

M. V. MELIKHOV¹, Senior Researcher, Candidate of Engineering Sciences, m.melikhov@ksc.ru

A. I. KALASHNIK¹, Leading Researcher, Candidate of Engineering Sciences

S. P. OSTAPENKO¹, Leading Researcher, Candidate of Engineering Sciences

E. Yu. LEBEDIK¹, Engineer Cat 2

D. N. EGRASHICHEVA¹, Leading Engineer

¹Mining Institute KSC RAS, Apatity, Russia

RESEARCH AND MONITORING OF HYDRAULIC ENGINEERING FACILITIES AT MINES IN THE NORTH-WEST ARCTIC ZONE OF THE RUSSIAN FEDERATION USING REMOTE AND AUTOMATED METHODS*

Introduction

Hydraulic structures (HS) are the critical engineering facilities in the mining industry and are intended for storing and managing colossal amounts of production waste. Operational features of these facilities in the North-West Arctic of Russia are conditioned by the territorial specifics, as well as by the local challenging geology, hydrogeology and climate [1, 2]. The test area accommodates 11 tailings dams of free flow/weak pressure flow types and hazard class I–III, which accumulate about 1 Bm³ of mineral waste. The inventory data of HS show the following service life distribution: 9% of the facilities operate for shorter than 25 years, 18%—from 35 to 50 years, 64%—from 50 to 75 years and 9%—over 75 years. Some of the structures are either put out of action (including disposal without proper isolation), or need engineering modification in compliance with the actual ecological and industrial safety standards, and with regard to new opportunities offered by technological innovations and up-to-date protective geomaterials. Construction and operation of HS involve high anthropogenic risks connected with possible dam failure, and with contamination of specially protected natural areas by industrial effluents and harmful air emissions [3–5]. These potentially hazardous facilities are located nearby populated and specially protected natural areas, and can affect human health and stability of ecosystems [6, 7].

HS control and supervision in the mining industry adheres to international standards (for example, provisions of the International Council on Mining and Metals (ICMM)), as well as national standards, federal laws and governmental regulations, and also industry standards and rules, in particular: FS-117, GOST-55100, SP-58.13330.2019, SP 39.13330.2012, RB-078-12 etc. As per the laws in action in Russia, a mine owner is obliged to ensure continuous control and monitoring of HS, and the methods and means to this effect are selected and justified with regard to the hazard and complexity class of a structure. In the world practice, there are many approaches and technologies meant for the real-time diagnostics and estimation of factual and future condition of test facilities and their impact [8–12]. These approaches and technologies generally use Global Positioning System (GPS) and land surveying, geophysics, laser scanning, unmanned aerial vehicles (UAV), satellite-based remote sensing, etc.

At the present time, HS control and monitoring in the North-West Arctic zone of Russia uses the classical methods of visual inspection, GPS and land surveying, as well as piezometric and hydrogeological

The most important aspects of industrial and environmental safety of hydraulic structures at mines in the North-West Arctic zone of Russia are analyzed. An integrated interdisciplinary approach is proposed for monitoring and assessing the man-made impact of hydraulic structures on specially protected natural areas using modern remote (including space-based) and automated digital systems. Industrial risk control and management is implemented through the creation of digital twins and information maps for visualizing and systematizing objects by a threat level based on the comprehensive comparison and interactive data analysis (technological, cartographic, geological, hydrogeological, geochemical, meteorological, etc.), computer modeling data and remote sensing data. As a case-study of iron ore mines, the results of 3D numerical geoflow modeling of mineral waste disposal sites, as well as the remote area assessment using multispectral optical–electronic spacecraft of their induced hydraulic and aerogenic impacts on the environment are presented.

Keywords: Arctic zone, mines, hydraulic structures, specially protected natural areas, industrial and environmental safety, monitoring, modeling, remote sensing, geodata

DOI: 10.17580/em.2026.01.11

observations. In addition, with the direct involvement of the Mining Institute, KSC RAS, the routine strip geophysical subsurface and ground surveying is carried out using UAVs. After the obtained data evaluation and generalization, the geotechnical and 3D model analyses are performed to determine the key check parameters and to estimate the geomechanical and hydrodynamic stability of hydraulic structures. Experience shows that in the local Arctic conditions, the listed approaches suffice for the use at simple and small facilities. However, at large facilities on a rough terrain and in bad weather conditions, including facilities situated alongside production plants or protected natural sites, it is advisable to integrate the up-to-date distance and automated methods and technologies of satellite-based remote sensing with the full-blown observation system in use. In this case, advanced technologies in addition to classical techniques will ensure remote, real-time and continuous control of certain selected criteria throughout the entire area of several thousand square kilometers without any human presence at a test object. In actual practice, remote sensing methods can solve effectively some applied problems of engineering, geodynamics and ecology [13]. The combination of such methods with computer-aided 3D modeling enables a more comprehensive analysis of water flow formation

* The initial data acquisition and analysis and the model calibration are performed by the Leading Engineer of the Mining Institute, Kola Science Center RAS D. N. Egrashicheva with the invaluable help of Researcher D. V. Zaporozhets.

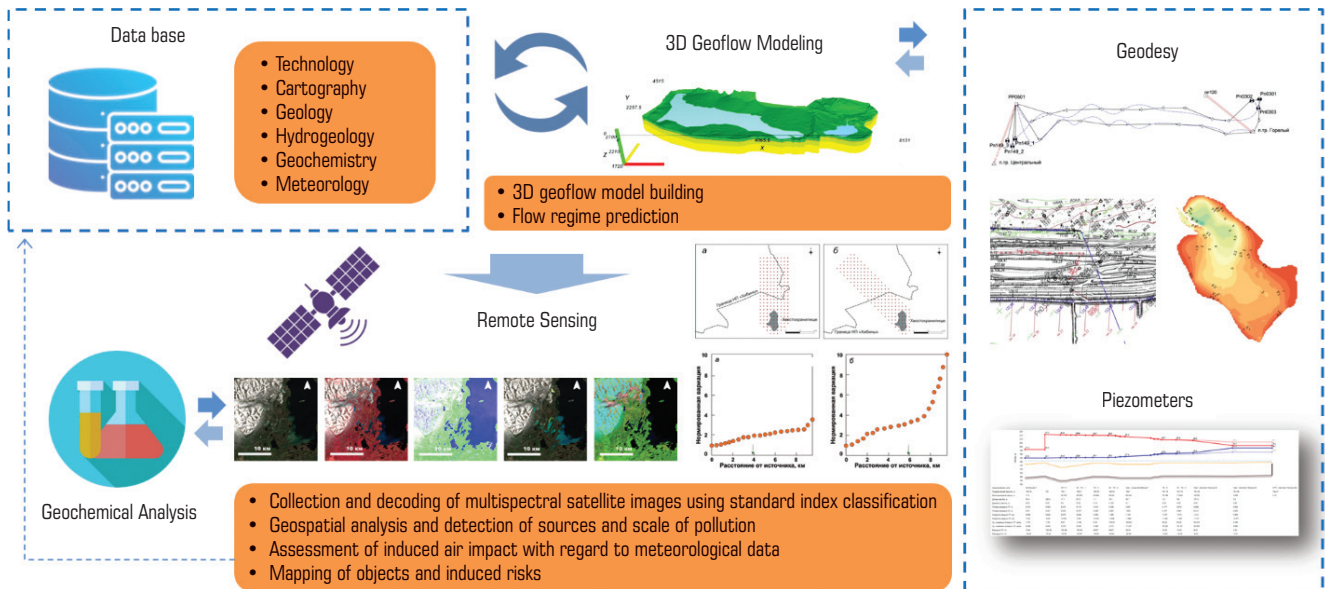


Fig. 1. Research methodology for HS at mines in Russia’s North-West Arctic zone using remote and automated techniques

and movement within the boundaries of watersheds and native habitats, which improves reliability of estimates of the mechanical and flow stability at the test hydraulic facilities.

The goal and objectives of the research consisted in the development and improvement of approaches to the remote and automated monitoring and evaluation of industrial locations of HS and specially protected natural areas on the basis of complexing of the advanced satellite-based (remote sensing) and digital (3D numerical modeling) technologies for the man-made risk prediction and management via creation of 3D virtual geoflow twins and information charts of induced risks with ranking of test objects with respect to the level of their environmental impact.

Methodology

The Mining Institute KSC RAS has accumulated considerable experience gained in the analysis and solution of basic problems connected with geomonitoring and safety of HS at mines in the harsh Arctic conditions [14, 15]. The applied approaches rest upon the concept of multi-level and multi-scale nature of various volumetric data and their integrated geospatial analysis. A wide range of technological tools and equipment is used to provide mining plants on a regular basis with information from subsurface, ground-based and aerospace monitoring.

Within the scope of this scientific trend, and within the framework of a project supported by the Russian Science Foundation, new methods and approaches (Fig. 1) to the remote and automated monitoring of HS in the interconnected natural-and-technical water environment using innovative digital and space-based technologies were developed and tested in mines [16]. The novelty of the approach in this article is complexing of the computer-aided modeling and remote sensing with the selected and validated criteria, with the subsequent integrated analysis of the obtained results and reliable in-situ data (technology, cartography, geology, hydrogeology, geochemistry, meteorology etc.). Methodically, as opposed to the previous approaches [16], 3D modeling results were compared with

the actual geodetic and hydrogeological (piezometric) measurements for the accurate calibration of the models, and the remote sensing data were collated with the data of geochemical mapping and water sampling. The goal was achieved using the methods of 3D numerical geoflow modeling and the multispectral infrared optical–electronic remote sensing systems. The research included the improvement of the methods and approaches to 3D digital geoflow modeling of HS within the limits of a watershed and to remote regional evaluation of the induced impact of HS on the specially protected natural areas, as well as the checkout and confirmation of the data reliability using the open-access information maps and resources. 3D numerical geoflow modeling consisted in the construction of 3D virtual twins of HS by the analysis of different variations of a model, and mechanisms of groundwater flow and related phenomena, with the detection of zones of potential infiltration and higher hydrostatic pressure. The satellite-based remote monitoring of the location areas of HS involved detection of signs of hazardous infiltration processes and industrial discharges on the surface of water areas (rivers and lakes), as well as assessment of scale and directions of propagation of pollutants. Remote collection and interactive geospatial analysis of the satellite data used a licensed applied software with the integrated automated functional allowing precise geopositioning and machine segmentation of images by classification signs on the basis of artificial intelligence. The final configuration of programs and survey instruments should be selected with regard to particular production tasks and specifics of the observation area. The research used the following programs: MODFLOW, 3D Groundwater Explorer, SNAP, Sentinel Hub EO Browser, ArcGIS (ESRI), QGIS, Google Earth and GRAL. Remote surveying involved acquisition and use of open data from satellite systems Sentinel-2 and -3 (ESA). These systems are subjected to annual routine testing and certification of the geodata reliability and accuracy. The developed methods and approaches were tested at HS at apatite–nepheline mines (Akron, Fosagro) [16] and at iron ore mines (EuroChem, Kola Mining and Metallurgical Company, Severstal).

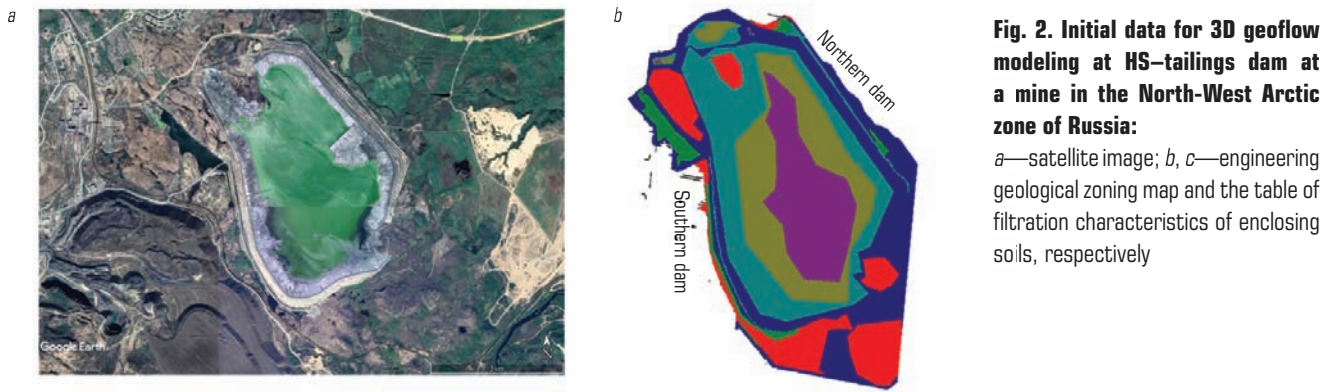


Fig. 2. Initial data for 3D geoflow modeling at HS-tailings dam at a mine in the North-West Arctic zone of Russia:
a—satellite image; *b, c*—engineering geological zoning map and the table of filtration characteristics of enclosing soils, respectively

| Type of soils | Alluvial soils | | | Dam body soils | Natural foundation soils | | | | |
|---------------|---------------------------------|--|---|----------------|--------------------------|--------------------------------|-----------------------|-------------------------------|---|
| | Pond sediments (loams) EGE-1 | Transitional zone deposits (sandy loam) EGE-2 | Beach deposits (sands and sandy loams) EGE-3 | EGE-4 | Turf EGE-5 | Loams and sandy loams EGE-7 | Fluid loams EGE-7a | Various-grained sand EGE-8 | Stone soil with sandy-loam aggregate EGE-9 |
| k_x [m/day] | 0.005 | 0.04 | 0.1 | 1.0 | 1.0 | 0.001 | 0.001 | 1.0 | 4.0 |
| k_y [m/day] | 0.005 | 0.04 | 0.1 | 1.0 | 1.0 | 0.001 | 0.001 | 1.0 | 4.0 |

Comments: k_x — filtration coefficient, EGE – engineering-geological element

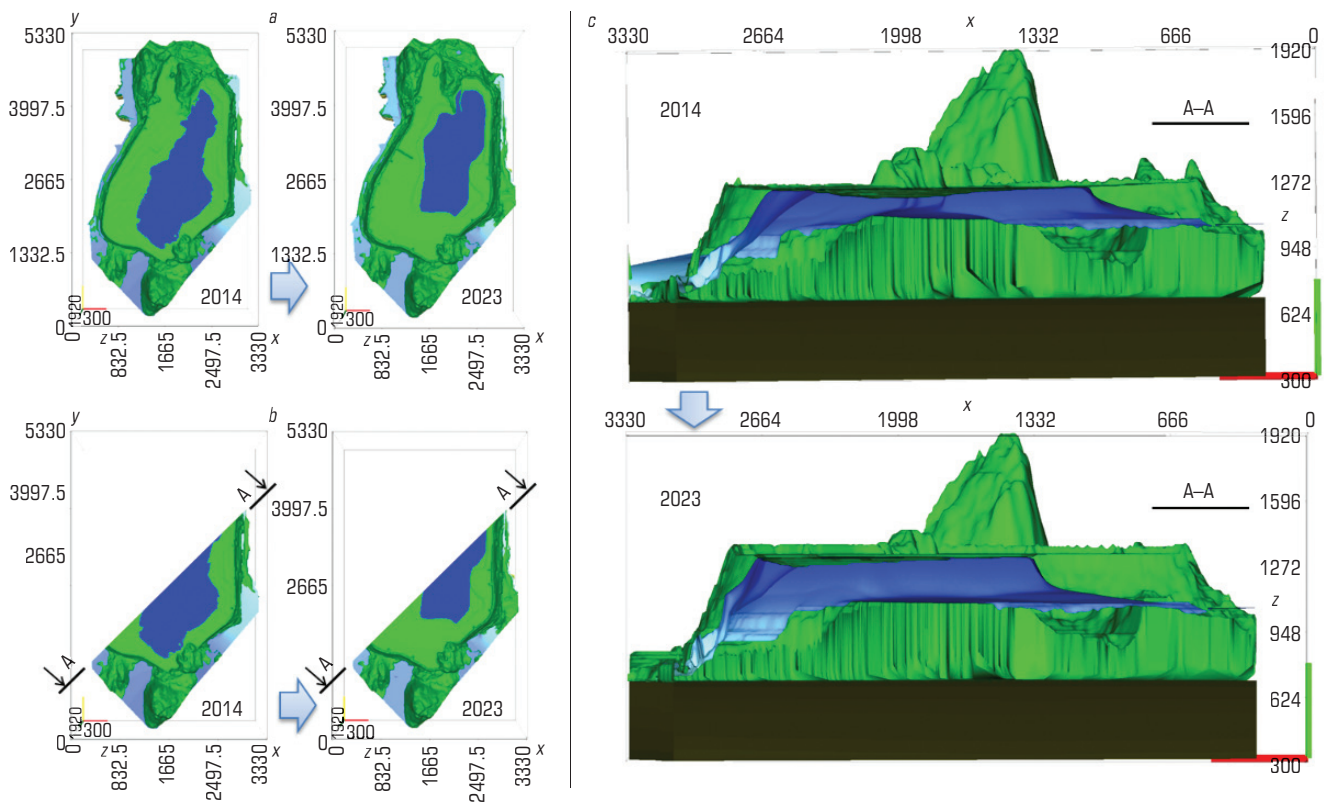


Fig. 3. 3D geoflow modeling at HS-tailings dam at a mine in the North-West Arctic zone of Russia in 2014–2023:
a—3D model; *b, c*—3D model cross-section and its segment, respectively

Results and analysis

The case-study of using the methods and approaches at iron ore mines (EuroChem, Kola Mining and Metallurgical Company, Severstal) in the Murmansk Region is described below.

3D geoflow modeling. For the conditions of HS—a tailings dam of Kola MMS, numerical modeling was performed to assess permeation stability of the dam and to predict changes in flow regime over the period of 2014–2023 (Figs. 2 and 3). A 3D geoflow model is built

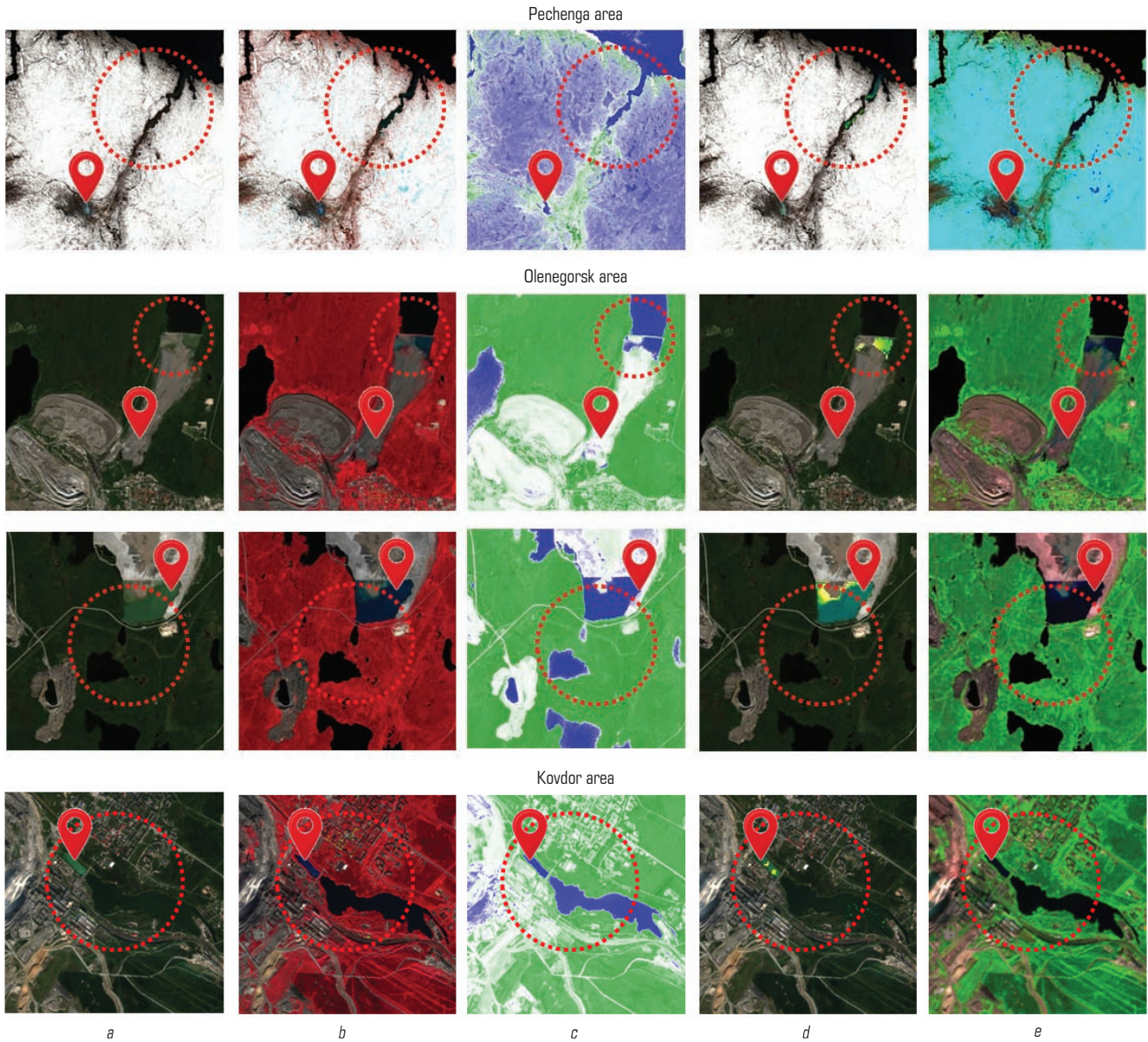


Fig. 4. Results of satellite-based monitoring and comparative analysis of images taken in location areas of HS-tailings dams at mines in the North-West Arctic zone of Russia using standard water quality indexes:

a—True color composite; *b*—False color; *c*—NDWI; *d*—UWQV; *e*—SWIR,

📍—location of HS, ○—satellite-based monitoring areas

in Processing Modflow 3D, and the model results are visualized in 3D Groundwater Explorer. Modflow 3D uses the block-centered finite-difference method for simulating nonstationary three-dimensional water flow with nonuniform permeability. In the reference scenario, the flow mode in structural geological layers was assumed to be forced/free flow with regard to estimated positions of groundwater levels. During modeling, they were automatically added together within the limits of the watershed, and their surface positions were found with regard to the total value of the levels. The problem was set in a stationary formulation and used the iterative conjugate gradient method. The permeability was determined for each engineering geological layer individually. The geometrical dimension of the model domain was

5330×3330 m. A 3D analytical model of the dam body and site was designed by means of generalization and patterning of the initial data. The flow regime was predicted for two variants of width of the above-water beach and with regard to the growth of the dam top during HS filling at a preset period of time.

Calibration of the 3D geoflow model used the data of visual inspection and reconnaissance investigation, including real-life geotechnical, geodetic and hydrogeological data for the 10 year-long period of observations. Additionally, during the mapping survey, the water level at the test HS was determined. Also, in the mapping survey, the planimetric positions of representative points of detail was determined using the polar method and completion survey, and the elevations—using

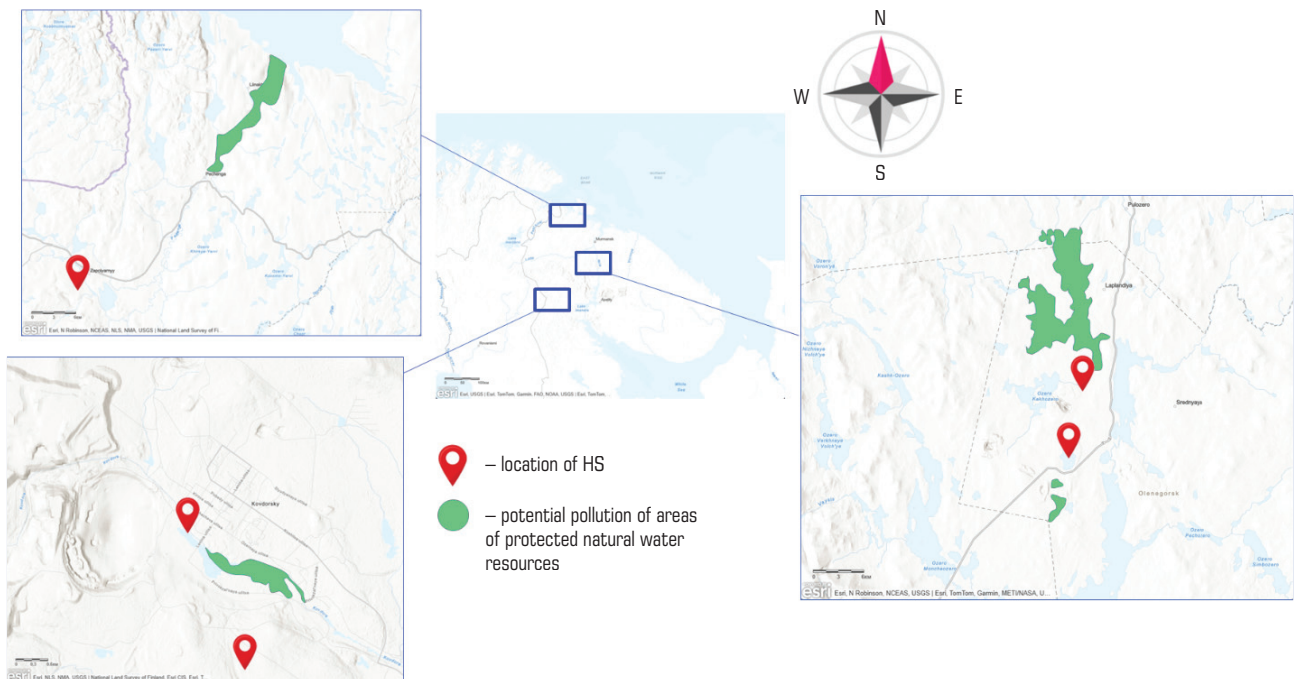


Fig. 5. Information map of induced pollution risk in natural water areas from satellite-based observations over HS–tailings dams at mines in the North-West Arctic zone of Russia

the indirect levelling and differential levelling. The mapping survey was implemented using robotic tachometer Leica TS16, high-precise digital levelling unit Leica LS15 and bar-code invar rods. The levelling along the axes of the dam tops was referenced with the local stationing. The measurement of depth of water and bottom sediments was carried out by two procedures, subject to the depth of water at a measurement point, using GPS tools and tachometer. The hydrogeological patterning of the 3D model domain was executed on the basis of the comparison of the engineering geological elements found from the analysis of the initial engineering geological and hydrogeological research, and from the lab-scale analysis of the permeability and strength properties of samples. Furthermore, the models were calibrated using the readings of 150 piezometers at 17 observation cross-sections.

From the 3D numerical geoflow modeling, the positions of the groundwater levels at the test HS were calculated and visualized. In the problems of the integrated diagnostics of such hydraulic structures, this method provides a more accurate assessment of their factual and future condition for the prompt detection of the potential zones of the increased hydrostatic pressure and infiltration in complex coupled media. The data of the flow regime change prediction were used to estimate reliability and permeation resistance of manmade soil bodies and sites of hydraulic-fill dams, and to study patterns of variation in the positions of the depression curves with regard to different values of widths of fill beaches. Using the data of the numerical modeling, the latent hazardous flow-induced deformations at downstream faces of dams were investigated. The quantitative changes of the segregation pool area were calculated, and the trends associated with the accumulation of tailings and with the dam growth were revealed. From the comparative analysis of the 3D models by the lengthwise and transverse sections, the steady-state hydrogeological operating regime of the test HS, in accord with

the project design, was confirmed, which made it possible to put the test hydraulic structure in the category of facilities of minimal environmental hazard and induced risk.

Monitoring of Water Areas. In four sites of HS–tailings dams and wastewater accumulation–settlers at mines of Kola MMC, Olkon and Kovdor GOK, a large-scale research of protected water areas was carried out in April–September 2016–2025 using remote sensing technique (Fig. 4). The remote sensing used multispectral wideband optical–electronic satellite systems Sentinel-2 (ESA) equipped with 12-channel camera MSI (RGB+NIR+SWIR) with a composite resolution of 10/20 m in the visible/infrared spectra, respectively. The satellite image collection and analysis was carried out using the following programs: ESA Sentinel Hub EO Browser, ArcGIS (ESRI), QGIS and Google Earth. The quality criteria of the surface condition of the test water areas were a group of standard indexes obtained by combining different channels in the electromagnetic spectrum: 1) True color composite, 2) False color, 3) Normalized Difference Water Index (NDWI), 4) Ulyssys Water Quality Viewer (UWQV) and 5) Short-Wave InfraRed (SWIR). All in all, 363 satellite images were analyzed, at the undercast to 10% and at the survey frequency of 5–12, by each of the five above-listed criteria (Kola MMC, Olkon and Kovdor GOK—146, 127 and 90 digital images, respectively). The images contain a set of initial metadata (date/time, coordinates, etc.) and have a high-precision reference with the terrain. On that base, the regional database of satellite images of HS and potential induced pollution zones was created. The remote sensing was aimed at detection and identification of high concentrations of suspended heavy metal particles (Ni, Cu, Co, Cd, Pb, As, Hg, Fe, Mn, Al, Sr, etc.) on the surface of water areas in the operation zones of HS. The satellite data, by the retrospective integrated analysis, were collated with the data of

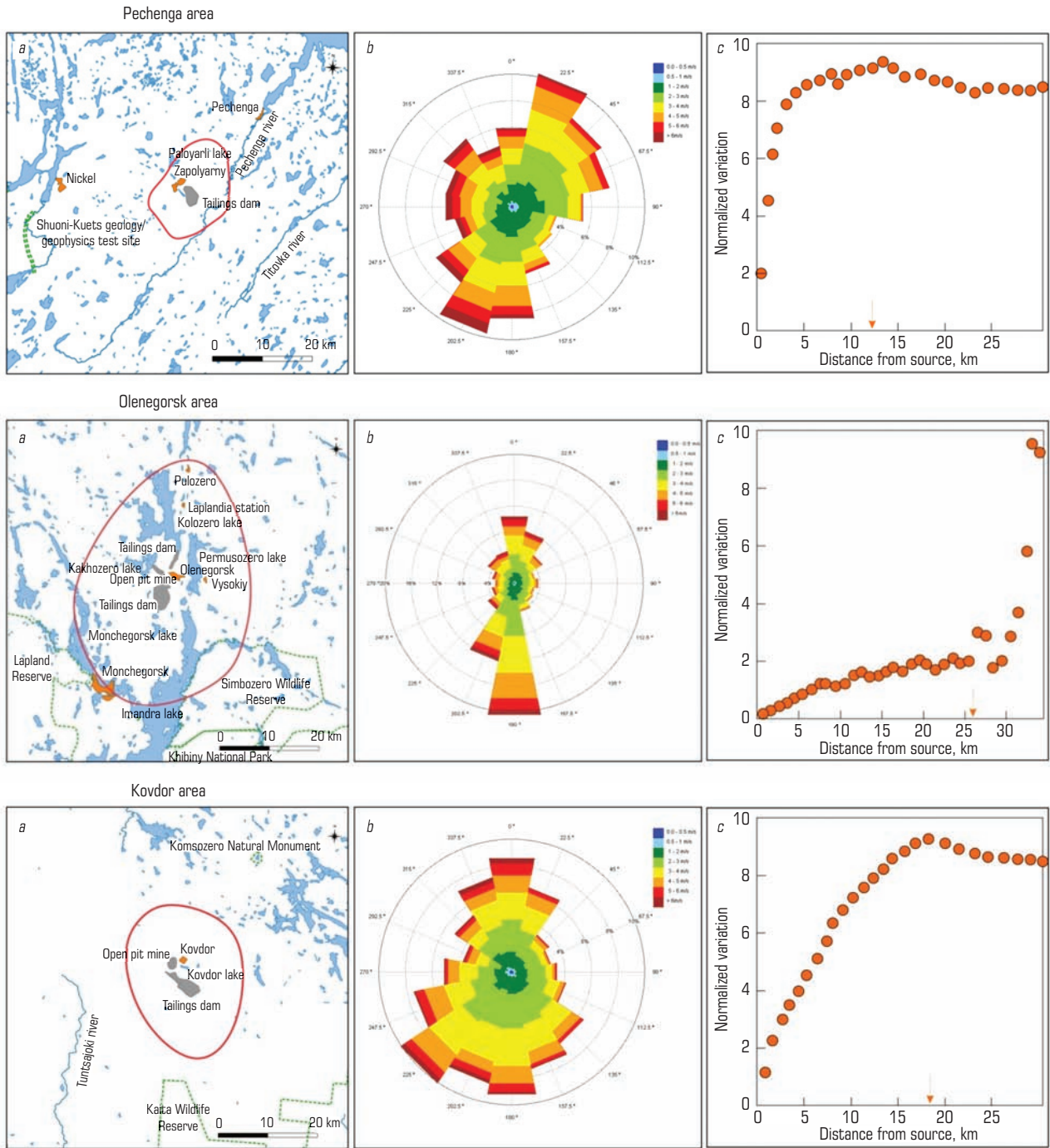


Fig. 6. Resultant estimates of induced air impact of HS–tailings dams at mines in the North-West Arctic zone of Russia: *a*—information map and location of test points; *b*—diagram of wind direction and velocity repetitiveness; *c*—estimated distance of induced air impact; ↓—distance from the test point to the limit boundary of induced air impact in the prevailing wind direction

the lab-scale sampling geochemical analysis of water from the open information sources.

On the ground of the 10 year-long satellite-based observations and from the comparative analysis of data using the above-mentioned standard water indexes, the signs of heavy metal pollution were revealed on the surface of some water areas, and the potential zones and scale of impact induced by HS at the test mines were identified. In the local

conditions, the largest information content was provided by the images processed by the index UWQV in the infrared part of the electromagnetic spectrum of 620/700 nm. The increased concentrations of harmful substances were locally spotted in the areas of the test HS, at individual dams, in the channels of large rivers (Pechenga and Kovdor) and in the water zones of lakes (Kolozero and Staroe). The high reliability and correlation of the remote sensing data was confirmed by their collation with

the lab-scale sampling geochemical analysis of water samples [17–19]. In some areas, it is required to undertake a systematic and comprehensive research through synchronization of satellite-based monitoring and geochemical water sampling as it is difficult to identify toxic pollutants because of their spread and concentration commonly in the lower layers of the water bodies. Based on the data generalization, the induced risk maps were drawn (Fig. 5). The highest induced risk is a feature of the Pechenga and Olenegorsk areas of location of HS as a consequence of discharge and infiltration of wastewater in case that the design reliability and safety of the engineering facilities is failed. It should be mentioned that the test hydraulic structures are located nearby population centers, and the adverse effect of these structures fuses with the induced impact of other potential pollution sources.

Monitoring of air impacts. In three location areas of HS–tailings dams at mines of Kola MMS, Olkon and Kovdor GOK, their impact on air in the natural water areas of preferential protection and in the national wildlife reserves in the period from 2020 to 2025 was estimated using remote sensing methods (Fig. 6). The remote sensing of the areas used multispectral optical–electronic satellite systems Sentinel-3 (ESA) equipped with camera SLSTR with channels of 555–12000 nm with resolution of 500–1000 m. Collection and interpretation of the satellite images was carried out in SNAP, and the weather data were processed using GRAL. A risk criterion was selected to be the limiting contour of aerosol effect of the observation points, which was determined from the comparison and calibration of the computer-aided modeling results on the distance of transfer of average aerosol pollution with wind on the bases of weather and satellite observations. When selecting parameters for the mathematical modeling of wind transfer of pollutants in the nearsurface air layer, we used the information obtained from the re-analysis and interpolation of the archival cloud data of the European Centre for Medium-Range Weather Forecasts (ECMWF). The analytical model provided the following meteorological data: direction and velocity of wind at a height of 10 m; rainfall amount; total cloud cover; direct solar radiation; air temperature at a height of 10 m. During reliability checkup and calibration of the analytical model of wind transfer, the variation in the spatial correlation of the spectral aerosol pollution index with the distance from the source was estimated from the in-situ measurement data. The calculations of the spectral index used the satellite-based observation data on the earth's radiant heat flux, which enabled remote identification of aerosol contamination of the nearsurface air layer by mining waste products.

Based on the 5 year-long observation results, the limit boundaries of the induced air impact exerted by industrial facilities on the specially protected natural areas were plotted by means of interpretation of satellite-based heat images. The remote sensing reveals that at all test HS facilities, the limit zone of the induced air impact, in accordance with the wind direction repetitiveness, stretches north–southward, which elevates the risk of aerosol pollution in the areas of the Kaita Wildlife Reserve, Lapland Reserve and the Khibiny National Park, situated southward of the impact source. For another thing, it is found that wind transfer from the surface of fine waste stockpiles of magnetite ore processing waste in the Zaimandra iron ore province covers areas of a few water bodies—the lakes of Imandra, Moncheozero, Kolozero, Kakhzero and Permuzero, which defines the priority of this aerosol pollution source in ranking of HS by the induced risk level. The smaller area of spread of the induced risk is a feature of copper–nickel ore waste in the Pechenga ore field, with the aerosol pollution observed in the area

up to the Paloyarvi lake and Pechenga river. The induced air impact of baddeleite–apatite–magnetite ore waste in the Kovdor iron ore field brings a lower risk, with the Kovdor lake inside its limiting contour. On the basis of the remote sensing data and their generalized analysis, the information maps of the induced risk of aerosol pollution in the specially protected natural areas and water bodies were plotted. It is shown that the areas of the Khibiny National Park, Simbozero Wildlife Reserve and, potentially, Lapland Reserve are exposed to the induced air impact of the test mines. The highest induced risk is a feature of magnetite ore waste in the Zaimandra iron ore province: the wind transfer of fine dispersed particles from the surface of these waste storages governs pollutions of the lakes of Imandra, Moncheozero, Kolozero, Kakhzero and Permuzero.

Conclusions


In this manner, within the framework of the integrated research connected with the remote and automated monitoring of hydraulic structures at mines and in the adjacent natural areas of preferential protection, the methods and approaches to the induced risk prediction and control have been developed as a case-study of the North-West Arctic zone of Russia. The goal of the research was attained using the advanced digital and satellite-based technologies in the form of computer-aided modeling and remote sensing of locations of HS for detecting hazardous induced processes and to assess their effect through creation of digital twins and information maps of potential risks and their ranking by the level of their environmental impact. The signature of the proposed approach is complexing of the methods of 3D numerical geoflow modeling and remote sensing using the multispectral optical–electronic satellite systems by means of the generalized and interactive analyses of omnifarious data, including highly reliable real-life information (geotechnology, cartography, geology, hydrogeology, geochemistry, meteorology, etc.). As a case-study of operating HS–tailings dams at iron ore mines and in the adjacent specially protected natural areas, the application of the development methods of remote monitoring and evaluation of condition of HS is described in solving problems connected with the prediction and control of ecological and industrial risks and hazards. It is wise to integrate the methods and approaches described in this article in the integrated observation systems in operation in mines. On the other hand, some of the proposed methods and approaches need no special field observations to be carried out; and they can be adapted to other extremely hazardous facilities of the mining industry.

Acknowledgements

The study was supported by the Russian Science Foundation, Project No. 24-27-20013.

References

1. Arkhipov A. V., Reshetnyak S. P. *Manmade Deposits. Formation and Management. Apatity* : KNC RAN, 2017. 175 p.
2. Lolaev A. B., Butygin V. V. *Geocological Problems of Water Engineering in Permafrost Zone*. Moscow : Nedra, 2005. 239 p.
3. *World Mine Tailings Failures—From 1915*. Available at: <https://worldminetailingsfailures.org/> (accessed: 10.11.2025).
4. Franks D. M., Stringer M., Torres-Cruz L. A. et al. Tailings facility disclosures reveal stability risks. *Scientific Reports*. 2021. Vol. 11, No. 1. ID 5353.

5. Lyu Z., Chai J., Xu Z., Qin Y., Cao J. A comprehensive review on reasons for tailings dam failures based on case history. *Advances in Civil Engineering*. 2019. Vol. 2019, Iss. 1. ID 4159306.
6. Dauvalter M. V., Dauvalter V. A., Sandimirov S. S., Denisov D. B., Slukovskii Z. I. Hydrochemical monitoring of surface waters in the influence zone of the Oleniy Ruchey mine. *Trudy Fersmanovskoj nauchnoj sessii GI KNC RAN*. 2022. No. 19. pp. 80–85.
7. Amosov P. V., Baklanov A. A., Goryachev A. A. Dusting of apatite-nepheline ores enrichment tailings: an environmental problem and pathways to solve it. *Apatity : FIC KNC RAN*, 2023. 168 p.
8. Yang Y., Zhou X., Chen X., Xie C. Numerical simulation of tailings flow from dam failure over complex terrain. *Materials*. 2022. Vol. 15, Iss. 6. ID 2288.
9. Haitao M., Yihai Zh. Physical Modeling of Tailings Dams in China: A Review. *Journal of Mining Science*. 2022. Vol. 58, No. 4. pp. 548–560.
10. Zare M., Nasategay F., Gomez J. A., Moayedi Far A., Sattarvand J. A review of tailings dam safety monitoring guidelines and systems. *Minerals*. 2024. Vol. 14, Iss. 6. ID 551.
11. Lumbroso D., McElroy C., Goff C. et al. The potential to reduce the risks posed by tailings dams using satellite-based information. *International Journal of Disaster Risk Reduction*. 2019. Vol. 38. ID 101209.
12. Clarkson L., Williams D., Seppälä J. Real-time monitoring of tailings dams. *Georisk*. 2020. Vol. 15, Iss. 2. pp. 113–127.
13. Raevich K. V., Vokin V. N., Kiryushina E. V., Maglinets Yu. A. Space technologies of Earth remote sensing in applied problems and theoretical studies in mining. *Eurasian Mining*. 2023. No. 1. pp. 3–6.
14. Melnikov N. N., Kalashnik A. I., Kalashnik N. A., Zaporozhets D. V. Integrated multi-level geomonitoring of natural-and-technical objects in the mining industry. *Journal of Mining Science*. 2018. Vol. 54, No. 4. pp. 535–540.
15. Kalashnik A. I., Maksimov D. A., Kalashnik N. A. et al. Multilevel Integrated Research and Monitoring of Tailings Dams at Mines in the Northwest Russian Sector of the Arctic. *Apatity : KNC RAN*, 2022. 250 p.
16. Melikhov M. V., Kalashnik A. I., Ostapenko S. P., Lebedik E. Yu. Integrated approach to remote monitoring of waterworks facilities in the mining industry using space and digital technologies. *Journal of Mining Science*. 2025. Vol. 61, No. 1. pp. 155–164.
17. Dauvalter V. A. Geochemistry of lakes in influence zone of an Arctic iron ore mine. *Geohimiya*. 2020. Vol. 65, No. 8. pp. 797–810.
18. Gorin S. L., Leman V. N. Hydrogeological regime and pollution in the basin and water area of the Pechanga bay (Varangerfjord in the Barents Sea) by long-term hydrometeorological survey data. *Trudy VNIRO*. 2017. Vol. 165. pp. 66–82.
19. Koroleva I. M., Valkova S. A., Vandysh O. I. et al. The state of lake Kovdor ecosystem and characteristics of its fish community. *Trudy KNC RAN*. 2012. No. 3(10). pp. 245–276. 

MINING INDUSTRY IN THE COMMONWEALTH OF INDEPENDENT STATES (CIS) COUNTRIES

A. Z. GRIGORYAN¹, Lecturer, Associate Professor, Candidate of Economic Sciences, ani.grigoryan@asue.am

P. VERHALLEN², PhD, Professor

¹Armenian State University of Economics, Yerevan, Armenia

²Poole College of Management, North Carolina State University, Raleigh, USA

DEVELOPMENT OF THE ZANGEZUR COPPER–MOLYBDENUM COMBINE AS A LEADING SEGMENT OF THE MINING INDUSTRY IN ARMENIA

Introduction

Zangezur Copper–Molybdenum Combine (ZCMC) established in 1951 is a backbone of the mining industry in Armenia. Primarily intended to supply the domestic industry with raw materials, it plays a key role in export and economic growth of the country [1]. For many decades, the Company makes a great contribution to the national economy by production of copper and molybdenum which are in high demand both on internal and external markets. The long-term production activities of the Company resulted in accumulation of unique and extensive resources and experience to comprehend various technical and economic aspects of resource management [2–4].

At the present time, the Company uses both conventional ore resources and mine waste accumulated within decades of production. The overall reserves are estimated as 45 Mt of ore with copper content of 0.45% and molybdenum content 0.025%. The annual production output is 35 thousand tons of copper and 1.2 thousand tons of

This research aims at the analysis of economic value of the mineral processing industry in Armenia, with spotlight on the Zangezur Copper–Molybdenum Combine (ZCMC). The analysis integrates economic and ecological aspects, and the strategic role of the mining industry in the national development of Armenia.

The article offers a structural and technological review of activities of ZCMC, including production stages of copper and molybdenum concentrates, mineral processing methods, and volumes of production. Emphasis is laid on contribution made by ZCMC to industrial production (10–15%) and export (25–30%) of Armenia owing to sales of mineral concentrates.

In addition, the socio-economic effects of activities of ZCMC are discussed, including job creation, infrastructure development and integration of local communities.

Keywords: Armenia, mining industry, copper–molybdenum combine, economic effect, sustainability, resource management

DOI: 10.17580/em.2026.01.12