EXPERIENCE OF MINING PROJECT IMPLEMENTATION

Research paper

https://doi.org/10.17073/2500-0632-2022-12-68
УДК 622:502.7

Detection of violations of open-pit mining lease boundaries using Sentinel-2 MSI data in the case of Lao Cai and Yen Bai provinces of North Vietnam

X.B. Tran[1], L.H. Trinh[2], Q.L. Nguyen[3], Yu.M. Levkin[4], I.V. Zenkov[5], T.H. Tong[2]
[1] *Hanoi University of Natural Resources and Environment, Hanoi, Vietnam*
[2] *Le Quy Don Technical University, Hanoi, Vietnam*
[3] *Hanoi University of Mining and Geology, Hanoi, Vietnam*
[4] *Russian Union of Surveyors, Moscow, Russian Federation*
[5] *Siberian Federal University, Krasnoyarsk, Russian Federation*
✉ *txbien.ph@hunre.edu.vn*

Abstract
Illegal mining, including the violation of lease boundaries during the extraction of mineral deposits in Vietnam, has witnessed a significant surge in recent years, leading to substantial environmental degradation. Due to the remote locations of mining areas in relation to settlements, the detection of illegal mining activities using conventional methods poses considerable challenges. This study presents a methodology for identifying lease boundary violations in open-pit mining of mineral deposits by utilizing high-resolution satellite images from the Sentinel-2 MSI system. The proposed methodology involves overlaying Sentinel-2 MSI radar-acquired satellite images to identify disparities between approved lease boundaries and actual boundaries of mining areas. The research focuses on the mineral-rich provinces of Lao Cai and Yen Bai in North Vietnam. The findings of this research rhold great potential for effectively monitoring and promptly detecting violations of mining lease boundaries.

Keywords
illegal mining, remote sensing, Sentinel-2B MSI data, Vietnam, Lao Cai and Yen Bai provinces

Acknowledgments
The researchers express their gratitude to the research sponsor for providing all the necessary materials, enabling the timely completion of the project. These materials played a crucial role in addressing the objectives outlined in the project titled “Monitoring of the boundaries of mining areas in some northern provinces of Vietnam using remote sensing and UAV imaging”, with code: SXTN.2020.08.01.

For citation
Tran X.B., Trinh L.H., Nguyen Q.L., Levkin Yu.M., Zenkov I.V., Tong T.H. Detection of violations of open-pit mining lease boundaries using Sentinel-2 MSI data in the case of Lao Cai and Yen Bai provinces of North Vietnam. *Mining Science and Technology* (*Russia*). 2023;8(2):173–182. https://doi.org/10.17073/2500-0632-2022-12-68

ОПЫТ РЕАЛИЗАЦИИ ПРОЕКТОВ В ГОРНОПРОМЫШЛЕННОМ СЕКТОРЕ ЭКОНОМИКИ

Научная статья

Выявление нарушений границ разработки месторождений полезных ископаемых открытым способом с использованием данных Sentinel-2 MSI на примере провинций Северного Вьетнама Лао Кай и Йень Бай

С.Б. Чан[1], Л.Х. Чинь[2], К.Л. Нгуен[3], Ю.М. Левкин[4], И.В. Зеньков[5], Т.Х. Тонг[2]
[1] *Ханойский университет природных ресурсов и окружающей среды, г. Ханой, Вьетнам*
[2] *Вьетнамский государственный технический университет им. Ле Куй Дона, г. Ханой, Вьетнам*
[3] *Ханойский университет горного дела и геологии, г. Ханой, Вьетнам*
[4] *Союз маркшейдеров России, г. Москва, Российская Федерация*
[5] *Сибирский федеральный университет, г. Красноярск, Российская Федерация*
✉ *txbien.ph@hunre.edu.vn*

Аннотация
Незаконная добыча полезных ископаемых, в том числе нарушение лицензионных границ при отработке месторождений полезных ископаемых во Вьетнаме за последние годы резко возросли. Это приводит к значительному ухудшению состояния окружающей среды. Поскольку районы добычи

полезных ископаемых часто расположены далеко от населенных пунктов, традиционными методами трудно обнаружить районы незаконной добычи. В данной работе представлена методика обнаружения нарушения лицензионной границы открытой разработки месторождений минерального сырья по спутниковым снимкам высокого разрешения Sentinel-2 MSI. В разработанной методике при наложении полученных радаром Sentinel-2 MSI снимков со спутника определяется несоответствие лицензионных границ месторождений полезных ископаемых фактическим. Район исследования расположен в богатых минеральными ресурсами Северного Вьетнама провинциях Лао Кай и Йень Бай. Полученные в ходе исследования результаты могут быть эффективно использованы для мониторинга и раннего выявления нарушений лицензированных границ горнодобывающего предприятия.

Ключевые слова
незаконная добыча полезных ископаемых, дистанционное зондирование, данные Sentinel-2B MSI, Вьетнам, провинции Лао Кай и Йень Бай

Благодарности
Научные сотрудники, проводившие исследования, благодарят заказчика проведения исследований за предоставление в полном объеме необходимых материалов, что позволило в установленные сроки выполнить поставленную задачу. Эти материалы помогли решить задачи, поставленные проектом «Мониторинг границ добычи полезных ископаемых в некоторых северных провинциях Вьетнама с использованием дистанционного зондирования и получения изображений с БПЛА». Код: SXTN.2020.08.01.

Для цитирования
Tran X.B., Trinh L.H., Nguyen Q.L., Levkin Yu.M., Zenkov I.V., Tong T.H. Detection of violations of open-pit mining lease boundaries using Sentinel-2 MSI data in the case of Lao Cai and Yen Bai provinces of North Vietnam. *Mining Science and Technology* (*Russia*). 2023;8(2):173–182. https://doi.org/10.17073/2500-0632-2022-12-68

Introduction

Monitoring mining lease boundaries in states involved in open-pit mining is carried out through various methods, such as radiation interferometry, image synthesis, and spectral analog techniques. Implementing these procedures can significantly increase the payments made by subsoil users to the state budget [1]. It also enables the control of mining parameters, land allotments, and the efficient utilization of mineral resources.

In Northern provinces of Vietnam, mining servses as a significant source of revenue for the state budget. However, the approved boundaries of land allotments for open-pit mining in Lao Cai and Yen Bai provinces are frequently violated. These violations have detrimental effect on the environment and the health of local population. The rugged terrain of mining areas allows lease owners who infringe upon boundaries to evade legal consequences. Advanced remote sensing techniques, such as using Sentinel-2 MSI radar aboard space satellites, provide high-resolution images of extensive areas of the Earth's surface. The frequent updating of these images facilitates the monitoring of lease boundaries to identify violators.

Remote sensing and other monitoring approaches of Earth's surface are employed in numerous countries worldwide to arrdess illegal mining, whish often occurs in remote regions [2, 3]. For example the Government of Ghana, detected illegal mining zones with areas measuring 102, 60, and 33 km^2 from 2015 to 201 by processing Sentinel-1 radar remote sensing satellite images using a threshold assessment method. This discovery significantly contributed to increased budget revenues through additional payments, such as MET [4, 5].

Similarly, Landsat satellite images were employed to curb illegal gold mining in India, occurring between 1986 and 2002 and from 2007 to 2013. These satellite images were used to compare the mining lease area with the actual mining area, facilitating the estimation of the extent of illegal mining [6]. The development of the DinSAR radar satellite interferometry technique has provided solutions for creating digital terrain models, aiding the detection of illegal open-pit mining areas, even in mountainous regions with dense vegetation [7–10].

This paper presents the research findings derived from analyzing satellite images captured by the Sentinel-2 MSI radar. The study resulted in the development of a methodology for detecting violations of open-pit mining lease boundaries by mining companies.

By overlapping satellite images, it was possible to identify and evaluate the degree of infringement of mining rights by mining enterprises in North Vietnam, including those with official lease boundaries.

The Sentinel-2 MSI radar information, with its frequent updates, is available free of charge to all interested organizations, thus enhancing the effectiveness of mining activity monitoring [11–13].

Materials and methodology

Study area

The study area encompasses the provinces of Lao Cai and Yen Bai in North Vietnam. These provinces are characterized by mountainous terrain, challenging topography, and undeveloped infrastructure. Extensive reserves of 35 minerals types, including iron, copper, zinc, and kaolin clays, have been explored in this region. The exploration efforts have resulted in the identification of substantional reserves, such as over 2.5 billion tons of apatite and copper ore, as well as 200 million tons of iron ore, including reserves of over 120 million tons in the Quy Sa mine. Additionally, rare earth ores, crucial for the advancement global high-tech industry, have also been discovered. The exploration of these mineral resources involves more than 500 small-scale mining enterprises, of which 240 possess valid licenss and leases. The lack of stringent plans for increasing mineral production and developing these regions creates opportunities for the illegal extraction of valuable minerals.

Materials

The study utilized multispectral data from the Sentinel-2 MSI radar, which were acquired in November 29, 2022, in Lao Cai Province, and in November 4, 2022, in Yen Bai Province, for the purpose of identifying illegal mining activities. The implementation of the Sentinel-2 MSI imaging technique enabled the capture of data across 13 spectral ranges, ranging from visible and near infrared (VNIR) to shortwave infrared (SWIR), at wavelengths within an orbital height of 290 km. The spatial resolution of the Sentinel-2 MSI images varied between 10 and 60 m, with the visible (2, 3, 4) and near-infrared (8) ranges having a spatial resolution of 10 m (Table 1).

Prior to analysis, the Sentinel-2 MSI radar images underwent pre-processing steps. These included the removal of clouds and the extraction of information within the boundaries of the research areas (Fig. 2). The images utilized in the study were L2A level products, obtained from the Copernicus Open Access Hub website (https://scihub.copernicus.eu). These products represent lower atmosphere reflectivity images (BOA) derived from the corresponding Level 1C products.

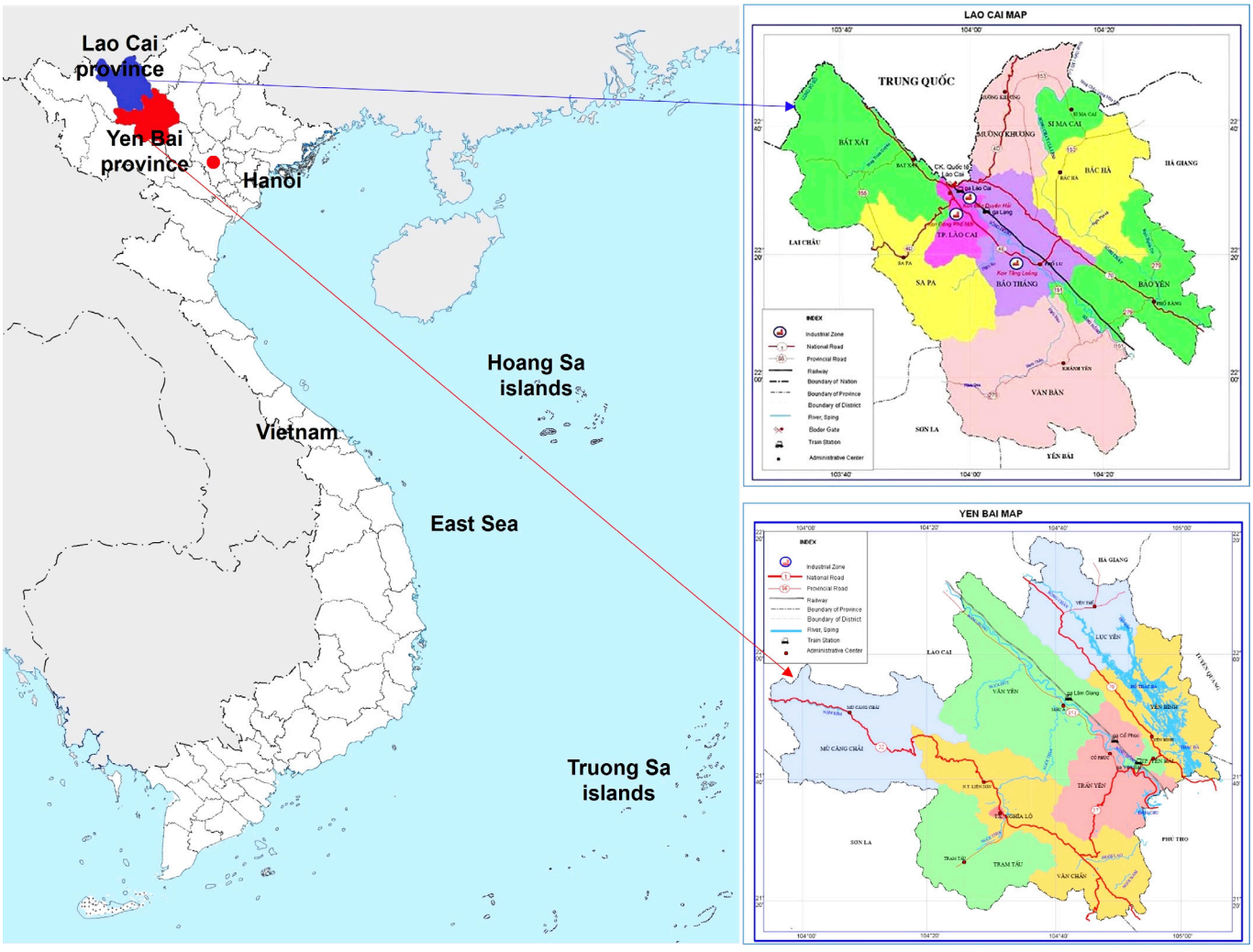


Fig. 1. Research areas in Lao Cai and Yen Bai provinces, Vietnam

Methodology

The multispectral processing of the Sentinel-2 MSI radar sensing images involved applying atmospheric and geometric corrections. The geometric correction process aimed to rectify geometric errors and transform the image coordinates captured by the Sentinel-2 MSI radar into local coordinates (VN-2000) consistent with the coordinate system of the lease boundary.

To identify illegal mining areas, spectral ranges with a spatial resolution of 10 m were utilized. These specific ranges were selected due to their highest spatial resolution among the available MSI Sentinel-2 ranges, enabling the detection of illegal mining areas with greater precision.

Subsequently, images depicting mining lease boundaries were superimposed onto Sentinel-2 MSI satellite images, allowing for a comparison between the designated lese boundaries and the actual boundaries. In this assessment, a digitization technique was employed to evaluate the extent of mining operation beyond the lease boundary, following the methodology for detecting illegal expansion of mining leases (Fig. 3).

Table 1

Sentinel-2 MSI images

Channels	Spectral range, μm	Spatial resolution, m
Coastal aerosol	0.421–0.457	60
Blue	0.439–0.535	10
Green	0.537–0.582	10
Red	0.646–0.685	10
Red edge of vegetation	0.694–0.714	20
Red edge of vegetation	0.731–0.749	20
Red edge of vegetation	0.768–0.796	20
Near IR	0.767–0.908	10
Red edge of vegetation	0.848–0.881	20
Water vapor	0.931–0.958	60
Shortwave infrared— cirrus cloud	1.338–1.414	60
Shortwave infrared	1.539–1.681	20
Shortwave infrared	2.072–2.312	20

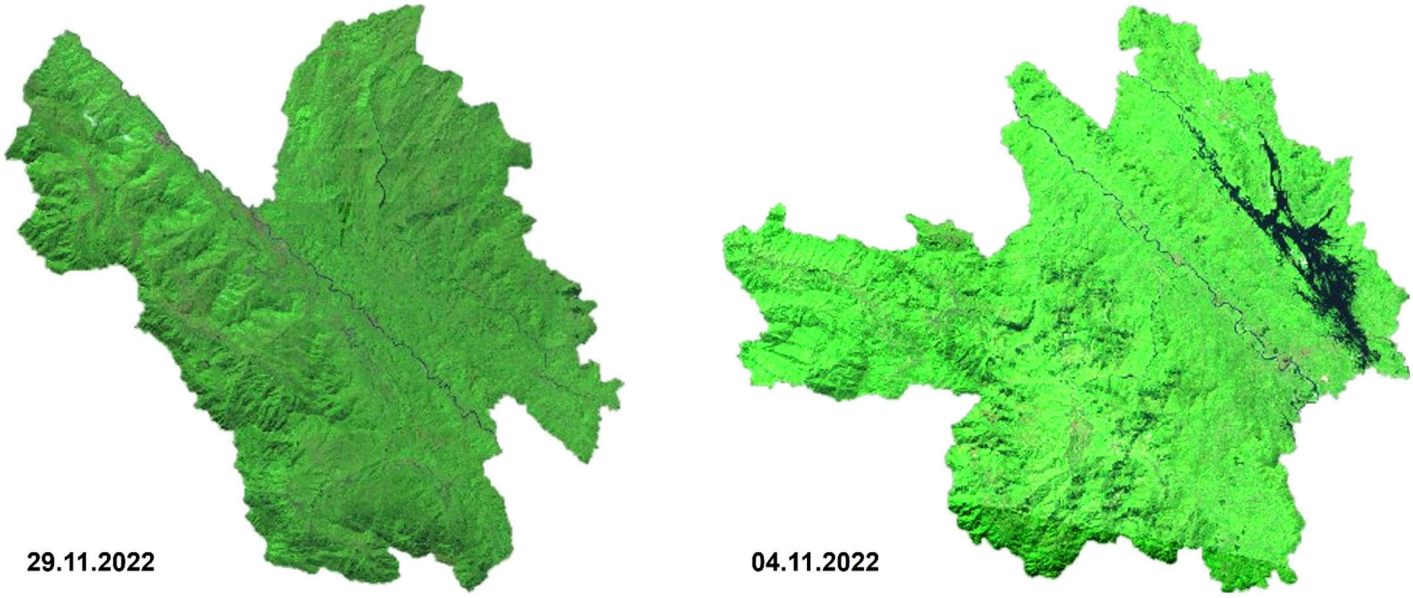


Fig. 2. Sentinel-2 MSI images within Lao Cai and Yen Bai provinces after pre-processing and cutting along the boundaries of the study areas

Scientific and methodological justification of solutions

a) General methodology for processing Sentinel-2 MSI multispectral images

The first step was to access the Sentinel-2 MSI image data from the Copernicus Open Access Hub database. This required selecting the coordinates of the study area and other conditions such as image type, processing level, cloudiness, and imaging time. Figure 4 provides a visual guide on how to select and download Sentinel-2 MSI images from https://scihub.copernicus.eu.

Spectral channels with a spatial resolution of 10 m (2, 3, 4, and 8) were used to detect illegal mining areas.

b) Models for converting image coordinates into local coordinates

The Sentinel-2 MSI images, obtained from the Copernicus database in the WGS 84 coordinate system, were converted to the local coordinate system (VN2000) (*Department of Geodesy, Map, and Geographic Information, Ministry of Natural Resources and Environment of Vietnam*) based on the following transformation equations:

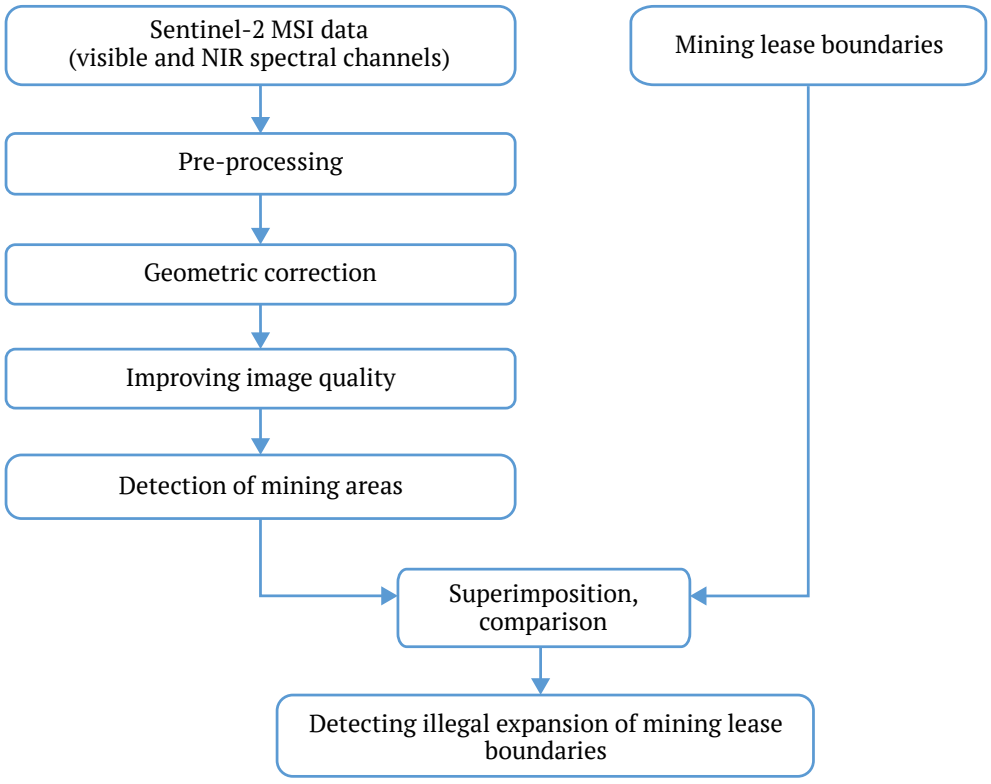


Fig. 3. The stages of the methodology for detecting illegal mining lease expansion based on Sentinel-2 MSI data

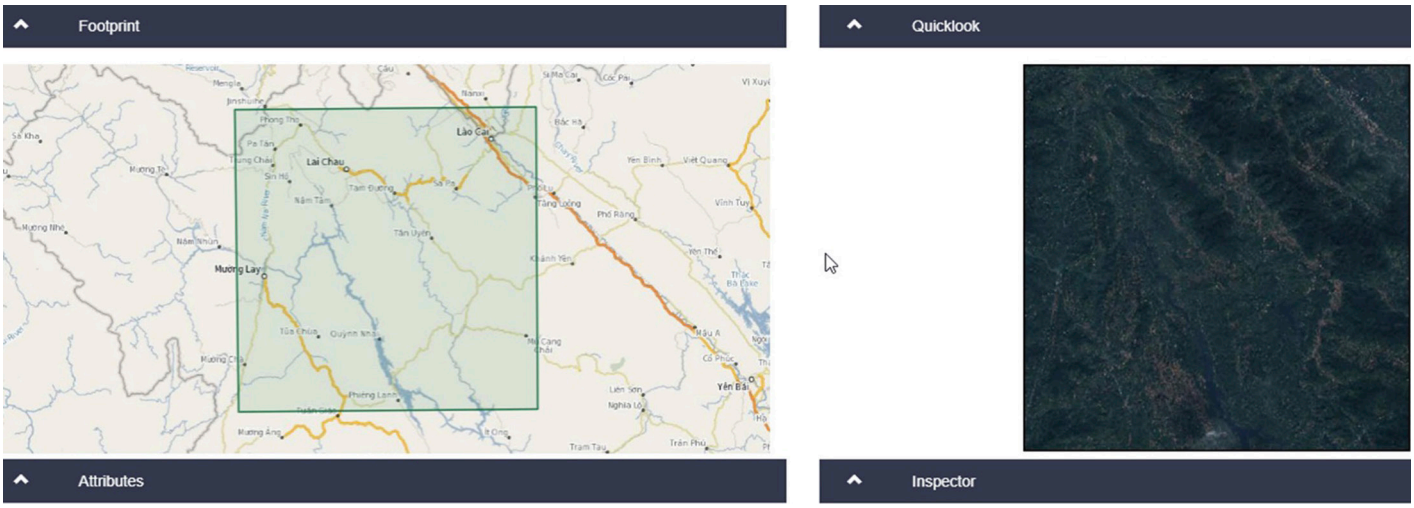


Fig. 4. Collection of Sentinel-2 image data in the Copernicus database

$$X = \Delta x_0 + k(X' + \varepsilon_0 Y' - \psi_0 Z');$$
$$Y = \Delta y_0 + k(-\varepsilon_0 X' + Y' + \omega_0 Z');$$
$$Z = \Delta z_0 + k(\psi_0 X' - \omega_0 Y' + Z'),$$

where X, Y, Z represent the coordinates in the Cartesian coordinate system that require convertion into meters; X', Y', Z' кrepresent the displacement coordinates in the Cartesian coordinate system, m; Δx_0, Δy_0, Δz_0 are parameters indicating the displacement of the coordinate origin, m; ω_0, ψ_0, ε_0 are the three rotation angles (Elege rotation), corresponding to the X, Y, Z axes, rad. The scale factor is denoted by k.

c) Proposals for improving the image processing method (or algorithm) for enhanced accuracy (resolution), accounting for atmospheric and geometric corrections

The Sentinel-2 MSI image underwent preprocessing procedures. This includes the application of geometric correction techniques and the conversion of the image to the local coordinate system (VN2000). Subsequently, clouds cover wes eliminated from the image, and specific information pertaining to the boundaries of the study areas was extracted and isolated.

The cloud filtering process for Sentinel-2 image is conducted using the Google Earth Engine (GEE) platform. GEE is a cloud-based geospatial analysis platform that provides users with the capability to visualize and analyze satellite images of the Earth. The offers a vast dataset containing remote sensing data collected from satellite systems spanning the past 40 years. Furthermore, GEE provides computational tools necessary for analyzing and utilizing this extensive data without the need to download to a local computer. Additionally, the data from GEE can be optimized to use in other software application such as QGIS, GIS, and Foris.

In order to filter and select the necessary images, the study utilized a reference image set from Sentinel-2, where the selected images had a cloud coverage of less then 80 %. The cloud filtering process was performed on the GEE platform using the CloudScore algorithm, which helps identify and filter out cloud pixels. Additionally, the Temporal Dark Outlier Mask (TDOM) algorithm was employed to detect and identify claud shadow pixels. used to. The outcomes of the cloud filtering and cropping of the Sentinel-2 MSI image along the boundaries of the study area are depicted in Fig. 2.

d) New technique and algorithm

This study introduces a novel approach by utilizing the GEE cloud computing platform for processing Sentinel-2 MSI satellite image data. The GEE platform offers an online JavaScript application interface (API) known as Code Editor, which is well-suited for handling large volumes of remote sensing data. Given the substantial amount of data generated by satellite remote sensing systems, the use of GEE enables efficient processing and analysis. Moreover, the platform enhances the capacity for monitoring and detecting changes on the Earth's surface by leveraging the temporal heterogeneous of remote sensing data.

This study pioneers the use of spectral imaging ranges with the highest spatial resolution among the MSI Sentinel-2 ranges, specifically the 10 m visible and near-infrared (NIR) bands. This selection allows for the detection of illegal mining areas concealed within dense jungle thickets. By utilizing the Sentinel-2 MSI multispectral images, which provide a short time resolution of 5 days, the monitoring of mining areas becomes more effective and timely.

Table 2

Comparison of lease and actual mining areas at several mines in Lao Cai Province

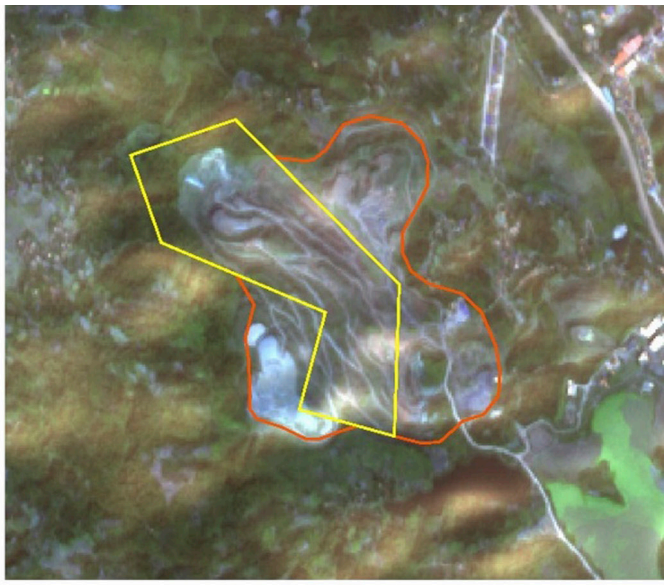
Mining enterprise	Address	Lease (licensed mining area), ha	Actual mining area, ha	Difference in mining area, ha
Apatite	Chieng Ken Municipality, Van Ban District	4.02	9.80	5.78
Kaolin	Lang Giang Municipality, Van Ban District	4.33	6.4	2.07
Apatite	Bao Ha Municipality, Bao Yen District	12.55	20.41	7.86
Kaolin	Van Hoa Municipality, Lao Cai City	28.32	43.57	15.25
Apatite	Cam Duong Municipality, Lao Cai City	49.85	63.91	14.06
Iron	Vo Lao Municipality, Van Ban District	51.03	96.96	45.93
Apatite	Dong Tuyen Municipality, Lao Cai City	76.19	150.32	74.13
Apatite	Ta Phoi Municipality, Lao Cai City	77.92	97.48	19.56
Iron	Quy Xa Municipality, Van Ban District	81.53	151.65	70.12
Apatite	Son Thuy Municipality, Van Ban District	91.96	107.59	15.63
Copper	Coc My Municipality, Bat Sat District	207.78	525.76	317.98

Findings and Discussion

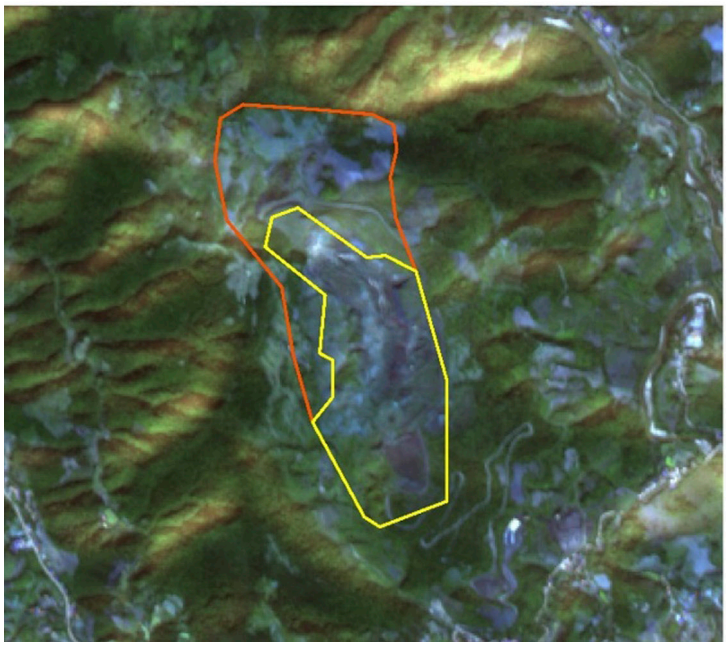
The analysis of Sentinel-2 MSI satellite images of open-pit mining areas reveals that the actual production areas often exceed the corresponding official lease areas (Table 2). Notably, at 11 mines, the actual mining areas significantly surpass their lease areas. For example, there are cases where the actual mining area is twice as large as the lease area, such as in a copper mine in Koc Mi Municipality, Bat Sat District; and an apatite mine in Dong Tuen Municipality, Lao Cai City (Fig. 5).

In the evaluation of open-pit mining areas in Yen Bai Province, a total of 12 mining zone were examined to determine the extent of illegal expansion (as indicated in Table 2). By analysing satellite images depicting the boundaries of the actual mining area (as shown in Fig. 6), it was confirmed the five leases had indeed experienced illegal expansion (as documented in Table 2). As an illustration, a limestone quarry located in Yen Thang Municipality, Luc Yen District, originally designated with a lease area of 2.18 hectares, was found to have expanded its production area to cover approximately 26.62 hectares (refer to Table 3).

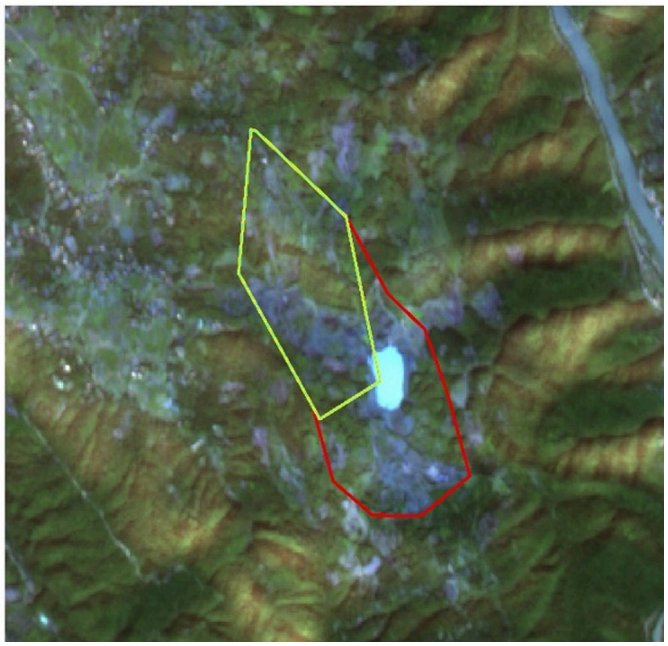
Sinh Quyen copper mine



Bao Ha apatite mine



Iron mine
(Vietnam mineral and metallurgical company)



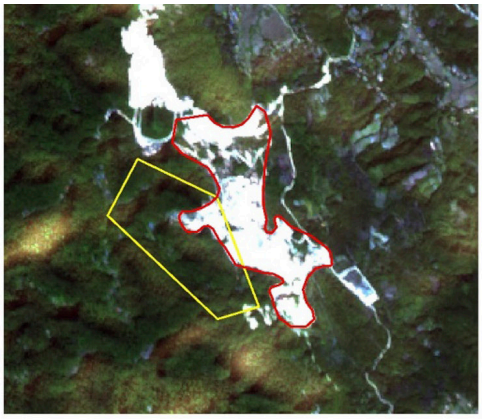
Lang Vinh iron mine

Fig. 5. Satellite images of actual mining areas (red) and lease (yellow) boundaries in Lao Cai Province, captured by the Sentinel-2 MSI radar

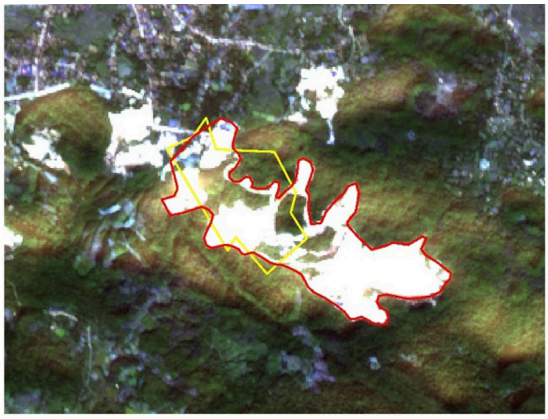
Table 3

Comparison of lease and actual mining areas at several mines in Yen Bai Province

Mining enterprise	Address	Lease (licensed mining area), ha	Actual mining area, ha	Difference in mining area, ha
White marble quarry	Yen Thang Municipality, Luc Yen District	26.80	51.87	25.07
K-feldspar	Tan Lap Municipality, Luc Yen District	5.01	16.25	11.24
Marble quarry	Yen The Municipality, Luc Yen District	43.32	98.18	54.86
Marble quarry	Mong Son Municipality, Yen Binh district	10.01	45.85	35.84
Graphite	Yen Thai Municipality, Van Yen district	11.65	24.70	13.05
Marble quarry	Lieu Do Municipality, Luc Yen District	49.80	65.88	16.08
White marble quarry	Tan Linh Municipality, Luc Yen District	5.21	16.48	11.27
Marble quarry	An Phu Municipality, Luc Yen District	5.91	36.84	30.93
Iron	Hung Khanh Municipality, Tran Yen District	113.00	146.63	33.63
Limestone quarry	Yen Thang Municipality, Luc Yen District	2.18	28.80	26.62
Quarry	Yen Thang Municipality, Luc Yen District	2.18	9.96	7.78
Marble quarry	An Phu Municipality, Luc Yen District	16.10	43.58	27.48



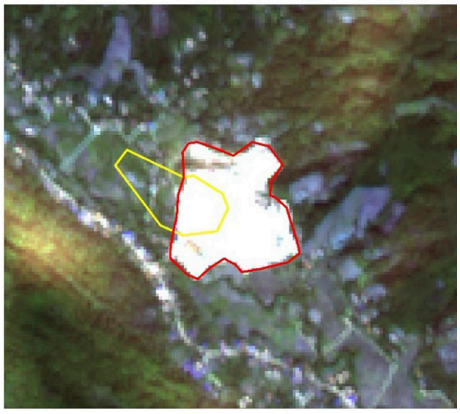
Quarry (Da Tu stone exploiting and processing company)



Quarry (RK Marble Vietnam company)

Quarry (Phanxipang company)

Quarry (Thai Duong company)



Quarry (Hung Dai company)

Fig. 6. Satellite images of actual mining areas (red) and lease (yellow) boundaries in Yen Bai Province, obtained by the Sentinel-2 MSI radar

Conclusions

In November 2022, the Sentinel-2 MSI radar captured satellite images of the mine areas in Lao Cai and Yen Bai provinces in Northern Vietna. These images were processed with the aim of detecting and assessing areas of illegal mining. The results of the analysis revealed that the actual mining areas in many of the surveyed districts significantly exceeded the designated lease areas. The use of Sentinel-2 MSI radar imaging provided high spatial resolution, with details down to 10 m. Additionally, the five-day time resolution of image capture enabled effective monitoring and early detection of violations in mining lease boundaries. The research findings offer valuable insights that will assist managers in monitoring and inspecting mining activities to ensure compliance with official lease boundaries set by mine operators.

References

1. Kozinska P., Gorniak-Zimroz J. A review of methods in the field of detecting illegal open-pit mining activities. In: *IOP Conference Series: Earth and Environmental Science*. *XXI Conference of PhD Students and Young Scientists (CPSYS 2021)*. 23–25 June 2021 (virtual), Wroclaw, Poland. 2021;942:012027. https://doi.org/10.1088/1755-1315/942/1/012027

2. Levkin Yu. M. The usage of modern surveying instruments in mining. In: Nguyen Q. L., Pham T. L., Nguyen V. N. et al. (Eds.) *The Proceeding of Geo-spatial Technologies and Earth Resources Conference* (GTER 2017). 5–6 October 2017, Hanoi, Vietnam. Hanoi: Publ. House for Science and Technology; 2017. Pp. 307–311.

3. Liu Y., Zhong C., Bai B., Zhou Y. Assessment of government supervision on the loss of sea sand resource in China. *Economic Research*. 2022;35(1):2732–2746. https://doi.org/10.1080/1331677X.2021.1977672

4. Forkuor G., Ullmann T., Griesbeck M. Mapping and monitoring small-scale mining activities in Ghana using Sentinel-1 time series (2015–2019). *Remote Sensing*. 2020;12(6):911. https://doi.org/10.3390/rs12060911

5. Owusu-Nimo F., Mantey J., Nyarko K. B., et al. Spatial distribution patterns of illegal artisanal small scale gold mining (Galamsey) operations in Ghana: A focus on the Western Region. *Heliyon*. 2018;4(2):e00534. https://doi.org/10.1016/j.heliyon.2018.e00534

6. Merugu S., Jain K. Change detection and estimation of illegal mining using satellite images. In: *Proceedings of 2nd International Conference on Innovations in Electronics and Communication Engineering (ICIECE-2013)*. 9–10 August 2013, Hyderabad, India. Pp. 246–251.

7. Hu Z., Ge L., Li X., Rizos C. Designing an illegal mining detection system based on DinSAR. In: *2010 IEEE International Geoscience and Remote Sensing Symposium*. 25–30 July 2010, Honolulu, HI, USA. Pp. 3952–3955. https://doi.org/10.1109/IGARSS.2010.5652978

8. Xia Y., Wan Y. InSAR- and PIM-based inclined goaf determination for illegal mining detection. *Remote Sensing*. 2020;12(23):3884. https://doi.org/10.3390/rs12233884

9. Wang L., Yang L., Wang W. et al. Monitoring mining activities using Sentinel-1A InSAR coherence in open-pit coal mines. *Remote Sensing*. 2021;13(21):4485. https://doi.org/10.3390/rs13214485

10. Zhang B., Wu S., Ding X. et al. Use of multiplatform SAR imagery in mining deformation monitoring with dense vegetation coverage: A case study in the Fengfeng Mining Area, China. *Remote Sensing*. 2021;13(16):3091. https://doi.org/10.3390/rs13163091

11. Le M. H., Do T. P. T., Vu T. T. H. et al. Using optical satellite images to detect the signs of illegal mining in Thai Nguyen province. *Science of* Natural Resources and Environment. 2018;20:30–42. (In Vietnamese)

12. Trinh L. H., Zablotskii V. R. The application of Landsat multi-temporal thermal infrared data to identify coal fire in the Khanh Hoa coal mine, Thai Nguyen province, Vietnam. *Izvestiya. Atmospheric and Oceanic Physics*. 2017;53(9):1181–1188. https://doi.org/10.1134/S0001433817090183

13. Trinh L. H. Hydrothermal minerals mapping using based on remotely sensed data from Sentinel 2 sattelite: a case study in Vinh Phuc Province, Northern Vietnam. *Mining Science and Technology* (*Russia*). 2019;4(4):309–317. https://doi.org/10.17073/2500-0632-2019-4-309-317

Information about the authors

Xuan Bien Tran – Lecturer, Hanoi University of Natural Resources and Environment, Hanoi, Vietnam; ORCID 0009-0005-1113-1545, Scopus ID 57951801800; e-mail txbien.ph@hunre.edu.vn

Le Hung Trinh– Cand. Sci. (Eng.), Associate Professor, Le Quy Don Technical University, Hanoi, Vietnam; ORCID 0000-0002-2403-063X, Scopus ID 57035066200; e-mail trinhlehung@lqdtu.edu.vn

Quoc Long Nguyen – Cand. Sci. (Mine Surveying), Head of Mine Surveying Department, Hanoi University of Mining and Geology, Hanoi, Vietnam; ORCID 0000-0002-4792-3684, Scopus ID 57204138384; e-mail nguyenquoclong@humg.edu.vn

Yuri M. Levkin – Dr. Sci. (Eng.), Professor, Russian Union of Surveyors, Moscow, Russian Federation; ORCID 0009-0004-4364-0785, Scopus ID 57297910200; e-mail lev5353@bk.ru

Igor V. Zenkov – Dr. Sci. (Eng.), Professor, Department of Ecology and Nature Management, Siberian Federal University, Krasnoyarsk, Russian Federation; ORCID 0000-0003-4427-4196, Scopus ID 57188958340; e-mail zenkoviv@mail.ru

Thi Hanh Tong – Lecturer, Le Quy Don Technical University, Hanoi, Vietnam; ORCID 0000-0002-6639-0318, Scopus ID 57314239400; e-mail hanhkhuenam@gmail.com

Received 22.12.2022
Revised 14.04.2023
Accepted 15.04.2023