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HIGH-RESOLUTION SATELLITE ESTIMATION OF SNOW COVER FOR FLOOD ANALYSIS IN EAST KAZAKHSTAN REGION

Abstract: The increasing frequency of extreme weather events linked to climate change has made flood forecasting an important issue, particularly in mountainous regions where snowmelt is a major driver of seasonal flooding. This study explores the application of snow cover estimation techniques to assess snowmelt dynamics and their potential impact on flood risks in the Ulba and Uba basins in East Kazakhstan. To achieve this, high-resolution multispectral satellite imagery from the Sentinel-2 Surface Reflectance dataset is used, focusing on images collected between March and October for the years 2021 to 2024. The images are processed in Google Earth engine platform with strict filtering based on spatial intersection with the basins and cloud cover pixels percentage, ensuring high-quality data for snow cover analysis. The study utilizes multiple remote sensing indices for snow cover estimation. The normalized difference snow index is calculated using the green and shortwave infrared bands to detect snow-covered pixels. Fractional snow-covered area is derived from the NDSI using the 'FRA6T' relationship, offering a more nuanced estimate of snow distribution across the basins. Additionally, a near-infrared to shortwave infrared ratio threshold is employed to minimize confusion between snow and water, improving the detection of snow cover, particularly in regions near water bodies or during melt periods. The resulting snow cover maps and fSCA estimates provide a detailed picture of snow distribution and melt dynamics, contributing to the assessment of snowmelt's role in flood risk development. The obtained insights can assist in refining flood forecasting models, improving early warning systems, and supporting informed water resource management in vulnerable regions.

Keywords: Remote sensing; satellite imagery; flood forecasting; snow cover.

Introduction

The problem of flood forecasting is becoming increasingly relevant in the context of climate change and the rising frequency of extreme weather events [1],[2]. In regions with distinct seasonality, especially in mountainous areas, floods are often triggered by the rapid melting of snow cover during spring and early summer. As such, accurately monitoring and analyzing the dynamics of snow cover is essential for effective flood forecasting and water resource management [3],[4]. The ability to predict snowmelt-driven floods is particularly important for communities and industries in flood-prone regions, as timely warnings and resource allocation can significantly mitigate the impact of flooding [5].

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Snow cover mapping is a key component in this context, as it provides critical insights into the spatial and temporal distribution of snow, which is a primary contributor to flood events in many regions [6]. By monitoring snow cover over time, it is possible to estimate the amount of water stored in snow and predict the rate at which this water will enter river systems as the snow melts. Snow cover mapping not only helps in forecasting flood risks but also plays a vital role in managing water resources for agricultural, industrial, and municipal needs, especially in regions where snowmelt is a major source of water. Modern Earth remote sensing technologies provide extensive opportunities for assessing the state of snow cover over large areas. Satellite data allow the tracking of parameters such as snow cover area, depth, density, and water content, which makes it possible to predict flood activity with greater detail. The analysis of these data, combined with hydrological models, can significantly improve the accuracy of predictions.

In this study, the primary goal is to explore the use of snow cover estimation techniques to analyse the dynamics of snow melt and its potential impact on flood development in the Ulba and Uba basins, which are located in a mountainous region prone to seasonal flooding in the East Kazakhstan region. Specifically, the research focuses on the following objectives:

- Collection of multispectral satellite imagery by gathering a filtered dataset of Sentinel-2 images for the Ulba and Uba basins, ensuring coverage of the study areas with high-quality.
- Calculation of fractional snow-covered area (fSCA) with utilizing the 'FRA6T' relationship based on the normalized difference snow index and incorporating an additional near-infrared to shortwave infrared ratio threshold to reduce snow-water confusion.
- Monitoring and analysis of snow melt dynamics by applying the calculated fSCA values to track and evaluate snow melt patterns over time.

This study aims to contribute to the understanding of snowmelt-driven floods by leveraging modern remote sensing techniques and snow cover mapping. By analysing Sentinel-2 multispectral imagery and calculating fSCA using advanced indices, this research will provide valuable insights into the snow melt dynamics in the Ulba and Uba basins. Ultimately, the findings of this study can support the development of more accurate flood forecasting models, enhancing early warning systems and improving water resource management in flood-prone regions.

Literature review

Flood forecasting is a complex task that requires accounting for many factors and constructing a spatio-temporal hydrological model based on numerous input variables. In climate zones where flood occurrence is also influenced by the amount of snow and the rate of snowmelt, this task becomes even more complicated and challenging to model. For example, in the work [7], the authors do not account for snow reserves and present a spatial hydrological model WetSpa (Water and Energy Transfer between Soil, Plants, and Atmosphere), based on rainfall data, terrain, and land use. Although both rain and snow are forms of precipitation that affect the volume of water in river runoff, snow accumulates during the cold season and can cause a sharp increase in river water volumes during the melting process. WetSpa operates on an hourly time scale and predicts the temporal flood schedule as well as the spatial distribution of hydrological characteristics within the watershed. The model was evaluated in a watershed in Belgium, for which topography and soil data are available through GIS services, while land use and soil cover data were obtained from remote sensing images.

In [8], to assess the spatial distribution of hazardous zones, six factors were considered: flow accumulation, slope, land use, precipitation intensity (also mainly in the form of rain), geology, and topography. As a result of the factor analysis, the study area was divided into

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VOLUME 19, SEPTEMBER 2024

five regions characterized by varying degrees of flood risk, ranging from very low to very high. The proposed methodology can be applied to any river basin, and in this work, it was applied to the Koiliaris River basin in Greece. In [9], remote sensing and GIS methods were combined with hydrological and statistical models to determine the spatial boundaries of flood hazard zones in communities in Ghana, Burkina Faso, and Benin. The proposed approach aimed to predict peak runoff concentrations at different elevations and subsequently applied statistical methods to develop a flood hazard index.

In [10], an overview of remote sensing methods for flood prediction is presented. A classification of remote sensing technologies used for flood forecasting is provided in three categories: multispectral, radar, and LIDAR. The limitations of each of the considered technologies were identified, and a flood forecasting and flood extent mapping model was proposed to overcome the identified shortcomings.

As for the studies that use snow cover data, [11] introduces a multi-objective calibration approach incorporating remote snow cover observations from MODIS datasets. By including snow cover dynamics as a critical factor, this study significantly enhances the model's capacity to predict snow-driven flood events. Moreover, the use of an additional objective function focused on peak runoff events improved the model's accuracy in forecasting the magnitude and timing of large floods, demonstrating the importance of incorporating snow data in regions prone to snowmelt-driven flooding. In [12], fSCA retrievals from multiple satellite sensors, including Landsat 8, Sentinel-2, and MODIS, were evaluated at a high-Arctic site for their accuracy. The study highlights that fSCA retrievals based on NDSI thresholding from higher resolution sensors tend to overestimate snow cover due to the mixed pixel problem. Spectral unmixing retrievals from Landsat 8 OLI and Sentinel-2 MSI provide more reliable estimates of fSCA. Another work on snow cover conditions in the High Arctic is presented in [13] with an extensive review of the literature focusing on observed and projected trends in key snow metrics such as snow cover duration, snow cover extent, snow depth, and snow water equivalent. The review finds that despite increasing snowfall over the last few decades, snow cover duration and extent have decreased, particularly in the spring and summer seasons. The study highlights the complex spatial and temporal variability of snow cover metrics in response to climate change.

In the work [14], the impact of snowmelt on flooding was investigated across four elevation zones in a mountainous region using the snowmelt runoff model and daily MODIS images from 2013 to 2018. The results showed that snowmelt accounted for only 23% of total runoff in areas below 2000 m, while this contribution increased with elevation, reaching up to 87% in areas above 3000 m. The authors of [15] propose a high-resolution assessment of snow-covered area using the blue snow threshold (BST) algorithm. The BST, designed for use with high-resolution satellite imagery in the visible spectrum, offers an alternative to the NDSI, which relies on shortwave-infrared (SWIR) wavelengths. The study highlights the potential of BST for fine-scale snow cover mapping where SWIR measurements are limited.

The study [16] was conducted on seasonal snow cover area mapping in the Miyar and Bhaga basins of the western Himalayas using high-resolution Sentinel-2 data for the hydrological year of 2017-2018. The snow cover area was estimated using NDSI, the near infrared and shortwave-infrared (NIR/SWIR) ratio, and the S3 index to reduce misclassification of water as snow and to detect snow cover under vegetation, respectively. It also represents the first attempt to use Sentinel-2 data for snow cover monitoring in the Himalayas. While the study [17] evaluated the sensitivity and accuracy of different NDSI thresholds used in MODIS Collection 6 snow cover products for snow mapping in Austria from 2002 to 2014. Using snow depth observations from 665 climate stations, the researchers found overall classification accuracy to exceed 97% and revealed that optimal NDSI thresholds vary by elevation, season, and land cover type.

In [18], a study was conducted in northern Fenno-Scandia using satellite-derived snow cover maps and publicly available data on runoff, precipitation, and air temperature to assess the variability of snowmelt-related flooding. The study found high variability in snow cover duration and spring flood discharge among eight unregulated river catchments. The snowmelt runoff model was used successfully to simulate flood types observed in previous flood years. The study highlighted the importance of integrating geospatial snow data with meteorological observations for accurate flood forecasting.

Methods and Materials

Dataset description

The calculation of snow cover for flood analysis and monitoring in the East Kazakhstan region were conducted using high-resolution multispectral satellite imagery from the Sentinel-2 Surface Reflectance (SR) dataset [19]. The satellite imagery was processed and analysed within the Google Earth Engine (GEE) platform, a cloud-based geospatial analysis tool that enables large-scale data processing [20]. The key steps involved in data collection, preprocessing, and preparation are outlined below.

The study area focuses on two river basins in the East Kazakhstan region: the Ulba River Basin and the Uba River Basin. Shapefile delineating these basins was used to define the region of interest (ROI) for satellite imagery collection. Sentinel-2 images were filtered to ensure that only those with at least 50% spatial intersection with the basin areas were included in the analysis. This spatial filtering criterion was employed to guarantee that the selected images provide sufficient coverage of the hydrological features relevant to the snow cover calculation and flood monitoring study as can be seen from the example in Fig. 1.

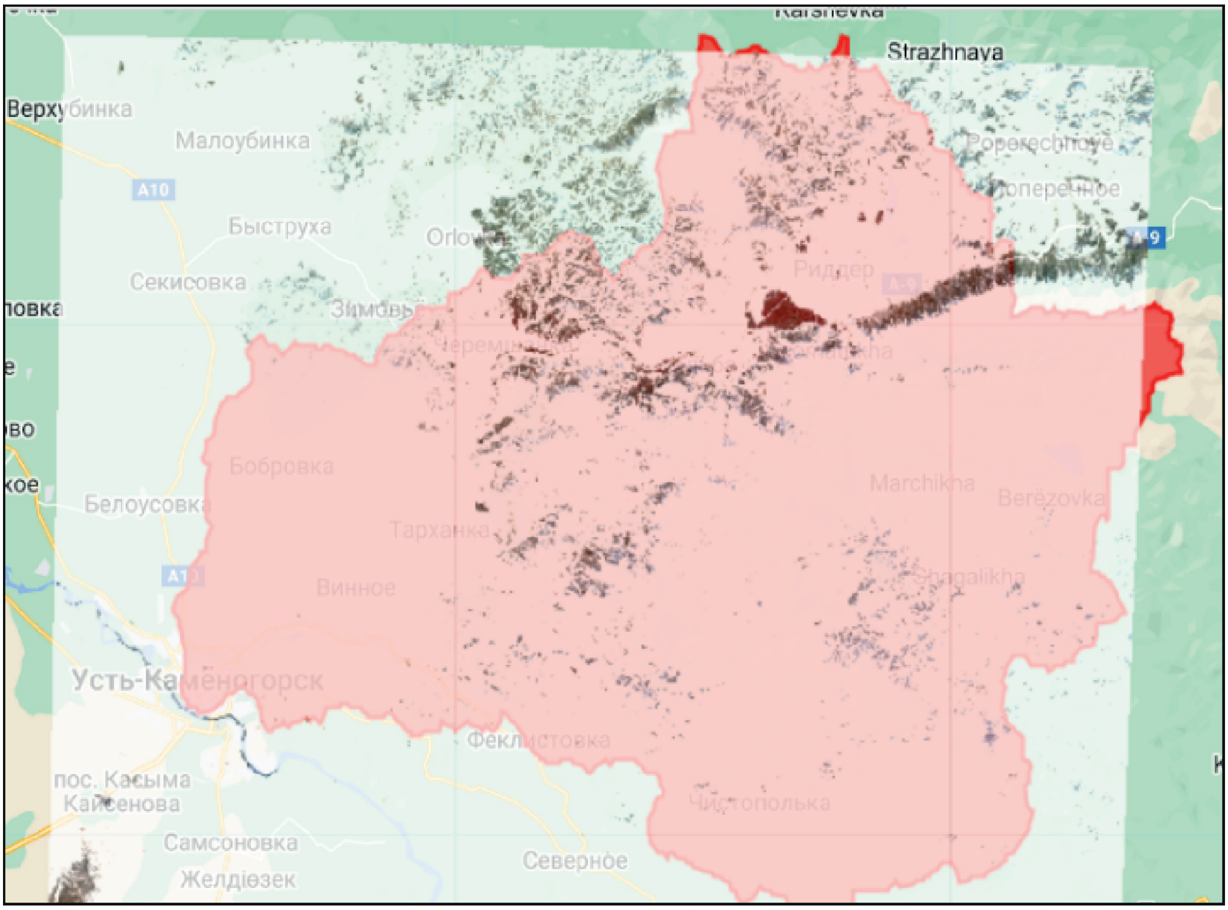

Figure 1. Spatial intersection of the image with basin area

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VOLUME 19, SEPTEMBER 2024

To minimize interference from cloud cover, which can obstruct the land surface in satellite images, a strict cloud-filtering process was applied. Sentinel-2 images include metadata on cloud cover, specifically the "CLOUDY_PIXEL_PERCENTAGE" field, which provides the percentage of pixels in the image obscured by clouds. To maintain data quality and ensure clear observations, images were filtered to retain only those with no more than 10% cloud cover. This filtering step was essential for reliable snow cover and flood analysis, ensuring that the study area was sufficiently visible in each image.

Sentinel-2 images were collected over a multi-year period to capture seasonal variations in snow cover and flooding patterns. The temporal range spanned the months of March through October for the years 2021 to 2024. This period was selected to cover both the melting season, when snow cover typically recedes and contributes to flood risks, and the primary flood season in the region.

In addition to the specific bands used for snow cover and flood analysis, all available spectral bands from the Sentinel-2 satellite were exported to enhance the flexibility and agility of the dataset, allowing it to be repurposed for a wide range of analytical tasks beyond the scope of the current study. By including the full suite of spectral bands, the dataset remains open for applying various remote sensing techniques, such as vegetation analysis, land cover classification, water quality monitoring, and other environmental assessments.

The data was exported from the GEE platform in GeoTIFF format after selecting suitable images based on spatial coverage and cloud filtering to create a dataset. This format was chosen for its compatibility with Geographic Information System (GIS) software and its ability to retain the high spatial resolution (10-20 meters) of Sentinel-2 imagery.

Snow Cover Estimation Techniques

In this study, several remote sensing indices and techniques were employed to estimate snow cover and assess its role in potential flood events in the East Kazakhstan region. The methods used include the normalized difference snow index (NDSI), the near-infrared to shortwave infrared (NIR-SWIR) ratio, and the fractional snow-covered area (fSCA). These methods were applied to the high-resolution Sentinel-2 Surface Reflectance images using specific spectral bands for snow cover estimation.

The normalized difference snow index or NDSI is a widely used spectral index for detecting snow cover. NDSI exploits the high reflectance of snow in the visible bands and the low reflectance in the shortwave infrared (SWIR) bands. It is calculated as:

$$NDSI = \frac{B3 - B11}{B3 + B11} \tag{1}$$

where $B3$ is the reflectance in the green band and $B11$ is the reflectance in the shortwave infrared band. NDSI values typically range from -1 to +1 and thresholds are set (e.g., NDSI > 0.4) to classify pixels as snow or non-snow.

To further refine snow detection and differentiate between snow and water, the NIR-SWIR ratio was calculated. This ratio helps distinguish snow from water, as snow typically has a lower NIR/SWIR ratio than water but similar NDSI values. The ratio is defined as:

$$NIR / SWIR = \frac{B8 - B11}{B8 + B11} \tag{2}$$

where $B8$ is the reflectance in the near-infrared band. In this study, we used the NIR/SWIR ratio to mask pixels that had a ratio greater than 0.45 based on following the scatter plot in Fig. 2 to effectively eliminate misclassification with water pixels:

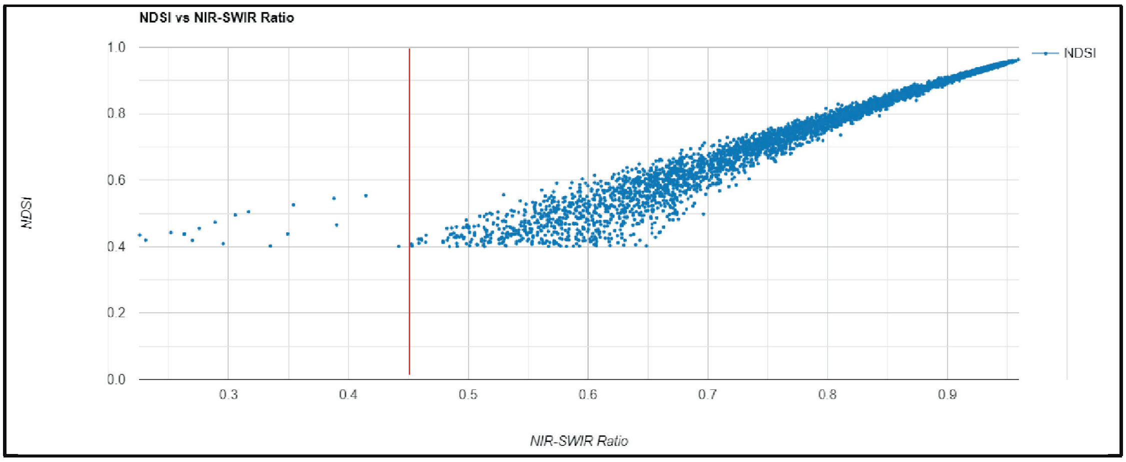


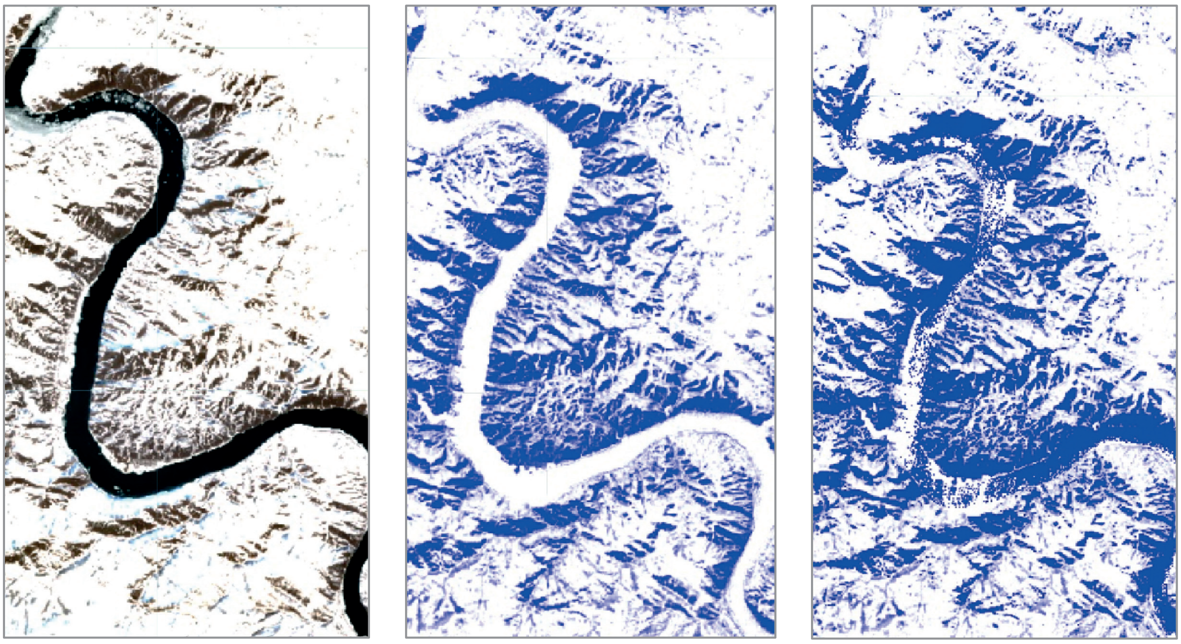
Figure 2. NIR/SWIR ratio threshold selection

The fractional snow-covered area (fSCA) represents the proportion of snow-covered pixels within a given area. It provides a more detailed understanding of snow distribution by estimating how much of a pixel is covered by snow, rather than using a binary classification. The fSCA was calculated using the following linear relationship derived from the NDSI:

$$fSCA = b_1 NDSI + b_0 \tag{3}$$

where the $b_1 = 1.45$ and $b_0 = -0.01$ are regression coefficients. The values for the coefficients are from the 'universal FRA6T' relationship which was introduced in [21]. It converts the NDSI values into fractional snow cover and after calculating fSCA, the values were clamped between 0 and 1 to ensure that all estimates were physically meaningful.

Additionally, the fSCA calculation was refined using the NIR/SWIR ratio described above to avoid confusion between snow and water. As can be seen in the example below in the Fig. 3, this step was particularly important for analysing snow-covered areas near water bodies, as well as during snowmelt periods when standing water may be present.



(a) (b) (c)

Figure 3. The impact of applying NIR/SWIR ratio threshold where blue represents non-snow pixels and white snow pixels: a) RGB image b) fSCA without the threshold c) fSCA with the threshold

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VOLUME 19, SEPTEMBER 2024

Overall, the workflow for snow cover estimation involved the following steps: 1) For each Sentinel-2 image, the normalized difference snow index or NDSI was computed using the green and shortwave infrared (SWIR) bands to detect snow-covered pixels 2) The fractional snow covered area was derived using the NDSI values, providing a more nuanced estimate of snow distribution within each pixel, allowing for a finer resolution of snow cover by accounting for mixed pixels that may contain both snow and non-snow surfaces. 3) The fSCA values were clamped to the range of 0 and 1 and further refined by applying the NIR/SWIR mask to decrease confusion with water pixels.

Results and Discussions

This study investigates the spatial and temporal dynamics of snow cover in the Ulba and Uba basins during the spring of 2023 and 2024, focusing on the period of snowmelt that influences river discharge and potential flood risks. The spatial distribution of snow cover is illustrated in Fig. 4. The left panels show true color Sentinel-2 images, while the right panels display the corresponding snow cover areas using the fSCA.

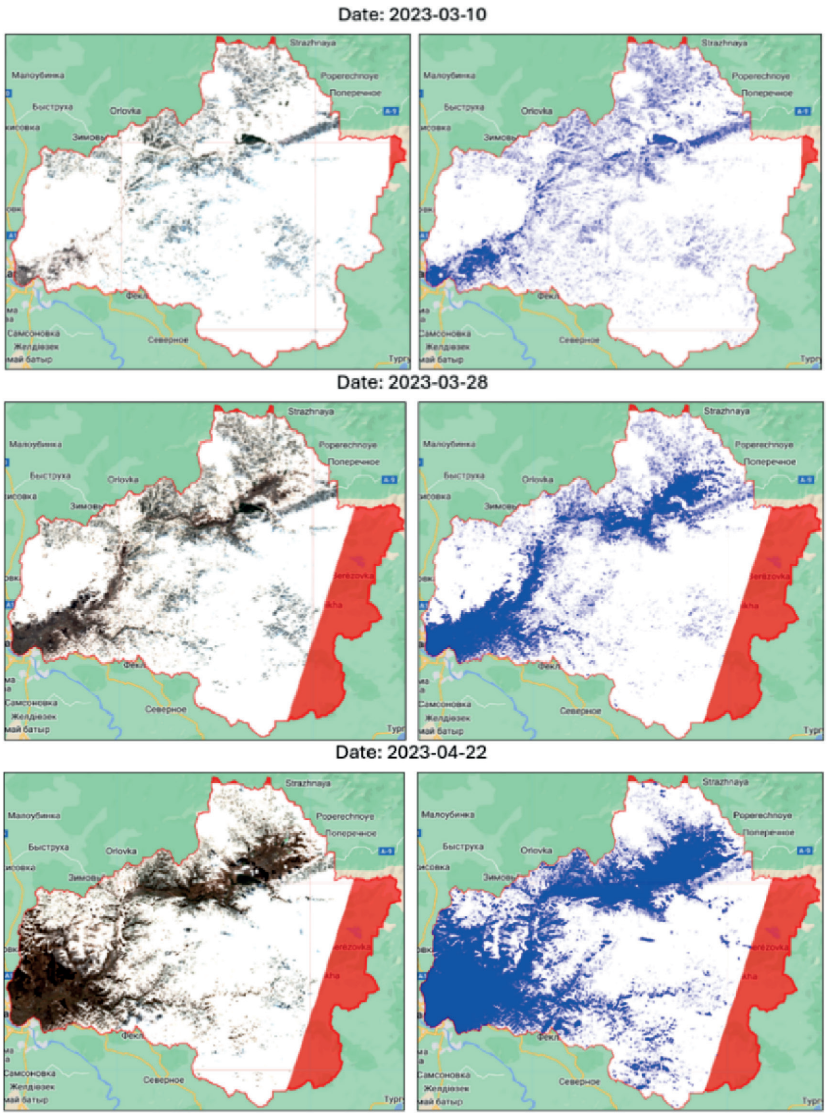

Figure 4. Spatial analysis of snow melt dynamics in a study area

This spatial analysis highlights snowmelt dynamics during the transition from winter to spring, as a gradual reduction in snow cover is observed in late March, and by late April, much of the basin is snow-free. The presented graphs in Fig. 5 and Fig. 6 show the dynamics of snow cover melting for 2023 and 2024 with the percentage of snow cover area.

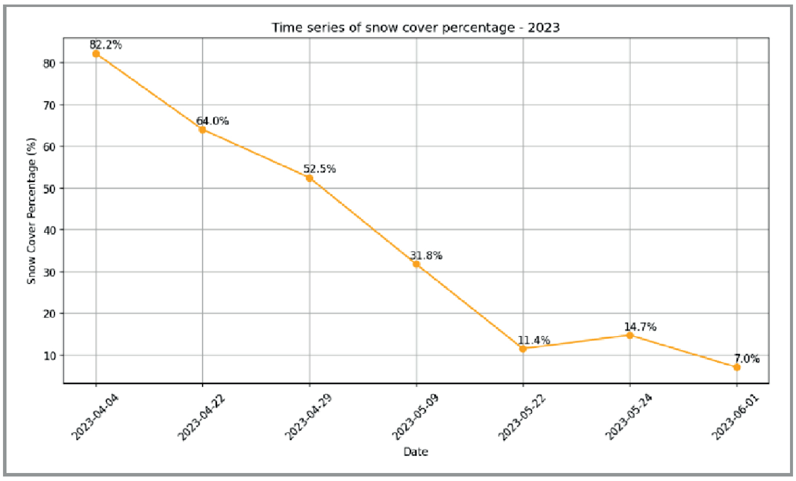

Figure 5. Snow melt dynamics for 2023

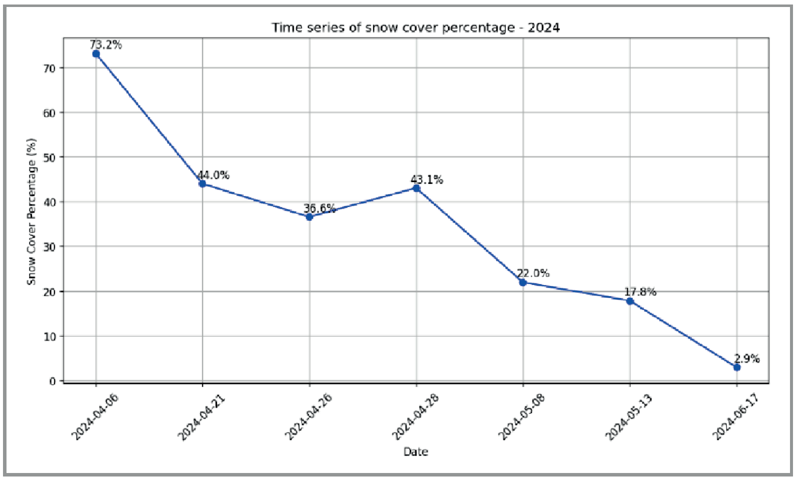

Figure 6. Snow melt dynamics for 2024

From the middle of the first decade of April to the end of the first decade of May, intensive snow melting is observed. The snow cover rapidly decreases from 82,2% to 31,8% of the studied area in 2023 and from 73,2% to 22% percent in 2024. From the end of May, the intensity of snow melting is minimal, and further changes in the snow cover are insignificant. In 2024 the snow melt occurs earlier compared to 2023. By early April 2024, the snow cover has already reduced to 73.2%, whereas in 2023 it was still at 82.2%. The melting process in 2024 intensifies more quickly, with snow cover dropping below 50% by mid-April.

Conclusion

The study successfully implemented the following steps to enhance the understanding of snowmelt dynamics in the Ulba and Uba basins and the East Kazakhstan region in general. First, high-quality multispectral Sentinel-2 imagery was collected and filtered to ensure adequate coverage of the study area with minimal cloud interference. Next, the fractional snow-covered area (fSCA) was calculated, and the near-infrared to shortwave infrared (NIR/SWIR) ratio was applied to reduce snow-water confusion. The resulting snow cover maps provided valuable insights into the spatial and temporal dynamics of snow melt in East Kazakh-

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stan Region. By utilizing high-resolution satellite imagery snow cover maps and snow melt dynamics monitoring, this research can contribute to more accurate flood forecasting models, offering the potential to enhance early warning systems and improve water resource management in flood-prone regions.

Additionally, despite the anticipated trends in the results, there is an increase in snow cover around late May of 2023, which could potentially be attributed to a localized snowfall event, particularly in mountainous regions. Further verification is needed to confirm whether this increase was caused by snowfall at higher elevations.

Future research may focus on improving satellite data processing methods, accounting for other factors such as temperature anomalies, climate change, ground freezing depth, and digital elevation models, as well as integrating additional data sources to create more accurate and comprehensive snow cover mapping and flood forecasting models.

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