ANNOTATION

to the dissertation for the degree of Doctor of Philosophy (PhD) in the specialty 6D071100– Geodesy

Nurakynov Serik

ASSESSMENT OF THE STATE OF MOUNTAIN CRYOSPHERE COMPONENTS USING SATELLITE TECHNOLOGIES

General characteristics of the work. The dissertation is devoted to the study of the cryosphere components of the Zhetysu Alatau based on satellite technologies. The main objectives of the research are as follows: to determine the spatio-temporal dynamics of mountain glacier changes using satellite data; to create a comprehensive catalog of rock glaciers and to establish their precise boundaries; to develop a modified methodology for the inventory of active rock glaciers; to calculate the geodetic mass balance of glaciers and to assess its variations. The results of the study will make it possible to predict the sustainability of the water resource potential of the Zhetysu Alatau and to model the role of glaciers in regional hydrological systems.

Relevance of the topic.

As a result of global climate change, the main components of the mountain cryosphere—glaciers, snow cover, and rock glaciers—are undergoing significant spatio-temporal transformations. The cryospheric elements located in the mountain systems of Central Asia and within the territory of Kazakhstan have experienced substantial degradation over the past 50 years: the glacier area in the Tien Shan mountain system has decreased by approximately 30–40%, and in the Zhetysu Alatau by 40–50%. These changes have a direct impact not only on the hydrological regime of the region, the stability of ecosystems, and socio-economic activities, but also belong to the class of spatio-dynamic processes that require high-precision geodetic observations. Traditional geodetic methods have limited capabilities for regular and large-scale monitoring of such processes. In this regard, the tools of space geodesy—radar interferometry (InSAR), global navigation satellite systems (GNSS), and satellite optical monitoring—come to the fore, enabling effective tracking of cryospheric changes with high accuracy and broad spatial coverage.

The assessment of the state of the mountain cryosphere and the modeling of its spatio-temporal dynamics represent a strategically important scientific task in the context of effective infrastructure planning, rational management of natural resources, and climate risk forecasting.

Research Aim and Objectives

The aim of this study is to provide a comprehensive assessment of the state and dynamics of changes in the main components of the mountain cryosphere of the Zhetysu Alatau based on satellite technologies. This includes analyzing the spatio-temporal dynamics of glacier areas, calculating the geodetic mass balance, and compiling a catalog of rock glaciers.

To achieve this aim, the following objectives have been set:

– To analyze the spatio-temporal dynamics of changes in the glacier area of the Zhetysu Alatau using satellite (optical) data;

– To compile a catalog of rock glaciers in the Zhetysu Alatau based on satellite data and to classify them according to the degree of activity;

– To develop a modified methodology for the inventory of active rock glaciers using satellite data;

– To assess the elevation changes of glaciers and to calculate the geodetic mass balance of glaciers in the Zhetysu Alatau based on satellite data

Object of the study – Cryospheric components of the Zhetysu Alatau mountain ranges.

Scientific Novelty.

– For the first time, the mapping of glacier area change dynamics (for the period 1956–2016) has been carried out, and a catalog of rock glaciers (since 1990) of the Zhetysu Alatau has been compiled based on satellite data.

– A modified methodology for the inventory of active rock glaciers has been developed.

– For the first time, maps of glacier elevation changes and the geodetic mass balance of glaciers in the Zhetysu Alatau have been produced using satellite data.

Scientific provisions submitted for defense:

– The map of glacier area change dynamics in the Zhetysu Alatau for the period 1956–2016, which shows that glacier area decreased by 49 ± 2.8% (from 813.6 to 414.6 km²), while the number of glaciers decreased from 985 to 813. The digital catalog includes 848 rock glaciers with a total area of 83.4 km².

– The modified methodology for the identification of active rock glaciers.

– The maps of glacier elevation changes and the geodetic mass balance of glaciers in the Zhetysu Alatau for the period 2000–2016.

The research methods. To address the research objectives, based on the analysis and review of modern methods and methodological approaches, the following set of methods was applied:

– Analysis of the spatio-temporal dynamics of glacier area changes: multispectral optical satellite imagery and visual interpretation methods were employed. In particular, the band ratio method was applied, which ensured high accuracy in delineating glacier boundaries.

– Compilation of the catalog of rock glaciers: a combination of two main approaches was used: a) *Geomorphological analysis* – determination of morphological characteristics based on digital elevation models (DEM) and high-resolution optical satellite imagery; b) *Kinematic analysis* – assessment of the dynamics of rock glacier movement using radar interferometry (InSAR) data.

– Estimation of the geodetic mass balance of glaciers: this was carried out through mathematical comparison of two digital elevation models of the Earth's surface – the historical SRTM (2000) and the modern TanDEM-X (post-2010). As a result of these calculations, the spatial distribution and volumetric changes in glacier mass were determined.

Description of the main research results.

1. *Analysis of the spatiotemporal dynamics of glacier area changes in the Zhetysu Alatau based on satellite (optical) data***.** The study analyzed the spatial and temporal dynamics of glacier area changes across seven major river basins in the Zhetysu Alatau from 1956 to 2016. Quantitative estimates of glacier degradation rates were calculated, revealing long-term change trends. In 2001, a total of 1,040 glaciers with a combined area of 517.4 km² were recorded and included in an updated glacier inventory. By 2012, this number decreased to 938 glaciers with an area of 453.7 km², and in 2016, 896 glaciers covering 414.6 km² were identified. Over the entire period (1956–2016), the total glacier area declined from 813.6 km² to 414.4 km², reflecting a reduction of 49 ± 2.8%. Additionally, equilibrium-line altitudes were determined for the largest glaciers, and the key factors influencing glacier melt were analyzed.

2. *Compilation of a catalog of rock glaciers in the Zhetysu Alatau and identification of their morphodynamic characteristics using satellite data.* Methods for identifying and classifying rock glaciers in the Zhetysu Alatau were modified and adapted to regional conditions. As a result, 848 rock glaciers with a total area of 83.4 km² were recorded and incorporated into a unified inventory. Morphodynamic analysis revealed that the largest concentration of rock glaciers (70.51 km² or 84.5% of the total area) is located at elevations between 2,800 and 3,400 meters above sea level. The largest rock glacier has an area of 1.53 km², while the smallest is 0.0043 km². Using

InSAR technology, the movement velocities of rock glaciers were calculated. The results showed that: – In the Aksu River basin, 93 active rock glaciers were identified with an average movement velocity of 240 mm/year; – In the Lepsy River basin, 111 rock glaciers were identified with an average movement velocity of 252 mm/year. A modified inventory methodology was also developed, and its accuracy was verified using satellite data. Based on their origin, the rock glaciers were classified as talus rock glaciers and moraine rock glaciers, and their regional distribution was analyzed.

3. Estimation and calculation of the geodetic mass balance of mountain glaciers in the Zhetysu Alatau using satellite data. To assess glacier elevation and mass changes in the Zhetysu Alatau, a mathematical comparison was conducted between two digital elevation models: historical SRTM (2000) and modern TanDEM-X (post-2010). At the regional scale, the average annual geodetic mass balance of glaciers was estimated at –0.44 m w.e. The most significant mass losses were observed in: – The Yrghayty River basin: –0.59 m w.e.; – The Tentek River basin: –0.55 m w.e. The lowest mass loss values were recorded in: – Aksu basin: –0.35 m w.e.; – Lepsy basin: –0.38 m w.e.; – Karatal basin: –0.40 m w.e.

The conducted research and the proposed methodologies offer opportunities to significantly reduce labor and financial costs in studying glaciation in the mountainous regions of Central Asia, while also enabling more efficient regional cryosphere monitoring.

Theoretical and practical significance of the work. *Contribution to Glaciology and Cryospheric Research* Through the analysis of the spatiotemporal dynamics of glaciers and rock glaciers in the Zhetysu Alatau, the study identified patterns of how regional climate change affects cryospheric components. Improved methodologies for assessing the geodetic mass balance of glaciers were proposed, providing a scientific foundation for the further development and refinement of glaciological models. Modified approaches for the classification and cataloging of rock glaciers contributed to strengthening the theoretical and methodological basis for studying morphodynamic processes. *Data Expansion.* For the first time, large-scale data on glacier area changes between 1956 and 2016 were systematized, forming a valuable scientific database for future glaciological and climatological studies.

Practical Significance of the Study. Assessment of glacier degradation rates enabled forecasting the future availability of water resources in the region. The results can serve as a basis for water resource management, irrigation planning in agriculture, and the development and optimization of hydropower infrastructure. *Determining the movement velocity of rock glaciers* provided the basis for proposing preventive measures to mitigate the risks of natural hazards such as debris flows, avalanches, and moraine lake outbursts. For instance, the identification of active rock glaciers moving at approximately 240 mm/year in the Yrghayty basin enhances preparedness for emergency situations in the area. *The average calculated glacier mass balance value* (–0.44 m w.e.) indicates a regional trend toward increasing aridity. This metric provides a scientifically grounded basis for developing adaptation strategies aimed at maintaining ecosystem stability. *Taking into account cryospheric changes in the Zhetysu Alatau*, maps and models were developed to assess risks in regional infrastructure planning (roads, bridges), including the construction of a planned nuclear power plant (NPP) near Lake Balkhash. The rivers originating in the Zhetysu Alatau – Aksu, Karatal, and Lepsy – supply approximately 20% of the total inflow to Lake Balkhash, highlighting their crucial role in shaping the lake's hydrological regime.

The scientific provisions, conclusions, and recommendations presented in this study are substantiated and confirmed as follows. The satellite technologies used in the research – radar interferometry (InSAR) and optical image analysis – are internationally recognized methods for studying glaciers and rock glaciers. These approaches are widely applied in research programs conducted by NASA and ESA. The comparison of SRTM (2000) and TanDEM-X (from 2010 onwards) datasets for the calculation of geodetic mass balance is currently regarded as the "gold standard" in glaciological studies.

To assess the impact of climatic and anthropogenic factors, meteorological data provided by the RSE “Kazhydromet” were used. Regression analysis and correlation coefficient calculations were employed–methods that are scientifically validated and widely accepted in climatological research. The quality and accuracy of the compiled rock glacier catalog were verified according to the international standards of the Global Land Ice Measurements from Space program.

Reliability of Conclusions: The observed reduction of glacier area in the Zhetysu Alatau by 20–25% between 1956 and 2016 serves as clear evidence of degradation processes in the region. This rate aligns with the average annual glacier shrinkage across Central Asia (approximately 0.5–1%), as reported in authoritative sources, including the IPCC 2019 report. The glacier dynamics in the Zhetysu Alatau are also comparable with results from studies in the Tien Shan and Pamir mountains (e.g., Farinotti et al., 2019). The calculated average annual geodetic mass balance (–0.44 m w.e.) closely matches the values recorded for glaciers in Greenland and the Himalayas, further validating the spatial and climatic relevance of the findings.

The research findings have been published in peer-reviewed international journals such as **Remote Sensing** and **Water**, indicating high recognition by the scientific community. Thus, the scientific soundness of the applied methods is validated by international standards, the credibility of the conclusions is supported by independent data sources, and the practical value of the recommendations aligns with national strategies. This study significantly contributes to strengthening the link between scientific methodology and practical decision-making.

Relevance of the topic to the research plan and various government programs. The present study was carried out within the framework of the scientific project titled "Regional Assessment of the Mass Balance of Glaciers in the Zhetysu Alatau and Inventory of Rock Glaciers Based on Remote Sensing Data," funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan for the period 2020–2022 (Project No. AP08856470).

Publications and approval of the work.

A total of 5 scientific papers were published as part of the doctoral research. Of these, 3 articles were published in peer-reviewed high-impact international journals indexed in the Scopus and Web of Science databases. Specifically, 2 articles were published in the Remote Sensing journal (percentile – 91, Q1 category), and one review article was published in the Water journal (percentile – 84, Q1 category). In addition, 2 articles were published in journals included in the official list recommended by the Ministry of Science and Higher Education of the Republic of Kazakhstan.

The personal contribution of the doctoral student to the preparation of each article.

In the article *“The First Inventory of Rock Glaciers in the Zhetysu Alatau: the Aksu and Lepsy River Basins”*, the doctoral candidate conducted an inventory of rock glaciers in the Zhetysu Alatau, in particular analyzing the spatial distribution, morphological characteristics, and classification of rock glaciers by origin in the Aksu and Lepsy river basins. As part of the study, he worked on modifying the inventory methodology using satellite remote sensing data and geospatial technologies. In addition, he made a significant contribution to the processing and interpretation of radar data through the use of InSAR technology.

In the research article *“Accelerated Glacier Area Loss in the Zhetysu (Dzhungar) Alatau Range (Tien Shan) for the Period of 1956–2016”*, the doctoral candidate was the lead author in assessing the dynamics of glacier area changes in the Zhetysu Alatau. A quantitative analysis of glacier area changes was carried out based on satellite images and aerial photographs covering the period 1956–2016, and a methodology was developed for determining the intensity of glacier degradation. The doctoral candidate made a substantial contribution to structuring the article, synthesizing the research results, and formulating the scientific conclusions.

In the review article *"Application of Artificial Intelligence in Glacier Studies: A State-of-the-Art Review"*, the doctoral student carried out the systematization and analysis of scientific literature devoted to the application of artificial intelligence technologies in glaciological research. A comprehensive analysis of thematic studies was conducted, and the potential of AI methods for glacier research was assessed. The doctoral student also structured the material and prepared an integrated scientific review reflecting the current state and future prospects in this field.