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Causes and environmental impact of the gold-tailings dam failure at Karamken, the Russian Far East

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ABSTRACT

Karamken was one of the most-productive gold-processing plants of the former Soviet Union located in the Magadan Region of the Russian North Far East. This paper discusses the causes, environmental damage and current geo-ecological conditions at the site facility after the accidental breakage of the storage pond in 2009 following industrial activity termination of this state enterprise (1994). The amassed water-saturated tailings from the mineral processing amounted ~280,000 m^3, corresponding to a total mass weight of 340,000 tons. The on-site multi-proxy investigations indicate synergic effects of hydrogeology, meteorology, engineering and human factors to have accounted for this major technical and environmental disaster. Piled sedimentary waste masses mobilized by removal of the dam-protective construction components initiated a water leakage into the main dam body and its eventual failure. Activated thixotropic processes of plagioclase clay-enriched sediments in conjunction with heavy machinery works on top of the 27 m-high frontal levee above destabilized permafrost grounds together with lack of the facility maintenance are the main causes for this industrial accident. The outburst of the accumulated deposits spilled large quantities of toxic elements stored in the pulverized saturated tailings, poisoning ground waters and causing severe damage to the local riverine ecosystem and fishery, as well as destruction of the nearby town with human casualties. The identified spillage risk factors could be used to forecast the stability of other similar facilities in the sub-Arctic areas.

1. Introduction

Magadan Region located in the North-East of the Russian Federation has seen over 80 years of intensive mining activity for extraction of precious metals, particularly gold, from both alluvial placers and ore bodies. About one third of all Russian gold comes from this geographic region about 45,000 population mostly employed in the gold mining industry. Eight gold mines are currently active including six open pits and two underground mines. The gold mining predetermines the economic and social development in the region for the next 20–30 years. Major infrastructure constraints imposed by seasonal permafrost fluctuations limit other industrial activities with an exception of marine fishery. Progress in extraction and processing technology opens the potential for new gold operations with production forecast of up to 60–70 tons per year. Such large-scale mining operations produce toxic slurries stored in dammed tailing ponds post-mineral pulverized wastes in a water-saturated state can be stored for a long time (Poulos et al., 1985; Moore and Luoma, 1990; Nardet Jr. and Stewart, 1996; Haneef and Yanful, 2007; Ashraf et al., 2011; Bedin et al., 2012). Tailings are waste repositories generated after processing precious metals from mechanically and chemically treated ores. Compact solidified masses of ore-waste pulp (also called “kekomi” or in Russian “khvosty”) are the principal post-extraction product of the gold-ore processing.

The safety of long-term storage of tails rises significant concern (e.g., Mittal and Morgenstern, 1976; Carrier et al., 1983; Manzano et al., 1999; Fourie et al., 2001; Peacy and Yanful, 2003. Ritcey, 2005; Zhang et al., 2006; Mata et al., 2007; Salgueiro et al., 2008; Loupasakis and Konstantopoulou, 2010; Fall et al., 2010; Guo, 2012; Craw and Rufaut, 2017; Martín-Crespo et al., 2018). Environmental risks are linked to their hydraulic structure (in)stability (HSS) aggravated by potential severe contamination of natural aquifers and surficial waters by cyanide by-products used in gold and silver ore processing (Ogola et al., 2002; Ozkan and Ipekoglu, 2002; Ata, 2003; Aysen, 2003; Ronconi et al., 2006).

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Fig. 1. A-B. Location of the Karamken site (KGOK), the central Magadan Region, North-East Russia. Legend: 1 – tailings dam, 2 – area of gold-exploitation processed in the Karamken metallurgic facility; also the area section contaminated by toxic wastes after the gold-processing storage dam breakage (29.08.2009), 3 – main communication roads.

The Karamken Tailing Plant (KGOK: *Карамкенский Горно-обогатительный Комбинат)* was built in the late 1970s' at the Tumannyy Brook, the tributary of the Khasyn River in the eastern Cherskogo Mountains (Figs. 1, 2A). This gold-processing facility used to be the major gold-copper operation in NE Siberia between 1978 and 1994 with approximately 1000 tons mill capacity of ore per day, 330 days per year of active extraction, and about 600 staff, Natural hazardous factors included slope stability, degrading permafrost ground. The Karamken tailing plant failure in 2009 is a prime example of such an accident and a major ecological catastrophe on the Russian territory caused by a combination of human behavior, industrial and natural factors.

The dam levee failure in the early morning of 29.08.2009 generated a slurry flow destroying the nearby village and a forest plantation in the Khasyn and Karamken floodplain. Two local villagers drowned, about 25 households and farm buildings were severely damaged. Vegetation downstream along the lower reaches of the Khasyn River valley was almost completely washed away. The spill caused a major water contamination by residual toxic elements and the suspended tailings pulp harming the local fishery and sources of drinking water. The total property loss, including the following mitigation costs, amounted to ~150 Mln RUB (~7.5 Mln USD). The paper discusses the causes and consequences of this environmental catastrophe.

2. Natural conditions and hydrogeological context

The gold-tailing plant of Karamken is located ~110 km north of the regional capital city of Magadan in the sub-arctic forest-tundra zone of the Northern Pacific area of Russia (Fig. 1). The Magadan Region is largely underlain by permafrost and maintains strongly continental climate with a protracted winter averaging 7 months that brings some of the coldest temperatures across Siberia and the Russian Far East (−5.7 °C in annual average, −27 °C during winter, and −45 °C in January). Average summer temperature is +20 °C, with hot spells of over +30 °C. Mean annual atmospheric precipitation is 411 mm of which 60% is rainfall. Further West in the direction of Yakutia, the lowest ground-air temperatures reached an absolute minimum of −81 °C (Glotov and Uchov, 2002). Geologically, the study area occurs

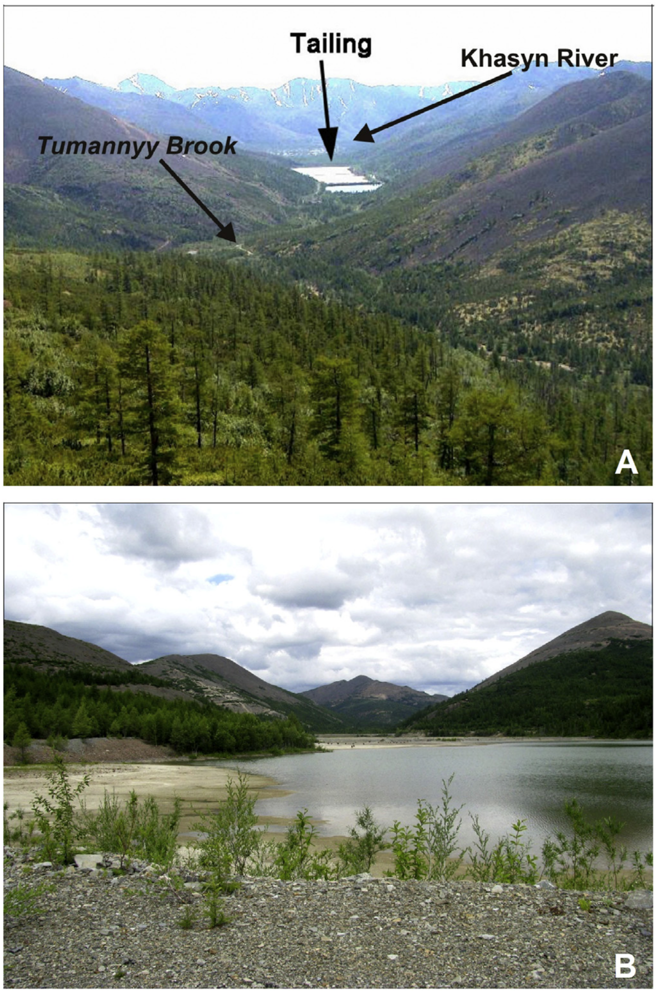

Fig. 2. A. An oblique aerial view of the Karamken gold-mineral tailings waste reservoir prior to the dam failure on 29.08.2009. B. View from the terminal part of the right dam crest wall (sandy-gravelly embankment). (photos by V.Ye. Glotov).

in the Okhotsk-Chukotka volcanic belt (Belyy, 1998). The Karamken gold-ore deposits are found in the Karamken caldera of Cretaceous age formed by andesitic and rhyolithic rocks penetrated by granite-porphyry dykes. The ore-gold minerals reside in 0.2–7.0 m thick quartz veins trace for a distance of 400–1000 m. Unconsolidated Quaternary (Holocene) colluvial slope and alluvial gravelly-sand deposits form the present surficial cover (data NEISRI FEB).

The relief of the study area is formed by hills of the Cherskogo Range rising at 700–1050 m ASL. The surface tailings at Karamken occur above the valley bottom at 452–455 m ASL (Fig. 2A-B). The catchment area of Khasyn River comprises ~140 km^2 and extends from the upper reaches to the mouth of Tumannyy Brook. The latter feeds the Karamken tailing dam. The stream channel during low-water is about 2 m wide with 1 m-high erosional sandy-gravelly banks cut into the Khasyn valley floodplain. Bedrocks in the study area are Cretaceous volcano-sedimentary formations. The tailings plant was built in the zone of permafrost reaching a continuous distribution on the adjoining water divides (Fig. 1B). Cryolithic conditions of the watershed headwaters constitute a major environmental factor. Seasonally frozen and thawed grounds are found on inter-fluvial levees of the Khasyn River valley (Fig. 3). Small taliks occur underneath riverbeds.

Hydrogeologically, taliks are formed by well-sorted coarse (gravel-pebble-size) unfrozen alluvial clastics which are up to 13 m thick. Permeability of these alluvial facies is 50–130 m/day. The surface channel flow gets arrested during winter, and the water level drops to 3–5 m below the surface. An aquifer beneath the river bed consists of gravelly sands with a fine-grained silty-clayey matrix sealing buried trees and other organic debris. The gravelly formation is partly cemented by loamy carbonates. Its thickness is not uniform reaching a maximum of 15–16 m at tectonic faults. Alluvium filtration properties in well tests do not exceed ~0.3–1.5 m *per* day in average. These low values, however, are largely influenced by the structure of the basin's sandy-loamy floor consolidated by cementation and compaction. Engineering-geology measurements showed that the practical values of these parameters that influenced the choice of the mechanical waterproofing of the accumulated ore waste in the tailing pond are qualitatively biased (Glotov et al., 2004). Below the local aquifer system, ground waters are stored in fractures and vein cavities inside the Cretaceous bedrock. The piezometric surface generally follows the water table, although being 2–7 m lower. This shows acting under-ground water filtration processes within the taliks downward from the alluvial deposits into the geological bedrock with limited permeability. Further detail on the natural setting of Karamken tailings and environmental aspects linked to the gold-processing are given in previous studies (Glotov, 2009; Glotov et al., 2010).

3. Construction aspects of the tailings facility

The Karamken storage pond (60°13′44″N, 151°04′22″E) was built in 1977 for tailings of waste pulp from the gold mining and mineral processing plant (Fig. 3). The gold-extraction procedure included ore-crushing to a fraction of 0.078 mm with subsequent gold and silver chemical extraction using sodium cyanide at an average rate of 300 tons/yr. The local tailings hydrology systems included one outer and two main dam lakes, infilling water channels, a subsidiary lake and an emergency siphon spillway (Figs. 2B, 4). At the time of dam breakage, the pond of a 5.1 million m^3 capacity was filled by 4.6 million m^3 of the pulverized gold-processing tailings. The facility remained shut down after closure of operations in 1994.

The main tailings pond measured 1200 × 230 m, and the dam wall was 28 m high with the crest length 320 m and width at the base of 10 m. About 8 m below the levee crest, the structure reached 6 m thickness (Fig. 2B). The unconsolidated loosely-pilled up levee with a certain water-filtering capacity was built from the local alluvial sandy-gravelly deposits of the Tumannyyy Brook and mountain-slope talus debris extracted in a nearby quarry (Fig. 2B). The technogene water-saturated wastes accumulated over the time of the gold-processing operations in the frontal part of the downstream dam to form a 7–8 m thick sedimentary body.

The Karamken tailings storage project presumed sufficient water-resistant properties of the basal alluvial layers forming the principal mass of the construction. Compacted loams and clays put into the dam core seemed to secure its waterproof property. Because of shortcomings of the site pre-construction engineering the dam turn out to be permeable to tailings effluents and leaking. Apart of this, a geological weakness was detected at the junction with the left-bank rock slope with underground streams absorbing waste waters from the pond. Finally, concentrations of clayey fines in the levee core were made too low. These technical deviations from the original project are held accountable for contamination downstream off the tailings. Hot summer of 1987 has increased evaporation from the tailing dam and correspondent increase of cyanide and thiocyanate levels in waters under the levee, up to, respectively, 3.6 and 15.12 mg/dm^3, which was about 36× and 151× higher than the allowed Russian water-resource safety and fishery water purity values (PDK)/maximum permissible chemical element concentrations (Federal Agency for Fisheries, 2010).

4. The Karamken tailings stability assessment: rationale, methods and approaches

The Karamken dam failure had the worst impact in this type of

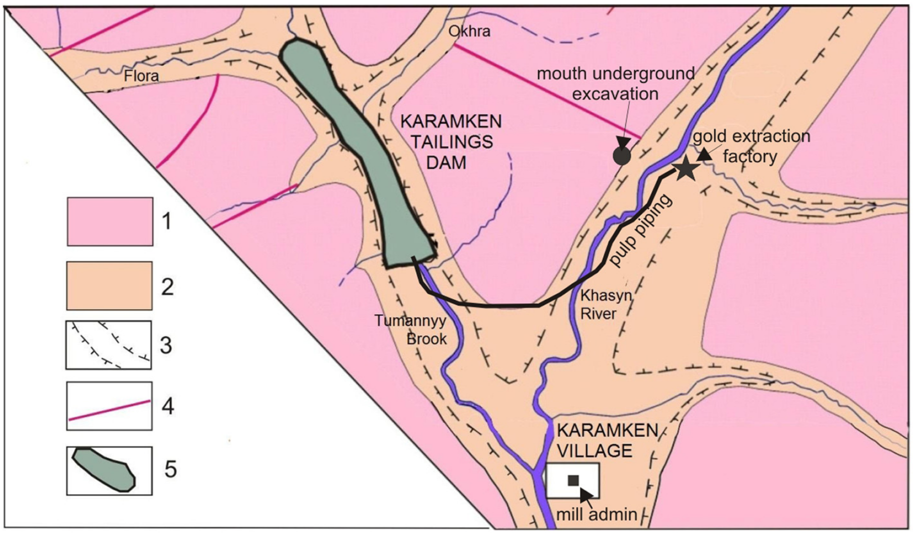

Fig. 3. Geology, cryology and hydrology of the Karamken tailings dam setting with a schematic technical mineral-processing base. Legend: 1 – Upper Cretaceous surficial geology (the surrounding mountain topography); 2 – Quaternary deposits (valley floodplains); 3 – limits of permafrost thaw zone; 4 – tectonic faults; 5 – the original tailings dam waste fillings.

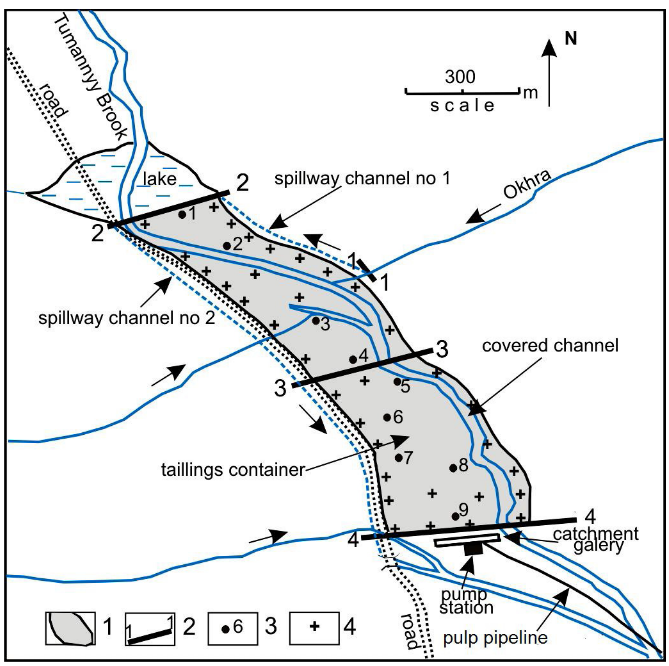

Fig. 4. Hydrographic scheme of the Tumannyy Brook valley with its principal tributaries (the Flora and Okhra streams) and location of the Karamken plant technical management facilities. Legend: 1 – tailings dam outer limits; 2 – dam construction alignments (1–1 Okhra Stream; 2–2 Tumannyy Brook; 3–3 central across the tailings dam; 4–4 terminal barrier); 3 – pulp sampling sites; 4 – surficial monitoring/sampling sites.

technogenic disasters ever happened in Siberia and the Russian Far East. As a specific case, it is a useful warming to prevent similar failures in permafrost areas.

The environmental hazard assessment of the site and the reconstruction of the causes of the dam failure followed after the facility had been shut down. This included geological monitoring of the tailings reservoir and the nearby gold mining area (2003 – 2013), with hydrogeological, cryolithic and geochemical investigations. Sampling was carried out in 2003, 2005, 2007 and 2009. In 2003, a total of 127 sediment and soil samples and 96 water samples were collected from the tailings dam and its vicinity to detect residual toxic mineral concentrations. This sampling campaign also assessed tailings for remaining precious metals. Samples were taken from the dry tailings surface at 20 cm intervals down to a depth of 80 cm along a 150 m transect parallel with the long axis of the reservoir (Fig. 4). Additional data (172 samples) were gathered on the waste waters hydrology and the tailings mineralogy including heavy minerals, cyanide (CN^{-1}) and rhodanide (SCN^{-1}). The spectrophotometer UVtiny-1240 was used for water tests (104 samples). The spectrophotometer Hitashi 180–70 was utilized for quantitative emission spectral analysis (21 measurements). The Polarized Zeeman Atomic Absorption was used for semi-liquid and solid samples (47 in total).

The sample processing was performed at North-Eastern Integrated Science Research Institute of the Far Eastern Branch of the Russian Academy of Sciences (NEISRI FEB RAS) in Magadan. Fieldwork included geology/hydrogeology studies supplemented by the analytical (tailings waste sediment) data collections. The solid and partly liquefied sedimentary samples were treated by cyanide and thiocyanate; environmental toxicity element tests were performed in the Centre for Laboratory Analysis and Technical Measurements for the Magadan Region. The sampling sites were chosen based on construction aspects of the dam and the outburst spillways in the Khasyn River valley. This study also utilized previous Karamken field monitoring reports archived at the Magadan Branch of the Territorial Geological Fund (former "Dalstroy" or IDSP) and the NEISRI FEB RAS).

5. Factors of dam breakage: research results

5.1. Technical factors

From the constructional viewpoint, the weak spot was the spillway channel no. 2 (Fig. 4). This spillway goes along the right slope of the valley at 0.0015° for a total length of 1360 m, average width of 8 m, and average depth of 2.8 m; the spillway was engineered for a maximum flow capacity of 48 m^3/s. The tailing plant spillway was built 2 years prior to the plant initiation. Originally, the channel was planned to be lined by concrete slabs. However, in the first year of the operation, there was an uneven and uncontrolled cryolithic collapse at the bottom of the channel in the head pickets for about 30 m. In December 1976, subsidence progressed, forming a trench 7 m deep that exposed large (up to 1 m) veins of underground ice, overlooked by preceding geoengineering survey due to insufficient number drill holes. A control trenching detected lenses of frozen peat covered by colluvial deposits testifying to active gravity slope creep processes. A decision was made to remove the frozen peat and ice wedges and replace the voids by gravelly filler to block expansion of underlying ice. To reduce pressure, iron slabs were placed along the channel instead of the concrete ones. Although the steel components were welded together, there was a channel tailings effluent leaking (up to 32 l/s) for a distance of 270 m from the head picket. In 2000, the steel lining was removed by metal looters. The trim was subsequently restored, but was replaced by loose iron sheets. This contributed to an enhanced leakage of the channel no. 2. Fed by water from the spillway channel, deposits started to accumulate at the bottom of the embankment along pond perimeter. The total flow rate in the low-flow summer averaged 280 l/s. Some water seeped into the submerged and liquefied tails, the rest accumulated on their surface within a shallow technogene lake.

Another identified technical factor was construction of a gravel-paved road on top of the dam wall. Its use by heavy trucks caused collapse into the receding permafrost and added pressure on the tailings dam levee. The road needed a constant supervision and maintenance, which was carried out sporadically over the life of the plant operation. Since 1994, the tailing facility was not active and left unattended. People started looting metal constructions for recycled steel market. In 2007, the emergency spillway – a siphon of 2 pipe diameters of 530 mm – was removed as well. Gravelly materials brought by trucks and bulldozers heightened the levee to prevent an accidental discharge of waste waters over the tailings dam.

5.2. Geochemical and neoformic mineral factors

Tailings usually contain ~10–20% of economic minerals that could not be technically recovered from the ore. At Karamken, the solid pulverized wastes of Au-ore processing were mixed with water at a ratio of 1 part of solids to 3–4 parts of water. This slurry was pumped into the tailings pond (Fig. 2B). A gradual precipitation of fines and mass compaction took place, and the released water was reused in the plant. Following the tailing deposition, toxic compounds were noted in the Tumannyy Brook through the supplying spillway channel discharging into the Khasyn River. Urgent measures were undertaken to mitigate river contamination. This included reduction of cyanides and thiocyanates in the pulp to values close to the national environmental PDK standards for surface waters. By early 1994, concentrations of toxic elements were diluted by waters from inflow streams draining the nearby slopes and by rainfall (Fig. 3). These measures resulted in decrease of toxicants to 10 mg/dm^3 in the groundwater system of alluvial reservoirs, in the cryogenic bedrock, and in the surface waters downstream of the tailing pond (Glotov et al., 2004).

The analytical results show that the geochemical reactions leading to changes in the mineral composition of wastes contributed to an activated fine-grained (clayey) sediment formation. This process likely involved large surface-area reactions of plagioclase with oxygen and water, which triggered a widespread development of capillary water membrane. By capillary rise, water migrated to the front layer of the seasonal freeze-thaw zone, i.e. to the day surface, with increased evaporation during permafrost degradation and active layer expansion. Summer desiccation of the tailings surface led to formation of a whitish silty salt crust of 5–30 mm in thickness. In mineral composition, this included melanterite ($FeSO_4 \cdot 7\ H_2O$), jarosite (KFe_4 + [(OH) 6·(SO_4) 2], halotrichite ($FeAl_2$ [SO_4] 4·22 H_20), gypsum ($CaSO_4 \cdot nH_2O$), and hydro-mica and kaolinite (Table 1).

The most recent samples collected in October 2008 showed that hydro-mica content in samples taken along the 20 m-high vertical wall near the levee tails grew by 15%. Monsoonal summer rains subsequently dissolved hardened salts and contributed to formation of small shallow ponds with the tailings waste-water pH 7.5 and the chemical composition of SO″$_4$ 702 mg/dm^3, Cl 1067 mg/dm^3, Mn 1.55 mg/dm^3; Li 0.04 mg/dm^3; Ti 0.74 mg/dm^3 and Au 0.0006 mg/dm^3. With the increased rainfall intensity and > 1–2 consecutive rainy days, the tailings pond formed a temporary technogene lake. The chemical composition of the pond-lake water is summarized in Table 2.

In accordance with theoretical prediction, the pulp deposited gradually at pond bottom and consolidated into compacted sediment with freezing propagated from the underlying permafrost (Glotov, 2009). Formation of this cryogenically influenced sediment was most intensive on the right bank of the reservoir adjoining the hill slope. The permeability of the thick sludge deposit was about 0.07 m/day reflecting a slow infiltration process of surface waters into the compacted pulp with a low hydraulic conductivity characteristic of fine-grained tailings deposits (e.g., Aubertin et al., 1996). This contributed to sulfide oxidation, hydrolysis, and transformation of silt fractions of plagioclase into clay minerals leading to growing clay content in the tailings. Mineralogical analysis of selected samples showed progressing enrichment of the sedimentary matrix in sulfates and clay mineral activation. This was accompanied by concentration decrease of the main rock-forming minerals such as calcite (Table 1). Water chemical composition remained annually stable at sampling sites near the tailings dam centre with prevalent concentrations of the main anions and cations (Table 2). Seasonal fluctuations were recorded with lows during rainfall season and highs during dry periods.

Table 1
Mineralogical composition of the gold-ore and tailings-pulp testing probes (%). Analysis: Au-Ore – Research Institute-1 TsNIGRI, Irgiredmet (Demin et al., 1974); tailings pulp –NEISRI FEB RAS (Savva, 2008).

Mineralogical composition	Au-Ore Average values (25 samples)		Tailings pulp Average values (25 samples)	
	Min.	Max.	Min.	Max.
Quartz	67.0	74.6	40	70
Feldspars	10.4	17.0	5	15
Clays (kaolinite, hydro-mica)	1.1	17.15	6	30
Calcite	2.9	7.0	–	–
Sulfides	0.3	0.7	0.2	0.5
Sulfates (melanterite, jarosite, halotrichite, gypsum)	no	no	7	20

The main toxic components (sodium cyanide – NaCN and lead nitrate – $Pb(NO_3)_2$) were used in the gold extraction. A chemical cleaning point with a circulating water supply was set up at the mineral-processing facility to remove these components. Tailings effluent decontamination was carried out by means of gaseous chlorine and a solution of pulverized lime. Cyanides were destroyed in this process and thiocyanates (SCN^{-1}) were formed instead. Control over the content of NaCN and SCN^{-1} was carried out 4–6 times per month with toxicity monitoring sampling. The effectiveness of toxin neutralization usually reached up to 100%, but occasionally it dropped for unknown reasons. In June 1989, the average chemical content in the cleaned purified pulp was 33.26 mg/dm^3, before treatment 750 mg/dm^3. After 1990, the cyanide content did not exceed 0.645 mg/dm^3, but the chlorine content in the waste water increased to 2870 mg/dm^3 and sulfate to 967 mg/dm^3.

In spite of installation of the toxic-chemicals' water-cleaning facility, the clay particle infiltration content (kaolinite, hydro-mica) pumped into the open water system from the tailings through the bypass filter was not regularly controlled. Because of the lack of an emergency spillway, sediments accumulated during high waters in the tailings pond partly evaporated but mostly filtered through the dam levee increasing by that concentration of clays. Lack of understanding of water migration processes and clay mobilization partly frozen man-made impoundments of low permeability under temperatures below 0 °C clearly account for the absence of prevention of the Karamken dam failure. Challenged properties of the processed ore-minerals with new specific geochemical and mechanical characteristics are believed to be one of the key aspects behind the accident (Glotov, 2009).

5.3. Physical (cryogenic, hydraulic and thixotropy) factors

Potential risks of cryogenic processes associated with the seasonally active permafrost are found along the southern margin of continuous permafrost (Fig. 1B). The main threat was seen in the mechanical levee

Table 2
Chemical composition of water samples near the dam centre in summer-fall 2008.

Site number	H_2O minera-lization (mg/dm^3)	Concentration of main components (mg/dm^3)							
Sample time		SO''_4	Cl′	HCO'_3	Mg^{2+}	Ca^{2+}	Na^+	K^+	NH_4^+
1 08.2008	185	74.5	31.2	18.3	4.3	44.1	8.7	2.0	0
2 08.2008	220	79.0	17.0	55.4	1.2	49.0	11.7	2.5	0
3 08.2008	790	377.0	8.5	150.8	23.1	172.3	71.3	8.8	0
4 10.2008	210	60.0	17.0	32.4	4.7	44.1	45.5	5.6	2.5

erosion. As observed in climatically similar geographic areas, change in hydrologic connectivity at the contact zone of an active layer with solid permafrost is undoubtedly another significant factor accountable for instability of tailings depositional overburden (Connon et al., 2014). The unfrozen contact of the waste tailings with the basal alluvial permafrost body can theoretically release the winter-frozen waste accumulations. Localized thaw release of the structural supports of the dam may have similar effect, although not yet confirmed by hard data. Absence of knowledge on the underground ice deposits and buried frozen turf, and colluvial talus beneath the spillway channel no. 2 (Fig. 4) is viewed as a factor that contributed to the initial levee instability momentum resulting in the complete destruction of the mineral pulp waste reservoir. Progressing development of taliks underneath the slope adjoining the Karamken tailings dam and associated collapse of loose destabilized grounds should have been taken as an alarm to urgently enforce the thawed-out base sediment with waterproof concrete. Instead, the site was propped up by a meshwork of metal plates at 300 m distance from the spillway head. These plates were subsequently looted away.

According to the hydrology safety assessment report (Geofizstroy, 2005), the dam failure may have generated a wave that surged water level in Tumannyy Brook and Khasyn River. Such water level increase is comparable in magnitude to an average 10-yr to 50-yr flood. The main environmental damage of such a modeled accident was because of increased stream turbidity and reduced water purity. This due to the floating fine (clay-size) mechanical particles accompanied by high concentrations of toxic minerals (manganese, aluminum, copper, arsenic, lead), all of which were above the Russian Ministry of Natural Resources MPC normative values for fishery water bodies. No threat of flooding was considered for the Karamken village located on the left bank of the Khasyn River opposite to the mouth of the Tumannyy Brook. This assumption was based on the environmental safety assessment report of the Karamken tailings pond (Shevchenko, 2005) backed up by the "Promgidrotekhnika" Company (Belgrade) expert report (Promgidrotekhnika, 2006).

The actual dam failure did not follow the simulated scenario. Torrential rainfalls lasted from 27th to 29th of August 2009 amounted 75.3 mm/m^2 (Hydro-Meteorology, 2009). In spite of the large drainage area (32.2 km^2), the right bank of Tumannyy Brook had the average flow of ~14.03 m^3 or about 3× less than the maximum capacity of the spillway channel. The trigger of the breakage is seen in subsidence of joints of the metal cladding alongside the concrete structure of the spillway channel draining into the pond causing water leakage. The levee at the site of overflow was washed away creating a free passage into the reservoir that became entirely flooded in the early hours of 29th of August 2009. The attempt to raise the dam levee by additional amassment of coarse sandy-gravel materials by heavy machinery failed. Instead, a small opening formed at the place of bulldozing, creating a crater immediately submerged in tailings pond waters. The levee crest subsided due to water saturation with a liquefied portion of the wall and the adjoining tailings collapsing downstream. This resulted in a 27 m deep and ~50 m wide breech for unrestricted outflow of floodwaters that submerged the floodplain located downstream of the dam. This process was promoted by the local relief gradient facilitating a speedy runoff corresponding to topography with similar hydrology patterns (e.g., Sushansky et al., 2002). During the ~30 min following the dam failure, the flood water volume of ~ 1.1 million m^3 went through the dam break at an estimated velocity of 10 m^3/s (Fig. 7A). After this catastrophic discharge, only a small stream of water of ~1.4 m^3/s was running through the destroyed tailings pond dam front (Fig. 7B). The pulp eroded from the cavity was precipitated into a conically shaped fan 60 m in radius. The sedimentary walls of the cavern were initially 20–25 m and became gradually eroded by stream to form small cascading waterfalls shaped into the thick bands. The remnants of the tailings remained fully water-saturated.

The thixotropy factor activated in the tailings dues to heavy mechanical (bulldozing) operations on the frontal dam crest (Figs. 2B, 7B). Saturated tailings compacted into a solid partly submerged mass with an enhanced shear-thinning ratio are susceptible to vibrations and gravity-flow processes analogously as in mudflows (Perret et al., 1996). After cessation of mechanical actions they normally return to a dense state with the expulsion of water (Seng and Tanaka, 2012). But under the intensive and protracted rainfall in the Karamken area, the backfill material of the dam wall mixed with the liquefied ore-processing waste and thinned to an average density of slurry (~1.2 t/m^3). The volume of this material is estimated at ~280,000 m^3 with a total mass weight of ~340,000 tons. The lateral pressure of the drifting saturated mineral-waste depositional mass with increased kinematic energy in conjunction with the progressively water-percolated levee body generated the ultimate dam-failure scenario (Fig. 5B) resulting in the catastrophic mud flood into the Khasyn River.

6. Environmental impact of the KGOK

Technical, human, cryogenic, meteorological, hydraulic, and thixotropy factors combined into the dam failure with catastrophic impact. The initially released slurry mass flushed tall (up to 20 m) poplar and larch trees downstream to the Khasyn River leading to deforestration of the 300 × 1000 m area in the central part of the valley. The velocity of the surge is estimated in 10 m/s with the proximal flood front width of 300 m. The momentum of the slurry surge was about 3.4 × 10^8 kg·m/s, which is about 20× less than the tailings waste flow energy level. The river flow rate after the dam breakage was ~45 m^3/s with the flow velocity 2 m/s. Estimated kinetic energy momentum of the Khasyn River waters in the area of confluence with the Tumannyy Brook was about 13.5 × 10^7 m/s, which was about 25× less than the pulse wave of the slurry waste mass. Eventually, a total of 1.1 Mm^3 of the pond water emptied into the valley over 3 days. The total water rushed across the Khasyn River channel, broke through the opposite river bank, destroyed ca. 25 Karamken village households (Fig. 8A-B), and killed two people. Nine years after operations closure, chemical contamination in the tailings pond and the draining stream showed just a minor seasonal increase in toxic substances mostly not exceeding the Russian national values of the fishery industry (PDK) without a major environmental

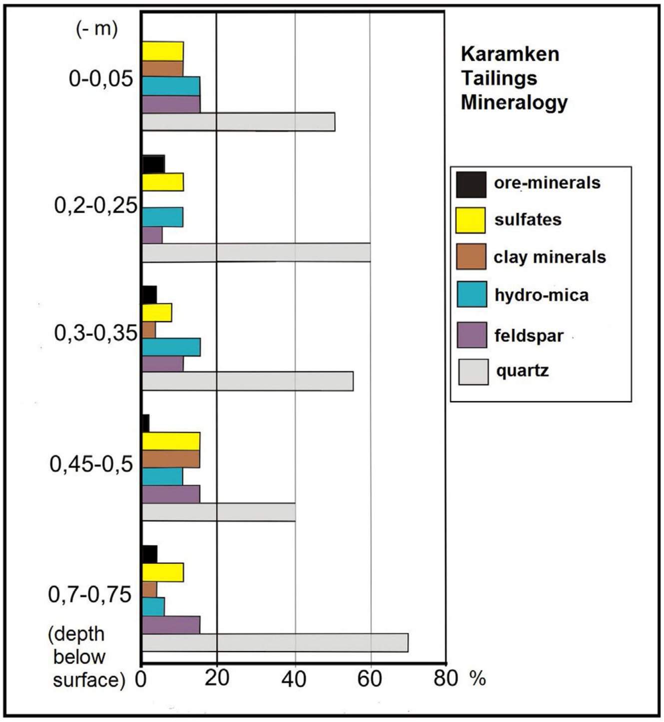

Fig. 5. Normalized mineralogical composition of the Karamken tailings in the original dam.

threat to the riparian zone and settlements of the Khasyn River floodplain (Table 3). The river with its mountain tributaries is state protected due to fish egg nestling and the high productivity of diverse salmon species.

In 2007, cyanide and thiocyanate-rhodanide (CN^{-1}/SCN^{-1}) were at maximum of ~300 m downstream of the dam (5/13 mg/dm^3), but progressively decreasing to ~0.05 mg/dm^3 (Fig. 6A). The latter value complies with the present Russian drinking water norms SanPiN 2.1.4.10749–01 (CN^{-1} 0.035, SCN^{-1} 0.1 mg/dm^3) as well as the national fishery norms (CN^{-1} 0.05, SCN^{-1} 0.15 mg/dm^3) (Federal Agency for Fisheries, 2010). Monitoring during plant operation and after its closure (1987 to 2003) provided evidence of a rapid decrease of both toxicants in the first years (Fig. 6B-C). These values correspond to the European Union 2006/44/EC normative physical and chemical water-purity parameters of the salmon and carp species protection (Directive, 2006).

Following the accident, a system of hydrology stations (Karamken, Palatka, Khasyn, Stekol'nyy) was established (Fig. 1B) providing a regular control of the quality of ground and surface waters (heavy mineral concentration, water turbidity, muddiness) of the Khasyn River. The concentration of fine mineral particles 1.5 km from the mouth of the Tumannyy Brook was ~10^4 higher (15,000 mg/dm^3) than the accepted national norm for the first 5 days after the tailings failure. Even at remote sites downstream of the Khasyn River near its confluence with the Arman' River, the muddiness index increased to 520 mg/dm^3 (NEISRI Internal Report, 2014). Suspended mud decreased to 0.01 of the highest value on day of catastrophe in one month from the accident. Contamination of ground waters was not detected. Currently, infiltration of the man-made clayey fractions in the Khasyn River significantly dropped, corresponding to about 150–200 mg/dm^3 during rainy summer-fall seasons; at the 10 km distance from the Tummanyy Brook where it empties into the Khasyn River values are 5–7 mg/dm^3, exceeding the Russian water-resource safety/fisheries PDK norms by only 3–5×. The latest field investigations (2016) accompanied by laboratory studies on the potential residual heavy-mineral contamination (Table 4) showed a marked drop of toxic elements that remain detectable just at the distance of a few km (currently 1 km) from the tailings site comparing to the upstream sites (1–3) closer to the dam with Al, Mn, Fe, Cu and Pb being the main persisting pollutants. This natural cleaning proceeded through dilution of Khasyn River waters from its mountain tributaries. Finally, in the freezing late days of October 2016, tailings were frozen to their base causing a cessation of pollution. Comparative studies of small rivers flowing into Okhotsk Sea provided similar results indicating improved water quality in winter seasons.

The former Karamken tailings facility was re-cultivated in 2010–2013 with financial compensations to the local inhabitants who were mostly moved into towns. At present, the Karamken site does not pose any environmental risks or danger to public health.

7. Technical and ecological security of tailings

Tailings accidents that cause major environmental damage are not limited to gold-mining facilities like the KGOK (Glotov et al., 2004). Bitumen extraction in oil sands in North America also produces massive tailings (e.g., Chalatumyk et al., 2002). In opposite to toxic mineral wastes, the latter generated from hydrocarbon repositories do allow

Table 3
Pre-failure normalized trace element contents in the waters draining from the tailings into the Tumannyy Brook and in-charging Khasyn River (mg/dm^3) (analysis by NEISRI).

Microelements	Fishery MPC max. normative allowed values	Probe number and sampling date			
		№ 1, 08.08.2003	№ 2, 12.08.2003	№ 3, 31.08.2003	№ 4, 02.10.2003
Antimony (Sb)	0.05	0.042	0.012	0.02	0.00043
Lead (Pb)	0.006	0.0001	0.0029	0	0
Arsenic (As)	0.03	0.0011	0.001	0.657	0
Manganese (Mn)	0.01	0.09	0.2	0.44	0.14
Bismuth (Bi)	0.1	0.00023	0	0.001	0
Beryllium (Be)	0.0002	0.0002	0.0002	0.0001	0.0003
Molybdenum (Mo)	0.25	0.0006	0.0005	0	0.002
Tin (Sn)	2.0	0.00006	0	0	0
Copper (Cu)	0.001	0.0018	0	0.003	0.0015
Silver (Ag)	0.05	0.00025	0.00025	0	0
Zinc (Zn)	0.01	0	0.00046	0	0
Nickel (Ni)	0.01	0.001	0.001	0	0
Cobalt(Co)	0.01	0.0002	0.0003	0	0
Strontium (Sr)	2.0	0.01	0.0095	0	0
Gold (Au)	no	0.00004	0.00004	0	0
Aluminum (Al)	0.04	1.014	3.25	1.93	0.31
Iron (Fe)	0.1	0.06	0.08	0.07	0.03

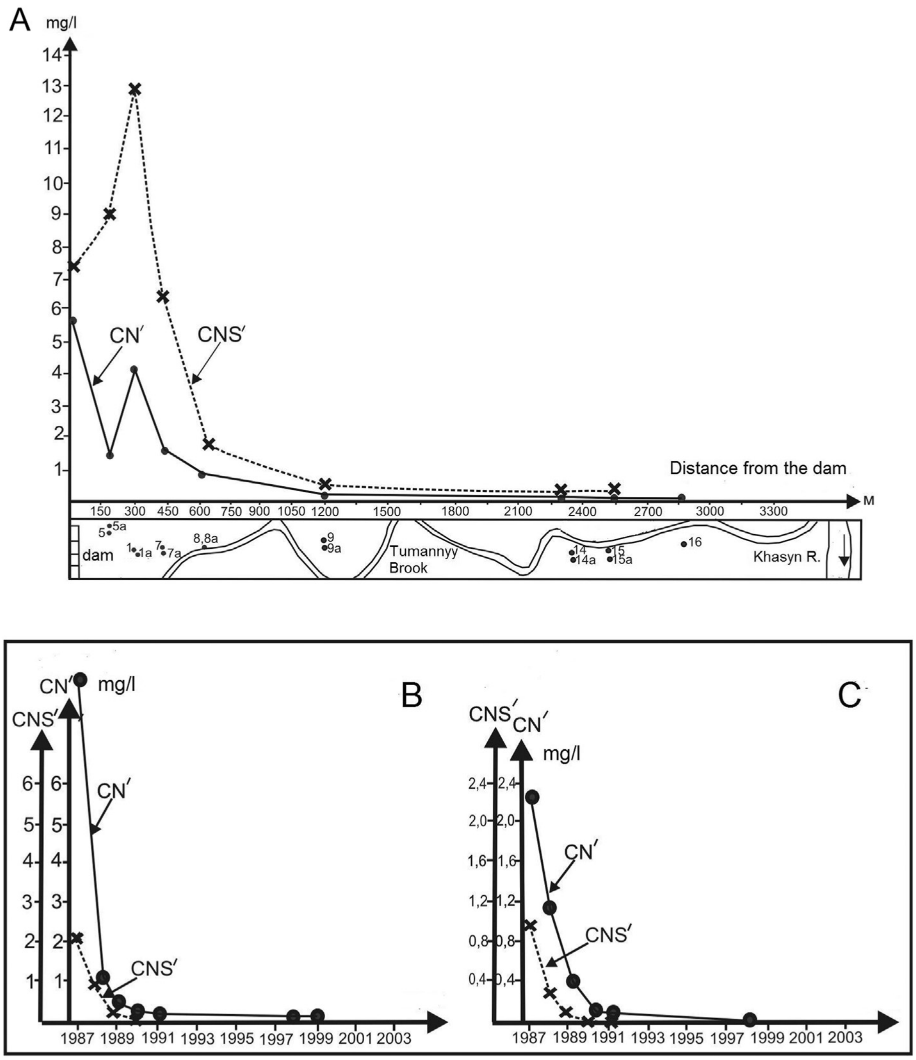

Fig. 6. A. Spatial concentration of cyanide (CN) & thiocyanate (CNS) (1987). The below scale shows the distance (m) from the tailings dam wall further downstream the Khasyn River; B–C. Temporal concentration changes of cyanide (CN) and thiocyanate/rodanite (CNS) at the tailings dam wall (B) and a 20 m-drilling well 150 m downstream (C) for the 1987–2004 period.

certain natural degradation and a post-sedimentary ecological recycling (Nix and Martin, 1992). Whereas safety of oil sands wastes can be secured by novel technologies (Ronconi et al., 2006) abandoned mineral tailings may pose long-term ecology threats (Zhang et al., 2006; Loupasakis and Konstantopoulou, 2010). In general, intensity and nature of environmental damage of a potential tailings breakage depends on several parameters such as hydraulics of a dam flood as a function of its composition and sediment liquefaction potential (Shen et al., 2018), toxicity, constellation of natural agents, modeled energy of the released waste slurry mass, as well as the local geological and geomorphic context such as the valley shape, topographic gradient, aquifer hydrology, cryogenic conditions, and vegetation cover.

Multifaceted analysis and ecology hazard modeling, inducing possible future dam failures at other places of Russia, must be performed to define and assist in the management of associated risks. In opposite to the KGOK, dramatic post-mineral extraction waste dam breakages having major environmental harm happened also in industrial regions with advanced safety monitoring (e.g., Grimalt et al., 1999; Manzano et al., 1999; Erikson and Adamek, 2000; Pastor et al., 2002). Toxic waste water leakages from large scale metal extractions pose an eminent threat to environment (Moore and Luoma, 1990; Datta, 2003; Ritcey, 2005). Mechanical parameters such as permeability, compressibility and compactness of tailings (Kealy and Williams, 1971; Carrier et al., 1983) and deficiencies in hydraulic structures causing a dam embankment seepage (e.g., Mittal and Morgenstern, 1976; Mata et al., 2007) are the principal controlling factors for the tailings accident scenarios (Chronology, 2017). Pulverized re-suspended technogenic solids in waste waters (Peacy and Yanful, 2003; Haneef and Yanful, 2007; Teper, 2009) along with waste saturation rates (Bedin et al., 2012; Bowker and Chambers, 2015) are another principal mineral tailings'-stability variables in conjunction with regular monitoring of fatigue of dams' construction elements.

At Karamken, the documented physical affect to the landscape was in congruence with the estimated mechanical strength of the total mass volume of the released tailings (Rico et al., 2008). The KGOK accident was similar in magnitude to the earthquake-triggered Tapo Canyon tailing dam failure in California in 1994 where toxic waters outburst downstream through a natural channel of impounded liquefied waste products and embankment materials (Nardet Jr. and Stewart, 1996). Simulations from other processing sites suggest that an increased clay content of the pulverized ore-extraction deposit (in a dry state) add to their overall cumulative stability and resistance to mechanical triggers such as earthquakes (e.g., Poulos et al., 1985). The overall assessment of safety regulations at mineral tailings sites is a proviso (Deng et al., 2011; Guo, 2012; Salgueiro et al., 2008).

The analytical results and on-site investigations at KGOK point to

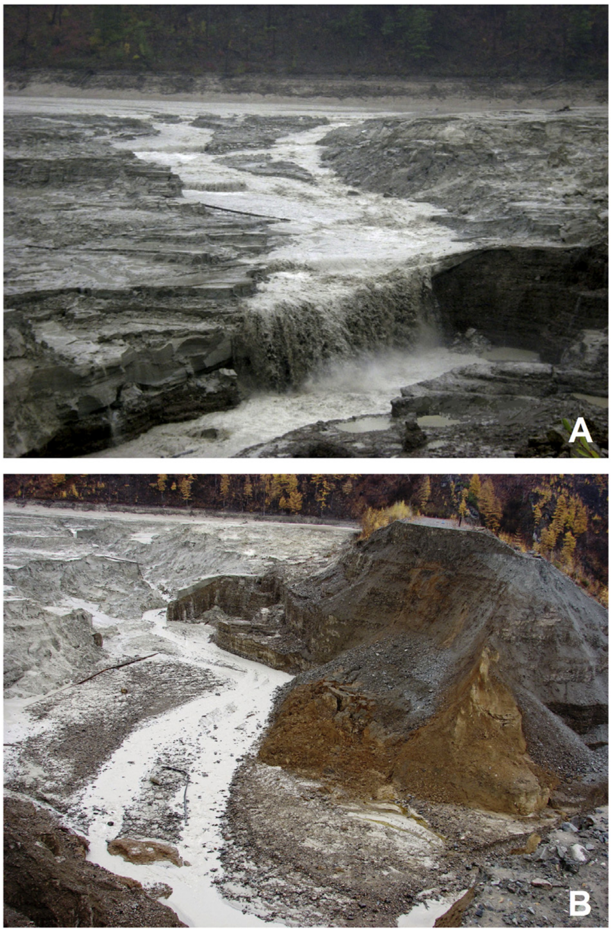

Fig. 7. A. Water flow over the tailings forming small caverns after release of the accumulated pulp after the Karamken dam breakage (situation 1 day later, on August 30th, 2009, 12:00); B. Tailings after breakage of the dam levee with the exposed pulp depositional masses.

activated dynamics of depository mineral pulp masses and the dam's construction behavior in the locally specific cryo-geological and hydrological context being the primary causes of the tailings failure. Similar accidents predisposed by seasonally unstable permafrost, and/or human factor shortcomings can happen at other mineral-processing sites in gold-mining regions with analogous natural conditions. Both factors impose serious environmental threats with respect to a potential geological base instability and dam construction aspects, respectively. Modeling of possible tailings breakages, the geo-ecological consequences of the released toxic wastes, as well as the provision of adequate mitigation strategies (including administrative and engineering controls) are of major relevance for similar events which may have major impacts to natural and settlement settings. The spill risk factors identified at Karamken may be used to forecast the stability of other similar facilities mainly in the northern regions.

8. Socio-economic feedback of mineral exploration in the Russian (sub-)arctic regions

The Russian Federation, with its immense territory, has been one of the major producers of gold and other precious metals in the World. About one third of all the Russian gold comes from the Magadan area with the peak of the gold extraction during the Second World War providing the financial means for buying the US military equipment. The gold production in the principal gold-mining regions (Krasnoyarsk, Irkutsk, Magadan, Khabarovsk, Amur and the Urals) (Fig. 9) saw a protracted decline in the 1990s'. Another plunge occurred during the financial crisis of 1997–1998 (Leskov et al., 2010). The Russian gold mining industry started picking up with the economic recovery, which was greatly promoted by the commodity price peaking on the World market in 2010–2012 (Fig. 10). About 275 t of gold was extracted in 2014 and further raised to about 300 t in 2015 (Russian Ministry of Natural Resources, cited by Lyubavina, 2015). Gold is usually extracted by water injection wells on a 4 × 4-m grid pattern for about one-month time interval. The deposit overburden is removed by a drag line and gold bearing gravels are either processed by hydraulic sorting followed by a sluice-box, or by a dredge. Though most of the Siberian and the Far Eastern gold originate from bedrock ores, placers represent significant portion.

Fig. 8. A-B. Destroyed taiga forest and the Karamken village downstream of the Khasyn River by the Karamken tailings dam outburst causing material damage and human casualties.

The increase in gold extraction and rise of ecological concerns bring new regulations and requirements on exploration security, technological processing and mineral waste storage (The Russian Federation Law on Mineral Resources, 1992). The former mineral mining and processing operations may pose acute ecology risks to natural as well as occupation habitats with necessity of their monitoring and mitigations. The relationship between private or state-own mining companies and residents in the (sub-)Arctic regions of Siberia and the Russian Far East is crucial. A certain progress in the national environmental consciousness and implemented legislative regulations in the Russian Federation is evident in respect to nature conservation priorities, population health as well as traditional cultural aspects (Environmental Protection, 2017). A wise PR policy of the precious mineral-mining companies in terms of

Fig. 9. The Russia's principal gold mining regions by referring to the national gold production (Fig. 10) with location of the study site (KGOK). Map: Mining.com (modified).

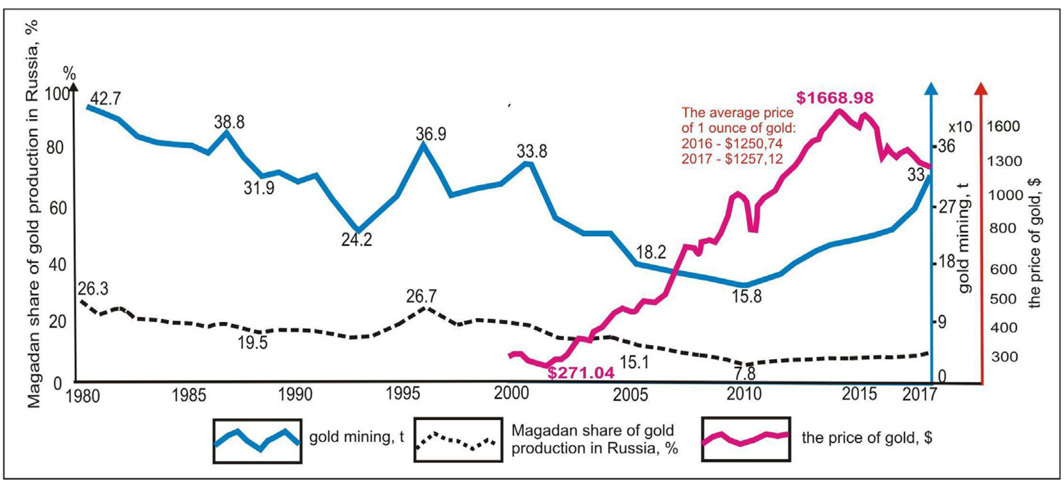

Fig. 10. Gold production in the USSR/the Russian Federation and the Magadan Region share for the 1980–2017 period in respect to world commodity price.

Table 4
Normalized trace element content at sites monitored during 2016 showing increased heavy metal values (in bold) (analysis by NEISRI FEB RAS Magadan) with respect to the PDK norms (2010) and WHO norms (1992). Sampling locations: 1 – Karamken dam wall, 2 – adjoining area 200 m downstream from the dam, 3 – the Khasyn River floodplain 200 m downstream, 4 – the Khasyn River floodplain 800 m downstream, 5 – Palatka Town, and 6 – Khasyn Town located 40 km and 50 km, respectively, from the destroyed Karamken tailings plant (Fig. 1B).

Sampling site no.	Metals concentration (mg/dm^3)							
	Al	V	Mn	Fe	Cu	Zn	Pb	Mo
PDK norm	0,04	0.001	0.01	0.1	0.001	0.01	0.006	0.001
WHO	0.2	0.1	0.1	0.3	0.1	3.0	0.01	0.07
1	**1.49**	**0.003**	**0.367**	**2.39**	**0,0096**	**0.017**	**0.081**	**0.0021**
2	**1.198**	**0.002**	**0.36**	**2,43**	**0.0092**	**0.0217**	**0,08**	**0.0022**
3	**0.451**	0.0008	**0.1**	**0.576**	**0.003**	0.0063	**0.021**	0.0006
4	**0.257**	0.0004	**0.059**	**0.555**	**0.0024**	0.006	**0.0102**	0.0005
5	0.015	-.	0.002	0.01	0.0006	0.0007	0.0002	0.0003
6	0.028	–	0.003	0.006	0.0016	–	0.0001	0.0002

Bold signifies excessive mineral contamination values with respect to the PDK and WHO norms.

public health and environmental rights' versus potentially negative ecology impacts is most essential (Ogola et al., 2002; (Safak and Ipekoglu, 2002; Bowker and Chambers, 2015). The high toxicity of gold-mining tailings due to the mainstream technology involving cyanide, waste deposits with elevated mercury and arsenic sulfides, and evolving chemistry in mineral wastes can cause major harms aquifers resources as well as local biota (Ata, 2003; Aysen, 2003. Ritcey, 2005; Elberling and Nicholson, 2010). The anthropogenically-triggered pollution in the (sub)-Arctic Siberian regions by various technogene materials, including post-mining toxic wastes, causing contamination of the traditional food resources, together with ongoing permafrost degradation are seen as the main negative factors affecting health of the native peoples and causing a long-term harm to the human organism (e.g., Kolpakova, 1999). Trace-elements concentrations among the inhabitants of the Magadan Region show increased concentrations of heavy metals (Gorbachev et al., 2003; Chlachula and Lugovaya, 2018). Environmental and social safety, public relations, and awareness of environmental responsibility of the Russian mining companies are, therefore, currently deemed increasingly important (Robinson, 2012).

The present-day mining operations in Siberia and the Russian Far East face logistic and technological challenges similar to the sub-Arctic and Arctic regions of the US (Alaska) and Canada (Yukon and NWT) found in the active permafrost zone (Natural Resources Canada, 2017). These northern regions can mutually benefit from experience exchange and transfer of novel mining technologies, tailings pond remediation and environmental protection approaches as well as public relation strategies (Robertson, 2001). Gold as well as other precious mineral mining industries must bring social and ecological responsibility, not just limited to tailings waste management storage, but also environmental risk prevention and public safety. Insolvencies from the abandoned mining and mineral-processing facilities bring challenges in the national legal regulatory systems (e.g., Government of Canada, 2002; Braker et al., 2013). All these aspects are particularly crucial and must be taken into consideration to prevent major tailings accidents such at Karamken, requiring an effective public warning system, a regular technical facility control, and eventual complex environmental mitigation and ecological damage restoration plans. All of these were largely absent in the case of the KGOK accident.

9. Conclusions

The Karamken dam failure of gold-exploitation tailings in the central Magadan Region in 2009 was a major of its kind in the Russian Federation. Co-acting human and natural site-specific factors are believed to account for the dam destruction. Lack of technical control together with deviations from the original project contributed to the dam's instability risks. The technogenic sediments produced over the 16 year-period of the KGOK operations amassed in the frontal part of the gravelly embankment body predisposed the initial levee instability weakened by a poor technical state of the facility construction. Mechanical effects (shocks and vibrations) caused by a heavy machinery from emergency engineering works prior to breakage added to the tailings thixotropy/pulp liquefaction momentum and generated basal leakage of waste waters over the seasonally unstable sedimentary cryolithic bedrock. The contextual studies suggest that intensified geochemical activity generating mobilization of clayey pulp can occur even at negative MAT (°C). The reconstructed causes of the KGOK tailings failure help in modeling of similar industrial accidents with assessment of potential environmental damage and preventing measures applied at mineral processing plants located in the zone of permafrost and built by using similar engineering technologies. The ecological and material loss with human casualties caused by the KGOK accident is a major warning bringing up imminent needs for legal regulations of the abandoned mining and mineral-processing operations in Siberia and the Russian Far East.

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