

Snow Cover Phenology Monitoring and Dynamic Analysis Using Google Earth Engine in Western Iran's Mountainous Regions

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Abstract

Snow cover in mountainous regions plays a vital role in regional climate regulation, freshwater supply, and ecosystem stability. Phenological variations in snow cover—ranging from shifts in onset and melting periods to fluctuations in snow extent and depth—serve as sensitive indicators of climate change impacts. Over the past decade, numerous studies have reported a decline in snow persistence and volume in high-altitude zones, primarily driven by global warming. Satellite data analysis and modeling approaches have validated these trends, warning of serious consequences such as freshwater shortages, biodiversity loss, and disruptions to agricultural systems if such patterns persist. In this study, we employed MODIS satellite products and ground-based synoptic station data across West Azerbaijan Province, Iran. Using the Google Earth Engine (GEE) platform, snow cover dynamics were assessed over four years (2021–2024), focusing on the months from January through April. The analysis applied the Normalized Difference Snow Index (NDSI) and FLDAS parameters—including Snow Depth, Snow Cover, Snow Fall Rate, and Snow Water Equivalent—to derive time-series plots and spatial distribution maps. Results indicate a significant decline in snow cover, particularly in southern and southeastern parts of the province. The decreasing trend was corroborated through both remote sensing and ground station validation. This study highlights the necessity for continuous snow phenology monitoring and emphasizes the need for strategic planning and adaptive policy measures at regional and global scales to address the implications of changing snow dynamics.

Keywords: Snow Phenology, MODIS, Remote Sensing, Google Earth Engine, Cryosphere Monitoring, West Azerbaijan

1. Introduction

Snow cover is a critical environmental parameter in mountainous ecosystems, where it plays a central role in maintaining ecological balance, regulating local climate, and serving as a major freshwater reservoir. In recent decades, the phenology of snow cover—defined by its onset, duration, and extent—has gained recognition as a key indicator of climate change (Brown et al., 2022). Tracking snow cover dynamics from 2000 to 2024 provides invaluable insight into the broader effects of global warming on natural resource management and hydrological cycles.

Multiple studies have confirmed that a shortening or delayed onset of the snow season can significantly impact water availability, agricultural productivity, and biodiversity in snow-dependent regions. As such, monitoring snow phenology, particularly in mountainous areas, has become a global priority for policymakers aiming to mitigate climate change impacts (Li et al., 2023).

Warming trends are now evident across all continents, with especially pronounced changes in high-altitude regions such as the Alps, the Himalayas, and the mountain ranges of North and South America (IPCC Reports, 2021). The World Meteorological Organization (WMO) and United Nations climate reports have also emphasized the growing vulnerability of snow-covered areas under current climate trajectories.

Evidence indicates a consistent, long-term decline in snow season duration across many global mountain regions since the early 21st century—a trend that closely aligns with rising global temperatures (Zhang and Liu, 2021).

In this context, the ability to accurately detect and quantify snow cover extent and depth using modern remote sensing

technologies is crucial for both scientific understanding and environmental planning. Google Earth Engine (Gorelick et al., 2017), with its cloud-based architecture and massive satellite data repositories, has emerged as a powerful platform for analyzing snow phenology efficiently and at scale, offering critical tools for researchers and natural resource managers worldwide.

2. Materials and Methods

2.1 Study Area

The study was conducted in West Azerbaijan Province, located in northwestern Iran between approximately 36°–38°N latitude and 44°–47°E longitude. The region encompasses a complex mountainous terrain formed by the intersection of the Zagros and Alborz mountain ranges. This topographical diversity contributes to a wide range of microclimates and ecological zones, including oak forests, hawthorn groves, and highland pastures, which play critical roles in regional biodiversity.

With a population of nearly three million, concentrated primarily in the cities of Urmia, Khoy, and Mahabad, the province's economy is largely based on agriculture, livestock, and traditional crafts. Understanding the phenological changes in snow and vegetation cover in this area is crucial for effective natural resource management and regional climate adaptation strategies (Figure 1).

2.2 Data Sources

Satellite observations were primarily derived from the MODIS sensor onboard NASA's Terra satellite. MODIS (Moderate Resolution Imaging Spectroradiometer) captures data in 36

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spectral bands ranging from visible to thermal infrared wavelengths. These data products enable analysis of diverse environmental phenomena, including vegetation cover, land surface conditions, snow and ice dynamics, atmospheric aerosols, and oceanic properties. For this study, MODIS-derived FLDAS (Land Data Assimilation System) products were utilized to extract four snow-related variables: Snow Depth, Snow Cover Fraction, Snow Fall Rate, and Snow Water Equivalent. In addition, NDSI (Normalized Difference Snow Index) was applied to delineate snow-covered areas. Ground-truth validation was supported by meteorological data from 16 synoptic stations across West Azerbaijan Province.

Given the limitations of ground observations—such as spatial gaps, high costs, and temporal inconsistencies—satellite-based remote sensing offers a consistent and cost-effective alternative for large-scale snow monitoring. Currently, MODIS and Sentinel-5 are among the most widely used sensors for snow analysis in Iran.

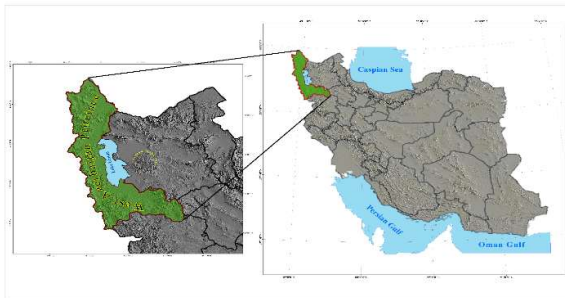


Figure 1: Location map of the study area in Iran.

2.3 Methodology

This study employed a descriptive-analytical, non-interventional research design. The Google Earth Engine (GEE) platform was used to process and analyze satellite data, leveraging its JavaScript-based cloud computing environment. The analysis covered the period from January 2021 to April 2024, focusing on snow dynamics during the late winter to early spring months. The spatial extent of the study area was defined by importing polygon shapefiles into GEE. The relevant MODIS products were then filtered by time and region to generate seasonal composites of the four snow parameters. Data were aggregated into quarterly means, and snow distribution was visualized using customized RGB composite settings to enhance contrast and interpretability. To take advantage of the high reflectance of snow in the visible and shortwave infrared wavelength bands and to highlight the presence of snow in the study area, we used NDSI after the cloud cover process. *swe* (snow equivalent water) is the water depth that would result from complete melting of a snowpack (Poggio and Ginoma, 2015). More precisely, the height of water resulting from the melting of a column from a ridge where no evaporation or runoff occurs. Temporal trends were evaluated through time-series plots showing monthly changes in snow-related parameters from January 2022 to January 2024. Ground station data were used to validate the number of snow-covered days and to assess agreement with remote sensing outputs.

3. Results

The spatial-temporal analysis of the four FLDAS snow-related parameters—Snow Depth, Snow Cover Fraction, Snow Fall Rate, and Snow Water Equivalent—revealed substantial

variability in snow distribution across West Azerbaijan Province during the study period. MODIS satellite imagery, processed through Google Earth Engine, proved highly effective for delineating snow-covered regions and quantifying associated hydrological parameters.

The results demonstrated that snow cover is most extensive in the northern and high-altitude regions of the province, with a marked decrease observed as one moves southward and southeastward. Time-series plots derived from quarterly means showed seasonal fluctuations in snow metrics, corresponding to expected winter accumulation and spring melting cycles (Figures 2–4).

A significant reduction in snow extent was observed over the four-year period. Based on NDSI analysis, the estimated snow-covered area from January 1 to April 1, 2022, was approximately 2,217,317 hectares, whereas for the same period in 2023, the snow-covered area had declined to 1,395,903 hectares. This represents a notable loss of over 800,000 hectares of seasonal snow cover within a one-year interval.

These findings underscore a declining trend in snow coverage between 2021 and 2024 (Figure 5-6-7), reflecting the influence of ongoing climate warming in the region. The average snow depth and snow water equivalent also exhibited corresponding declines during this period, further confirming the weakening intensity and persistence of winter snowpack. NDSI only indicates the presence/absence of snow. SWE is dependent on snow density and depth.

These patterns suggest that continued warming may exacerbate hydrological stress in the region, affecting water availability, agriculture, and ecological balance. Remote sensing-based monitoring, combined with ground station validation, thus remains critical for sustainable resource planning in mountainous areas.

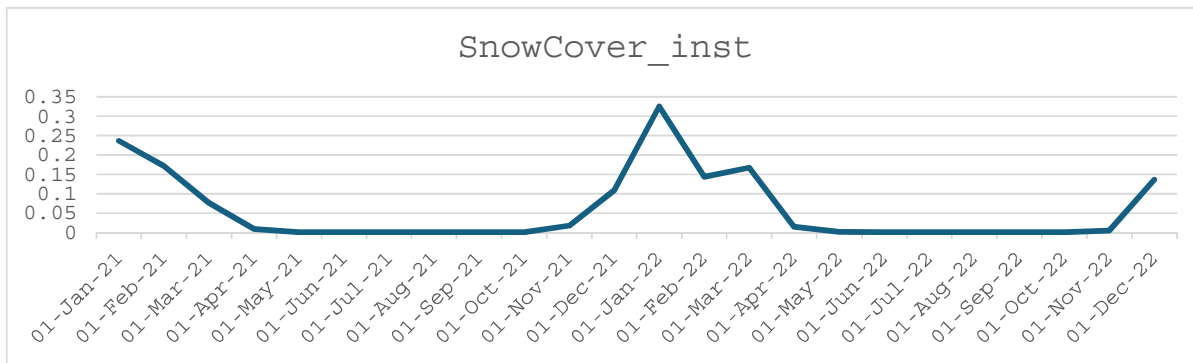


Figure 2: Temporal distribution of snow cover fraction across winter months

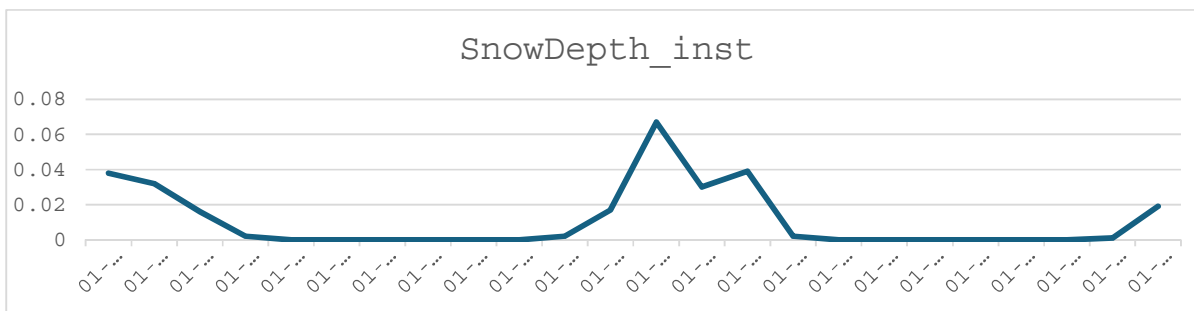


Figure 3: Interannual snow depth variation for 2021 and 2022.

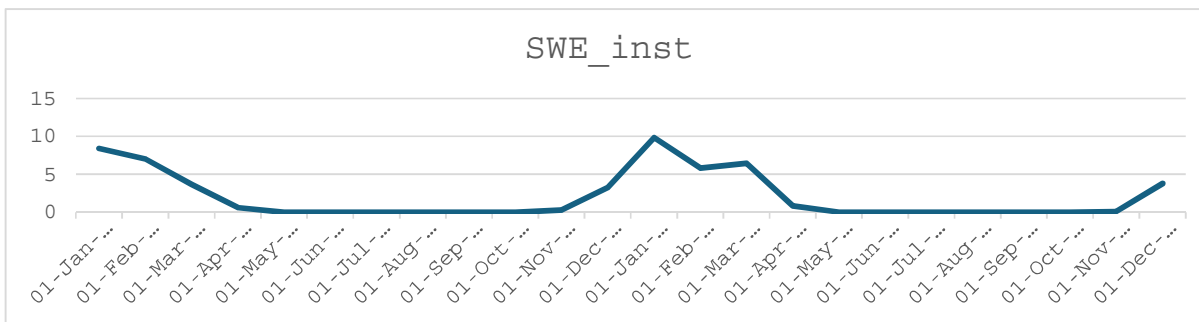


Figure 4: Interannual snow water equivalent variation for 2021 and 2022.

4. Discussion and Conclusion

The observed decline in snow cover extent and intensity across West Azerbaijan Province from 2021 to 2024 reflects broader global trends in mountain snowpack phenology under changing climatic conditions (Zhao et al., 2022; IPCC Reports, 2021). The significant reduction of over 800,000 hectares in snow-covered area, as derived from NDSI composites, underscores the vulnerability of regional snow resources to rising temperatures.

The decreasing trends in snow depth and snow water equivalent are consistent with previous studies in other mountain systems, including the Alps, Himalayas, and North American Rockies, which have reported earlier snowmelt onset and shorter snow seasons (Notarnicola, 2024; Yarahmadi et al., 2022). These shifts can disrupt regional water balances, impact downstream agriculture, and exacerbate water scarcity during the dry season.

Remote sensing tools such as MODIS and platforms like Google Earth Engine have proven essential for capturing these dynamics at both spatial and temporal scales (Ghaderi and Azizi, 2019,2020). The integration of ground-based synoptic station data further validates the reliability of satellite-derived snow parameters, reinforcing their use in long-term environmental monitoring (Gorelick et al., 2017). From a policy perspective, these findings highlight the need for adaptive water resource management, particularly in semi-arid and mountainous regions where snowmelt contributes significantly to annual runoff. Strategic planning must incorporate snow phenology indicators into regional climate adaptation frameworks, especially in areas reliant on snow-fed agriculture and ecosystems.

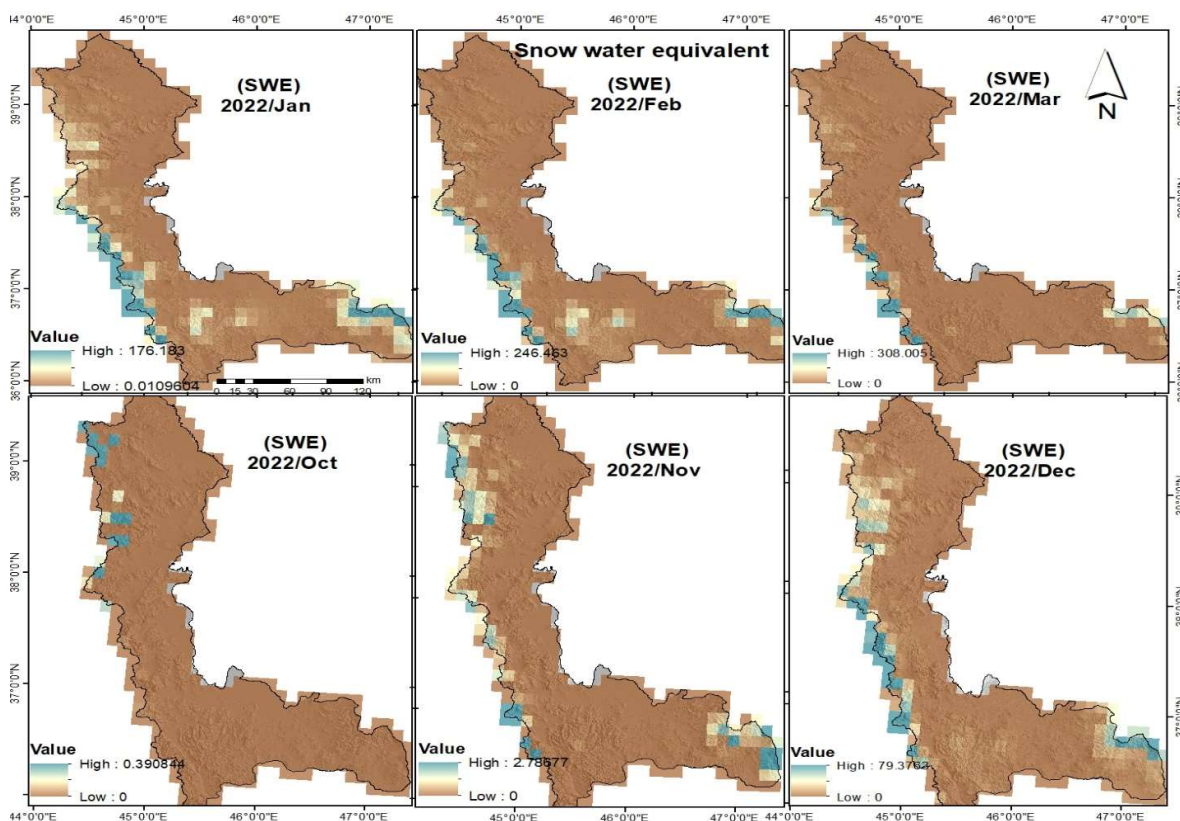


Figure 5: Snow equivalent water map in the wettest months (autumn - winter) in 2024 in the western mountains of the region.

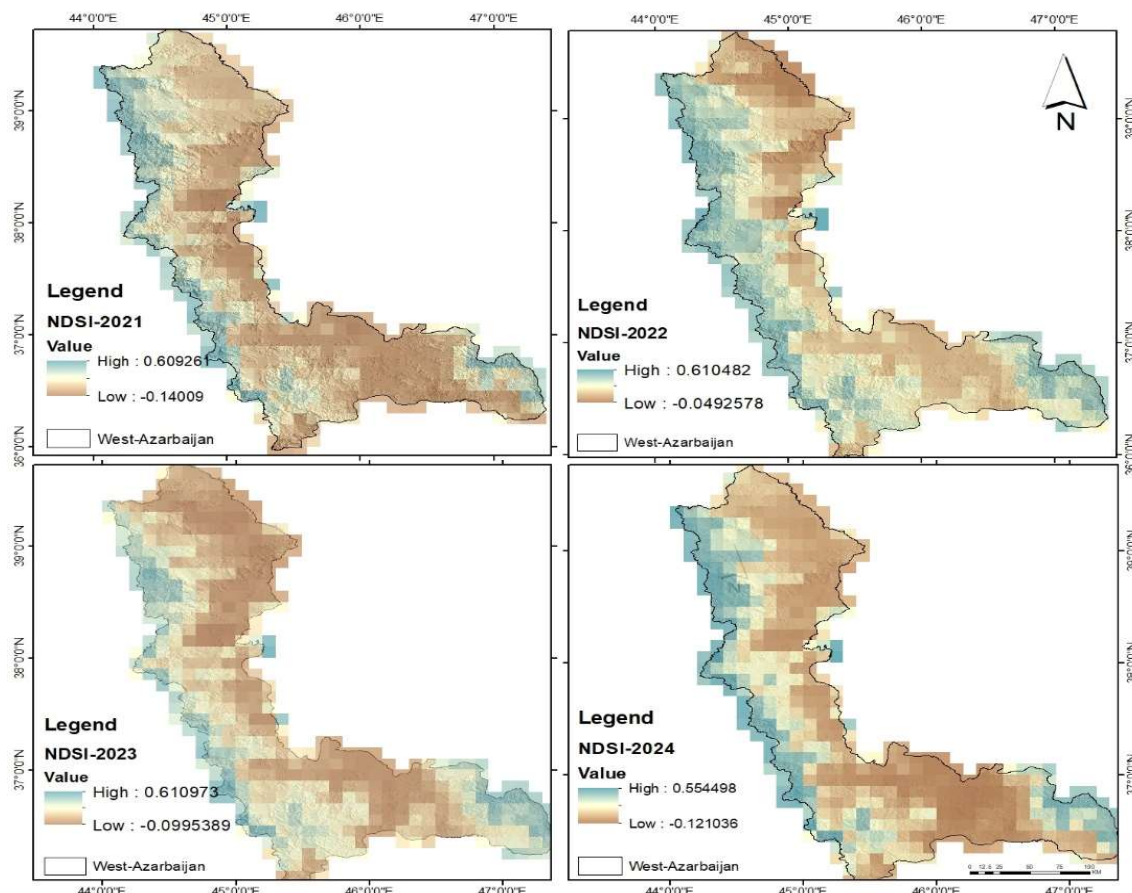


Figure 6: NDSI composite maps for winter months (–March) across the years 2021–2024, highlighting snow-covered regions in blue tones

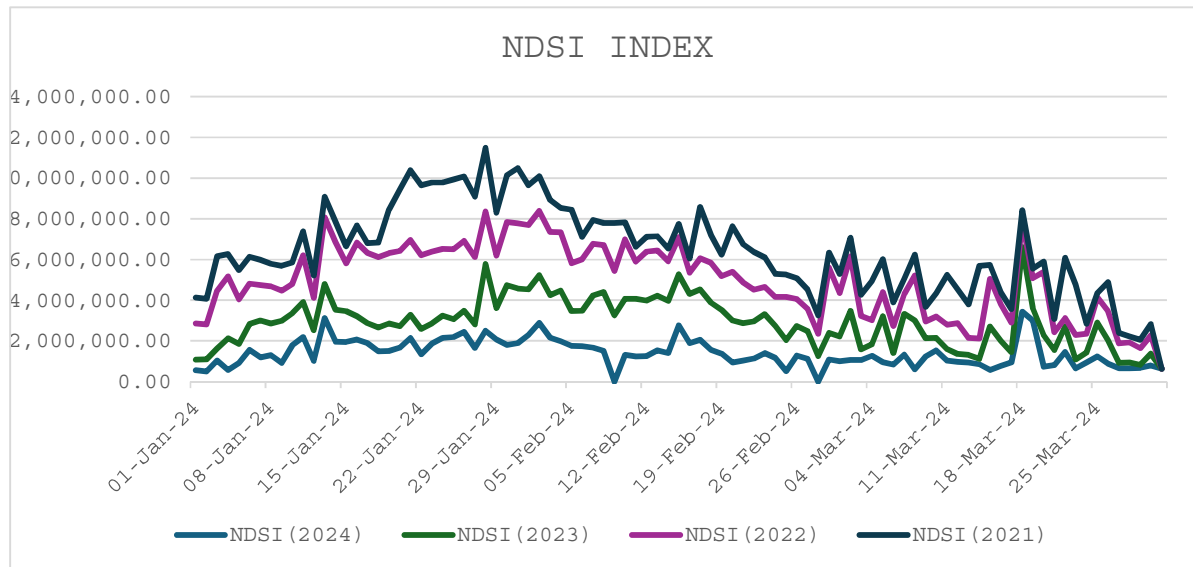


Figure 7: Interannual variation of the NDSI from 2021 to 2024.

In conclusion, the study demonstrates a pronounced and accelerating decline in snow cover across West Azerbaijan Province, aligning with global patterns of cryospheric change. Continued monitoring through high-resolution satellite data and climate-integrated decision-making will be critical in mitigating the socio-environmental risks posed by diminishing snow resources. The decreasing trends in snow depth and snow water equivalent are consistent with previous studies in other mountain systems, including the Alps, Himalayas, and North American Rockies, which have reported earlier snowmelt onset and shorter snow seasons (Notarnicola, 2024; Yarahmadi et al., 2022). These shifts can disrupt regional water balances, impact downstream agriculture, and exacerbate water scarcity during the dry season.

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