multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

Codice progetto MUR: **PE00000005** – CUP LEAD PARTNER: J33C22002840002

Field-to-Num_Lab: experiencing innovative solutions for a real-time digital twin between in-site monitoring and numerical computation systems

Deliverable ID: **DV 2.3.3**

Due date: **31/07/2023**

Submission date: **31/07/2023**

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Technical references

Project Acronym	RETURN
Project Title	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
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Project Duration	December 2022 – November 2025 (36 months)

Deliverable No.	DV2.3.3
Dissemination level*	PU
Work Package	WP2.3 - Monitoring & Modelling: toward a digital twin of ground instabilities effects
Task	T2.3.2 - Numerical laboratories for digital twin reconstruction: numerical analyses devoted to quantifying the preparation parameters through multi-physical approaches based on data monitoring
Lead beneficiary	UNIBO
Contributing beneficiary/ies	UNIROMA1, UNIBA, UNINA, OGS, UNIGE, UNIPA, ENEA, POLITO

* 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)

Document history

Version	Date	Lead contributor	Description
0.1	12.07.2023	Filippo Zaniboni (UNIBO)	First draft
0.2	24.07.2023	Enrico Paolucci (UNIBO), Fabio Rollo (UNIROMA1)	Critical review and proofreading
0.3	27.07.2023	Salvatore Martino, Francesca Bozzano (UniRoma1); Domenico Calcaterra, Diego Di Martire (UniNA)	Edits for approval
1.0	31.07.2023	Participants to TK 2.3.2	Final version

Abstract

The project RETURN focuses on the study of natural risks and their effects on human and natural environment in view of the recent challenges associated with the climate changes. Among the other phenomena, Vertical Spoke 2 (VS2) addresses the theme of ground instabilities, in terms of landslides, sinkholes, subsidence and liquefaction. To analyze these occurrences, the whole process is schematized into three main classes of factors, dealing with different phases of the instability onset: predisposing, preparatory and trigger.

In the first year of activity, RETURN aims at building a Proof of Concept (PoC), e.g., a "synthesizer" of the factors leading to instability, moving from the available studies (learning phase). This goal is reached in different steps, that are here described: at first, the definition of an inventory of cases (the Learning Examples, LE), addressing the phenomena with different approaches and techniques; then, from this database a set of preparatory processes are identified and outlined; finally, the individual contribution of each LE to the process is characterized, describing its level of quantification and the constraints of applicability of such tool.

This document illustrates the different phases of the rationalization process, describing the procedure adopted to collect the tools contributing to the PoC and highlighting the main critical points rising from this kind of analysis.

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DV2.3.1	Deliverable 2.3.1 - *Data collection and analysis; implementation of geodatabases in advanced computing cloud systems*
DV2.3.3	Deliverable 2.3.3 - *Field-to-Num_Lab: experiencing innovative solutions for a real-time digital twin between in-site monitoring and numerical computation systems*
LE	Learning Example
P#	Process number
PoC	Proof of Concept
RETURN	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
TK1	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*
TK2	Task 2.3.2 - *Numerical laboratories for digital twin reconstruction: numerical analyses devoted to quantifying the preparation parameters through multi-physical approaches based on data monitoring*
TK3	Task 2.3.3 - *Deep learning and machine learning for mass wasting characterization in subaerial and submarine areas*
VS2	Vertical Spoke 2 – "Ground Instabilities"
WP2	Work Package 2.2 – State of the art and knowledge base to define impact-oriented hazard indicators
WP3	Work Package 2.3 - *Monitoring & Modelling: toward a digital twin of ground instabilities effects*
WP4	Work Package 2.4 - Trigger-based multiple geohazard scenarios

1. Introduction

This Deliverable is drawn up as part of Milestone 2.2 of Spoke 2 having as its topic (from the Executive Work Pan – Milestone 2.1) "Identification of impact-oriented indicators". The Deliverables of Spoke 2 for this Milestone have therefore set themselves as an overall objective the identification of rationales, starting from specific learning examples of literature, for identifying both the ground instabilities through macrocategories of factors (predisposing, preparatory, triggers) and the construction of analytical tools which, arranged in a specific logical-executive order (tool-chain), should lead to the design of an IT platform for the restitution in the PoC of the spatial overlap (multiple-hazard) or the temporal succession (multi-hazard, i.e. chain effects) of ground instability processes. This will allow quantifying the ground instabilities effects on the territory with a view to their impact on buildings and communities also evaluating their suitability and reliability.

This report aims to describe the activities undertaken in the framework of **Task 2.3.2**: Numerical laboratories for digital twin reconstruction: numerical analyses devoted to quantifying the preparation parameters through multi-physical approaches based on data monitoring (hereafter named **TK2**) included in the Work Package **WP2.3**: Monitoring & Modelling: toward a digital twin of ground instabilities effects (hereafter **WP3**), which is, in turn, part of the Vertical Spoke 2 – **VS2**: Ground Instabilities, that is one of the components of the Extended Partnership RETURN.

The general frame is the **RETURN** project (multi-Risk sciencE for resilienT commUnities undeR a chaNging climate), 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.

Such phenomena are approached in terms of three different factors controlling the destabilization process:

PREDISPOSITION (accounted for in WP2)

PREPARATION (WP3)

TRIGGERING and CASCADING HAZARD (WP4)

In short, the main aspect characterizing each factor is the **temporal scale**: "predisposition" refers to all phenomena that can be considered invariant at the scale of observation (morphology, geological features); "preparation" accounts for cyclical changes or trend that can be monitored and measured in the same timeframe (rainfall, groundwater level, sedimentation rate); "trigger" describes the impulsive, almost instantaneous event, causing the detachment (seismic shaking, intense rainfall). In this regard, the preparatory factors represent a contribution to a time-dependent quantification of expected effects in view of scenario modelling and restitution.

Such aspects are mainly studied in two distinct stages: in the first one, which is called "**learning phase**", the focus is on what is already available in previous studies and on what we can "learn" from them; the second one is the "**generation phase**", where all the information gathered from the first are applied to new contexts, to validate the assumptions and the results produced.

This report refers to the activities carried out in the period 01/01/2023 – 31/07/23, that are completely dedicated to the learning phase, which has as the main goal the development and realization of a Rationale for all destabilization processes that will be used as input to the Proof of Concept (**PoC**). This stage has been carried out simultaneously by all WPs (then for different factors causing the instability) and has been structured in different ways within each WP.

Concerning **WP3**, concentrating on the analysis of **preparatory factors**, this phase has been articulated in three stages, which will be addressed more in detail in the next sections:

i. Inventory of Learning Examples (**LE**, described in Section 2.1).

ii. Individuation of the **preparatory processes** analyzed in each LE (Section 2.2).

iii. Definition of a **Rationale** for each process based on the available LE (Section 2.3).

A further differentiation has been implemented, within WP3, on the basis of the methods adopted for the learning phase. Each of them has been addressed into a dedicated task with the following structure:

Task 2.3.1: learning from on-site and remote sensing monitoring data (hereafter **TK1**).

Task 2.3.2: learning from numerical modelling and simulations (hereafter **TK2**).

Task 2.3.3: machine learning techniques (hereafter **TK3**).

Indeed, the Tasks research activities have been accomplished across such distinctions, since the workflow was common: in specific, the three phases described above are the same for TK1, TK2 and TK3. In **PART A** of this document, then, the **rationalization of preparatory factors through numerical and statistical techniques (TK2)** is accounted for. Moreover, should such learning methods implement **machine learning techniques** (pertaining TK3) as well, they will be accounted for here. The results dealing with monitoring procedures (TK1) are reported in a separate report (DV 2.3.1).

Following the Executive Working Plan of RETURN which was delivered as Milestone 2.1 on 31 Dec 2022, the institutions cooperating with 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 led by Filippo Catani (UNIPD).

As previously mentioned, the learning phase involved each WP. As to **WP4 (trigger and multi-hazard)**, since the road to rationalization was very similar (with the same three phases) and such stage will not be accounted for in a dedicated report, the results that are compatible with TK2 activities will be included in **PART B** of this report, while the ones ascribable to monitoring techniques will be reported in DV 2.3.1.

Within WP4, the analysis of the results is not subdivided in terms of learning methods, as for WP3, but basing on the environment (apart from the last, dealing with a crucial element, i.e., uncertainty):

Task 2.4.1 (TK1): near-shore and coastal areas, volcanic islands.

Task 2.4.2 (TK2): hilly and mountain areas.

Task 2.4.3 (TK3): large plains, sinkhole zones.

Task 2.4.4 (TK4): uncertainty assessment.

Following the Executive Working Plan of RETURN which was delivered as Milestone 2.1 on 31 Dec 2022, the institutions cooperating with 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 led 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 occur: coast and near-shore areas (TK1), mountain and hilly areas (TK2), and plains (TK3). TK4 of WP4 is devoted to the quantification of the uncertainty for trigger evaluation.

As mentioned above, despite the different WP arrangements, both WP3 and WP4 followed the same approach for the study of preparatory processes and trigger/multi-hazard. The timeline of the WPs is summarized in Figure 1. The analysis of the LEs lead 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 constitute the base for the construction of the PoC in the next year of the project.

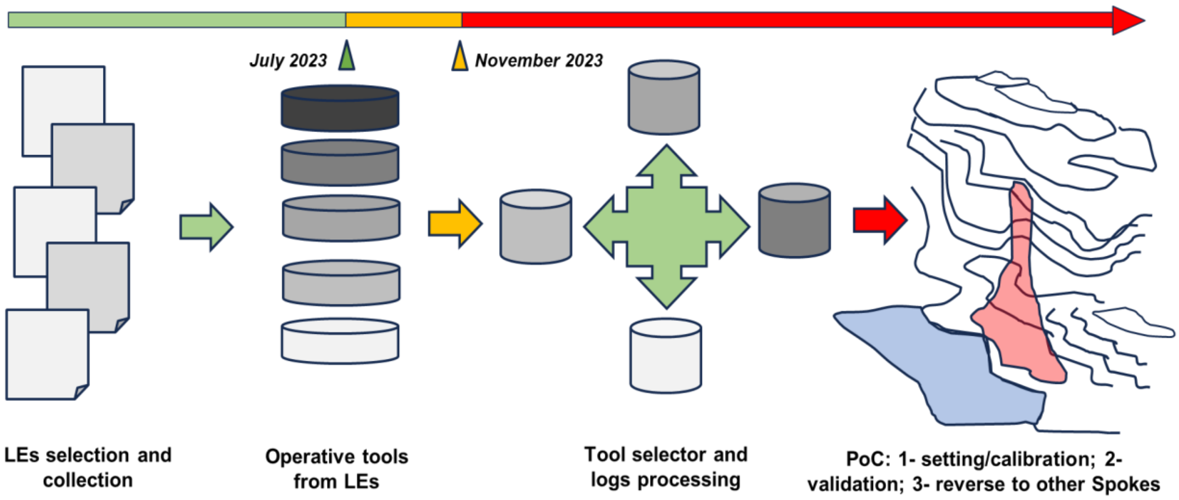

Figure 1. Timeline of WP3 and WP4 activities. The collection and analysis of LEs and their rationalization are reported in the present deliverable with a focus on monitoring applications and results.

2. Part A – WP3

2.1 Inventory of Learning Examples (LEs)

As stated in the previous section, the first two stages of the learning phase are in common among the three tasks: the description of the actions taken in these frameworks (TK1 and TK2) is then inevitably overlapped in the two respective deliverables (DV 2.3.1 and this document).

In the specific, this Section describes the activities related to the LEs collection, representing the already studied cases that provide the information needed to analyze and rationalize the preparation process to the ground instability. At the beginning of the project (***January – March 2023***) each institution involved in the VS2 was asked to identify an average of 3 LEs for each WP, relating the three aspects of the destabilization process illustrated in the Introduction. Two reference papers had to be stored in a corresponding WP ***shared online repository*** (Windows Teams), visible and accessible to all the participants. To support the discussion about LEs, the list of papers collected for WP3 is reported in Section 2.5. Similarly, WP4 repository is listed in Section 3.3.

Besides the upload of the reference papers, each LE was inserted in an ***online inventory list***, where the LE responsible had to include further information, codified as follows:

- proposing institution (abbreviation);
- name/denomination of the LEs (site name and/or geographical location or area of interest);
- environment (subaerial/submerged);
- context (mountain/hill/plain/coast/near-shore);
- effect (landslide/subsidence/sinkhole/liquefaction);
- scale (local/intermediate/regional);
- 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 the progressive number of the LE within the institution, *y* is the WP number relative to the destabilizing aspect, or aspects, addressed by the LE). Table 1 summarizes the most significant LE information pertaining to preparatory factors (WP3). Figure 2 reports the localization of all the LEs identified in this phase.

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			
	OG_2_WP3	*Canyon di Squillace (margine calabro ionico)*		X				X		X				X				X			
	OG_3_WP3	*Frana di Assi (margine calabro ionico)*		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_4_WP3	*Canyon Golfo di Palermo*		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 (La Thuile, Gressoney), Val Germanasca, Val di Susa (Thures, Champlas)*	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_2_WP3	*Provincia Napoli N*	X				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
UNIROMA1	**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		

It is worth reminding that some readjustments have been done during the whole process of rationalization: some LEs were removed from the original location and moved to another WP, both with a bottom-up procedure (on initiative of the LE responsible, realizing that the frame was not fitting the results and the analysis presented), and with top-down decisions (after proposals from WP or Task leaders during the collective analysis phase).

Figure 2. Localization of the LEs inventoried in the framework of WP2, WP3 and WP4.

2.2 LEs vs Preparatory Processes

The following phase of rationalization is the individuation of the preparatory processes based on the analysis of the LEs provided by the researchers. This was accomplished in the following months (mainly ***March – May 2023***).

The WP3 and TK leaders reviewed the LEs inventory with the proposing institution, aiming at the consolidation of the database, and assigning each case to the correct WP based on the aspects (predisposition, preparation, trigger) addressed in the study. Once identified the works pertaining to each frame, it was possible to identify the **salient processes preparing the ground instability**. These were identified starting from the reference papers, deducing from these the preparatory processes, and trying to group them into classes, embracing similar, or at least correlated, cases.

The result of this analysis and "extraction" activities is visible in Table 2: 15 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 (with anthropogenic or geological origin, for example). 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.

The following step consists of the inversion of the LE-processes matrix: the focus is shifted to the second, with the first that can be considered as the data "sources" to the rationalization. Table 3 reports the LEs associated to 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)

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
	PA_6_WP3
	SA_4_WP3
	SA_5_WP3
	SA_6_WP3
	TO_3_WP3
	BO_4_WP3
	BO_5_WP3

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.

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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, Figure 3a) highlights that the studies of the second type currently focus only on a subset of them (WP3_P8 to WP3_P11). A challenge for the RETURN project might be to reach a more comprehensive view of submerged processes to better unify the treatment between the two environments, even though this is not possible for all listed processes.

The distribution by environmental contexts (Figure 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 (Figure 3c).

The distribution of preparatory processes by type of effect (Figure 3d) highlights the clear prevalence of expertise gained by the VS2 research team on landslides. A non-negligible learning experience is also available for sinkholes, while further research efforts should be spent on the analysis of the preparation for liquefaction and subsidence.

The distribution of preparatory processes by type of monitoring (remote or contact/onsite, Figure 3e) appears balanced.

Regarding the types of analyses (Figure 3f), the distribution over preparatory processes is wider for deterministic and statistical analyses than for 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 (Figure 3e).

2.3 Towards the rationale

The final stage of this phase (carried out mainly in **June and July 2023**) is the building of the Rationale, i.e., the extraction of the information from each LE for the composition of the PoC. Such activity needs the full involvement of the LE's authors, who are the most expert and proficient in the knowledge of the analyses and results produced. This activity has been driven by the WP and TK leaders moving from the process classification presented in the previous section, preparing a rationalization sheet aimed at gathering all the information about the LE contribution to the process quantification.

The scheme of the sheet is reported in Table 4 and consists of an input section, where the LE responsible inserts the parameters controlling the process and explains how this input works and the constraints of applicability, and an output section, describing what result can be expected and in which form. Further description is visible in the sheet.

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.

Table 4. Process-LE sheet structure for the Rationale, with the 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)*
2) INPUT DATA TO THE RATIONALE for the analysis of the process	Input parameters needed to operate this learning tool. *What does this tool do?* *What input data are needed to make this tool work in the PoC?*
3) LEARNING METHODS (from which the input data were derived) *(onsite/remote monitoring – Task 1; numerical modelling – 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/modelling/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)*	*Basing 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?*

Within WP3 the rationalization proceeded in parallel between the 3 tasks as well (TK1 – learning from monitoring data, TK2 – learning from numerical modelling, 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.

An example of a completed WP3 sheet concerning activities within TK2 is provided in Table 5. All the WP3 Rational sheets related to this task (modelling) are attached to the present DV (Attachment 1).

Table 5. Example of WP3-TK2 rationale sheet.

PROCESS	**WP3_13** **Anthropogenic preparation related to static loads and variations of the groundwater level**
LEARNED FROM *(indicate the code of the reference LE - learning example)*	**SA_10_WP3**
1) PROCESS CONTROL PARAMETERS	1) geometry of the slope and hydraulic regime 2) physical and mechanical properties of soils (strength, stiffness, hydraulic conductivity) 3) predisposing factors: variation of the stress state and of the hydraulic regime induced by processes of excavation of the quarry slope
2) INPUT DATA TO THE RATIONALE for the analysis of the process	1) time-modification of the slope geometry induced by the excavations processes of the quarry 2) excavations combined with consolidation processes in soils related to a time-modification of the hydraulic regime in the slope

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)***	**Task 1** – on site monitoring (piezometers and inclinometers) **Task 2** – Limit equilibrium analyses and finite difference numerical 2D analyses using a coupled hydromechanical approach (u-p approach)
4) APPLICABILITY CONSTRAINTS ***(specify the application context/environment, highlight the spatial and temporal scale limits and the requirements for applicability)***	The scale is that of the slope. Inclination of the slope: 10 ÷ 15° with respect to the horizontal plane, with groundwater level located between 2 and 6 m depth from the ground level and failure occurring along rotational neo-formation mechanisms induced by quarrying activities at the toe of the slope. Soil characteristics: sub-Apennine saturated blue clays of medium plasticity (PI = 20 ÷ 30 %) characterised by overconsolidation ratio OCR = 3 ÷ 10 (higher values at shallow depths, lower values attained around 50 m depth). Hydraulic conductivity in the range of 5x10-11 and 7x10-11 m/s.
5) ANALYSIS LOGS ***(specify if qualitative, semi-qualitative or quantitative)***	**semi-qualitative**: the numerical analyses carried out in this case allow to define typical patterns of the instability mechanisms as compared to the monitoring results. Lesson learned is that the effect of the quarry excavation on the modification of the hydraulic regime in slopes and the consequent displacements induces by the attainment of the shear strength are characterised by a certain delay that depends on the consolidation processes.
6) OUTPUTS ***(specify if categories or indexes or algorithms according to the analysis logs and provide a full description of each output)***	The results indicate that the deep retrogressive failure mechanism leading to a neo-formation landslide was triggered by the pore pressure equalisation process, still occurring in the slope well after the end of quarrying. The retrogressive failure typically occurs along circular slip surfaces connecting the toe and the top of the slope, with a longitudinal extension within the range of 1.5÷2 times the height of the front of excavation of the quarry. The displacement rates are in the range of 4-5 mm/day and are typical of slow movements, hence the time required to reach a stabilisation of the process ranges within 20÷30 years after the conclusion of the quarrying.

This rationalization phase required many interactions between the WP – TK responsible and the LE referents since this quantification was not always trivial or easy to synthesize. Figure 4 shows some statistics concerning TK2: it can be noticed that the modelling approach is adopted only in a fraction of processes (Figure 4a), 7 of 15 total.

The other plots refer to other characteristics and subdivisions relative only to the LEs contributing to TK2, i.e., that reports numerical modelling as a learning method. It is possible to note that the local scale of observation is prevalent (>60%, Figure 4g) and the subaerial environment prevails on the underwater one (Figure 4d), as already noticed. Within modelling learning techniques, landslides are largely the most studied phenomena (Figure 4e), while the different contexts are well distributed (Figure 4f), as well as the analysis logs (Figure 4i). Four processes were quantified, i.e., P3, P6, P8 and P15; only one process (P15) is rationalized with qualitative, semi-qualitative and quantitative analysis logs.

Only one rationalization process is based exclusively on modelling techniques (Figure 5a and Figure 5b). The most frequent approach (about 75%) adopts a mixed monitoring-modelling technique: in these cases, monitoring is dominated by contact measurements and by on-site monitoring network with respect to remote sensing, similarly to what has been observed for TK1 (Figure 4b). In three cases, this mixed approach is integrated with machine learning techniques (TK3, Figure 5a). The combination of modelling and ML without monitoring is not accounted for.

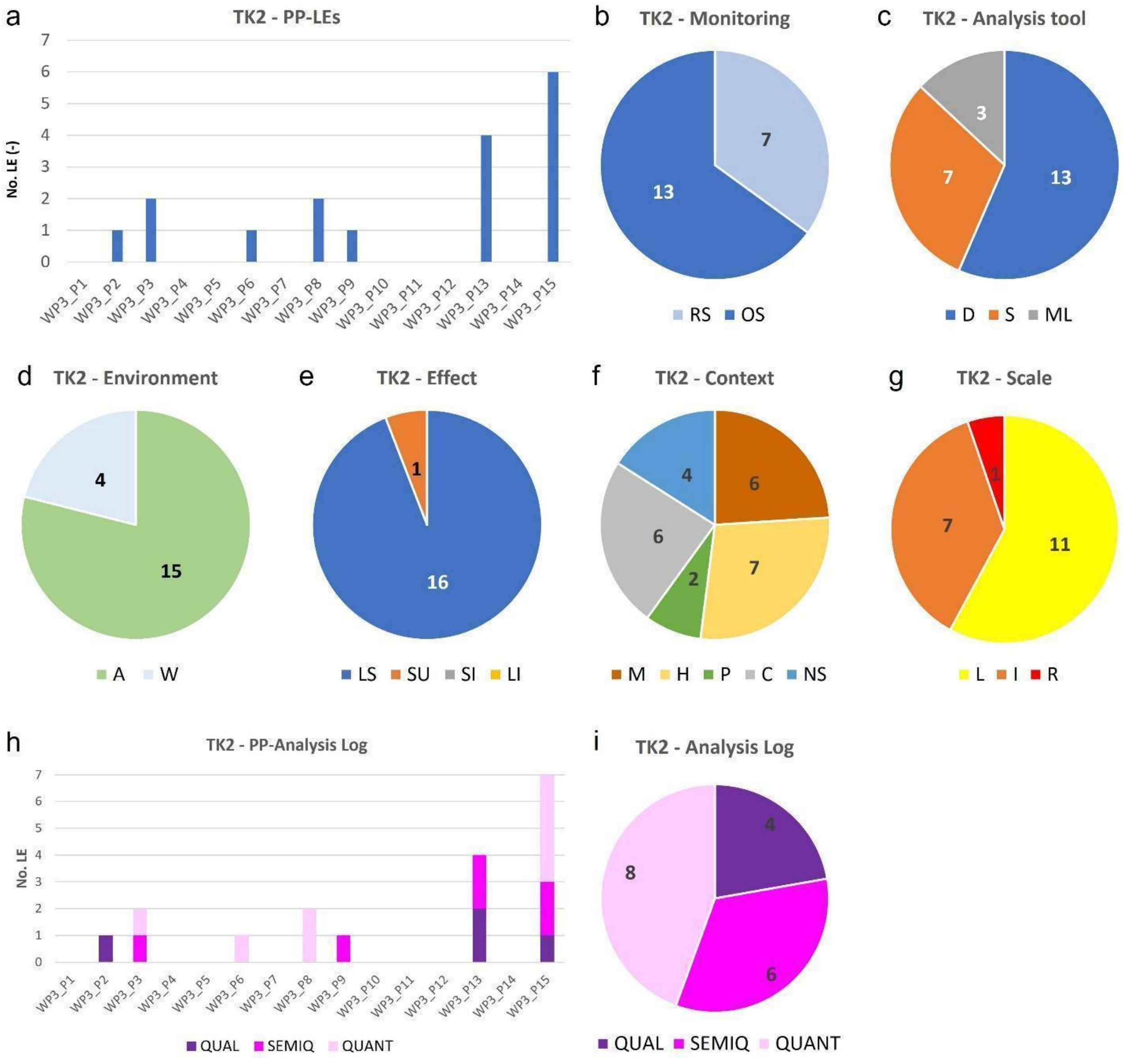


Figure 4. WP3-TK2 rationale from LE reporting modelling techniques as learning methods. (a) Number of LEs per preparatory process from which the rationale was achieved. (b) Monitoring tools: RS – Remote; OS – onsite/contact. (c) Analysis tools: D - deterministic analysis; S – statistical analysis; ML – Machine Learning. (d) Environment: A - subaerial; W – underwater. (e) Effect: LS – landslide; SU – subsidence; SI – sinkhole; LI – liquefaction. (f) Context: M – mountain; H – hill; P – plain; C – coast; NS – near-shore. (g) Scale: L – local; I – intermediate; R – regional. (h) Number of LEs per preparatory process divided for analysis log: QUAL - qualitative; SEMIQ – semi-qualitative; QUANT – quantitative. (i) Analysis log methods referred to the total number of cases: QUAL - qualitative; SEMIQ – semi-qualitative; QUANT – quantitative.

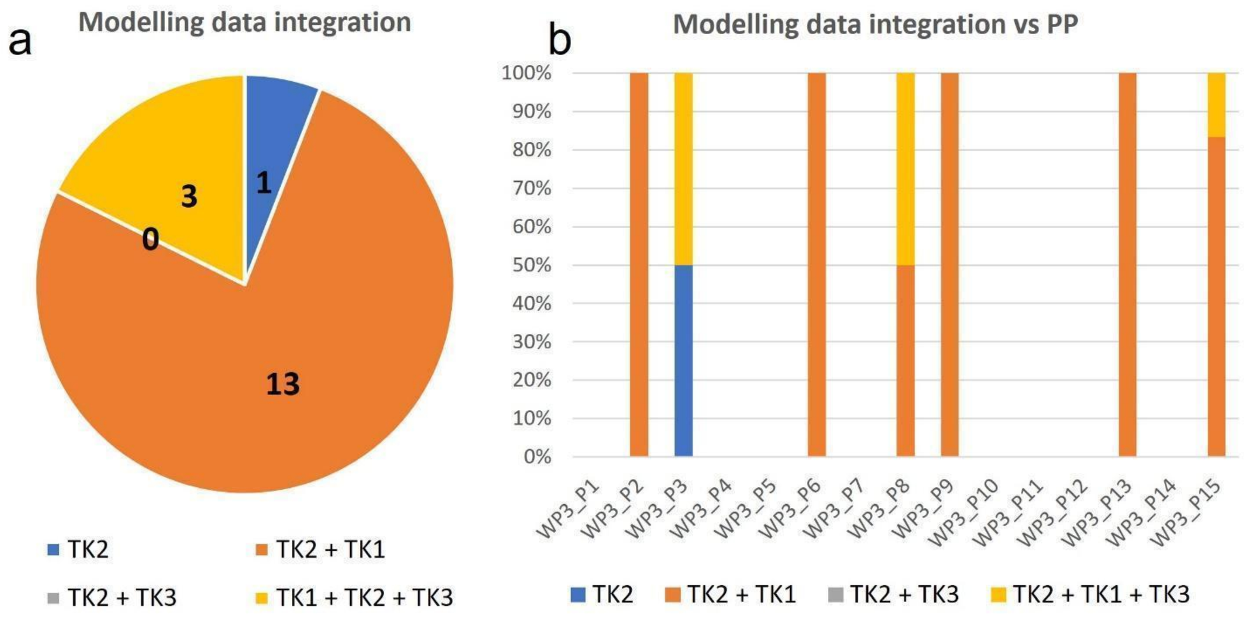


Figure 5. Learning methods adopted within TK2, with quantification of integration with respect to other approaches (TK1 – learning from monitoring; TK3 – machine learning). (a) Percentage of LEs involving modelling activities alone or coupled with other methods. (b) Level of coupling of learning methods for the specific processes.

2.4 WP3 Processes figures

Table 6. List and description of the processes/classes of processes, with references and caption of the related figures, reported subsequently.

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)	a) View of the Cheminée (Northern Italy) rockfall scar. b) 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;) sand and conglomerate; 2) clay; 3) sliding surface.
WP3_P9	Preparation for coastal landslides or at canyon heads and/or continental margins	Fig. 1: Casalbore et al. (2020)	1) On the left: Difference map obtained by comparing multibeam bathymetries acquired pre- (February 2002) and post-slide (January 2003) showing the geometry of

	related to debris accumulation from riverbeds (deltaic systems) and subaerial processes (e.g. coastal landslides, lava flows)	Fig. 2: Chiocci et al. (2008)	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. 2) 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)	Fig. 1: Rosone et al. (2018) Fig. 2: Delchiaro et al. (2019)	1) 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

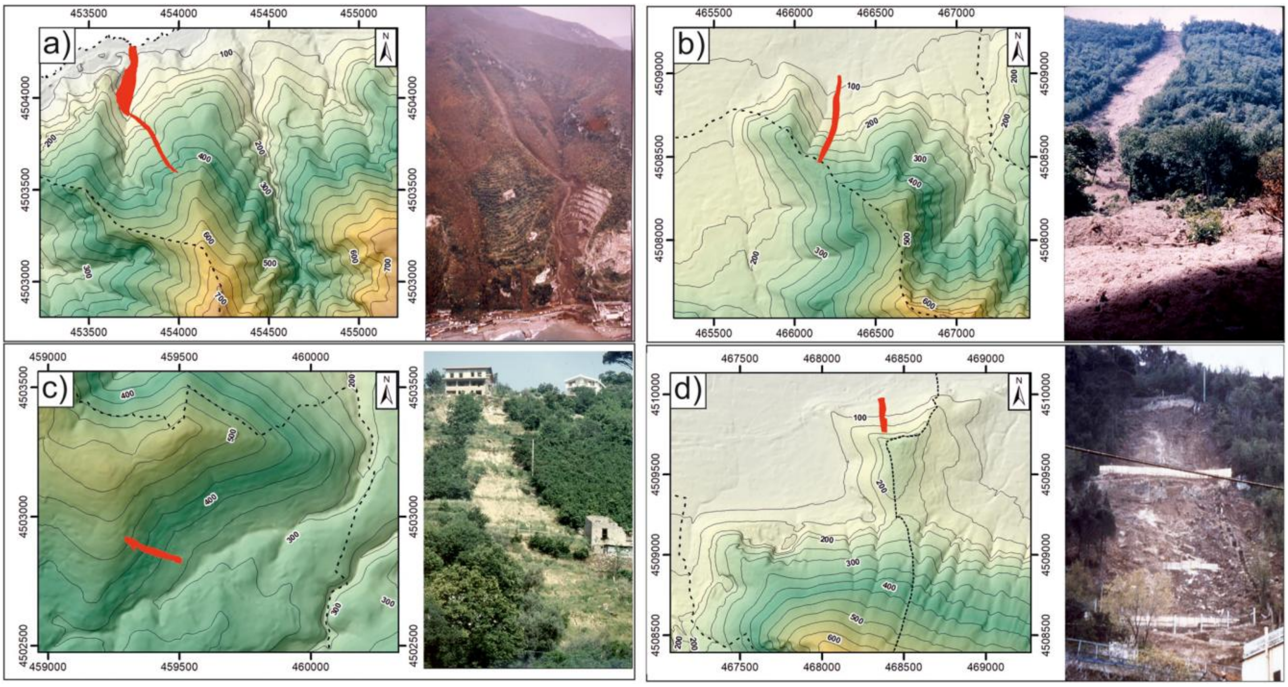
		Fig. 3: Borgatti et al. (2015)	spring 2009 and the main geotechnical investigations performed. 2) Evolutionary model of the Seymareh River valley. **a)** setting of a paleo-Seymareh river into a synclinal valley, likely developed in the Pliocene, to the west of the present position of the Seymareh River and deposition of fan deposits (Cg_m); **b)** 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); **c)** 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; **d)** 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; e) 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); **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; **f)** 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; g) complete emptying of the lake and generation of the suite of fill terraces entrenched in the deposits of Seymareh Lake (4.5 ka–present). 3) Tentative reconstruction of the time evolution of the landslide event

a)

b)

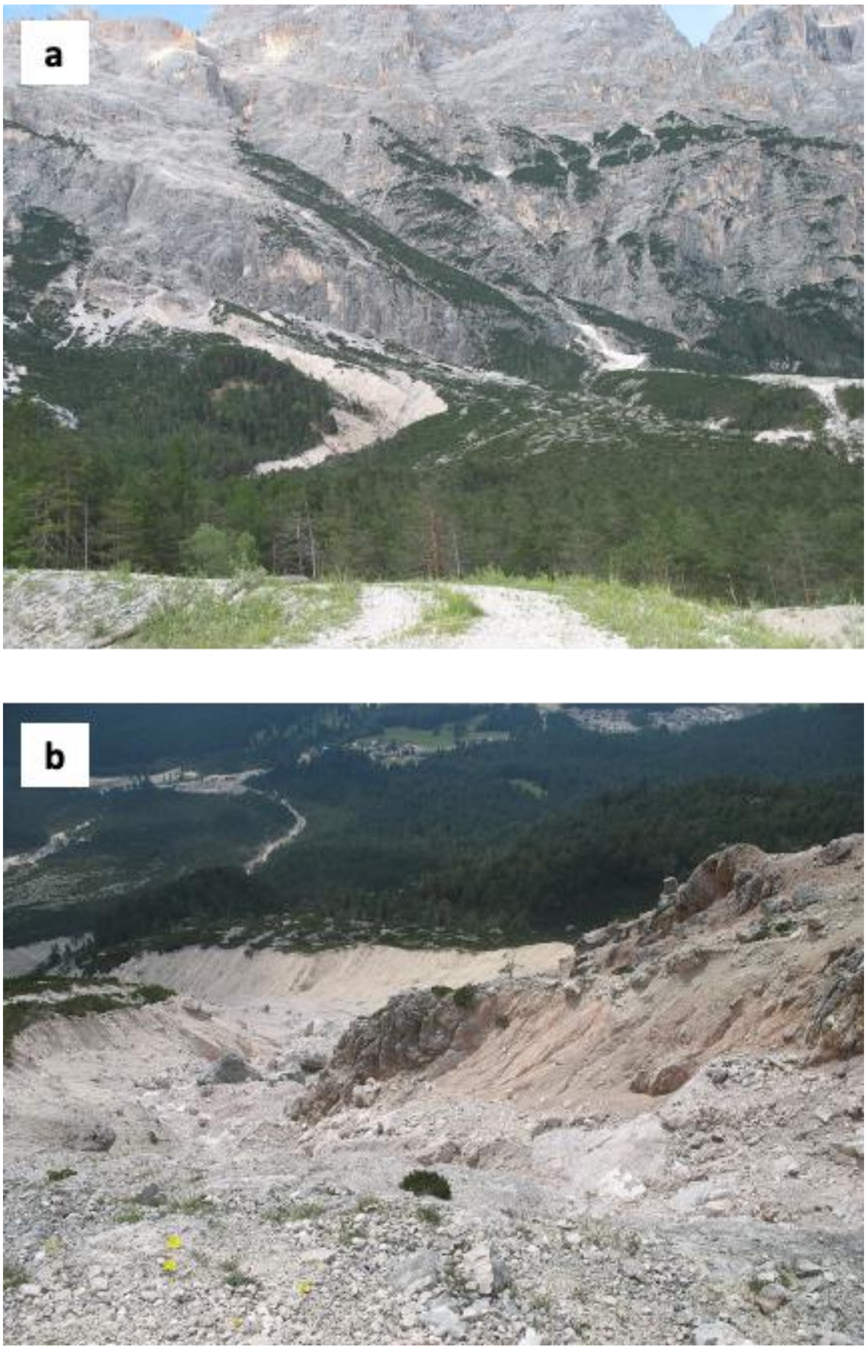
c)

P2 - Preparation for the detachment of soils related to variations in the saturation due to seasonal cumulated rainfalls



P3 - Preparation for the detachment of soils related to the effects of wildfires

P4 - Preparation for debris flows related to seasonal accumulation of debris in the high elevation feeding areas



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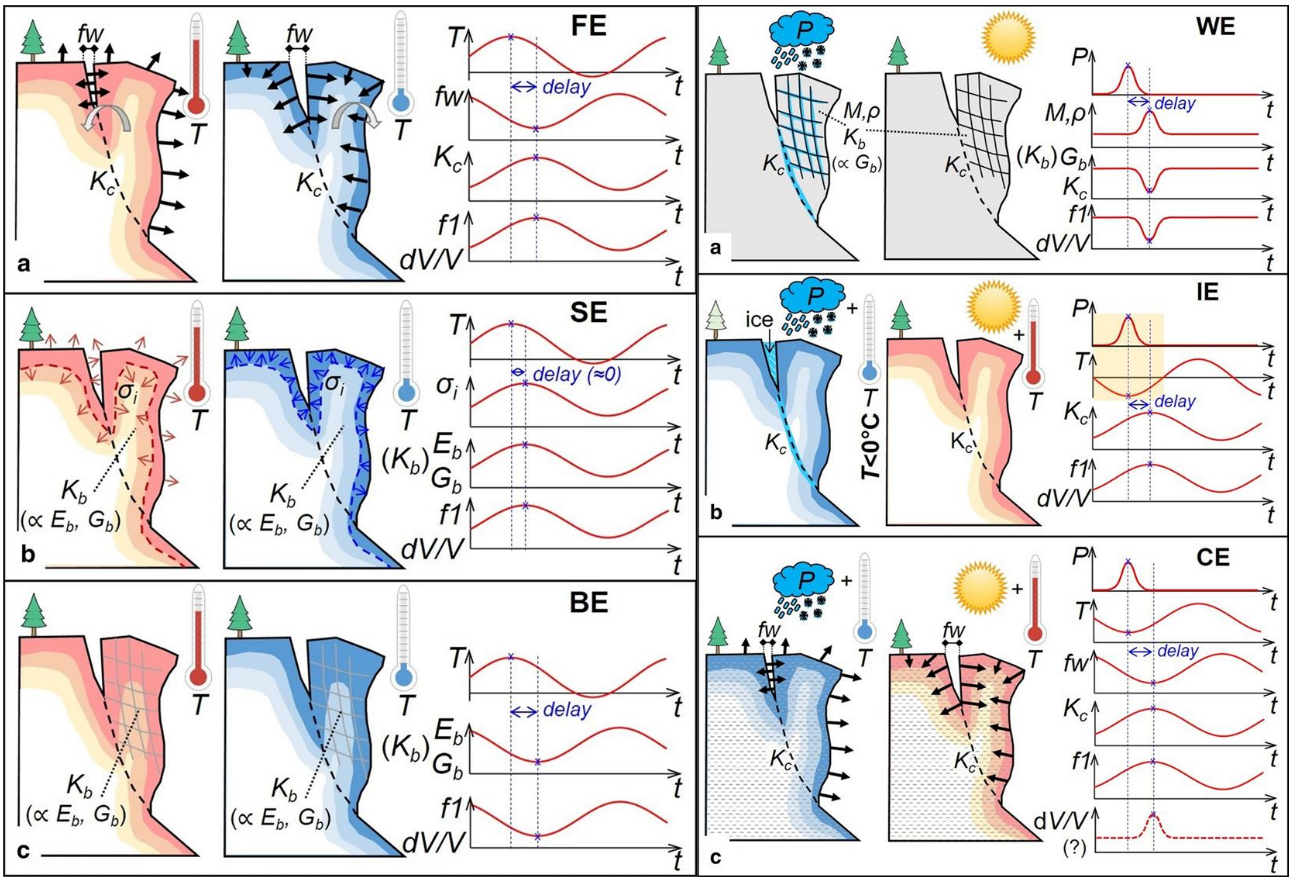
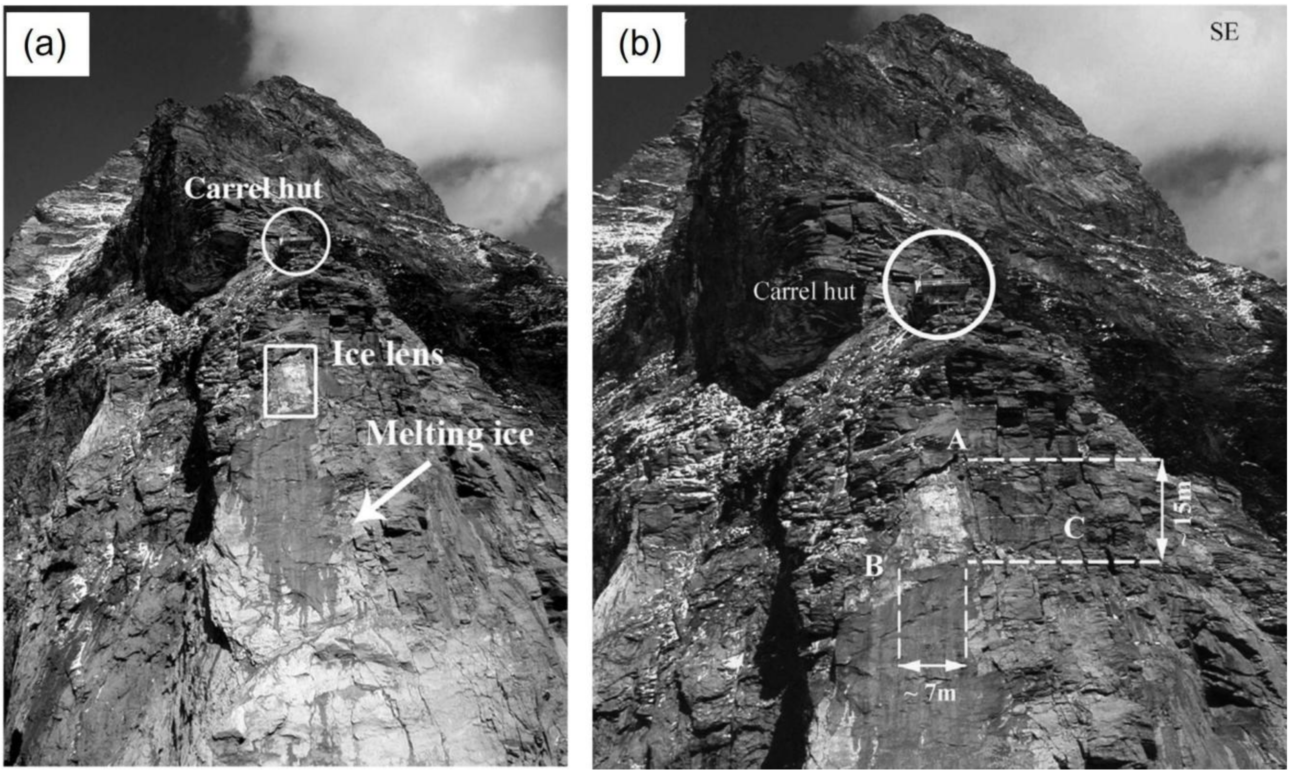
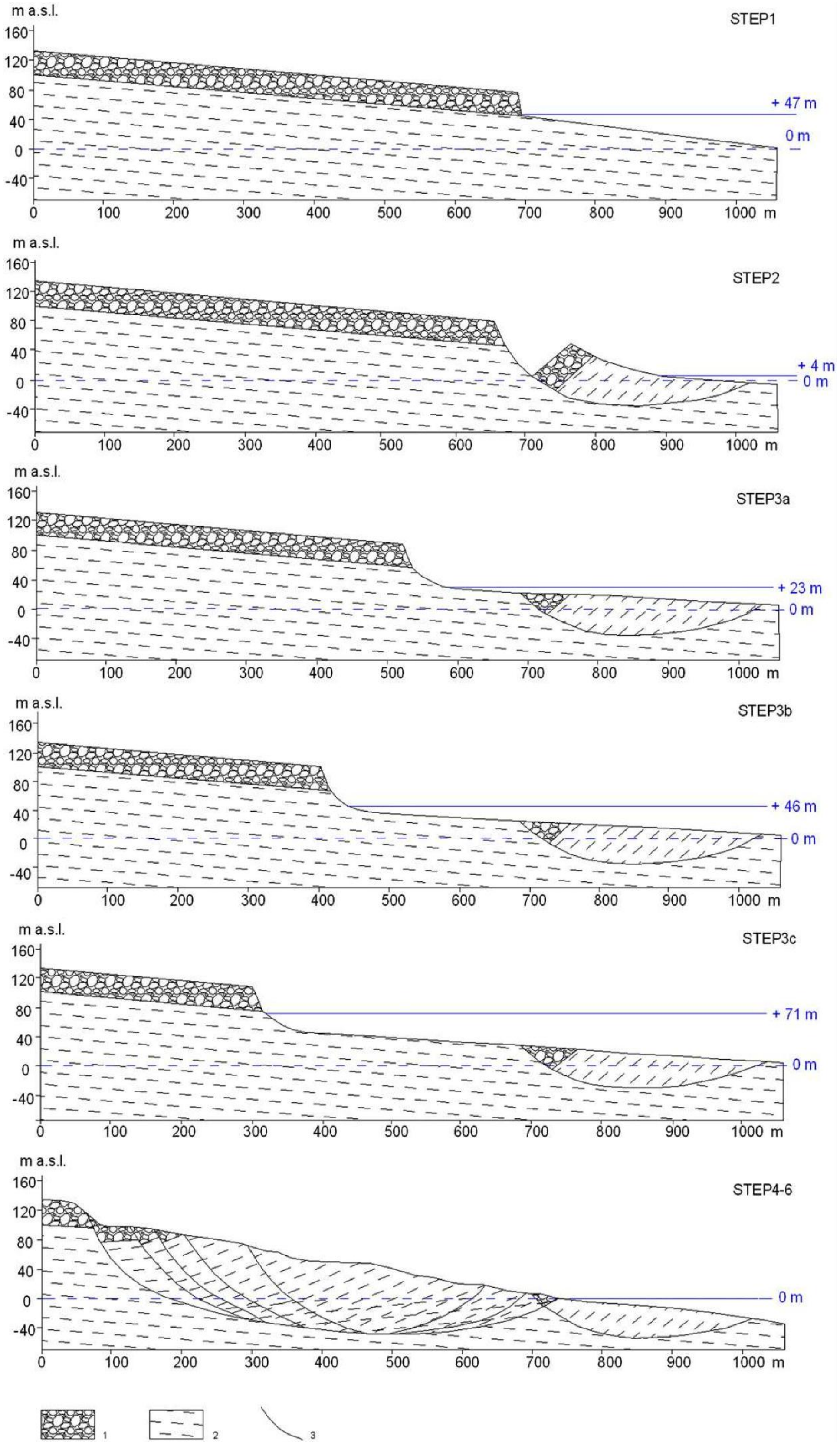
P5 - Preparation related to durability of debris damming bodies in the riverbed

P6 – Preparation for the detachment of rock volumes related to diurnal and seasonal thermal stressors



P7 - Preparation for the detachment of rock volumes related to permafrost degradation




STEP1
+ 47 m
0 m
STEP2
+ 4 m
0 m
STEP3a
+ 23 m
0 m
STEP3b
+ 46 m
0 m
STEP3c
+ 71 m
0 m
STEP4-6
0 m
m a.s.l.
1
2
3

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)

Fig. 1

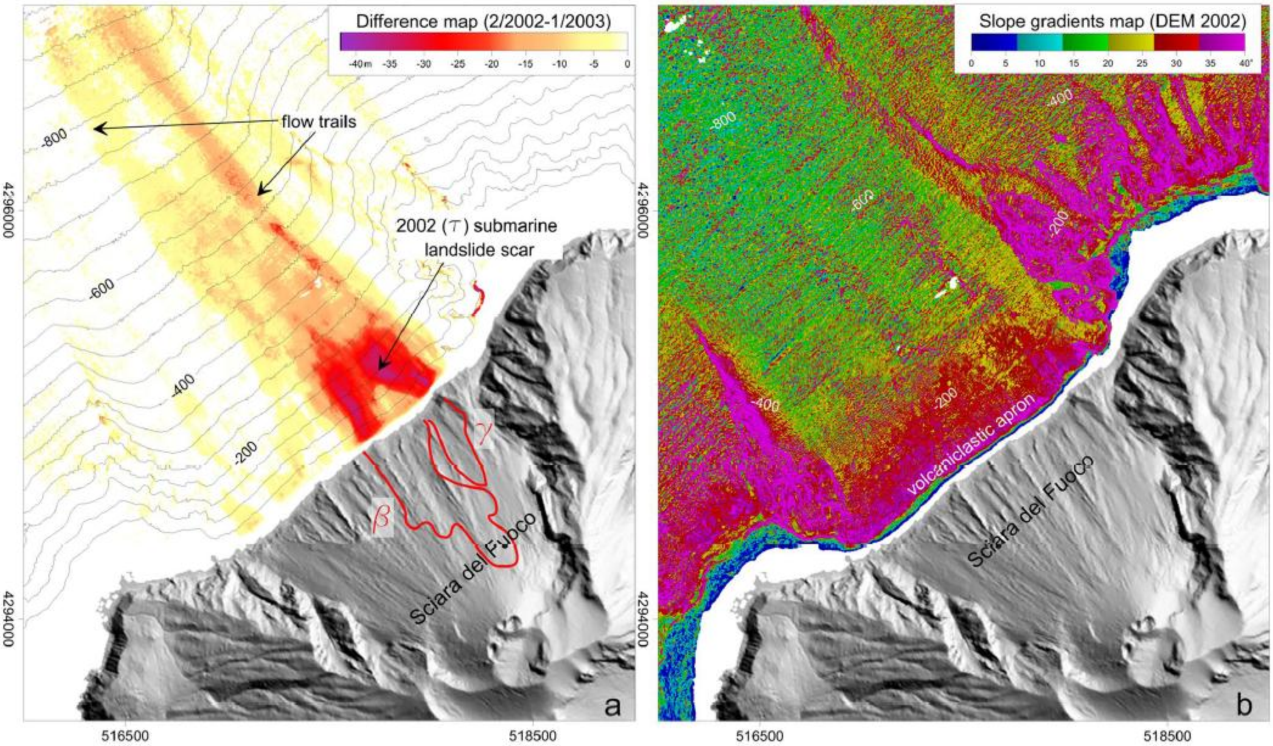
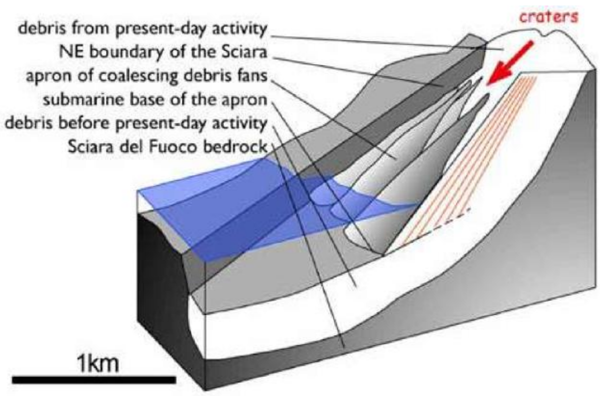
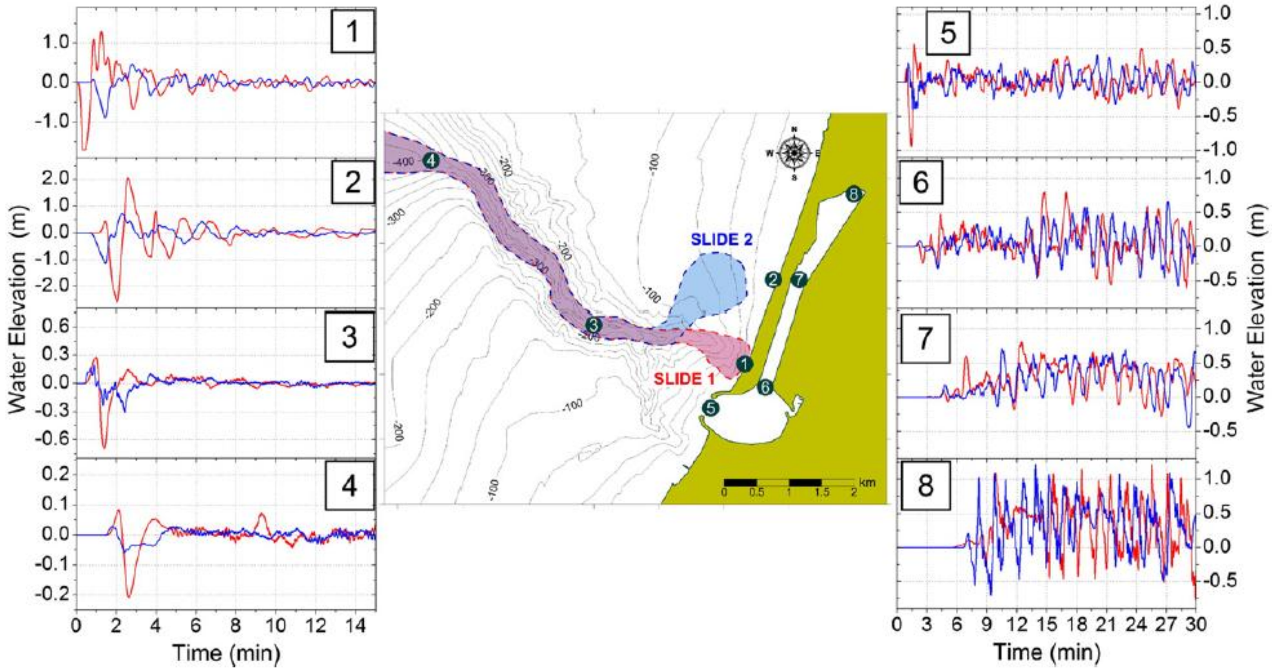
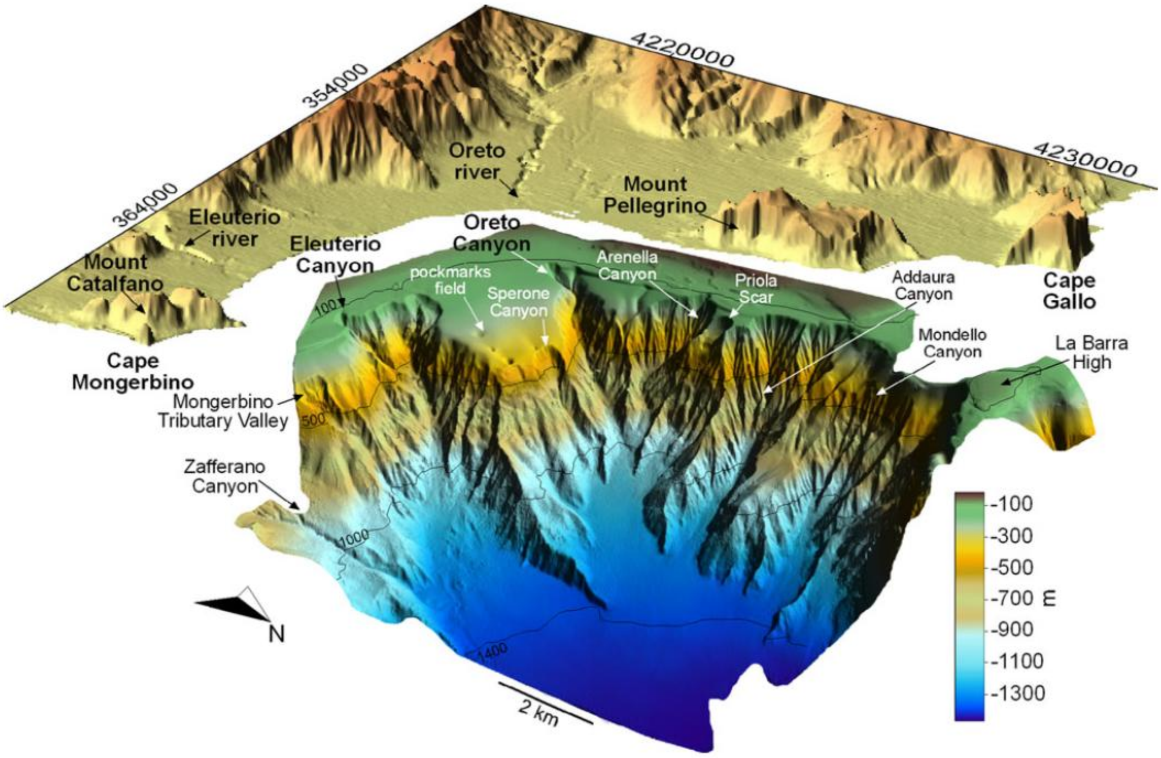
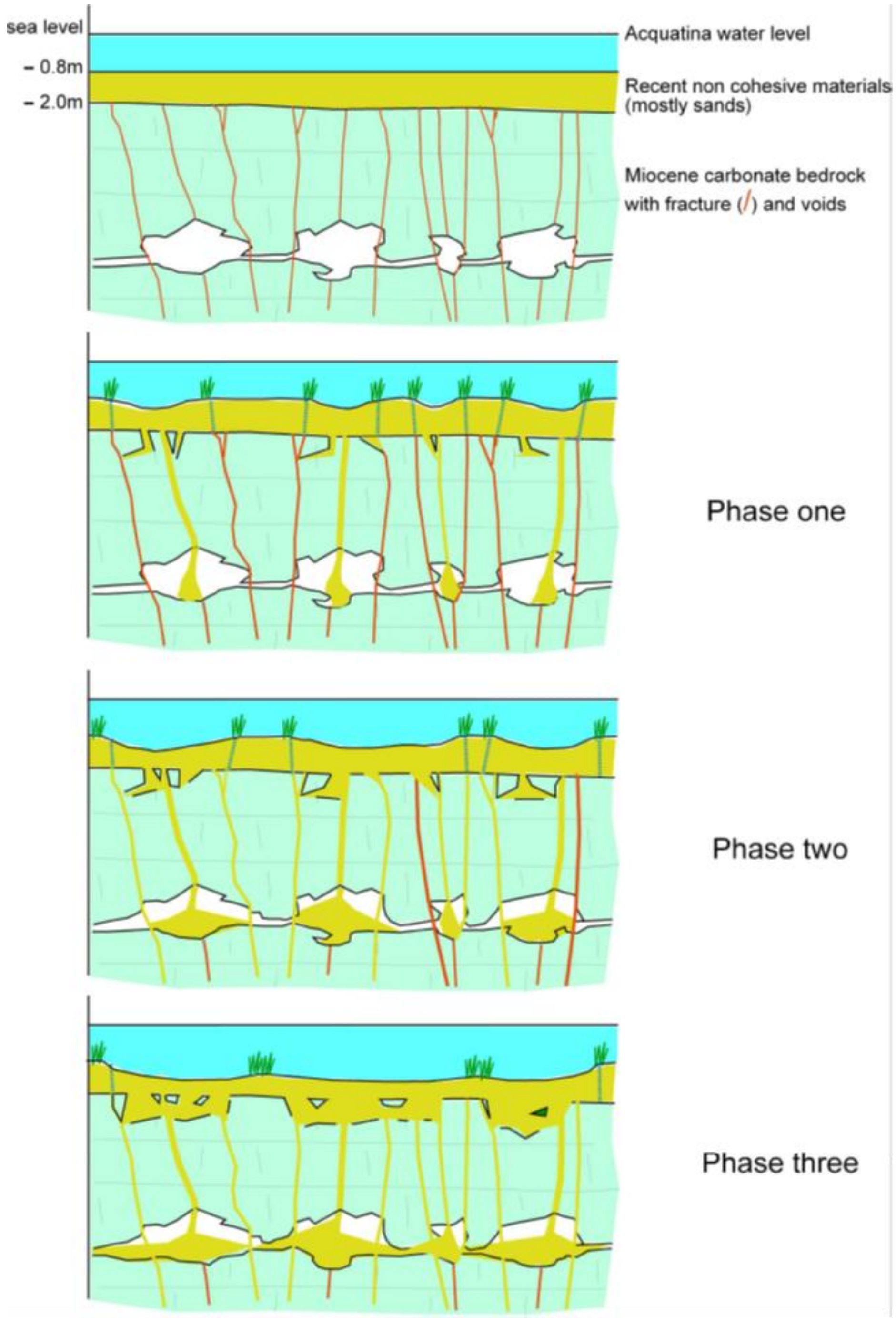


Fig. 2




Water Elevation (m)
Time (min)
SLIDE 1
SLIDE 2
km


354000
364000
4220000
4230000
Oreto river
Mount Pellegrino
Eleuterio river
Oreto Canyon
Eleuterio Canyon
Mount Catalfano
pockmarks field
Sperone Canyon
Arenella Canyon
Priola Scar
Addaura Canyon
Cape Gallo
Cape Mongerbino
Mondello Canyon
La Barra High
Mongerbino Tributary Valley
Zafferano Canyon
100
500
1000
1400
N
2 km
-100
-300
-500
-700
-900
-1100
-1300
m


sea level
- 0.8m
- 2.0m
Acquatina water level
Recent non cohesive materials (mostly sands)
Miocene carbonate bedrock with fracture (/) and voids
Phase one
Phase two
Phase three

P13 - Anthropogenic preparation related to static loads or changes in subsurface fluid pressures or groundwater level

P14 - Preparation related to changes in the vegetation cover due to anthropogenic or natural causes (including vegetation diseases)

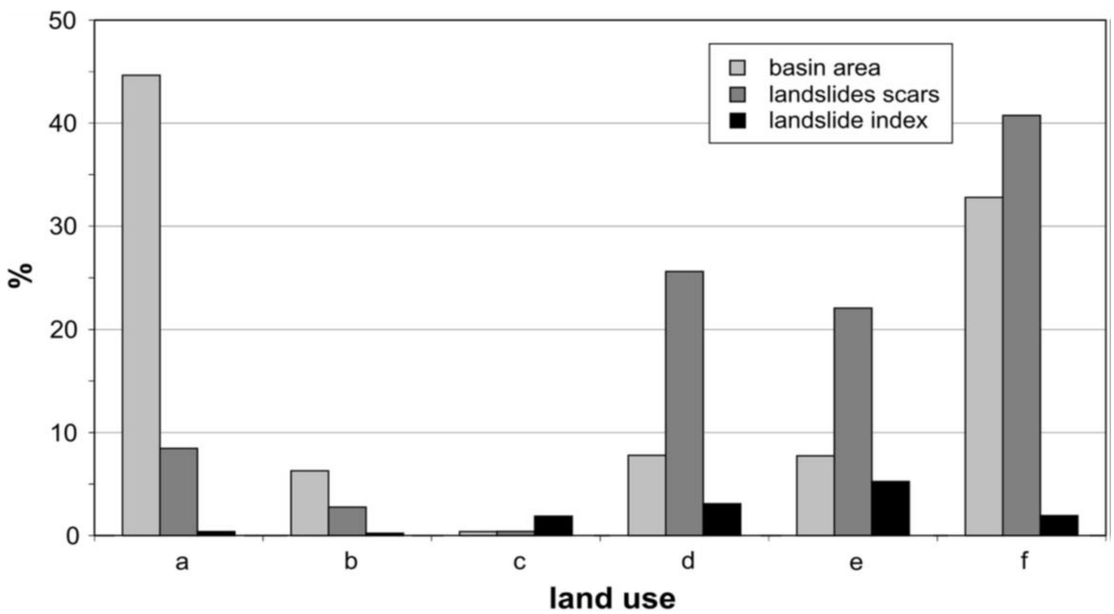


Fig. 1

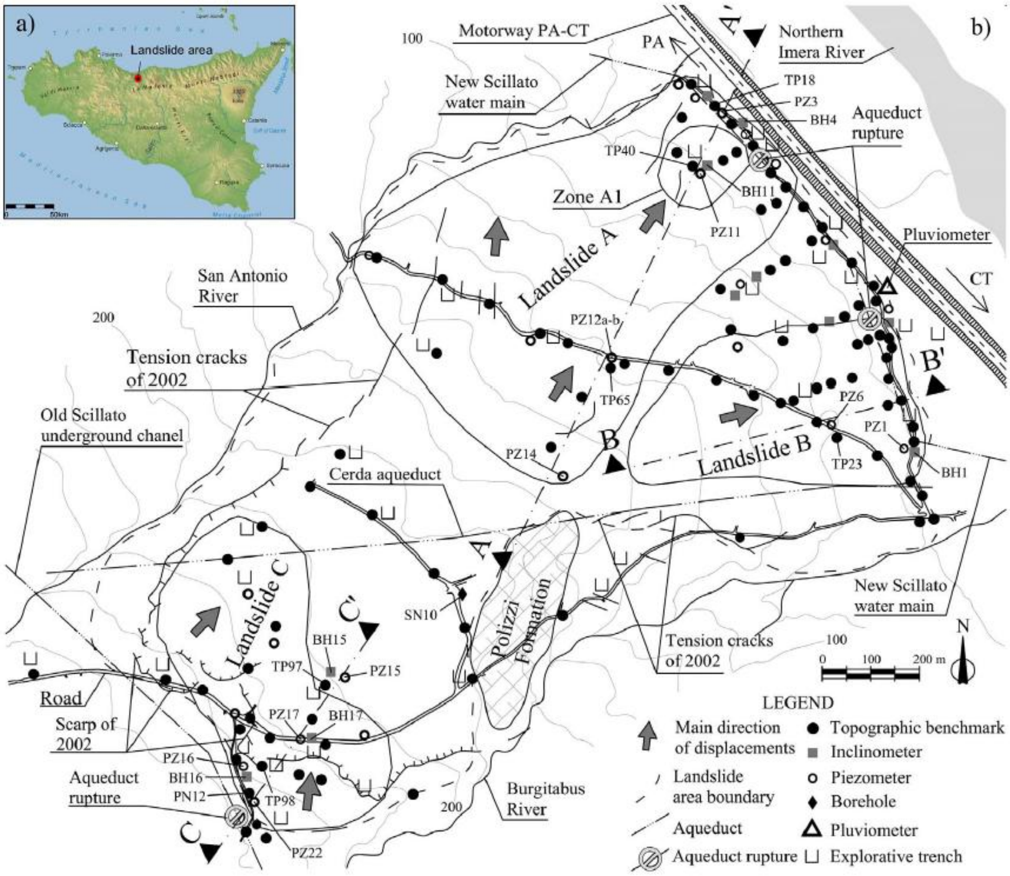

a)
Landslide area
b)
Motorway PA-CT
PA
CT
Northern Imera River
New Scillato water main
TP18
PZ3
BH4
Aqueduct rupture
TP40
BH11
Zone A1
PZ11
Pluviometer
Landslide A
San Antonio River
PZ12a-b
Tension cracks of 2002
TP65
PZ6
PZ1
Old Scillato underground chanel
PZ14
B
Landslide B
TP23
BH1
B'
A'
A
Cerda aqueduct
Landslide C
SN10
C'
BH15
TP97
PZ15
Polizzi Formation
New Scillato water main
Tension cracks of 2002
Road
Scarp of 2002
PZ17
BH17
PZ16
Aqueduct rupture
BH16
PN12
TP98
PZ22
C
Burgitabus River
100
200
0 100 200 m
N
LEGEND
Main direction of displacements
Landslide area boundary
Aqueduct
Aqueduct rupture
Topographic benchmark
Inclinometer
Piezometer
Borehole
Pluviometer
Explorative trench

Fig. 2

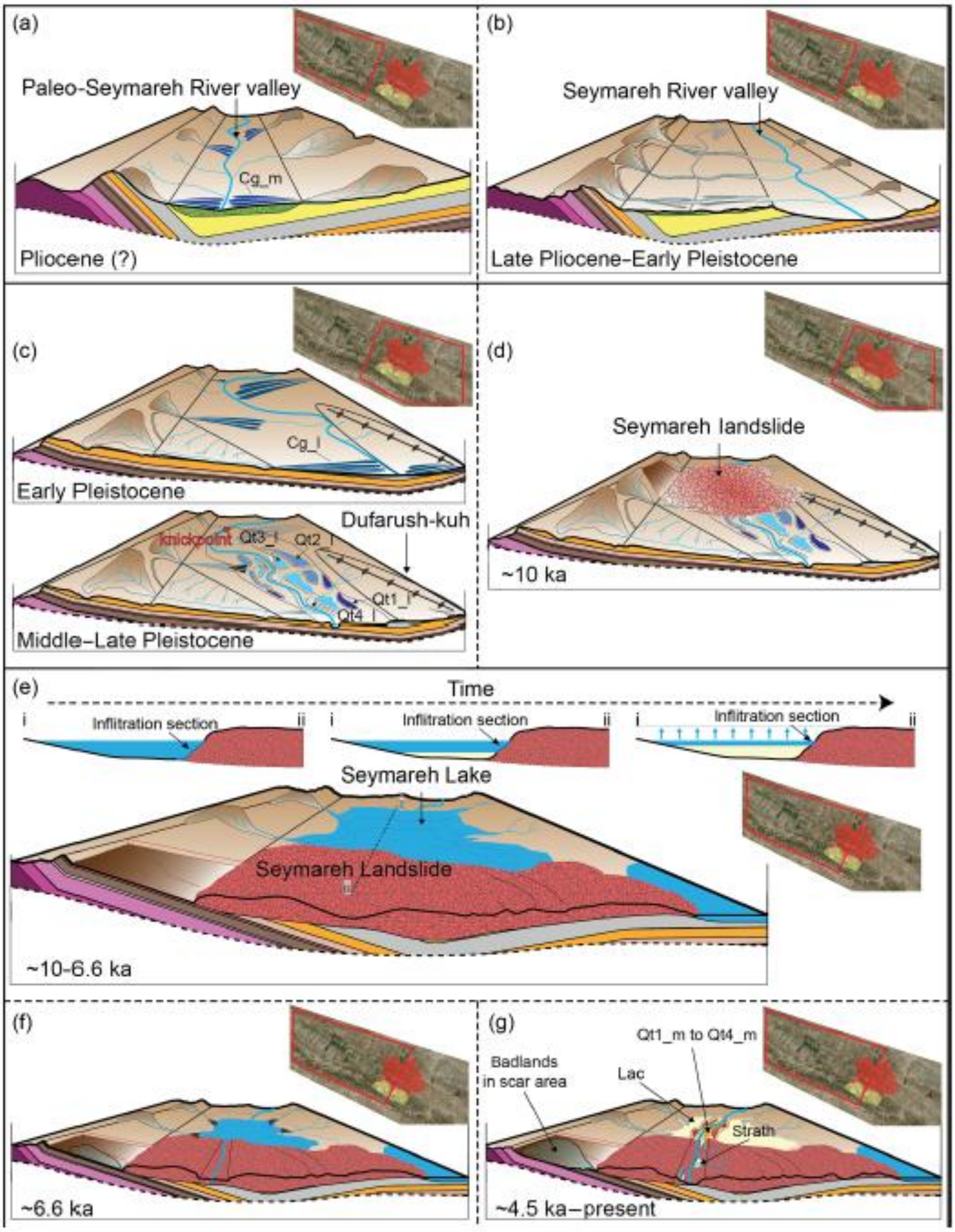
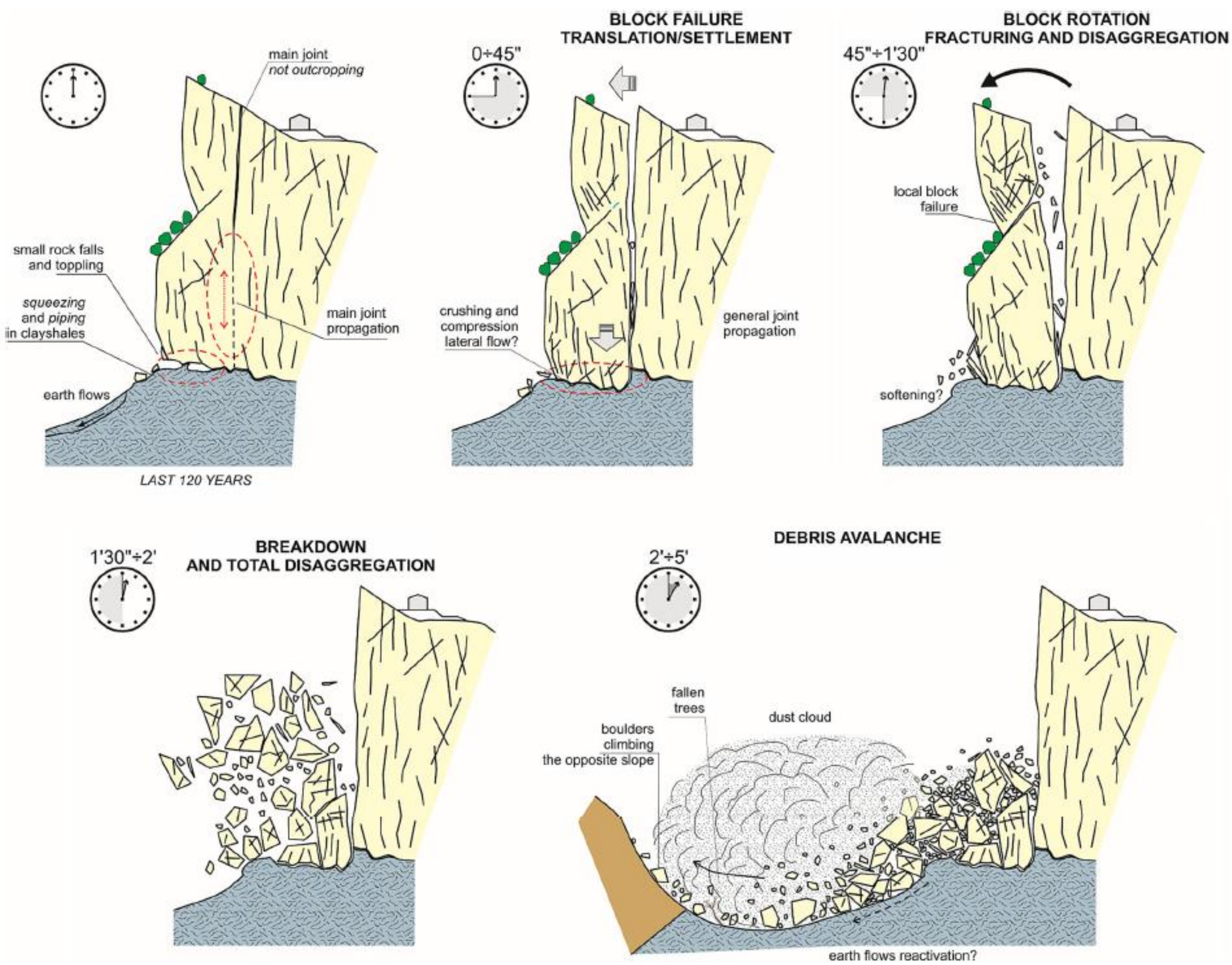

(a)
Paleo-Seymareh River valley
Cg_m
Pliocene (?)
(b)
Seymareh River valley
Late Pliocene-Early Pleistocene
(c)
Cg_l
Early Pleistocene
Dufarush-kuh
knickpoint
Qt3_l
Qt2_l
Qt1_l
Qt4_l
Middle–Late Pleistocene
(d)
Seymareh landslide
~10 ka
(e)
Time
i
Inflitration section
ii
Seymareh Lake
Seymareh Landslide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

Fig. 3


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, but focusing on LEs related to trigger and multi-hazards:

i. Inventory of Learning Examples (LEs, Table 7).

ii. Individuation of LEs related to trigger and/or devoted to multi-hazard 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).

WP4 is organized in 4 tasks:

- Task 2.4.1 (hereafter TK1): Multiple geohazards for ground instabilities in ***near-shore and coastal areas***, volcanic islands.

- Task 2.4.2 (hereafter TK2: 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 (hereafter TK3): Multiple geohazards for ground instabilities in ***large plains***, ***sinkhole*** zones.

- Task 2.4.4 (hereafter TK4): ***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 7. Given that the present DV is related to numerical modelling and simulations, the LEs and LE rationale sheets, for which the learning of trigger and cascading processes were retrieved from numerical modelling and simulations, are highlighted (in red) in Table 7 and fully reported in Attachment 2 respectively. Moreover, Section 3.2 reports examples of events pertaining to each environment characterizing the WP4 Tasks.

In general, a good distribution of WP4 LEs was found over the different environments considered for trigger and multi-hazard (TK1 to TK3, Figure 6a), 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 modelling is slightly more common than monitoring, while the combination of monitoring and modelling is generally the most common approach to the problems (Figure 6b).

As a whole, the LEs including a modelling approach are 34 out of 44; in 33 of these cases, the trigger event occurred. Figure 7 shows the distribution of these 33 LEs as a function of trigger type, the context, the scale of the study and the effect, highlighting the single event and multihazard studies. It is possible to note that the most common trigger is rainfall, followed by earthquakes and anthropic activity (Figure 7a). Cascading effects and multi-hazard are dominant with respect to single-triggered events in almost all contexts and scales of observations (Figure 7b and Figure 7c); regarding the context, coastal and near-shore environments are less represented than the others (Figure 7b). As usual, landslides are the most studied effect by far, and are dominated by single events situations (Figure 7d).

Table 7. 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 – Large Plains, sinkhole zones. TK4: Uncertainty assessment. Rationale from monitoring data (Mon) or numerical modelling (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_2WP4	***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

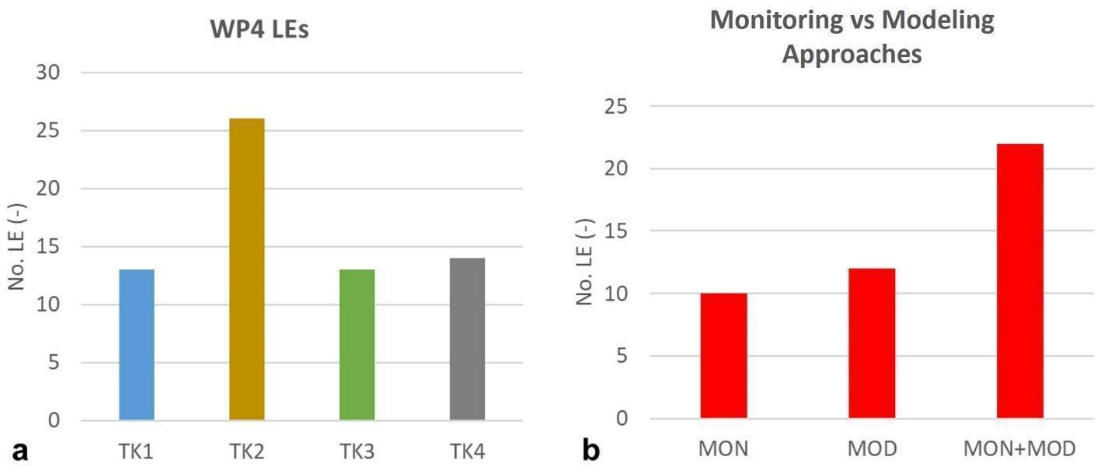


Figure 6. (a) Distribution of WP4 LEs on WP4 Tasks. (b) Distribution of WP4 LEs on the adopted study approaches: MON – monitoring; MOD – modelling.

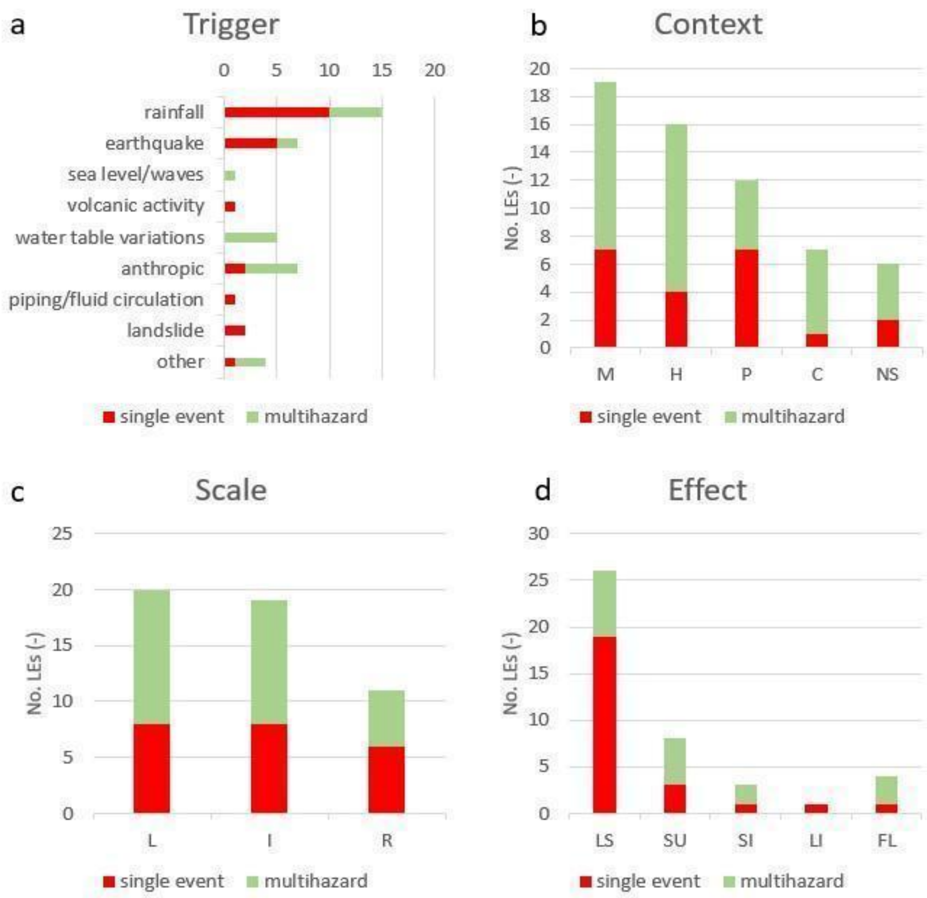


Figure 7. WP4 rationale information derived from LEs including modeling approach where the trigger event occurred. (a) Trigger cause. (b) Context (M – mountain; H – hill; P – plain; C – coast; NS – near-shore). (c) Scale (L – local; I – intermediate; R – regional). (d) Effect (LS – landslide; SU – subsidence; SI – sinkhole; LI – liquefaction; FL – fluvial dynamics). Single-triggered events are reported in red; cascading events are highlighted in green.

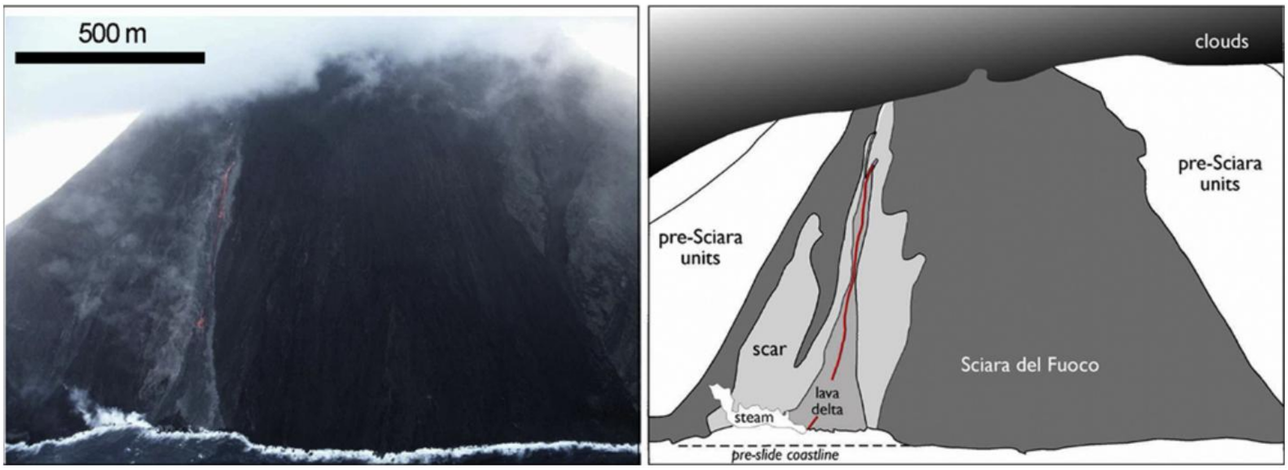
3.2 WP4 Environment figures

Table 8. List and description of the environments, with references and caption of the related figures, reported subsequently.

Task	Environment	Reference	Figure Caption
2.4.1a	Near-shore and coastal areas	Sansò et al. (2016)	Cliffs showing a very shallow water-depth at their foot are fastly retreating because of deep solution notches development linked to solution processes produced by sea/fresh waters mixing.
2.4.1b	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).

Task 2.4.1a. Near-shore and coastal areas

Task 2.4.1b. Volcanic Islands



Task 2.4.3. Large plains, Sinkholes zones

3.3 WP4 LE reference papers

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4. Conclusions

In the period **January - July 2023**, the research activities of WP3-TK2 were devoted to the definition of a Rationale for the processes preparing to ground instabilities from **numerical modelling analysis and simulations**.

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; 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 modelling,** and **machine learning**. Despite the different internal organizations, WP4 activities followed the same approach. The outcomes of both WPs derived from numerical modelling analysis 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 **local 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, most of the identified processes were rationalized through the information and logs derived from less than 2 LEs, emphasizing the need to integrate them with further analyses.

As concerns the studies with **numerical modelling** analysis (specific object of TK2), they are available only for half of the processes, and usually coupled with monitoring techniques; quantitative logs are available in about 50% of the preparatory processes. **Machine learning** is occasionally adopted together with the other techniques, but never with numerical modelling only. To overcome these limitations, in parallel with future project activities and the definition of a Rationale and PoC, different strategies might be pursued:

Internal recall to collect extra LEs from the institutions cooperating with WP3 for the processes, environments and effects that were found to be less represented.

External call (exploiting the cascade funding opportunities) to enroll new partners bringing expertise and new LEs to the partnership in the highlighted weak areas.

Targeted investigation, based on **bibliographic research**, to improve at least the learning about the less represented processes.

WP4 results obtained from numerical modelling analysis are more represented than in WP3. The **combined procedure** through these analysis and monitoring data was found to be the dominant approach to the study of triggering and multi-hazard. The **triggering of landslides** was found to be the most studied effect also for WP4. The results also highlighted that multi-hazard is highly common for different environments and scales of observations. Further research efforts are still needed for the analysis of the propagation of 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 9 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 9. Main critical points derived from WP3 and WP4 research work of January - July 2023 and proposed solutions.

Critical point	*Proposed Solution*
Lack of marine and underwater LEs for the definition of a comprehensive Rationale for the related preparatory processes (WP3) and trigger/multi-hazard 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 multi-hazard 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.

Acknowledgments

This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005)

Attachment 1 - WP3 Rationale Sheets (TK2)

The original working documents (WP3 LEs Sheets) have been classified and are available on the VS2 sharing platform (Microsoft Teams). They may be provided as a further appendix at a later stage of the Project.

Attachment 2 - WP4 Rationale Sheets (derived from Modelling)

The original working documents (WP4 LEs Sheets) have been classified and are available on the VS2 sharing platform (Microsoft Teams). They may be provided as a further appendix at a later stage of the Project.