AN EXPERIMENT FOR MONITORING THE "SNEZHNIKA" GLACIERET IN THE PIRIN MOUNTAINS USING HIGH- AND MEDIUM-RESOLUTION SATELLITE DATA

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Abstract: *This study presents the results of monitoring the "Snezhnika" glacieret in the Pirin Mountains, utilizing a collection of optical satellite imagery from the Landsat 7, RapidEye, WorldView-2, Landsat 8, Sentinel-2 MSI, and PlanetScope missions over a 27-year period (1999–2026). The methodology involved processing pseudo-composite images and generating the Normalized Difference Snow Index (NDSI). Based on the resulting values, the spatial dynamics of the "Snezhnika" micro-glacier were monitored through the calculation of the surface areas covered by firn mass.*

ОПИТ ЗА МОНИТОРИНГ НА МИКРОЛЕДНИК „СНЕЖНИКА" В ПИРИН ПЛАНИНА ЧРЕЗ ИЗПОЛЗВАНЕ НА СПЪТНИКОВИ ДАННИ С ВИСОКА И СРЕДНА РАЗДЕЛИТЕЛНА СПОСОБНОСТ

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Резюме: *В проведеното изследване са представени резултати от извършен мониторинг на микроледник „Снежника" от територията на Пирин планина чрез използване на набор от оптични спътникови изображения от мисиите Landsat 7, Rapideye, Worldview-2, Landsat 8, Sentinel-2 MSI и Planetscope за период от 27 години (1999-2026). Извършена е обработка на псевдокомпозитни изображения, генериран е нормиран разликов снежен индекс NDSI, и на база получените стойности е проследена динамиката на пространственото разпределение на микроледник „Снежника" след като са изчислени площите заети от фирнова маса.*

Introduction

Small glacial bodies, glacierets, and perennial snow-firn fields in high-mountain regions serve as sensitive indicators of changes in climatic and microclimatic conditions. Due to their small size and limited reserves of firn and ice, their area and volume respond relatively quickly to changes in air temperature, the amount and seasonal distribution of precipitation, the duration of snow cover, and the intensity of summer ablation. Their stability depends not only on the regional climate but also on local factors such as altitude, aspect, topographic shading, terrain morphology and lithology, as well as the redistribution of snow by avalanches and wind [1–4]. Consequently, small glacial bodies can function as natural indicators of the interaction between climate variability and local geomorphological conditions.

The Snezhnika glacieret is located in the Golemiya Kazan cirque in the Northern Pirin Mountains, Southwestern Bulgaria, situated directly beneath the northeastern slopes of Vihren Peak (2914 m) at approximately 41°46′ N and 23°24′ E, at an elevation of approximately 2400–2500 m (Fig. 1), and is considered the southernmost extant micro-glacier in Europe [1] Its location below 42° N well below the regional climatic snowline makes it an exceptionally suitable site for studying

the conditions under which perennial snow, firn, and ice can persist long-term within a climatic regime that lies at the threshold for contemporary glaciation.

Snezhnika is a small yet stable perennial body of snow, firn, and ice, with an average surface area of approximately 0.5 ha (≈ 5000 m²). This area fluctuates significantly, both within individual seasons and from year to year [4]. Its minimum extent is typically reached at the end of the ablation season, reflecting the net balance between snow accumulation during the colder part of the year and the loss of snow and ice mass throughout the spring and summer. Due to its small dimensions, Snezhnika is subject to substantial interannual variability, making it a sensitive indicator of both temperature conditions during the ablation season and the volume and redistribution of the winter snowpack [3, 4].

The specific geological and geomorphological conditions of the Northern Pirin Mountains are essential for the formation and preservation of the Snezhnik glacieret (perennial snow patch). The high-mountain zone surrounding the peaks of Vihren and Kutelo is composed primarily of marble. The interplay between Pleistocene glaciation, karst terrain, and cryogenic processes has shaped a distinctive glacio-karst landscape, characterized by deep cirques, steep rock faces, scree slopes, moraine deposits, and various karst landforms [3, 5]. The Snezhnik is situated at the base of the Golemiya Kazan cirque, beneath the steep northeastern marble face of Vihren Peak. This morphology provides prolonged topographic shading, limiting the direct solar radiation that reaches the snow and firn surface. At the same time, the steepness of the slopes facilitates snow accumulation through avalanches and wind transport; this increases the local snow mass beyond what would result from direct snowfall alone [1–3].

An additional factor is the geological nature of the terrain and the presence of a substrate composed of marble rocks. Their light-colored surface possesses a relatively high reflectivity, absorbing a smaller portion of incoming shortwave solar radiation compared to darker rock surfaces. The influence of this factor on Snezhnika should be viewed as part of a complex local radiation balance, which depends on a combination of albedo, slope inclination, aspect, shading, and the geometry of the surrounding slopes. The karst-related fracturing of the marble substrate facilitates the rapid drainage of water resulting from the melting of snow and ice, thereby limiting its prolonged retention around the base of the snow-ice body [3, 4]. It is significant that the two persistent contemporary micro-glaciers in the Pirin Mountains Snezhnika and Banski Suhodol are located precisely within the high-mountain marble section of the massif. This underscores the importance of local lithological and topographical conditions for their existence [3].

Snezhnika is not merely a seasonally accumulated snow patch. The presence of perennial firn and ice, the distinct morphological features associated with the snow-ice body, and the significant thickness determined via geophysical methods justify its classification as a glacieret (micro-glacier) [1, 2, 6]. Geophysical investigations using Ground-Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) further reveal the existence of subsurface zones with high electrical resistivity beneath and in the immediate vicinity of Snezhnika.



Fig. 1. Snezhnika glacieret, Pirin mountain, 26 August 2026 © photo credits: Nadya Yanakieva

In addition to traditional field and geophysical measurements, remote sensing enables the systematic monitoring of the dynamics of small snow-firn bodies and the spatial comparison of results. The use of optical satellite data for snow monitoring relies on snow's characteristic spectral reflectance profile—high reflectivity in the visible spectrum and significant absorption in the shortwave infrared range [7]. This property forms the basis of the Normalized Difference Snow Index (NDSI), which is widely used for distinguishing and mapping snow cover. Existing research on Snezhnika has focused

primarily on long-term field measurements of its surface area, the climatic factors driving interannual dynamics, its glaciokarst morphology, the internal structure of the snow-firn body, and the presence of permafrost [2–6]. In contrast, systematic multi-temporal analysis of Snezhnika based on satellite data remains less developed; this presents an opportunity to complement existing ground-based observations with results derived from satellite data.

The present study aims to analyze the spatiotemporal dynamics of the Snezhnika micro-glacier by integrating multispectral optical imagery from the archives of the Landsat 7, RapidEye, WorldView-2, Landsat 8, Sentinel-2 MSI, and PlanetScope missions over a 27-year period (1999–2026). The primary focus is on determining changes in the spatial extent of the snow-firn body. The study seeks to supplement existing long-term field and geophysical observations and to evaluate the potential of high-spatial-resolution satellite data for monitoring one of the smallest and southernmost contemporary glacial bodies in Europe.

Methods and data

SWIR-NIR-Green band composite

SWIR-NIR-Green band composites used in the study are consisted of bands: **5** (1.55–1.75 µm), **4** (0.76–0.90 µm), **2** (0.52–0.60 µm) for Landsat 7 ETM+ [8]; **6** (1.57–1.65 µm), **5** (0.85–0.88 µm), **3** (0.53–0.59 µm) for Landsat 8-9 OLI [9] and **11** (1.61 µm), **8** (832 µm), **3** (559 µm) for Sentinel-2 MSI [10]. It allows to highlights areas of snow cover distribution in the study area and serves as reference for monitoring, analysis and comparison with the results obtained from the applied indices NDSI and firn area calculation.

NIR-Red-Green band composite

Are used in the for the sensors with high resolution (Rapideye, Worldview-2 and Planetscope [11]) where SWIR bands are missing and were used for validation of Sentinel-2 super-resolved imagery and for contouring of the glacieret and calculation its area size.

Normalized Difference Snow Index (NDSI)

Normalized Difference Snow Index (NDSI) [12] (Equation 1) represents normalized difference of two bands in the visible green and short-wave infrared (SWIR) parts of the spectrum. Snow has high reflectance in the visible part of the electromagnetic spectrum and high absorption in the NIR or SWIR parts of the spectrum, whereas the reflectance of most clouds remains high in those parts of the spectrum, allowing good separation of most clouds and snow as the accepted NDSI threshold value used to determine snow cover is 0.4. [12].

(1) $$NDSI = \frac{(Green - SWIR)}{(Green + SWIR)}$$

The generated, calibrated and post-processed NDSI maps with the resulted values were used for contouring the snow-firn mass and area calculation in Arcgis Pro and used for correlation with the terrain data obtained by Grunevald and Gachev [1, 4].

Deep learning model SEN2SR

The model SEN2SR increases the resolution of Sentinel-2 imagery from 10m / px to 2.5 m / px and enables finer discrimination of small-scale land cover features, providing valuable information and improves visual interpretability of satellite images and enhances the reliability of downstream tasks such as classification, segmentation, and change detection, where high spatial detail and consistent spectral information are essential [13]. The SEN2SR deep learning framework preserving spectral and spatial alignment consistency of Sentinel-2 native resolution, ensuring realistic and artifact-free enhancements [13].

S2DR4 (Sentinel-2 Deep Resolution 4)

S2DR4 is a deep-learning super-resolution AI model developed by Gamma Earth. It is designed to upscale free public European Space Agency (ESA) Sentinel-2 satellite imagery from its native 10-meter and 20-meter resolution up to a sharp 1-meter per pixel resolution across all 10 spectral bands [14]

All satellite images (Table 1) were selected at the end of the ablation period for the glacier under study a period which, for the Pirin Mountains, encompasses approximately the months of September and October, depending on the first snowfall of the upcoming winter season (the beginning of the accumulation period).

Table 1. Timeframe of the study and data used

Time of acquisition (Year/Month/day)	Satellite, Sensor	Spectral bands	Spatial resolution (m/px)
07.09.1999 31.08.2000 28.09.2001 27.08.2010	Landsat 7 ETM+	Green (B2) NIR (B4) SWIR (B5)	15 x 15 pansharpened
10.09.2011 24.09.2012 04.09.2013 18.09.2015	RapidEye	Green (B2) Red (B3) NIR (B5)	5 x 5
24.09.2014	Landsat 8 OLI	Green (B3) NIR (B5) SWIR (B6)	15 x 15 pansharpened
15.08.2016	Planetscope	Green (B4) Red (B6) NIR (B8)	3 x 3
16.09.2017 and 18.09.2017 06.10.2018 and 27.09.2018 21.09.2019 and 21.09.2019 20.09.2020 and 21.09.2020 25.09.2021 and 22.09.2021 25.09.2022 and 09.09.2022 09.09.2023 and 09.09.2023 25.08.2024 and 24.08.2024 19.09.2025 and 22.09.2025 14.09.2026 and 09.09.2026	Sentinel 2 MSI and Planetscope	Green (B3) NIR (B8) SWIR (B11) Green (B4) Red (B6) NIR (B8)	1 x 1 (S2DR4) 2.5 x 2.5 (SEN2SR) 3 x 3

Results

Different samples of the results obtained by the applied methodology for calculating area of the glacieret including maps of Landsat 7 pansharpened image (Fig. 2, 3), Landsat 8 pansharpened image (Fig. 4) and super-resolved Sentinel-2 imagery (Fig 5, 6, 7, 8, 9). On Fig.8 a Planetscope image with native spatial resolution of 3 m in NIR-Red-Green band composite and super-resolved Sentinel-2 image with spatial resolution of 2.5 m in SWIR-NIR-Green band composite are shown for visual comparison and verification of glacieret's appearance and its extent. All the area sizes are calculated by contouring the outline of glacieret's patch highlighted in generated NDSI values for Landsat 7, Landsat 8 and Sentinel 2 imagery where SWIR bands are available and in NIR-Red-Green band pseudocomposites for Rapideye and Planetscopte imagery where SWIR bands are missing.

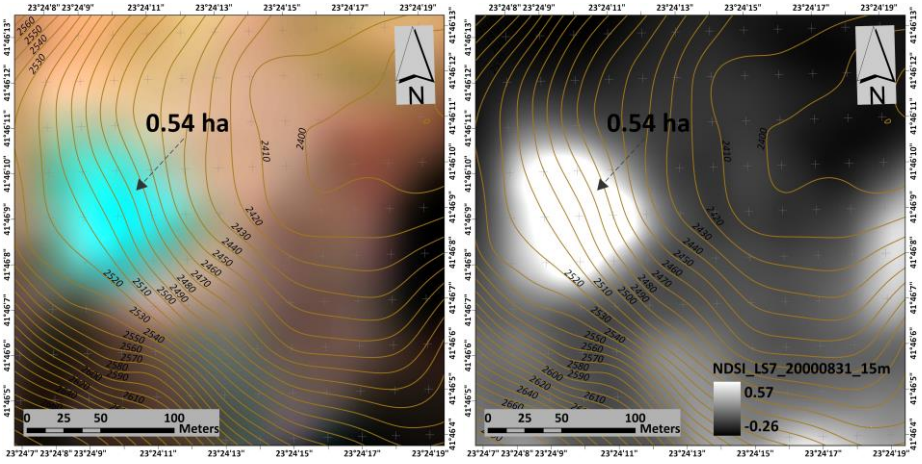


Fig. 2. Maps of pansharpened Landsat 7 image (15m / px) in SWIR-NIR-Green pseudocomposite and NDSI values from 31.08.2000

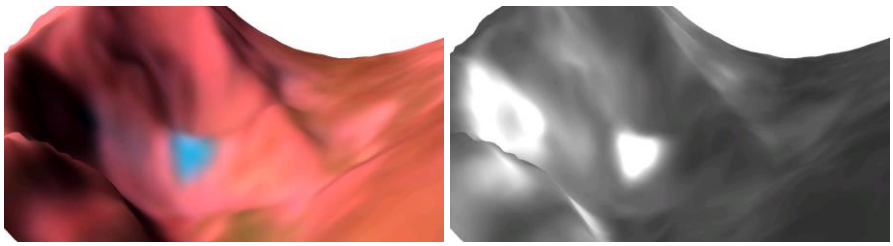


Fig. 3. 3D Maps of pansharpened Landsat 7 image (15m / px) in SWIR-NIR-Green pseudocomposite and NDSI values from 31.08.2000

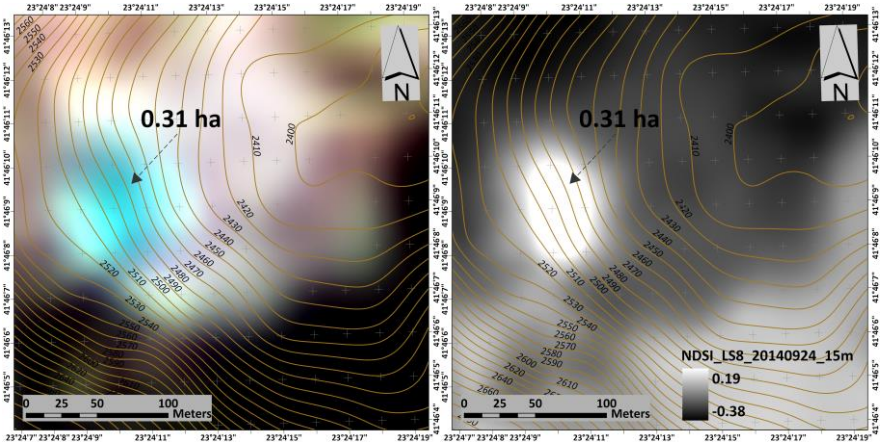


Fig. 4. Maps of pansharpened Landsat 8 image (15m / px) in SWIR-NIR-Green pseudocomposite and NDSI values from 24.09.2014

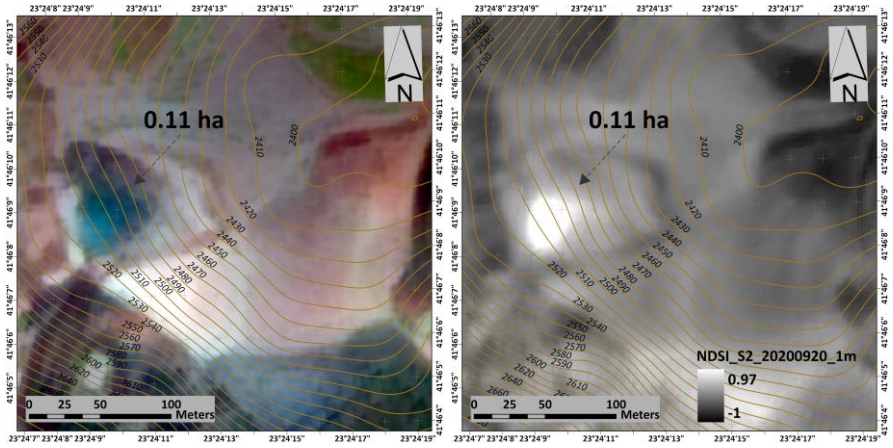


Fig. 5. Maps of super-resolved Sentinel-2 image (1m / px) in SWIR-NIR-Green pseudocomposite and NDSI values from 20.09.2020

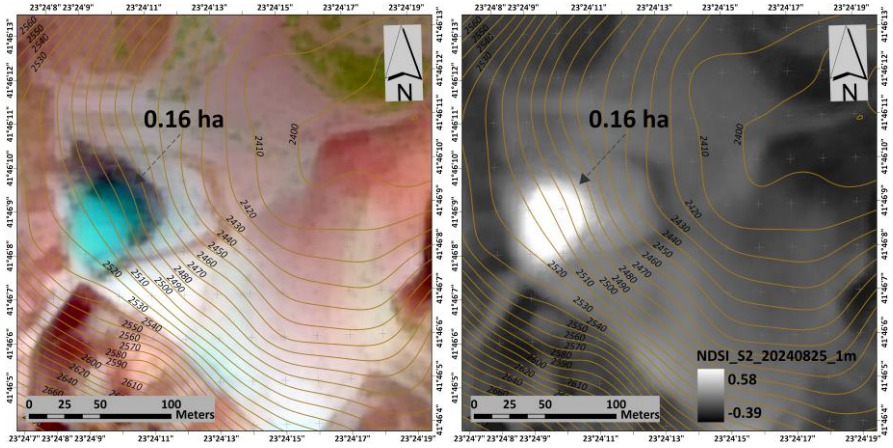


Fig. 6. Maps of super-resolved Sentinel-2 image (1m / px) in SWIR-NIR-Green pseudocomposite and NDSI values from 25.08.2024

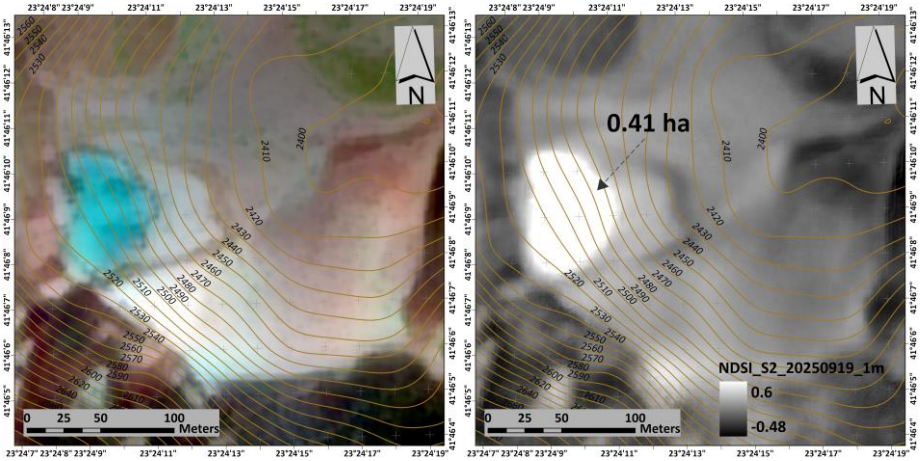


Fig. 7. Maps of super-resolved Sentinel-2 image (1m / px) in SWIR-NIR-Green pseudocomposite and NDSI values from 19.09.2025

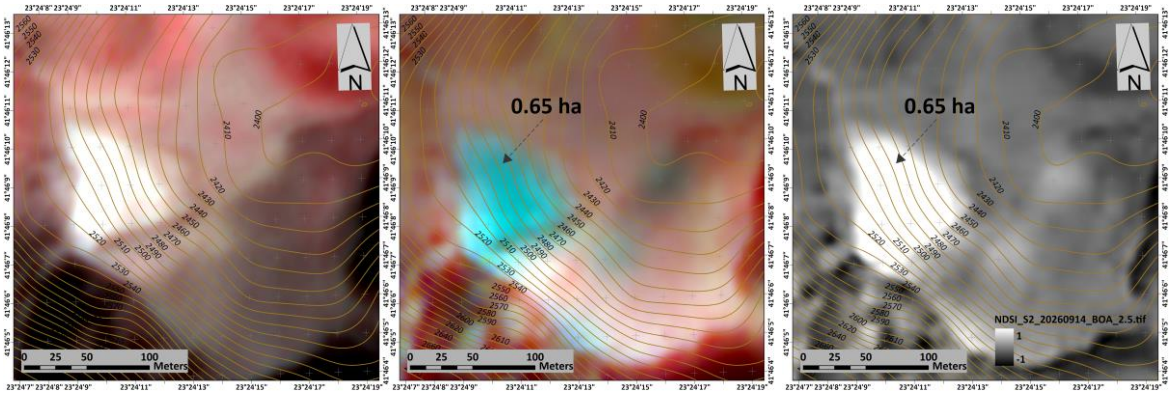


Fig. 8. Maps Planetscope image from 09.09.2026 (Image © 2026 Planet Labs PBC) and super-resolved Sentinel-2 image (1m / px) in SWIR-NIR-Green pseudocomposite and NDSI values from 14.09.2026

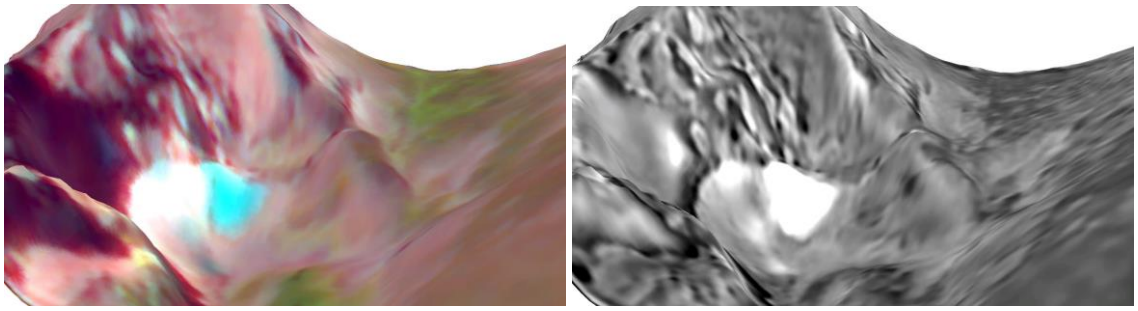


Fig. 9. 3D Maps of super-resolved Sentinel-2 image (1m / px) in SWIR-NIR-Green pseudocomposite and NDSI values from 14.09.2026.

The results with calculated areas of the glacieret for the whole temporal period are presented on table 2 and Fig.10. In 2020 the size of the Snezhnika glacieret reached a minimum area of 0.10 ha and maximum values are in the years 2010, 2021 and 2026. For the studied time period a small overall negative trend is monitored while preserving its average size of 0.5 ha.

Table 2. Calculated areas by years, methods, satellite data and *in-situ* data

Years	Calculation Method **NDSI or RGB pseudocomposite (contouring)**	Calculated Firn Area by Satellite data (*ha*)	*In-situ* data by Grunevald, Gachev,(*ha*)
1999	NDSI	**0.43**	**0.45**
2000	NDSI	**0.54**	**0.52**
2001	NDSI	**0.37**	**0.45**
2010	NDSI	**0.67**	**0.69**
2011	RGB pseudocomposite	**0.54**	**0.54**
2012	RGB pseudocomposite	**0.59**	**0.37**
2013	RGB pseudocomposite	**0.53**	**0.65**
2014	NDSI	**0.31**	**0.39**
2015	RGB pseudocomposite	**0.51**	**0.52**
2016	RGB pseudocomposite	**0.64**	**0.51**
2017	NDSI	**0.26**	**0.32**
2018	NDSI	**0.61**	**0.64**
2019	NDSI	**0.47**	**0.37**
2020	NDSI	**0.10**	**0.30**
2021	NDSI	**0.67**	**0.53**
2022	NDSI	**0.47**	**0.45**
2023	NDSI	**0.35**	**No data**
2024	NDSI	**0.16**	**No data**
2025	NDSI	**0.41**	**No data**
2026	NDSI	**0.65**	**No data**

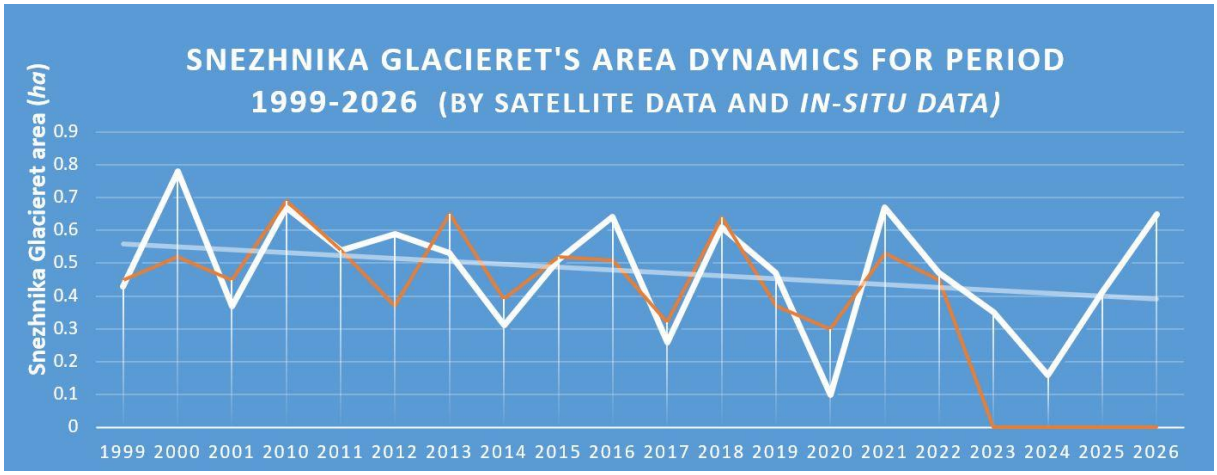


Fig. 10. Graph with calculated areas by satellite data and field measurement

The Pearson correlation coefficient between the two datasets: the Snezhnika glacieret area sizes obtained by applied methodology using satellite data and those obtained by the field measurements is **0.74** (Table 2 and Fig.10) which indicates a strong positive linear relationship between. Based on satellite data for the selected time period, a slight downward trend is observed in the area covered by snow and firn, with the maintaining an average extent of 0.5 ha.

Conclusion

The results obtained from the monitoring of the Snezhnika glacieret using satellite data, along with a comparative analysis with the field measurements, demonstrate a high degree of correlation (0.74). The use and application of optical satellite data, combined with the methodology proposed by the authors, prove to be highly effective, reliable, and accurate for conducting this type of research and addressing such tasks and problems.

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