multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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Technical references

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* PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

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ABSTRACT

This report summarizes the scientific research activities carried out in the period January – July 2023 by the Task 2.3.1 of the Work Package 2.3 inside the vertical spoke VS2 "Ground Instabilities" of the Extended Partnership RETURN.

The research activities of the task have been devoted to the analysis of the processes preparatory to ground instabilities. This analysis was based on the learning from on site and remote sensing monitoring data collected on already deeply studied and analyzed case studies, or Learning Examples (LEs), supplied by the partner institutions.

This learning phase had the objective of building a Rationale for preparatory processes to be used as input to the Proof of Concept (PoC). This phase has been articulated in three stages:

i) Inventory of Learning Examples (LEs);
ii) Individuation of the preparatory processes analyzed in each LE;
iii) Definition of a Rationale for each identified preparatory process based on the available LEs;

which are described in detail in the PART A of the deliverable. In particular, fifteen preparatory processes were identified from the inventory of LEs and a tool for the rationalization of each process was derived from each LE.

Beside the learning from monitoring data, also machine learning approaches are included in the statistics and discussion of this deliverable, to report in parallel about the advancements of the Task 2.3.3.

The deliverable also includes a PART B, in which the workflow and activities of WP 2.4 are summarized. WP4 followed the same three-stage approach for the analysis of trigger and multihazard processes. The LEs of the work package in which monitoring data and processing techniques are collected and applied are presented here, since no related DVs were due at this project month.

In both WPs, the analysis of the LEs led to the definition of operative tools that will be merged and organized in a Rationale of each WP (due for November 2023). The Rationale will serve as a base for the construction of the PoC in the next year of the project.

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1. Introduction

This report summarizes the scientific research activities carried out in the period January – July 2023 by the **Task 2.3.1** "*Natural onshore and offshore field laboratories for remote and in-site monitoring of environmental forcings and deformation responses. Validation of cutting-edge sensors, technological devices, and techniques to identify and monitor precursor signals of ground instability, as well as the occurrence of ongoing deformations"* (hereinafter referred to as **TK1**) of the **Work Package 2.3** "*Monitoring & Modelling: toward a digital twin of ground instabilities effects*" (hereinafter referred to as **WP3**) inside the vertical spoke **VS2** "*Ground Instabilities"* of the Extended Partnership RETURN.

The general frame of **RETURN** (multi-Risk sciencE for resilienT commUnities undeR a chaNging climate) is devoted to the study of natural risks and their impacts on the anthropic and the natural context with particular attention to the effects related to climatic drivers. A detailed description of the project is out of the scope of this report and can be found at the link https://www.fondazionereturn.it/. Here it is worth recalling that, among the several natural phenomena addressed, the attention of VS2 focuses on ground instabilities, specifically landslides, sinkholes, subsidence, and liquefaction.

VS2 involves 41 official researchers (13 females, 28 males) and 107 affiliated researchers (35 females, 72 males), for a total of 148 researchers from ENEA, OGS, POLITO, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPA, UNIPD and UNIROMA1. From the project start, 17 researchers (RTDA) have been enrolled on RETURN (8 females, 9 males), together with 6 PhD candidates (4 females, 2 males) and 3 fellowships (1 female, 2 males).

As a premise and recall, the architecture and content of VS2 WPs related to the research activity's core is briefly summarized. The distinction between the different core WPs is made on the basis of the different factors/processes controlling ground instabilities targeted and analyzed in each of them. In particular:

- WP2 focuses on the detection and analysis of **PREDISPOSING** factors to ground instabilities.
- WP3 targets **PREPARATORY** factors to ground instabilities.
- WP4 is centered on **TRIGGERING** and multiple geohazards cascading scenarios (**MULTIHAZARD**).

The distinction between predisposing, preparatory and triggering factors/processes is based on the temporal scale of action. Predisposing factors are considered to be invariable at the scale of observation, while preparatory factors exhibit cyclical changes or trends during the same period. Finally, the trigger acts within a very short and well-defined time frame. Based on this definition, in the view of restitution of scenarios, the preparatory factors provide a "time dimension" to the quantitative evaluations of effects, allowing to take into account different intensity of time-dependent variables in the analytical/quantitative models.

Inside the WP3, the different task activities carried out between 01/01/2023 and 31/07/2023 have been devoted to the analysis of the processes preparatory to ground instabilities. This analysis was based on the learning from already deeply studied and analyzed case studies, or Learning Examples (LEs).

Following the Executive Working Plan of RETURN, which was delivered as Milestone 2.1 on 31 December 2022, the institutions cooperating to the WP3 objectives are ENEA, OGS, POLITO, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPA, UNIPD and UNIROMA1. WP3 leader and coordinator is Salvatore Martino (UNIROMA1), TK1 leader is Chiara Colombero (POLITO), TK2 leader is Filippo Zaniboni (UNIBO), TK3 is leaded by Filippo Catani (UNIPD).

All the WP3 tasks followed the same workflow. The distinction between the task activities has been done on the basis of the applied learning methods, in particular:

- TK1: learning from on site and remote sensing monitoring data;
- TK2: learning from numerical modeling and simulations;
- TK3: machine learning techniques.

The learning phase had the objective of building a Rationale for preparatory processes to be used as input to the Proof of Concept (PoC). This phase has been articulated in three stages:

iv) Inventory of Learning Examples (LEs).
v) Individuation of the preparatory processes analyzed in each LE.
vi) Definition of a Rationale for each process based on the available LEs.

These three stages and the related research outcomes are summarized in the **PART A** of the present document for **TK1** (learning from monitoring data). ***If the monitoring data are processed and analyzed through machine learning techniques, the activity outcomes of TK3 are further reported and included in the discussion.*** The results of TK2 (learning from numerical modeling) are detailed in a separate deliverable (DV 2.3.3).

WP4 followed the same three-stage approach for the analysis of trigger and multihazard. As a consequence, the **PART B** of the present deliverable is dedicated to the ***activities of WP4 related to monitoring data and processing techniques***. Following a similar approach, WP4 activities related to numerical modeling of trigger and multihazard can be further found in DV 2.3.3. This offers the opportunity also to report about the WP4 advancements, since no related DVs are due at this project month.

Following the Executive Working Plan of RETURN, which was delivered as Milestone 2.1 on 31 December 2022, the institutions cooperating to the WP4 objectives are ENEA, OGS, POLITO, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPA, UNIPD and UNIROMA1. WP4 leader is Filippo Catani (UNIPD), TK1 leader is Silvia Ceramicola (OGS), TK2 leader is Carlo Esposito (UNIROMA1), TK3 is leaded by Giovanni Forte (UNINA) and TK4 by Simone Bizzi (UNIPD). WP4 task articulation is made on the basis of the context in which ground instabilities develop: coast and near-shore areas (TK1), mountain and hilly areas (TK2), plains (TK3). TK4 of WP4 is devoted to the quantification of the uncertainty for trigger evaluation.

Despite the different WP organization, both WP3 and WP4 followed the same approach for the study of preparatory processes and trigger/multihazard. The timeline of the WPs is summarized in Figure 1. The analysis of the LEs led to the definition of operative tools that will be merged and organized in a Rationale of each WP (due for November 2023). The Rationale will serve as a base for the construction of the PoC in the next year of the project.

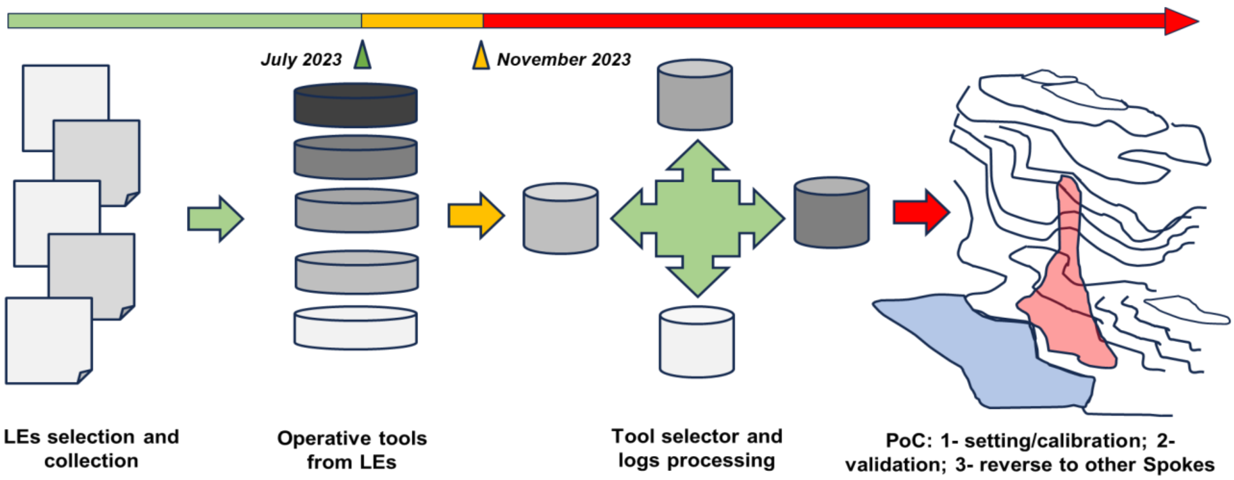

Figure 1. Timeline of WP3 and WP4 activities. The collection and analysis of LEs and their rationalization are reported in the present deliverable with a focus on monitoring applications and results.

2.1 Inventory of Learning Examples (LEs)

At the beginning of the project (***January – March 2023***) each institution involved in the VS2 was asked to identify an average of three consolidated and published cases from which the learning activities could already be undertaken. These case studies were defined as Learning Examples (LEs) to be used in WP2 and/or WP3 and/or WP4. Depending on the factor/process investigated in each LE, at least 2 reference papers were stored in a corresponding WP ***shared online repository*** (Windows Teams), visible and accessible to all the institutions. To support the discussion about LEs, the list of papers collected for WP3 is reported at the end of PART A, in Section 2.5. Similarly, WP4 bibliography repository will be listed at the end of PART B, Section 3.3.

Beside the upload of the reference papers, each LE was inserted in an ***online inventory file***, including:

- The proposing institution (abbreviation);
- The name/denomination of the LE (site name and/or geographical location or area of interest);
- The environment (subaerial/submerged);
- The context (mountain/hill/plain/coast/near-shore);
- The effect (landslide/subsidence/sinkhole/liquefaction);
- The scale (local/intermediate/regional);
- The analysis tools and techniques (on site monitoring/remote monitoring/deterministic analysis/statistical analysis/machine learning).

The resulting LEs were coded for each WP (ID: **XX_n_WPy**, where XX is a 2-letter code referring to the proposing institution, n is a progressive number, y is the WP number in which the LE is used for learning). Salient information for WP3 LEs is summarized in Table 1, while the location of all the LEs and related proposing institutions in reported in the map of Figure 2.

Table 1. Inventory of LEs for WP3. Env: environment (A - subaerial; W - underwater). Context: M – mountain; H – hill; P – plain; C – coast; NS – near-shore. Effect: LS – landslide; SU – subsidence; SI – sinkhole; LI – liquefaction. Scale: L – local ; I – intermediate ; R – regional. Learning Tools: RS - remote sensing monitoring; OS – onsite monitoring; D - deterministic analysis; S – statistical analysis; ML – Machine Learning.

Institution	LE ID	LE name	Env		Context					Effect				Scale			Tools				
			A	*W*	*M*	*H*	*P*	*C*	*NS*	*LS*	*SU*	*SI*	*LI*	*L*	*I*	*R*	*RS*	*OS*	*D*	*S*	*ML*
UNIBA	BA_2_WP3	*Coste Puglia e Basilicata*	X					X		X				X		X	X	X	X	X	X
	BA_3_WP3	*Regione Puglia*	X				X	X				X		X		X		X	X	X	
UNIBO	BO_1_WP3	*Passo della Morte (BZ)*	X		X					X				X				X	X		
	BO_4_WP3	*Costa romagnola*	X	X			X	X	X	X					X			X	X	X	
	BO_5_WP3	*San Leo*	X			X				X				X				X	X		
ENEA	EN_1_WP3	*Provincia di Messina*	X		X	X				X				X	X			X	X	X	
OGS	OG_1_WP3	*Provincia di Udine (Tolmezzo)*	X		X	X				X				X				X			
UNIPA	PA_1_WP3	*Frana di Scopello*	X		X	X	X	X		X				X	X		X	X		X	

	PA_2_WP3	***Sicilia occidentale***	X		X	X	X			X					X			X		X	
	PA_3_WP3	***Fronti carbonatici Sicilia occidentale***	X		X	X				X				X	X			X		X	
	PA_5_WP3	***Frana di Cerda (PA)***	X			X				X				X				X	X		
	PA_6_WP3	***Canyon Gioiosa Marea (ME)***		X				X	X	X				X			X		X		
POLITO	**TO_1_WP3**	***Western Alps unstable rock masses***	X		X	X				X				X				X	X		
	TO_2_WP3	***Cervino***	X		X					X				X	X			X	X		
	T0_3_WP3	***Valle d'Aosta, Val Germanasca, Val di Susa***	X		X					X				X	X			X	X		
UNIFI	**FI_2_WP3**	***Landslide dams***	X		X					X				X						X	
	FI_3_WP3	***Italia settentrionale***	X		X	X				X						X	X			X	
	FI_4_WP3	***Guidonia-Bagni di Tivoli***	X				X				X	X		X			X			X	X
UNIGE	**GE_1_WP3**	***Liguria e Piemonte***	X		X	X				X						X				X	
	GE_2_WP3	***Piccoli bacini idrografici del versante ligure-tirrenico***	X		X	X				X				X	X				X	X	
UNINA	**NA_1_WP3**	***Terreni piroclastici dei Monti Lattari (campo prove M.te Faito)***	X		X					X				X			X				X
	NA_6_WP3	***Napoli***	X			X				X					X			X		X	X
UNIPD	**PD_1_WP3**	***Dolomiti***	X		X					X					X		X	X	X	X	X
	PD_2_WP3	***Delta del Po***	X	X			X	X	X		X						X			X	X
U NIROMA1	**SA_1_WP3**	***AcutoFieldLab (FR)***	X			X				X				X				X		X	X
	SA_2_WP3	***Frane su versanti costieri di Conero, Vasto, Petacciato***	X					X		X				X	X		X	X	X		
	SA_3_WP3	***Camaldoli (wildFires)***	X			X				X					X		X		X		
	SA_4_WP3	***Molise (sismoinduzione)***	X			X				X						X	X		X		
	SA_5_WP3	***Seymareh***	X		X					X					X					X	
	SA_6_WP3	***Loumar***	X		X					X					X		X			X	
	SA_7_WP3	***Alta Val d'Orcia (SI)***	X			X				X					x		X			X	
	SA_8_WP3	***Stromboli***		X				X	X	X			X	X				X			
	SA_9_WP3	***Gioia Tauro***		X				X	X	X				X				X			
	SA_10_WP3	***Frana di Lucera (Subappenino Dauno)***	X			X				X				X				X	X		
	SA_11_WP3	***Appennino Tosco-emiliano: Ripoli Santa Maria Maddalena***	X		X	X				X				X			X	X	X		

Figure 2. Map of VS2 LEs divided by WP (WP3 LEs are reported in orange). The proposing institutions are highlighted by the black triangles.

2.2 LEs vs Preparatory Processes

In the following months (***March – May 2023***), WP and TK leaders reviewed the inventory file to check the correct assignment of each LE to the reference factors/processes of each WP (predisposing processes: WP2; preparatory processes: WP3 and trigger: WP4), with continuous exchanges and interactions with the proposing institutions and researchers.

Through independent reading and analysis of each reference paper, the WP and TK leaders tried to ***identify the salient processes preparing for ground instability*** studied in each WP3 LE. After this identification, each of the proposing institutions was asked to give feedback on the association between each LE and one (or more) processes.

After these interactions, few LEs were found to be more suitable for other WPs and moved accordingly, until a final list of LEs (Table 1) and preparatory factors (Table 2) was built. Fifteen preparatory processes (or rather, classes of processes) have been recognized and defined: it can be noticed that they are both related to climatic drivers (such as rainfall, weathering, seasonal thermal and sea level fluctuations, groundwater level, storm surges, permafrost degradation) and to non-climatic drivers (e.g. with anthropogenic or geological origin). A further, important, characterization concerns the different potential levels of rationalization: since the state of knowledge for each type of phenomenon can be at a different level, not all processes can be described and quantified in the same way. Section 2.4 reports representative images for each process.

Table 2. Preparatory processes identified from the LEs of WP3.

Process ID	Identified PREPARATORY PROCESS
WP3_P1	*Preparation for the detachment of soils related to physical and chemical alteration (weathering)*
WP3_P2	*Preparation for the detachment of soils related to variations in the saturation due to seasonal cumulated rainfalls*
WP3_P3	*Preparation for the detachment of soils related to the effects of wildfires*
WP3_P4	*Preparation for debris flows related to seasonal accumulation of debris in the high elevation feeding areas*
WP3_P5	*Preparation related to durability of debris damming bodies in the riverbed*
WP3_P6	*Preparation for the detachment of rock volumes related to diurnal and seasonal thermal stressors*
WP3_P7	*Preparation for the detachment of rock volumes related to permafrost degradation*
WP3_P8	*Preparation for coastal landslides related to climatic sea level fluctuations (sea level rise)*
WP3_P9	*Preparation for coastal landslides or at canyon heads and/or continental margins related to debris accumulation from riverbeds (deltaic systems) and subaerial processes (e.g. coastal landslides, lava flows)*
WP3_P10	*Preparation for underwater landslides, at canyon heads and/or continental margins, related to underwater solid transport under the coast (currents/waves)*
WP3_P11	*Preparation for detachment of submarine sediments related to outgassing phenomena*
WP3_P12	*Preparation for sinkholes related to the evolution/maturation of karst phenomena*
WP3_P13	*Anthropogenic preparation related to static loads or changes in subsurface fluid pressures or groundwater level*
WP3_P14	*Preparation related to changes in the vegetation cover due to anthropogenic or natural causes (including vegetation diseases)*
WP3_P15	*Preparation related to pre-trigger events (e.g., seismic sequences, recurrent storm surges, cumulative intense rainfall events, landslide succession, creep and rock mass damaging)*

At the end of this stage, the “matrix inversion” was performed (Table 3). The focus of the analysis was turned to the processes (instead of the single LEs) quantified through the outputs of the related LEs.

Integrating the information of Table 3 and Table 1, a preliminary overview of the LE coverage of the different preparatory processes is reported in Figure 3.

Table 3. Identified processes and related LEs for the learning phase.

Process ID	LE ID
WP3_P1	SA_7_WP3
WP3_P2	EN_1_WP3
	OG_1_WP3
	PA_2_WP3
	GE_1_WP3
	NA_1_WP3
WP3_P3	NA_6_WP3
	PA_3_WP3
	SA_3_WP3
WP3_P4	PD_1_WP3
WP3_P5	FI_2_WP3
WP3_P6	TO_1_WP3
	SA_1_WP3
WP3_P7	TO_2_WP3
WP3_P8	BA_2_WP3
	SA_2_WP3
	PA_1_WP3
WP3_P9	PA_6_WP3
	SA_8_WP3
WP3_P10	SA_9_WP3
WP3_P11	PA_4_WP3
WP3_P12	BA_3_WP3
WP3_P13	BA_2_WP3
	BA_3_WP3
	BO_1_WP3
	FI_4_WP3
	SA_10_WP3
	SA_11_WP3
	PD_2_WP3
WP3_P14	FI_3_WP3
	GE_1_WP3
	GE_2_WP3
	PD_1_WP3
	SA_7_WP3
WP3_P15	BA_2_WP3
	BA_3_WP3
	PA_5_WP3
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	BO_4_WP3
	BO_5_WP3

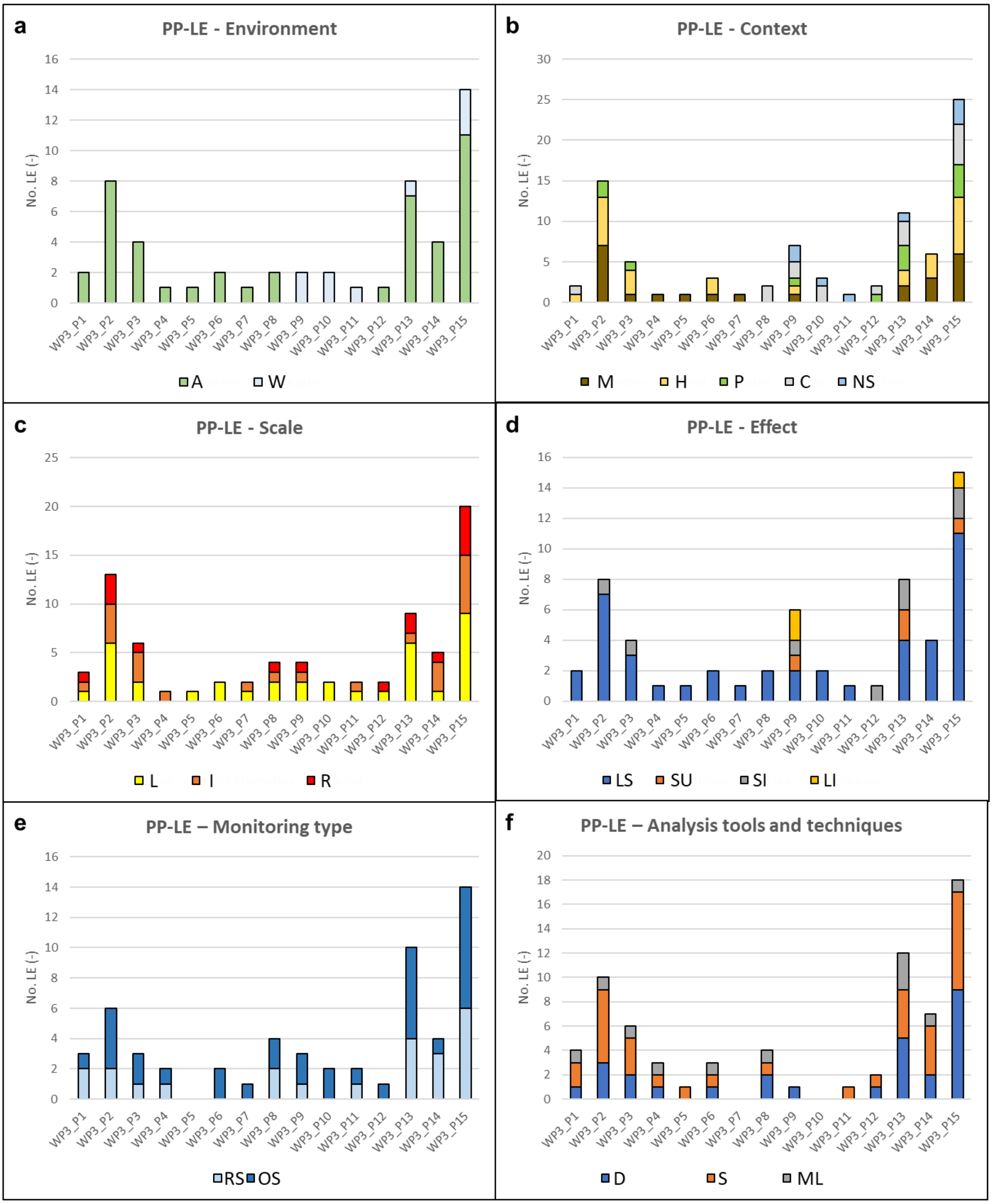


Figure 3. Distribution of preparatory processes (PPs) learned from the reference WP3 LEs as a function of (a) Environment: A - subaerial; W – underwater. (b) Context: M – mountain; H – hill; P – plain; C – coast; NS – near-shore. (c) Scale: L – local; I – intermediate ; R – regional. (d) Effect: LS – landslide; SU – subsidence; SI – sinkhole; LI – liquefaction. (e) Monitoring tools: RS – Remote; OS – onsite/contact. (f) Analysis tools: D - deterministic analysis; S – statistical analysis; ML – Machine Learning.

The preliminary distribution of preparatory processes by environment (subaerial vs underwater in Fig. 3a) highlights that marine studies currently focus only on a subset of them (mainly WP3_P9 to WP3_P11, WP3_P13 and WP3_P15). The marine studies are also globally a small percentage of the total inventory (<20%), with a maximum of 3 marine LEs for WP3_P15. A challenge for the RETURN project might be to reach a more comprehensive view of submerged processes to better unify the treatment between the subaerial and underwater environments. The distribution by environmental contexts (Fig. 3b) is wide, with a dominant number of processes and LEs covering mountain and hilly areas. All the scales of observations are well represented among the different preparatory processes (Fig. 3c). The distribution of preparatory processes by type of effect (Fig. 3d) highlights the clear prevalence of expertise gained by the VS2 research team on landslides. Non negligible learning experience is also available for sinkholes, while further research efforts should be spent for the analysis of the preparation to liquefaction and subsidence. As it regards the liquefaction process an interaction with WP5 has been already proposed to better constrain the role of anthropogenic actions before, during and after liquefaction effects occurrences. The distribution of preparatory processes by type of monitoring (remote or contact/onsite, Fig. 3e) appears balanced. Regarding the types of analyses (Fig. 3f), the distribution over preparatory processes is wider for deterministic and statistical analyses than machine learning, which can be considered reasonable at this stage. Two of the preparatory processes do not have a corresponding assessed analysis tool (WP3_P7 and WP3_P10) but are essentially being monitored (Fig. 3e), while there is no sufficient monitoring data to explore and analyze WP3_P5.

2.3 Towards the Rationale – WP3 outcomes

In the period between ***June and July 2023***, WPs and TKs dedicated the research efforts to the rationalization of each process through the learning from the respective associated LEs. The Rationale under construction has the objective to define input data and constraints to be inserted in the Proof of Concept (PoC). This PoC will be able to take these inputs and return specific outputs within the constraints of validity of learning tools derived for each factor/process from the LEs.

Within VS2, the rationalization went in parallel between WP2, WP3 and WP4. To achieve this goal, a specific rationalization sheet was designed for each WP. To optimize the process, WP2 predisposing factors were analyzed with a table approach, while WP3 and WP4 processes and triggers adopted a more descriptive form. The PP-LE sheet for the rationale of WP3 is summarized in Table 4. The structure and expected content of each section are highlighted in the second column.

Within WP3, the rationalization proceeded in parallel between the 3 tasks (TK1 – learning from monitoring data, TK2 – learning from numerical modeling and TK3 – learning from machine learning). For the learning methods made explicit by the research team in Section 3 of Table 3, the association between PP-LE and learning tools/tasks was straightforward.

Dealing with TK1, an example of a completed WP3 sheet is provided in Table 5. All the WP3 Rationale sheets related to this task (monitoring) are attached to the present DV (Attachment 1).

Table 4. Process-LE sheet structure for the Rationale, with explanation of the expected content on the right column. Yellow fields refer to the PP and LE codes. Blue fields highlight input data for the Rationale. Green fields summarize the expected output.

PROCESS	WP3_x
LEARNED FROM *(indicate the LE ID)*	LE_x_WP3
1) PROCESS CONTROL PARAMETERS	Parameters that control the preparatory process WP3_x according to what has been learned. *In addition to preparatory factors under consideration in WP3, they could involve also predisposing factors (not studied by this tool, but arising from the WP2 learning tools)* *What input data are needed to make this tool work in the PoC?*
2) INPUT DATA TO THE RATIONALE for the analysis of the process	Input parameters that the tool will provide to the PoC (output of the tool). *What does this tool do? What does it provide to the PoC?*
3) LEARNING METHODS (from which the input data were derived) *(onsite/remote monitoring – Task 1; numerical modeling – Task 2; machine learning – Task 3; specify the type/task and provide the methodological description for each input to the rationale)*	Data and processing methods used for the learning (e.g. monitoring/modeling/machine learning) *How does the tool work?* *How and from what data was it derived?*
4) APPLICABILITY CONSTRAINTS *(specify the application context/environment, highlight the spatial and temporal scale limits and the requirements for applicability)*	Values/ranges of the parameters and conditions within which the learning tool is valid and applicable (context, spatial/temporal scale). *Under what conditions can I apply the tool in the PoC?*
5) ANALYSIS LOGS *(specify if qualitative, semi-qualitative or quantitative)*	*Based on the previous learning, how does the PoC have to return the results?*
6) OUTPUTS ***(specify if categories or indexes or algorithms*** *according to the analysis logs and provide a full description of each output)*	Learning outcomes. Applicable to other similar cases or sites within the validity constraints of the tool. *What will the PoC return in which the tool is valid and applicable?*

Table 5. Example of WP3-TK1 Rationale sheet.

PROCESS	**WP3_P14** ***Preparation related to the vegetation cover change due to anthropic or natural causes (including diseases)***
LEARNED FROM *(indicate the code of the reference LE - learning example)*	**GE_2_WP3**
1) PROCESS CONTROL PARAMETERS	Land use change over time in terraced areas: – use of the degree of vegetation cover as an indicator of the degree of abandonment and maintenance of agricultural terraces.
2) INPUT DATA TO THE RATIONALE for the analysis of the process	The tool analyses the role of the degree of abandonment of agricultural terraces as a preparatory factor for rainfall-induced shallow landslides. The degree of vegetation cover is taken as an indicator of the degree of abandonment and maintenance of the agricultural terraces. The analysis focuses on the relationships between the spatial distribution of shallow landslides and the degree of abandonment of agricultural terraces.
3) LEARNING METHODS (from which the input data were derived) ***(onsite/remote sensing monitoring – Task 1; numerical modeling – Task 2; machine learning – Task 3; specify the type/task and provide the methodological description for each input to the rationale)***	▪ Remote sensing - **TASK1**: – analysis of aerial photos/orthophotos, historical maps and cadastral maps in a GIS environment to produce multi-temporal land use maps; – detailed inventory of landslides through post-event field surveys and high-resolution orthophoto analysis; – quantitative analysis of land use changes and of the degree of abandonment of agricultural terraces through change detection procedures in the GIS environment; in the LE, land use changes occurred over a period of approximately 60 years (between 1950 and 2011) were analysed; – comparison of pre- and post-event digital terrain models (DEMs) to estimate the volumes of soil mobilized by rain-induced shallow landslides on terraced slopes characterized by different degree of abandonment; – assessment of indices (severity indices) aimed at quantifying the spatial frequency (i.e., number) and the magnitude (expressed in terms of landslide area and mobilized volumes) of shallow landslides for each selected land use class. Indices used: ▪ LN (%): ratio between the number of landslides in each land use class and the total number of inventoried landslides: $$LN = \frac{n_{l,i}}{n_{lt}}$$ – n_l: number of landslides triggered in the land use class i; – n_{lt}: total number of inventoried landslides. ▪ LA (%): ratio between the landslide area in each land use class and the total landslide area: $$LA = \frac{A_{l,i}}{A_t}$$ – A_l: landslide area in the land use class i; – A_t: total area of the inventoried landslides. ▪ LIA (%): ratio between the landslide area in each land use class and the total area of that land use class:

	$$LIA = \frac{A_{l,i}}{A_i}$$ — A_l: landslide area in the land use class i; — A_i: total area of the land use class i. ▪ $LVI_{er,i}$ (m^3/km^2): ratio between the landslide mobilized volume amount in each land use class and the total area of the land use class: $$LVI_{er,i} = \frac{Vt_{er,i}}{A_i}$$ — $Vt_{er,i}$: volume of debris mobilized by landslides in the land use class i; — A_i: total area of the land use class i.
4) APPLICABILITY CONSTRAINTS ***(specify the application context/environment, highlight the spatial and temporal scale limits and the requirements for applicability)***	Application context: hilly-mountain catchments/zones characterized by steep slopes, largely terraced, originally covered by thin eluvial-colluvial debris layers (average thicknesses 1-3 m) reworked in historical times for the construction of terraces, potentially mobilized by intense and localized rainfall-induced surface landslides. Types of landslide movements: roto-translational and sliding mechanisms which, following the first failure, can evolve into flow-type movements, such as debris avalanches and debris flows. Spatial scale limits: from basin to local scale. Temporal scale limits: from ten-year to multi-decade scale.
5) ANALYSIS LOGS ***(specify if qualitative, semi-qualitative or quantitative)***	Qualitative
6) OUTPUTS ***(specify if categories or indexes or algorithms according to the analysis logs and provide a full description of each output)***	Land use classes considered: ▪ CT – cultivated terraced slopes; ▪ ATP – abandoned terraced slopes with poor vegetation cover; ATP are considered to have been abandoned for a short time (less than 25–30 years) and are mainly characterized by herbaceous cover or shrubs; ▪ ATD – abandoned terraced slopes with dense vegetation cover. ATD are considered to have been abandoned for a long period of time (more than 25–30 years) and mainly covered by forest tree species. The abandonment of agricultural activities played an important role in controlling/influencing both the distribution and magnitude of landslides: — terraced slopes abandoned for a short time (ATP, less than 25–30 years) are the land use class most affected by landslides, both in terms of area involved and volumes mobilized, compared to the class of abandoned terraced areas for a long time (ATD, more than 25–30 years) and that of cultivated terraced slopes (CT), respectively; — landslides occurred in the class of cultivated terraced slopes (CT) are characterized, on average, by magnitude (i.e., size) lower than those triggered in the class of terraced slopes abandoned for a short (ATP) and long (ATD) time, respectively. The LE highlights: — the negative role of farmland abandonment on the stability of terraced slopes; — the time interval that elapses between the abandonment of agricultural activities and the development of a dense

	spontaneous vegetation cover represents the most critical phase for the stability of terraced slopes; – terraced slopes abandoned for a short time (<25-30 years), suffering poorer maintenance than cultivated terraces (CT) and being scarcely colonized by forest tree species, still do not benefit from the stabilizing effects of the vegetation; – abandoned terraced slopes, even if completely unmaintained, become more stable when colonized by dense vegetation and, therefore, after longer periods of abandonment (ATD, >25-30 years).

The rationalization phase required strong research efforts mainly for the determination of the analysis logs and outputs (qualitative-classes and/or semi-qualitative-indexes and correlations and/or quantitative-equations and algorithms, Sections 5 and 6 of Table 4). With respect to the original association between preparatory processes and LEs (Table 3), a satisfactory rationalization sheet was obtained for more than 95% of the PP-LE associations. Some statistics related to WP3-TK1 Rationale are further shown in Figure 4.

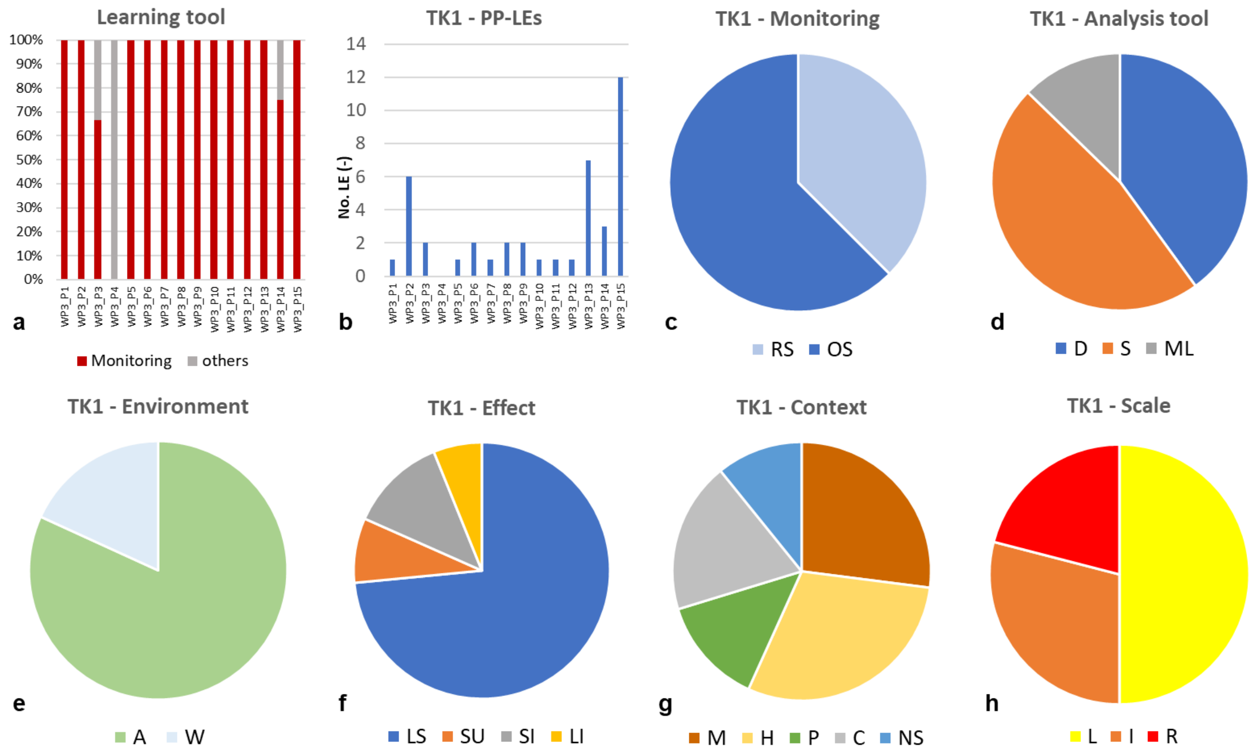


Figure 4. WP3-TK1 Rationale from monitoring data. (a) Percentage of LEs rationalized through monitoring data (TK1) with respect to numerical modeling and machine learning only (TK2 and TK3 only). (b) Number of LEs per preparatory process from which the rationale was achieved only/also from monitoring data. (c) Monitoring tools: RS – Remote; OS – onsite/contact. (d) Analysis tools: D - deterministic analysis; S – statistical analysis; ML – Machine Learning. (e) Environment: A - subaerial; W – underwater. (f) Effect: LS – landslide; SU – subsidence; SI – sinkhole; LI – liquefaction. (g) Context: M – mountain; H – hill; P – plain; C – coast; NS – near-shore. (h) Scale: L – local ; I – intermediate; R – regional.

The results show that monitoring data is the dominant learning tool for the identified preparatory processes (Fig. 4a). With the only exception of WP3_P4, monitoring is present in at least 60% of the analyzed preparatory processes. The rationale confirms difficulties in the monitoring and quantification of specific preparatory processes (WP3_P4, Fig. 4b), for which further research efforts are needed. The monitoring data are dominantly derived from contact measurements and on site monitoring network (63%) with respect to remote sensing (38%, Fig. 4c). As a result, the local scale of observation is prevalent (50%, Fig. 4h). The distribution of monitoring activities in different environments, effects and contexts (Figs. 4e to 4g) follows the preliminary considerations described for the LE inventory.

The Rationale is derived only from monitoring data and analyses in the 55% of the LEs and processes related to TK1 (Fig. 5a). In the remaining 45%, the rationale is mainly derived through the integration of monitoring data with numerical modeling (TK1+TK2, 31%) and, in a few cases, machine learning (TK1+TK3 or TK1+TK2+TK3). Most of the analyzed preparatory processes require the integration between monitoring data and other learning techniques (Fig. 5b). This is particularly needed for WP3_P6 and WP3_P8, for which numerical modeling and machine learning techniques are fundamental for the processing and interpretation of monitoring data.

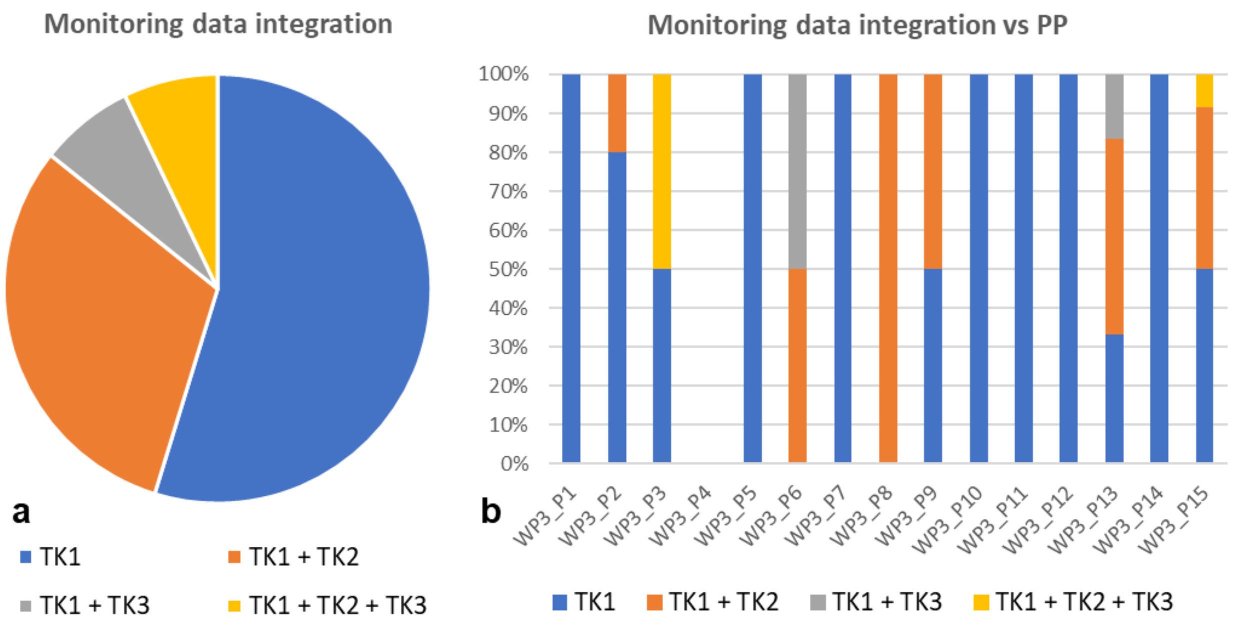


Figure 5. Rationale outcomes divided by WP3 tasks (TK1 – learning from monitoring; TK2 – learning from numerical modeling; TK3 – machine learning). (a) Percentage of LEs involving monitoring activities alone or coupled with other methods. (b) Percentages of (a) divided by preparatory process.

The analysis logs derived for each preparatory process and LE from the Rationale sheets are summarized in Figure 5. Qualitative logs are generally related to the definition of classes, quantitative logs report algorithms and equations, semi-quantitative logs are expressed through tables and simple correlations. Semi-qualitative logs for the preparatory factors derived from monitoring data analyses are dominant (40%), followed by quantitative logs (36%, Fig. 6a). Quantitative logs are however available only for 6 preparatory processes over 15 (<50%, Fig. 6b). Only qualitative information can be derived at this stage for processes WP3_P1 and WP3_P10 (Fig. 6b).

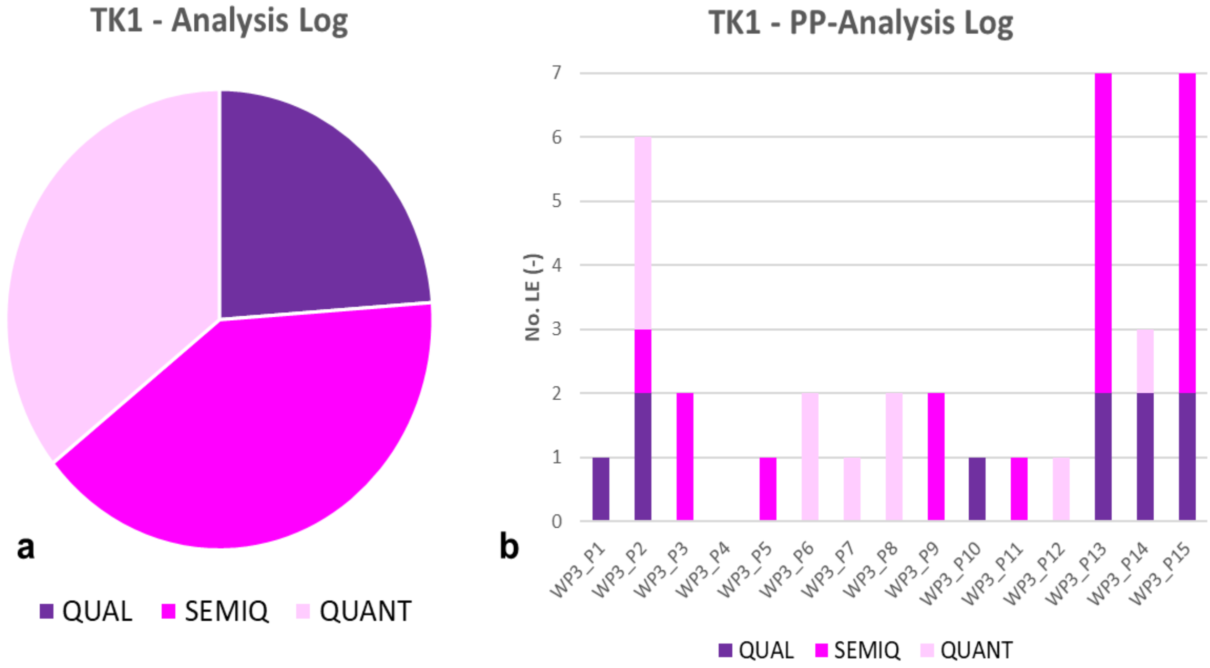


Figure 6. Rationale outcomes related to monitoring divided by type of analysis log. (a) Global percentage of LEs rationalized through qualitative – semi-quantitative – quantitative log information. (b) Percentages of (a) divided by preparatory process.

2.4 Examples and Figure of WP3 preparatory processes

Table A1. Summary list and description of the identified preparatory processes and related LEs.

Process ID	Process description	LE ID	LE description
WP3_P1	*Preparation for the detachment of soils related to physical and chemical alteration (weathering)*	**SA_7_WP3**	*Alta Val d'Orcia (SI)*
WP3_P2	*Preparation for the detachment of soils related to variations in the saturation due to seasonal cumulated rainfalls*	**EN_1_WP3**	*Provincia di Messina*
		OG_1_WP3	*Provincia di Udine (Tolmezzo)*
		PA_2_WP3	*Sicilia occidentale*
		GE_1_WP3	*Liguria e Piemonte*
		NA_1_WP3	*Monti Lattari (M.te Faito)*
WP3_P3	*Preparation for the detachment of soils related to the effects of wildfires*	**NA_6_WP3**	*Napoli*
		PA_3_WP3	*Fronti carbonatici Sicilia occidentale*
		SA_3_WP3	*Camaldoli (wildFires)*
WP3_P4	*Preparation for debris flows related to seasonal accumulation of debris in the high elevation feeding areas*	**PD_1_WP3**	*Dolomiti*
WP3_P5	*Preparation related to durability of debris damming bodies in the riverbed*	**FI_2_WP3**	*Landslide dams*
WP3_P6	*Preparation for the detachment of rock volumes related to diurnal and seasonal thermal stressors*	**TO_1_WP3**	*Western Alps unstable rock masses*
		SA_1_WP3	*AcutoFieldLab (FR)*
WP3_P7	*Preparation for the detachment of rock volumes related to permafrost degradation*	**TO_2_WP3**	*Cervino*
WP3_P8	*Preparation for coastal landslides related to climatic sea level fluctuations (sea level rise)*	**BA_2_WP3**	*Coste Puglia e Basilicata*
		SA_2_WP3	*Frane su versanti costieri di Conero, Vasto*
		PA_1_WP3	*Frana di Scopello*
WP3_P9	*Preparation for coastal landslides or at canyon heads and/or continental margins related to debris accumulation from riverbeds (deltaic systems) and subaerial processes (e.g. coastal landslides, lava flows)*	**PA_6_WP3**	*Canyon Gioiosa Marea (ME)*
		SA_8_WP3	*Stromboli*
WP3_P10	*Preparation for underwater landslides, at canyon heads and/or continental margins, related to underwater solid transport under the coast (currents/waves)*	**SA_9_WP3**	*Gioia Tauro*
WP3_P11	*Preparation for detachment of submarine sediments related to outgassing phenomena*	**PA_4_WP3**	*Canyon Golfo di Palermo*
WP3_P12	*Preparation for sinkholes related to the evolution/maturation of karst phenomena*	**BA_3_WP3**	*Regione Puglia*
WP3_P13	*Anthropogenic preparation related to static loads or changes in subsurface fluid pressures or groundwater level*	**BA_2_WP3**	*Coste Puglia e Basilicata*
		BA_3_WP3	*Regione Puglia*
		BO_1_WP3	*Passo della Morte (BZ)*
		FI_4_WP3	*Guidonia-Bagni di Tivoli*
		SA_10_WP3	*Frana di Lucera*
		SA_11_WP3	*Appennino Tosco-emiliano*
WP3_P14	*Preparation related to changes in the vegetation cover due to anthropogenic or natural causes (including vegetation diseases)*	**FI_3_WP3**	*Italia settentrionale*
		GE_1_WP3	*Liguria e Piemonte*
		GE_2_WP3	*Bacini idrografici del versante ligure-tirrenico*
		PD_1_WP3	*Dolomiti*
		SA_7_WP3	*Alta Val d'Orcia (SI)*
WP3_P15	*Preparation related to pre-trigger events (e.g., seismic sequences, recurrent storm surges, cumulative intense rainfall events, landslide succession, creep and rock mass damaging)*	**BA_2_WP3**	*Coste Puglia e Basilicata*
		BA_3_WP3	*Regione Puglia*
		PA_5_WP3	*Frana di Cerda (PA)*
		PA_6_WP3	*Canyon Gioiosa Marea (ME)*
		SA_4_WP3	*Molise (sismoinduzione)*
		SA_5_WP3	*Seymareh*
		SA_6_WP3	*Loumar*
		TO_3_WP3	*Valle d'Aosta, Val Germanasca, Val di Susa*
		BO_4_WP3	*Costa romagnola*
		BO_5_WP3	*San Leo*

Table A2. List and description of the preparatory processes, with the captions of the related representative figures collected in the section (for reference papers see Section 2.5).

Process ID	Process Description	Reference	Figure Caption
WP3_P1	*Preparation for the detachment of soils related to physical and chemical alteration (weathering)*	Vergari et al. (2013)	Sample sites for the measurement of the relation between sediment dispersivity and pore water composition in the Upper Orcia Valley: a) embryonic biancane badlands; b) cropland; c) calanchi badlands affected by mass movements.
WP3_P2	*Preparation for the detachment of soils related to variations in the saturation due to seasonal cumulated rainfalls*	Forte et al. (2019)	Relevant examples of flow-like landslides in the Lattari Mts., landslide body and picture of the events: a) Castellammare 1997; b) S. Egidio Monte Albino; c) Pimonte 1997; d) Pagani 1997.
WP3_P3	*Preparation for the detachment of soils related to the effects of wildfires*	Di Napoli et al. (2020)	On the left, post-fire erosion phenomena (15 September 2001); on the right, the post-fire landslides triggered in the summer of 1996. Both images refer to the Soccavo slopes (Campania, Italy, photos by D. Calcaterra).
WP3_P4	*Preparation for debris flows related to seasonal accumulation of debris in the high elevation feeding areas*	Scotton et al. (2011)	a) Source areas above Acquabona debris flow channels (Dolomites, Northern Italy) – Recurrent rock falls feed debris deposits on the fan apex which, in turn, create conditions for the triggering of debris flows. b) The main source area as seen from upslope.
WP3_P5	*Preparation related to durability of debris damming bodies in the riverbed*	Petley (2008)	View of Sichuan landslide dam (China).
WP3_P6	*Preparation for the detachment of rock volumes related to diurnal and seasonal thermal stressors*	Colombero et al. (2021)	Left panels: Temperature-driven mechanisms causing f1 and/or dV/V reversible variations: a) fracture effect; b) surface effect; c) bulk effect. Right panels: Temperature–precipitation-driven mechanisms causing f1 and/or dV/V reversible variations: a) water effect; b) ice effect; c) clay effect. T: air temperature, P: precipitation, fw: fracture width, Kc: contact stiffness, Kb: bulk stiffness, Gb: bulk shear modulus, M: mass, ρ: density, fw: fracture width, t: time (daily and/or seasonal scale)
WP3_P7	*Preparation for the detachment of rock volumes related to permafrost degradation*	Occhiena and Pirulli (2012); Occhiena et al. (2014)	View of the Cheminée (Northern Italy) rockfall scar. The letters A, B and C indicate the detachment area of the Cheminée rockfall.
WP3_P8	*Preparation for coastal landslides related to climatic sea level fluctuations (sea level rise)*	Della Seta et al. (2013)	Sequential steps illustrating the evolution of the Vasto landslide slope from, 140 ka to the present; 1) sand and conglomerate; 2) clay; 3) sliding surface.
WP3_P9	*Preparation for coastal landslides or at canyon heads and/or continental margins related to debris accumulation from riverbeds (deltaic systems) and subaerial processes (e.g. coastal landslides, lava flows)*	a) Casalbore et al. (2020) b) Chiocci et al. (2008)	a) On the left: Difference map obtained by comparing multibeam bathymetries acquired pre- (February 2002) and post-slide (January 2003) showing the geometry of the 30th December 2002 submarine scar down to—350 m; at greater depths two flow trails, associated to the erosion exerted on the seafloor by the sliding mass, are also recognizable. On the right: slope map (in degrees) computed on the pre- (February 2002) slide DEM, indicating a steeper part of the submarine slope (volcaniclastic apron) in the first 300 m of depth b) Schematic diagram of Sciara del Fuoco setting (not to scale), showing the major morphostructural and depositional features.
WP3_P10	*Preparation for underwater landslides, at canyon heads and/or continental margins, related to underwater solid transport under the coast (currents/waves)*	Zaniboni et al. (2014)	Synthetic marigrams computed for the nodes shown in the central panel. Red lines mark Slide 1 tsunami, and blue lines mark the Slide 2 tsunami. Nodes 1 and 2 account for tsunami oscillations along the coast, 3 and 4 for perturbation directing towards the open sea, 5 to 8 inside the harbor.
WP3_P11	*Preparation for detachment of submarine sediments related to outgassing phenomena*	Lo Iacono et al. (2011)	3-D shaded relief bathymetric map of the Palermo Gulf showing the main submarine canyons and morphostructures of the slope region. The figure shows the correspondence between the Oreto River and the Oreto Canyon and the Eleuterio River and the Eleuterio Canyon.
WP3_P12	*Preparation for sinkholes related to the evolution/maturation of karst phenomena*	Margiotta et al. (2021)	Sketch of the sinkhole evolution (not to scale). Please note that the first sinkholes developed in correspondence of the two artificial canals, probably because of the reduced thickness of the recent sands. Phase one: sands move down into the voids, which are progressively enlarged by the joints, thus forming small depressions at the surface. Rising brackish water through the joints favours plants to take root; however, continuous settling of sands pushes them at the rims of the depressions. Phase two: both dissolution and sand infilling go on, and wider depressions are originated due to coalescing sinkholes. Phase three: continuing infilling determines a general lowering of the basin bottom.

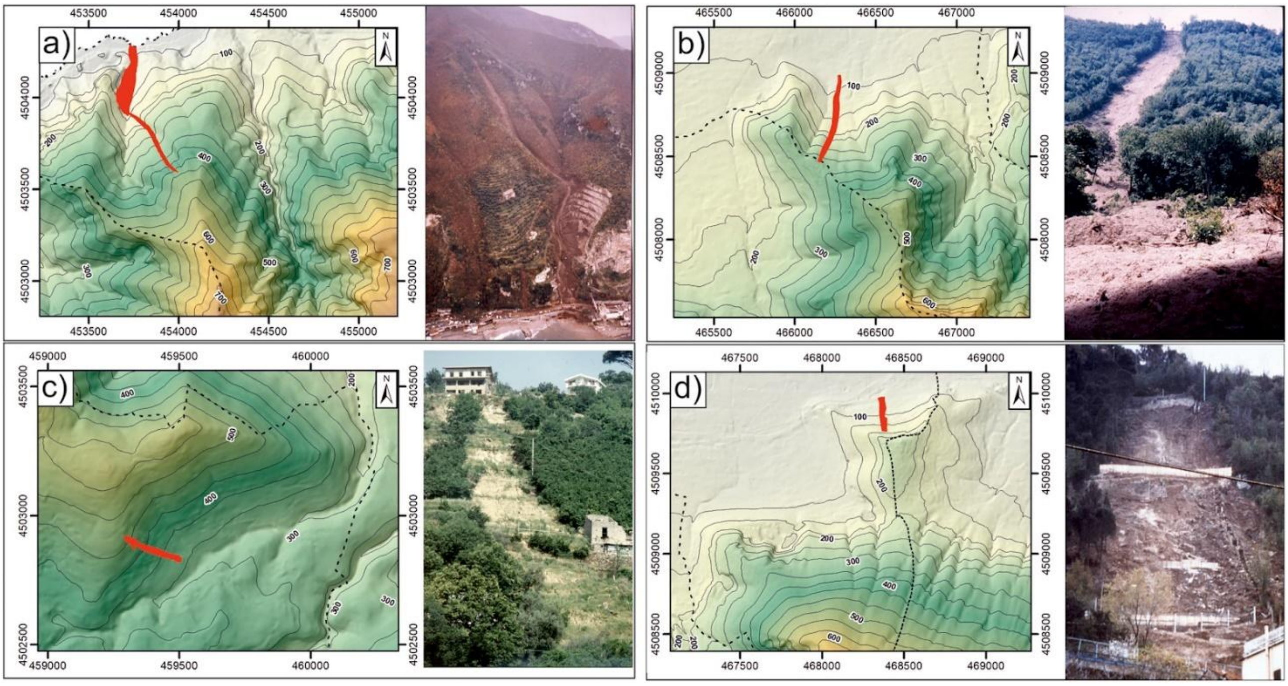
WP3_P13	*Anthropogenic preparation related to static loads or changes in subsurface fluid pressures or groundwater level*	Parise & Vennari (2017) in Renard & Bertrand (Eds.)	The San Procopio sinkhole at Barletta (May 2010), produced by collapse of an underground calcarenite quarry
WP3_P14	*Preparation related to changes in the vegetation cover due to anthropogenic or natural causes (including vegetation diseases)*	Cevasco et al. (2014)	Examples of shallow landslides induced by the 25 October 2011 rainfall event in the Vernazza basin (a–c). All photographs by A. Cevasco. Bottom histogram: distribution of landslides in relation to land use. a woods; b scrubland; c grassland; d cultivated terraces; e abandoned terraces (poor cover); f abandoned terraces (dense cover)
WP3_P15	*Preparation related to pre-trigger events (e.g., seismic sequences, recurrent storm surges, cumulative intense rainfall events, landslide succession, creep and rock mass damaging)*	a) Rosone et al. (2018) b) Delchiaro et al. (2019) c) Borgatti et al. (2015)	a) Sketch map of the landslide area. a) Location; b) limits of the landslide area triggered by the September 6th, 2002 earthquake (within which landslides A, B and C reactivated by rainfall in the period 2008–2011 are drawn. Inside the landslide A has been detected a second shallow landslide indicated in the figure as zone A1). The figure shows the main “infrastructures” affected by the landslide, the monitoring system implemented in autumn 2008 - late spring 2009 and the main geotechnical investigations performed. b) Evolutionary model of the Seymareh River valley. 1. Setting of a paleo-Seymareh river into a synclinal valley, likely developed in the Pliocene, to the west of the present position of the Seymareh River and deposition of fan deposits (Cg_m) (Fig.a). 2. Development of the valley with local base level correlated to the Seymareh longitudinal profile segment upstream of the major knickpoint along the Seymareh River and coeval to the deposition of the Bakhtiari Formation (Late Pliocene–Early Pleistocene) (Fig. b). 3. Emplacement of the downstream fan deposits corresponding to the Cg_l conglomerates (Early Pleistocene) and generation of the four orders of Middle–Late Pleistocene alluvial terraces (Qt1_l–Qt4_l) preserved downstream of the landslide and formed during the progressive migration of the major knickpoint, which is presently located upstream of the landslide (Fig. c). 4. Seymareh landslide event (~10 ka), according to the 14C ages by Roberts and Evans (2013) and to the OSL ages provided in this work for the lacustrine deposits (Lac) (Fig. d). 5. Formation and permanence of the Seymareh Lake (~10–6.6 ka), according to the 14C estimated ages by Roberts and Evans (2013) and to the OSL ages provided in this study for the lacustrine deposits (Lac) (Fig. e). The progressive infilling of the lake reservoir progressively reduced the infiltration section on the upstream side of the landslide dam. The presence of a minor emissary on the downstream side of the landslide debris cannot be excluded. 6. Overflow of the lake and cut of the natural dam with formation of the first strath terrace (6.59±0.49 ka), followed by a second strath terrace and a flood plain during the emptying of the lake, which upstream is associated with the sedimentation of a fluvio-lacustrine sequence at the top of the lacustrine sediments (Fig. f). 7. Complete emptying of the lake and generation of the suite of fill terraces entrenched in the deposits of Seymareh Lake (4.5 ka–present) (Fig. g). c) Tentative reconstruction of the time evolution of the landslide event

a)

b)

c)

WP3_P2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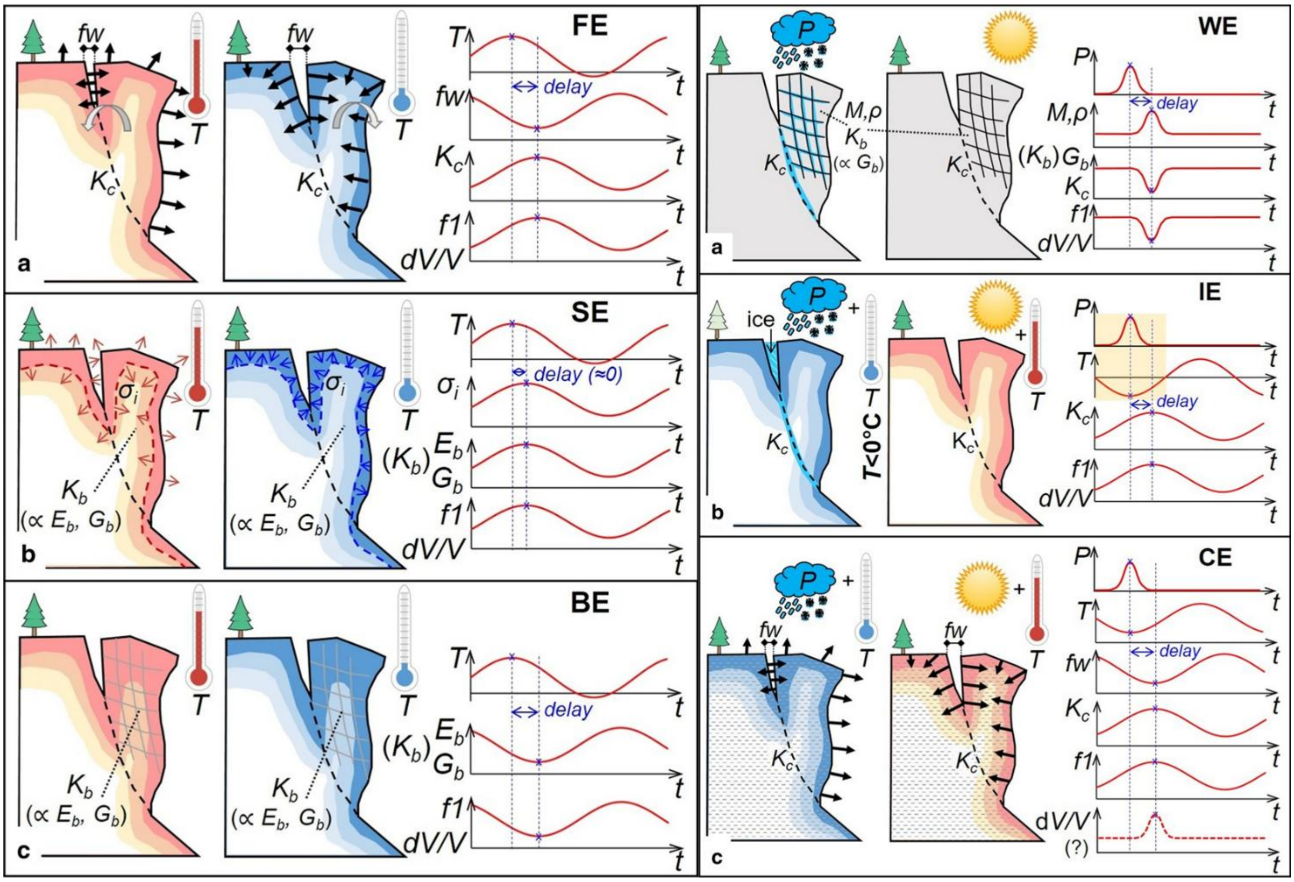
WP3_P3


a


b

WP3_P5

WP3_P6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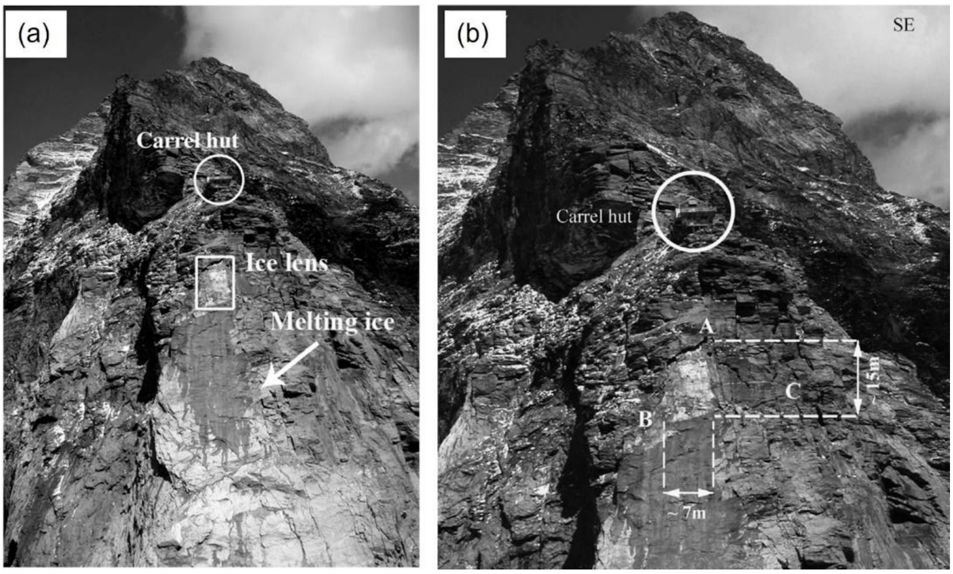
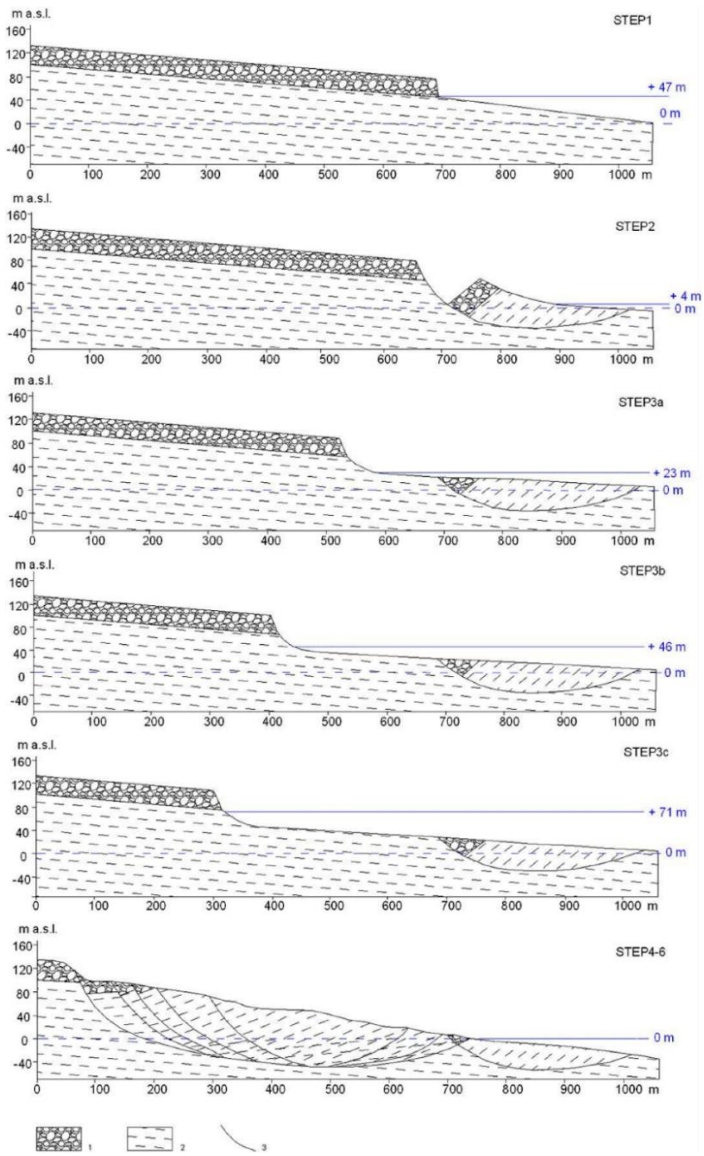
WP3_P7


(a)
Carrel hut
Ice lens
Melting ice
(b)
SE
Carrel hut
A
B
C
~15m
~ 7m

WP3_P8


m a.s.l.
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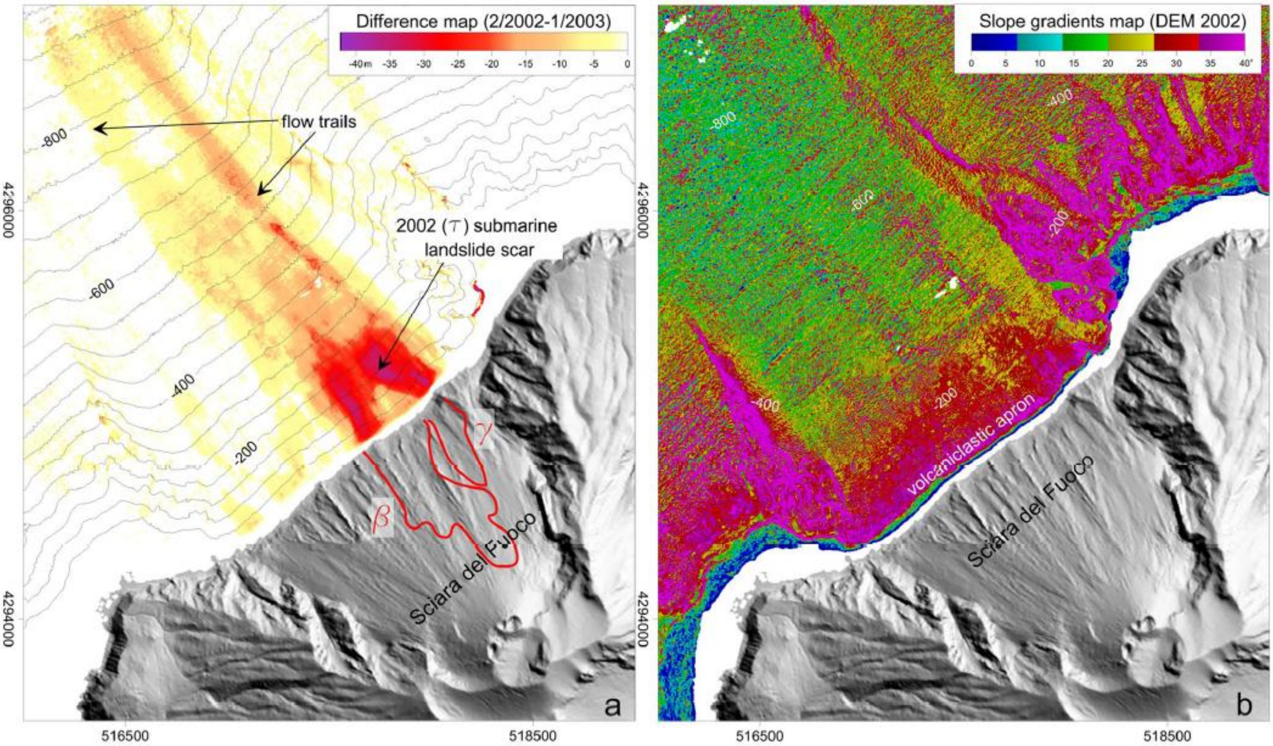
+ 47 m
0 m
STEP2
+ 4 m
STEP3a
+ 23 m
STEP3b
+ 46 m
STEP3c
+ 71 m
STEP4-6
1000 m

WP3_P9

a)


Difference map (2/2002-1/2003)
flow trails
2002 (τ) submarine landslide scar
Sciara del Fuoco
Slope gradients map (DEM 2002)
volcaniclastic apron
Sciara del Fuoco
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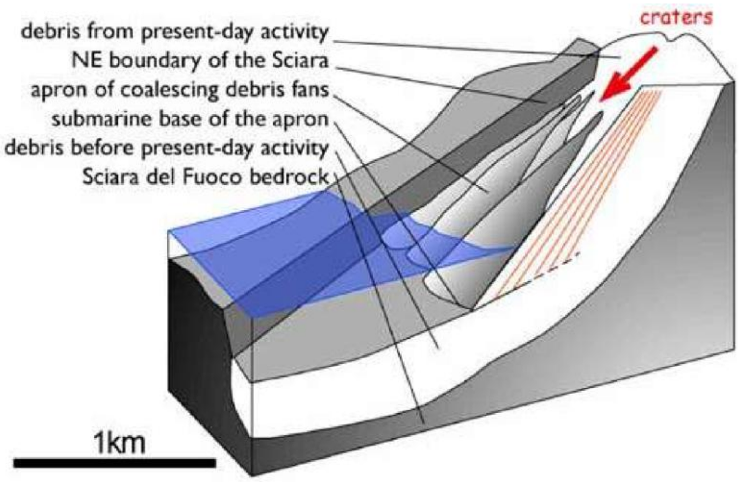
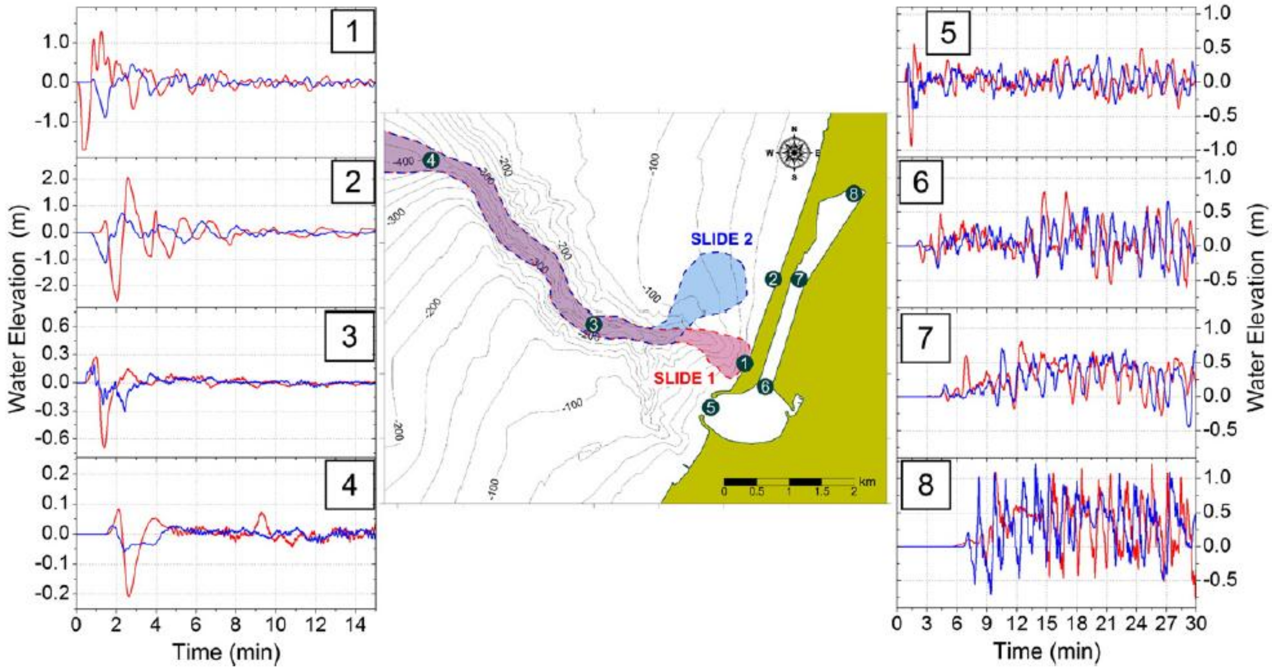
b)


debris from present-day activity
NE boundary of the Sciara
apron of coalescing debris fans
submarine base of the apron
debris before present-day activity
Sciara del Fuoco bedrock
craters
1km

WP3_P10



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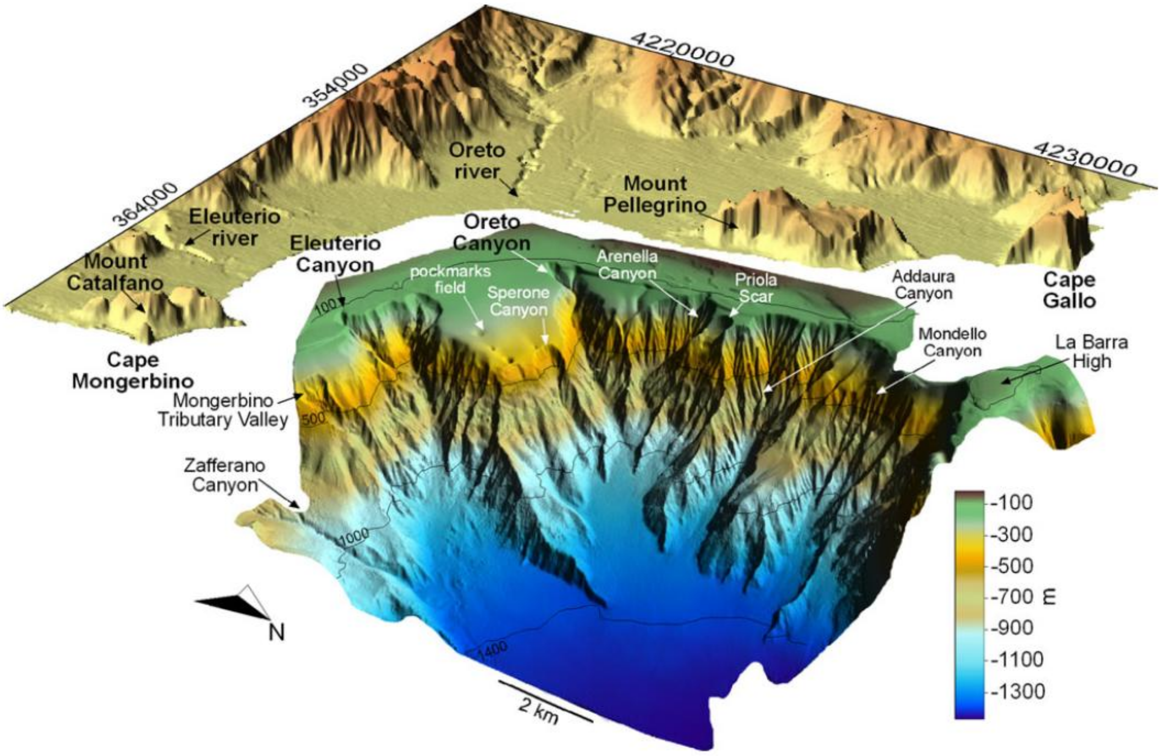
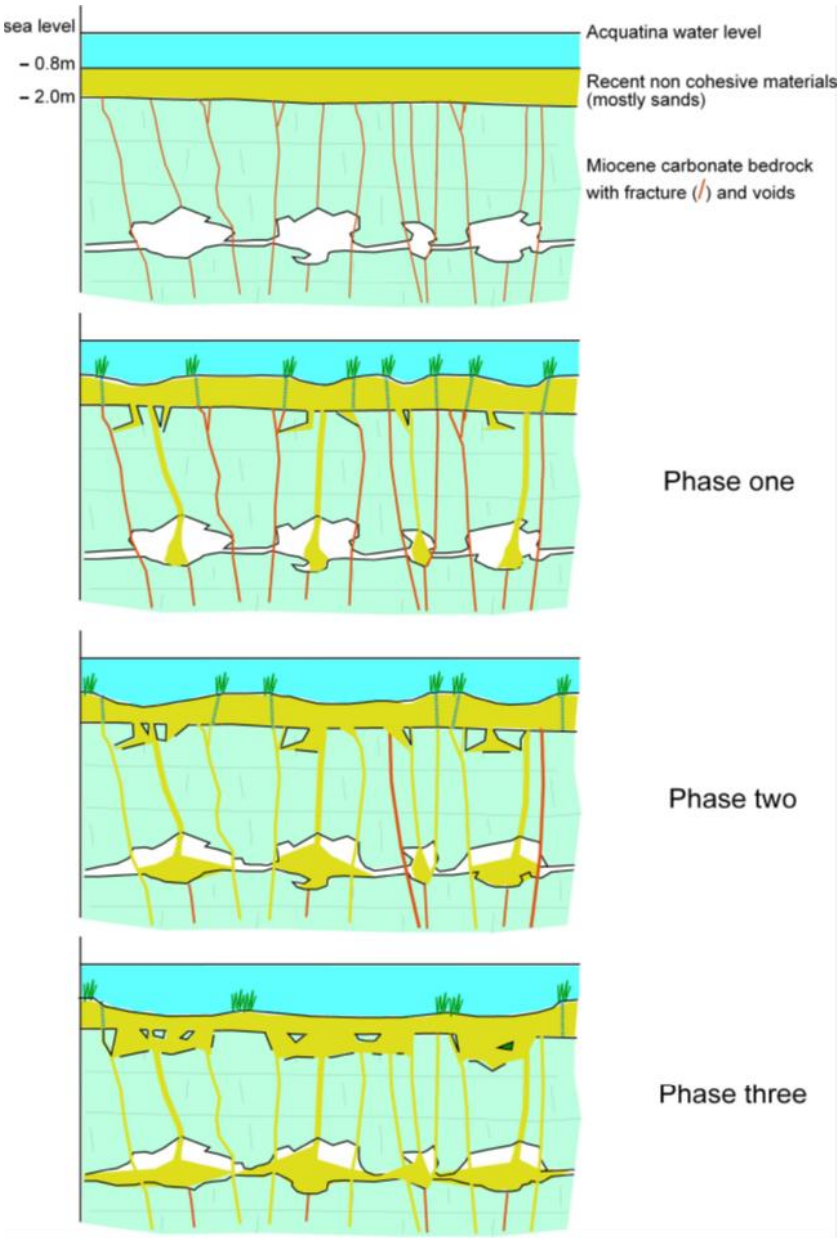
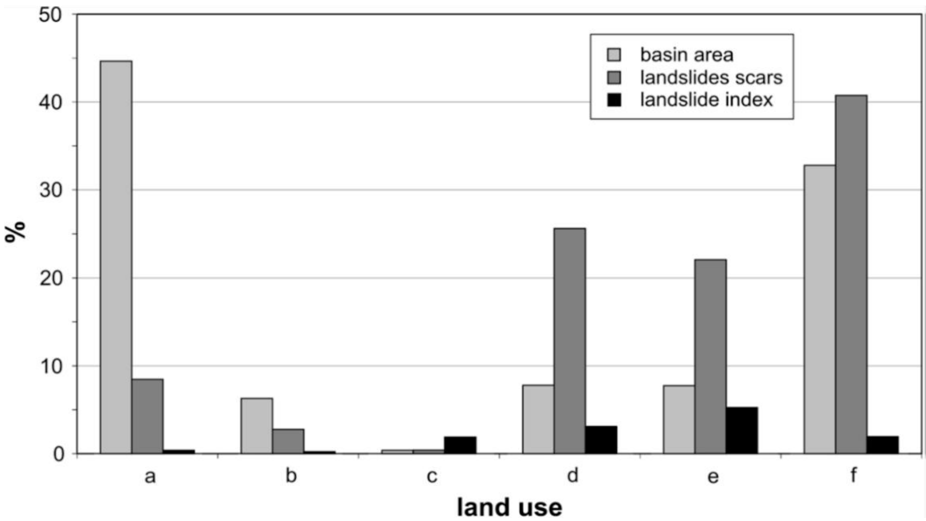


WP3_P12



WP3_P13


a
b
c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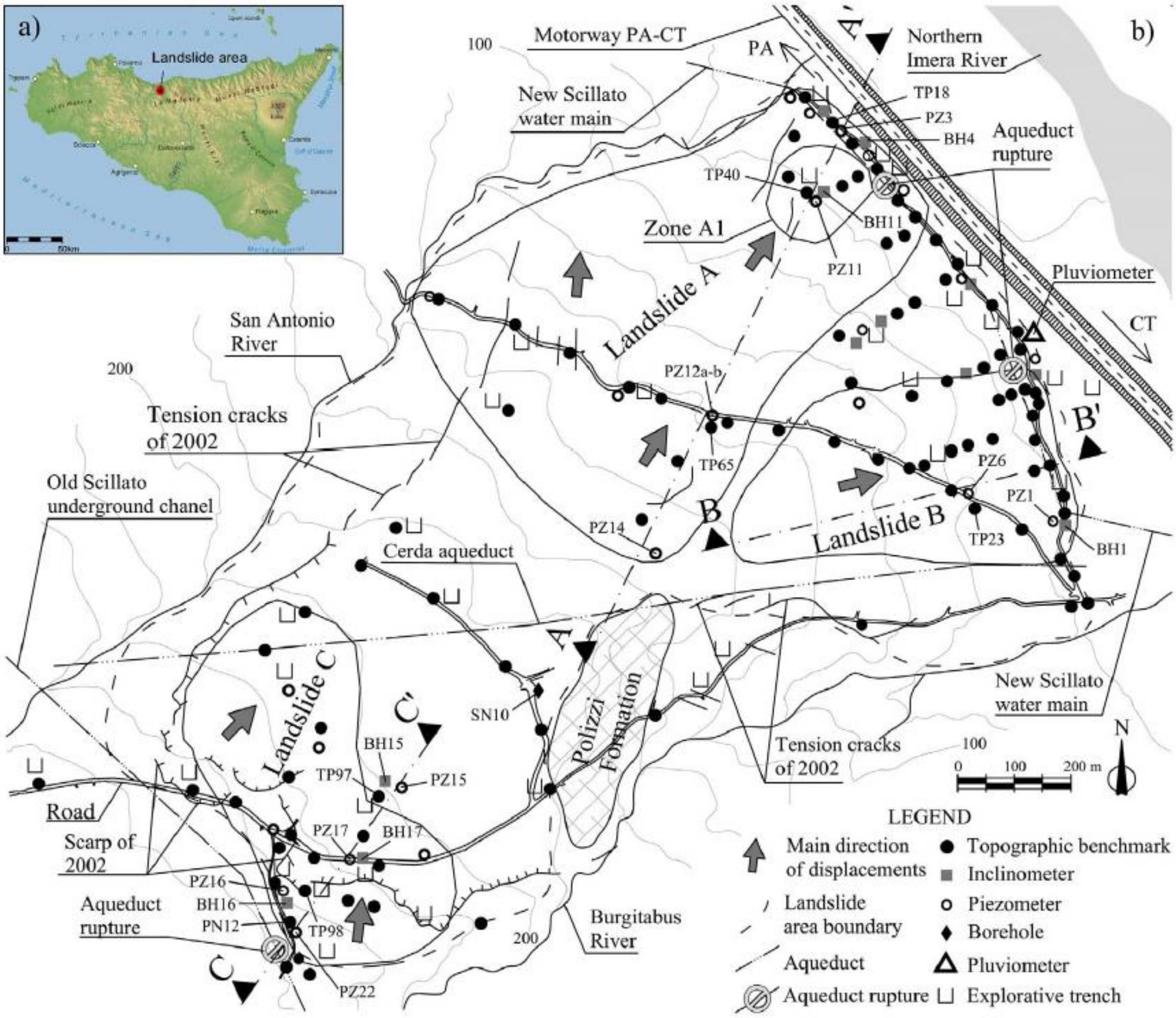
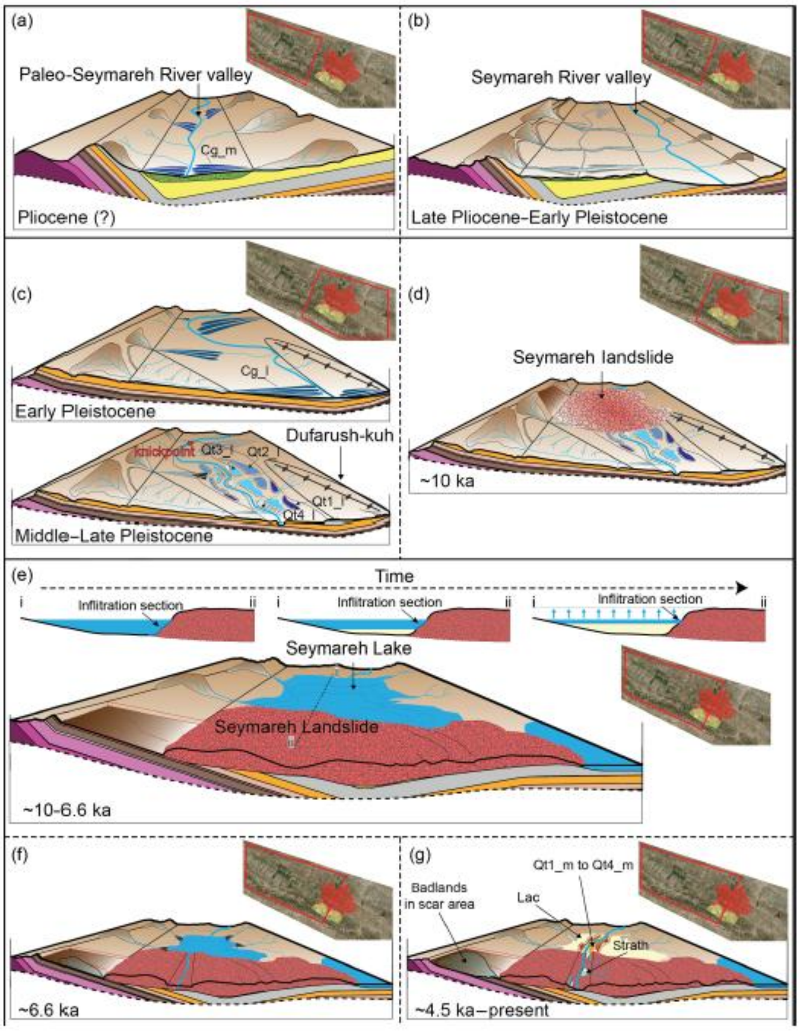
basin area
landslides scars
landslide index
a
b
c
d
e
f
land use

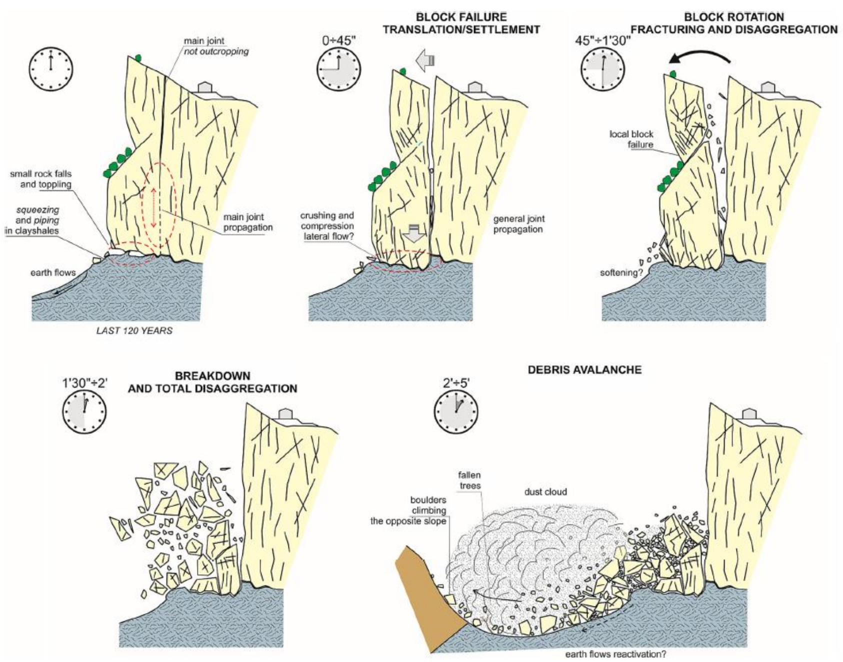
a)


a)
Landslide area
b)
Motorway PA-CT
Northern Imera River
New Scillato water main
Aqueduct rupture
Zone A1
Landslide A
Pluviometer
San Antonio River
Tension cracks of 2002
Old Scillato underground chanel
Cerda aqueduct
Landslide B
Landslide C
Polizzi Formation
New Scillato water main
Tension cracks of 2002
Road
Scarp of 2002
Aqueduct rupture
Burgitabus River
LEGEND
Main direction of displacements
Topographic benchmark
Inclinometer
Landslide area boundary
Piezometer
Borehole
Aqueduct
Pluviometer
Aqueduct rupture
Explorative trench

b)


(a)
Paleo-Seymareh River valley
Cg_m
Pliocene (?)
(b)
Seymareh River valley
Late Pliocene–Early Pleistocene
(c)
Cg_l
Early Pleistocene
Dufarush-kuh
knickpoint
Qt3_l
Qt2_l
Qt1_l
Qt4_l
Middle–Late Pleistocene
(d)
Seymareh landslide
~10 ka
(e)
Time
Infiltration section
Seymareh Lake
Seymareh Landslide
~10–6.6 ka
(f)
~6.6 ka
(g)
Qt1_m to Qt4_m
Badlands in scar area
Lac
Strath
~4.5 ka–present

c)


main joint not outcropping
small rock falls and toppling
squeezing and piping in clayshales
main joint propagation
earth flows
LAST 120 YEARS
BLOCK FAILURE TRANSLATION/SETTLEMENT
0÷45"
crushing and compression lateral flow?
general joint propagation
BLOCK ROTATION FRACTURING AND DISAGGREGATION
45"÷1'30"
local block failure
softening?
BREAKDOWN AND TOTAL DISAGGREGATION
1'30"÷2'
DEBRIS AVALANCHE
2'÷5'
fallen trees
dust cloud
boulders climbing the opposite slope
earth flows reactivation?

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3. PART B – WP4

3.1 Workflow summary and results

WP4 followed the same three-phase approach described for WP3 in PART A (Sections 2.1 to 2.3), but focusing of LEs related to trigger and multihazard:

i) Inventory of Learning Examples (LEs, Table 6).
ii) Individuation of LEs related to trigger and/or devoted to multihazard and/or uncertainty estimation.
iii) Definition of a Rationale for each process based on the available LEs (with a trigger/LE sheet almost identical to the one used for WP3, Table 4).

Differently from WP3, WP4 is organized in 4 tasks related to the context of analysis and not the methods of analysis, in particular:

- Task 2.4.1: Multiple geohazards for ground instabilities in ***near-shore and coastal areas***, volcanic islands.

- Task 2.4.2: Multiple geohazards for ground instabilities in ***hilly and mountain areas***, including destressed glacial valleys, high-intensity erosion slopes, permafrost deglaciation areas, and thermally stressed rock walls.

- Task 2.4.3: Multiple geohazards for ground instabilities in ***large plains***, ***sinkhole*** zones.

- Task 2.4.4: ***Reliability and uncertainness of statistical solutions***. Uncertainty assessment methods, based on back analysis of event distribution, for ensemble and single process as well as for coupled/cascade multiple triggers.

The association between the inventoried LEs and the reference tasks is shown in Table 6 and Figure 7. Given that the present DV is related to monitoring data and processing techniques, the LEs and LE rationale sheets, for which the learning of trigger and cascading processes were retrieved from monitoring, are highlighted in yellow in Table 6 and fully reported in the attachment 2 respectively.

In general, a good distribution of WP4 LEs was found over the different environments considered for trigger and multihazard (TK1 to TK3, Fig. 7a), with a dominant number of triggers and processes related to the mountain and hilly environment. A good number of LEs was also selected for the uncertainty estimation activities of TK4. Dealing with trigger and cascading processes, different study approaches with respect to WP3 were highlighted. In this case, numerical modeling is often more common than monitoring, while the combination of monitoring and modeling is generally the most common approach to the problems (Fig. 7b).

LEs and trigger/multihazard information derived from monitoring data are summarized in Figure 8. The most monitored trigger causes are rainfalls, followed by anthropic activities and earthquakes and water table variations (Fig. 8a). Cascading effects and multihazard are dominant with respect to single triggered events in all contexts and scales of observations (Fig. 8b and 8c). Only for landslides the number of single events overcomes the cascading LEs (Fig. 8d).

Table 6. Inventory of LEs for WP4 and related distribution on WP4 tasks. TK1: Task 2.4.1 – Near-shore and coastal areas, volcanic islands. TK2: Task 2.4.2 – Hilly and mountain areas. TK3: Task 2.4.3 – Plains, sinkhole zones. TK4: Uncertainty assessment. Rationale from monitoring data (Mon) or numerical modeling (Mod).

Institution	LE ID	LE name	TK1	TK2	TK3	TK4	*Mon*	*Mod*
ENEA	**EN_1_WP4**	***Provincia di Messina***		X		X	X	X
OGS	**OGS_1_WP4**	***Canyon di Squillace***	X				X	
	OGS_2_WP4	***Frana di Assi***	X			X		X
POLITO	**TO_1_WP4**	***Ammassi rocciosi instabili Alpi Occidentali***		X		X	X	
UNIBA	**BA_1_WP4**	***Daunia***		X			X	X
	BA_2_WP4	***Fossa Bradanica***		X	X	X	X	
	BA_3_WP4	***Coste Puglia e Basilicata***	X				X	X
UNIBO	**BO_1_WP4**	***Lago di Iseo (BS)***		X		X		X
	BO_2_WP4	***Costa romagnola***	X				X	
	BO_3_WP4	***Isola di Stromboli***		X				X
	BO_4_WP4	***Bologna area urbana***			X		X	
UNIFI	**FI_1_WP4**	***Regione Toscana***		X	X		X	
	FI_2_WP4	***Landslide dams***		X				X
	FI_3_WP4	***Italia settentrionale***		X			X	X
	FI_4_WP4	***Guidonia-Bagni di Tivoli***			X			X
UNIGE	**GE_1_WP4**	***Liguria e Piemonte***		X				X
UNINA	**NA_1_WP4**	***Provincia Napoli Nord***			X			X
	NA_2_WP4	***Emilia-Romagna***			X	X		X
	NA_3_WP4	***Monti Lattari (Campania)***		X				X
	NA_4_WP4	***Umbria-Marche***		X		X		X
	NA_5_WP4	***Napoli***		X			X	
	NA_6_WP4	***Bisaccia***		X		X	X	
	NA_7_WP4	***Ischia***		X		X		X
UNIPA	**PA_1_WP4**	***Frana di Scopello***	X	X	X		X	X
	PA_2_WP4	***Bacini Imera-Torto***		X	X		X	X
	PA_3_WP4	***Messinese ionico***	X	X			X	X
	PA_4_WP4	***Canyon Golfo di Palermo***	X				X	X
	PA_5_WP4	***Canyon di Gioiosa Marea***	X				X	X
UNIPD	**PD_1_WP4**	***Dolomiti***		X			X	X
	PD_2_WP4	***Po delta***	X		X		X	X
	PD_3_WP4	***Pianura Veneto-Friuliana***			X	X	X	X
	PD_4_WP4	***Torrenti montani (Multiple CA)***		X			X	X
UNIROMA	**SA_1_WP4**	***Molise (sismoinduzione)***		X			X	X
	SA_3_WP4	***Frane su versanti costieri di Conero, Vasto, Petacciato***				X	X	X
	SA_4_WP4	***Frana di Monte Mario (Via Teulada)***		X			X	X
	SA_5_WP4	***PARSIFAL (Multiple Case Studies)***		X			X	X
	SA_6_WP4	***Tivoli-Guidonia***			X		X	X
	SA_7_WP4	***Fiumicino***			X		X	X
	SA_8_WP4	***Time to failure Prediction (Multiple Case Studies)***		X			X	X
	SA_9_WP4	***Scilla***	X			X	X	X
	SA_12_WP4	***Roma (soglie pluviometriche innesco)***		X		X	X	X
	SA_14_WP4	***Stromboli***	X				X	
	SA_15_WP4	***Gioia Tauro (+ Cirò Marina)***	X				X	
	SA_16_WP4	***Stima probabilistica spostamenti co-sismici***	X	X		X		X

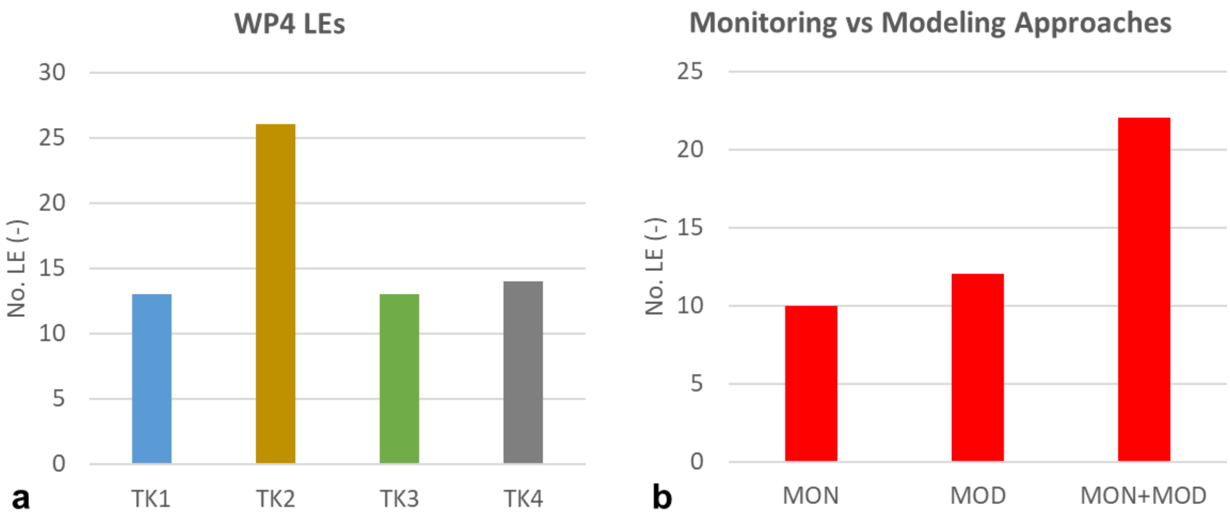


Figure 7. (a) Global distribution of WP4 LEs over the 4 tasks. TK1: Task 2.4.1 – Near-shore and coastal areas, volcanic islands. TK2: Task 2.4.2 – Hilly and mountain areas. TK3: Task 2.4.3 – Large Plains, sinkhole zones. TK4: Uncertainty assessment. (b) WP4 rationale outcomes derived from monitoring data (Mon) and/or numerical modeling (Mod).

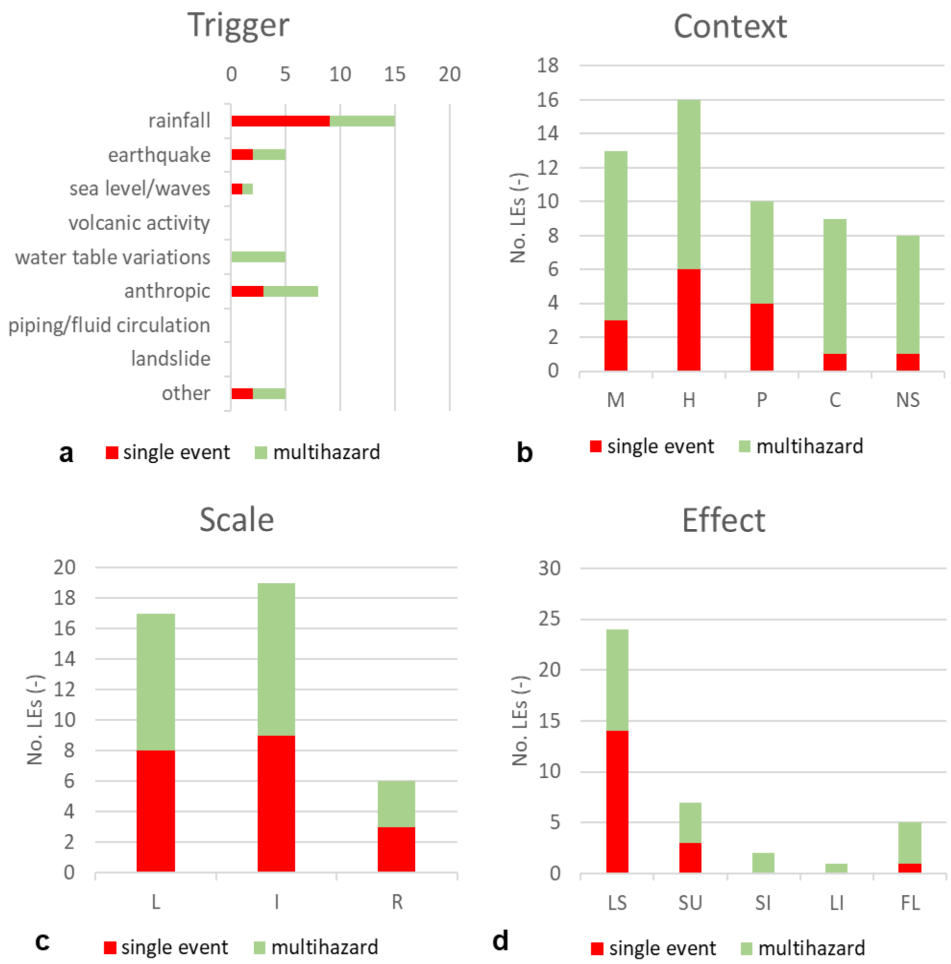


Figure 8. WP4 rationale information derived from monitoring data. (a) Trigger cause. (b) Context (M – mountain; H – hill; P – plain; C – coast; NS – near-shore). (c) Scale (L – local ; I – intermediate ; R – regional). (d) Effect (LS – landslide; SU – subsidence; SI – sinkhole; LI – liquefaction ; FL – fluvial dynamics). Single triggered events are reported in red, cascading events are highlighted in green.

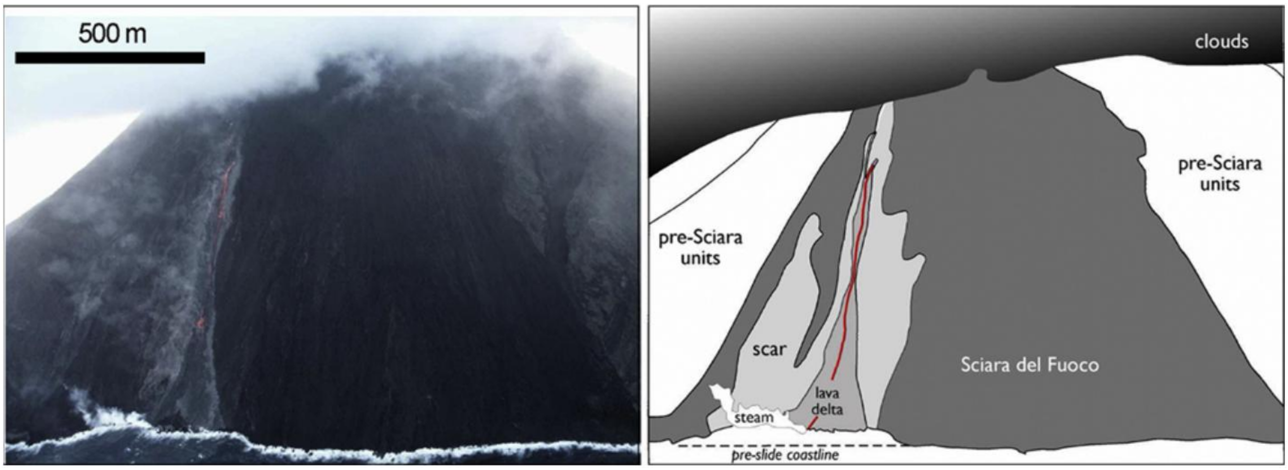
3.2 Examples and Figures of WP4 trigger and multihazard environments and effects

Table B1. List and description of the WP4 environments, with the captions of the related representative figures shown in this section (for reference papers see section 3.3).

Task	Environment	Reference	Figure Caption
2.4.1	**Near-shore and coastal areas**	Sansò et al. (2016)	*Cliffs showing a very shallow water-depth at their foot are fast retreating because of deep solution notches development linked to solution processes produced by sea/fresh waters mixing.*
2.4.1	**Volcanic islands**	Chiocci et al. (2008)	*Photograph of the Sciara del Fuoco lower slope 6 days after the landslide event (courtesy of the Civil Protection Department). The slide scar notching the coastline and the lava delta built inside it are clearly visible to left of the image*
2.4.2	**Hilly and mountain areas**	Brezzi et al. (2021)	*Frontal view of the Sant'Andrea landslide showing the complex composition of the soil involved.*
2.4.3	**Large plains, sinkhole zones**	Esposito et al. (2021)	*Example of a sinkhole occurred in 2017 within the study area. a) General view of the sinkhole (photo credits: https://roma.repubblica.it) and b) detail showing the presence of anthropic structures, thus testifying for the preexistence of anthropogenic underground cavities (photo credits: Francesco Fotia / AGF).*

TK 2.4.1 - Near-shore and coastal areas

TK 2.4.1 - Volcanic Islands



TK 2.4.2 - Hilly and Mountain areas

TK 2.4.3 - Large plains, sinkhole zones

3.3 WP4 LE reference papers

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4. Conclusions and further perspectives

In the period between January and July 2023, the research activities of WP3 and WP4 were devoted to the definition of a Rationale for the processes preparing ground instabilities and the trigger/multihazard events respectively.

To achieve this objective, the workflow was organized in three phases including: i) the selection and inventory of learning examples; ii) the analysis of the LEs for the definition of a reference list of preparatory processes (WP3)/trigger events and causes (WP4); iii) the creation of a rationale for each preparatory process based on the key points learned from each LE. Within the WP3, TK1-TK2-TK3 activities proceeded in parallel, since in a significant number of LEs the learning approach was mixing monitoring data, numerical modeling and machine learning. Despite the different internal organization, WP4 activities followed the same approach. The outcomes of both WPs derived from the analysis of monitoring data are summarized in the present DV.

For WP3, the first project phase highlighted the presence of 15 different preparatory processes with associated LEs. These processes are mainly studied in the subaerial environment, at the locale scale, in mountains and hilly areas and with a monitoring approach. As a result, the main studied effects are landslides. For the marine environment and the study of subsidence and liquefaction very little information was collected. In addition, despite the 15 identified preparatory processes, the majority of them were rationalized through the information and logs derived from less than 2 LEs. Quantitative logs are available for less than 50% of the preparatory processes. To overcome these limitations, in parallel with the future project activities and the definition of a Rationale and PoC, different strategies might be pursued:

1) Internal recall to collect extra LEs from the institutions cooperating to WP3 for the processes, environments and effects that were found to be less represented.
2) External call (exploiting the cascade funding opportunities) to enroll new partners bringing expertise and new LEs to the partnership in the highlighted weak areas.
3) Targeted search, with bibliographic research, to improve at least the learning about processes without sufficient monitoring data.

WP4 results obtained from monitoring data were found to be less represented than in WP3. The combined analysis through modeling data analysis and numerical modeling was found to be the dominant approach to the study of triggering and multihazard. The triggering of landslides was found to be the most studied effect also for WP4. The results also highlighted that multihazard is highly common for different environments and scales of observations. Further research efforts are still needed for the analysis of the propagation of the solid transport in the fluvial environment. In addition, the uncertainty estimation and quantification should be soon addressed by WP4 for the building of the Rationale, due for November 2023. The above mentioned strategies for the implementation of the robustness of the learning outcomes might be applied also to WP4 for a more comprehensive and effective definition of the Rationale and PoC.

In conclusion, Table 7 summarizes the main criticalities and weaknesses highlighted by WP3 and WP4 research work, together with the possible solution strategies that will be implemented in the future project months.

Table 7. Main critical points derived from WP3 and WP4 research work of January - July 2023 and proposed solutions.

Critical point	***Solution to be implemented***
Lack of marine and underwater LEs for the definition of a comprehensive Rationale for the related preparatory processes (WP3) and trigger/multihazard scenarios (WP4)	Dedicated ***cascade funding call*** to recruit new researchers with specific expertise in the marine environment
Minor representation of liquefaction, subsidence and sinkhole effects with respect to landslide studies and LEs (WP3 and WP4)	***Internal recall*** for LEs devoted to these analyses and eventual ***target search*** for international bibliographic data and processing methods
Lack of coverage with sufficient LEs for selected WP3 preparatory processes (e.g. WP3_P4)	***Internal recall*** for LEs devoted to these analyses and eventual ***target search*** for international bibliographic data and processing methods
Lack of WP4 LEs for multihazard related to propagation and solid transport in the fluvial environment	Dedicated ***cascade funding call*** to recruit new researchers with specific expertise in the field
Uncertainty assessment and evaluation for the Rationale	Dedicated ***cascade funding call*** to recruit new researchers with specific expertise in the field

Attachment 1 - WP3 Rationale Sheets (TK1)

The original working documents (WP3 Rationale Sheets related to TK1) have been classified and are available on the VS2 sharing platform (Microsoft Teams, link: Spoke VS2). They may be provided as a further attachment at a later stage of the Project.

Attachment 2 - WP4 Rationale Sheets (derived from Monitoring)

The original working documents (WP4 Rationale Sheets derived from Monitoring) have been classified and are available on the VS2 sharing platform (Microsoft Teams, link: Spoke VS2). They may be provided as a further attachment at a later stage of the Project.