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Evaluation of Babkhinsky sludge landfill impact on groundwater in Lake Baikal coastal zone

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Abstract. The main purpose of the work was to analyze the current state of pollutant distribution in the area of the Babkhinsky sludge storage landfill of the Baikal Pulp and Paper Mill. To solve the set problem the long-term data reflecting the chemical composition of natural and above-sludge waters during various periods of plant operation and after its closure were analyzed, followed by modeling and evaluation of the geological, structural and hydrogeological conditions of the area, technological features of engineering structures and wastewater composition, which together influenced the nature and extent of pollutants in the coastal area of Lake Baikal. As a result of the conducted analysis, it was concluded that the highest concentrations are demonstrated by the following indicators: lead, iron, arsenic, increased turbidity and color of water. The maximum pollution is concentrated within the area of map no. 14, as well as on the border area between the areas of maps no. 14 and 13 located located approximately 1.5 km from the water's edge of Lake Baikal. This situation is due to the fact that during the closure of the Baikal Pulp and Paper Mill, in addition to Class IV and V hazard waste disposed of in the plant's ash disposal site, highly toxic green liquor was discharged into the area shown on map no. 14. Since this area is dominated by low-permeability rocks, the groundwater composition stabilized and its recovery is extremely slow. To eliminate accumulated environmental damage and prevent further groundwater pollution, it is necessary to restore routine monitoring of changes in the chemical composition of groundwater, intensify the ongoing multi-stage treatment of above-sludge waters, and subsequently reclaim the area, including the use of impermeable materials to line the bottom and sides of ash and sludge disposal sites and the construction of flood and mudflow control structures.

Keywords: Baikal, Babkhinsky sludge storage landfill, maps, groundwater, pollution, Baikal Pulp and Paper Mill, pollutant content

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Научная статья
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Оценка воздействия Бабхинского полигона шламонакопителей на подземные воды прибрежной зоны озера Байкал

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Резюме. Основной целью работы являлся анализ современного состояния распространения загрязняющих веществ в районе Бабхинского полигона шламонакопителей Байкальского целлюлозно-бумажного комбината. Для решения поставленной задачи были проанализированы многолетние данные, отражающие химический состав природных и надшламовых вод в различные периоды работы комбината и после его закрытия, с последующим моделированием и оценкой геолого-структурных и гидрогеологических условий территории, технологических особенностей инженерных сооружений и состава сточных вод, в совокупности повлиявших на характер и степень распространения загрязнителей в прибрежной зоне озера Байкал. В результате проведенного анализа сделаны выводы о том, что наиболее высокие концентрации имеют следующие показатели: свинец, железо, мышьяк, повышенная мутность и цветность воды, при этом максимальное загрязнение сосредоточено в пределах территории карты № 14, а также на приграничной площади между территориями карт № 14 и 13, находящимися на расстоянии около 1,5 км от уреза воды озера Байкал. Сложившаяся ситуация обусловлена тем, что при закрытии Байкальского целлюлозно-бумажного комбината в дополнение к отходам IV и V классов опасности, утилизировавшимся на золошламоотвале предприятия, на территорию, отраженную на карте № 14, сливали высокотоксичный зеленый щелок, а, поскольку на этом участке в наибольшей степени распространены слабопроницаемые породы, состав подземных вод стабилизировался и его восстановление происходит крайне медленно. Для ликвидации накопленного экологического вреда и предотвращения дальнейшего загрязнения подземных вод необходимо восстановить режимные наблюдения за изменением химического состава подземных вод, интенсифицировать начатую многоступенчатую очистку надшламовых вод с последующей рекультивацией территории, предусматривающей использование водоупорных материалов для покрытия дна и бортов золошламоотвалов, создание противопаводковых и противоселевых сооружений.

Ключевые слова: Байкал, Бабхинский полигон шламонакопителей, карты, подземные воды, загрязнение, Байкальский целлюлозно-бумажный комбинат, содержание загрязняющих веществ

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Introduction

The Baikal Pulp and Paper Mill (BPPM) is an industrial enterprise located in the town of Baikalsk, Slyudyansky District, Irkutsk Oblast, on the southern part of the eastern shore of Lake Baikal (Russia). The facility is widely known as a major source of pollution in Lake Baikal. The mill was commissioned in the autumn of 1966. The sludge storage facilities were constructed in the 1960 and 1970s as temporary waste storage sites for the plant [1]. The sludge storage maps are situated across three waste disposal sites: the Solzansky, Babkhinsky, and the site located on the BPPM industrial premises (Fig. 1)[1]. In total, the operation of BPPM left behind 14 sludge storage facilities. These are enormous artificial hydraulic reservoirs covering an area of 180 hectares with a volume exceeding 6.5 million m³. In addition to coal combustion ash and slag, the Babkhinsky site received sludge lignin, bark-containing waste, municipal solid waste, construction waste, fly ash from coal and sludge lignin combustion, green liquor sludge, and solid municipal waste. Besides impacting groundwater, the BPPM ash and sludge disposal sites also had adverse effects on atmospheric air, soil cover, and vegetation in adjacent areas due to dust dispersion.

In 2013, the Government of the Russian Federation decided to close OJSC "BPPM". As of September 14, 2013, the primary production activity involving the manufacture of sulfate viscose cellulose ceased.

Despite the long period that has elapsed since the shutdown of BPPM and the cessation of using the sludge storage facilities for industrial purposes, groundwater contamination continues to the present day due to several reasons.

A significant contribution to this process is made by the hydraulic connection between the supernatant water (water above the sludge) and groundwater, which discharges into Lake Baikal. Tons of pollutant sediments in the basins of the maps further "enrich" this supernatant water.

Furthermore, the maps are constantly being filled with meltwater and rainwater, leading to their overfilling and creating a threat of pollutants entering Lake Baikal. Over the half-century of BPPM's operation, not only millions of tons of solid and liquid waste have accumulated in the maps[2], but also 1.5 million tons of sludge supernatant water, which risks overflowing the map embankments. This risk led to the declaration of a state of emergency in Baikalsk on April 13, 2021. To eliminate the threat of waste leaks, the supernatant water is being pumped out, discharging the flow of technogenic groundwater into Lake Baikal.

Additional risks stem from the fact that the sludge storage facility site is under constant threat of mudflows. Examples are provided by Artem Rybchenko, Head of the Engineering Geology and Geoecology Laboratory at the Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences (Irkutsk, Russia): in 1971, one of the storage maps was already filled with mudflow deposits; in 2019, a mudflow nearly carried BPPM waste into the lake; and in June 2022, mudflows in the Slyudyansky District of Irkutsk Oblast repeatedly blocked traffic on the federal highway[3].

[1] On the problem of liquidating accumulated waste from the activities of OJSC «Baikal PPM». *Geol.irk.ru.* Available from: http://www.geol.irk.ru/baikal/baikal/baikal_law_fulfilment/mvk/050609/reports/report_Othody.pdf [Accessed 26th February 2025].

[2] Emelyanenkov A. Baikal is being protected from a breakthrough of supernatant water from the PPM's storage maps. *Rg.ru.* Available from: https://rg.ru/2021/05/31/reg-dfo/bajkal-pytaiutsia-zashchitit-ot-proryva-nadshlamovyh-vod-iz-kart-nakopitelej-cbk.html [Accessed 26th February 2025].

[3] Scientist explains how landslides and mudflows could affect waste in BPPM sludge storage facilities. *Irkutskmedia.ru.* Available from: https://irkutskmedia.ru/news/1308856/ [Accessed 26th February 2025].

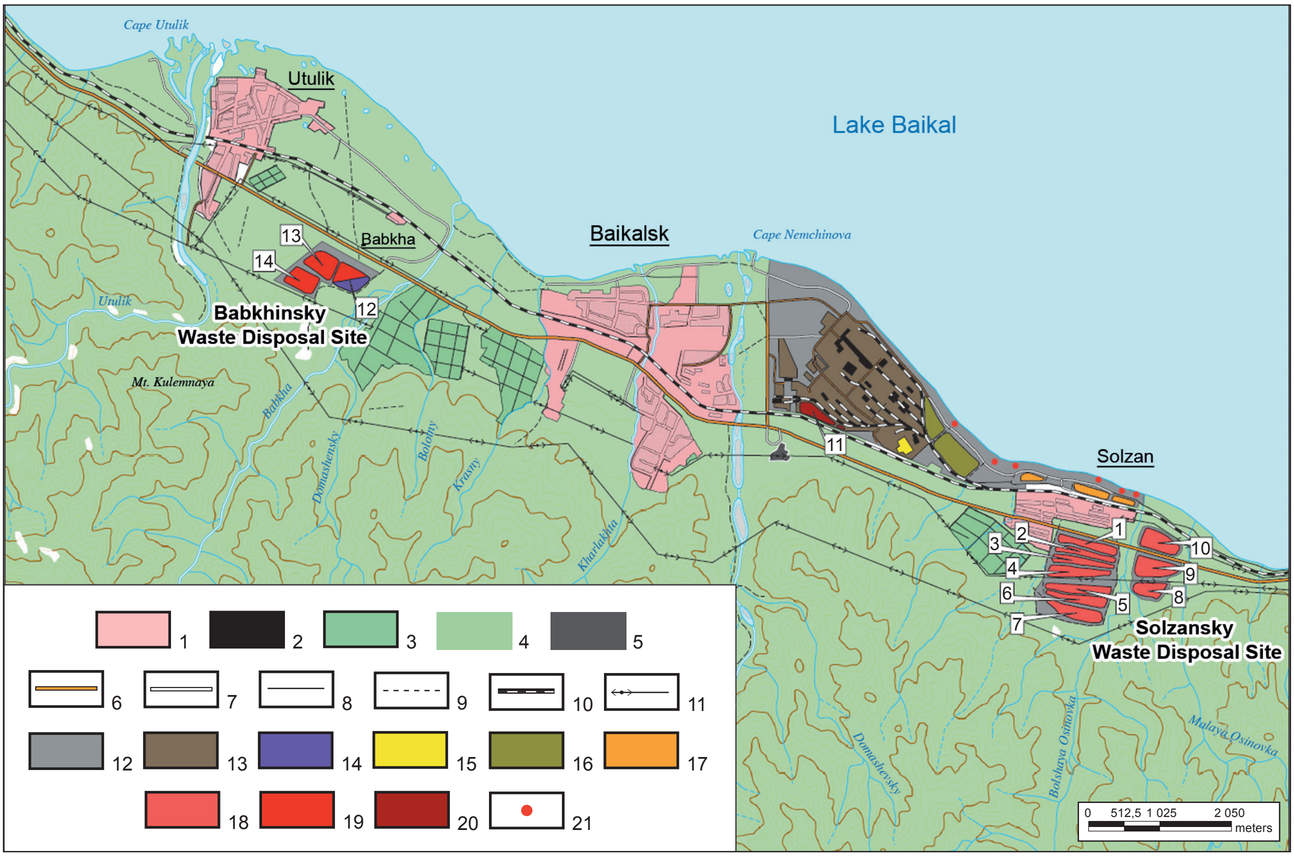


Fig. 1. Situational plan*[1]*:
1 – settlements; 2 – individual buildings; 3 – summer cottages and garden plots; 4 – vegetation; 5 – cemeteries; 6–11 – roads: 6 – highways, 7 – improved unpaved roads, 8 – unpaved country roads, 9 – field and forest roads, 10 – railways, 11 – power lines; 12 – land drainage of JSC Baikal Pulp and Paper Mill; 13 – industrial site of the plant; 14 – landfill of solid household waste (map no. 12); 15 – sewage treatment plants; 16 – reclamation ash dump; 17 – settling pond; 18 – Solzansky waste landfill (maps no. 1–10); 19 – Babkhinsky waste landfill (maps no. 12–14); 20 – map no. 11; 21 – wood waste disposal

Рис. 1. Ситуационный план*[1]*:
1 – населенные пункты; 2 – отдельные строения; 3 – дачные и садовые участки; 4 – растительность; 5 – кладбища; 6–11 – дороги: 6 – шоссе, 7 – улучшенные грунтовые дороги, 8 – грунтовые проселочные дороги, 9 – полевые и лесные дороги, 10 – железные дороги, 11 – линии электропередач; 12 – землеотвод ОАО «Байкальский целлюлозно-бумажный комбинат»; 13 – промплощадка комбината; 14 – полигон твердых бытовых отходов (карта № 12); 15 – очистные сооружения; 16 – рекультивационный золоотвал; 17 – пруд-отстойник; 18 – Солзанский полигон отходов (карты № 1–10); 19 – Бабхинский полигон отходов (карты № 12–14); 20 – карта № 11; 21 – захоронение древесных отходов

Currently, a high-tech tourism cluster is planned for development at the BPPM site and adjacent territories. As part of this project, the mill's production structures are being dismantled: 17 facilities were demolished in 2025, and the dismantling of another 150 facilities is set to begin in 2026.

Furthermore, it is planned that in 2026, the pumping and treatment of liquor-containing wastewater and sludge supernatant water will commence, aiming to meet the environmental protection standards of the Central Ecological Zone of the Baikal Natural Territory. The full scope of work is scheduled for completion in 2027. At the Babkhinsky site, the treatment of 400,000 m³ of sludge supernatant water[4] is envisaged.

Materials and Methods

The primary objective of this work was to assess the impact of the Babkha ash and sludge disposal site on groundwater, and to determine the presence, degree, and sources of groundwater pollution. To achieve this, an analysis was conducted of long-term ob-

[4] Preparation begins for launching treatment equipment at the former BPPM site to eliminate accumulated environmental damage. *Energybase.ru.* Available from: https://energybase.ru/news/companies/rosatom-predstavil-vice-premeru-rf-dmitriu-patrusevu-hod-rabot-po-likvidac-2025-08-28 [Accessed 13th October 2025].

servations on the state of natural and supernatant waters in the vicinity of the sludge disposal site, including the results of sampling and laboratory analyses of groundwater and surface water presented in studies[1,5] [2]. Additionally, a comprehensive site survey and modeling of pollutant distribution were carried out.

Over 40 years of operation, the mill accumulated a vast amount of waste, stored at disposal sites in close proximity to Lake Baikal (see Fig. 1). The primary pollutant by volume is sludge lignin. The BPPM sludge storage and ash settling facilities cover an area of 350 hectares, of which the storage maps themselves occupy 123 hectares. They contain 6.2 million m³ of sludge lignin (maps no. 1–7, 9, 10) and 2.6 million tons of ash (maps no. 11–14)[6]. The Babkhinsky site is located west of BPPM, between the Babkha and Utulik Rivers, 1.35–2 km from Lake Baikal. It consists of four maps: 11, 12, 13, and 14, containing 2.6 million tons of ash [3].

In hydrogeological terms, the study area is confined to the Baikal Folded Region, characterized by the predominant occurrence of groundwater in fractured Archean rocks and pore-stratal waters in unconsolidated Neogene-Quaternary sediments (Figs. 2, 3). The latter is of greatest interest, as these pore-stratal waters are the most susceptible to intensive pollution.

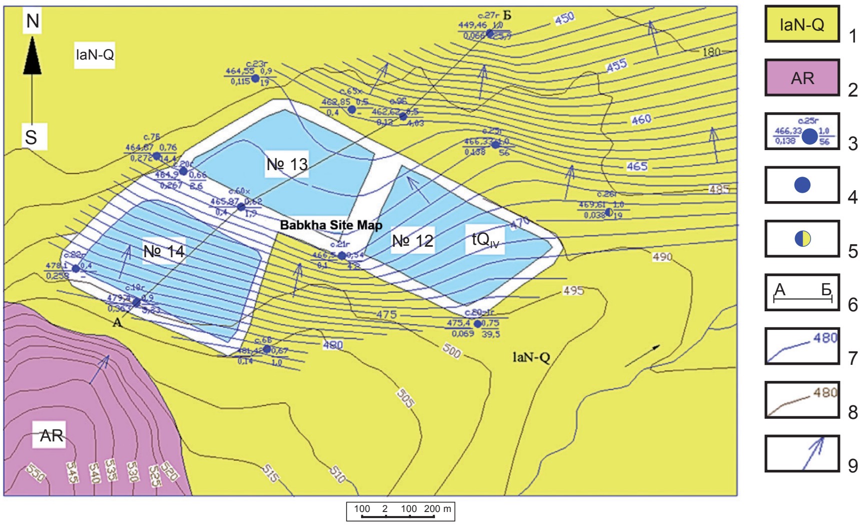


Fig. 2. Schematic hydrogeological map of the Babkhinsky landfill (made by the author based on the materials of the Angarsk geological expedition of the Irkutsk Geophysics Research Institute):
1, 2 – aquifers widespread in the area: 1 – aquifer of lacustrine-alluvial Neogene-Quaternary deposits, 2 – Archean aquifer fracturing zone; 3 – hydrogeological well (October – November 2021; at the top – well number; numbers on the left: numerator – absolute groundwater level, m, denominator – mineralization, g/l, on the right in the numerator – flow rate, l/s, denominator – filtration coefficient, m/day.); 4, 5 – groundwater chemical composition: 4 – water with bicarbonate ion predominance, 5 – water with the predominance of bicarbonate and sulfide ions; 6 – hydrogeological section line; 7 – waterproofing gypsums (October – November 2021); 8 – relief contours (2021); 9 – direction of groundwater flow movement

Рис. 2. Схематическая гидрогеологическая карта района Бабхинского полигона (составлено автором по материалам Ангарской геологической экспедиции ФГУНПГП «Иркутскгеофизика»):
1, 2 – распространенные по площади водоносные подразделения: 1 – водоносный горизонт озерно-аллювиальных неоген-четвертичных отложений, 2 – архейская водоносная зона трещиноватости; 3 – скважина гидрогеологическая (октябрь – ноябрь 2021 года; вверху – номер скважины; цифры слева в числителе – абсолютные отметки уровня грунтовых вод, м, в знаменателе – минерализация, г/л, справа в числителе – дебит, л/с, в знаменателе – коэффициент фильтрации, м/сут.); 4, 5 – химический состав подземных вод: 4 – вода с преобладанием гидрокарбонатного иона, 5 – вода с преобладанием гидрокарбонатного и сульфидного ионов; 6 – линия гидрогеологического разреза; 7 – гидроизогипсы (октябрь – ноябрь 2021 года); 8 – горизонтали рельефа (2021 год); 9 – направление движения потока подземных вод

[5] *State report "On the state of Lake Baikal and measures for its protection in 2011".* Irkutsk: Siberian Branch of the Federal State Unitary Scientific and Production Enterprise "Rosgeolfond"; 2012, 412 p.

[6] Dambinov Y.A. Study of the composition of sludge lignin from the BPPM for the development of methods for the remediation of industrial waste sites. *Conf.nsc.ru.* Available from: http://conf.nsc.ru/youngconf-2013/ru/reportview/151272 [Accessed 26th February 2025].

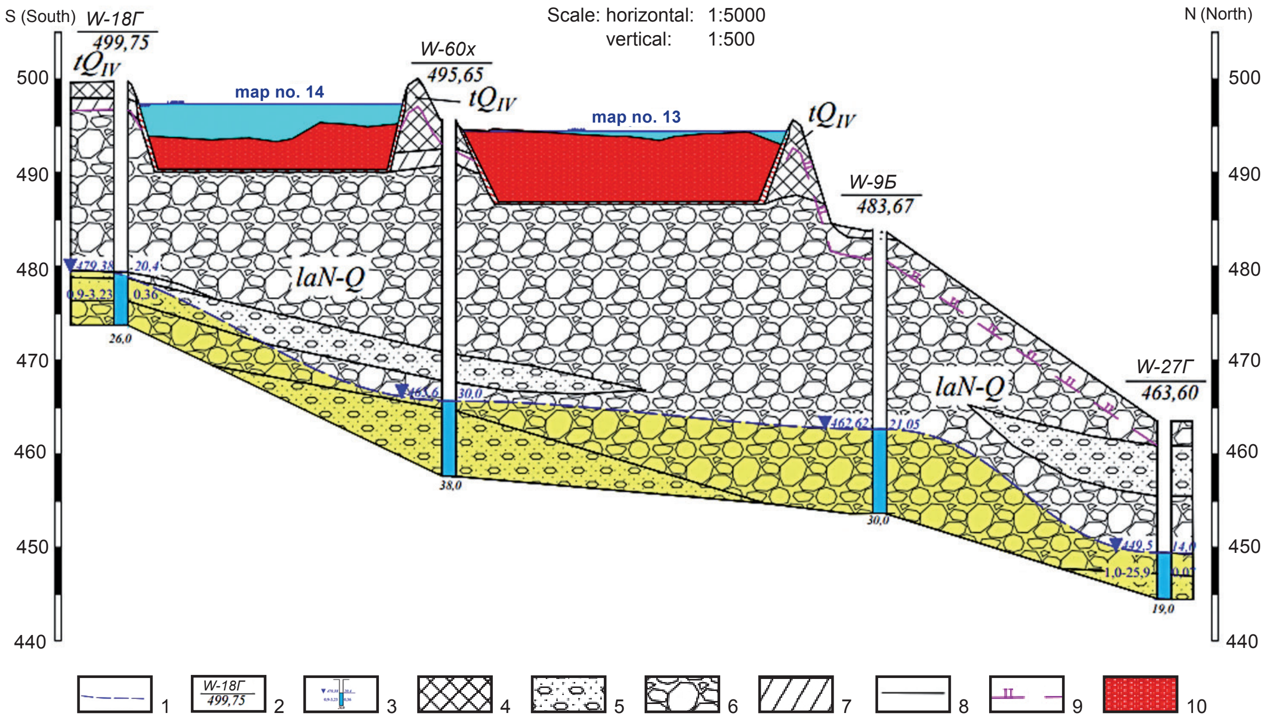


Fig. 3. Hydrogeological section of the territory of the Babkhinsky landfill along the A-Б line:
1 – piezometric groundwater level; 2 – hydrogeological well (numerator at the top – source number, denominator – absolute wellhead elevation, m); 3 – designation of well parameters (numbers at top left – absolute groundwater level elevation, m; on the right – groundwater level depth, m; color indicates groundwater anionic composition; numbers in the middle on the left – pumping flow rate, l/s; on the right – mineralization, g/dm³; numbers at bottom – well depth, m); 4 – fill soils: pebble, boulder-pebble soil with sandy aggregate; 5 – pebble soil with sandy aggregate; 6 – boulder-pebble soil with sandy aggregate; 7 – loam; 8 – boundary between different genetic types of rocks; 9 – boundary of seasonal freezing of rocks; 10 – technogenic (alluvial) soils in storage maps

Рис. 3. Гидрогеологический разрез территории Бабхинского полигона по линии А-Б:
1 – пьезометрический уровень подземных вод; 2 – скважина гидрогеологическая (вверху в числителе – номер по первоисточнику, в знаменателе – абсолютная отметка устья, м); 3 – обозначение параметров скважин (цифры вверху слева – абсолютная отметка уровня подземных вод, м, справа – глубина уровня подземных вод, м, цвет указывает на анионный состав подземных вод; цифры в середине слева – дебит откачки, л/с, справа – минерализация, г/дм³; цифры снизу – глубина скважины, м); 4 – насыпные грунты: галечниковый, валунно-галечниковый грунт с песчаным заполнителем; 5 – галечниковый грунт с песчаным заполнителем; 6 – валунно-галечниковый грунт с песчаным заполнителем; 7 – суглинок; 8 – граница между различными генетическими типами пород; 9 – граница сезонного промерзания пород; 10 – техногенные (намывные) грунты в картах-накопителях

The aquifer in the lacustrine-alluvial Neogene-Quaternary deposits (laN-Q) was formed in a Cenozoic accumulative basin, extending several kilometers wide along the shoreline of Lake Baikal. It is confined to the floodplains of the Solzan, Babkha, Bolshaya Osinovka, and Kharlakhta Rivers. The water-bearing rocks are represented by boulder-gravel-pebble deposits with a sandy filler; the penetrated thickness exceeds 30 m (see Fig. 3). The depth to the groundwater table generally varies from 1 to 3 m, reaching up to 22.5 m below ground surface in some areas. Due to the extremely heterogeneous composition of the water-bearing deposits, filtration parameters vary significantly, with the filtration coefficient ranging from 2.6 to 39.5 m/day (Fig. 4).

Recharge of the complex occurs through the infiltration of atmospheric precipitation and surface waters. The groundwater of this horizon is unprotected from pollution and serves as one of the main sources of water supply for the town of Baikalsk.

The pollution structure is well-understood and universal [4, 5]: meteoric and technogenic waters entering the sludge storage facility interact with the accumulated sludge; subsequently, during infiltration, the formed solutions interact with groundwater in the zone beneath the storage facilities [6, 7] and migrate accord-

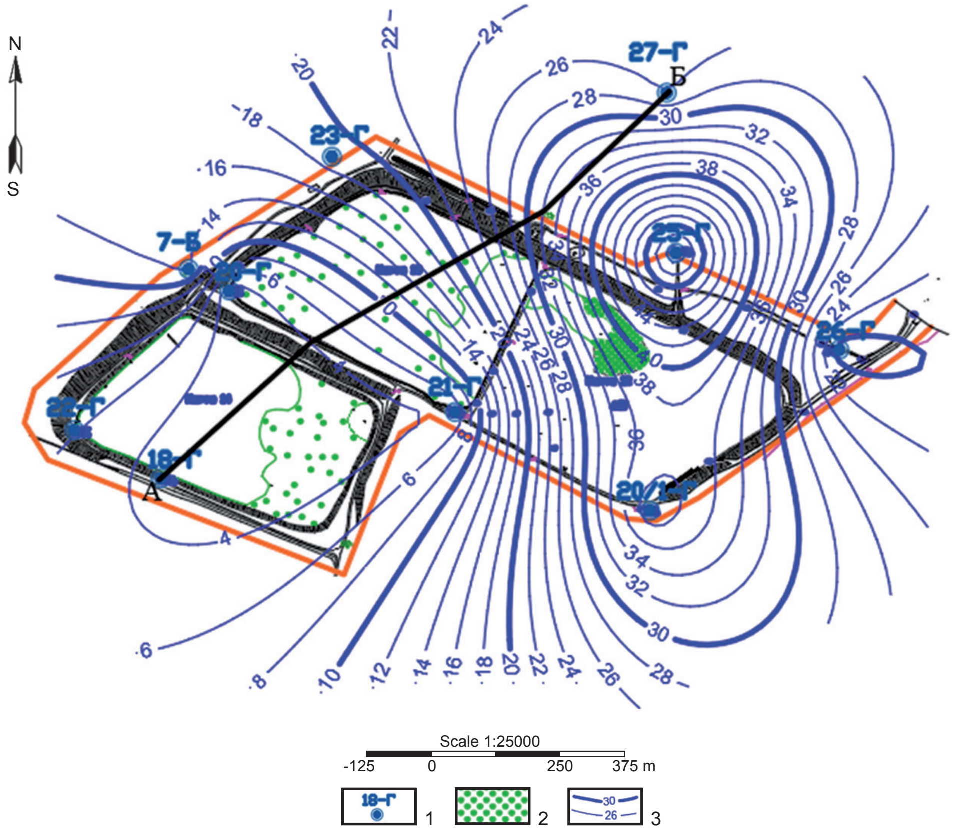


Fig. 4. Distribution diagram of filtration coefficients of Neogene-Quaternary sediments on the territory of the Babkhinsky landfill (2022):
1 – hydrogeological well (number according to the original source at the top); 2 – vegetation;
3 – isolines of filtration coefficient values, m/day
Рис. 4. Схема распределения коэффициентов фильтрации неоген-четвертичных отложений на территории Бабхинского полигона (2022 год):
1 – скважина гидрогеологическая (вверху – номер по первоисточнику); 2 – растительность;
3 – изолинии значений коэффициента фильтрации, м/сут.

ing to the general flow direction, in this case towards Lake Baikal, discharging there as subaqueous springs. This is confirmed by observations conducted since 2013. Starting from that time, a zone contaminated with a black, slimy sediment has been recorded on the western shore of the lake. The results of spectroscopy of the black deposits on rocks were compared with the spectra of pulp production waste (fresh sludge lignin and the dry residue of the mill's wastewater) and showed their identity, likely due to the seepage of technogenic groundwater from BPPM. Furthermore, observations from 2013–2015 revealed the enrichment of interstitial waters with sulfates (up to 28 mg/l), sodium (up to 14 mg/l), chloride ions (up to 3.5 mg/l), and nitrogen compounds[7]. The presented evidence confirms the discharge of untreated technogenic BPPM waters (via groundwater) into the shallow zone of the lake. It is evident that the upper part of the beach and coastal zone served as their discharge area. In June 2023, another survey of the beach and coastal waters opposite the BPPM site was conducted[7]. The obtained hydrochemical data indicate that even 10 years after the mill's closure, contamination of interstitial and coastal lake waters in this area persists. The concentrations of pollutants obtained in 2023 in the interstitial water are comparable to those obtained in 2013–2015[7]. The composition of water sampled from the near-bottom layer of the lake at a depth of 1 m suggests that the discharge of groundwater enriched with sulfates, chlorine, sodium, phos-

[7] Tomberg I.V., Timoshkin O.A. Inflow of pollutants from the BPPM industrial site with groundwater discharge into the coastal waters of Lake Baikal. In: *State report "On Lake Baikal and its protection, 2023"*. Moscow: All-Russian Research Institute of Ecology; 2024, p. 312-316.

phates, and organic matter continues and occurs directly into the lake. The twofold increase in pollutant concentrations in the coastal lake water (at the water's edge) compared to the 2013–2015 period may indicate an increase in the volume of groundwater inflow.

Within the maps, a wide range of pollutants is observed in the groundwater, among which arsenic, manganese, lead, iron, and mercury are most widespread, and elevated water turbidity is also recorded.

The level of environmental pollution during the BPPM's operational period is documented in many sources, including the reports "On the state of Lake Baikal and measures for its protection" from various years[8,9] [8]. Table 1 presents the dynamics of changes in the content of pollutants in natural waters at the Babkhinsky site for the period 2011–2017.

In 2018, at the Isotopy and Geochronology Laboratory of the Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences (Irkutsk, Russia), samples of supernatant water from several storage maps, including map no. 14[10], were analyzed using mass spectrometry. Elevated concentrations of aluminum, sulfur (SO_4^{2-}), iron, copper, strontium, molybdenum, as well as vanadium, gallium, chromium, and thallium (typically found in mining waste and posing a significant environmental hazard) were recorded[11].

Table 1. Dynamics of changes in pollutant content in natural waters at the Babkhinsky landfill
Таблица 1. Динамика изменения содержания загрязняющих компонентов в природных водах на Бабхинском полигоне

Year	Pollutant Component	Content	Notes
2011	Chemical Oxygen Demand	12–16 MPC	–
	Permanganate oxidizability	–	–
2012	Total Dissolved Solids	1–5 MPC	Intercepting water intake area
	Formaldehyde	1.2 MPC	–
	Phosphates	up to 4.6 MPC	–
	Petroleum Products	up to 7 MPC	–
	Aluminum	7–16 MPC	–
	Hydrogen Sulfide	up to 24 MPC	–
	Iron	up to 43 mg/l	–
	Lignin	up to 49 mg/l	–
	Chemical Oxygen Demand	up to 88 mg/l	–
	Permanganate oxidizability	up to 122 mg/l	–
	Color	up to 156 degrees	–
	Temperature	up to 55 °C	Background 4 °C
2013	Chemical Oxygen Demand	1.6 mg/l	–
	Iron	up to 20 mg/l	–
2014	Chemical Oxygen Demand	1.4 mg/l	–
	Petroleum Products	1.4 mg/l	–
	Iron	up to 33 mg/l	–
2017	Iron	14.17 mg/l	–
	Manganese	2.74 mg/l	–

[8] *State report "On the state of Lake Baikal and measures for its protection in 2012".* Irkutsk: Siberian Branch of the Federal State Unitary Scientific and Production Enterprise "Rosgeolfond"; 2013, 436 p.

[9] *State report "On the state of Lake Baikal and measures for its protection in 2017".* Irkutsk: Autonomous Non-Profit Organization "Consulting Center Expert"; 2018, 340 p.

[10] Petrov I.V. *Secondary resources generated in the mining industry.* Moscow: Financial University under the Government of the Russian Federation; 2020, 35 p.

[11] *State report "On the state of Lake Baikal and measures for its protection in 2015".* Irkutsk: Institute of Chemistry and Chemical Technology; 2016, 372 p.

Thus, according to literature data, during the 2012–2018 period, the greatest concerns were raised by the following water pollutants: iron, aluminum, and color. Furthermore, until 2014 (before the mill closure), concerns also included chemical oxygen demand (COD), halogenated organic compounds (detected in map sediments and supernatant water but not in groundwater), as well as non-ferrous metals and their compounds[10,11][9].

In 2021, as part of collaborative work aimed at assessing the impact of the "Babkha" ash and sludge disposal site on groundwater, LLC "Geoengineering" drilled 13 hydrogeological wells on the Babkhinsky site. Water samples from the Neogene-Quaternary aquifer complex were collected during pumping tests and analyzed. Forty parameters were determined; the concentrations of 21 of these exceeded the maximum permissible concentrations (MPC) to varying degrees, including arsenic, lead, iron, turbidity, color, lithium, manganese, mercury, antimony, aluminum, anionic surfactants (AS), and phenols. Exceedances of several other components (petroleum products, COD, boron, barium) were recorded at specific points.

Based on the data analysis, the current major pollutants among the chemical components are arsenic, lead, iron, elevated water turbidity, and to a lesser extent, water color, anionic surfactants, manganese, lithium, antimony, and mercury. This largely confirms the results obtained by scientists from the Institute of the Earth's Crust SB RAS in 2018 during the analysis of supernatant water from map no. 14[12]. The maximum pollution level was recorded in wells 7-Г and 18-Г, with somewhat less contaminated water in wells 20-Г, 22-Г, and 23-Г (Figs. 5–7). Thus, groundwater within map no. 14 is the most polluted (Table 2).

Subsequent assessment of pollutant distribution in the study area was performed using modeling techniques with the software packages Golden Software Surfer 16.6 and Visual Modflow Premium. As a result, schemes showing the distribution of pollutant chemical elements were compiled, the most significant of which are depicted in Figs. 5–7. Figure 7 shows the distribution of the integral pollution index, used in various forms in research studies [11–13], and calculated here according to the authors methodology based on the expert assessment method [9, 14], considering the contribution of 15 components (color, turbidity, aluminum, anionic surfactants, iron, lithium, manganese, copper, molybdenum, arsenic, petroleum products, mercury, lead, antimony, phenols).

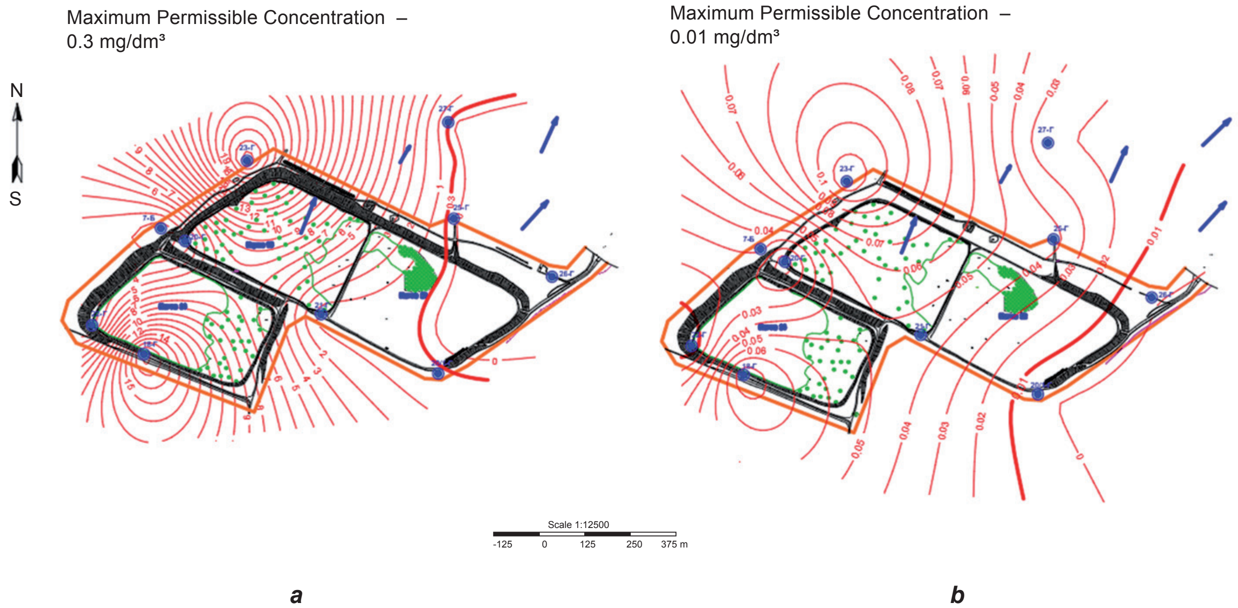
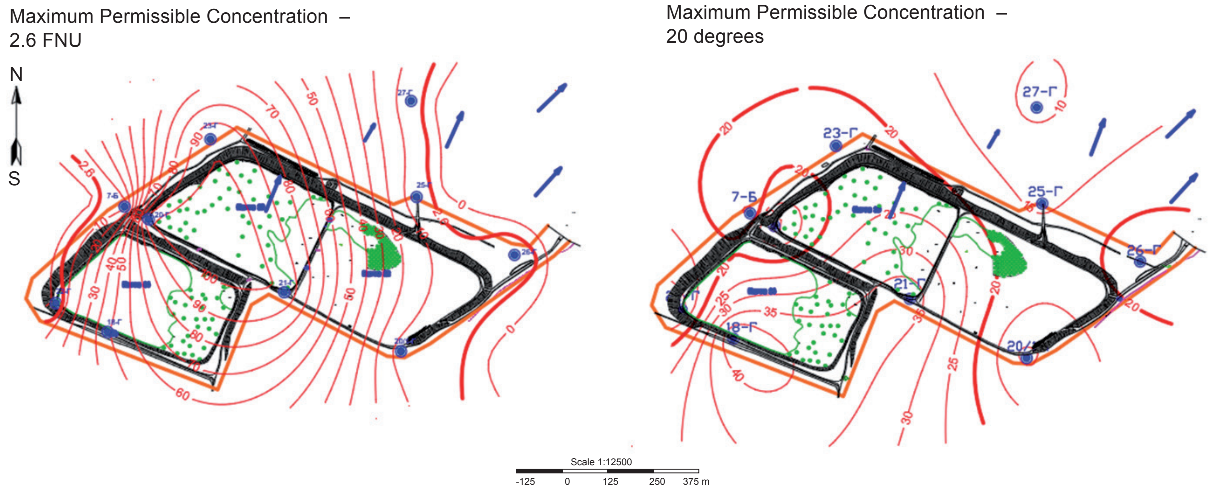


Fig. 5. Distribution diagrams of iron (a) and lead (b) contents in groundwater within the Babkhinsky landfill, mg/dm³
Рис. 5. Схемы распределения содержания железа (a) и свинца (b) в подземных водах на территории Бабхинского полигона, мг/дм³

[12] *State report "On the condition and protection of the environment of Irkutsk region for 2012"*. Irkutsk: Institute of Geography, Siberian Branch of the Russian Academy of Sciences; 2013, 337 p.



a *b*

Fig. 6. Distribution diagrams of turbidity (a) and color (b) in groundwater within the Babkhinsky landfill, mg/dm³

Рис. 6. Схемы распределения показателей мутности (a) и цветности (b) в подземных водах на территории Бабхинского полигона, мг/дм³

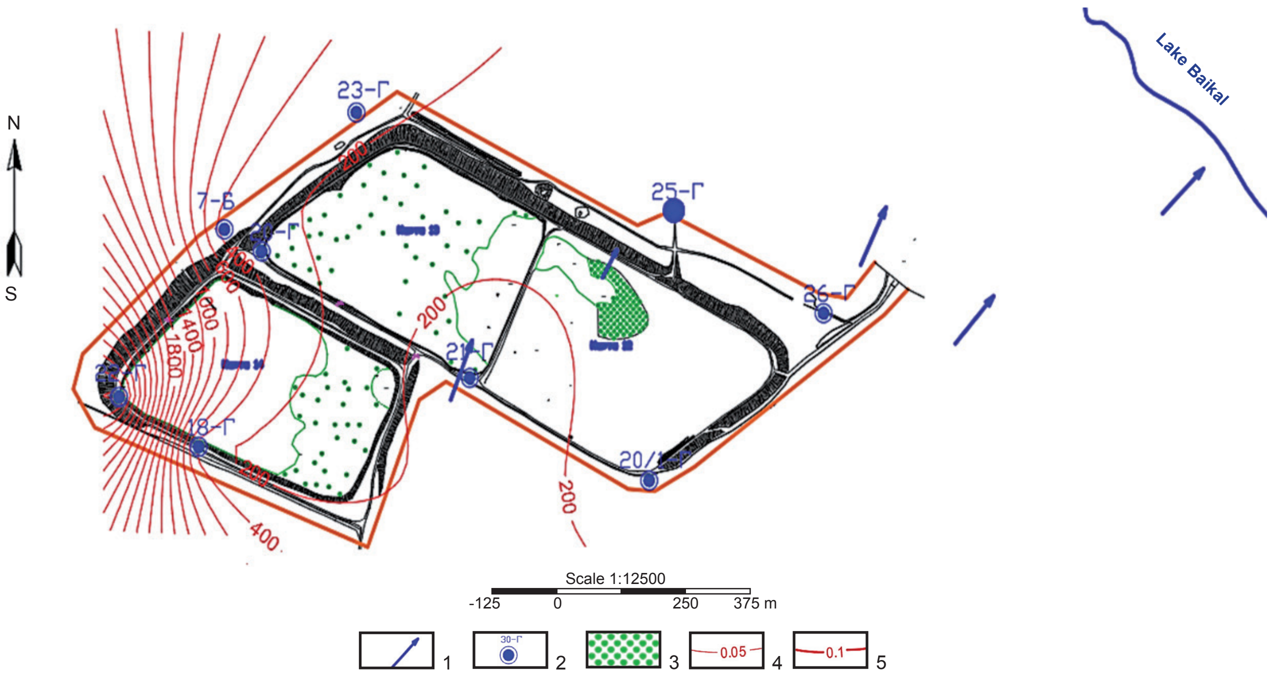


Fig. 7. Distribution diagram of the total groundwater pollution index in the territory of the Babkhinsky landfill [10]:

1 – groundwater movement direction; 2 – hydrogeological well (number according to the original source at the top);
3 – vegetation; 4 – isolines of the pollutant component content in groundwater, mg/dm³;
5 – isoline of the content corresponding to the maximum permissible pollutant concentration

Рис. 7. Схема распределения суммарного индекса загрязнения подземных вод на территории Бабхинского полигона [10]:

1 – направление движения подземных вод; 2 – скважина гидрогеологическая (вверху – номер по первоисточнику);
3 – растительность; 4 – изолинии содержания загрязняющего компонента в подземных водах, мг/дм³;
5 – изолиния содержания, соответствующая предельно допустимой концентрации загрязнителя

Results and Discussion

The analysis of the initial data and the modeling results indicate that the following parameters exhibit the highest concentrations: arsenic, lead, iron, and elevated water turbidity (Table 3). To a lesser extent, elevated levels are observed for water color, manganese, lithium, and antimony.

Table 2. Distribution of polluting components by wells and maps
Таблица 2. Распределение загрязняющих компонентов по скважинам и картам

Map number	Well number	Additional well location description	Pollutant component
12	20/1-Г	Southern outskirts	Li, Pb, Fe, turbidity, color
13	20-Г	Western outskirts	Anionic surfactants, Fe, As, Mn, Li, turbidity
14	18-Г	Southwestern outskirts	Anionic surfactants, phenols, As, Mn, Pb, Fe, Hg, turbidity, color
	22-Г		Li, Al, Fe, Pb, turbidity, color
Between maps 13 and 14	7-Б	Western outskirts	Chemical Oxygen Demand, petroleum products, phenols, anionic surfactants, Li, Mn, Hg, Al, As, Fe, B
Between maps 12 and 13	21		Li, Pb, Fe, turbidity, color
Northwest of map 13	23	Outside the sludge storage facility area	B, Al, Fe, Pb, Mn, turbidity, color
Northwest of map 12	25	Outside the sludge storage facility area	Sr, Pb, As, turbidity
	26		As, Sr, turbidity, color (slightly)
–	27	Outside the sludge storage facility area to the northeast	As, Sr, Pb, turbidity (slightly)
–	28	Outside the sludge storage facility area to the northeast	Anionic surfactants, Hg, benzopyrene, turbidity, color
–	29	Outside the sludge storage facility area to the northeast	Hg, benzopyrene
–	30	Along the route	As, Pb, Sr, turbidity (slightly)

Maximum pollution is concentrated within the area of map no. 14 (wells 18-Г, 22-Г), as well as in the border area between maps no. 14 and 13 (wells 7-Б, 20-Г, 21-Г). Significantly lower pollution levels are found in the area of maps no. 12 and 13 (see Fig. 7).

In the southwestern part of map no. 14, the integral pollution index is almost twice as high as that in the coastal part of the town of Baikalsk (see Fig. 7). Within this area, the Neogene-Quaternary section is characterized by the widespread occurrence of loamy interlayers with low filtration parameters (see Fig. 4). This impedes the free groundwater flow towards Lake Baikal (the main groundwater flow direction is from southwest to northeast, (see Fig. 2)) and contributes to stagnation in water-saturated soils in the southern and southwestern parts, while promoting greater flushing of rocks in the north and northeast of the area (maps no. 13 and 12).

The maximum groundwater pollution recorded in the area of map no. 14 is even more predictable given that upon the closure of BPPM, in addition to waste hazard classes IV and V (ash and slag from coal combustion, ash from wastewater sludge incineration, bark waste, ash from bark boilers, cellulose fiber waste) disposed of at the enterprise's ash and sludge dump, highly toxic green liquor was discharged into the area of map no. 14. Since poorly permeable rocks are most prevalent here, the groundwater composition stabilized and its restoration is currently proceeding extremely slowly. The discharged liquor also contained fine cellulose fiber [15], which accounts for the elevated turbidity and color of the groundwater. This process across the entire site was further facilitated by the fact that at OJSC "BPPM" during chemical treatment using alumina and polyacrylamide, dissolved and colloidal sludge lignin compounds present in the wastewater were thickened to a sediment concentration of 0.5 %[5].

It should be noted that water samples were collected during the low-water period (October – November 2021). During flood events, groundwater turbidity and color indicators are likely to be higher.

Table 3. Indicators exceeding maximum permissible concentrations
Таблица 3. Показатели, превышающие предельно допустимые концентрации

Indicator	Maximum permissible concentration	Well number												
		7-Б	22-Г	18-Г	20/1-Г	21-Г	20-Г	23-Г	25-Г	27-Г	26-Г	30-Г	28-Г	29-Г
		Content of indicators exceeding the Maximum Permissible Concentration												
Total Dissolved Solids, mg/l	–	272	258	363	69	101	267	115	138	66	38	115	74	82
Chemical Oxygen Demand, mg/l	34.0	–	260	–	–	–	–	–	–	–	–	–	–	–
Petroleum Products, mg/l	0.1	–	0.43	–	–	–	–	–	–	–	–	–	–	–
Phenol (hydroxybenzene), mg/l	0.001	–	0.0042	0.0021	–	–	–	–	–	–	–	–	–	–
Anionic Surfactants, mg/l	0.05	–	0.19	0.054	–	–	0.066	–	–	–	–	–	0.07	–
Aluminum, mg/l	0.5	0.63	2.3		–	–		1.3	–	–	–	–	–	–
Arsenic, mg/l	0.01	–	0.015	0.026	–	–	0.035		0.41	0.29	0.16	0.35	–	–
Boron, mg/l	0.5	–	–	–	–	–	–	3.6	–	–	–	–	–	–
Cadmium, mg/l	0.001	0.0016	–	–	–	–	–	–	0.0036	0.0013	0.0014	–	–	–
Lithium, mg/l	0.03	0.76	0.76	–	0.083	0.76	0.9	–	–	–	–	–	–	–
Manganese, mg/l	0.1	–	0.21	0.18	–	–	0.25	0.26	–	–	–	–	–	–
Lead, mg/l	0.01	0.033	–	0.09	–	0.046	–	0.12	0.044	0.021		0.032	–	–
Antimony, mg/l	0.005	–	–	–	–	–	–	–	0.14	0.31	0.157	0.38	–	–
Iron, mg/l	0.3	1.2	2.2	19	0.2	0.34	2.2	23	–	–	–	–	–	–
Barium, mg/l	0.7	–	1.5	–	–	–	–	–	–	–	–	–	–	–
Mercury, mg/l	0.5	–	1.9	–	–	–	–	–	–	–	–	–	0.51	0.52
Benzopyrene, mg/l	0.00001	Less than 0.05											1.4	0.68
Turbidity (formazine and kaolin), EMF	2.6 EMF (1.5)	3.5	–	49	4.9	99	More than 100	More than 100	3.3	3.3	3.6	3.3	9.1	–
Color, degrees	20(35)	26	–	45	–	39	–	23	–	–	24	–	31.6	–

Several studies[13] [14, 16] have reported high pH values (exceeding 12) in the supernatant water of ash and sludge disposal sites. This is attributed to the presence of alkali, originating from green liquor sludge. Currently, this indicator in groundwater reflects a nearly neutral environment, ranging from 6.1 to 7.2.

The elevated content of components such as manganese, arsenic, lead, lithium, and antimony is justified by their presence in the maps filled with ash, lignin, solid waste, and other wastes of hazard classes IV and V[14].

The elevated arsenic content (see Table 3, Fig. 5) is nearly areal in nature, with maximum concentrations corresponding to the north-

[13] *On the approval of sanitary rules and norms SanPiN 1.2.3685-21 "Hygienic standards and requirements for ensuring the safety and (or) harmlessness of environmental factors to humans" (together with "SanPiN 1.2.3685-21. Sanitary rules and norms..."): Decree of the chief state sanitary physician of the Russian Federation no. 2 dated January 28, 2021 (as amended on December 30, 2022),* 1029 p.

[14] *Information bulletin on the state of the subsurface of the territory of the Siberian Federal district in 2020.* Issue 17. Book 1. Tomsk: Branch "Siberian Regional Center for State Monitoring of Subsoil Resources" of the Federal State Budgetary Institution "Gidrospetsgeologiya"; 2021, 196 p.

eastern part of the study area. This is one of the most toxic components contained in the sludge lignin stored in the maps[15,16] [15] and, according to the groundwater flow direction, is transported towards well 25-Г, where its maximum concentration was recorded.

The significant iron content (see Fig. 7), characteristic of most of the study area, as well as aluminum, whose levels exceed the MPC (see Table 3), is due to their high concentration in the main stored waste – ash slurry and ash from the BPPM thermal power plant [16] – as well as their content in sludge lignin and supernatant water[5].

From the west and southwest, the area of map no. 14 (wells 22-Г, 7-Б) receives petroleum products, phenols, anionic surfactants, and lead. This is likely associated not only with these components being part of the sludge lignin discharged into the Babkhinsky site maps at various times but also with domestic waste from nearby settlements and the operation of the railway and highway located near the site (see Fig. 1).

It should be noted that the concentration of almost all pollutants decreases significantly, approaching or reaching the MPC, in the north-northeast direction. This is particularly noticeable in the area of map no. 12 (see Fig. 7). Most likely, the high filtration properties of the boulder-pebble Neogene-Quaternary deposits in this area (see Fig. 4) facilitate the leaching of pollutants. Furthermore, the decrease in pollutant concentrations may be associated with the natural freezing out of colloidal sludge lignin sediments[5,17].

Various methods for the disposal of accumulated waste are being proposed. These include a biological method for treating supernatant water using the water hyacinth plant (*Eichhornia*); the complete reprocessing of sludge lignin and ash waste from maps no. 13 and 14 of the Babkhinsky site into marketable construction products using vibroforming equipment[18]. Researchers from Irkutsk National Research Technical University (Irkutsk, Russia) consider a technology involving the intensification of natural processes, specifically the freezing of lignin-containing sediments, to be highly effective. This process improves their dewatering properties, reduces sediment volume by up to 40 %, and also decreases the concentration of toxic organic substances due to their transfer into the aqueous phase (desorption), leading to reduced toxicity of sludge lignin and ash sediments. Subsequently, the scientists from Irkutsk National Research Technical University propose using the resulting substrate in agriculture as soil and fertilizer[12] [17]. Specialists from Ural Federal University (Ekaterinburg, Russia) propose using pulp and paper production waste (lignosulfonates) in the processing of ores containing heavy and precious metals [18].

Conclusion

Thus, the highest content of chemical pollutants in groundwater corresponds to the area of map no. 14 and the adjacent territory of map no. 13. These pollutants include heavy metals such as lead, iron, arsenic, manganese, and antimony, as well as elevated indicators of water turbidity and color.

The pollution sources are quite diverse: sludge lignin, ash slurry and ash from the thermal power plant, green liquor, bark waste, domestic waste from nearby settlements, and runoff from the railway and highways.

Approaches for the disposal of sludge lignin are being developed, and some have already been tested on the BPPM maps [17].

At the same time, it must not be forgotten that sludge lignin is not the sole source of groundwater pollution. The issue of eliminating heavy metals, which continue to enter the groundwater, remains unresolved. Several developments exist in this area, including a technique for immobilizing heavy metals using

[15] Terentyeva E.P., Udovenko N.K., Pavlova E.A. *Integrated chemical processing of wood.* Saint Petersburg: Saint Petersburg State University of Industrial Technologies and Design; 2012, 74 p.

[16] Guidance document 52.24.309-2016. *Organization and conduct of regime observations of the state and pollution of surface waters on land.* Rostov-on-Don; 2016, 104 p.

[17] Deception worth 3.5 billion rubles: "Rosgeologiya" will recultivate only 5 out of 14 in BPPM sludge storage facilities. *Pikabu.ru.* Available from: https://pikabu.ru/story/obman_na_35_milliarda_rubley_rosgeologiya_rekultiviruet_tolko_5_shlamonakopiteley_btsbk_iz_14_5967731 [Accessed 26th February 2025].

[18] Bychkov I.V., Bekker Yu.L., Dodonov A.N., et al. *Report on the execution of expert work on the topic: "Analysis of technological proposals and conduct of primary scientific and technical expertise of the concept for eliminating accumulated environmental damage resulting from the activities of the open joint stock company 'Baikal Pulp and Paper Mill' at the 'Solzansky' site and the territory occupied by wastewater treatment facilities with production premises containing black liquor". Analytical note: "Analysis of technological proposals for the elimination of accumulated environmental damage at the Solzansky site and the liquor-containing liquid".* Novosibirsk: Siberian Branch of the Russian Academy of Sciences; 2021, 386 p.

biochar[19] [15, 19], which is currently at the experimental testing stage.

Most likely, the most realistic approach at present to remediating the accumulated environmental damage and preventing further groundwater pollution involves not only the intensification of the initiated multi-stage biological and chemical treatment of supernatant water but also the subsequent reclamation of the territory using impermeable materials to line the bottom and sides of the ash and sludge disposal sites, and the construction of flood and mudflow protection structures [20, 21].

Assessing the impact of sludge storage facilities on groundwater in the coastal zone of Lake Baikal requires an integrated approach, including scientific research and monitoring observations of the distribution of pollutants in groundwater. In the current situation, addressing these problems is critically important for preserving the unique ecosystem of the Baikal region.

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