Date of Submission	21/06/2024

IPL Project (IPL-Number) Annual Report Form

Period of activity under report from 1 January 2023 to 31 December 2023

1. **Project Number and Title:** IPL Project 221 (2017): PS continuous streaming for landslide monitoring and mapping

2. **Main Project Fields**

   Select the suitable topics. If no suitable one, you may add new field.

   (X) Technology Development

   B. Hazard Mapping, Vulnerability and Risk Assessment

   (2) Targeted Landslides: Mechanisms and Impacts

   A. Catastrophic Landslides

   (3) Capacity Building

   B. Collating and Disseminating Information/ Knowledge

   (4) Mitigation, Preparedness and Recovery

   A. Preparedness

3. **Name of Project Leader: Federico Raspini** and **Silvia Bianchini,** Associate Professor

   Affiliation: **Earth Sciences Department of the University of Firenze (DST-UNIFI) - Via La Pira, 4 - 50121, Firenze, (Italy) - Phone: +39 055 2757551;**

   Telephone: **+39 3398929831**

   Email: **federico.raspini@unifi.it**

   Core members of the Project:

   Nicola Casagli, Full Professor, DST-UNIFI

   Veronica Tofani, Researcher, DST-UNIFI

   Matteo del Soldato, Research Assistant, DST-UNIFI

4. **Objectives**

The main objective of this project is to perform the transition from historical analysis of radar satellite image archives to monitoring of ground deformation at wide scale using radar satellite scenes. To accomplish this objective the global coverage, the short revisiting time and regularity of acquisitions of Sentinel-1 constellation of SAR (Synthetic Aperture Radar) satellite sensors were exploited.

5. Study Area

Natural damming of rivers by landslides can have disastrous consequences, posing a major hazard in mountainous areas dissected by deep, narrow valleys. Some of the existing landslide-dammed lakes in Central Asia can be considered stable and relatively safe. On the other hand, other river blockages represent a very large hazard, as catastrophic outburst floods can occur. Long-term stability assessments of these dams and lake banks are of paramount importance, as they represent a significant threat to the communities living there.

Tajikistan is a region of Central Asia characterized by approximately 1300 lakes, mostly resulting from rockfalls: landslides have occurred in the Tajikistan area mainly due to very strong earthquakes and moraine deposit collapse. The Usoi dam, which generated Lake Sarez (Figure 1) on the eastern side of the country, was created by rockfalls and rock avalanches that were predominantly composed of crushed rocks with a wide grain size distribution and that are characterized by rapid movements and large volumes of fallen material of approximately 106 m^3. The Usoi landslide dam is the tallest in the world (approximately 600 m) among natural and artificial dams.

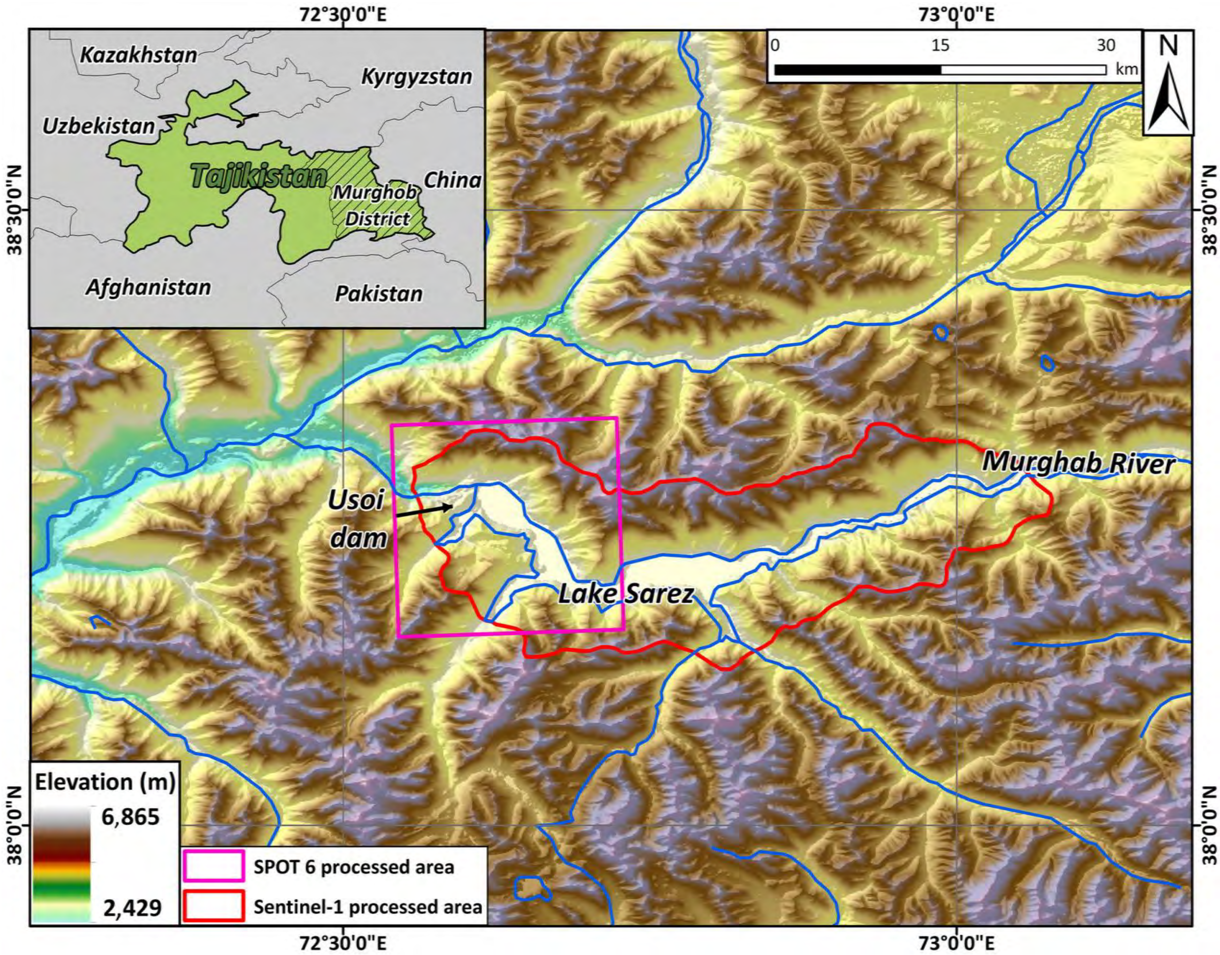

Figure 1: Location of the Usoi dam and Lake Sarez in eastern Tajikistan. The extension of the areas processed with Sentinel-1 and SPOT images is also indicated.

In particular, the purpose of the activities performed during the refence period (January – December 2023) is to provide an overview of the ground deformation of the two landslides that affect and threaten the area of Lake Sarez and the Usoi dam in Tajikistan (Central Asia) exploiting the combination of two different satellite techniques: *i*) the Interferometric Synthetic Aperture Radar (InSAR) method with the SqueeSAR approach and *ii*) optical image analysis through the use of COSI-Corr software. The combination of these two techniques turned out to be useful and provide more information because InSAR method balances lack the optical analysis and vice versa giving the possibility to obtain a complete overview of the displacement of the area. Moreover, InSAR data have been used to reconstruct the geometry and depth of the sliding surface of a potential landslide that could affect the lake, generating a wave that could overtop the dam and affect the villages downstream.

Progress on *i*) generation and analysis of ground deformation maps for the Lake Sarez using radar images acquired by Sentinel-1 satellites and *ii*) generation and analysis of deformation pattern of major landslides affecting the surrounding of Lake Sarez using multispectral images acquired by SPOT satellites have been already presented and reported in the Project annual report of 2022.

6. Project Duration

The duration of the project is six years: the project has been proposed in 2017 and it started in 2018.

7. Report

1) Progress in the project

InSAR data have also been used to postulate the geometry and depth of the sliding surface of both right-bank and left-bank landslides using a method originally developed by Carter and Bentley (1985), improved by Cruden (1986), and validated with the use of satellite interferometric data by Intrieri et al. (2020), who also dubbed it the vector inclination method (VIM). This method assumes that the direction of the superficial ground reflects the geometry of the sliding surface, which is generally true in the case of landslides with no strong internal deformations along the vertical axis.

Notably, the VIM is affected only by the direction of the superficial movement and not by the amount of displacement, which means that variations in the modulus of the displacement vector with depth are allowed as long as the direction is relatively unchanged. Through a geometric process, the whole sliding surface can be reconstructed along a cross-section to provide a kinematically possible solution. The method is based on three assumptions: a point on a landslide surface will move in a parallel slope direction of the sliding surface beneath; the mass will move as a rigid body; there is only one sliding surface. The procedure consists in drawing the cross-section of the landslide which intersects the measurement points. Starting from the back scarp, the normal lines to two consecutive movement vectors are obtained, and their intersection becomes the rotation centre of the sliding surface passing through the first vector and ending at the second one. This process is then repeated for each movement vector. Even though the surface is obtained as a series of circular sections, the results may well represent planar shapes as well, as a result of circular sectors with a long curvature radius. The application to InSAR displacement data, which are notoriously referred to as the sensor's line of sight, implies that the vectors must be decomposed into the vertical and horizontal components and that the real direction of movement on the horizontal plane must be assumed to be generally parallel to the slope direction. The major issues in the applications of this method arise due to the noise of interferometric measurements (especially for slow-moving and N–S-oriented landslides) and when the MPs are not well distributed along the cross-section or are not dense enough, which is not the case for the right-bank slide. While the VIM works best with a calibration derived from independent information on the landslide's thickness (such as an inclinometric measurement), in a case such as this, which is characterized by extreme difficulty in carrying out field investigations and monitoring, this method probably represents one of the most practical ways to form a data-based hypothesis on the geometry and depth of the sliding surface.

The results of the VIM on the right-bank slide along the C-C cross-section (Figure 2 and Figure 3) show the presence of a slightly compound surface, with a major translational mechanism and a depth ranging from 70 to 140 m in the central part of the landslide along the middle longitudinal axis, corresponding to 110 m of equivalent thickness (*i.e.*, the value that provides the same cross-section surface if multiplied by the length of the sliding surface).

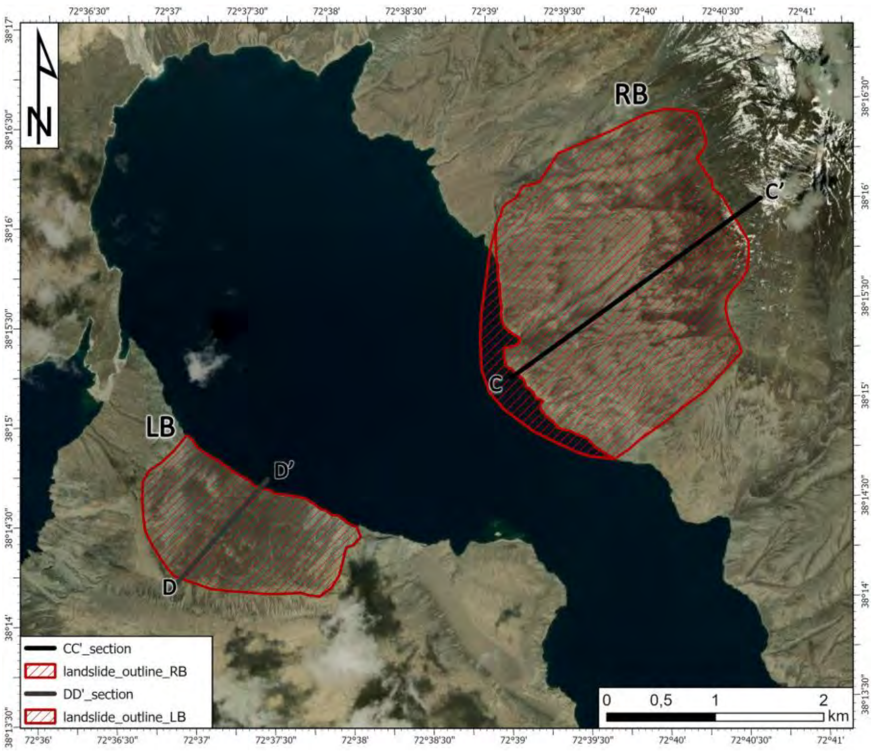

Figure 2: Landslide outline at surface level and submerged cross-section C-C′ for the Right Bank (RB) landslide and cross-section D-D′ for the Left Bank (LB) landslide.

Since the satellite data can also provide information on the area of the landslide ($5.34 \cdot 10^7$ m^2), the emerged volume of the landslide can be estimated to be approximately $1.4 \cdot 10^9$ m^3, thus narrowing down the $0.3 \cdot 10^9$–$2 \cdot 10^9$ m^3 range from the state-of-the-art technique. Interestingly, the displacement data at the foot of the landslide suggest its continuation below the lake level. While it is impossible to make precise assessments with no knowledge of the topography or the interferometric data below Lake Sarez, it can be conservatively assumed that the sliding surface ends with a circular shape (as suggested by some uplifting MPs on the right side of the toe) and that the topographic profile, which is slightly concave, can either continue by keeping the same average slope or with the slope of its most terminal part. In both cases, the landslide, which already visibly narrows the lake by some 500 m, appears to extend for another 275–325 m below the water level, whereas the lake in that location has a width ranging from 1 to 2 km. The total volume of the landslide considering this submerged part would then rise to approximately $1.5 \cdot 10^9$ m$^{3.}$

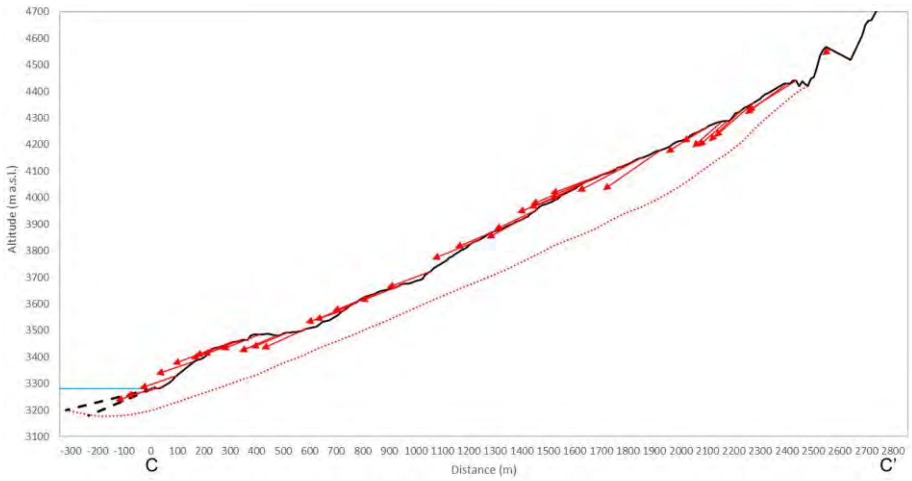

Figure 3: Reconstruction of the sliding surface (red dotted line) of the right-bank slide using the VIM along the C-C′ cross-section. The two black dashed lines represent possible interpolations of the topography below the lake level (in cyan). The red arrows indicate the displacement vectors of the MPs projected along the cross-section.

Similarly, the VIM has been applied to the left-bank landslide (Figure 2 and Figure 4), which exhibits a nearly constant dip marking a translational sliding surface. Since this surface is steeper than the topography, the landslide depth increases downhill, up to 125 m (69 m of equivalent thickness). There is no trace of more horizontal or slower displacement at the base of the slope, which suggests that the landslide continues underwater, although the absence of any changes in the inclination of the movement vectors prevents us from making data-based hypotheses on the submerged part, thus making any estimation of the total volume an undefined underestimation, while the volume of the emerged part is estimated at approximately $2.1 \cdot 10^8$ m^3.

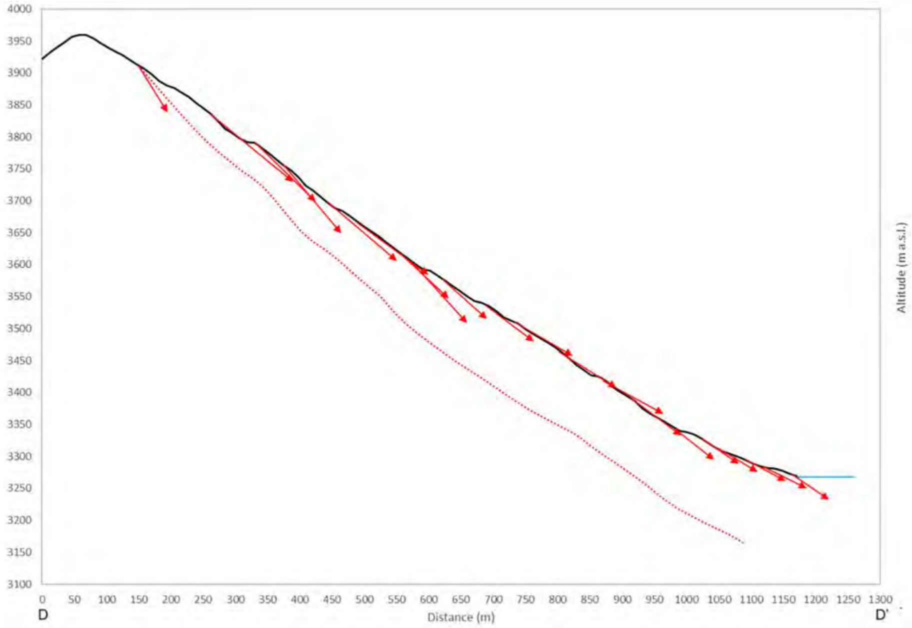

Figure 4: Reconstruction of the sliding surface (red dotted line) of the right-bank slide using the VIM along the C-C′ cross-section. The two black dashed lines represent possible interpolations of the topography below the lake level (in cyan). The red arrows indicate the displacement vectors of the MPs projected along the cross-section.

2) Planned future activities or statement of completion of the Project

Next step of the work will be the analysis and interpretation of other landslides affecting elements at risk by using different satellites approaches and methods. In particular, the focus will be those landslides, whose remoteness makes in situ analysis difficult and deployment of ground sensors unfeasible.

3) Beneficiaries of Project for Science, Education and/or Society

Overall, this project provides authorities continuous information on where, when and how fast the ground is moving. However, prioritization and mitigation of these hazards can be done, starting with issues deemed to be most urgent. Further beneficiaries include Civil Protection Authorities, Regional Authorities, local authorities and any other entities in charge of management of risk posed by landslide. The successful application of InSAR analysis, coupled with the global coverage, and regular acquisition planning ensured by the Sentinel-1 constellation, allowed to deliver very precise and spatially dense information on ground motion. These qualities make it possible to scan wide areas, and to identify unstable zones, especially where remoteness, vastness, and climatic conditions make it difficult to perform field activities. We demonstrate the effectiveness of InSAR in the Lake Sarez in Tajikistan. Here, we identify all possible ground deformation with potential to directly impact on the community and we localize areas within the landslide where ground deformation is more intense for prioritized further investigations.

4) Results

In this section a list of papers, deriving from the activities performed within the IPL project 221 on *PS continuous streaming for landslide monitoring and mapping*, is presented:

The paper "*Continuous, semi-automatic monitoring of ground deformation using Sentinel-1 satellites*" by Federico Raspini et *alii* has been published on Scientific Reports in 2018. https://www.nature.com/articles/s41598-018-25369-w/;

The paper "*Permanent Scatterers continuous streaming for landslide monitoring and mapping: the case of Tuscany Region (Italy)*" by Federico Raspini *et alii* has been published on Landslides in 2019. https://link.springer.com/article/10.1007/s10346-019-01249-w;

The paper "*Monitoring Ground Instabilities Using SAR Satellite Data: A Practical Approach*" by Matteo Del Soldato *et alii* has been published on ISPRS International Journal of Geo-Information in 2019. https://www.mdpi.com/2220-9964/8/7/307;

A chapter entitled "*InSAR data for the continuous monitoring of ground deformation at regional scale*" by Nicola Casagli *et alii*, has been published in the Book "*Advances in Remote Sensing for Infrastructure Monitoring*" edited by Springer. https://link.springer.com/chapter/10.1007/978-3-030-59109-0_3

The paper "*Spatial and temporal characterization of landslide deformation pattern with Sentinel-1*" by Poggi et alii has been published in the book titled Progress in Landslide Research and Technology (P-LRT) Volume 2 Issue, released in 2023. https://link.springer.com/chapter/10.1007/978-3-031-39012-8_15

The paper "Integration of satellite SAR and optical acquisitions for the characterization of the Lake Sarez landslides in Tajikistan" by Nardini *et alii* has been published on Landslides in 2024. https://link.springer.com/article/10.1007/s10346-024-02214-y