multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate

Codice progetto MUR: **PE00000005** – CUP: **F83C22001660002**

Deliverable title: *Nearshore and coastal areas, volcanic islands: Rationale for trigger-based multiple geohazard severity mapping and zoning*

Deliverable ID: ***Deliverable 2.4.1***

Due date: ***30th November 2023***

Submission date: ***27th November 2023***

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1. 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.	DV2.4.1
Dissemination level*	PU
Work Package	WP4 - Trigger-based multiple geohazard scenarios<
Task	T2.4.1 - Multiple geohazards for ground instabilities in nearshore and coastal areas, volcanic islands.
Lead beneficiary	SC
Contributing beneficiary/ies	ES; MLN

* 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	22.10.23	SC; ES; MLN	First draft
	24.11.23	SC; ES; MLN	Second draft
0.2			Critical review and proofreading
0.3	27.11.23	Salvatore Martino, Francesca Bozzano (UniRoma1), Domenico Calcaterra, Diego Di Martire (UniNA), Filippo Catani (UniPD)	Edits for approval
1.0	28.11.23	SC; ES; MLN	Final version

2. ABSTRACT

Nearshore and coastal areas as well as volcanic islands face complex geohazard challenges, often subjected to single or multiple ground instabilities. These regions experience a number of different geological processes, including volcanic activity, seismicity, coastal erosion subsidence and vertical uplift. Understanding the interplay of these processes is crucial for assessing geohazards and implementing effective coastal mitigation strategies.

Coastal areas are dynamic environments where land and sea converge, presenting unique challenges and opportunities for geohazard assessment. These areas are densely populated and economically significant, hosting key infrastructure, industries, and habitats. Moreover, coastal regions are subject to ongoing environmental changes, such as climate variability and human-induced alterations, amplifying their vulnerability to hazards. Assessing geohazards here aids in risk mitigation, safeguarding lives, properties, and livelihoods.

Observing ground instabilities, both on land and underwater, necessitates a diverse array of methods due to the varying scales and environments involved. On land, techniques like LiDAR (Light Detection and Ranging), satellite imagery, and ground-based monitoring provide high-resolution insights into surface movements, such as landslides, subsidence, or fault activity. This is not yet possible in the marine realm.

Underwater, in situ observations are not yet available, thus employing sonar imaging, bathymetric surveys, and marine seismic profiling allow us to image submarine ground instabilities at a much lower scale and resolutions than the onland counterparts.

Integrating these diverse methodologies would enhance our ability to detect, monitor, and assess ground instabilities along coastal areas comprehensively, both on land and beneath the water's surface. Such multi-scale observations facilitate a more holistic understanding of geological hazards, contributing significantly to risk assessment and mitigation strategies in coastal and marine environments.

The aim of RETURN Task 2.4.1 is to analyze different occurrences and types of on land and submarine ground instabilities, observed by the two scientific communities using different methods, scale and resolutions and address them developing a conformal approach. This is done by identifying triggers and multihazard occurrences in both realms (subaerial and submarine) in relation to specific predisposing and preparatory factors, in order to identify criticalities and gaps in knowledge.

To achieve that, we have selected and analyzed specific learning examples (LEs), extracted the working tools (algorithms, numerical calculator used to model the different geological processes), built toolchains (sequence of connected interoperable tools) in a conceptual way so as to provide a suitable framework able to summarize all possible processes responsible to ground instabilities occurring in these critical areas of the continental margins. This conceptual framework (flow charts) will constitute the kernel of the PoC for grounded instabilities occurring at nearshore and coastal areas, volcanic islands.

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3. First Section

3.1. Overview of Task 2.4.1

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 theirsuitability and reliability.

Following the Executive Working Plan of RETURN, which was delivered as Milestone 2.1 on 31 December 2022, inside the vertical spoke VS2 “Ground Instabilities”, the Work Package 2.4 deals with “Trigger-based multiple geohazard scenarios” (hereinafter referred to as WP4). 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).

It should be noted that VS2 structured WP2, WP3, and WP4 by identifying the following areas of interest for each of them:

- 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 as well as MAPPING tools in terms of severity and zoning also in the framework of multiple geohazards cascading scenarios (MULTIHAZARD).

Following the definitions given within the VS2, the distinction between predisposing, preparatory and triggering factors/processes is made on a temporal basis: in fact, it means that the predisposing factors are considered invariable on the observation scale, while the preparatory factors show changes or cyclical trends during the same period. Therefore, a trigger is considered a process that acts in a very short and well-defined time.

Differently from WP2 and WP3, WP4 is organized in 4 tasks related to the geomorphological setting/context in which ground instabilities develop and not on 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 distressed 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.

In particular, this deliverable (DV 2.4.1) focuses on nearshore and coastal areas, volcanic islands. Rationale for trigger-based multiple geohazard severity mapping and zoning. This report summarized the scientific research activities carried out in the period January – November 2023 by the Task 2.4.1 "Multiple geohazards for ground instabilities in nearshore and coastal areas, volcanic islands" (hereinafter referred to as TK1).

The task is focused on ground instabilities in nearshore and coastal areas as well as volcanic islands. Objects of this task will concern multi-hazard effects and indicators in case of ground instability (G.I.) in nearshore (submarine), coastal (onland) as well as in volcanic islands by combining process understanding (DV 4.5) and hazard mapping (DV 2.4.6) for multiple triggers and cascading effects. Processes to be considered include Precipitation, Earthquake, Anthropic factors, Volcanic activity, whereas "Piping/Fluids in sediments" and "Flash floods" are typical trigger progress only for the submarine G.I.

At the beginning of the project (January – March 2023) each institution involved in the VS2 was asked to identify an average of 3 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 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);
- Analysis tools and techniques (on site monitoring/remote monitoring/deterministic analysis/statistical analysis/machine learning).

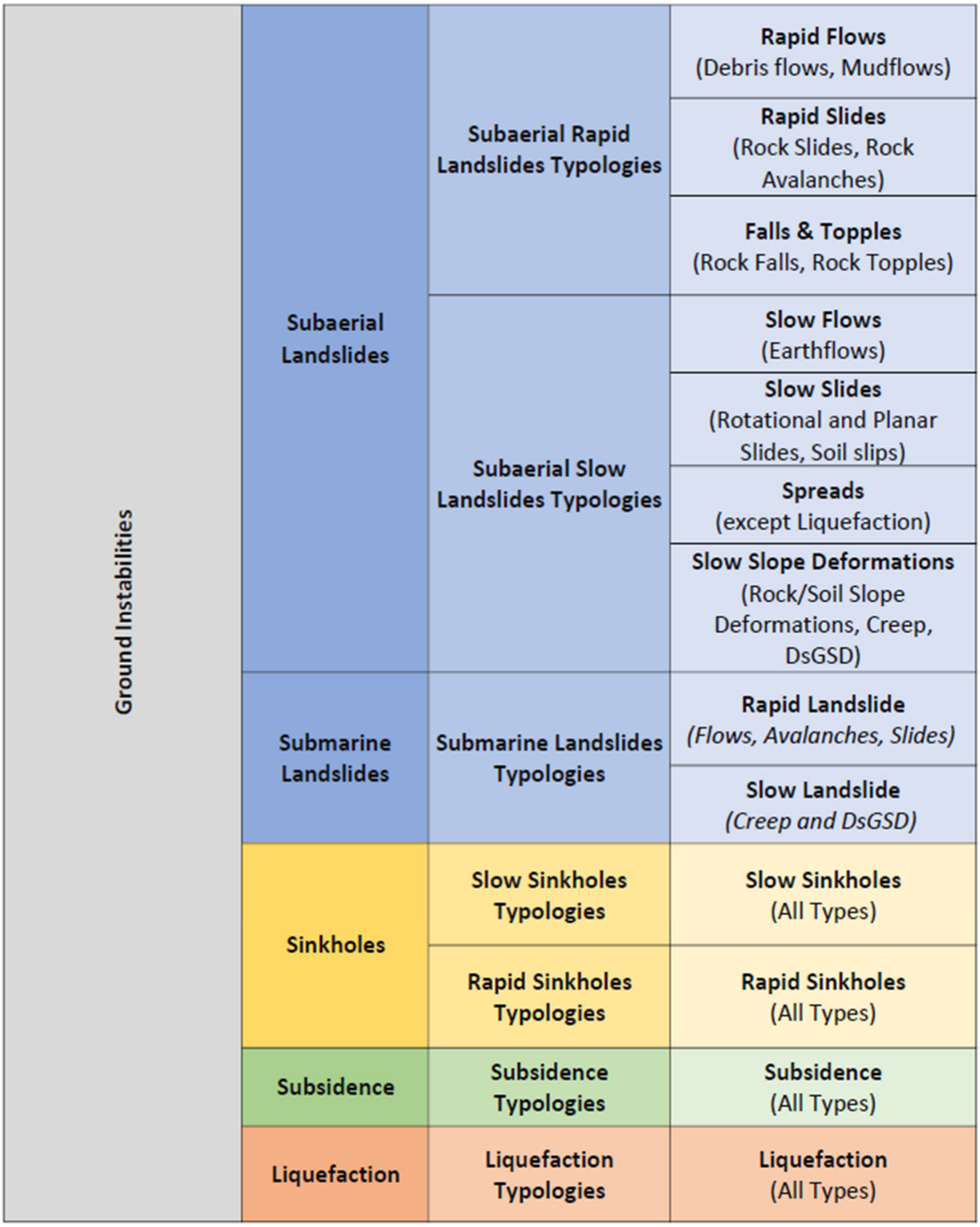
The resulting LEs were coded for each WP (ID: XX_n_WPy, where XX is a 2-letter code referring to the proposing institution, n is a progressive number, y is the WP number in which the LE is used for learning).

WP4 followed the same three-phase approach described in the previous Deliverable (July 2023), but focusing on LEs related to mapping methods, trigger and multihazard:

- Inventory of Learning Examples (LEs).
- Individuation of LEs related to mapping methods, trigger and/or devoted to multihazard and/or uncertainty estimation.
- 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).

In general, a good distribution of WP4 LEs was found over the different environments for TK2 and TK3, with a dominant number of triggers and processes related to the mountain and hilly environment (TK2). Only 15 have been accepted as representative LEs for TK1 (Fig. 4) and they are mostly located in southern Italy (Calabria and Sicily). Nevertheless, the southern coasts of Italy are considered as the most critical areas and potential geohazard occurrence (Mangano et al 2023; Chiocci et al 2021; Zecchin et al. 2018). Only 4 LEs for coastal (onland) G.I. were included in this study. Thus, this occurrence was considered insufficient to represent all the processes occurring in coastal subaerial environments. As such, in agreement with WP4 Leader and Spoke coordinator it was decided to benefit from the analyses achieved from LEs of TK2 and TK3 for the G.Is. that show processes compatible with coastal areas. In this way the rationale was conceived for the moment creating separate flow charts for subaerial and submerged realm. However, one of the main aims for the next few months, in preparation of the PoC construction, is to try to identify those parameters that would be important to extract for onland G.I. that are reasonably applicable to the marine analogues.

The LEs collection permitted to identify and classify the G.I. in the categories of processes and kinematics as summarized in Figure 1.



Ground Instabilities	**Subaerial Landslides**	**Subaerial Rapid Landslides Typologies**	**Rapid Flows** (Debris flows, Mudflows)
			Rapid Slides (Rock Slides, Rock Avalanches)
			Falls & Topples (Rock Falls, Rock Topples)
		Subaerial Slow Landslides Typologies	**Slow Flows** (Earthflows)
			Slow Slides (Rotational and Planar Slides, Soil slips)
			Spreads (except Liquefaction)
			Slow Slope Deformations (Rock/Soil Slope Deformations, Creep, DsGSD)
	Submarine Landslides	**Submarine Landslides Typologies**	**Rapid Landslide** *(Flows, Avalanches, Slides)*
			Slow Landslide *(Creep and DsGSD)*
	Sinkholes	**Slow Sinkholes Typologies**	**Slow Sinkholes** (All Types)
		Rapid Sinkholes Typologies	**Rapid Sinkholes** (All Types)
	Subsidence	**Subsidence Typologies**	**Subsidence** (All Types)
	Liquefaction	**Liquefaction Typologies**	**Liquefaction** (All Types)

Figure 1: Classification of Ground Instabilities according to the type of process and associated kinematics

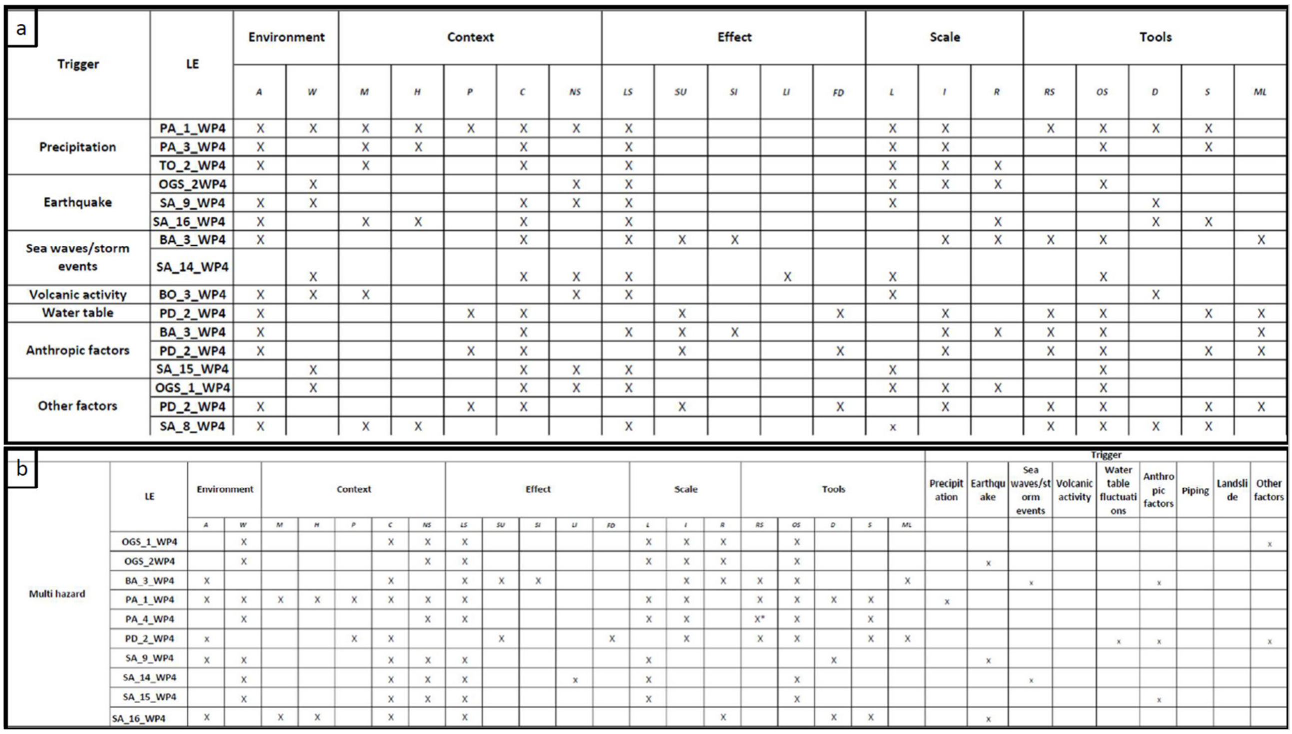
Most of the processes pertain to the category of landslides that are divided into subaerial and submarine, the details of their classifications can be found in Deliverable 2.4.4 prepared by the TK2. The processes that involve the plain areas, hence pertaining to the TK3 are **Sinkholes**, characterized by both slow and rapid kinematics, **Subsidence**, which is only a slow-moving process, and **Soil Liquefaction**, which is a process characterized by rapid occurrence.

3.2. Identification of collected LEs

During the first months of the project all the partners of the Spoke carried out an internal review of past and recent research works, with the aim of selecting the most complete case studies that allow to extract learning and principles that could be extended to other contexts. These case studies, defined “Learning Examples” (LEs), concerned topics focusing on i) the detection and analysis of PREDISPOSING factors to ground instabilities (WP2), ii) PREPARATORY factors to ground instabilities (WP3), iii) TRIGGERING and multiple geohazards cascading scenarios. The scientific papers were stored in a repository (Windows Teams) accessible to all the institutions, in order to provide the reference for the contents of the works.

Once the database of the papers was populated, each LE has been inserted in an online inventory (one for each WPs), represented by a shared online table file. This table constituted a synoptic view of the research works, for which several information was provided by the authors of the LEs, including (as shown in Figure 2):

- 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/flood dynamic);
- the scale (local/intermediate/regional);
- the analysis tools and techniques (on site monitoring/remote monitoring/deterministic analysis/statistical analysis/machine learning).



Trigger	LE	Environment		Context					Effect					Scale			Tools				
		A	W	M	H	P	C	NS	LS	SU	SI	LI	FD	L	I	R	RS	OS	D	S	ML
Precipitation	PA_1_WP4	X	X	X	X	X	X	X	X					X	X		X	X	X	X	
	PA_3_WP4	X		X	X		X		X					X	X			X		X	
	TO_2_WP4	X		X			X		X					X	X	X					
Earthquake	OGS_2WP4		X					X	X					X	X	X		X			
	SA_9_WP4	X	X				X	X	X					X					X		
	SA_16_WP4	X		X	X		X		X							X			X	X	
Sea waves/storm events	BA_3_WP4	X					X		X	X	X				X	X	X	X			X
	SA_14_WP4		X				X	X	X			X		X				X			
Volcanic activity	BO_3_WP4	X	X	X				X	X					X					X		
Water table	PD_2_WP4	X				X	X			X			X		X		X	X		X	X
Anthropic factors	BA_3_WP4	X					X		X	X	X				X	X	X	X			X
	PD_2_WP4	X				X	X			X			X		X		X	X		X	X
	SA_15_WP4		X				X	X	X					X				X			
Other factors	OGS_1_WP4		X				X	X	X					X	X	X		X			
	PD_2_WP4	X				X	X			X			X		X		X	X		X	X
	SA_8_WP4	X		X	X				X					x			X	X	X	X	

	LE	Environment		Context					Effect					Scale			Tools					Trigger								
		A	W	M	H	P	C	NS	LS	SU	SI	LI	FD	L	I	R	RS	OS	D	S	ML	Precipitation	Earthquake	Sea waves/storm events	Volcanic activity	Water table fluctuations	Anthropic factors	Piping	Landslide	Other factors
Multi hazard	OGS_1_WP4		X				X	X	X					X	X	X		X												x
	OGS_2WP4		X					X	X					X	X	X		X					x							
	BA_3_WP4	X					X		X	X	X				X	X	X	X			X			x			x			
	PA_1_WP4	X	X	X	X	X	X	X	X					X	X		X	X	X	X		x								
	PA_4_WP4		X					X	X					X	X		X*	X		X										
	PD_2_WP4	x				X	X			X			X		X		X	X		X	X					x	x			x
	SA_9_WP4	X	X				X	X	X					X					X				x							
	SA_14_WP4		X				X	X	X			x		X				X						x						
	SA_15_WP4		X				X	X	X					X				X									x			
	SA_16_WP4	X		X	X		X		X							X			X	X			x							

Figure 2. (a) LEs referring to WP4.1 and related to different triggering factors (b) LEs referring to Tk4.1 and related to multi hazards only

Furthermore, each Partner was asked to translate the chosen LEs in a more specific way according to specific guidelines provided for its compilation (Figure 3). A specific form was then compiled by each LE's leader, in order to provide more detailed information on the phenomenon and on the factors controlling the LEs. The forms have been compiled and stored in the Windows Teams platform.

PROCESS	WP4_x Indicate if the LE refers to trigger and/or multi-hazard and/or impact (e.g., runout) assessment
LEARNED FROM *(indicate the LE ID)*	LE_x_WP4
1) PROCESS CONTROL PARAMETERS	Parameters that control the triggering process WP4_x according to what has been learned. *In addition to triggering factors under consideration in WP4, they could involve also preparatory and predisposing factors (not studied by this tool, but arising from the WP2/3 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)** *(specify the type/task and provide the methodological description for each input to the rationale)*	Data and processing methods used for the 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?*

Figure 3. Table provided to LEs authors to better highlight relevant information for TK2 activities

4. Toward the Rationale

4.1. Advanced analysis and final selection of Learning Examples

The rationalization sheets of the Learning Examples (LEs) assigned to the TK1 by previous evaluations, were thoroughly analyzed in the period between September and October 2023. In this phase, in order to verify the coherence and the quality of the information provided, each LE was classified by the Task working group with the following labels:

- Accepted after revisions
- LE not suitable for the WP4/TK1
- New insertion

Such labels have represented a helpful guide for the sequent updating/improvement phase.

The first analysis revealed n. 6 LEs are not suitable for the WP4/TK1, 10 LEs are suitable (in the present form or after integration). In this phase, an internal recall has been useful to update/improve the contents of the LEs suitable for the rationalization process and to propose new LEs that consider processes not already addressed. After the internal recall 5 new LEs were added with very few modifications. Table 1 and Figure 4 shows the structure of such a summarizing table.

Table 1. Final inventory of LEs for WP4 – Task 1.

Institution	LE ID	LE name	Accepted	Not suitable for WP/TK	New insertion
OGS	OGS_1_WP4	Canyon di Squillace			X
	OGS_BO_3_WP4	Frana di Assi			X
UNIPA	PA_1_WP4	Frana di Scopello		X	
	PA_3_WP4	Messinese Ionico		X	
	PA_4_WP4	Golfo di Palermo	X		
	PA_5_WP4	Canyon di Gioiosa Marea	X		
UNIBO	BO_1_WP4	Lago D'iseo	X		

	BO_2_WP4	Costa Romagnola		X	
	BO_3_WP4	Isola di Stromboli	X		
UNIROMA	SA_9_WP4	Scilla	X		
	SA_14_ WP4	Stromboli	X		
	SA_15_ WP4	Gioia Tauro	X		
	SA_16_WP4	Var Canyon			X
	SA_17_ WP4	Madonna del Mare			X
	SA_18_ WP4	Scaletta canyon			X
	SA_19_WP4	Probabilistic estimation of co-seismic displacements.		X	
UNIBA	BA_3.1_WP4	Puglia and Basilicata coasts - Sant’Andrea	X		
	BA_3.2_WP4	Puglia and Basilicata coasts - Torre dell’Orso/San'Andrea	X		
	BA_3.3_WP4	Puglia and Basilicata coasts		X	
UNIPD	PD_2_WP4	Po Delta		X	
POLITO	TO_1_WP4	Capo Calavà	X		

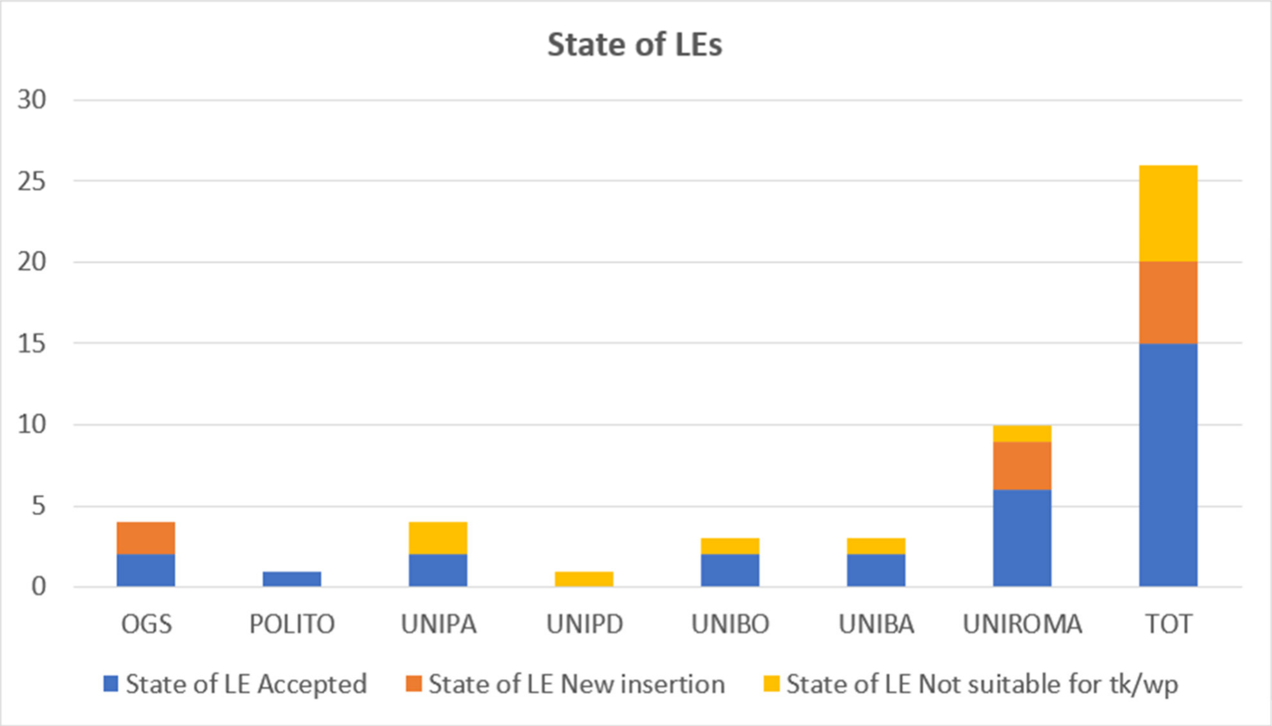


Figure 4. Inventory of LEs for WP4 – Number of LEs included after revisions, not suitable for WP or TK and new derived from 2 rounds of recall and included without modifications.

Furthermore, for each of the 15 LEs selected for the Task purpose, as a preparatory phase for the rationalization process, the following information has been extracted:

- Context
- Scale of validity
- Kinematics
- Type of process
- Triggering factor(s)

The dataset was composed of n. 15 ground instabilities case studies from different areas of Italy distributed as shown in Fig. 4. Within the dataset, there are n. 4 case studies in the coastal context, n. 2 in the volcanic context, and n. 9 in the nearshore context (Figure 5 and 6). The scale at which these studies are conducted varies from the regional to the local scale, and in some cases a multi-scale approach is adopted. In detail, the investigation is at the regional scale in n. 1 LEs, at the basin scale in n. 4 LEs, and at the local scale in n. 10 LEs (Figure 7).

With reference to the kinematic of the ground instabilities of each LE, all the LEs presented in Tk4.1 relate to rapid landslides (Figure 8).

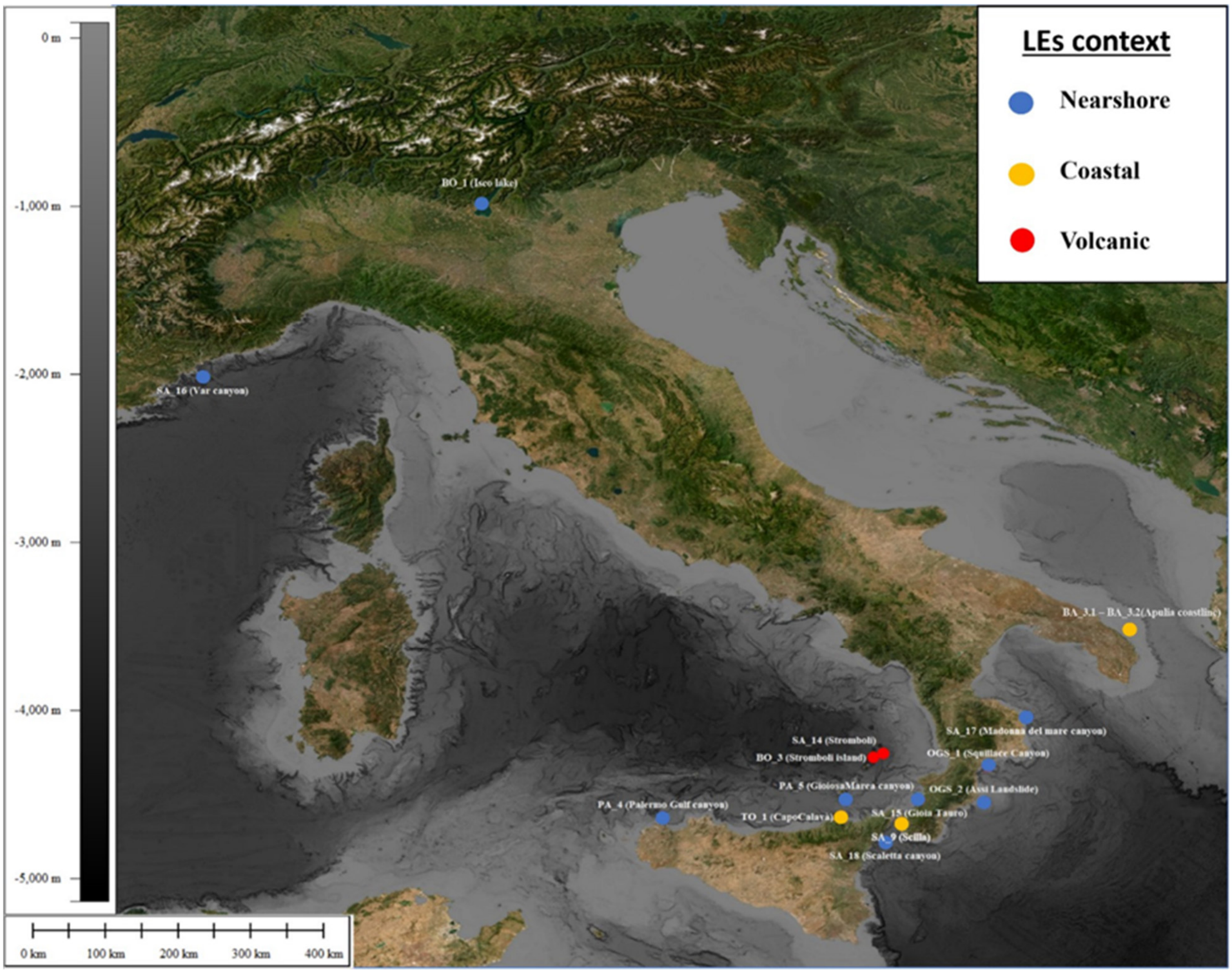


Figure 5. shows the location of the 15 LEs accepted as most representative of the Tk4.1. Map of LEs distribution shows that most of the LEs refers to sites located in the south of Italy.

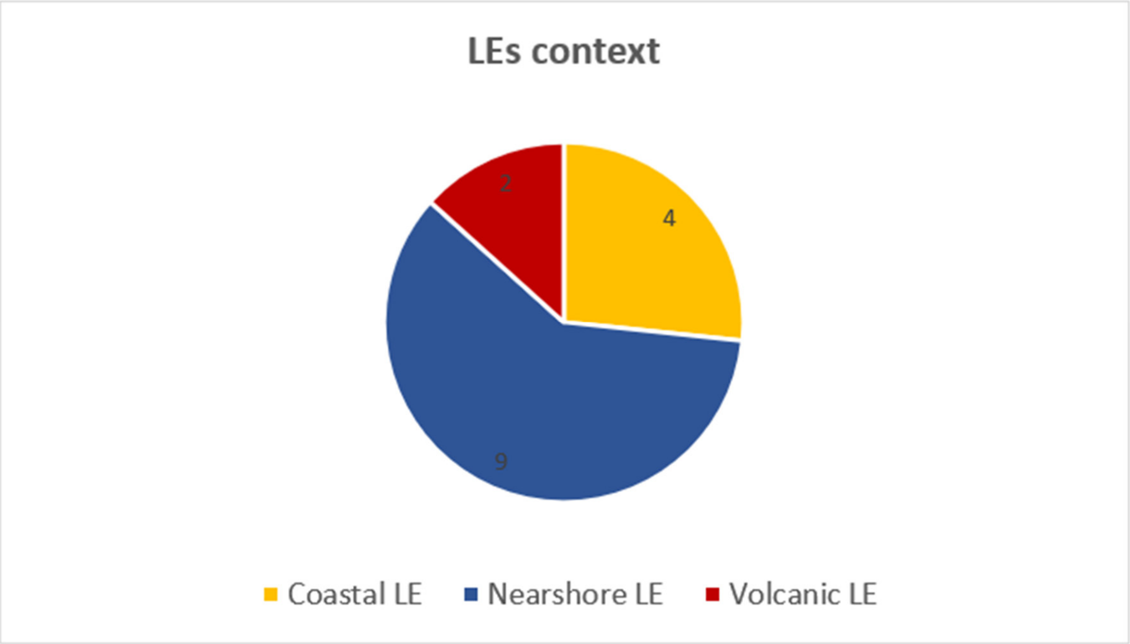


Figure 6. Graph showing the context of the ground instabilities composing the analyzed dataset.

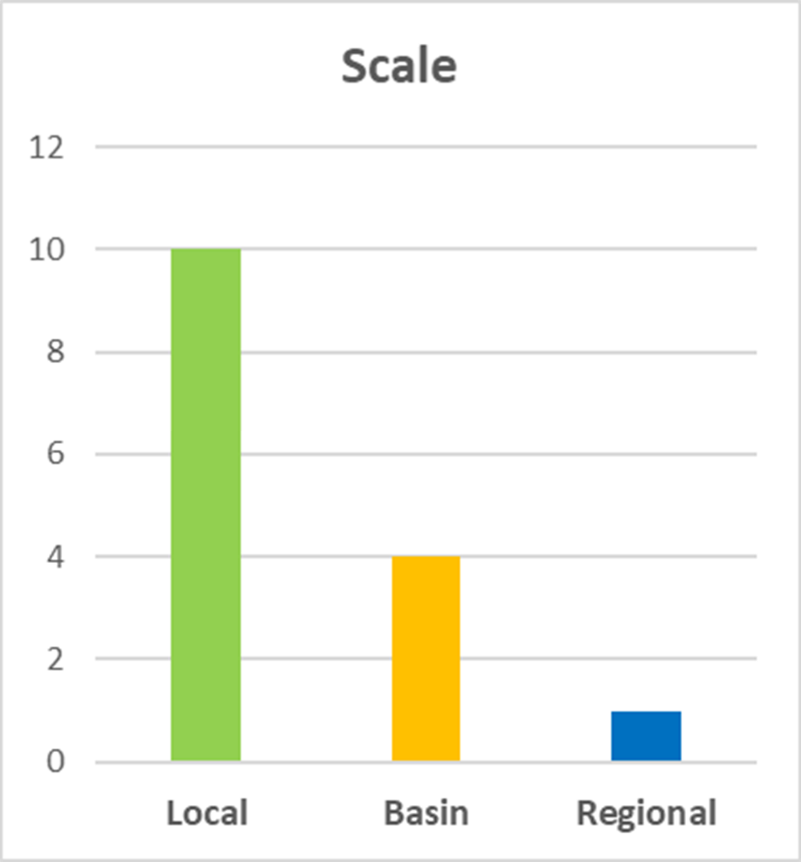


Figure 7. Graph showing the scale of the studies (regional, basin, or local scale) composing the analyzed dataset.

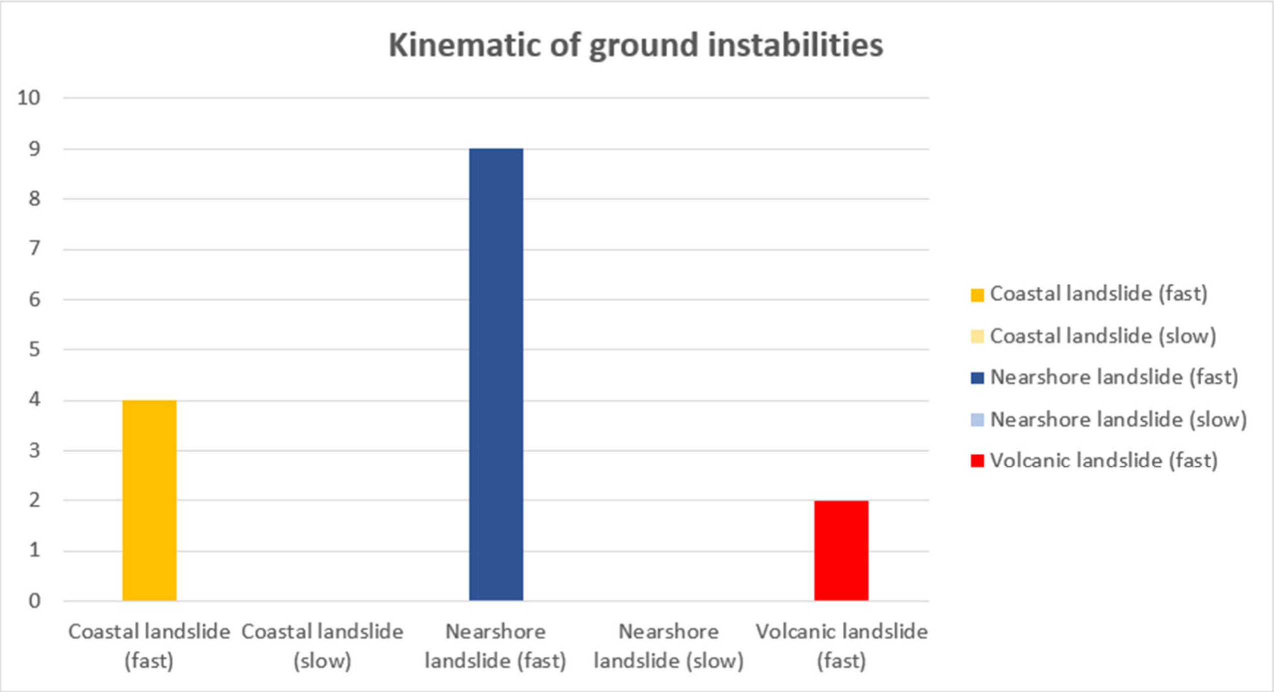


Figure 8. Kinematic of ground instabilities for the different contexts (coastal, nearshore and volcanic)

WP4 leaders and TK leaders grouped the proposed LEs considering the triggering factors and possible multi-hazards. 10 main triggering factors were identified:

1) Rainfall
2) Earthquake
3) Anthropic factors
4) Volcanic activity
5) Piping/Fluids in sediments
6) Flash floods
7) Storm events

Specifically, an increase in the LEs related to the triggers "Earthquake", "Anthropic" and "Storm events" was obtained after the recall. Moreover, two additional triggers have been found related to nearshore areas: "Piping/Fluids in sediments" (3LEs) and "Flash floods" (4 LEs). Figure 9 highlights the advantages of the recall in increasing the number of LEs for each triggering process.

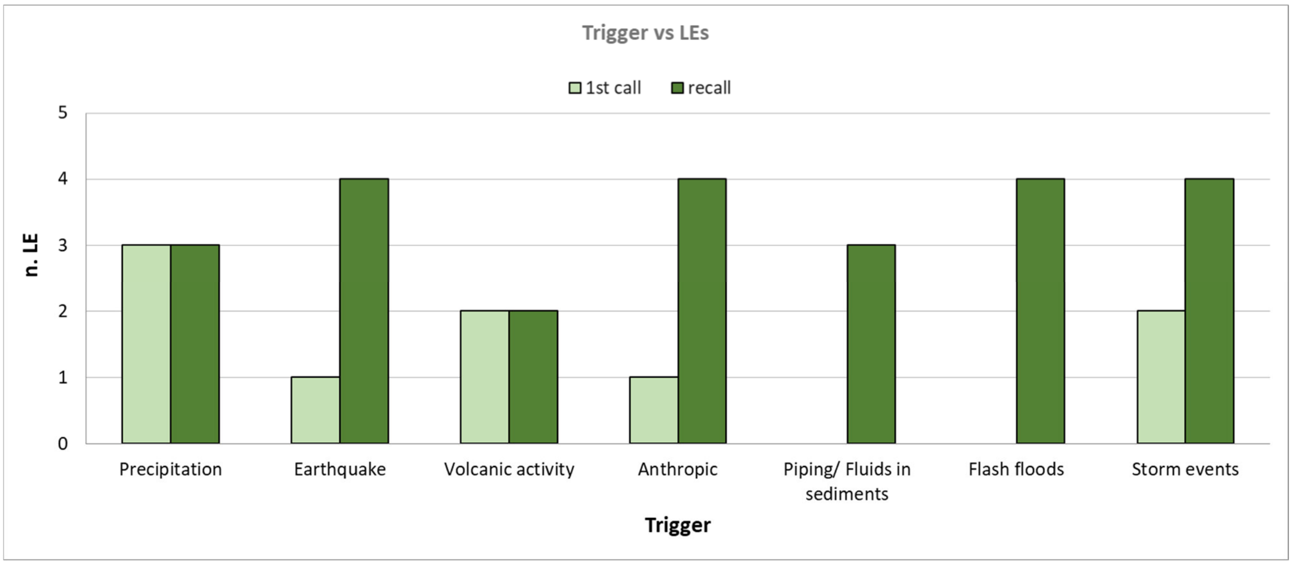


Figure 9. Occurrence of the triggering factors within the LEs, and comparison between the first call and the recall.

The different triggers have been subdivided according to the context to which they refer (coastal, nearshore and volcanic), and the result of this operation is illustrated in the graphs in Figure 10. From these graphs it is evident how the majority of LEs and triggers refer to nearshore landslides (5 LEs), 3 LEs refer to coastal landslides and only 1 trigger (related to 3LEs) refers to volcanic contexts. Moreover, it is worth highlighting that only the triggers "earthquake" and "storm events" are present in LEs concerning both coastal and nearshore contexts.

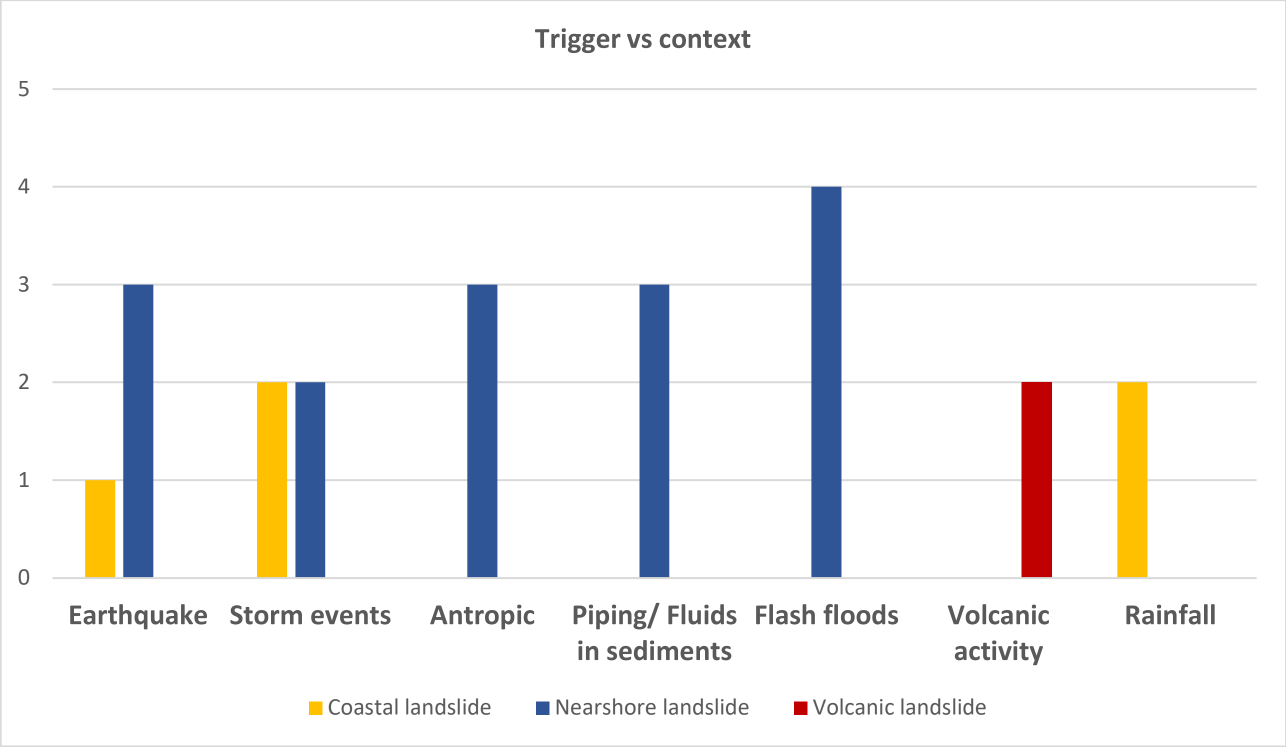


Figure 10. Occurrence of triggering factors in the different LEs according to the contexts.

4.2. From Learning Examples to the extraction of working tools

As discussed in detail in the previous chapter (5.1), upon completion of the review and recall activities, the number of Learning Examples (LE) included in Task 2.4.1 is equal to 15. One of the main purposes of this task is to define tools that can address issues related to triggering of different types of ground instabilities in coastal and nearshore areas, and the associated run out, also in the view of possible multiple geohazards that may characterize a certain portion of a territory.

In order to ensure better integration with the results provided by the WPs dealing with the predisposing factors (WP 2.2) and the preparatory processes (WP 2.3) for a certain ground instability, the identification of the tools followed a tree pattern based primarily on the kinematic and category of ground instabilities, secondarily on the category of trigger factors and, lastly, on the type of output provided in relation to the above-mentioned issues of interest of the task (Figure 11).

In more detail, the classificatory criteria adopted to define and extract a working tool from a LE are as follows:

- Kinematics of ground instability
    - Rapid
    - Slow
- Ground instability macro-categories
    - Landslide
    - Sinkhole
    - Subsidence
    - Liquefaction

- Ground instability types

- **Coastal landslides**
    - Rockfall/Toppling
    - Rock Avalanches
    - Debris flows/Debris floods/Debris avalanches/Mud flows
    - Rock slides
    - Soil slides
    - Earth flows
    - Soil slips
    - Roto-translational slides
    - Spread
    - Rock slides/Rock-Mountain slope deformations
- **Nearshore landslides**
    - Rapid Submarine landslide
    - Slow Submarine landslide

- Categories of triggering factor
    - Seismic (S)
    - Rainfall (R)
    - Anthropic (A)
    - Storm events (SL/SW)
    - Volcanic activity (V)
    - Piping/Fluids in sediments (P/F)
    - Flash Floods (Ff)
- Run-out
    - Presence (Y)
    - Absence (N)
- Spatial scale of tool applicability
    - Regional
    - Basin
    - Local
- Multihazard application (MH)

These working tool extraction operations were carried out based on the information available in the summary sheets developed by the LEs proponents following the scheme of Figure 3.

One example of tools extraction from LEs is given below (Table 2), relative to LE OGS_BO_3 referring to a landslide caused by an earthquake and the consequent generation of a tsunami as multihazard.

Table 2. Summary sheet proposed for the LE OGS_BO_3

<table>
<tr><td>ACQUIRED FROM
(Specify reference CA)</td><td>OGS_BO_3_WP4 (Frana di Assi) – Task 4.1
Referenti: Silvia Ceramicola (OGS), Filippo Zaniboni (UniBO)</td></tr>
<tr><td>TRIGGER/PROCESS</td><td>Shallow and deep submarine landslides generating tsunami.
Trigger: earthquake.
Process: multihazard.</td></tr>
<tr><td>1) PROCESS CONTROL PARAMETERS</td><td>Parameters controlling sliding dynamics and tsunami generation:
1) Sliding body volume
2) Landslide aspect ratio (landslide length/width)
3) Average slope during the slide motion
4) Slide elevation
5) Basal friction angle Ø</td></tr>
<tr><td>2) INPUT DATA TO THE RATIONALE for the analysis of the process</td><td>The set of tools provides in output:
1) the velocity and the run-out of the landslide
2) the impact of the tsunami on the shoreline, here parametrized in terms of the maximum wave amplitude along the coast.</td></tr>
<tr><td>3) LEARNING METHODS (from which the input data were derived)
<i>(methods relative to processes triggered in near-shore and coastal areas, volcanic islands (Task 4.1), hilly and mountain areas (Task 4.2), large plains, sinkhole zones (Task 4.3), uncertainty assessment methods (Task 4.4); methods for the evaluation of multi-hazard)</i></td><td>The quantification of the tsunami generation and coastal impact has been performed through a numerical routine that has already been applied in many cases by the UniBO research team.
It is based on the application of a sequence of codes simulating: i) the sliding motion, providing the geometry and dynamics time series necessary to compute the tsunamigenic impulse; ii) the tsunami generation process, that is not instantaneous (as for the case of earthquake-generated tsunamis); iii) the wave propagation in the basin and its impact on the coast, both in terms of maximum wave amplitude on the coast and of inland flooding (inundation and run-up), if needed.</td></tr>
<tr><td>4) APPLICABILITY CONSTRAINTS
<i>(specify the application context/environment, highlight the spatial and temporal scale limits and the requirements for applicability)</i></td><td>Adopted values for the CA
Three scenarios of landslide have been simulated, with the following characteristics:
<table>
<tr><th>Landslide scenario</th><th>A</th><th>B</th><th>C</th></tr>
<tr><td>1) Volume (km³)</td><td>0.059</td><td>0.711</td><td>1.947</td></tr>
<tr><td>2) Aspect ratio</td><td>3.0</td><td>0.8</td><td>2.5</td></tr>
</table></td></tr>
</table>

<table>
<tr>
<td></td>
<td>
<table>
<tr><td>3) Average slope (°)</td><td>2.5</td><td>2.2</td><td>1.7</td></tr>
<tr><td>4) Slide depth (m below sea level)</td><td>185</td><td>439</td><td>714</td></tr>
<tr><td>5) Basal friction angle (°)</td><td>2</td><td>2</td><td>2</td></tr>
</table>
<p>Possible constraints on the parameters</p>
<p>The following constraints on the landslide characteristics are based on experience and personal evaluations of the authors:</p>
<p>1) Three different orders of magnitude for the volume have been considered, each of them representing a typology of mass collapse.
2) Aspect ratio: ± 0.5 for each case
3) Average slope during the slide motion: ± 1°
4) Slide elevation: the three scenarios are placed at different sea depth, accounting for shallow and deep landslide scenarios.
5) Basal friction angle ∅: ± 1°</p>
</td>
</tr>
<tr>
<td>
<p>5) ANALYSIS LOGS</p>
<p><i>(specify if qualitative, semi-qualitative or quantitative)</i></p>
</td>
<td>
<p>Quantitative. The results of a tsunami simulation are mostly site-dependent since bathymetry and coastal morphology affect deeply the tsunami propagation.</p>
<p>An example of quantification of the tsunami effects at the coast with representative values is reported below.</p>
</td>
</tr>
<tr>
<td>
<p>6) OUTPUTS</p>
<p><i>(specify if categories or indexes or algorithms according to the analysis logs and provide a full description of each output)</i></p>
</td>
<td>
<p>Landslide simulation output</p>
<p>The following data come from the application of the landslide simulation code.</p>
<table>
<tr><th>Landslide scenario</th><th>A</th><th>B</th><th>C</th></tr>
<tr><td>Maximum velocity (m/s)</td><td>16.9</td><td>24.2</td><td>16.5</td></tr>
<tr><td>Deposit runout (km)</td><td>13.9</td><td>27.2</td><td>30.5</td></tr>
</table>
<p>Tsunami simulation output</p>
<p>Table of maximum water amplitude along the coast (in m), obtained through the application of the tsunami simulation code, corresponding to the three landslide scenarios.</p>
</td>
</tr>
</table>

Landslide scenario	A	B	C
Maximum Wave Amplitude along the coast (m)	0.6	1.8	1.6

In this specific case, we were able to extract two working tools, which refer to the GI macro-category "Landslide" and the category "Rapid submarine landslide". Both these tools focus on a ground instability trigger, which in this specific case is the occurrence of a landslide, going then to evaluate two different specific aspects. The first tool "OGSBO3_1" evaluates the velocity and the run-out of the landslide (marked with Y in the run-out section Table 3). While the second tool "OGSBO3_2" evaluates impact of the tsunami on the shoreline. Note that the two tools have been distinguished since one (OGSNO3_1) calculates the run-out while this operation is not provided by the other (OGSBO3_2).

Based on the aforementioned criteria, a total of 25 working tools dedicated to a specific issue of interest of the task were extracted from the 15 LEs (Table 3). The resulting tools were coded as : XXn_nTOOL, where XX is a 2/3-letter code referring to the proposing institution, n is the progressive number assigned to the LE while nTOOL is a progressive number indicating the number of the tool.

Table 3. The 24 working tools extracted from the 15 LEs.

LE	TOOL	KINEMATICS	GI MACROCATEGORY	GI TYPE	TRIGGER CATEGORY	RUN-OUT	SCALE	MH APPLICATION
TO_1_WP4	TO1_1	RAPID	LANDSLIDE	Rockfall		y	B	
TO_1_WP4	TO1_2	RAPID	LANDSLIDE	Rockfall		y	R	
BA_3.1_WP4	BA3.1_1	RAPID	LANDSLIDE	Rockfall	R	N	B	
BA_3.1_WP4	BA3.1_2	RAPID	LANDSLIDE	Rockfall	R	N	L	
BA_3.1_WP4	BA3.1_3	RAPID	LANDSLIDE	Rockfall	SL/SW	N	B	
BA_3.1_WP4	BA3.1_4	RAPID	LANDSLIDE	Rockfall	SL/SW	N	L	

BA_3.2_WP4	BA3.2_1	RAPID	LANDSLIDE	Rockfall	R	N	B	
BA_3.2_WP4	BA3.2_2	RAPID	LANDSLIDE	Rockfall	SL/SW	N	L	
BA_3.2_WP4	BA3.2_3	RAPID	LANDSLIDE	Rockfall	SL/SW	N	B	
SA_9_WP4	SA9_1	RAPID	LANDSLIDE	Rock slide/Rock avalanche	S/R	N	L	
BO_3_WP4	BO3_1	RAPID	LANDSLIDE	Rapid Submarine landslide	V	N	L	
BO_3_WP4	BO3_2	RAPID	LANDSLIDE	Rapid Submarine landslide	V	Y	L	
BO_1_WP4	BO1_1	RAPID	LANDSLIDE	Rock slide	A	N	L	MH
BO_1_WP4	BO1_2	RAPID	LANDSLIDE	Rock slide	A	y	L	MH
OGS_1_WP4	OGS1_1	RAPID	LANDSLIDE	Rapid Submarine landslide	R	N	B	
OGS_1_WP4	OGS1_2	RAPID	LANDSLIDE	Rapid Submarine landslide	R	Y	B	MH
OGS_BO_3_WP4	OGSBO3_1	RAPID	LANDSLIDE	Rapid Submarine landslide	S	N	L	
OGS_BO_3_WP4	OGSBO3_2	RAPID	LANDSLIDE	Rapid Submarine landslide	S	y	L	MH
PA_4_WP4	PA4_1	RAPID	LANDSLIDE	Rapid Submarine landslide e	S	N	L	MH
PA_5_WP4	PA_1	RAPID	LANDSLIDE	Rapid Submarine landslide	S	N	L	MH

SA_14_WP4	SA14_1	RAPID	LANDSLIDE	Rapid Submarine landslide	V	N	L	MH
SA_15_WP4	SA15_1	RAPID	LANDSLIDE	Rapid Submarine landslide	A	N	L	MH
SA_16_WP4	SA16_1	RAPID	LANDSLIDE	Rapid Submarine landslide	A	N	L	MH
SA_17_WP4	SA17_1	RAPID	LANDSLIDE	Rapid Submarine landslide	SL/SW	N	L	
SA_18_WP4	SA18_1	RAPID	LANDSLIDE	Rapid Submarine landslide	Ff	N	L	

4.3. From single tools to the tool chains for coastal, nearshore, and volcanic islands

Once the working tools have been extracted, the subsequent phase has been addressed towards the construction of the «tool chains», i.e. the logical and operational workflows that combine the sequence of tools that can lead to the assessment of expected impact scenarios for different GIs, starting from predisposing factors (WP2) and passing through possible preparatory processes (WP3) up to the triggering from the selected LEs (WP4).

Propaedeutically to the chain construction, each trigger/multihazard/scenario generation (e.g., runout assessment in case of landslides) tool has been framed in a logical structure, conceived as a sort of “inverse tree” rooted in the different GI categories and increasingly branched off according to additional criteria (kinematic, GI type, trigger category, run-out assessment). Furthermore, working scales (i.e., scales at which each tool is valid or validated) are nested within such a structure.

Being the registry associated with each tool still valid (see chapter 4.2), the same information has been somehow transposed in order to have a quick and informative glance of the usability of the tools. Specifically, the logical structure has been set as follows (Figure 11 a and b):

- The “root” is the G.I. macro-category (i.e., Landslide, Erosion, etc.)
- The second subdivision criterion accounts for the Context (i.e., coastal, nearshore, etc.)
- The third level refers to the kinematic (i.e., rapid, slow)
- The fourth level refers to the specific GI category (i.e. Rockfall/Toppling, Rock Avalanches, etc.)

- The last level accounts for the triggering process (i.e., “S” - Seismic; “R” - Rainfall; “A” - Anthropic; “SL/SW” - Storm events (Sea Level/Sea Waves); “V” - Volcanic activity; “P/F” - Piping/ Fluids in sediments; “Ff” - Flash floods)

The information about the output log (quantitative, semi-quantitative, qualitative) is still preserved as filling color of the cell in which the tools are located.

In general terms it is possible to observe the following main gaps of knowledge:

- Absence of tools dealing with all rapid landslides in coastal areas at the regional scales
- Scarcity of tools dealing with rapid landslides in coastal areas at the local scale
- Absence of tools dealing with rapid landslides in coastal areas at the local scale for Mud flows, Rockslides and Soil slides G.I.s
- Scarcity of tools dealing with rapid nearshore landslides at the regional scale
- Absence of tools dealing with slow landslides at all scales for nearshore G.I.s

The “inverse tree” represents the basis on which a general framework for the construction of tool chains has been set up. Specifically, on the basis of the extraction of tools and their classification and placement within the logical structure described in the previous paragraph, a logical-operational scheme has been proposed, addressed to the systematization of the individual tools extracted in the different WPs. These tools are useful, in concatenation, to return scenarios resulting from GI processes, thus starting from the predisposing factors, moving - where necessary - through the preparatory processes and, finally, taking into account the triggering factors (Figure 11).

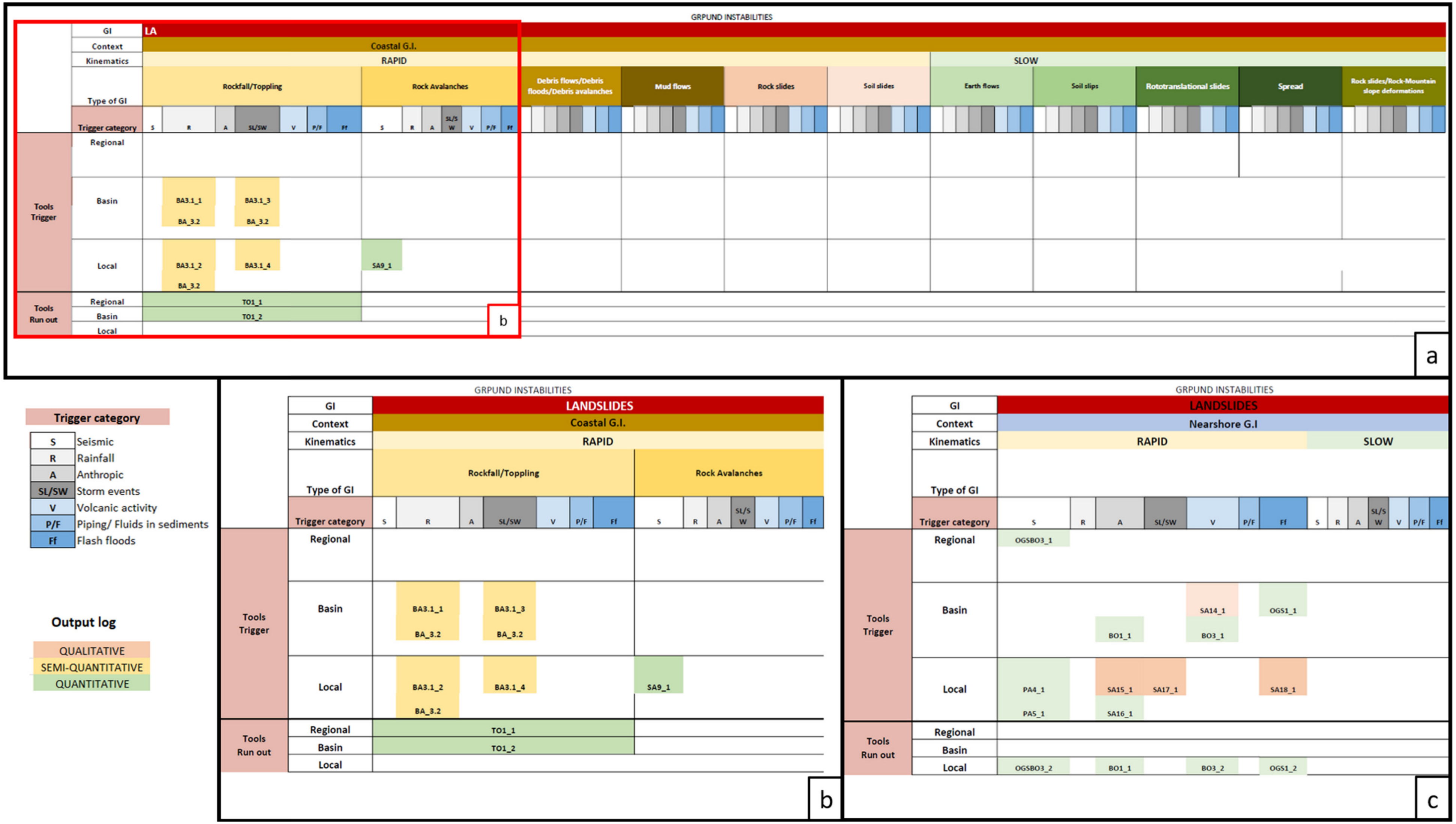

GRPUND INSTABILITIES
GI
Context
Kinematics
Type of GI
Trigger category
LA
Coastal G.I.
RAPID
SLOW
Rockfall/Toppling
Rock Avalanches
Debris flows/Debris floods/Debris avalanches
Mud flows
Rock slides
Soil slides
Earth flows
Soil slips
Rototranslational slides
Spread
Rock slides/Rock-Mountain slope deformations
S
R
A
SL/SW
V
P/F
Ff
SL/S W
Tools Trigger
Tools Run out
Regional
Basin
Local
BA3.1_1
BA_3.2
BA3.1_3
BA_3.2
BA3.1_2
BA_3.2
BA3.1_4
SA9_1
TO1_1
TO1_2
b
a
LANDSLIDES
Nearshore G.I
OGSBO3_1
SA14_1
OGS1_1
BO1_1
BO3_1
PA4_1
SA15_1
SA17_1
SA18_1
PA5_1
SA16_1
OGSBO3_2
BO1_1
BO3_2
OGS1_2
c
Trigger category
S Seismic
R Rainfall
A Anthropic
SL/SW Storm events
V Volcanic activity
P/F Piping/ Fluids in sediments
Ff Flash floods
Output log
QUALITATIVE
SEMI-QUANTITATIVE
QUANTITATIVE

Figure 11. Conceptual framework providing a synoptical view of topics / processes dealt with by the working tools. a) inverse tree for coastal G.I. b) Zoom of the inverse tree for coastal G.I where most of the tool occur c) inverse tree for nearshore and volcanic islands G.I.

With reference to the logical structure in which the extracted tools are placed, for each environment (coastal and nearshore, for TK1) it would theoretically be possible to construct a number of tool chains equal to the possible combinations of environments (2), scales (3), kinematic categories (2) and types of GI (13); however, it is evident that already from the view of the so-called "inverse tree," in which many branches are not populated, only some of these combinations can actually be developed.

Going into the details of the proposed logical-operational scheme, for sequentially composing the tools related to the predisposing, preparatory, and triggering factors, it is possible to summarize each flow construction as follows:

1. Having defined the environment and scale of work, the tools made available by WP2 guide toward the choice of the GI process(es) for which possible scenarios capable of generating consequences on the environment (and the built environment) are expected, as well as providing guidance on the location of areas of greatest potential criticality.

2. Once the potential GI process(es) have been identified, the tools produced by WP3 are called up. It should be emphasized that the step for preparatory factors is to be considered optional, to the extent that: i) they are to be considered factors that are sometimes not necessary for the occurrence of GI (i.e., for the liquefaction GI case). The preparatory factors (in white color) have been associated to each (preparatory) tool, for the sake of clarity. Three colors have been used for the tools contained in each tool chain, according to the output type (qualitative: light pink; semi-quantitative: orange; quantitative: green).

3. Given the similarities between GIs occurring both in mountain and coastal (emerged) areas, the tool chains were built by also integrating the triggering tools relating to Tasks 2 (mountain and hilly areas) and 3 (large plains, sinkhole zones). In this regard, an asterisk has been added close to those tools not related to TK 1. Moreover, an explanation of the trigger acronyms, related to other Tasks and included in the tool chains of TK 1, has been added below each tool chain, for the sake of clarity. Similarly to preparatory tools and factors (point 2. above), three colors have been used for the trigger tools contained in each tool chain, according to the output type (qualitative: light pink; semi-quantitative: orange; quantitative: green), while the corresponding factor has been reported with the white color.

4. The next step is to apply the useful tools to return the instability scenarios in terms of:
    a) for kinematic category of rapid processes: the evaluation of displacements (in one or more components depending on the type of process), volumes involved, velocity and, consequently, kinetic energy.
    b) for kinematic category of slow processes: the evaluation of displacements (in one or more components depending on the type of process) and the rates at which they occur, while the spatial restitution may consist of identification of the area affected by deformation.

Nine examples of tool chains are given below for Rapid landslides (i.e. Falls and topples and rockslides – basin scale, and rock avalanches - local scale) (Figure 12-14) and Slow landslides (i.e. Earth flows - Regional scale) (Figure 13) in coastal areas, Rapid submarine landslides in nearshore areas (Figure 18) and volcanic islands (Figure 19), Subsidence (Figure 15), Liquefaction (Figure 16) and Sinkholes (Figure 17).

These tool chains are useful mainly to make a point in view of the transfer of this logical-operational scheme into an IT structure for simulating IM scenarios: once set the environment and scale of analysis, if there is more than one predisposition and/or triggering tool, the choice may be dictated primarily by the validity constraints specific to each tool, and secondarily by output log requirements.

All the working tools included in the tool chains (e.g. BA3.1_1, BA3.1_2, etc. included in the tool chain of Figure 12) have been reported in Table 3. The corresponding LE summary sheets (as shown in Figure 3) can be found within the Teams folder "SpokeV2" (link: https://communitystudentiunina.sharepoint.com/:f:/s/PE3RETURN935/EjEstw5-tmJLsbx8xnhgPVsBwwY5H4VEvim-13MangcHVg?e=pwPYWa).

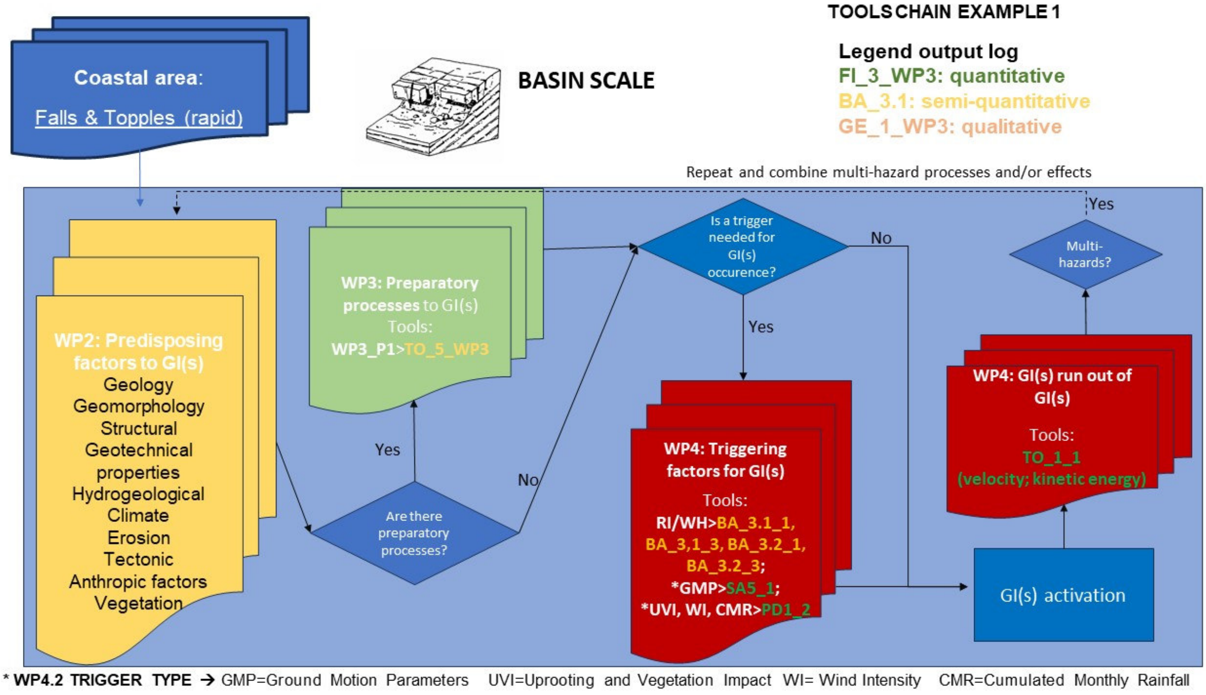
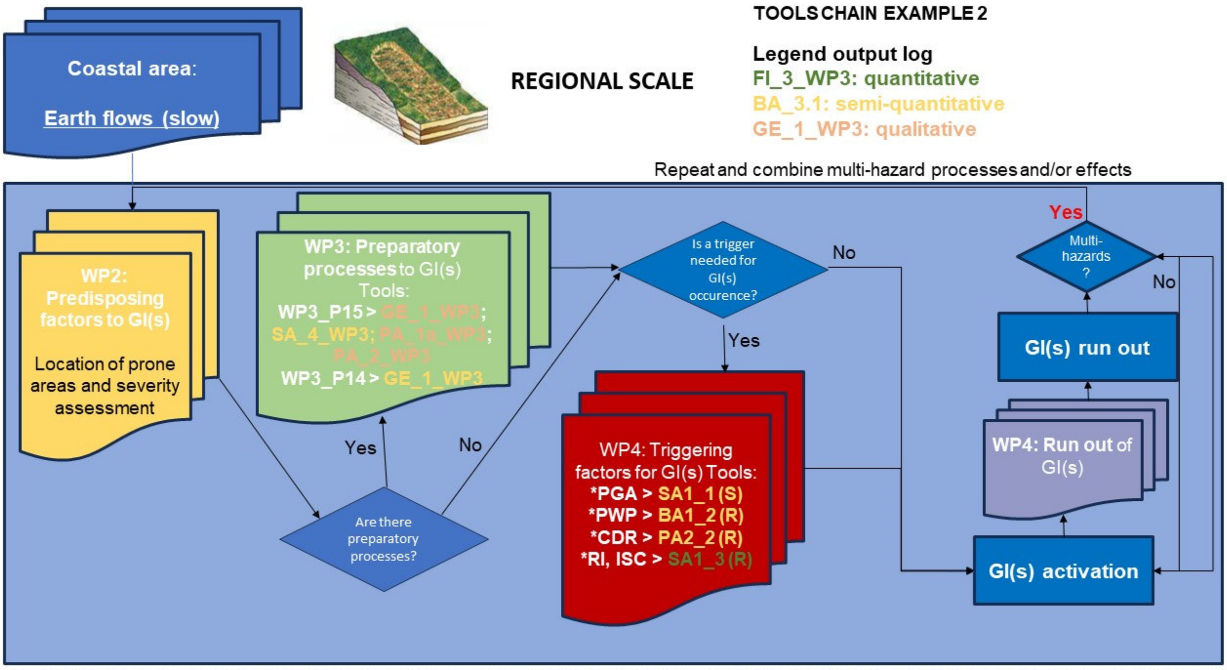
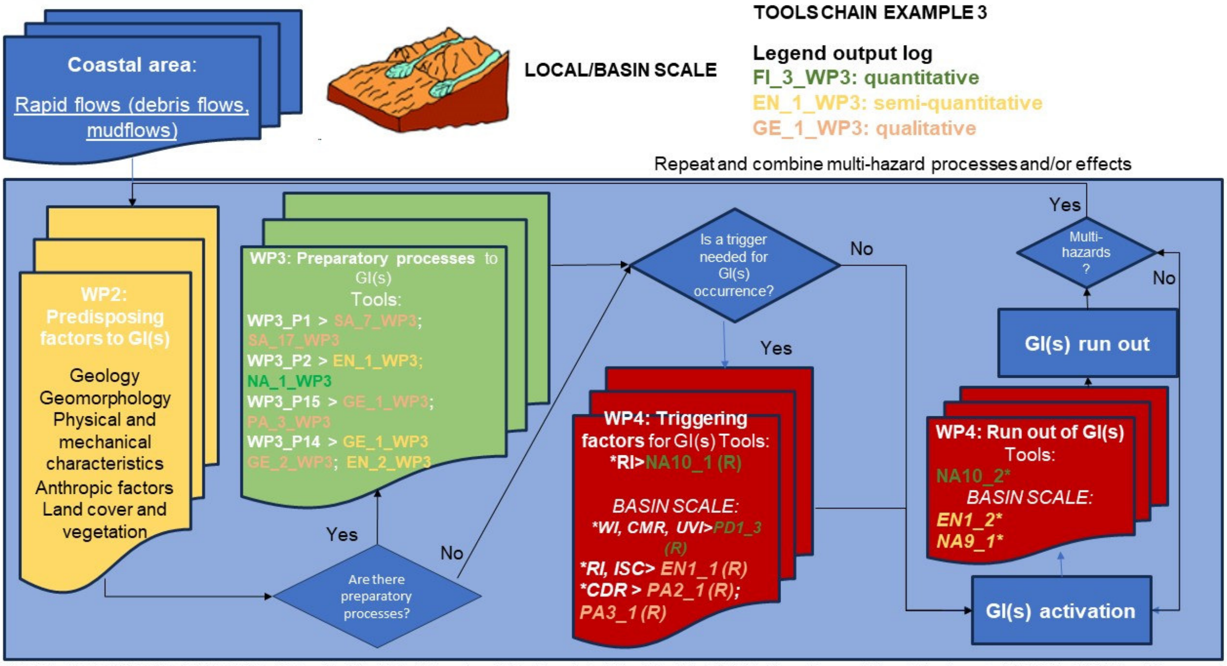


Figure 12. Tool chain for Rapid rock landslides (rockfall) occurring at basin scales. The tools with the asterisk refer to TK2.



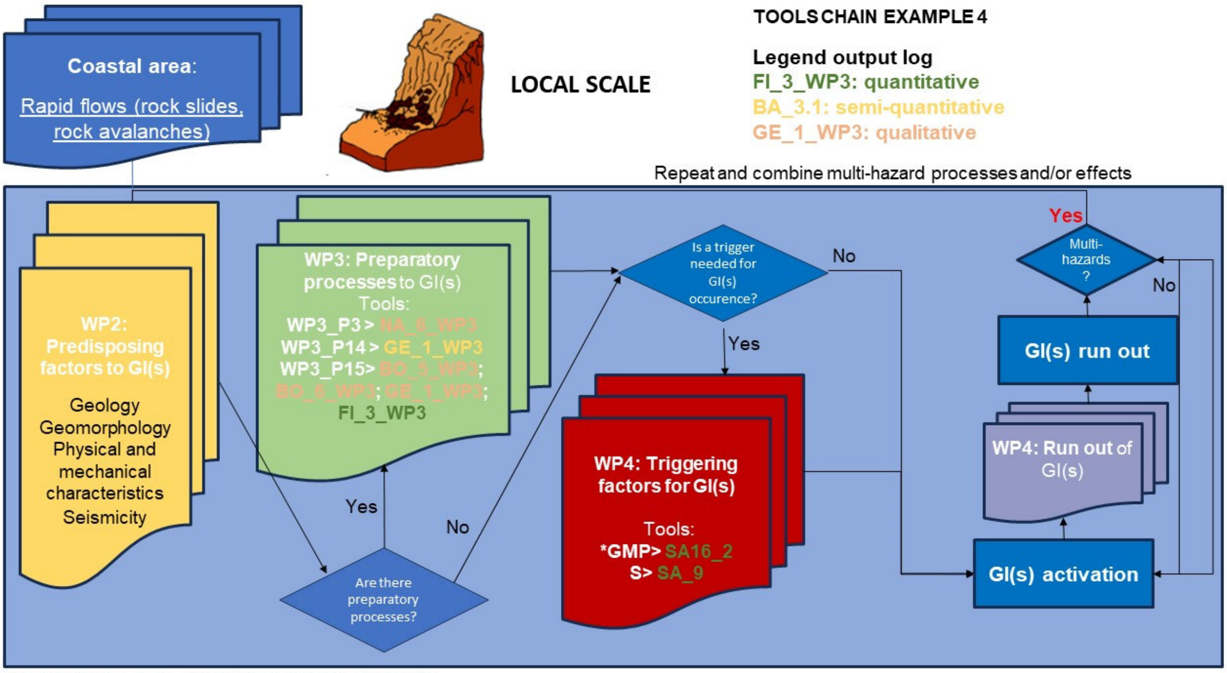
* **WP4.2 TRIGGER TYPE →** PGA=Peak Ground Acceleration PWP=Pore Water Pressure CDR=Cumulated Daily Rainfall RI=Rainfall Intensity ISC=Initial Soil Condition

Figure 13. Tool chain for Slow earth flows occurring at regional scales. The tools with the asterisk refer to TK2.



* **WP4.2 - TRIGGER TYPE →** RI=Rainfall Intensity WI= Wind Intensity CMR=Cumulated Monthly Rainfall UVI=Uprooting and Vegetation Impact ISC=Initial Soil Condition CDR=Cumulated Daily Rainfall

Figure 14. Tool chain for rapid flows, such as debris flows and mudflows, occurring at local/basin scales. The tools with the asterisk refer to TK2.



* **WP4.2 TRIGGER TYPE** → GMP=Ground Motion Parameters

Figure 15. Tool chain for rapid flows, such as rockslides and rock avalanches, occurring at local scales. The tools with the asterisk refer to TK2.

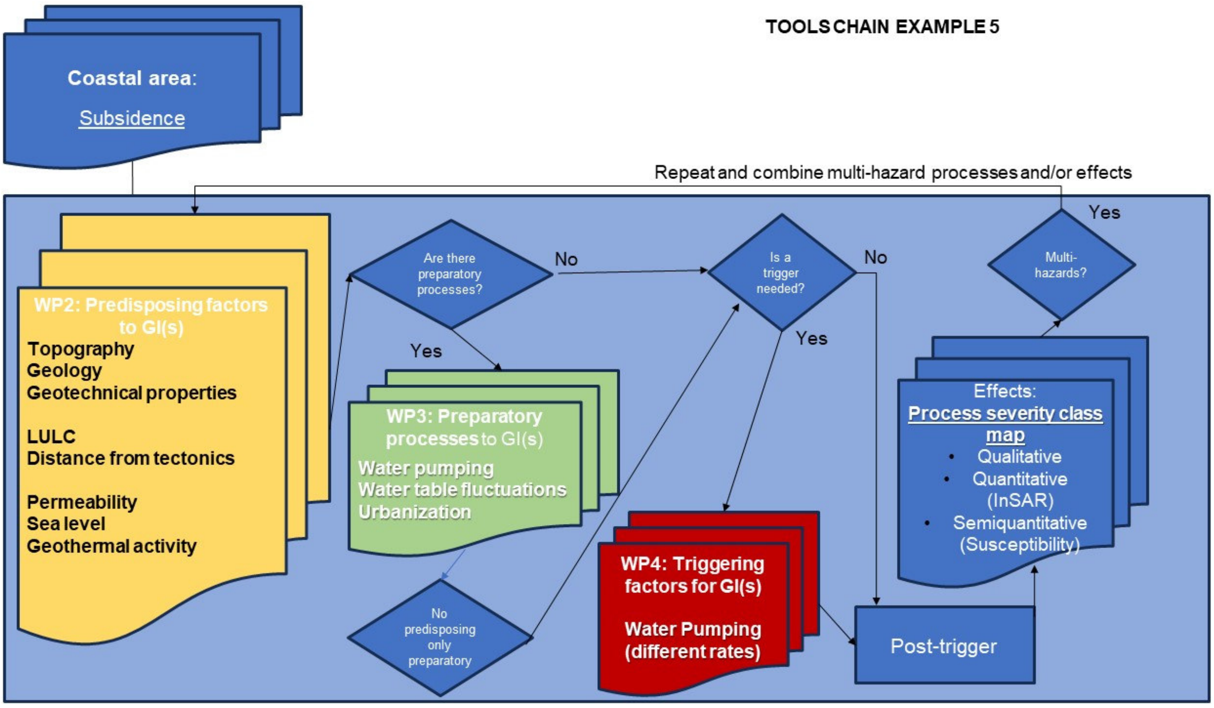


Figure 16. Tool chain for Subsidence. For the development of the tool chain, reference has been made to TK3.

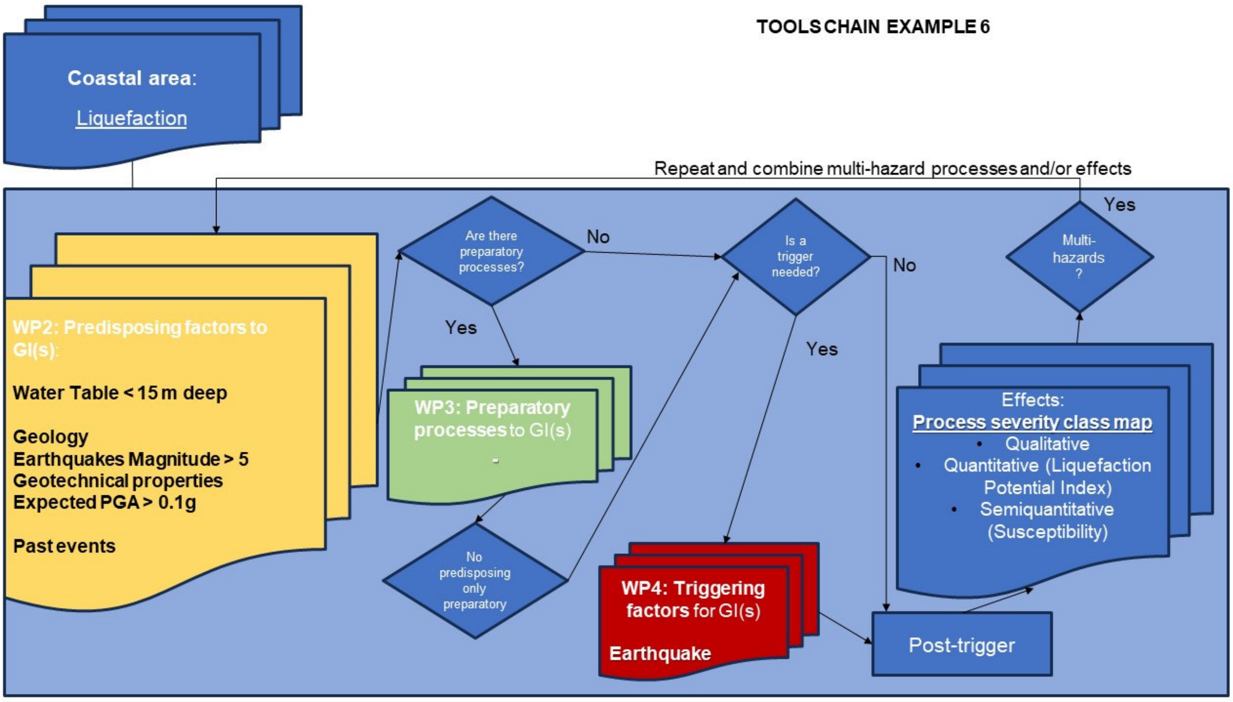


Figure 16. Tool chain for Liquefaction. For the development of the tool chain, reference has been made to TK3.

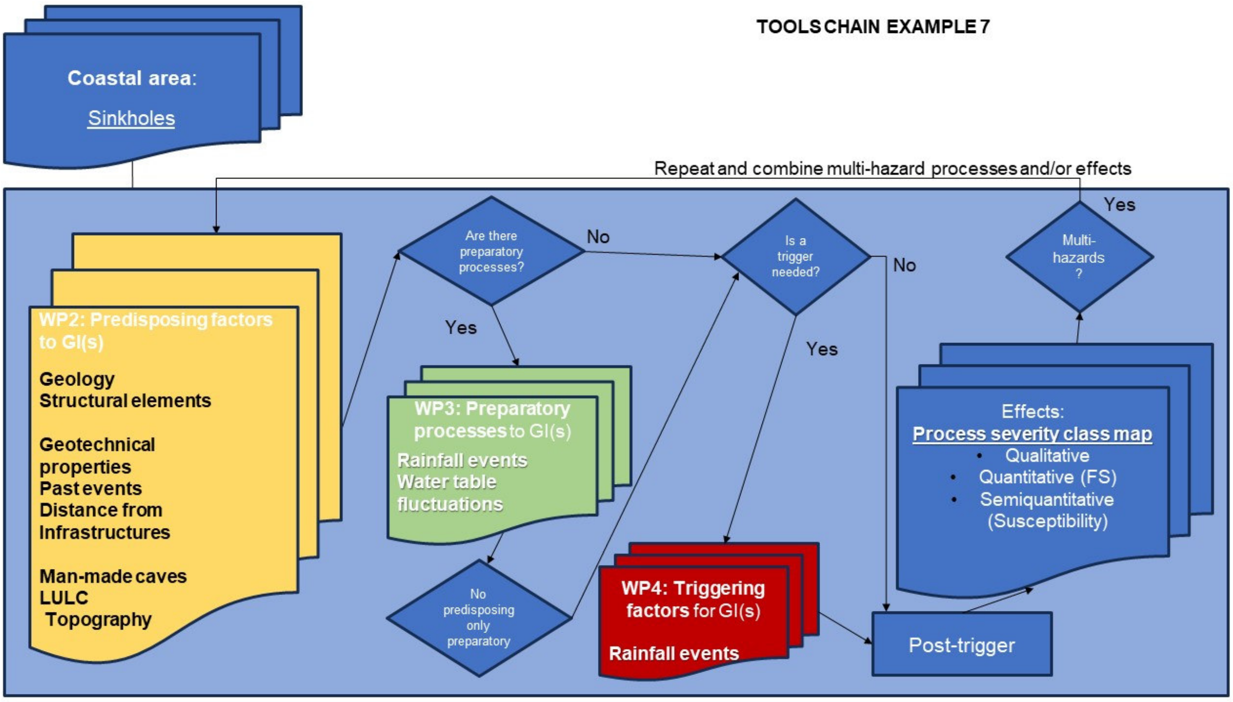


Figure 17. Tool chain for sinkholes. For the development of the tool chain, reference has been made to TK3.

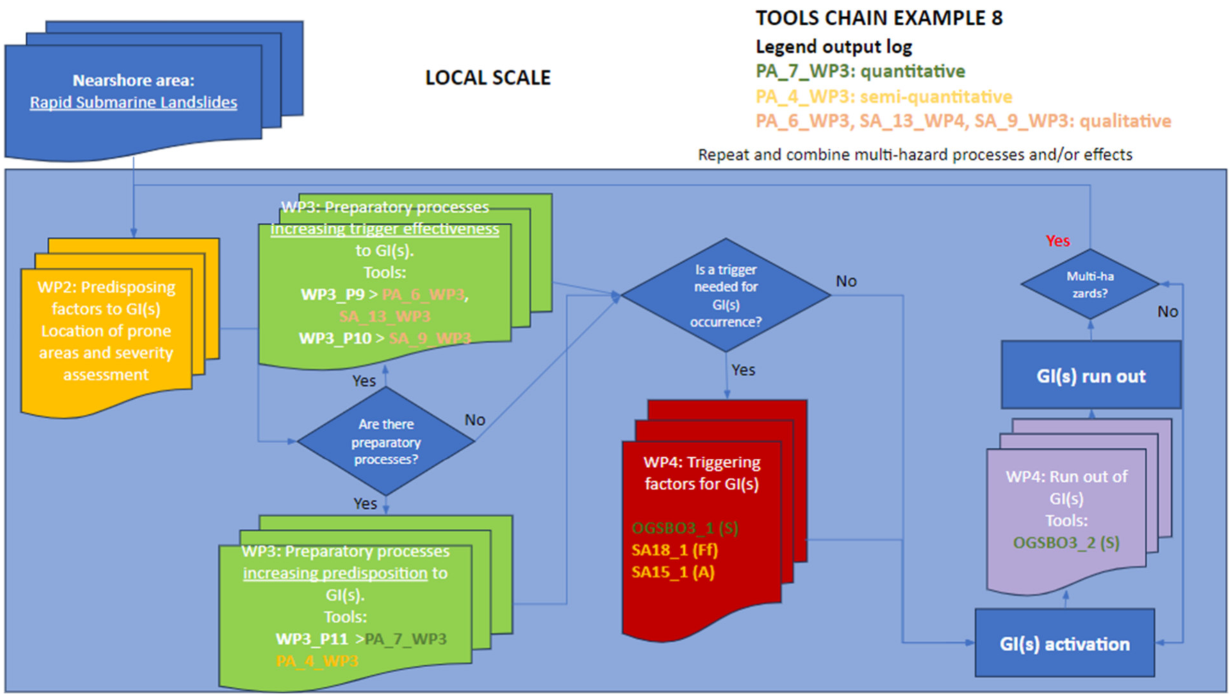


Figure 18. Tool chain for rapid submarine landslides at the local scale in nearshore areas.

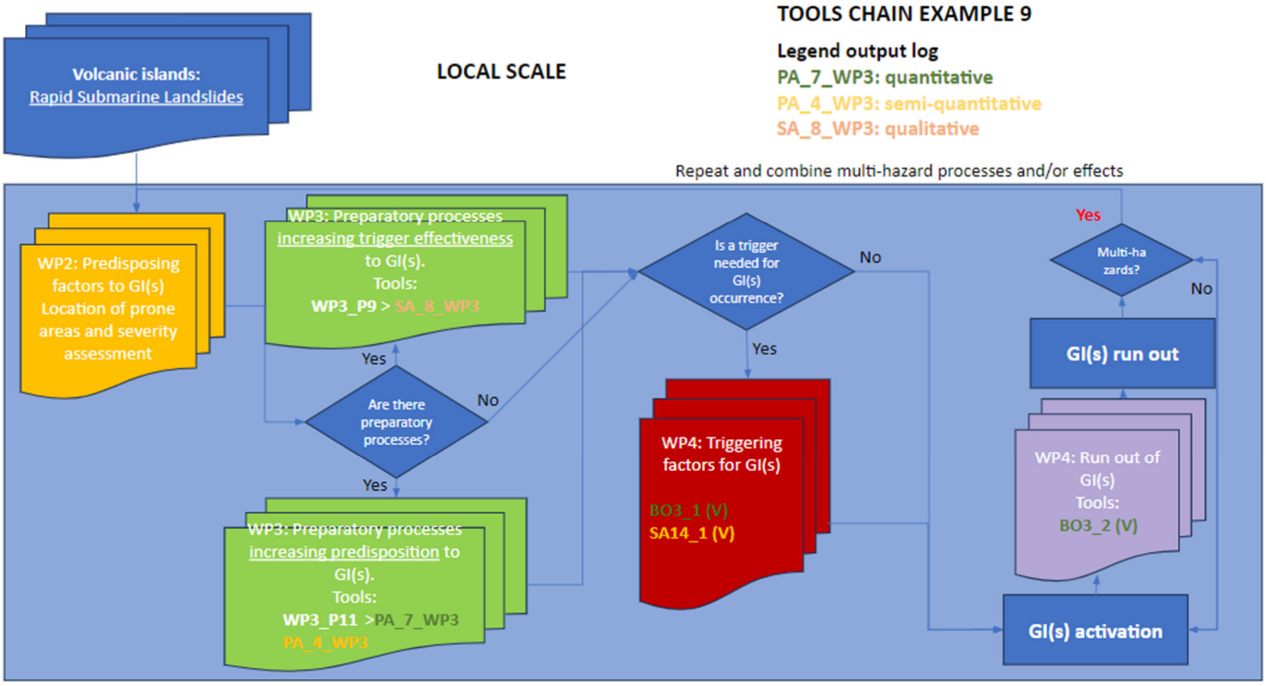


Figure 19. Tool chain for rapid submarine landslides at the local scale in volcanic islands.

5. Strengths and weaknesses

The inventory of LEs presented in the WP4 for Task 2.4.1 provides valuable insight into the strengths and, principally, the weaknesses of the method adopted for the study of triggering factors of ground instability. For this reason, some valuable recommendations for future improvement are proposed for the integration in the successive phases of the project.

One of the strengths of this approach is the good selection of Learning Examples (LEs) by the project partners. These LEs serve as the cornerstone for the analysis, presenting real-world case studies that researchers have meticulously studied and analyzed. This hands-on approach ensures that the dataset is not derived from a generic state-of-the-art but is instead grounded in empirical evidence obtained from actual fieldwork and research efforts. Moreover, through the analysis of the chosen Learning Examples (LEs), detailed information regarding the triggering factors associated with the selected ground instabilities came to light.

Another strong point is the actual utility that the recall of new LEs has had in expanding the casuistry and in satisfying a sufficient number of LEs for each trigger identified in the first call and, in addition to this, new triggers have been identified (i.e Flashfloods).

Despite these strengths, it is crucial to recognize the inherent limitations of the approach. While the quality of the presented Learning Examples (LEs) is positive, despite the increase in case studies resulting from the recall, the available LEs for the task are not sufficient and may not cover the entire range of ground instability scenarios. This lack of comprehensiveness presents a challenge when attempting to draw generalized conclusions about the triggering factors of ground instabilities and for the number of tools effectively produced for the coastal and nearshore instability.

An uneven distribution of Learning Examples (LEs) has been observed in the national scenario. The majority of LEs are located in southern Italy, primarily in Calabria and Sicily (Figure 4). This bias is attributed to the fact that these areas are particularly prone to landslides and that most of the data available to the project's partner institutions are from these regions. It would therefore be desirable to expand the study cases to other areas of the Italian peninsula.

Another weakness is highlighted by Figure 5 illustrating the distribution of LEs in different contexts (Coastal, Nearshore and Volcanic). There is a noticeable underrepresentation of study cases related to coastal and volcanic instabilities compared to nearshore ones. This limitation is linked to the fact that some of the presented LEs did not align with the objectives of WP4 or of specific Task 2.4.1. A significant portion of the Italian coasts is rocky and includes cliffs, areas highly susceptible to instabilities. Given the substantial tourist pressure, especially in the summer season, in the rocky coastal area, they pose a high risk.

Another limitation is related to the scale of phenomena. As depicted in Figure 6, the majority of Learning Examples (LEs) are at the local scale, while the basin and regional scales are significantly underrepresented. This poses a significant constraint on the application of tools in larger study areas. Considering the importance of coastal instabilities, both due to their widespread presence in the Italian territory and the associated risks, greater integration of such cases in this dataset is necessary.

Figure 7 depicting the kinematics of instabilities reveals another critical aspect. Both in nearshore and coastal environments, slow-moving landslides are not represented. Regarding submarine landslides, this is partly since the ground instabilities studied by the partners involved in this project primarily involve DSGSDs (Deep-

Seated Gravitational Slope Deformations). DSGSDs are primarily “triggered” by significant compressive tectonic phases or high rates of uplift. Due to their nature, these geological processes unfold at extremely slow rates, making it challenging to classify them as triggers; they are more akin to predisposing factors. To bring new insights into slow-moving landslides in coastal areas, two DSGSD examples will be taken into consideration in the next few months to fill this gap in knowledge. They are the Squillace complex (Mangano et al., 2023) and the Crotone megaslide (Zecchin et al., 2018) both located along the Ionian Calabrian margin, moving in relation to a Messinian weak layer, triggered by contractional/transpressional tectonic events related to Calabrian arc migration and subduction. In addition, future integration could provide other types of slow-moving landslides in the nearshore areas (e.g., creeps) where triggers are more easily distinguishable.

The last identified issue is inherently connected to the previous one. Only one type of submarine instability has been observed, specifically retrogressive landslides at the canyon heads. This overrepresentation is linked to the extensive study of this type of ground instability, both due to their high occurrence along the Italian continental margin and the associated geohazards, as they are located very close to the coast and related infrastructures. However, this type of instability is not the only one occurring in nearshore areas. Therefore, a future integration is anticipated, encompassing other types of landslides such as the creeps or those involving the collapse of the shelf-edge.

6. Conclusions

Along continental margins, coasts are among the most critical areas for geohazards occurrence, as they are important hotspots for living communities and onshore offshore infrastructures (railways, harbors, pipelines) especially in the Mediterranean Sea.

In coastal areas both subaerial and submarine landslides occur and often interact (multi-hazards), but the two scientific communities ‘observe’ them using different methods, scale and resolutions.

Submarine landslide investigation presents distinct challenges compared to characterizing and monitoring ground instabilities on land. While on-land ground instabilities benefit from detailed in situ and direct observation methods such as LiDAR, GPS, and seismic monitoring, studying submarine landslides involves unique techniques due to the underwater environment. While advances in technology have allowed for improved monitoring through cabled observatories or autonomous underwater vehicles (AUVs), real-time continuous and long-term observation comparable to on-land methods remain a considerable challenge due to the logistical complexities of deploying monitoring equipment in deep-sea environments.

The comprehensive analysis of on-land and submarine ground instabilities has provided a foundational framework for understanding triggers, multihazard occurrences, and the interplay of predisposing factors. However, this examination has also unveiled critical gaps in knowledge and terminology, which are pivotal to address for a more holistic understanding of coastal areas, both on land and in the marine realm.

Key areas that require immediate attention include the standardization of geological terminology to ensure consistency between on-land and submarine ground instabilities. Codifying vocabulary will streamline communication and understanding across these domains.

Furthermore, there's a pressing need to expand the tool chains to incorporate submarine ground instabilities with slow kinematics, such as the Squillace Megaslide and Crotone Megaslide. Additionally, subdividing tool chains for submarine ground instabilities with fast kinematics, akin to on-land rock falls and debris flows, will enhance the precision of analyses and predictive models in the construction of the PoC.

An additional critical aspect involves the comparative analysis of analogous processes occurring on land and at sea, such as sinkholes/pockmarks, subsidence at local scales on land versus regional scales at sea driven by tectonics, and erosion gullies in hills vs. submarine canyons. This comparative study, conducted for the first time, will yield valuable insights into the similarities, differences, and underlying mechanisms of these phenomena across terrestrial and marine environments.

Addressing these knowledge gaps and criticalities in the next few months will be crucial for refining the conceptual framework established for on-land ground instabilities and extending it to encompass the complexities of the marine realm. This endeavor not only furthers our understanding but also lays the groundwork for more robust risk assessment, mitigation strategies, and the preservation of coastal areas worldwide.

7. References

Chiocci Francesco, F Budillon, S Ceramicola, FG Orrù (2021) Atlante dei lineamenti di pericolosità geologica dei mari italiani-Risultati del progetto MaGIC. CNR edizioni

Mangano, G., S Ceramicola, T Alves, M Zecchin, D Civile, A Del Ben, Salvatore Critelli (2023). A new large-scale gravitational complex discovered in the Squillace Embayment (central Mediterranean): Tectonic implications. Scientific Reports.

Zecchin M. , F. Accaino, S. Ceramicola, D. Civile, S. Critelli, C. Da Lio, G. Mangano, G. Prosser, P. Teatini & L. Tosi (2018) The Crotone Megalandslide, southern Italy: Architecture, timing and tectonic control Scientific Reports, 8:7778, DOI:10.1038/s41598-

8. WP4 Task 1 LEs references

Casalbore, D., Bosman, A., & Chiocci, F. L. (2012). Submarine Mass Movements and Their Consequences. *Submarine Mass Movements and Their Consequences*, 573–582. https://doi.org/10.1007/978-94-007-2162-3

Casalbore, D., Chiocci, F. L., Mugnozza, G. S., Tommasi, P., & Sposato, A. (2011). Flash-flood hyperpycnal flows generating shallow-water landslides at Fiumara mouths in Western Messina Strait (Italy). *Marine Geophysical Research*, *32*(1), 257–271. https://doi.org/10.1007/s11001-011-9128-y

Ceramicola, S., Coste, M., Praeg, D., Migeon, S., & Zecchin, M. (2015). Submarine canyon systems along the Ionian Calabrian margin, Central Mediterranean Sea. *Submarine Canyon Dynamics in the Mediterranean and Tributary Seas - An Integrated Geological, Oceanographic and Biological Perspective. CIESM Monograph 47*, *April*, 157–163. https://noc.ac.uk/seminars/g3-seminars/submarine-canyon-systems-along-ionian-calabrian-margin-central-mediterranean

Corradino, M., Morelli, D., Ceramicola, S., Scarfì, L., Barberi, G., Monaco, C., & Pepe, F. (2023). Active tectonics in the Calabrian Arc: Insights from the Late Miocene to Recent structural evolution of the Squillace Basin (offshore eastern Calabria). *Tectonophysics*, *851*(February). https://doi.org/10.1016/j.tecto.2023.229772

Dan, G., Sultan, N., & Savoye, B. (2007). The 1979 Nice harbour catastrophe revisited: Trigger mechanism inferred from geotechnical measurements and numerical modelling. *Marine Geology*, *245*(1–4), 40–64. https://doi.org/10.1016/j.margeo.2007.06.011

Fazio, N. L., Perrotti, M., Andriani, G. F., Mancini, F., Rossi, P., Castagnetti, C., & Lollino, P. (2019). A new methodological approach to assess the stability of discontinuous rocky cliffs using in-situ surveys supported by UAV-based techniques and 3-D finite element model: a case study. *Engineering Geology*, *260*(December 2018). https://doi.org/10.1016/j.enggeo.2019.105205

Lo Iacono, C. Lo, Sulli, A., Agate, M., Lo Presti, V., Pepe, F., & Catalano, R. (2011). Submarine canyon morphologies in the Gulf of Palermo (Southern Tyrrhenian Sea) and possible implications for geo-hazard. *Marine Geophysical Research*, *32*(1), 127–138. https://doi.org/10.1007/s11001-011-9118-0

Lo Presti, V., Antonioli, F., Casalbore, D., Chiocci, F. L., Lanza, S., Sulli, A., & Randazzo, G. (2022). Geohazard assessment of the north-eastern Sicily continental margin (SW Mediterranean): coastal erosion, sea-level rise and retrogressive canyon head dynamics. *Marine Geophysical Research*, *43*(1), 1–18. https://doi.org/10.1007/s11001-021-09463-9

Lollino, P., Pagliarulo, R., Trizzino, R., Santaloia, F., Pisano, L., Zumpano, V., Perrotti, M., & Fazio, N. L. (2021). Multi-scale approach to analyse the evolution of soft rock coastal cliffs and role of controlling factors: a case study in South-Eastern Italy. *Geomatics, Natural Hazards and Risk*, *12*(1), 1058–1081. https://doi.org/10.1080/19475705.2021.1910351

Napoli, M. L., Barbero, M., Castelli, F., Castelli, M., & Lentini, V. (2023). A Semi-quantitative Approach to Assess the Propensity of Rockfall Source Areas to Instability Based on the Susceptibility Index to Failure (SIF): the Case Study of Capo Calavà (Italy). *Springer Series in Geomechanics and Geoengineering*, 715–723. https://doi.org/10.1007/978-3-031-34761-0_86

Sansò, P., Gianfreda, F., Leucci, G., & Mastronuzzi, G. (2016). Cliff evolution and late Holocene relative sea level change along the Otranto coast (Salento peninsula, southern Apulia, Italy). *GeoResJ*, *9–12*, 42–53. https://doi.org/10.1016/j.grj.2016.07.001

Sassa, K., Canuti, P., & Yin, Y. (2014). Landslide science for a safer geoenvironment: Volume 3: Targeted landslides. *Landslide Science for a Safer Geoenvironment: Volume 3: Targeted Landslides*, *3*, 1–717. https://doi.org/10.1007/978-3-319-04996-0

Scardino, G., Anzidei, M., Petio, P., Serpelloni, E., De Santis, V., Rizzo, A., Liso, S. I., Zingaro, M., Capolongo, D., Vecchio, A., Refice, A., & Scicchitano, G. (2022). The Impact of Future Sea-Level Rise on Low-Lying Subsiding Coasts: A Case Study of Tavoliere Delle Puglie (Southern Italy). *Remote Sensing*, *14*(19), 1–23. https://doi.org/10.3390/rs14194936

Scardino, G., Sabatier, F., Scicchitano, G., Piscitelli, A., Milella, M., Vecchio, A., Anzidei, M., & Mastronuzzi, G. (2020). Sea-level rise and shoreline changes along an open sandy coast: Case study of gulf of taranto, Italy. *Water (Switzerland)*, *12*(5), 13–20. https://doi.org/10.3390/w12051414

Sulli, A., Agate, M., Zizzo, E., Gasparo Morticelli, M., & Lo Iacono, C. (2021). Geo-hazards of the San Vito peninsula offshore (southwestern Tyrrhenian Sea). *Journal of Maps*, *17*(3), 185–196. https://doi.org/10.1080/17445647.2020.1866703

Teatini, P., Tosi, L., & Strozzi, T. (2011). Quantitative evidence that compaction of Holocene sediments drives the present land subsidence of the Po Delta, Italy. *Journal of Geophysical Research: Solid Earth*, *116*(8), 1–10. https://doi.org/10.1029/2010JB008122

Terme, C., Island, I., Ceres, R., Gargiulo, F., & Silvestri, F. (n.d.). *Inter-disciplinary and multi-level study of seismic liquefaction susceptibility in the coastal area of. c*.

Tinti, S., Pagnoni, G., Zaniboni, F., & Bortolucci, E. (2003). Tsunami generation in Stromboli island and impact on the south-east Tyrrhenian coasts. *Natural Hazards and Earth System Science*, *3*(5), 299–309. https://doi.org/10.5194/nhess-3-299-2003

Zanuttigh, B., Simcic, D., Bagli, S., Bozzeda, F., Pietrantoni, L., Zagonari, F., Hoggart, S., & Nicholls, R. J. (2014). THESEUS decision support system for coastal risk management. *Coastal Engineering*, *87*, 218–239. https://doi.org/10.1016/j.coastaleng.2013.11.013

9. Appendix 1 - Description of triggers and multihazards

For the better understanding of the triggering factors causing gravitational instability a short description of their influence on generating instabilities has been produced. Moreover, also the main multihazard connected to the occurrence of submarine gravitational instability (i.e tsunami) has been described:

- **Earthquake**

Marine/coastal areas located in tectonically active areas may be subject to repetitive seismic stress. Ground shaking during an earthquake can be enough to weaken rock or cause failure on slopes that are already weakened. Seismic events can induce the fracturing of hard rocks or further deteriorate an already fractured rock mass. In nearshore environments, where sediments are more common than rocks, the cyclic loading driven by seismic shaking causes an increase in shear stress. In cohesive marine soils, when the shear stress induced by earthquake shaking exceeds the undrained shear strength of the sediments, a submarine landslide is triggered. While, in non-cohesive marine soil, the vibration can cause the liquefaction of the soils, resulting in loss of the soil shear strength. High-PGA as that associated with high-magnitude, near-field events cause extensive mass wasting especially in steep slopes. However, not all earthquakes are of sufficient magnitude to cause landslides. Recent studies highlighted that if earthquake shaking does not result in a submarine landslide, sediment will dewater in situ resulting in consolidation, which in turn increases the undrained shear strength.

- **Storm events**

A storm event is characterized by an increase in wave amplitude and frequency in a minor time of impact with respect to ordinary waves. The action of storm events on coastal and nearshore areas is extremely variable as it is linked to wind intensity, exposure of the coast, seafloor topography, tidal waves, etc. Nowadays, storm events are an important triggering factor since, in recent years, extreme weather has been more frequent and storm surges have increased. In the coastal environment, storm events can produce the removal of protective debris from the lower seacliff face, and a reduction of rock strength due to variations in groundwater level, which change the mobilized strength particularly in soft materials, because of the ability of waves to exploit fractures (thus dissecting the rock mass) and as a consequence of weathering/alteration factors (such as sea-spray and mechanical abrasion of suspended material, also through the compressional force of impact and the tractive force of uprush). These processes can cause cliff toe erosion and recession. Large storms frequently cause shallow landslides in nearshore areas characterized by steep slope values or high sedimentation rates (i.e prograding delta or submarine depositional terraces). These landslides are a result of increased pore pressures along a soil-bedrock interface or within the soil profile at an interface of reduced permeability. Variation in pore pressures are due to combined pressure difference below the wave crest and trough.

- **Anthropic**

Coastal and nearshore areas are frequently subjected to anthropic activities due to the presence of commercial infrastructures (i.e port) or industries. Excavations, land reclamations and building new constructions are common procedures related to infrastructure projects. These activities, especially if occurring in underconsolidated and submerged soft soil, can bring catastrophic slope failures. The modification of the slope profile, adding or subtracting land, alters the stress distribution and the pore pressures modifying the safety factor of the slope. Also increasing weight of sediments during the construction bring to an increase in pore water pressure increase possibly occurring in slope failures.

- **Piping/Fluids in sediments**

The presence of submarine morphological structures (mud volcanoes, mud diapirs, pockmarks) linked with escaping fluids alongside continental margin have been largely documented. Released fluids have effects on the seafloor topography (creating positive or negative features) and on the geotechnical properties of the subsurfaces. The presence of pressurized fluid (gas,fluid) influences pore water pressures, changing the effective normal stresses, and therefore the shear strength that could be almost completely nullified. In this context, paroxistic events of fluid escape can cause a drastic increase in pore pressures and a consequent decrease in shear strength leading to slope failures. These mechanisms significantly amplify the effects if they occur in environments with much steeper slopes or where faults are present, as they behave as preferential pathways for the migration of fluids from deep seated reservoirs.

- **Flash floods**

A flash flood is a rapid flooding most often occurring in dry areas that have recently received precipitation. Flash floods are mixtures of sediment and water (sediment >5-10% of the volume) and can travel very long distances . The Mediterranean area is particularly exposed to rainfall-induced flash floods; this is due to the local climate, which is prone to short intense bursts of rainfall (hundreds of mm in a few hours). In the Italian region, these events mainly occur in fall and are particularly destructive in south and north-western Italy. The entrance to the sea of flash floods may result in hyperpycnal flow, which interaction with the seafloor may exert shear stress and erode the bedrock and/or mobilize loose sediments. Moreover, the high solid transport exerted by flash floods-generated hyperpycnal flows, is known to cause a drastic increase in sedimentation rate in a small time interval increasing the vertical stress on the shelf and the consequent increase in pore water pressure possibly causing failures at the slope. Most susceptible areas are those where we have a high coastal range running parallel and not far to the coast (Sila, Aspromonte) and where the continental shelf is narrow (<1 Km). In such a contest, the river that connects the source precipitation area with the marine environment is called *fiumara.* Since flash floods are highly efficient in transporting large amounts of sediments they often connect directly to submarine canyon heads. Even though *fiumare* do not always connect to canyon headwalls, flash floods are regarded as one of the main factors favoring incision and inception of shelf-incising submarine canyons by triggering simple and complex submarine landslide events.

- **Volcanic activity**

Active volcanic edifices are prone to hazards including subaerial and submarine landslides. Volcanic flanks are naturally predisposed to slope instabilities due to the high slope values and terrains weakened by hydrothermal alteration. The direct effect of the volcanic activity in triggering landslides is related to eruptions with the consequent deposition of pyroclasts and lavas altering the profile of the slope that becomes insatiable due to high slope values and loose character of sediments. Also a dome collapse or intrusion can further increase the slope angle leading to the volcanic flank collapse or small-scale landslides. Also other events, indirectly related to the volcanic activity, can trigger landslides as seismically-triggered slope failure caused by volume variations in the magma chamber; volcanic activity seismic events are particularly effective on weak volcanic sediments.

- **Precipitation**

Rainfall infiltration and the amount of groundwater are primary agents in the generation of landslides. Surface run-off can remove loose weathered material and may cause rapid gullying in poorly lithified materials. Intense precipitations can produce ground-water levels rise, can increase soil/rock saturation and can lead to ground-water flows, generating dynamic forces that decrease strength and can lead to gravitational failures. Rainfall can also produce particularly negative consequences when (superficial) permeable strata lie directly over less permeable strata, allowing a perched water table to develop. In this condition, the fine soil strata become saturated and their strength decreases significantly.

- **Tsunami**

One of the main and more important multihazard connected to submarine/coastal landslides are tsunamis. A tsunami is a succession of waves of extremely long wavelength generated by a powerful, underwater disturbance that causes a sudden displacement of a large volume of water from the sea floor. Tsunamis may be triggered by earthquakes, volcanic eruptions, submarine landslides, and by onshore landslides in which large volumes of debris fall into the water. The waves travel away from the area of origin and can be extremely damaging when they reach the shore. Around islands or on a continental shelf, the speed of the waves decreases but the height increases. Depending on the seafloor morphology, wave heights may reach more than 20 m.