NEW REMOTE SENSING METHODOLOGY TO MAP THE GLACIER EXTENT: THE NEW INVENTORY OF GLACIERS IN PAKISTAN

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ABSTRACT:

Satellite imagery from the Sentinel-2 MSI platforms provides systematic global acquisitions of high-resolution imagery of the Earth's surface with a 5-day revisit time at the equator, having a great potential for monitoring and mapping regions where the land cover is particularly sensitive to the dynamics of climate change, such as the glaciers environments.
Although several attempts at automatic procedures have been tested by the scientific community in recent years, very often the remote sensing mapping of the glaciers requires the use of personnel with expertise in the photo-interpretation of the glacial morphology, for the detection of the landform features. The strategy of this project can be divided in two main goals: i) Developing a new methodology to map the glaciers in the region of Hindu-Kush Karakorum ranges in Pakistan, where a number of more than 10,000, with a large number of them debris-covered, has been reported; ii) Involving the Pakistani and Italian students into the process of recognition of the glacier's boundaries and their mapping. In order to reduce the subjectivity of the human interpretation, a new proposal of a semi-automated process for the classification of glacial landform features from Sentinel-2 data was implemented.

1. INTRODUCTION

Optical satellite data has been widely used for the glacier mapping, starting from the first Landsat imagery in the '70s years. The revisit time and the availability of these data can be considered the most important characteristics the researchers employed to create the first existing glaciers inventories based on the satellite imagery interpretation. Multispectral data allowed to propose algorithms, like the spectral indexes, for the masking of the cloud cover and the recognition of snow and ice and then map the glacier extent (Paul et al., 2005). The resulting new images can support the mapping, but two main concerns can be measured: i) a unique threshold of the adopted spectral index is inclined to give a good result only locally with homogeneous geomorphological, slope and aspect conditions; ii) multispectral indexes based on optical data cannot clearly identify the debris-covered or partially covered glaciers confused with the surroundings moraines or rock outcrops. This last is one of the primary and well-known challenge, especially when it comes to identifying glacier terminus points (snouts). Researchers propose different methods based on thermal data or the integration of high spatial resolution optical and topographic data, to compare the landform due to the presence of debris (Kraaijenbrink et al., 2016; Mölg et al., 2020).
Moreover, the application of automatic classification of spectral data, supported by high performance of digital processing systems has been applied in limited glacier areas (Paul et al., 2016), suggesting that when analysing a very large area, a systematic step-by-step approach must be implemented, with a thorough examination of the results. For this reason, in this project the automatic extraction of the glacier's boundaries using a pattern recognition technique has been controlled by human interpretation.
This study is designed to describe and discuss a new methodology to map the glaciers from satellite data. The research has been developed in the framework of the UNDP (United Nations Development Programme) and EvK2CNR-Italy Project "Glaciers and Students - A scientific based approach to monitor climate and glaciers in Pakistan Mountain Regions to support hydrogeological risk prevention". The main expected result of this project will be the updated glaciers inventory of Pakistan. The region of Hindu-Kush Karakorum ranges in Pakistan hosts a number of more than 10,000 glaciers, and a large number of them are debris-covered.
Starting from these expected outputs, and considering the new technical performance that can be activated in the using by satellite data, the strategy of this project can be divided in two main goals:

- Developing a new methodological approach to map the glaciers;
- Involving the Pakistani and Italian students into the process of recognition of the glacier's boundaries.

Based on these objectives, the results presented in this research primarily centre around detailing the newly discussed glacier inventory methodology.

2. DATA AND METHODS

2.1 Satellite data and software environment

The new inventory of Pakistan's glaciers has been developed using optical data obtained from the European Space Agency's Sentinel-2 twin satellites. This choice is dictated by the need to

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respond to the requirement to have homogeneous coverage of the entire territory under examination in terms of image acquisition dates, cloud cover and good spatial resolution, that allow the recognition of glaciers and their mapping.
Furthermore, particular attention in the selection of the data processing and mapping methods was given for the expected prospect activity of updating the glaciers perimeters and monitoring changes in the future.
Sentinel-2 twin satellites acquire data through an optical multispectral sensor with 10 meters of spatial resolution in the visible and Near-Infrared and 20 meters in the Short-Wave Infrared, allows to apply the useful algorithms for the spectral recognition of the glaciers (Kääb et al., 2016; Paul et al., 2016).
Several software can be used for image processing and editing in GIS environment, either free or commercial.
Moreover, the available DEM has been used to divide the Gilgit-Baltistan region in hydrographic basins allowing the recognition of glaciers in each of them separately, and to let each user to concentrate the analysis and the glaciers classification in a bordered area.
IMPACT Toolbox has been chosen for the pre-processing and the semi-automatic classification of the satellite data (http://forobs.jrc.ec.europa.eu/products/software). GIS

2.2 Methodology

The applied methods can be divided in two main sections, as in Figure 1:

- Satellite data arrangement
- Glaciers recognition (classification) and mapping

The first section was dedicated to the preparation of the base data used by the researchers and students for the classification: recognition and mapping of the glacier's boundaries. The second part of the methodology includes the activities of mapping, recognizing the polygons of the segmentation belonging to the glacier surface.
The applied classification of satellite data is based on the Segmentation function of the composite image. In the next paragraph, the specific steps to create the composite image used to spectrally discriminate the glacial bodies and extract their limits is described. The output of these functions is a file in polygonal vector format (shapefile), where each feature can belong to a glacier.

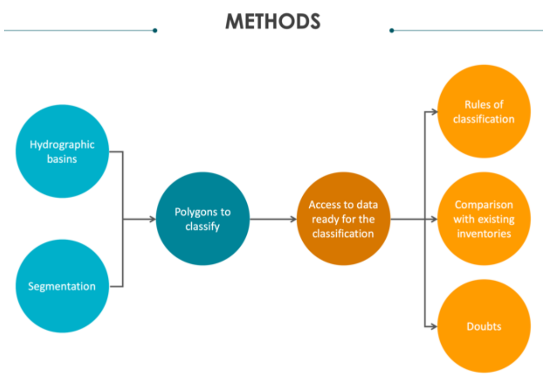

Figure 1. Schema of the approach with the steps of the adopted methodology

From the synthetic image of Sentinel 2, spectral indexes referred to snow and ice-cover, and the image segmentation to partitioning of the composite into relatively homogeneous regions were applied. The resulting regions (polygons) can belong or not to a glacier, and the interpretation by the users is supported by their boundaries.

2.3 Image Segmentation

The workflow in the applied procedure is constituted of three main steps:

- Satellite data acquisition and composite;
- Spectral Index extraction;
- Data classification and segmentation.

Satellite data acquisition and composite
The first step aims at the production of a single/mosaic multi-spectral dataset reproducing the mountain range in northern Pakistan free of clouds, cloud-shadows and haze. A large number of Sentinel-2 data are needed to cover this area and to guarantee the cloud-free observations. Considering the swath of each image and the temporal resolution of these data, the possibility to use the cloud platform Google Earth Engine has been adopted for the creation of a unique multispectral data for the whole region. It is generally known, finding all cloud-free images covering the whole is highly challenging. So, the approach in this project has been based on the creation of a single multi-band composite cloud-free image, starting from the selection of acquisitions during the summer season.
The cloud-cleaning technique applied in this project is based on the PINO cloud mask image processing procedure, applied in JavaScript code through the Google Earth Engine platform to create multi-temporal data composites (Simonetti et al., 2021). The PINO function returns the same Sentinel-2 image received as input after replacing every pixel, classified as clouds or shadows, with no-data. Filtering the annual image collection before extracting the median value of each pixel, increases the probability of obtaining a cloud-free composite in cloud-prone areas or whenever the atmospheric contaminations affect more than 50% of the acquisitions. For each pixel of the resulting image, and for each band, the most frequent pixel value (median) at the correspondent position in the given time series is assigned. For the computation of median digital numbers, pixel values recognized as belonging to clouds, cloud-shadows or haze by the PINO cloud mask algorithm, are automatically skipped, resulting in a data composite clean from atmospheric contaminants. The time series of Sentinel-2 L1C data in the acquisition period from "2022-07-31" to "2022-10-01" was processed. The resulting image composite is a cloud free Sentinel-2 multiband dataset, time-centred at the end of August (Figure 2)

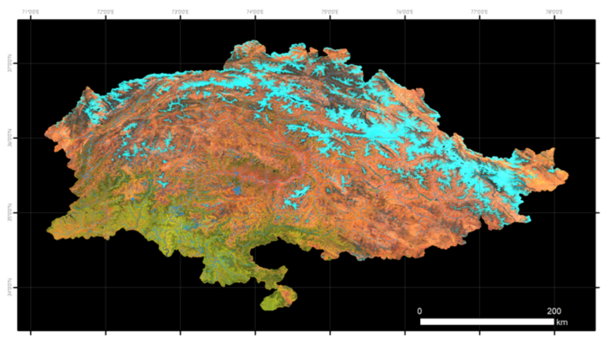

Figure 2. Sentinel-2 RGB composite image of the Pakistan region used in this inventory. This image is the synthesis of all the images acquired by the Sentinel-2 satellites in the period "2022-07-31" -"2022-10-01. In the Red, Green and Blue channels the SWIR, NIR and Red bands are represented. The main land cover types can be identified: in bright blue the snow, in dark blue the ice, in bright and dark tones of red the bare soils and rocks, and in green the vegetated areas.

Spectral Index extraction
The second step of the approach is focused on the enhancement of the spectral differences among objects composing the scene,

and the spectral investigation was concentrated on the distinction of glaciers ice/snow, glaciers debris and rocky slopes. The normalized-difference snow index (NDSI) was adopted (Dozier, 1989):

$$NDSI = (B3(green) - B11(SWIR1)) / (B3(green) + B11(SWIR1))$$

In order to distinguish the glaciers debris (not covered by ice or snow) from rocky slopes, it is hypothesized that the vegetation has a discriminating role, being present in the second (especially during the summer, such as the acquisition period chosen for the synthetic composite), even if sparse and low, and is almost absent in the first, because of the slow but constant friction, movement and tilling of sediments in the dynamism of the glaciers. According to this hypothesis, the normalized-difference vegetation index (NDVI) was calculated:

$$NDVI = (B8(NIR) - B4(Red)) / (B8(NIR) + B4(Red))$$

Since, the best contrast strategy to distinguishing the landforms of interest is based on the spectral indices mentioned above, a new dataset was prepared using NDSI, NDVI and Band4 (red), creating a new multiband image stack. Then, the segmentation classification algorithm was applied to this new multiband dataset, in order to aggregate pixels on the base of the proximity and of the similarity in the response in the NDSI, NDVI and Red reflectance.

Data classification and segmentation

The third step in the workflow regards the data classification. In this project we adopted image segmentation technique, aimed at the partitioning of the dataset into multiple polygons (segments) based on spectral, geometric or texture properties, calculated in conjunction with user-defined parameters describing size, shape and similarity to adjacent segments.

The following parameters have to be considered in the classification process:

• bands and weights: raster bands and associated weight values to use;

• scale factor: factor that controls the spectral heterogeneity of the objects in the image and is therefore related to their average size, the low value of which allows obtaining a high number of objects and vice versa;

• colour: spectral component of the Baatz algorithm [0,0; 1.0] (Baatz et al., 2000);

• compactness: morphological component of the Baatz algorithm [0,0; 1.0];

• Euclidean distance: minimum distance (expressed in DN values) to set for the process union of the segments that cross two adjacent links; high values will allow the aggregation of heterogeneous objects between the meshes, while low values will preserve the sharp boundaries of the meshes;

• MMU: minimum map unit, i.e. the spatial resolution in meters per pixel of the segmentation layer; for the images collected by Sentinel-2, 1 MMU corresponds to an area of 100 m^2, i.e. a surface of 10 x 10 m on each side, the spatial resolution of Sentinel-2 being 10 m (Simonetti et al., 2015).

In this project, the segmentation process was applied through the functionality available in the JRC IMPACT free software, which is based on the Baatz-Schape open source segmenter libraries (Inpe's TerraAIDA Operators). The NDSI-NDVI-B4 multiband dataset was processed adopting the setting, as proposed by the application as optimal ("majority" as aggregation rule, 0.8 as compactness, 0.9 as similarity in a scale 0-1, 0.9 as colour). The minimum map unit (MMU) parameter was empirically tested by setting two different values: 250 and 100. Applying the first value, the segmentation process produces a reduced number of aggregations, distinguishing landforms quite correctly. However, in some cases (e.g. where the slope shadow affects the scene) the detail of the output is not enough accurate to precisely perimeter the landforms as efficiently as the MMU parameter 100 does. On the other end, the output of the segmentation achieved setting 100 as MMU parameter, returns a number of aggregations blocks considerably higher, less easy to analyse for a photo-interpreter (Figure 3).

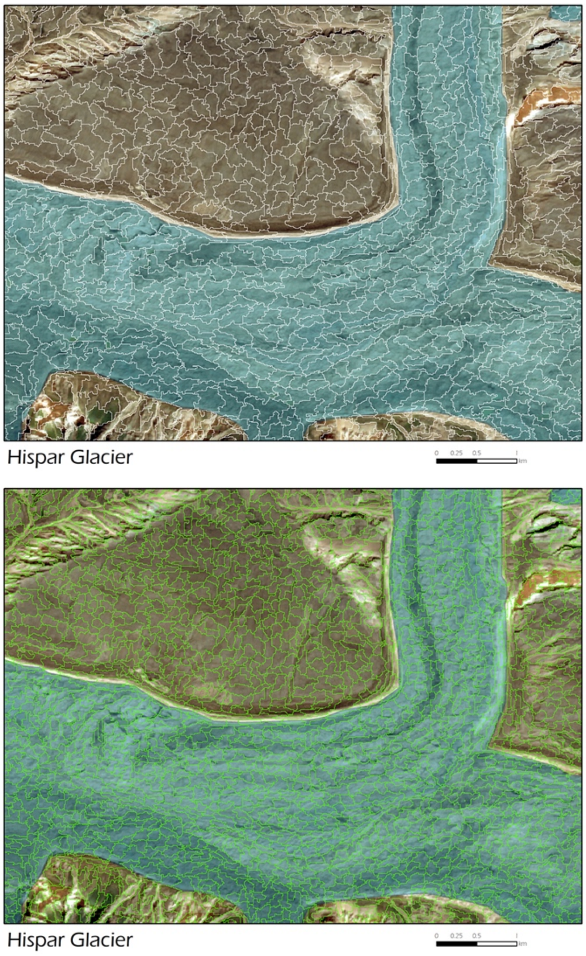

Figure 3. Comparison of the subsets of the image in true colour representing a central region of Hispar glacier. The area covered by the glacier is in blue, and is delineated merging the segmented polygons belonging to the glacier. In the upper image, the polygons with MMU of 250 are represented in white, and in the lower image, the polygons with MMU 100 are in green.

3. RESULTS AND DISCUSSION

3.1 Glaciers recognition (classification) and mapping

The methodology has been implemented in a Geographic Information System (GIS) environment. Subsets of the composite have been created for each basin. In a dedicated cloud server all the data has been uploaded, allowing each researcher and student to access to an assigned basin in a folder. For each basin, four thematic data were available, as shown in Figure 4:

- The composite multiband image with the bands
- The spectral indexes
- The shapefile with the polygons of the segmentation with the MMU of 250
- The shapefile with the polygons of the segmentation with the MMU of 100.

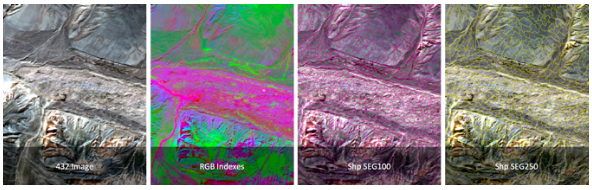

Figure 4. Contents of the working folders for each basin.

As in Figure 1, starting from these data, the steps of mapping were driven by an initial training activity and periodic online meetings which allowed the working group to discuss and share the procedures for assigning each polygon to a glacier or not. The first results of this activity can be seen in the Figure 3: the polygons created with the segmentation follow the limit of the glacial tongues with a good accuracy, allowing them to be identified very precisely. The process of identification of the polygons has been supported by accessible datasets, like the existing glaciers inventories, the very high-resolution satellite data of Google Earth and Google maps, and the base map available in the GIS software. However, the final decision and the final limit was drawn based on the Sentinel image, thus ensuring a homogeneity of the detection date.
A specific activity of comparison of each glacier with the available high-resolution imagery has been done in the final phase of validation, considering their acquisition date.

4. CONCLUSIONS

The improvement of knowledge of the cryosphere processes and the impacts of the climate changes can generate a new awareness in the local communities in formulating long term strategies for disaster risk reduction and for the environment sustainability. As resulting effects, better decisions and actions in these sectors will have positive impacts on the management of water and land resources, ultimately enabling to establish better responses to climate change and contribute in poverty reduction (Sustainable Development Goals No. 1, 6, 13 and 15). The use of remote sensing confirms their potential as monitoring system in the areas data particularly sensitive to climate change and capable of rapid geomorphic responses to perturbation (Melis et al., 2023).
The final product of the research project described in this study is a map in vector format (shapefile), where each glacier results from the merging of the polygons inside its boundary. The proposed method, and the software infrastructure planned for this study, has been considered suited to familiarize with the mapping process using satellite images by the students from the Italian and Pakistan universities involved in the project with a basic knowledge of remote sensing, GIS, and glacier's mapping. For these topics, training activities have been organized and guidance materials in form of videos have been shared.
Although in the proposed method the assignment of a "Glacier label" is based on visual recognition, each interpreter is guided by a vector basis automatically extracted from the Sentinel-2 spectral products.
The outcomes of this study allow to plan the updating of the inventory annually, according to a procedure that guarantees the replicability and comparability of the results. Furthermore, in this way, the method can be adopted to guarantee the necessary monitoring action of these immense water reservoirs which constitute the primary resource for the life of millions of people living in the Asian region.

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