Advanced Technologies for Landslides—ATLaS (WCoE 2020–2023)

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Abstract

The UNESCO Chair on Prevention and Sustainable Management of Geo-Hydrological Hazards, University of Florence has been a member of the International Consortium on Landslides (ICL) since 2002. It was designated as one of World Centres of Excellence (WCoE) for Landslide Risk Reduction five times for 2008–2011, 2011–2014, 2014–2017, 2017–2020 and 2020–2023, with a project entitled “Advanced Technologies for Landslides”. In this paper, we describe the activities carried out by the UNESCO Chair as a member of ICL and as WCoE, and its contribution to the risk reduction policies promoted by the 2020 Kyoto Commitment.

Keywords

Landslides • Monitoring • Remote sensing • Risk reduction • Kyoto commitment

1 Introduction

The UNESCO Chair on Prevention and Sustainable Management of Geo-hydrological Hazards (UNESCO Chair) was funded in 2016 at University of Florence (UNIFI), a major academic organization for research and higher education in Italy. The UNESCO chair carries out research and development (R&D) for the prevention and management of landslides, in order to support policies and actions of risk reduction.

The University of Florence (UNIFI) is a founding member of ICL since 2002 and in 2008 was named as a World Centre of Excellence (WCoE) on Landslide Risk Reduction for the triennium 2008–2011 by the Global Promotion Committee of International Programme on Landslides of UN-ISDR. This recognition was reaffirmed four times over for 2011–2014, 2014–2017, 2017–2020 and 2020–2023.

In particular, in the framework of the project ATLaS (Advanced Technologies for LandSlides), the WCoE focuses on research activities concerning the landslide monitoring and early warning through innovative technologies, exploitation of EO (Earth Observation) data and technology to detect, map, monitor and forecast ground deformations, regional forecasting models and on activities related to education and training on landslides risk reduction.

The expertise of the WCoE research team includes remote-sensing techniques and application of space-borne and ground-based SAR interferometry, monitoring ground instabilities and development of early warning systems and GIS-based quantitative models for hazard and risk prediction.

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The group participates in research and technological development projects in several areas of the world, often in active collaboration with international, national, and regional organizations and agencies. Since 2002, the UNESCO Chair has coordinated or has been involved in several ICL/IPL projects and is the proposer of the ICL Italian network that was officially established in December 2018.

Based on the expertise gathered during the last years in the abovementioned activities, the UNESCO Chair can provide its contribution to Kyoto 2020 Commitment for Global Promotion of Understanding and Reducing Landslide Disaster Risk that signed the Kyoto Commitment during the 2019 ICL-IPL Conference which at UNESCO Headquarters, Paris, on 16–19 September 2019 (Sassa 2018a, b, c; 2019).

2 Research Activity of WCoE

The WCoE ATLaS project focuses on the three main activities structured in three packages:

WP1—Monitoring unstable slopes and integration of different techniques for the set-up of early warning systems.

WP2—EO data for mapping, characterization and monitoring of landslides.

WP3—Landslide risk assessment and regional landslide forecasting models.

2.1 WP1

This activity focuses on the application of innovative monitoring techniques to estimate the deformational evolution of the landslide events (in space and time) and to implement the most suitable operational early warning systems (EWS), according to different critical situations (Carlà et al. 2017, 2019a, b; Frodella et al. 2018; Bardi et al. 2017). Several sites are monitored in Italy and all of them were monitored by using advanced sensors and portable instrumentations as ground-based synthetic aperture radar interferometers (GB-InSAR), terrestrial laser scanning (LIDAR), satellite interferometry (PS-InSAR), UAVs equipped with different sensors, GPS antennas, infrared thermography and traditional instrumentation (e.g. strain gauges, inclinometers, piezometers) (Del Soldato et al. 2018a; Di Traglia et al. 2018; Rossi et al. 2018; Casagli et al. 2017; Frodella et al. 2017; Lombardi et al. 2017; Carlà et al. 2019a, b).

As the use of these techniques has proliferated over the years, the advantages provided by the implementation of long-term monitoring campaigns for understanding the mechanism of complex slope instabilities have become increasingly apparent. One such example is represented by the Ruinon rockslide (Central Italian Alps), a ~ 30 million m^3 highly disaggregated translational slide in phyllites and blocky/chaotic debris (Crosta and Agliardi 2003), which has been continuously monitored for more than a decade by means of a ground-based radar interferometer (Crosta et al. 2017). Phases of intense reactivation in the mid-lower part of the slide area have repeatedly caused the closure of a road travelling along the adjacent valley floor and the consequent isolation of a nearby village. For instance, in the summer of 2019, surface velocities locally increased to unprecedented values and often exceeded 1 m/day.

Most of the instrumentation installed on the slide area (mainly wire extensometers and borehole inclinometers) was therefore progressively damaged, leaving the GB-InSAR system as the sole operational tool for quantifying the slope displacements in space and time. This large set of data was exploited to directly or indirectly derive an updated assessment of the thickness of upper debris affected by greater deformation; the differences in deformation behaviour at different slide locations and depths; and the nature of hydrological forcing behind the recent reactivation phases (Carlà et al. 2021). In particular, slope displacements were combined with groundwater level measurements from two standpipe piezometers located behind the upper limit of the slide area. Readings at one of the two standpipe piezometers were carried out at irregular intervals since April 2012, while the second instrument was put into operation in June 2017 and equipped with a data logger for automatic piezometric monitoring at a fixed interval of 30 min.

It was observed that velocities cyclically increased up to their maximum yearly value in late spring or early summer, closely following sharp rises of groundwater level—as most likely determined by the superimposition of rainfalls and seasonal snowmelt at higher elevations (Fig. 1).

In addition, reactivations of secondary importance were revealed to occasionally occur during the fall, when heavy rainfalls were associated with small temporary reversals of the otherwise decreasing trend of groundwater level. Eventually, a clear exponential-like correlation between the yearly peak of surface velocity and the yearly peak of groundwater level was identified (Carlà et al. 2021), highlighting how even small variations of the latter variable may profoundly alter the evolutionary trends of complex slope instabilities. The experience gained at Ruinon also supports the proposition that long-term GBInSAR monitoring may be an essential tool in the case of highly disaggregated and rapidly evolving alpine rockslides that being subject to recurrent reactivations and associated large displacements would otherwise be difficult to investigate owing to the difficult accessibility of the site. The instrument was in fact essential for setting up a management strategy for the adjacent road at risk based on a scale of differentiated early-warning thresholds.

More specifically, by exploiting the spatial properties of interferometric data, the slide area was divided into several

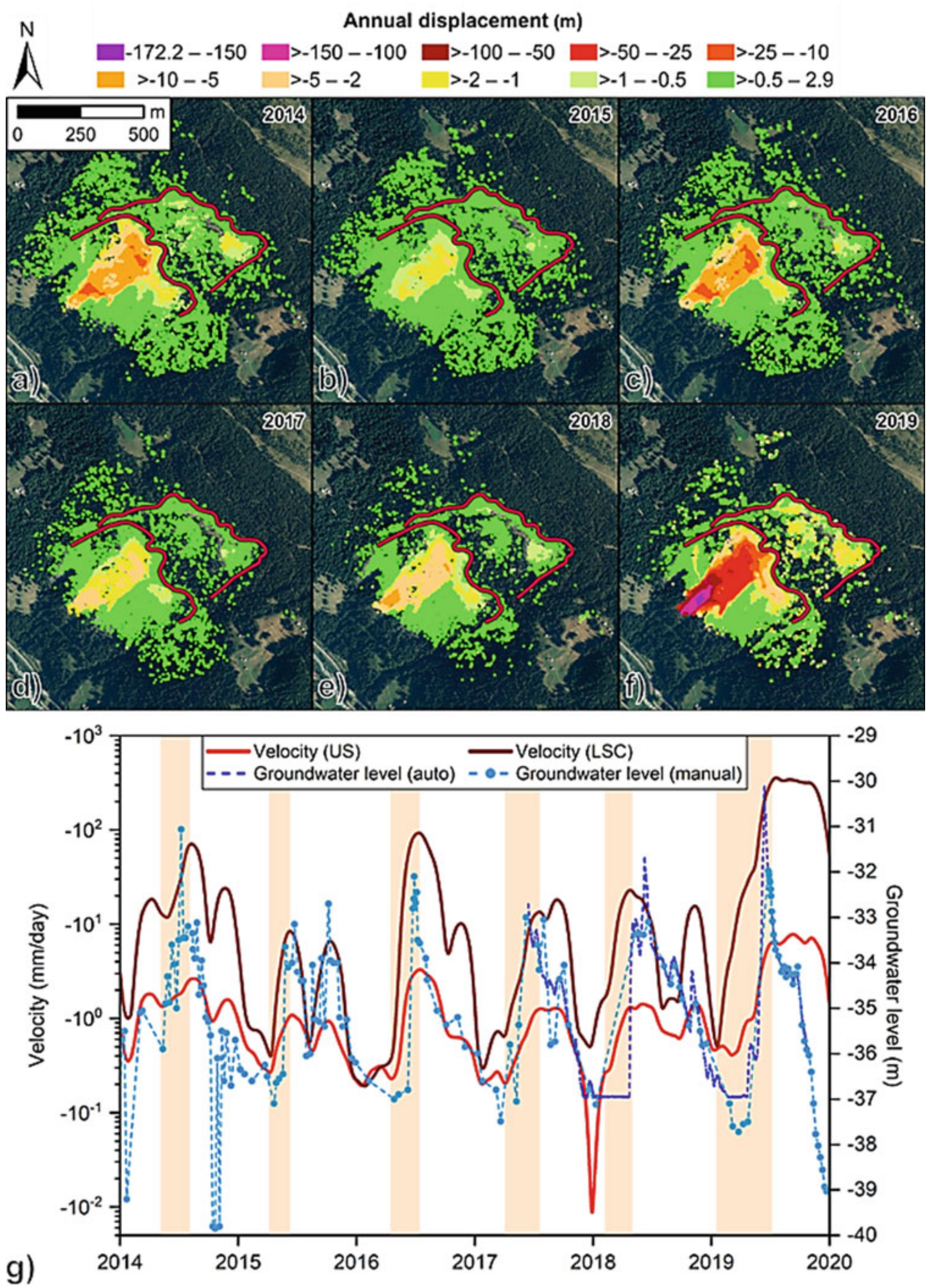

Fig. 1 Annual cumulative displacements of the Ruinon slide area measured by the GBInSAR system from 2014 to 2019 (a–f), and dependency between slide velocity and groundwater level (h). US and LSC are abbreviations for Upper Scarp and Lower Scarp, respectively, which are the two main geomorphological features within the Ruinon slide area (see red lines in panels a–f). Accordingly, values of US velocity derive from averaging all pixels located between the upper and lower scarp, whereas values of LSC velocity derive from averaging all pixels located downslope of the lower scarp. In g), yellow areas delimit the periods of sustained increase of velocities in late spring and/or early summer

sub-sectors, each one having a characteristic deformation behaviour. The presence of multiple mutually interacting blocks is in fact common in these types of landslides because of local variations in material composition, rupture surface (s) geometry, and/or degree of slope damage.

2.2 WP2

This activity is devoted to the application of high resolution EO data for the ground deformation mapping and monitoring with millimetric precision, from local to regional scales. The final aim is a satellite surveillance system based on all the Earth Observation data (radar hyperspectral) available from several constellations of satellites.

WP2 activities deal with the development of satellite surveillance system exploiting Earth Observation (EO) data (radar, multi- and hyperspectral data) for the identification, mapping and monitoring of ground deformations associated with landslides from local to regional scales (Solari et al. 2020). In particular, advanced multi-temporal InSAR techniques are successfully exploited for detecting and characterizing slow-moving ground surface displacements thanks to their millimetre precision and wide area coverage. Applications rely on historical SAR archives at medium resolution (e.g., ERS and ENVISAT, RADARSAT images) and on data from currently operative satellites at high resolution (e.g., COSMO-SkyMed constellation). Moreover, nowadays the availability of regular and systematic Sentinel-1 SAR data acquisitions with short revisiting time (e.g., 12 days) combined with advances in InSAR processing algorithm across time allows not only the mapping of geo-hydrological phenomena (for instance, for updating pre-existing landslide inventories), but also to perform recurring monitoring of the deformative scenario at a regional scale (Raspini et al. 2018; Bianchini et al. 2018).

An innovative monitoring system based on the systematic processing of current Sentinel-1 data has been set up and tested in Italy on Tuscany Region (since 2016), Valle d'Aosta (since 2018) and Veneto Region (since 2019) (Fig. 2a). Such satellite-based services rely on PSI data elaborated through SqueeSAR algorithm (Ferretti et al. 2011) and consist in two activities named "PS mapping" and "PS monitoring".

The "PS mapping" activity exploited PSI-based ground deformation maps and semi-automatic hotspot-like analysis to map the most relevant long-term active deformational processes on the whole regional territory, as they represent the fastest moving areas, e.g., mainly related to already known or not known landslides (Fig. 2b) (Bianchini et al. 2021).

The "PS monitoring" activity is based on regularly updated terrain deformation maps from systematic processing of Sentinel-1 data stack (e.g., after every new satellite acquisition: 12 days). In more detail, once a new Sentinel-1 image is available, it is automatically downloaded and added to the existing SAR archive and the new data stack is entirely reprocessed to generate new ground deformation maps, providing an updated view of the regional deformational scenario (Fig. 2c) (Confuorto et al. 2021). The time series of displacement of each radar benchmark is systematically analyzed to promptly detect any velocity-change in the deformation pattern, in order to identify the so-called Anomalous Point (AP), e.g., measurement PSI points that show trend variations or abrupt velocity changes (e.g. related to landslide accelerations) in the time series (Raspini et al. 2019).

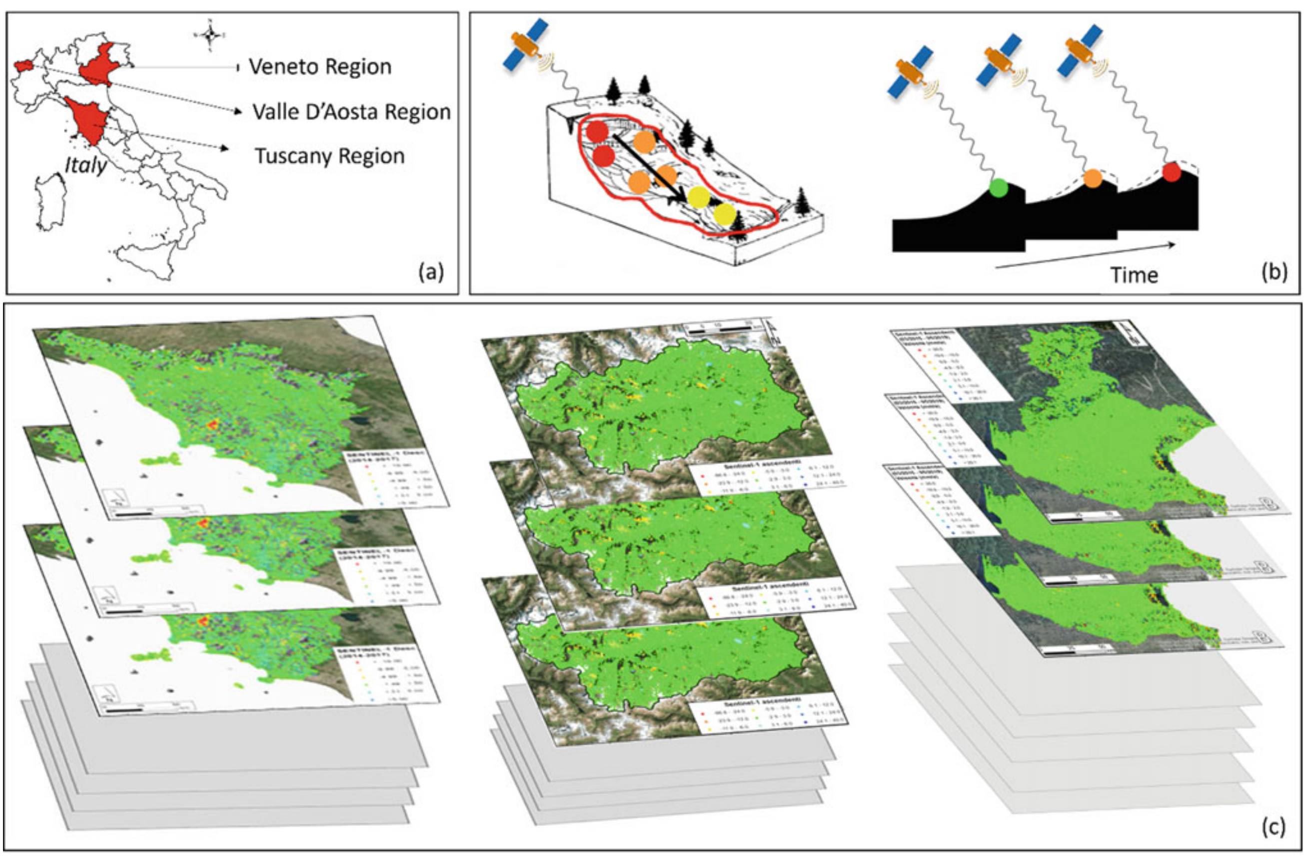

Fig. 2 Satellite-based services at regional scale in Italy: **a** Location of Tuscany, Valle d'Aosta, Veneto Region in Italy; **b** Example of "PS mapping" activity to highlight highest ground motion rates and of "PS monitoring" activity to periodically scan the territory across time; **c** Sketch of systematically updated ground deformation maps based on Sentinel-1 PSI data of Tuscany, Valle d'Aosta, Veneto Region

This near-real-time monitoring of ground instability at regional scale has demonstrated to be very useful tool as it scans periodically the territory and rapidly points out the fastest deformations and most hazardous sites over the entire regional area. The sites where significant AP are retrieved need to be reported and can be notified to the regional authority for in-situ validation or for further analysis within risk mitigation strategies.

2.3 WP3

WP3 activities focus on developing operational and pre-operational regional scale landslide early warning systems (RLEWS). This objective is achieved by a multiscale approach integrating different methodologies, including statistical rainfall thresholds, landslide susceptibility assessment, and distributed physically based modelling.

To date, statistical rainfall thresholds are the state-of-the art technique used for RLEWS (Segoni et al. 2018a). ATLaS is active on this topic with several research projects aimed at: (i) developing innovative approaches, as the use of 3D rainfall thresholds that are operated daily by the Emilia Romagna Region Civil Protection (Rosi et al. 2021) (Fig. 3); (ii) transferring consolidated approaches (namely, the models MaCumBA and SIGMA) to new test sites (including developing countries), customizing the model design and RLEWS settings according to the technical constraints and the physical features encountered in the new sites (Abraham et al. 2020a); (iii) hybridizing the rainfall threshold approach with other methodologies such as landslide susceptibility maps, to get a finer spatial resolution (Segoni et al. 2018b) or by integrating slope-scale instrumental monitoring in the rainfall threshold-based RLEWS algorithms to reduce false alarms (Abraham et al. 2020b).

With respect to physically based modelling, to date this approach is used for early warning only at the slope scale or in small areas. In contrast, the efforts of ATLaS are mainly aimed at applying this approach over very wide areas (e.g., hundreds or thousands of square kilometres) to establish prototypal RLEWS for rainfall-induced shallow landslides.

To pursue this objective, a High-Resolution Slope Stability Simulator (HIRESS—Rossi et al. 2013) has been developed and for its implementation, several issues have been addressed. One of the main constraints is the difficulty in coping with the high spatial variability of the values assumed by geotechnical and hydrological parameters like cohesion, internal friction angle, hydraulic conductivity and so on, which are inputs to the slope stability model.

To this end, efforts are continuously accomplished to measure such parameters in as many sample points as possible, assessing the statistical distribution of their values over lithological or geomorphological units and reproducing the same variability with a Monte Carlo approach when feeding the slope stability model (Tofani et al. 2017; Salvatici et al. 2018).

The research about the input parameters also includes the stabilizing effect exerted by roots systems. To this aim HIRESSS formulation has been modified to include the additional root cohesion and studies have been undertaken to characterize how to correctly parameterize this additional factor (Cuomo et al. 2021; Masi et al. 2021). In addition, the application to operational RLEWS demands a robust criterium to interpret the model outputs and to convert them in warnings. The raw outputs of the model, which consists of slope failure probability at the pixel level, are aggregated over larger spatial units (e.g., slope units or small basins) according to a criterium that is necessarily very site specific and dependent on the needs of the end-users. Therefore, a semi-automated tool has been developed to objectively identify the criterium that maximizes the correct predictions while minimizing the errors (Bulzinetti et al. 2021). With these features, it has been possible to apply HIRESSS to several Italian test sites ranging from 18 km^2 to 3500 km^2 in areal extension, demonstrating a promising potential for a pre-operational use.

The activities pursued in WP3 allow the setting up of RLEWSs with a multi-tier framework: the rainfall thresholds technique allows for warnings differentiated over large alert, while with a combined approach using rainfall thresholds and susceptibility maps the spatial resolution can be refined up to the municipality level (whose width is typically in the order of tens of square kilometers); and finally finer-spatial resolution warnings can be obtained with the physically based modeling, which starts from landslide triggering probabilities at the pixel level (typically, 10 m cell size) which are aggregated to issue warnings over spatial units whose extension is typically on the order of 1 km^2.

3 IPL Projects

Since its involvement in ICL, the UNESCO Chair has proposed several IPL projects. Currently, the active projects are:

- IPL196: Development and applications of a multi-sensors drone for geohazards monitoring and mapping, Proposer: Veronica Tofani
- IPL198: Multi-scale rainfall triggering models for Early Warning of Landslides (MUSE), Proposer: Filippo Catani
- IPL 221: PS continuous streaming for landslide monitoring and mapping, Proposer: Federico Raspini and Silvia Bianchini

IPL 196 has the objective to test the applicability of a multi-sensors drone for the mapping and monitoring of geohazards. In particular, the project has two specific

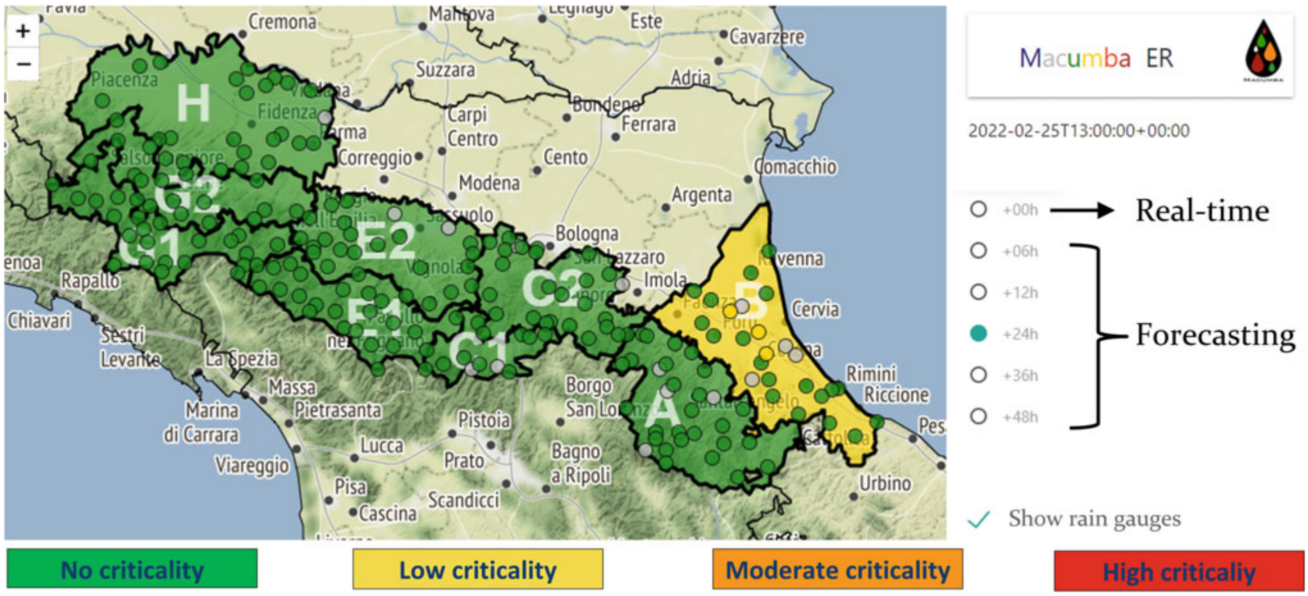

Fig. 3 Overview of the web interface of the RLEWS based on 3D rainfall thresholds, which is currently operated in the hilly and mountainous sectors of Emilia Romagna region

objectives: (i) development of the drone, sensors, safety and automation and (ii) application of the drone as a platform of integrated sensors (multispectral sensor, visible light camera, infrared camera and LIDAR) for the mapping and monitoring of geohazards.

IPL 198 aims at the enhancement of knowledge and methodologies related to the integration of landslide prediction models at different scales to build an effective operational multi-scale system for real-time early warning of rainfall triggered mass movements.

The objective of IPL 221 is to perform the transition from historical analysis of radar satellite image archives to real-time monitoring of ground deformation at regional scale using radar satellite scenes. To accomplish this objective, the short revisiting time and regularity of acquisitions of Sentinel-1 constellation of SAR (Synthetic Aperture Radar) satellite sensors were exploited.

The activity reports are regularly published in the ICL IPL website, while their outcomes have been published in the *Landslides* journal (IPL-196, Rossi et al. 2018; IPL-198, Tofani et al. 2017; IPL-221, Raspini et al. 2019).

4 Contribution to Kyoto 2020 Commitment

As a member of the International Consortium on Landslides (ICL) the UNESCO Chair is signatory of the ISDR-ICL Sendai Partnership 2015–2025 (Sassa 2015). The Sendai Partnership was accepted and signed during the 3rd United Nations World Conference on Disaster Risk Reduction (WCDRR) in Sendai (March 11-15th 2015). During the 4th World Landslide Forum (WLF4), held in Ljubljana from May 29-June 2 2017, the Chair has contributed to the "Ljubljana Declaration" on Landslide Risk Reduction, together with all of the participants to the forum, as a further commitment on the part of the global landslide community to the Sendai Framework for Disaster Risk Reduction 2015–2030 (Sassa 2017).

The Chair has been signatory and promoter of the Kyoto 2020 Commitment (KLC2020) for global promotion of understanding and reducing landslide disaster risk, during the 2019 ICL-IPL Conference at UNESCO Headquarters, Paris, on 16–19 September 2019. The Kyoto 2020 Commitment is a duty to the Sendai Landslide Partnerships 2015–2025, the Sendai Framework for Disaster Risk Reduction 2015–2030, the 2030 Agenda Sustainable Development Goals, the New Urban Agenda, and the Paris Climate Agreement (Sassa 2019).

The UNESCO Chair, in line with the activity carried out in the framework of the WCoE and IPL projects, will particularly contribute to some priority actions of Kyoto 2020 Commitment (Sassa 2018c):

Action 1: Promote the development of people-centered early warning technology for landslides with increased precision and reliable prediction both in time and location, especially in a changing climate context.

Action 2: Advance hazard and vulnerability mapping, including vulnerability and risk assessment with increased precision, as well as reliability as part of multi-hazard risk identification and management.

Action 3: Improve the technologies for monitoring, testing, analyzing, simulating, and effective early warning for landslides suitable for specific regions considering natural, cultural, and financial aspects.

Action 6: Investigate the effect of climate change on rainfall-induced landslides and promote the development of effective rainfall forecasting models to provide earlier warning and evacuation especially in developing countries.

Action 9: Foster new initiatives to study research frontiers in understanding and reducing landslide disaster risk by promoting joint efforts by researchers, policy makers and funding agencies.

In the framework of the contribution to policies for risk reduction, the UNESCO Chair contributed to the organization of the 5th World Forum on landslides (WLF5), which due to the COVID-19 pandemic was held in mixed virtual and in-person mode from November 2–6, 2021 in Kyoto (Japan) (Fig. 5).

The UNESCO Chair is currently organizing the 6th World Landslide Forum, which will be held in Florence from the 14th to the 17th of November 2023 (Fig. 4). The Forum will have the theme "Landslide Science for Sustainable Development." The event is jointly organized by the International Consortium on Landslides (Kyoto, Japan), the International Programme on Landslides (IPL) and the UNESCO Chair on Prevention and Sustainable Management of Geohydrological Hazards at the University of Florence.

The Forum is focused on Landslide Science for Sustainable Development, as a contribution to the Kyoto 2020 Commitment for global promotion of understanding and reducing landslide disaster risk (KLC2020).

The aim of the Forum is to provide a platform to achieve a fruitful cooperation among landslide researchers to define shared priority actions for landslide risk reduction on a global scale. The Forum will deal with the main aspects related to landslide analysis: landslide monitoring and early warning, landslide modelling, landslide hazard and risk assessment, mitigation techniques, landslide triggering mechanism and climate change. In line with the 2030 Agenda and the Sustainable Development Goals, the Forum will be a sustainable event. The Forum is hosted in Florence city center, with everything at walking distance and no printed material. The Forum programme and proceedings will be distributed to the participants in electronic format.

The Forum will focus on 6 main themes:

- Theme 1: Kyoto Landslide Commitment for sustainable development
- Theme 2: Remote sensing, monitoring and early warning
- Theme 3: Testing, modeling, and mitigation techniques
- Theme 4: Mapping, hazard, risk assessment and management
- Theme 5: Climate change, extreme weather, earthquakes, and landslides
- Theme 6: Progress in landslide science and applications

5 ICL Italian Network

The ICL Italian network was officially established in December 2018 during the ICL-IPL Conference, held in Kyoto on 1–4 December 2018. ICL Italian network, proposed and coordinated by the UNESCO Chair on Prevention

Fig. 4 Home page of the 6th World Landslide Forum Website (https://wlf6.org)

and Sustainable Management of Geo-hydrological hazards, currently counts 13 ICL members (7 Full members, 5 Associates and 1 Supporter) (Casagli and Tofani 2018).

The general objective of the Italian ICL Network is to contribute at a national level to the Sendai Partnership for Disaster Risk Reduction 2015–2025 for the national promotion of understanding, prevention and sustainable management of landslide risk disaster, for the safety of human life, society and the environment and to the Kyoto Commitment 2020 for Global Promotion of Understanding and Reducing Landslide Disaster Risk.

The Italian ICL network on landslides is formed by well-established scientific institutions, recognized both at national and international levels, with a long-dated expertise on landslide research for hydrogeological hazard assessment and landslide disaster risk reduction. The network partners have also developed strong and widespread synergies with national, regional and local administrations, technical stakeholders, and end-users for developing policies and procedures for landslide disaster prevention, management and mitigation.

On March 26, 2021, a virtual meeting of the Italian Network of ICL took place. During the meeting, the activities carried out by ICL were discussed with reference to the organization of WLF5 and WLF6. It was also discussed how to improve networking activities between the Italian partners of ICL through the strengthening of joint research and training activities. During the meeting, Dr. Claudio Margottini was appointed as coordinator of the Italian Network for the next three years.

References

Abraham MT, Satyam N, Kushal S, Rosi A, Pradhan B, Segoni S (2020a) Rainfall threshold estimation and landslide forecasting for Kalimpong India Using SIGMA model. Water 12(4):1195

Abraham MT, Satyam N, Bulzinetti MA, Pradhan B, Pham BT, Segoni S (2020b) Using field-based monitoring to enhance the performance of rainfall thresholds for landslide warning. Water 12 (12):3453

Bardi F, Raspini F, Frodella W, Lombardi L, Nocentini M, Gigli G, Morelli S, Corsini A, Casagli N (2017) Monitoring the rapid-moving reactivation of earth flows by means of GB-InSAR: the April 2013 Capriglio landslide (Northern Appennines, Italy). Remote Sens 9(2):165

Bianchini S, Raspini F, Solari L, Del Soldato M, Ciampalini A, Rosi A, Casagli N (2018) From picture to movie: twenty years of ground deformation recording over Tuscany region (Italy) with satellite InSAR. Frontiers Earth Sci, 177

Bianchini S, Solari L, Bertolo D, Thuegaz P, Catani F (2021) Integration of satellite interferometric data in civil protection strategies for landslide studies at a regional scale. Remote Sens 13(10):1881

Bulzinetti MA, Segoni S, Pappafico G, Masi EB, Rossi G, Tofani V (2021) A tool for the automatic aggregation and validation of the results of physically based distributed slope stability models. Water 13(17):2313

Carlà T, Intrieri E, Di Traglia F, Nolesini T, Gigli G, Casagli N (2017) Guidelines on the use of inverse velocity method as a tool for setting alarm thresholds and forecasting landslides and structure collapses. Landslides 14(2):517–534

Carlà T, Tofani V, Lombardi L, Raspini F, Bianchini S, Bertolo D, Thuegaz P, Casagli N (2019a) Combination of GNSS, satellite InSAR, and GBInSAR remote sensing monitoring to improve the understanding of a large landslide in high alpine environment. Geomorphology 335:62–75

Carlà T, Nolesini T, Solari L, Rivolta C, Dei Cas L, Casagli N (2019b) Rockfall forecasting and risk management along a major transportation corridor in the Alps through ground-based radar interferometry. Landslides 16:1425–1435

Carlà T, Gigli G, Lombardi L, Nocentini M, Carlà T (2021) Monitoring and analysis of the exceptional displacements affecting debris at the top of a highly disaggregated rockslide. Eng Geol 294:106345

Casagli N, Frodella W, Morelli S, Tofani V, Ciampalini A, Intrieri E, Raspini F, Rossi G, Tanteri L, Lu P (2017) Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring and early warning. Geoenviron Disasters 4(9):27p

Confuorto P, Del Soldato M, Solari L, Festa D, Bianchini S, Raspini F, Casagli N (2021) Sentinel-1-based monitoring services at regional scale in Italy: state of the art and main findings. Int J Appl Earth Obs Geoinf 102:102448

Crosta GB, Agliardi F (2003) Failure forecast for large rockslides by surface displacement measurements. Can Geotech J 40:176–191

Crosta GB, Agliardi F, Rivolta C, Alberti S, Dei Cas L (2017) Long-term evolution and early warning strategies for complex rockslides by real-time monitoring. Landslides 14:1615–1632

Cuomo S, Masi EB, Tofani V, Moscariello M, Rossi G, Matano F (2021) Multiseasonal probabilistic slope stability analysis of a large area of unsaturated pyroclastic soils. Landslides 18(4):1259–1274

Del Soldato M, Riquelme A, Bianchini S, Tomàs R, Di Martire D, De Vita P, Moretti S, Calcaterra D (2018) Multisource data integration to investigate one century of evolution for the Agnone landslide (Molise, southern Italy). Landslides 78:2387–2408

Di Traglia F, Nolesini T, Ciampalini A, Solari L, Frodella W, Bellotti F, Fumagalli A, De Rosa G, Casagli N (2018) Tracking morphological changes and slope instability using spaceborne and ground-based SAR data. Geomorphology 300:95–112

Ferretti A, Fumagalli A, Novali F, Prati C, Rocca F, Rucci A (2011) A new algorithm for processing interferometric data-stacks: SqueeSAR. IEEE Trans Geosci Remote Sens 49:3460–3470

Frodella W, Ciampalini A, Bardi F, Salvatici T, Di Traglia F, Basile G, Casagli N (2018) A method for assessing and managing landslide residual hazard in urban areas. Landslides 15:183–197

Frodella W, Gigli G, Morelli S, Lombardi L, Casagli N (2017) Landslide mapping and characterization through infrared thermography (IRT): suggestions for a methodological approach from some case studies. Remote Sens 9(12):1281

Masi EB, Segoni S, Tofani V (2021) Root reinforcement in slope stability models: a review. Geosci 11(5):212

Raspini F, Bianchini S, Ciampalini A, Del Soldato M, Solari L, Novali F, Del Conte S, Rucci A, Ferretti A, Casagli N (2018) Continuous, semi-automatic monitoring of ground deformation using sentinel-1 satellites. Sci Rep 8(1):1–11

Raspini F, Bianchini S, Ciampalini A, Del Soldato M, Montalti R, Solari L, Casagli N (2019) Persistent scatterers continuous streaming for landslide monitoring and mapping: the case of the Tuscany region (Italy). Landslides 16(10):2033–2044

Rosi A, Segoni S, Canavesi V, Monni A, Gallucci A, Casagli N (2021) Definition of 3D rainfall thresholds to increase operative landslide early warning system performances. Landslides 18(3):1045–1057

Rossi G, Catani F, Leoni L, Segoni S, Tofani V (2013) HIRESSS: a physically based slope stability simulator for HPC applications. Nat Hazards Earth Syst Sci 13:151–166
Rossi G, Tanteri L, Tofani V, Vannocci P, Moretti S, Casagli N (2018) Multitemporal UAV surveys for landslide mapping and characterization. Landslides 15(5):1045–1052
Salvatici T, Tofani V, Rossi G, D'Ambrosio M, Tacconi Stefanelli C, Masi EB, Rosi A, Pazzi V, Vannocci P, Petrolo M, Catani F, Ratto S, Stevenin H, Casagli N (2018) Application of a physically based model to forecast shallow landslides at a regional scale. Nat Hazard 18(7):1919–1935
Sassa K (2015) ISDR-ICL Sendai Partnerships 2015–2025 for global promotion of understanding and reducing landslide disaster risk. Landslides 12(4):631–640
Sassa K (2017) The 2017 Ljubljana declaration on landslide risk reduction and the Kyoto 2020 commitment for global promotion of understanding and reducing landslide disaster risk. Landslides 14 (4):1289–1296
Sassa K (2018a) Zero draft of the Kyoto 2020 commitment for global promotion of understanding and reducing landslide disaster risk. Landslides 15(3):389–392
Sassa K (2018b) The Fifth world landslide forum—implementing and monitoring the ISDR-ICL Sendai partnerships 2015–2025 - organization plans, themes and sessions. Landslides 15(3):617–620
Sassa K (2018c) ICL journal "Landslides" and the Kyoto 2020 commitment. Landslides 15(9):1705–1712
Sassa K (2019) The fifth world landslide forum and the final draft of the Kyoto 2020 commitment. Landslides 16(2):201–221
Segoni S, Piciullo L, Gariano SL (2018a) A review of the recent literature on rainfall thresholds for landslide occurrence. Landslides 15(8):1483–1501
Segoni S, Tofani V, Rosi A, Catani F, Casagli N (2018b) Combination of rainfall thresholds and susceptibility maps for dynamic landslide hazard assessment at regional scale. Front Earth Sci 6:1–11
Solari L, Del Soldato M, Raspini F, Barra A, Bianchini S, Confuorto P, Casagli N, Crosetto M (2020) Review of satellite interferometry for landslide detection in Italy. Remote Sensing 12(8):1351
Tofani V, Bicocchi G, Rossi G, Segoni S, D'Ambrosio M, Casagli N, Catani F (2017) Soil characterization for shallow landslides modeling: a case study in the Northern Apennines (Central Italy). Landslides 14(2):755–770