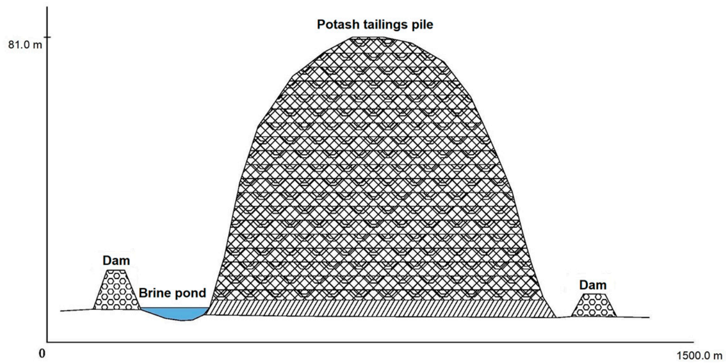
Waste is stored on a specially prepared rock pile site, which is surrounded by dams and has access roads. After processing, a conveyor transports the waste to the potash tailings pile [87]. Various authors also refer to the potash tailings pile as the salt tailings pile or the salt dump [35,39]. Figure 4 shows examples of potash waste disposal facilities (potash tailings pile and tailings slurry) on the Verkhnekamskoe deposit's territory.

(**a**)

(**b**)

Figure 4. Potash ore processing waste disposal facilities on the Verkhnekamskoe deposit's territory: (**a**) potash tailings pile; (**b**) potash tailings slurry.

At the world's largest potash production sites, the total area of land withdrawn for a salt tailings pile exceeds 5600 hectares [81]. To date, the total area of land allocated for the salt tailings pile at the Verkhnekamskoe deposit is 8.69 km^2, while the tailings slurry covers 7.12 km^2. In 2021, the total area of disturbed land due to the negative impact of the potash tailings pile and tailings slurry facilities was 135.7 hectares. The Potash tailings pile's height at the Verkhnekamskoe deposit ranges from 64 to 97 m. It is up to 2200 m long and 940 m wide. The total thickness of the salt dump's rocks is 81 m, which was discovered after drilling. At the drilling site, grayish-white, grayish-brown, coarse-grained, and low-moisture salts were found in the section. They were dumped between 1981 and 1987 (Figure 5a). The potash tailings pile is saturated with brine, starting at a depth of 41.7 m. Brines are generated when the solid phase of waste is compacted, and the liquid phase is squeezed (Figure 5b). These are typical processes for potash tailings piles.



(**a**)

(**b**)

Figure 5. (**a**) Potash tailings pile scheme based on drilling data; (**b**) photographs from the site showing the brine pond and potash tailings pile at the Verkhnekamskoe deposit.

Liquid waste is a suspension containing a solution saturated with NaCl and KCl, solid particles of the same salts, and clay minerals, which is disposed of as tailings slurry at the Berezniki and Solikamsk potash mines [88]. The tailings slurry at the Verkhnekamskoe deposit is filled with clay–salt slurry saturated with brine (101–300 g/L). In Belaruskali, tailings slurry facilities contain up to 350 g/L of brine [89–91]. Since the mid-1970s, approximately 8 million m^3 of liquid waste has been accumulated in the tailings slurry at the Balakhontsevsky mining site of the Verkhnekamskoe deposit [92].

Long-term disposal of liquid and solid potash waste in tailings at the Verkhnekamskoe deposit using compacted clay liner became one of the most significant environmental risks associated with the migration of salt contaminants into the surrounding environment and groundwater [93]. Liquid potash waste is stored in containment facilities surrounded by dams and equipped with geosynthetic clay liners, cut-off walls, drainage zones, leachate collection systems, and/or containment wells for seepage control and collection [94]. Potash tailings have historically been mostly compacted clay lined, but increasing in their use of geotextile geomembrane liners in recent times (Figure 6). Highly efficient materials (such as high-density polyethylene geomembrane) are being used to protect groundwater from the release of saturated brine and salt-contaminated rain water from potash tailings slurry [95,96].

Figure 6. Use a geomembrane in new tailing slurry facility of potash mine at the Verkhnekamskoe deposit (Balakhontsevsky mining site).

4. Environmental Consequences of Potash Mining

Potash tailings piles and tailings slurry are thought to be the primary sources of salinization of surface water and groundwater at the Verkhnekamskoe deposit (Russia) [82,83,92,97], the Starobinskoe deposit (Belarus) [27,74], the Alsatian deposit (France) [98], and the old potash deposit in Germany [99]. Potash wastes transform the chemical composition of groundwater and surface water, which results in landscape degradation and land disturbance [100]. According to preliminary estimates, the potash tailings pile contributes insignificantly to groundwater salinization when compared to tailings slurry facilities.

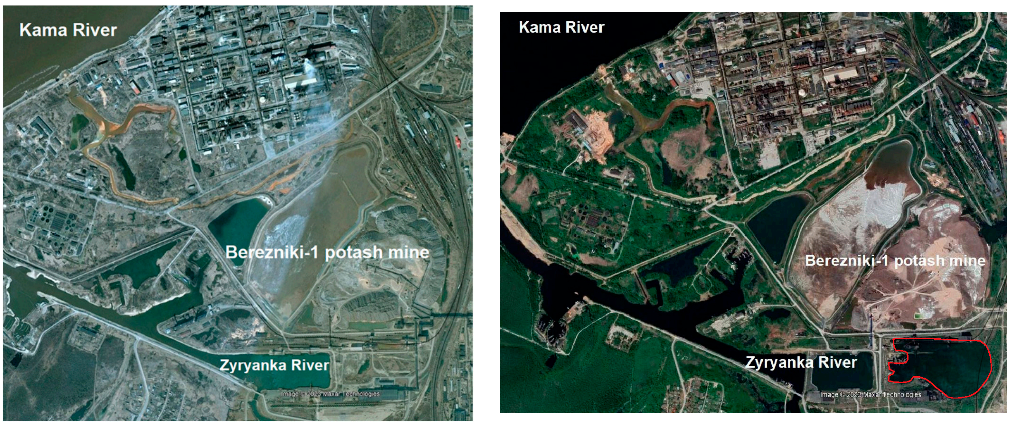
Saline contaminants in humid climates enter the environment much faster from potash tailings. Uncontrolled discharge of hypersaline effluents from potash waste disposal sites is an important source of groundwater salinization and surface water. Potash mining activities significant influence the chemical composition of groundwater, which is predominantly Na-Cl in composition. The hydrochemical type of groundwater and surface water changed from an HCO_3-Ca type to a Cl-Na type with high salinity [82,92]. At the Verkhnekamskoe deposit, the most salt-affected alluvial plain landscapes are located in the area affected by potash mine tailings facilities [101].

4.1. Ground Subsidence

The safe and efficient use of the Verkhnekamskoe deposit subsoil is heavily reliant on mining and geological survey, as well as waterproof formation studies [102]. The main challenges of mining at the Verkhnekamskoe potash deposit are the high solubility of potash salts, the water content of the rock mass overlying the salt massif, the risk of groundwater inflow into mine workings, and subsequent flooding of the mine. Water-soluble ore mining is unique due to the need to protect mine workings from the inflow of freshwaters [103].

The practical background of potash mine operations shows that the savings on backfilling mined spaces outweigh the financial losses in the event of mine flooding. For example, the lost profit from flooding a mine with approved reserves for 20 years of mining will be around 60 billion rubles [104].

At the Verkhnekamskoe deposit, several well-documented subsidence/collapse sinkholes were caused by the flooding of potash mines in Berezniki and Solikamsk [105]. The Berezniki-3 potash mine was flooded in 1986. Later, in 2006, one of the world's largest accidents in water-soluble ore extraction occurred at the Berezniki-1 potash mine [106,107]. The inflow of water into the underground mine at a rate of 1200 m^3/h caused flooding and the closure of the mine, resulting in the destruction of underground workings [108]. The accident at the Berezniki-1 potash mine jeopardized the operation of urban and industrial buildings and structures above the mine (Figure 7a) [109]. Five sinkholes have formed since the flooding [110]. The largest sinkhole (440 × 320 m) is currently completely flooded by groundwater (Figure 7b). As a result, extensive monitoring was initiated following the mine flooding, including control over seismicity, hydro-geological parameters, and gravimetry [111]. The observations show that uneven building subsidence occurs almost continuously at a nearly constant rate, with the exception of a few buildings where the rate of deformation has increased over time. The potash company spent 16.5 billion rubles to mitigate the consequences of the Berezniki-1 potash mine accident. The mitigation measures included the construction of a new railway, a new neighborhood and its infrastructure, and citizen resettlement [112].



(**a**) (**b**)

Figure 7. The Berezniki-1 potash mine location; the background image was obtained from Google Earth: (**a**) May, 2006; (**b**) May, 2010; the red line—collapse of the Berezniki-1 potash mine.

One of the most recent collapse sinkholes (152 × 181 m) occurred in 2014, 2.3 kilometers from the Solikamsk-2 potash mine (Figure 8a), as a result of the groundwater inflow to the mine at a rate of 150 m^3/h [113]. A set of measures was implemented to mitigate the consequences of the accident. A dewatering system was installed; water was pumped through 32 water interception wells (25 million m^3/year); a seepage curtain was built; plugging through 34 inclined wells on the perimeter of the failure was implemented; 1.7 million m^3 of clay solution was injected; and 395,000 m^3 of clay material was backfilled [112]. The sinkhole has now been eliminated, and the situation continues to be monitored (Figure 8b).

Sinkholes occurred in linearly elongated zones of large tectonic faults on the territory of the Verkhnekamskoe Deposit in 1986, 2007, 2010, 2011, and 2014 [114]. The analysis of mine engineering situations and mining and geological conditions at 11 emergency sites with sinkholes in salt mines in Canada, the United States, Spain, Russia, France, Germany, and Belarus is associated with the locations of water-conducting cracks in the mined rock mass in the area of the water-protective layer above productive salt layers. In these areas, zones with unusual geological structures were discovered in the water-protective stratum [113,115]. According to surveys conducted over the Alsatian potassic basin [116], surface subsidence decreases rapidly after mining is completed.

Subsidence control measures are being implemented at all underground potash and potassium–magnesium ore mining sites around the world [117,118]. At the Verkhnekamskoe deposit, the following integrated system of geological environmental monitoring is used: "Data of detailed and operational geological exploration", "Land subsidence", "Hydrogeological monitoring", "Monitoring of mining and stowing operations and the state of workings", "Monitoring of the physical and mechanical properties of the rock mass", "Data on gas-dynamic phenomena", "Seismological monitoring", "Seismic monitoring", and "Hydrogeodeformational monitoring" [119,120].

(**a**) (**b**)

Figure 8. Solikamsk-2 potash mine location; the background image was obtained from Google Earth: (**a**) August, 2016; the red line—collapse of the Solikamsk-2 potash mine; (**b**) August, 2022; the green line—the eliminated collapse sinkhole.

4.2. The Impact of Potash Mines on the Chemical Composition of the Atmosphere

The chemical composition of atmospheric precipitation (snowmelt) in potash mining areas around the world has changed over the last century [121–123]. In potash mining areas, the main water-soluble ions in the atmosphere are associated with NaCl in the composition of the atmospheric dust coming from the salt mine shaft to the surface [124]. Salt dust easily migrates from mine workings through air flow, aided by potash salt mine dedusting solutions and mining equipment [125]. The potash mine aerosol in underground chambers contains sodium chloride, which constitutes more than 80% of particulate matter. It is highly soluble in water, mainly in a dissociated state [126].

The impact of the potash industry on the chemical composition of atmospheric air can be assessed using snow measurements, considering the average duration of snow cover in Perm Krai (174 days; 124 to 203 days if the snow is scattered) and its high sorption capacity [127]. For more than ten years, the authors have been conducting such studies in the area affected by potash mining. The snow sampling procedure is shown in

In the area affected by atmospheric emissions from the Verkhnekamskoe potash deposit plants, the chemical composition of the snow reflects the input of potash extraction and processing ingredients—Cl^-, Na^+, and K^+ [128]. High values of Cl^-/Na^+, Cl^-/SO_4^{2-}, and Na^+/K^+ ratios in snowmelt indicate increased contributions to air emissions from potash plants [129]. In comparison to the average characteristics of snowmelt water in the Berezniki urban district, the TDS level is high in the area from the SPZ (sanitary protection zone) border to the residential area, with its maximum level in the transport zone. It is considerably lower in the mining area and even lower in the recreational area (Table 3). Snowmelt water in potash mining areas is acidic, with an average pH of 5.27. In contrast to other parts of the city, the priority ions in snowmelt water within the potash mining area are Na^+, K^+, and Cl^-. Figure 9.

(**a**) (**b**)

Figure 9. Snow sampling procedure: (**a**) measuring the height of the snow cover; (**b**) weighing the snow.

Table 3. Average values of the major ions in snowmelt in the Berezniki urban district.

Parameter	Unit	Potash Mines		Functional Zones of Berezniki		
		On the Territory	At the SPZ Border	Transport	Residential	Recreational
pH	-	5.27	6.18	7.04	6.82	6.21
HCO_3^-	mg/L	4.01	21.97	2.19	9.31	3.42
SO_4^{2-}	mg/L	1.31	0.96	0.59	1.15	0.83
Cl^-	mg/L	7.35	6.59	2.94	1.67	0.65
NO_3^-	mg/L	1.97	1.57	0.45	1.64	1.29
Ca^{2+}	mg/L	0.95	0.99	6.64	2.68	0.89
Mg^{2+}	mg/L	0.26	<0.25	0.40	<0.25	<0.25
Na^+	mg/L	2.68	1.78	1.40	1.32	0.52
K^+	mg/L	2.78	3.94	1.19	0.96	0.60
TDS	mg/L	19.77	34.50	42.95	39.20	16.70

The hydrochemical type of snowmelt on the territory of potash plants ranges from Cl^--K^+-Na^+ to HCO_3^--NO_3^--SO_4^{2-}. Snowmelt at the SPZ border is dominated by the HCO_3^--Cl^--K^+ set, whereas snowmelt in other areas of the Berezniki urban district is dominated by HCO_3^--Ca^{2+} associations. The identified anomalies in the potash mining area are local in nature and do not extend beyond the enterprises' SPZ.

4.3. The Impact of Potash Waste on the Chemical Composition of Surface Water

At the Verkhnekamskoe deposit, salinization of the freshwater ecosystem caused by the effect of potash tailings is currently widespread in local rivers. Mainly, potash mine tailings cause surface water salinization in the Lyonva River on the Balakhontsevsky mining site. In natural conditions, the rivers at the Verkhnekamskoe deposit have a calcium-hydrocarbonate chemical composition, but brine-impacted waters from several potash mine tailings changed the river water's composition into a sodium chloride composition in 2018–2019 [92] and 2020.

Table 4 shows the high TDS levels and water-soluble ion content of the Lyonva River. The presence of potash mines and tailings facilities in the upper and middle reaches of the Lyonva River (Figure 10) greatly affects its chemical composition. In the upstream (sampling point 1) of the Lyonva River, 12 g/L of TDS were found. After the brine inflow from the potash tailings slurry and a series of salt spring discharges, 14 g/L of TDS and 12 g/L of Cl^- were found in the midstream (sampling point 2). High contents of soluble salts and TDS persist up to the area near the Lyonva River mouth (sampling point 3): 8.3 g/L (Cl^-), 2.5 g/L (Na^+), 1.8 g/L (K^+), and 18 g/L (TDS).

Table 4. Chemical compositions of the Lyonva River and the background river.

No.	Lyonva River	Distance from Sampling Point to the River Mouth, km	pH	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	TDS
				g/L							
1	Upstream	16.6	7.4	0.19	0.06	3.64	1.07	0.21	1.26	1.05	12.1
2	Midstream	10.2	7.1	0.18	0.23	12.06	1.00	0.20	3.17	1.20	14.1
3	Downstream	1.7	7.2	0.13	0.11	8.31	1.21	0.27	2.57	1.87	18.4
B	Telepayevka River (background concentrations)		6.8	0.18	0.01	0.15	0.09	0.02	0.01	<MDL *	0.4

* MDL-method detection limit.

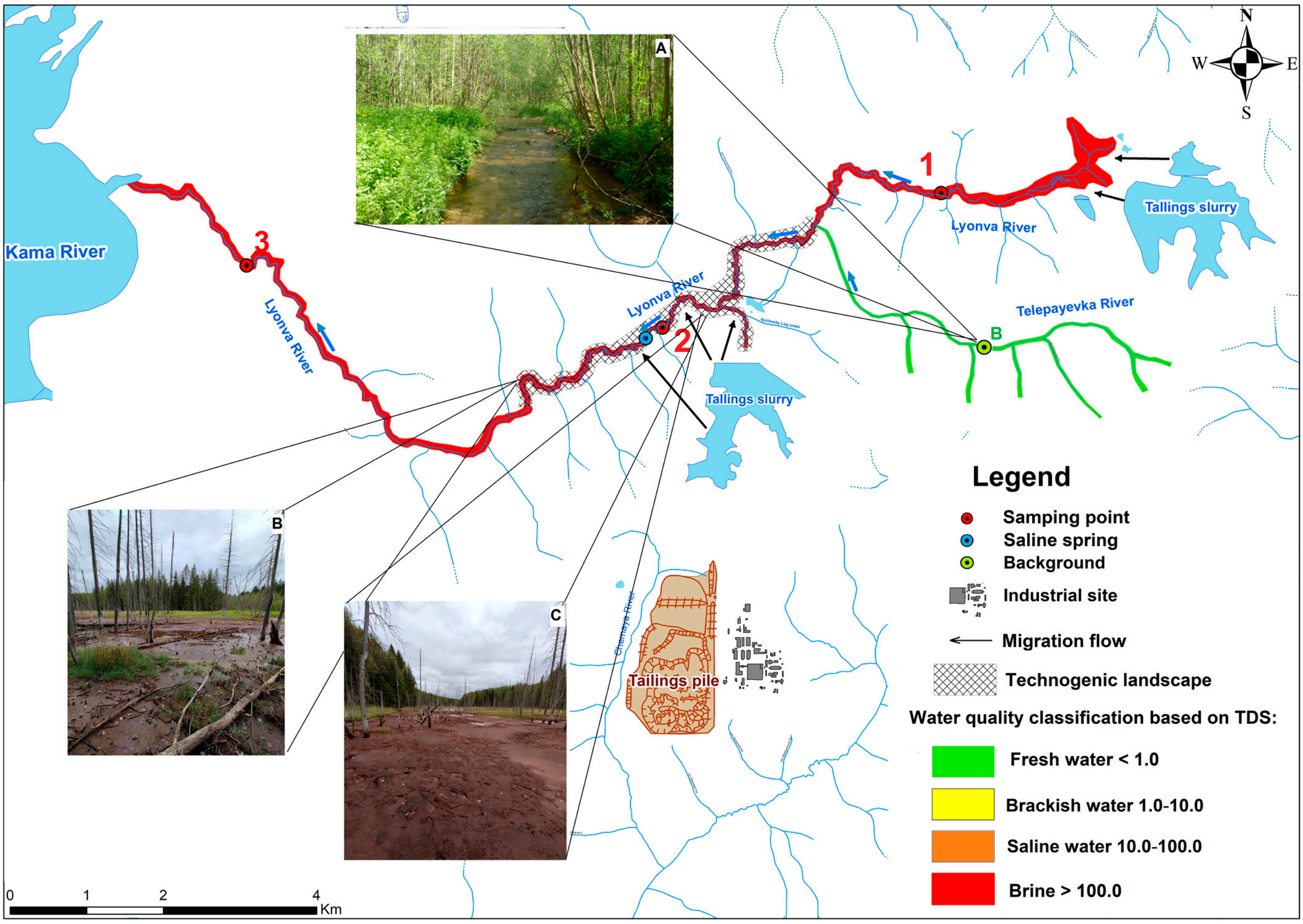


Figure 10. Location of sampling point in the area affected by the potash tailings slurry and tailings pile in the Lyonva River (Balakhontsevsky mining site).

The total length of the Lyonva River is 21 km, of which approximately 17 km is subject to salinization (Cl and Na ions predominate). TDS values in the Lyonva River exceed those of the background sampling point in the Telepayevka River by 30–45 times.

Freshwater salinization on the territory of the Verkhnekamskoe Deposit is accompanied by a decrease in total biomass, a decrease in species diversity in aquatic ecosystems with a predominance of halophilic rotifers and copepods, and a disturbance in the fish population [130]. The values of algocenoses' structural indicators (biomass and density) are lower in rivers with high salinity [131]. Thus, long-term discharge of Cl^-–Na^+ effluents from waste disposal sites alters the chemical composition of groundwater and surface water and causes soil salinization in river floodplains affected by potash mining [82,83,92].

4.4. The Impact of Potash Waste on the Chemical Composition of Groundwater

The impact of surface potash waste storage is the most important factor influencing groundwater composition [132,133]. The main environmental problem for the potash industry is vertical or lateral brine migration from the potash tailings to groundwater and soils. The chemical composition of groundwater in the aquiferous Upper Solikamsk horizon (P_1sl_2) was studied as an example of such an influence. It is the primary fresh groundwater collector, and it can be found in the Upper Permian sediments of the Verkhnekamskoe deposit's upper profile (Figure 3).

The groundwater of the Upper Permian Solikamsk sediments above the Kama River valley level (105–110 m) is mainly fresh with a hydrocarbonic magnesium–calcium and calcium–sodium composition (up to 0.6 g/L). Below it are saline waters of mainly chloride–sulfate, sulfate–chloride, and rarely sulfate composition with 1.6–14.0 g/L of TDS, which are replaced by chloride-rich brines with depth [46].

The study area is located in the northern part of the Novo-Solikamsky mining site of the Verkhnekamskoe potash deposit (Figure 11). The highest elevations (220–251 m) on the Usolka River's left bank are in the watershed between the Usolka and Selyanka Rivers, where potash mining waste disposal facilities are located. The lowest elevations (110–120 m) are found in the Usolka River, where springs S1–S4 are located.

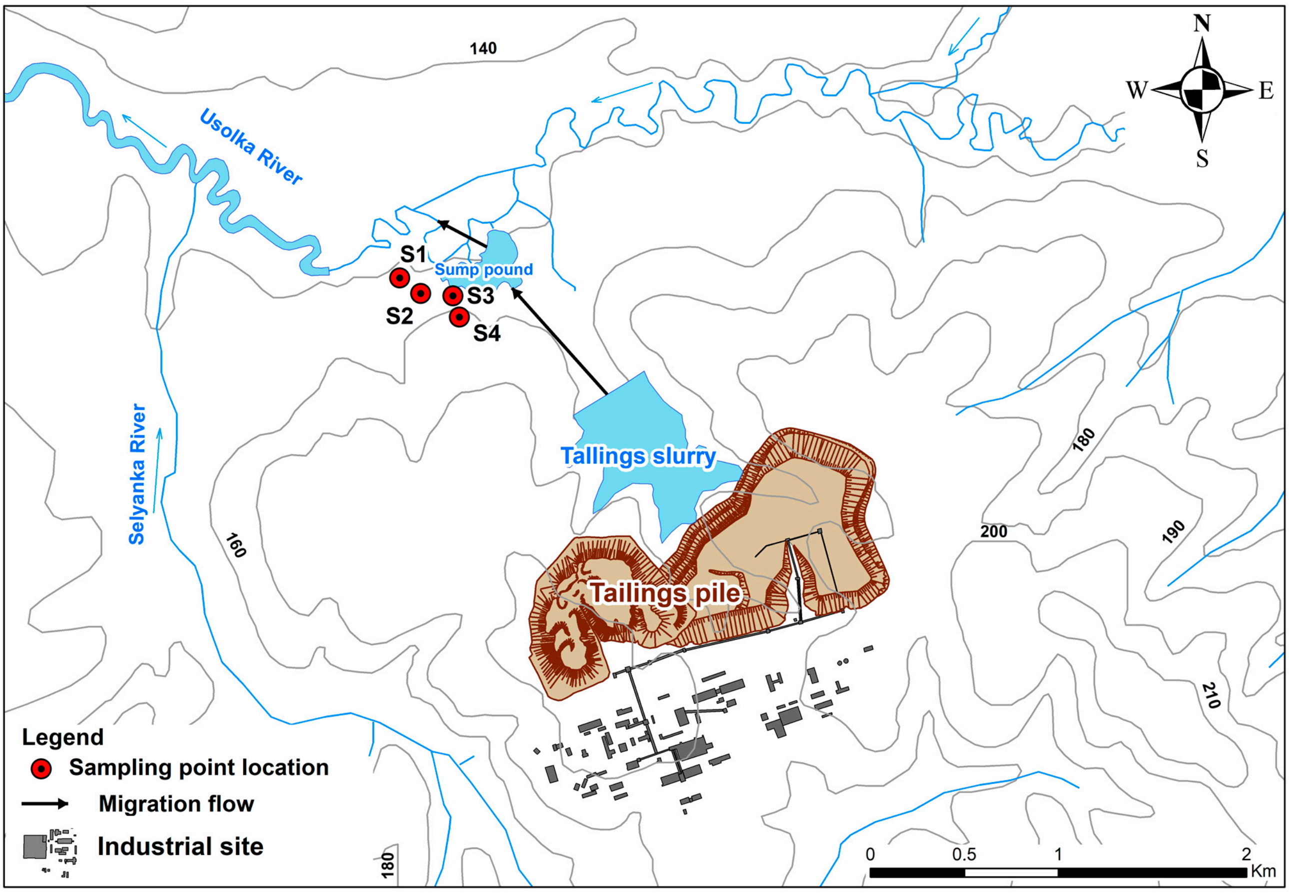


Figure 11. Location of springs in the area affected by the potash tailings slurry and tailings pile of the Novo-Solikamsky mining site.

A group of springs discharged on the southwestern shore of a technogenic lake located 800 m northwest of the tailings slurry was studied to characterize technogenic changes in the chemical composition of spring runoff. From 1998 to 2016, springs were sampled four times a year during major phases of the hydrological cycle (winter low flow, spring flood, summer–autumn low flow, and autumn floods). A total of 59–60 samples were examined each spring. Table 5 shows the findings of the studies. The ionic composition was characterized based on the OST 41-05-263-86 ionic composition formula.

According to spring sampling, groundwater in the Upper Solikamsk horizon has a calcium–sodium chloride composition. The waters are neutral according to the pH value, and the concentration of bromides increases proportionally to the increase in mineralization. There is a consistent seasonal increase in dissolved substances during low flow periods. There are no signs of natural salinization of groundwater (seen as an increase in the concentration of sulfate ions).

The most saline spring (S1) has Cl^--Na^+ hydrochemical facies, while the less-saline springs (S2–S4) have an Cl^--Na^+-Ca^{2+} facies. The heterogeneous filtration characteristics of the aquifer can cause differences in the chemical composition of groundwater in different springs. As a result, sodium chloride water from a tailings slurry can reach the discharge point faster (sampling point S1) or slower. The filtration rate determines the degree of dilution of the brine with fresh groundwater and the intensity of ion exchange reactions that enrich calcium ions.

The processes of chloride water formation with high concentrations of calcium and magnesium cations within mining areas of the Verkhnekamskoe deposit were studied in a laboratory using brines and soil samples. The findings of the "brine-rock" system interaction study confirmed the occurrence of ion-exchange processes between the solid phase of rocks and the liquid phase of the brine. Calcium and magnesium ions enter saturated brines, which, after further dilution, form groundwater with atypical magnesium–calcium and calcium–sodium chloride compositions. Exchangeable sodium and potassium are present in soil [134,135].

Table 5. Chemical composition summary of the Upper Solikamsk subformation springs in the area affected by potash surface tailings storage facilities, based on monitoring data from 1998 to 2016.

Spring No.	Ionic Composition Formula	Hydrochemical Facies	Variations in TDS, g/L (Seasonal Average)			
			Winter Low Flow	Spring Flood	Summer–Autumn Low Flow	Autumn Floods
S1	$M_{15,95}\frac{Cl\ 98\ HCO_3 1\ SO_4 1}{Na\ 48\ Ca\ 29\ Mg\ 16\ K7}pH\ 7.2\ Br\ 47.1$	Cl^--Na^+	12.7	14.9	23.7	13.1
S2	$M_{3.64}\frac{Cl\ 94\ HCO_3 5\ SO_4 1}{Na\ 40\ Ca\ 37\ Mg\ 19\ K4}pH\ 7.5\ Br\ 5.7$	Cl^--Na^+-Ca^{2+}	3.8	3.4	4.8	2.7
S3	$M_{7.06}\frac{Cl\ 97\ HCO_3 2\ SO_4 1}{Na\ 47\ Ca\ 33\ Mg\ 13\ K6}pH\ 7.4\ Br\ 10.4$	Cl^--Na^+-Ca^{2+}	6.5	6.3	10.1	5.3
S4	$M_{2.42}\frac{Cl\ 91\ HCO_3 7\ SO_4 2}{Na\ 44\ Ca\ 38\ Mg\ 16\ K2}pH\ 7.5\ Br\ 2.7$	Cl^--Na^+-Ca^{2+}	2.3	2.3	2.7	2.4

The results of springs sampling (the discharge of which occurs near existing potash plants and surface tailings storage facilities) showed a considerable change in groundwater chemical composition. These springs are characterized by a significant increase in the levels of salinity and general hardness, and the water facies have evolved from HCO_3-Ca type to Na-Cl type. Groundwater salinization caused by potash tailings has shown similar results in Germany and France [98,136].

4.5. The Impact of Potash Waste on the Chemical Composition of Soils

Potash tailings caused the salinization of floodplain soils of the Lyonva River and Chyornaya River (Balakhontsevsky mining site of the Verkhnekamskoe deposit) (Figures 12 and 13). Soddy-podzolic soils typical of the taiga zone are most common on the territory of the Verkhnekamskoe potash deposit. This type of soil forms in coniferous forests and has low agrochemical properties, is acidic, and has a humus content of 2–6% on average. Soddy-podzolic soils on sandy and sandy loamy rocks are structureless. Sandy loamy soils with a large silt fraction may have a fragile structure: layered in the podzolic horizon and a fragile cloddy in the texture-differentiated (illuvial) horizon.

Three soil samples were collected in the area from potash tailings slurry, downhill, and towards the Lyonva River floodplain. The soils were sampled at three different distances from the potash tailings slurry on three different types of geochemical landscapes: sampling point 1–140 m from the tailings slurry (eluvial landscape); sampling point 2–770 m from the tailings slurry (transit landscape); and sampling point 3–1250 m from the tailings slurry (alluvial landscape in the Lyonva River floodplain). The elevation of the relief between the potash tailings slurry and the Lyonva River floodplain is 180 and 130 m.

Sampling point 1 has no distinct soil horizons and no underlayer. It has a large number of crushed stone inclusions, a loose structure on the surface, and a more solid structure at depth. The granulometric composition is clayey and heavy loamy. The WRB (2015) [137] classifies this soil as a technogenic surface formation (Technosols Loamic). Low SAR, Cl^-, Na^+, and $SO_4{}^{2-}$ values in the soil indicate no salinity (Table 6).

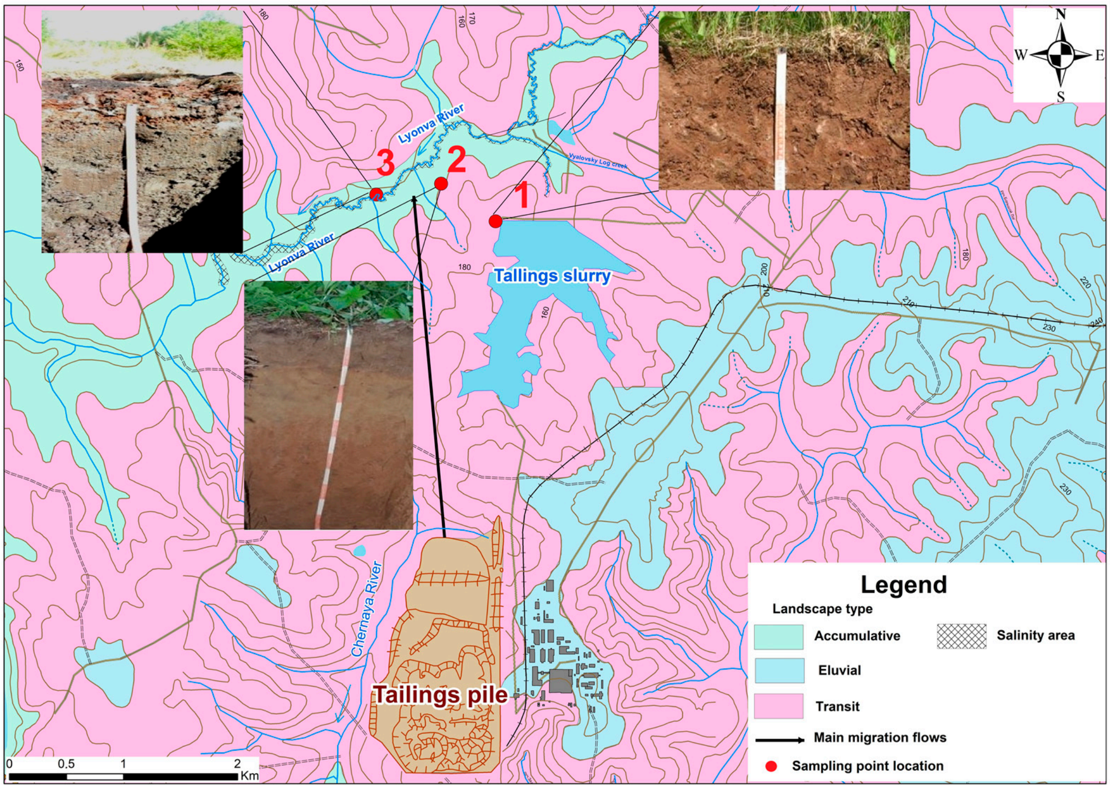


Figure 12. Locations of soil sampling points in the area affected by the potash tailings slurry and tailings pile of the Balakhontsevsky mining site.

Table 6. Content of SAR, Cl^-, Na^+, and $SO_4{}^{2-}$ in soils affected by the potash tailings slurry.

Parameter	Sampling Point 1	Sampling Point 2	Sampling Point 3
	Soil Type		
	Technosols Loamic	Podzols	Chloridic Gleyic Fluvic Solonchak
SAR, %	0.5–1.0	1.00	3.0–16.0
Cl^-, g/kg	0.125–0.135	0.011–0.138	30.1–193.0
Na^+, g/kg	0.025–0.210	0.05–0.035	9.5–46.4
$SO_4{}^{2-}$, g/kg	0.011–0.027	0.004–0.027	1.03–7.8

Sampling point 2 (transit landscape) is located in a mixed forest. This soil is classified by the WRB (2015) as a typical soddy-podzolic sandy loam soil and Podzols (Figure 12) [131]. This type of soil has no structure and an extremely low water-holding capacity. The humus content ranges from 1.5 to 6% in the humus horizon and 0.2 to 0.5% in the illuvial horizon. Sampling point 2 is located on a slope; therefore, the SAR, Cl^-, Na^+, and SO_4^{2-} values indicate no salinity (Table 6).

The soil profile (sampling point 3) in the Lyonva River floodplain was chemically and physically altered as a result of strong salinization processes. Soil salinization centers are most prominent in superaqueous (accumulative) landscape types, where saline groundwater in the Lyonva River valley discharges areally. The groundwater has a Cl-Na composition, with chloride concentrations ranging from 6.5 to 26 g/L, and sodium concentrations ranging from 2.5 to 11.0 g/L [83]. This saline groundwater was formed as a result of brine filtration through the dam of the tailings slurry. The salinization process transformed the alluvial soil into a secondary gleyic Chloridic Gleyic Fluvic Solonchak (Hypersalic, Loamic, Technic), according to the WRB Classification (2015) [137] (Figure 12, Point 3) [92]. In sampling point 3, a salinity gradient was detected. Elevated values of SAR, Cl^-, Na^+, and SO_4^{2-} are presented in Table 3 and indicate a high soil salinity at this sampling point.

Soil salinization has also been found in the floodplains of the Chyornaya River, the Volim River (Balakhontsevsky mining site), the Popovka River, the Usolka River (Solikamsk mining site), and the Bygel River (Bygelsko-Troitsky mining site) [83,133]. According to [92,138], the potash waste transformed typical alluvial humic gley clay soils in the superaquatic (accumulative) landscapes of the Lyonva River, Chyornaya River, and Bygel River into various types of solonchak. Salinization of alluvial soil (in local river floodplains) is mainly caused by the brine inflow from potash tailings (lateral movement of released brine into freshwater aquifers).

Soil salinization is associated with brine filtration from the potash tailings pile in the Chyornaya River floodplains (alluvial soil types) (Figure 13a). The topsoil (up to 0.1 m) of these alluvial soils contain cations and anions in the following order (by concentration): $CO_3^- > Cl^- > SO_4^{2-}$. The predominant cations and anions HCO_3^-, Na^+, and Cl^- reach the following values: 0.52 g/kg, 0.15 g/kg, and 0.12 g/kg, respectively. The subsoil (up to 0.4 m) has the highest salt concentration with the following order (by concentration): $Cl^- > HCO_3^- > SO_4^{2-}$. Major ion concentrations (Cl^-, Na^+, and K^+) are 0.46 g/kg, 0.22 g/kg, and 0.14 g/kg, respectively. Moose traces are frequently found in saline areas (Figure 13b). High salt concentrations in such areas compensate for a lack of salt in horned males as well as pregnant and lactating females.

The highest salt concentrations were found in alluvial soils in superaqueous (accumulative) landscapes and river floodplains. Saline areas form at the base of slopes where swampy areas exist. The stagnant hydrodynamic regime in these areas enhances salt concentrations and creates an environmentally hazardous situation. Transformed alluvial soils of the Lyonva River and the Chyornaya River have a salinity gradient as a result of the long-term influence of highly saturated brine from potash tailings mine on the territory of the Balakhontsevsky mining site.

(a) (b)

Figure 13. (**a**) Salinization processes in the Chyornaya River floodplain sections in areas affected by the potash tailings pile; (**b**) moose traces in the salinity zone.

Salinization of the fertile soil layer was found near the Soligorsk mining district (Belarus) [139]. High contents of soluble salts and trace elements were found in soils affected by the Soligorsk potash plant [140]. In comparison to the background values, an excess amount of K^+, Na^+, and Cl^- (7–10 times) was found at the SPZ border. At a distance of 3 km from the plant, the excess is 3–5 times greater, and at a distance of 10 km, the excess is 1.5 times greater. Salinization in the floodplain soil of the Werra River (Germany) had a strong depressive effect on the microbial biomass and shifted the microbial community structure [141]. The salinization process in the Werra River floodplain is caused by saline liquid residues injected into the underground geological formations.

4.6. The Impact of Potash Waste on the Vegetation

Based on the monitoring data, two vegetation groups can be distinguished in areas of stable and unstable salinization near the potash tailings pile of the Solikamsk-1 and Solikamsk-2 potash mines [142]. In the stable salinization zone (1–5 m from the potash tailings pile), vegetation communities have low projective cover (no more than 10–30%) and low species diversity. Typical species for this area are blue lettuce (*Lactuca tatarica*), oak-leaved goosefoot (*Chenopodium glaucum*), weeping alkali grass (*Puccinellia distans*), bush grass (*Calamagrostis epigeus*), dandelion (*Taraxacum* spp.), and bull's-foot (*Tussilago farfara*). Grasses were also found in this area (*Agropyron repens, Bromus inermis,* and *Poa pratensis*).

The predominant part of the Solikamsk-1 and Solikamsk-2 potash mines of potash tailings piles (unstable salinization zone at 5–90 m from the tailings piles) were occupied by ruderal communities with a predominance of perennial grasses (*Calamagrostis epigeios, Bromus inermis, Agropyron repens,* and *Phleum pratense*) and herbaceous elements (*Lathyrus pratensis, Leucanthemum vulgare, Melilotus albus, Trifolium repens,* etc.); projective cover is 100% (Figure 14). This plant grouping represents the pre-meadow stage of regenerative succession.

Figure 14. Grass and reedgrass meadow near the potash tailings pile of the Solikamsk-2 mine.

The vegetation near the potash tailings pile is represented mainly by meadow plant communities (the Verkhnekamskoe deposit) with ruderal species, but invasive halotolerant plant species are found in saline areas.

In soil salinization centers (floodplain of the Lyonva River), meadow plant communities are found with a small portion of halophilic grasses (*Calamagrostis epigejos, Festuca rubra, Typha latifolia L.* (bulrush)) and halophytes (*Atriplex prostrata, Puccinellia hauptiana,* and *Spercularia salina*) [143].

In addition, among the salt-tolerant flora, we found the weeping alkaligrass *Puccinellia distans* (Jacq.) Parl., blue lettuce *Lactuca tatarica* (L.) C.A. Mey., oak-leaved goosefoot *Chenopodium glaucum* L., spear saltbush *Atriplex patula* L. Among the unique flora, arrowgrass *Triglochin maritimum* L. was found (Figure 15). Typical habitats of this species are moistened saline soils on the northern sea coasts and solonchaks [143,144]. Typical taiga plant species die as a result of intense salt stress in terrestrial landscapes, and the liberated ecotopes are replaced by salt-resistant plant communities [83,93,144].

Figure 15. Arrow-grass (*Triglochin maritimum* L.) on the floodplain soils of the Lyonva River.

4.7. Radiation Situation at the Verkhnekamskoe Potash Deposit

Currently, gamma spectrometric measurements of the natural radionuclides activity in various environmental objects are widely used to assess the ecological state of the territory. Similar studies have been conducted for soils, bottom sediments [145,146], and various wastes [147,148], and are frequently used in the coal industry [149,150].

The research area includes the Solikamsky, Novo-Solikamsky, and Polovodovsky mining sites. A total of 75 soil samples (from 0–0.4 m layer) and 6 bottom sediment samples were taken from representative sites around the potash plant. Soil samples and bottom sediment samples were air-dried at room temperature under laboratory conditions. The entire organic portion of the dried samples was removed, and the samples were prepared for the study of the specific activity of natural radionuclides (^{40}K, ^{226}Ra, ^{232}Th). An MKS-01A MULTIRAD device (Russia) was used for gamma spectrometry. The Progress software package was used to process gamma spectra. The specific activity error was approximately ±(20–30)% of the measured value.

In soils, the activity values of ^{226}Ra, ^{232}Th, and ^{40}K ranged from 2.67–36.1 Bq/kg, 0.55–28.1 Bq/kg, and 19.9–562.0 Bq/kg, respectively (Table 5). Bottom sediments (six samples of the finely dispersed fraction) were collected from streams near operating potash enterprises. In bottom sediments, the activity values of ^{226}Ra, ^{232}Th, and ^{40}K ranged from 2.39 to 12.6 Bq/kg, from 6.08 to 16.8 Bq/kg, and from 131.2 to 314.0 Bq/kg, respectively (Table 7).

Table 7. Generalized data on the activity concentration of natural radionuclides in soils and bottom sediments within the territory of the Verkhnekamskoe deposit and other parts of the world, Bq/kg.

Specific Activity	**Activity Value, Bq/kg**				
	$\mathbf{A_{226Ra}}$	$\mathbf{A_{232Th}}$	$\mathbf{A_{40K}}$	$\mathbf{A_{eff}}$	**References**
Soils					
Natural radionuclide activity at the Verkhnekamskoe Potash Deposit (average value for 75 samples)	2.67–36.12 (17.4)	0.55–28.08 (10.9)	19.9–562 (297.7)	19.0–108.35 (50.6)	This study
SanPiN 2.6.1.2523-09. Radiation safety standards	–	–	–	740	[151]
World averages (average value)	16–116 (33)	7–50 (45)	100–700 (420)	–	[152]
Bottom sediments					
Natural radionuclide activity at the Verkhnekamskoe Potash Deposit (average value for 6 fine fraction samples)	2.39–12.6 (7.52)	6.08–16.8 (9.98)	131.2–314.0 (236.67)	21.51–61.3 (41.12)	This study
Generalized data on the content in Qarun Lake sediments	6.2–22.4	5.2–26.6	410–1426	–	[153]
Average 2019 values for sediments in Moscow	15	20	279	66	[154]

Potash ore mining releases ^{40}K into the environment. A radiation study of the core sample from an exploration well in the study area (Table 8) shows that productive potash formations have high ^{40}K activity due to their mineral composition [151]. The highest values for the studied deposit are typical for speckled sylvinites (up to 4967 Bq/kg), which is considerably higher than the activity of ^{40}K for sedimentary rocks and the continental crust. At the same time, all tested rock samples of milled ore, and halite waste do not exceed the permissible value of 740 Bq/kg in terms of the rated specific effective activity [151].

Table 8. Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in rocks from an exploration well and milled ore.

Rock	Sampling Interval, m	Activity Concentration (Bq/kg)			
		^{40}K	^{232}Th	^{226}Ra	Aeff
Loam	3.5–4.0	333 ± 55	15.3 ± 5	17.3 ± 3	67.16 ± 14.45
Mergel	13.0–13.5	177 ± 37	7.5 ± 4	4.9 ± 3	30.58 ± 11.53
Clay Mergel	26.2–26.4	382 ± 60	12.9 ± 5	7.3 ± 3	58.45 ± 14.90
Clay Mergel	29.4–29.5	346 ± 56	17.3 ± 5	7 ± 3	60.63 ± 14.54
Clay Mergel	151.9–152.1	359 ± 57	20.9 ± 5	4.6 ± 3	64.08 ± 14.63
Mergel-gypsum rock	173.4–173.8	927 ± 195	22.2 ± 6.26	6.26 ± 4.89	118.55 ± 30.58
Rock salt	197.0–197.3	3 ± 0	3.2 ± 3	3 ± 0	7.43 ± 3.9
Carnallite	226.7–227.0	2896 ± 330	19.8 ± 5	3 ± 0	289.38 ± 36.2
Carnallite	245.5–245.9	3031 ± 340	17.8 ± 5	3 ± 0	298.93 ± 37.1
Carnallite	272.8–273.2	2824 ± 320	16.7 ± 5	3 ± 0	278.87 ± 35.3
Variegated sylvinite	282.6–283.0	4967 ± 540	38.3 ± 8	3 ± 0	499.82 ± 59.00
Striated sylvinite	284.9–285.4	3393 ± 380	41 ± 8	3 ± 0	361.67 ± 44.60
Red sylvinite	296.5–297.1	2055 ± 240	16.4 ± 5	3 ± 0	209.27 ± 28.10
Striated sylvinite	304.0–304.55	4542 ± 470	24.9 ± 6	3 ± 0	418.05 ± 50.10
Rock salt	348.3–348.9	3 ± 0	3 ± 0	3 ± 0	7.17 ± 0.00
Milled ore					
Sylvinite ground	–	4510 ± 730	<8	14.5 ± 4.2	398 ± 66
Sylvinite ground	–	4612 ± 742	<8	<8	418 ± 67
Halite waste	–	283 ± 70	<8	<8	24 ± 6
Halite waste	–	297 ± 66	<8	<8	27 ± 7
Generalized data on salts from the Khewera Mines, Pakistan [153]	–	36 ± 20	–	–	–
Generalized data on rocks [154] Sedimentary rocks Continental crust	–	<300–900 850	<8–50 44	– –	– –

A walking gamma survey was conducted on the territory of the Verkhnekamskoe deposit to estimate the ambient dose equivalent of continuous gamma radiation using the MKS/SRP-08A search dosimeter-radiometer (Russia). The measured values during the gamma survey ranged from 0.06 to 0.25 µSv/h, which is less than the established ambient dose equivalent rate of continuous gamma radiation for residential and industrial areas (0.3 and 0.6 µSv/h, respectively).

Despite the high activity of ^{40}K in extracted potash ores, the value of this indicator for most of the studied soil and bottom sediment samples from the Solikamsky, Novo-

Solikamsky, and Polovodovsky mining sites does not exceed the permissible limits, nor does it exceed the world average.

5. Environmental Impact Minimization

Hydraulic backfilling of solid and liquid potash wastes into mined-out underground openings at the Verkhnekamskoe deposit recommended by the Russian state standard (GOST R 55100-2012) [155] in the field of resource-saving for mining waste management, taking into account the availability of technology [156]. Data from Uralkali show that backfilling is the most common method of utilizing large-tonnage wastes from the potash industry, with a directional growth trend in recent years (Table 9). The information provided is attributed to the efficiency of ensuring the environmental safety of potash mining, which involves a combination of protecting underground mines from flooding, reducing the earth's surface subsidence, and reducing the areas of salt dumps and slurry storage facilities, the expansion of which requires considerable financial investments. According to official data, Uralkali's total expenses for hydraulic backfill operations from 2011 to 2017 amounted to 12.7 billion rubles. Existing hardening backfill technologies [157] aim to increase salt mining by reducing inter-chamber pillars.

Table 9. Waste generation and use by Uralkali according to the reports "On the state and protection of the environment in Perm Krai" [158].

Year	Waste Generation Volume, Thousand Tons	Waste Usage for Preparation of NaCl Solution for Soda Ash Production, Thousand Tons	Hydraulic Backfilling with Halite Waste and Clay–Salt Slurry, Thousand Tons	Total Use of Generated Waste, %
2021	32,925	-	22,994	68.84
2020	30,521	-	20,935	68.59
2019	30,213	-	1176	3.9
2018	32,386	2185	16,624	58.08
2017	32,697	990	13,480	44.25
2016	30,153	910	11,306	40.52
2015	31,272	910	9560	33.48
2014	34,767	857	6010	19.75
2013	28,145	842	10,000	38.52
2012	26,705	10,200		38.20
2011	30,059	400	8300	28.94

The implementation of the integrated use of raw materials in the production of potash fertilizers involved brine preparation for the needs of soda ash production, technical salt production, and the shipment of unrefined technical salt. Official reports [158] do not currently include information on the extent of these activities.

Potash plants in Berezniki and Solikamsk are using industrial water supply systems to reduce the environmental impact of potash mining. They are also reusing treated and disinfected domestic effluent, treated rainwater, and industrial effluent. These measures allow for major reductions in both the volume of wastewater discharged into water bodies and the intake of natural water into the production cycle. Despite the abovementioned measures, Uralkali is among the enterprises that contribute to water pollution in Perm Krai (Table 10). Uralkali produces 12–20% of the total mass of pollutants wastewater discharging into rivers and Kama reservoirs in Perm Krai.

The primary sources of fine particulate matter (NaCl and KCl) emissions from potash fertilizer production are the dry crushing of sylvinite ore, drying of fine-grained concentrate, and granulation of potassium chloride. In order to capture these emissions, modern exhaust gas purification systems are installed at all sources of gas and dust emissions.

Table 10. Water consumption and disposal in Perm Krai, according to the report "On the state and protection of the environment in Perm Krai" [158].

Year	Perm Krai			Potash Plants in Perm Krai
	Freshwater Abstractions, Million m^3	Water Reuse & Recycling, Million m^3	Discharge of Untreated Wastewater, Million m^3	Discharge of Polluted Wastewater, Thousand Tons
2021	1307	2099	160	150
2020	1158	1986	194	162
2019	1309	1992	209	215
2018	1532	2091	211	187
2017	1661	1868	317	169

The results of data monitoring show that there are no exceedances of the maximum allowable concentrations (0.3 mg/m^3 for KCl and 0.5 mg/m^3 for NaCl). The air emissions from potash plants are assessed by studying the specific activity of ^{40}K in soils and bottom sediments around near potash mining areas [145,146].

6. Abandoned Potash Mine Ecological Resource Development

When looking at the history of potash mining, three operational stages can be identified: operation (mining), abandonment, flooding, or flooding of abandoned salt mines [159]. The final stage of potash mining is the closure of potash mines, which is usually performed by a "wet" method. As a result of an emergency situation and the freshwater inflow into the underground mine, the mine is flooded and then abandoned [160]. There are currently approximately 100 flooded mines in various countries, including Vanscoy and Patience Lake (Canada), Holle (Congo), Von der Heydt, Agathe, and Manteuffel (Germany), and the Berezniki-1 and Berezniki-3 potash mines (Russia), which were never restored and remain flooded [161]. In general, the closure of potash mines and chemical plants has greatly reduced chloride pollution in these areas [162].

The extraction of rare metals and minerals from waste, as well as the use of mines for hazardous waste disposal, are the directions for implementing circular economy principles in potash waste and underground mine management [163]. Thus, underground disposal of hazardous waste has been practiced in Germany for the past 20 years [164,165]. The Morsleben and Asse repositories are notable examples of radioactive waste disposal in the Zechstein beds [166]. European legislation defines hazardous waste storage in salt mines as the use of a host rock environment as a geological barrier that prevents hazardous substances from migrating [167].

Salts and brines from evaporite deposits are potential sources of not only basic elements such as sodium (Na), calcium (Ca), magnesium (Mg), potassium (K), chlorine (Cl), bromine (Br), and iodine (I), but also a large number of rare trace elements such as lithium (Li), strontium (Sr), rubidium (Rb), boron (B), cesium (Cs), and orgallium (Ga), which are considered in the world as strategic and critical ore materials [168,169]. Sc was found in considerable amounts in the clay–salt slurry in Solikamsk-1 potash mine [170], which is in demand by the nuclear power, space, and aviation industries. The element is associated with calcium minerals (gypsum, dolomite, and apatite) in insoluble salt sediment. In addition, after processing potassium–magnesium ores, a complex of noble metals (Au, Ag, Pt, and Pd) was found in the waste at the Verkhnekamskoe deposit, where it was discovered that the content of noble metals in the liquid waste corresponds to industrially significant ones [171].

Lithium demand has greatly increased over the last decade as the element has become a critical component in the manufacturing of a variety of new products, particularly batteries for electronic devices and electric vehicles. Furthermore, an increase in demand for this element has been observed in the glass and ceramic industries, owing to lower energy costs and easier product processing when using Li [172]. At the same time, the structure of the natural sources of its production has greatly changed over the last 50 years, and today, up to 70% of the world's extraction of this element is carried out through the exploitation of brines from endorheic salt lakes [173]. Because lithium is geochemically associated with magnesium and potassium, it is promising to investigate the content of this metal in salt waste and clay–salt slurry from potash deposits.

Brines are prepared for the needs of soda ash production, technical salt production, and shipment of unrefined technical salt as part of the implementation of approaches for the integrated use of raw materials in the production of potash fertilizers at the Verkhnekamskoe deposit. Components from liquid waste can be used as cement mortar and concrete additives [174].

The health improvement of the population is an important and already implemented direction of using the underground mine of such enterprises. The microclimate underground salt chambers are actively used as a health resort for respiratory disease treatment [175]. The climatotherapy method (subterraneotherapy) is used in a few places around the world, including the Salt Mines in Wieliczka and Bochnia (Poland), in Turda (Romania), in Zlote Hory (Czech Republic), and Berchtesgaden (Germany) [126,176].

7. Conclusions

In many parts of the world, potash ore mining is the backbone of the economy and a source of national wealth. The use of fertilizers to increase agricultural productivity is a global standard for ensuring the population's life and health. Enterprises producing potash fertilizers contribute to one of the global sustainable mining goals by ensuring food security, improving nutrition, and promoting sustainable agricultural development as the most important measure in the fight against hunger. At the same time, the production of a significant quantity of fertilizers implies an increase in the volume of mining and processing potash ores, as well as an increase in the volume of liquid and solid waste, which is primarily disposed of on the earth's surface in potash tailings piles and tailings slurry. Responsible and detailed forecasting of the environmental consequences of potash ore mining is a priority in the mining of these water-soluble potash salt deposits. The direction toward reducing environmental impact is also environmental management, which uses elements of a circular economy and is supported by strict environmental regulations.

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