multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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AUTHORS

Carlo Esposito (UniRoma1); Rita Tufano (UniNA); Andrea Brenna (UniPD)

1. Technical references

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* PU = Public

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

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Document history

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2. ABSTRACT

This document provides a summary of the main activities carried out within Task 2.4.2 of WP4. Specifically, this deliverable 2.4.3 summarizes the results of the activities dedicated to rationalization for trigger-based multiple geohazards severity mapping and zoning, with the main aim of defining tools that can address issues related to triggering of different types of ground instabilities in hilly and mountain areas, and the associated run out, also in the view of possible multiple geohazards that may characterize a certain portion of a territory. The research activities have been articulated in several phases.

1. First phase of analysis and rationalization of LEs preliminarily proposed by the different Partners.

Each LE has been independently checked by a "transversal" working group of WP4 and the relevant information has been summarized. The processes that involve the hilly-mountainous areas, hence pertaining to the T 2.4.2, are Landslides, characterized by both slow and rapid kinematics; only few LEs deal with different processes, such as Erosion and Fluvial Dynamics. 5 LEs directly deal with run-out assessment of rapid landslides.

2. Revision, withdrawal and integration of the proposed LEs in relation to their actual suitability for the purposes of the Task.

The final count of the LEs can be summarized as: i) n. 11 LEs not suitable for the WP4/T 2.4.2 and withdrawn by the Authors; ii) n. 15 LEs usable for the tools rationalization process, ii) n. 5 newly presented LEs. upon completion of the review and recall activities, the number of Learning Examples (LE) included in Task 2.4.2 is equal to 20. Furthermore, for each of the 20 LEs selected for the Task purpose, as a preparatory phase for the rationalization process, the following information has been extracted: type of kinematics; category of ground instability (GI); involved material; trigger category; scale of validity; analysis log; run out assessment.

3. Extraction from each LE of one or more working tools useful for analyzing trigger processes and returning GI scenarios.

The approach selected to accomplish this operation was to identify, for each LE, all the working tools explicitly or implicitly contained therein, defining the working tool as a specific procedure (or set of procedures) capable of providing an output relative to one of the following issues of interest in this task. 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 issues of interest of the task. Then, a total of 43 working tools dedicated to a specific issue of interest of the task were extracted from the 20 LEs. The kinematics covered by the tools are evenly distributed between slow (19 tools) and rapid ground instabilities (26 tools). Considering the macro-categories of ground instabilities, most of the tools are devoted to landslide phenomena (39 tools). Rainfall is the most considered forcing (24 tools), although numerous tools concern ground instabilities triggered by seismic phenomena (11 tools).

4. Construction of "tool chains" as a sequence of tools that can lead to the assessment of expected impact scenarios for different GIs.

Each trigger / multihazard / scenario generation (e.g., runout assessment in case of landslides) tool has been framed in a logical structure, conceived as a hierarchical tree rooted in the different GI categories and increasingly branched off according to additional criteria (kinematic, GI type, trigger category, run-out assessment). Based on the hints provided by such a hierarchical tree structure, a conceptual workflow has been proposed (and implemented by means of exemplifications), addressed to the systematization of the individual tools extracted in the different WPs and useful, in concatenation, to return scenarios resulting from GI processes, thus starting from the predisposing factors, passing - where necessary - through the preparatory processes and, finally, taking into account the triggering factors.

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4. First Chapter: Introductory information

4.1 Overview of Task 2.4.2

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.

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 considers 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 time 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 (T 2.4.1).
- Task 2.4.2: Multiple geohazards for ground instabilities in hilly and mountain areas, including destressed glacial valleys, high-intensity erosion slopes, permafrost deglaciation areas, and thermally stressed rock walls (T 2.4.2).
- Task 2.4.3: Multiple geohazards for ground instabilities in large plains, sinkhole zones (T 2.4.3).
- 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 (T 2.4.4).

This report summarized the scientific research activities carried out in the period January – November 2023 by the Task 2.4.2 "Multiple geohazards for ground instabilities in hilly and mountain areas".

The task 2.4.2 is focused on ground instabilities in hilly and mountain areas, including debutressed glacial valleys, high-intensity erosion slopes, permafrost deglaciation areas, and thermally stressed rock walls. Objects of this task will concern multi-hazard effects and severity indicators in case of ground instabilities in hilly and mountain areas by combining process understanding (DV 2.4.3) and hazard mapping (DV 2.4.4) for multiple triggers and cascading events. Processes to be considered should include mainly gravity-driven processes as well as possible interactions with anthropic activities.

Finally, for sake of synthesis it is possible to state that tasks of WP4 have been conceived with a twofold objective: i) analyzing triggering processes for Ground Instabilities (GIs) and/or multihazard (MH) effects, and ii) rationalizing the whole "chain" from the predisposing factors up to the triggers and related scenarios (i.e., indicators of intensity and spatial extent of selected instabilities). Furthermore, it is worth noting that tasks within WP4 have been assigned based on an "environment-based criterion", i.e. each task deals with a variety of GI in a specific environmental context.

4.2 Preliminary identification of Learning Examples

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 task 2.4.2 bibliography repository will be listed in Section 6.

To retrieve information about the experiences gained (and, thus, the lessons learned) by the Partnership on the topics of triggering processes and/or multi-hazard effects and/or assessment of impact scenarios (i.e., areal extent and intensity of the instabilities), a first call for Learning Examples (LEs) has been initiated: each member of the Partnership has been invited to propose case histories, usually consisting of selected scientific papers, fitting some minimum requirements for their eligibility as LEs, based on indications provided by the WP in a dedicated table.

After this first acquisition, each LE has been independently checked by a "transversal" working group of WP4 and the relevant information has been summarized in an online inventory file, including:

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

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

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 from T 2.4.1 to T 2.4.3, with a dominant number of triggers and processes related to the mountain and hilly environment (T 2.4.2).

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

Ground Instabilities	Subaerial Landslides	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)
		Subaerial Rapid Landslides Typologies	Rapid Flows (Debris flows, Mudflows)
			Rapid Slides (Rock Slides, Rock Avalanches)
			Falls & Topples (Rock Falls, Rock Topples)
	Submarine Landslides	*Submarine Landslides Typologies*	*Slow Landslides*
			Rapid Landslides
	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 Deliverables 2.2.1 and 2.2.2 prepared by the WP2. Based on the LEs proposed, the processes that involve the hilly-mountainous areas, hence pertaining to the T 2.4.2, are Landslides, characterized by both slow and rapid kinematics; only few LEs deal with different processes, such as Erosion and Fluvial Dynamics. 5 LEs directly deal with run-out assessment of rapid landslides.

5. Second Chapter: Towards the Rationale

5.1 Advanced analysis and final selection of Learning Examples

The rationalization sheets of the Learning Examples (LEs) assigned to the T2.4.2 by previous evaluations, were deeply 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:

- suitable in its current form
- suitable after integration
- to be deeply revised
- LE not suitable for the WP2
- LE not suitable for the T 2.4.2

Such labels have represented an indicator of the information provided by the rationalization sheet (Table 4 of the DV 2.3.1 VS2) for the proposed LEs and a helpful guide for the sequent updating/improvement phase.

The first analysis revealed n. 3 LEs as not suitable for the WP4, n. 1 LE not suitable for the T2.4.2, 7 LEs to be deeply revised, and n. 14 LEs that were considered as 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. To efficiently achieve this goal, a revised (and more informative) version of the table to summarize the main features of the proposed LEs as well as some synthetic guidelines have been provided to the authors. Figure 2 shows the structure of such a summarizing table.

PROCESS	WP4_x
LEARNED FROM *(indicate the LE ID)*	LE_x_WP4
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)*
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?*
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?*
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?*
ANALYSIS LOGS *(specify if qualitative, semi-qualitative or quantitative)*	*Basing on the previous learning, how does the PoC have to return the results?*
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 2: Table provided to LEs authors to better highlight relevant information for T 2.4.2 activities

The final count of the LEs can be summarized as: i) n. 11 LEs not suitable for the WP4/T 2.4.2 and withdrawn by the Authors; ii) n. 15 LEs usable for the tools rationalization process, ii) n. 5 newly presented LEs. Table 1 and Figure 3a report the current state of the LEs proposed for the T 2.4.2. In Table 1 each LE has been labeled (field "LE ID") to keep track of the proposing partner, the progressive number of LE proposed by each partner and the WP for which the LE has been proposed. Such labels allow to identify the original source of information, i.e., the summary sheet updated after the "re-call" phase and stored in a repository made available for this project. This repository is available in the PE3 RETURN Team, "Generale", "Spoke VS2" folder. Figure 3b indicates the number of LEs on the base of the institution that proposed them.

Table 1 – Inventory of LEs for WP4 – T 2.4.2.

Institution	LE ID	LE name	Suitable in present form	Integrated/ Revised	Not suitable for WP/TK	New insertion
UNIBA	BA_1_WP4	Daunia		X		
	BA_2_WP4	Fossa Bradanica		X		
UNIBO	BO_1_WP4	Lago d'Iseo (BS)			X	
	BO_3_WP4	Isola di Stromboli			X	
ENEA	EN_1_WP4	Provincia di Messina		X		

UNIPA	PA_1_WP4	Frana di Scopello			X	
	PA_2_WP4	Bacini Imera-Torto		X		
	PA_3_WP4	Messinese Ionico		X		
POLITO	TO_1_WP4	Valle d'Aosta (La Thuile, Gressoney), Val Germanasca, Val di Susa (Thures, Champlas)			X	
	TO_2_WP4	Thurwieser rock avalanche				X
	TO_X_WP4	Capo Calavà				X
UNIFI	FI_1_WP4	Regione Toscana			X	
	FI_2_WP4	Landslide dams		X		
	FI_3_WP4	Italia settentrionale		X		
UNIGE	GE_1_WP4	Liguria e Piemonte		X		
UNINA	NA_3_WP4	Monti Lattari (Campania)			X	
	NA_4_WP4	Umbria-Marche			X	
	NA_5_WP4	Napoli			X	
	NA_6_WP4	Bisaccia			X	
	NA_7_WP4	Ischia			X	
	NA_8_WP4	Buonalbergo				X
	NA_9_WP4	Napoli				X
	NA_10_WP4	Palma Campania				X
UNIPD	PD_1_WP	Dolomiti		X		
	PD_4_WP4	Torrenti montani (Multiple LE)		X		
UNIROMA1	SA_1_WP4	Molise (sismoinduzione: cosismico e postsimico)		X		
	SA_4_WP4	Frana di Monte Mario (Via Teulada)	X			
	SA_5_WP4	PARSIFAL (Multiple Case Studies)	X			
	SA_8_WP4	Time to failure Prediction (Multiple Case Studies)			X	
	SA_12_WP4	Roma (soglie pluviometriche innesco)	X			

	SA_16_WP4	Stima probabilistica spostamenti co-sismici	X			

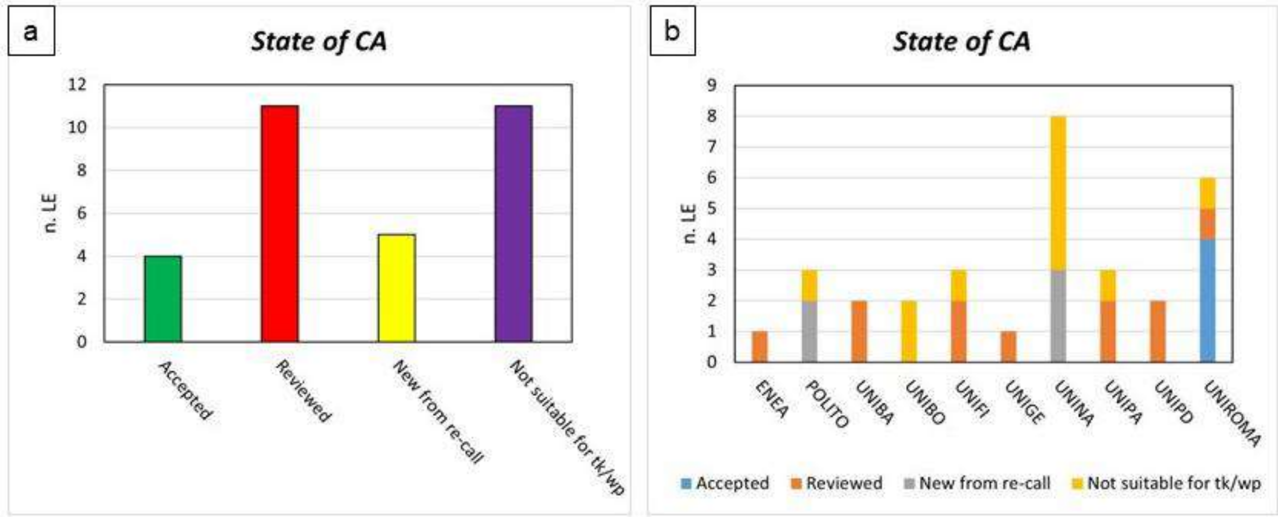

Figure 3: Inventory of LEs for T 2.4.2 expressed as: (a) number of LEs accepted, reviewed, new derived from the recall, and not suitable for the WP4/T 2.4.2; (b) number of LEs accepted, reviewed, new derived from the recall, and not suitable for the WP4/T 2.4.2, for each institution which proposed them.

Furthermore, for each of the 20 LEs selected for the Task purpose, as a preparatory phase for the rationalization process, the following information has been extracted:

- type of kinematics;
- category of ground instability (GI);
- involved material;
- trigger category;
- scale of validity;
- analysis log;
- run out.

All this information is reported in Table 2. Moving to the substantial issues, Table 2 possibly highlights a significant variation among the types of kinematics with n. 12 LEs focusing on rapid GI, n. 5 LEs on slow GI, and n.3 LEs on both slow and rapid GI (Figure 4a). The type of GI more present is landslide (n. 16 LEs), as expected according to the environment (hilly and mountains area) of the T 2.4.2, then fluvial dynamic with n. 2 LEs, erosion with n. 1 LE and, finally, n. 1 LE focusing on landslide and multi-hazard (Figure 4b). About the type of material considered from the LEs, n. 10 cases involve soil or incoherent materials, n. 7 LEs work with both soil and rock and n. 3 LEs only with rock (Figure 4c). N. 10 LEs highlight the rainfall as a trigger category, while n. 3 LEs the seismic input, n. 1 LE a landslide as trigger category of the GI, n.1 LE the anthropic trigger, n. 1 LE the fluvial trigger, n. 2 LEs consider two possible triggers: rainfall and windstorm, and rainfall and seismic input (Figure 4d). The scale of investigation is represented by n. 1 LE as regional, n. 5 LEs as basin, n. 5 LEs as local, n. 5 LEs as regional/basin/local, and n. 4 LEs as regional/basin (Figure 4e). The analysis log is represented by an elevated number of quantitative or semi-quantitative outputs. In the specific, n. 8 LEs provide a quantitative output, n. 7 LEs a semi-quantitative output, n. 3 Les a quantitative/semiquantitative output, n. 1 LE a qualitative output, and n. 1 a semiquantitative/qualitative output (Figure 4f). Finally, n. 5 LEs provide a tool for run out evaluation.

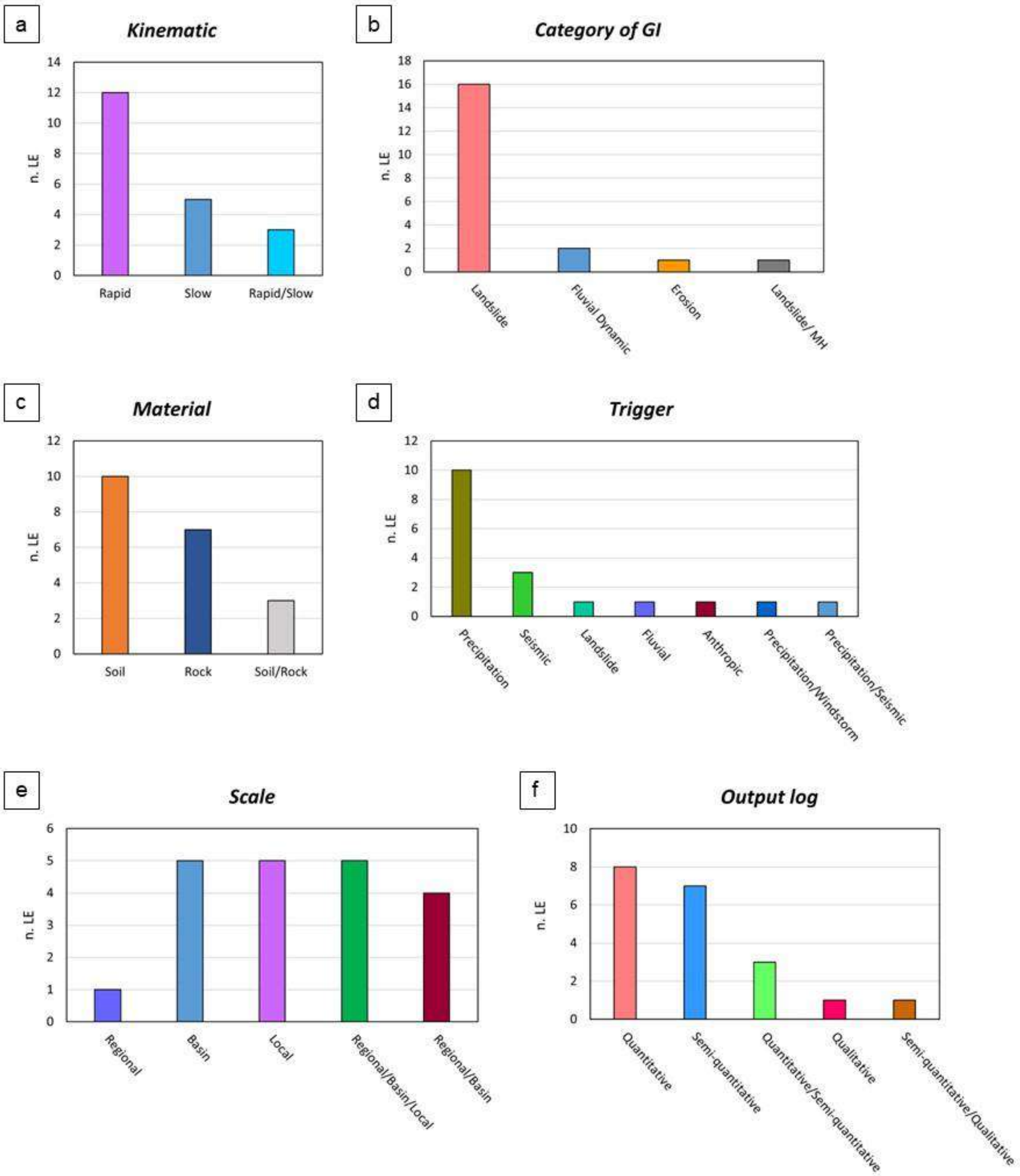

Figure 4: Graphs reporting the statistics of the LEs. (a) Type of kinematic. (b) Category of ground instability GI. (c) Involved material. (d) Trigger type. (e) logscale of validity. (f) Output log.

Table 2 - Extraction of information from the LEs.

LE ID	Kinematic	Category of GI	Materials	Trigger	Scale	Analysis Log	Run out
EN_1_WP4	R	L	Soil	P	B	QUAL/SQ	X
TO_2_WP4	R	L	Rock		L	QUANT	X
TO_X_WP4	R	L	Rock		R/B/L	SQ	X
BA_1_WP4	R/S	L	Soil/Rock	E	R/B/L	QUANT/SQ	
BA_2_WP4	S	E	Soil	P	L	SQ	
FI_2_WP4	R	FD	Soil/Rock	L	R/B/L	QUAL	
FI_3_WP4	R	L	Soil	P	R/B	QUANT	
GE_1_WP4	R	L	Soil/Rock	P	R	SQ	
NA_8_WP4	S	L	Rock	P	L	QUANT	
NA_9_WP4	R	L	Soil	P	B	SQ	X
NA_10_WP4	R	L	Soil	P	L	QUANT	X
PA_2_WP4	S	L	Soil/Rock	P	B	SQ	
PA_3_WP4	R	L	Soil	P	B	SQ	
PD_1_WP4	R/S	L	Soil/Rock	P/WS	R/B	QUANT/SQ	
PD_4_WP4	R	FD	Soil	F	R/B/L	SQ	
SA_1_WP4	S	L/MH	Soil	P/E	R/B	QUANT/SQ	
SA_4_WP4	S	L	Soil	A	L	QUANT	
SA_5_WP4	R	L	Soil/Rock	E	R/B	QUANT	
SA_12_WP4	R	L	Soil	P	B	QUANT	
SA_16_WP4	R/S	L	Soil/Rock	E	R/B/L	QUANT	

Legend: Type of kinematics: R-rapid, S-slow, R/S-rapid and slow. Macro-category of ground instability GI: L-landslide, E-erosion, FD-fluvial dynamic; L/MH-landslide and multi-hazard. Involved material: soil, rock. Trigger category: P-precipitation, E-seismic, L-landslide, WS-windstorm, A-anthropic. Scale of validity: R-regional, B-basin, L-local. Analysis log (qualitative QUAL; semi-quantitative SQ; quantitative QUANT). Presence of run out tools.

5.2 From Learning Examples to the extraction of working tools

As discussed in detail in the previous Section (5.1), upon completion of the review and recall activities, the number of Learning Examples (LE) included in Task 2.4.2 is equal to 20. 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 hilly and mountain areas, and the associated run out, also in the view of possible multiple geohazards that may characterize a certain portion of a territory.

In the light of this, preliminary rationalization activities focused on extracting such tools from the available LEs. The approach selected to accomplish this operation was to identify, for each LE, all the working tools explicitly or implicitly contained therein, defining the working tool as a specific procedure (or set of procedures) capable of providing an output relative to one of the following issues of interest in this task:

- Factors capable of triggering a specific type of ground instability in hilly and mountain areas;
- Run out caused by a specific ground instability occurring at a certain location, which can also be characterized in terms of:
    - Displacement;
    - Velocity;
    - Kinetic energy;
    - Volumes of involved material.

For rapid ground instabilities

Or:

- Displacement and relative rate;
- Area affected by deformation.

For slow ground instabilities.

- Possible occurrence of multiple geohazards that may affect a certain portion of the territory, understood both as:
  - More than one hazard that can occur simultaneously over a certain portion of territory;
  - Cascading events in which the occurrence of one ground instability can be the trigger for a subsequent ground instability.

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.

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
- Macro-categories and categories of ground instability
  - Rapid landslide
    - Rockfall/Toppling
    - Rock Avalanches = RA
    - Debris flows/Debris floods/Debris avalanches/Mud flows
    - Rock slides
    - Soil slides
  - Slow landslide
    - Earth flows
    - Soil slips
    - Roto-translational slides
    - Spread
    - Rock slides/Rock-Mountain slope deformations
  - Slow erosion
    - Gulling/Riling
  - Rapid fluvial dynamics
    - Channel widening
    - Landslide river damming
    - Riverbed elevation changes
- Categories of triggering factor

- Seismic
- Rainfall
- Anthropic
- Windstorm
- Flood
- Landslide

- Types of issue addressed
  - Triggering of the ground instability
  - Run out of the ground instability
  - Multiple geohazards
- Spatial scale of tool applicability
  - Regional
  - Basin
  - Local

These working tool extraction operations were carried out based on the information available in the summary sheets (see Figure 2) developed by the LEs proponents and the corresponding reference scientific literature. One example of tools extraction from LEs is given below (Table 3), relative to LE FI2 referring to river damming caused by landslides of any typology that can reach and occlude a stream channel.

Table 3 – Summary sheet proposed for the LE FI2.

LEARNING EXAMPLE	FI2
TRIGGER/PROCESS	Landslides of any typology (and material) that create a dam in the downslope river/stream. Landslides here are intended as the triggering factor. The process is the landslide dam evolution (whether the dam is formed or not; whether the dam is stable or not in the long term).
1) PROCESS CONTROL PARAMETERS	The main triggering factor is the landslide volume. Other control parameters are the valley width (expressing the geomorphic characteristics of the valley), the upslope contributing area and the local slope gradient of the riverbed (expressing the main hydrological and hydraulic characteristics of the valley).
2) INPUT DATA TO THE RATIONALE	The tool characterizes a target site with two empirical indexes (Morphological Obstruction Index – MOI – and Hydrological Dam Stability Index – HDSI) and based on the landslide volume and the characteristics of the valley (width, local gradient of the riverbed, upslope contribute area), it predicts the evolution of a landslide dam (see section 6). The input data "landslide volume" is provided by an estimation or by outputs from other tools/models. All

	the other parameters can be easily extracted by a DTM in GIS environment.
3) LEARNING METHODS	The selection of the input parameters is the consequence of a literature review that identified some key indexes, which were modified to have a larger possibility of application. In particular, the indexes defined in this LE are based on morphometric attributes that can be defined in any test site because they can be easily computed on widely available open data. For each of the two indexes (MOI and HDSI), threshold values were identified (according to an empirical analysis of over 300 Italian case of studies) to discriminate between possible evolution scenario of the process (see section 6).
4) APPLICABILITY CONSTRAINTS	Application suited for small scales (hundreds and thousands of square kilometers). Local scale applications are possible as well, to fast characterization of slope scale cases of study. It can be applied to any typology of landslide on any kind of material.
5) ANALYSIS LOGS	Although quantitative indexes are used, the output is qualitative (classes describing the expected evolution of the process).
6) OUTPUTS	Qualitative classes to predict a multihazard scenario. The tool operates on a two steps procedure, in which the morphometric attributes of the site of application are used to assess the MOI and HDSI indexes, which are then compared with threshold values. 1- MOI determines the capacity of a landslide to obstruct a river using the formula MOI = log (Vl/Wv) where Vl is the landslide volume and Wv is the fluvial valley width. Three possible outputs are possible, according to MOI threshold values: MOI < 3 = a landslide dam is not formed 3 < MOI < 4.6 = uncertain evolution MOI > 4.6 A landslide dam is formed 2- In case of dam formation, HDSI evaluates the dam's stability through the formula HDSI = log (Vl/Ab × S) where Ab is the basin area and S is the river slope. Three possible outputs are possible, according to HDI threshold values: HDSI < 5.74 = the dam is unstable 5.74 < HDSI < 7.44 = uncertain evolution of the dam HDI > 7.44) the dam is stable.

In this specific case, we were able to extract two working tools, which refer to the GI macro-category "river dynamics" and the category "Landslide River damming". 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 FI2_1 evaluates whether the ground instability "Landslide River damming" actually occurs, while the second tool FI2_2 evaluates the stability over time of the obstruction possibly created along the stream by the landslide.

Based on the aforementioned criteria, a total of 43 working tools dedicated to a specific issue of interest of the task were extracted from the 20 LEs (Table 4). Each tool has been named with a double label: field "LE" refers to the proposing partner and the progressive number of LE from which the tool has been proposed (see the "root" of field "LE ID" in Tables 1 and 2), while the field "Tool" simply add a progressive number to LE as a one-to-many relationship among LEs and Tools occurs in many cases.

Table 4 – The 43 working tools extracted from the 20 LEs.

LE	TOOL	KINEMATIC	GI MACROCATEGORY	GI CATEGORY	TRIGGER CATEGORY	RUN OUT	SCALE	MH APPLICATION
EN1	EN1_1	RAPID	LANDSLIDE	DF	R		B	
EN1	EN1_2	RAPID	LANDSLIDE	DF		YES	B	
PA2	PA2_1	RAPID	LANDSLIDE	DF	R		B	
PA2	PA2_2	SLOW	LANDSLIDE	EF	R		B	
PA2	PA2_3	SLOW	LANDSLIDE	RTS	R		B	
PA3	PA3_1	RAPID	LANDSLIDE	DF	R		B	
SA1	SA1_1	SLOW	LANDSLIDE	EF	S		R-B	MH – COMP.
SA1	SA1_2	SLOW	LANDSLIDE	RTS	S		R-B	MH – COMP.
SA1	SA1_3	SLOW	LANDSLIDE	EF	R		R-B	MH – COMP.
SA1	SA1_4	SLOW	LANDSLIDE	RTS	R		R-B	MH – COMP.
SA1	SA1_5	SLOW	MH (E-L)	EF	S		R-B	MH – AMP.
SA1	SA1_6	SLOW	MH (E-L)	RTS	S		R-B	MH – AMP.
SA12	SA12_1	RAPID	LANDSLIDE	SS	R		B	
SA16	SA16_1	RAPID	LANDSLIDE	SS	S		R-B-L	
SA16	SA16_2	RAPID	LANDSLIDE	RS	S		R-B-L	
SA16	SA16_3	SLOW	LANDSLIDE	Sslips	S		R-B-L	
SA4	SA4_1	SLOW	LANDSLIDE	RTS	A		L	
SA5	SA5_1	RAPID	LANDSLIDE	RS	S		R-B	MH – COMP.
SA5	SA5_2	RAPID	LANDSLIDE	SS	S		R-B	MH – COMP.
TO2	TO2_3	RAPID	LANDSLIDE	RA		YES	L	
FI3	FI3_1	RAPID	LANDSLIDE	SS	R		R-B	
TOX	TOX_1	RAPID	LANDSLIDE	RFT		YES	R-B-L	
NA8	NA8_1	SLOW	LANDSLIDE	MD	R		L	
NA8	NA8_2	SLOW	LANDSLIDE	EF	R		L	
NA9	NA9_1	RAPID	LANDSLIDE	DF	R	YES	B	
NA10	NA10_1	RAPID	LANDSLIDE	DF	R		L	
NA10	NA10_2	RAPID	LANDSLIDE	DF		YES	L	
BA1	BA1_1	RAPID	LANDSLIDE	SS	R		R-B	MH – COMP.
BA1	BA1_2	SLOW	LANDSLIDE	EF	R		R-B	MH – COMP.
BA1	BA1_3	RAPID	LANDSLIDE	SS	R		L	MH – COMP.
BA1	BA1_4	SLOW	LANDSLIDE	EF	R		L	MH – COMP.
BA1	BA1_5	RAPID	LANDSLIDE	SS	S		L	MH – COMP.
BA1	BA1_6	SLOW	LANDSLIDE	EF	S		L	MH – COMP.
BA2	BA2_1	SLOW	EROSION	GR	R		L	

FI2	FI2_1	RAPID	FLUVIAL DYN.	LD	L		R-B-L	MH – TRIG.
FI2	FI2_2	RAPID	FLUVIAL DYN.	LD	L		R-B-L	MH – TRIG.
GE1	GE1_1	RAPID	LANDSLIDE	RS	R		R	
GE1	GE1_2	RAPID	LANDSLIDE	DF	R		R	
PD1	PD1_1	RAPID	LANDSLIDE	RS	R + WS		R-B	MH – AMP.
PD1	PD1_2	RAPID	LANDSLIDE	RFT	R + WS		R-B	MH – AMP.
PD1	PD1_3	RAPID	LANDSLIDE	DF	R + WS		R-B	MH – AMP.
PD1	PD1_4	SLOW	LANDSLIDE	RTS	R + WS		R-B	MH – AMP.
PD4	PD4_1	RAPID	FLUVIAL DYN.	CW	F		R-B-L	

Legend: GI CATEGORY (RFT: rockfall/toppling; RA: rock avalanches; DF: debris flow/debris flood/debris avalanches; MF: mud flow; RS: rock slide; SS: soil slide; EF: earth flow; Sslip: soil slip; RTS: rototranslational slide; Sp: spread; MD: rock slides/rock-Mountain slope deformations; GR: gulling/rilling; CW: river channel widening; LD: landslide river damming), TRIGGER CATEGORY (S: seismic; R: rainfall; A: anthropic; WS: windstorm; L: landslide; F: flood), SCALE (R: regional; B: basin; L: local), MH APPLICATION (COMP: compound; AMP: amplification; TRIG: trigger). Highlighted in gray are tools that focus on run out.

Each tool is characterized by a number of specific features (Table 5), relating to:

- The input data that the tool needs to run;

  The input data required can be quantitative, semi-quantitative or qualitative (input log). The input data required can be quantitative, semi-quantitative or qualitative. Specific types of input required by each tool (input type; e.g., cumulated daily rainfall, Newmark displacement thresholds; unit stream power) are indicated in the summary LE sheets.

- The applicability constrains of the tool, i.e., the contextual characteristics necessary for the tool to be applied;
- The type of output provided by the tool;

  Similar to input data, the outputs of a tool can be distinguished into quantitative, semi-quantitative or qualitative (output log). Also in this case, the specific types of output (output type; e.g., permanent co-seismic displacement, erosion rate) are indicated in the summary LE sheets.

- The dependence or independence of the trigger tool on previous assessments of susceptibility and/or preparation for ground instability provided by approaches and/or tools developed by WP2 and WP3. This feature makes explicit the fact that the trigger tool can be applied independently or, conversely, that its application can only occur following an assessment of the conditions of susceptibility and/or preparedness for a certain type of ground instability.

Table 5 – Specific features of the 43 working tools.

LE	TOOL	INPUT TYPE	INPUT LOG	OUTPUT TYPE	OUTPUT LOG	DEPENDANCY ON SUC-PREP
EN1	EN1_1	RI - ISC	QUANT	THRESHOLD	QUAL	YES
EN1	EN1_2			DIST-ENERGY	SQ	YES
PA2	PA2_1	CDR	QUANT	CLASSES	SQ	YES
PA2	PA2_2	CDR	QUANT	CLASSES	SQ	YES
PA2	PA2_3	CDR	QUANT	CLASSES	SQ	YES
PA3	PA3_1	CDR	QUANT	CLASSES	SQ	YES
SA1	SA1_1	PGA	QUANT	PCSD	SQ	NO

SA1	SA1_2	PGA	QUANT	PCSD	SQ	NO
SA1	SA1_3	RI - ISC	QUANT	SSA	QUANT	NO
SA1	SA1_4	RI - ISC	QUANT	SSA	QUANT	NO
SA1	SA1_5	KEEFER RADIUS	QUAL	CLASSES	SQ	YES
SA1	SA1_6	KEEFER RADIUS	QUAL	CLASSES	SQ	YES
SA12	SA12_1	RI - ISC	QUANT	SSA	QUANT	NO
SA16	SA16_1	GMP	QUANT	PCSD	QUANT	NO
SA16	SA16_2	GMP	QUANT	PCSD	QUANT	NO
SA16	SA16_3	GMP	QUANT	PCSD	QUANT	NO
SA4	SA4_1	CUT GEOMETRY	QUANT	SSA	QUANT	NO
SA5	SA5_1	GMP	QUANT	PCSD	QUANT	YES
SA5	SA5_2	GMP	QUANT	PCSD	QUANT	YES
TO2	TO2_3			FLOW PARAMETERS	QUANT	NO
FI3	FI3_1	RI - ISC	QUANT	SSA	QUANT	NO
TOX	TOX_1			DIST-ENERGY-CLASSES	SQ	YES
NA8	NA8_1	ISC - PWP	QUANT	SSA	QUANT	NO
NA8	NA8_2	ISC - PWP	QUANT	SSA	QUANT	NO
NA9	NA9_1	RI - ISC	QUANT	DIST-ENERGY-CLASSES	SQ	YES
NA10	NA10_1	RI	QUANT	SSA	QUANT	YES
NA10	NA10_2			DIST-ENERGY	QUANT	YES
BA1	BA1_1	PWP	QUANT	CLASSES	SQ	YES
BA1	BA1_2	PWP	QUANT	CLASSES	SQ	YES
BA1	BA1_3	PWP	QUANT	SFV	QUANT	YES
BA1	BA1_4	PWP	QUANT	SFV	QUANT	YES
BA1	BA1_5	NDT - GMP	QUANT	CLASSES	SQ	YES
BA1	BA1_6	NDT - GMP	QUANT	CLASSES	SQ	YES
BA2	BA2_1	RI	QUANT - SQ	ER	SQ	YES
FI2	FI2_1	LV - VW	QUANT	CLASSES	QUAL	NO
FI2	FI2_2	LV - DA - S	QUANT	CLASSES	QUAL	NO
GE1	GE1_1	CA	QUANT	CLASSES	SQ	YES
GE1	GE1_2	CA	QUANT	CLASSES	SQ	YES
PD1	PD1_1	WI - CMR - UVI	QUANT - SQ	SRPT - CLASSES	QUANT - SQ	YES
PD1	PD1_2	WI - CMR - UVI	QUANT - SQ	SRPT - CLASSES	QUANT - SQ	YES
PD1	PD1_3	WI - CMR - UVI	QUANT - SQ	SRPT - CLASSES	QUANT - SQ	YES
PD1	PD1_4	WI - CMR - UVI	QUANT - SQ	SRPT - CLASSES	QUANT - SQ	YES
PD4	PD4_1	USP - TP	QUANT - QUAL	CLASSES	SQ	NO

Legend: QUANT: quantitative, SQ: semi-quantitative, QUAL: qualitative; INPUT TYPE [RI: rainfall intensity; WI: wind intensity; ISC: initial soil conditions (moisture, water content, suction, etc.); PWP: pore water pressure; CDR: cumulated daily rainfall; CMR: cumulated monthly rainfall; UVI: uprooting and vegetation impact; GMP: ground motion parameters; NDT: Newmark displacement thresholds; LV: landslide volume; VW: valley width; DA: drainage area; S: river slope; CA: climatic aggressiveness (average monthly rainfall / average yearly rainfall); TP: type of transport process (water flow, debris flood); USP: unit stream power (function of discharge, slope, channel width)], OUTPUT TYPE (PCSD: permanent co-seismic displacements; SSA: slope stability analysis;

SRPT: scale of relative probability of triggering; SFV: safety factor variation; ER: erosion rate). Highlighted in gray are tools that focus on run out.

Some of the statistics presented at the LEs level, are shown here based on the extracted working tools (Figures 5 – 10).

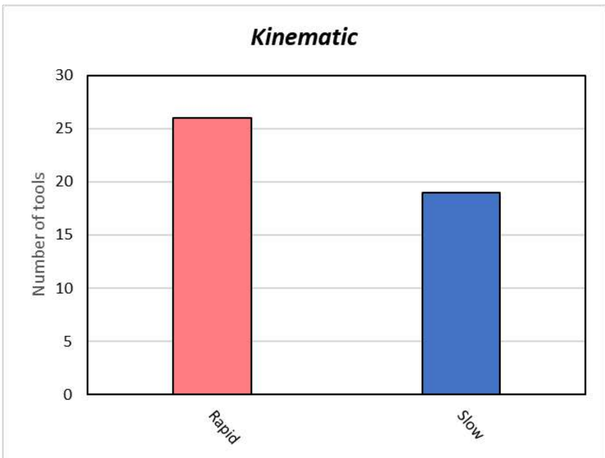

Figure 5: Number of working tools obtained for rapid and slow ground instabilities.

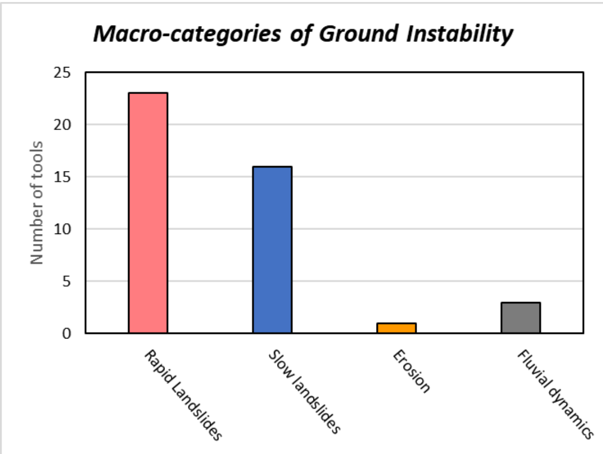

Figure 6: Number of working tools obtained for each macro-category of ground instabilities.

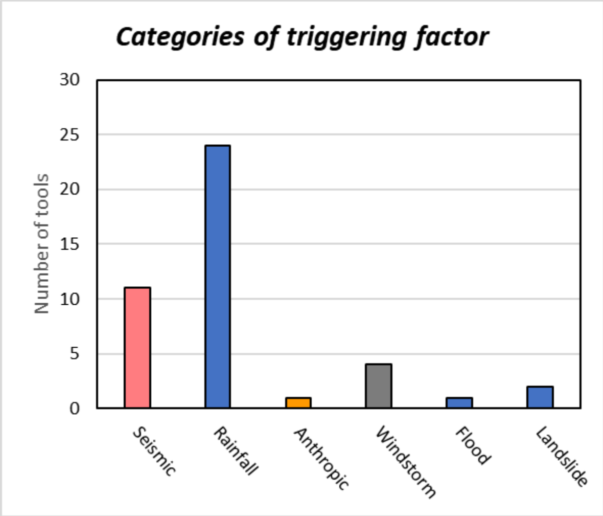

Figure 7: Number of working tools obtained for each category of triggering factors.

The kinematics covered by the tools are evenly distributed between slow (19 tools) and rapid ground instabilities (26 tools) (Figure 5). Considering instead the macro-categories of ground instabilities, it is evident that most of the tools are devoted to landslide phenomena (39 tools), while only 1 and 3 tools deal with erosional processes and river dynamics, respectively (Figure 6). Considering that the focus of this task is devoted to the mountain-hill areas, a predominance of landslides is physiological. However, other types of ground instability that can occur in such settings are certainly under-represented. At the level of types of triggering factors, rainfall is the most considered forcing (24 tools), although numerous tools concern ground instabilities triggered by seismic phenomena (11 tools) (Figure 7). Far fewer tools consider other triggers, specifically anthropogenic ones (1 tool), windstorms (4 tools), river floods (1 tool) and landslides that can activate other ground instabilities (i.e., river damming; 2 tools).

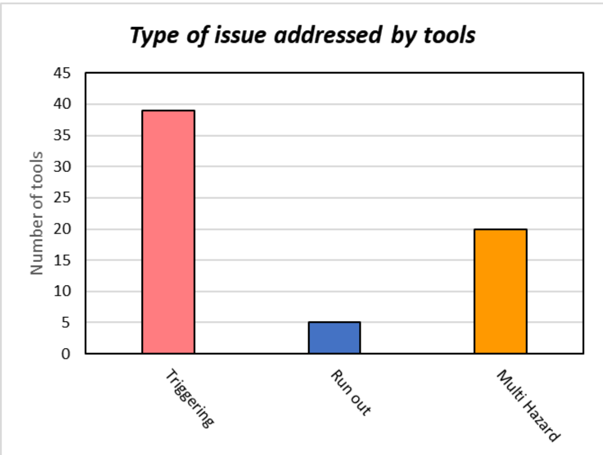

Figure 8: Number of working tools considering specific issues of interest for this task.

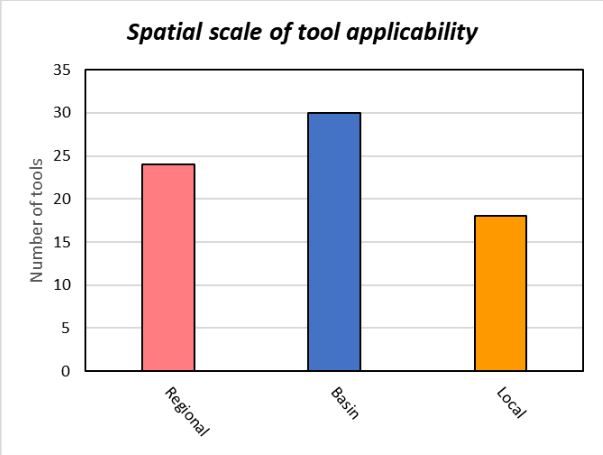

Figure 9: Number of working tools considering specific spatial scales of applicability.

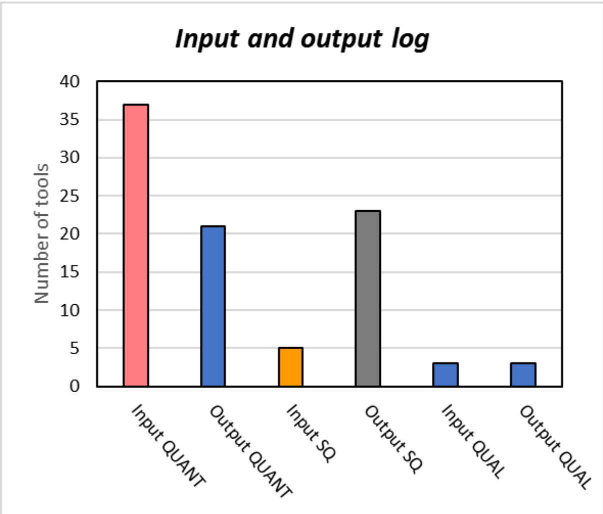

Figure 10: Number of working tools requiring quantitative (QUANT), semi-quantitative (SQ) and qualitative (QUAL) input data, and providing quantitative, semi-quantitative and qualitative outputs.

Most of the working tools are devoted to evaluating the triggering ability of one (or more) ground instability by one (or more) triggering factors (39 tools) (Figure 8). Many of the tools also consider the possibility of multi-hazards occurrence taking into account for compounding, amplification and triggering conditions (20 tools). The least considered aspect is the run out, with only 5 tools specifically focusing on it. The spatial scales of applicability of the tools are equally distributed between regional and basin (24 and 30, respectively), with slightly fewer tools applicable specifically at the local scale (18 tools) (Figure 9). The inputs required for the tools to operate are largely quantitative (37 tools), while a much smaller number of tools operate through semi-quantitative or qualitative inputs (5 and 3, respectively) (Figure 10). The type of outputs is significantly different, in fact many tools that require quantitative inputs are able to provide only semi-quantitative or qualitative outputs (see Table 5). Thus, in total there are 21 tools providing quantitative outputs, 23 tools providing semi-quantitative outputs, and 3 tools providing qualitative outputs (Figure 10).

5.3 From single tools to the tool chains: The logical framework to classify the extracted working tools

Once the working tools have been extracted (and classified in terms of categories of ground instability, spatial scales of applicability and output logs), the subsequent phase has been addressed towards the construction of the «tool chains», i.e. the logical and operational workflow that put together the outcomes of WP2, WP3 and WP4 by combining the sequence of tools that can lead to the assessment of expected impact scenarios for different GIs, starting from predisposing factors and passing through possible preparatory processes up to the triggering.

Propaedeutically to the chain construction, each trigger / multihazard / scenario generation (e.g., runout assessment in case of landslides) tool identified within T 2.4.2 has been framed in a logical structure, conceived as a hierarchical 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 Section 5.2), 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):

- The "root" is the GI macro-category
- The second subdivision criterion accounts for the kinematic (rapid vs. slow)
- The third level refers to the specific GI category
- The fourth level accounts for the triggering process (to get insights on possible lack of coverage, each trigger process is evaluated as: i) expected and addressed by tool(s), ii) expected but not addressed by any tool, iii) rarely possible but not addressed by any tool, iv) not expected)

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. Furthermore, in order to distinguish "self-standing" tools from those that are necessarily linked to predisposing / preparatory processes, the dependency of each tool on previous susceptibility/hazard assessment is indicated.

The idea behind this structure is to facilitate the connection between tools (and toolsets, intended as ensembles of tools dealing with the same GI, scale, trigger process) coming from the different WPs. Specifically, the highest hierarchical (but at the same time, coarser) information, i.e. the GI category, is the main junction and hooking point to the flow of tools made available by previous WPs, each of one being an elementary link of the whole chain.

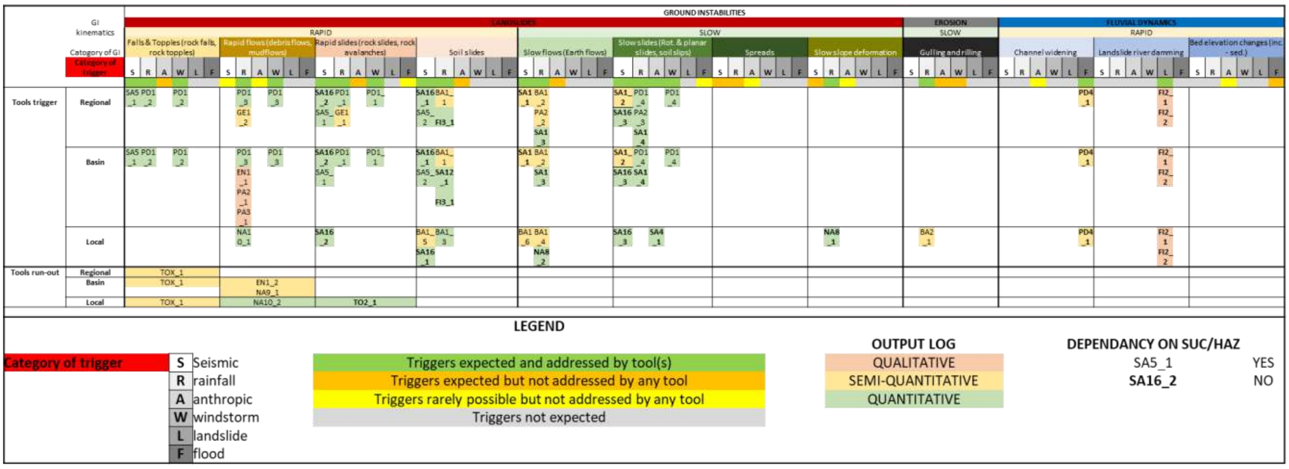

Figure 11: Conceptual framework (hierarchical tree structure) providing a synoptical view of topics / processes dealt with by the working tools.

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

- Absence of tools dealing with Falls & Topples at the local scale
- Absence of tools for spread-like landslides
- Scarcity of tools for erosional processes, slow slope deformations and fluvial dynamics
- Scarcity of tools for the quantitative assessment of rapid landslides propagation at both local and basin scales
- Absence of tools for the assessment of the areal extent of the impact of all other considered GIs, at any scales

5.4 Conceptual framework to setup the tool chains

The above-described logical structure is 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 and useful, in concatenation, to return scenarios resulting from GI processes, thus starting from the predisposing factors, passing - where necessary - through the preparatory processes and, finally, taking into account the triggering factors (Figure 12).

With reference to the logical structure in which the extracted tools are placed, for each environment (hilly-mountainous for T 2.4.2) it would theoretically be possible to construct a number of tool chains equal to the possible combinations of environments (3), scales (3), kinematic categories (2) and types of GI (13); however, it is evident that already from the view of the hierarchical tree, in which many branches are not populated, only some of these combinations actually turn out to be possible.

Going into the details of the proposed logical-operational scheme for sequentially composing the tools related to the macro-categories of factors (predisposition, preparation, and trigger), it is possible to summarize the flow as follows:

1. Having defined the environment and scale of work, the information 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 predisposition and potential criticality.
2. Once the potential GI process(es) have been identified, the tools produced to assess the effect of preparatory processes that may impact in terms of enhancing predisposition conditions and/or increasing sensitivity to trigger processes 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, or ii) tools are not available for that specific context or type of GI, or iii) the validity constraints of the tools do not allow their application in a specific territorial context.
3. Entirely similar discussion applies to the next step, since not all types of GI need trigger factors.
4. The next step is to apply the useful tools to return the instability scenarios in terms of:
   a. for "rapid" kinematic category processes evaluation of: displacements (in one or more components depending on the type of process), volumes involved, velocity and, consequently, kinetic energy. The spatial restitution of these processes will not be able to neglect the encumbrance caused by the moved debris and, therefore, the analysis of its transport and propagation modes.
   b. for "slow" kinematic category processes 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.

5. Finally, the output of the tool chain can be put in combination with the results of other chains concerning the same environment and scale to evaluate possible multi-hazard effects (minimally according to a multi-layer single-hazard approach).

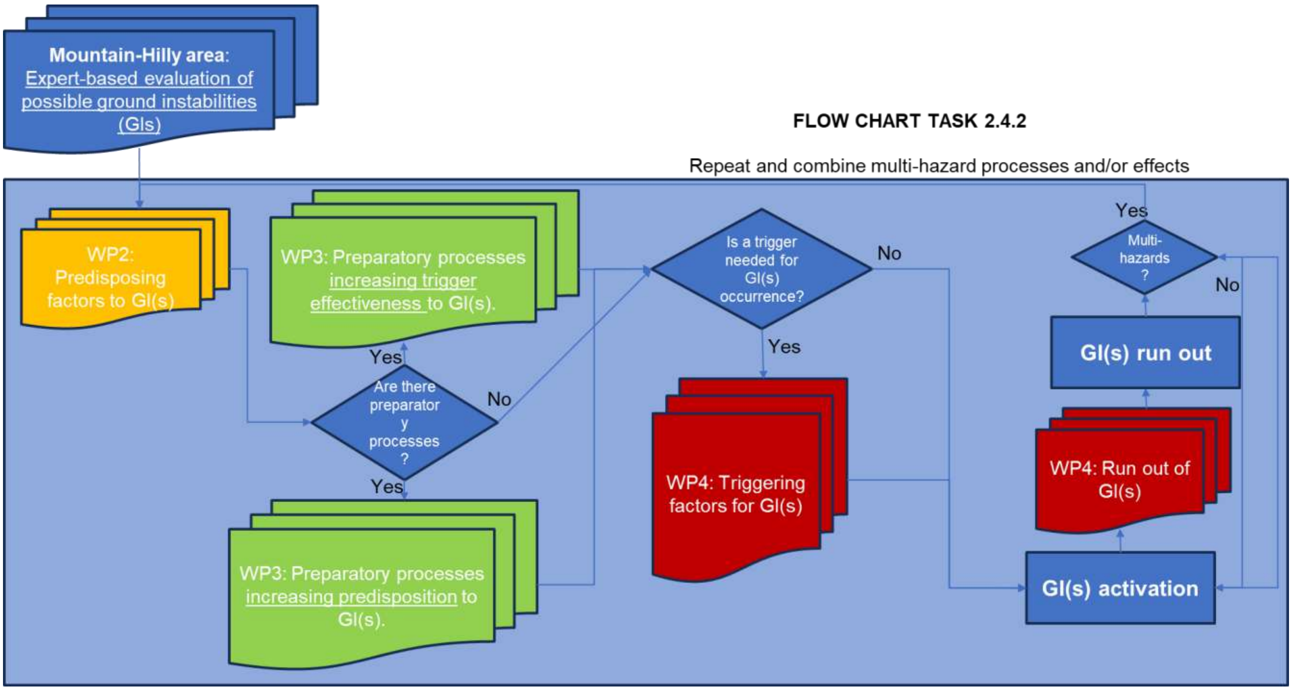

Figure 12: Conceptual framework to construct tool chains for providing assessment of instability scenarios.

Some examples of tool chains are given below (Figures 13 – 22), useful mainly to make a point in view of the transfer of this logical-operational scheme into an IT structure for simulating GI scenarios: once defined the environment and scale of analysis, if for the same GI there are more than one predisposition and/or trigger tool, the choice may be dictated primarily by the validity constraints specific to each tool and secondarily by output log requirements.

In particular, referring to the first tool chain example (Falls and topples at the regional scale; Figure 13), the first step consists in the detection of the prone areas to the specific ground instability (i.e., rapid falls and topples) and predisposition assessment using the factors and approaches made available by the WP2 (refer to DV2.2.3 and DV2.2.5 for additional details). Then, it is possible to identify one tool as a preparatory process increasing predisposition to GI (TO_5_WP3: preparation for detachment due to weathering; process WP3_P1), which provides a semi-quantitative output log, and one tool as a preparatory process increasing trigger effectiveness to GI (FI_3_WP3: preparation related to preparatory events of trigger; process WP3_P15), which provides a quantitative output log (refer to DV2.3.1 and DV2.3.3 for additional details). Tools available from this task as triggers for the considered GI at the regional scale are two, both of which provide a quantitative output log: i) SA5_1, which considers seismic input as trigger factor; and ii) PD1_2, which considers rainfall and windstorm as trigger factors. Subsequently, the tool TOX_1 can be activated for this tool chain to quantify in semi-quantitative terms the run out of the GI.

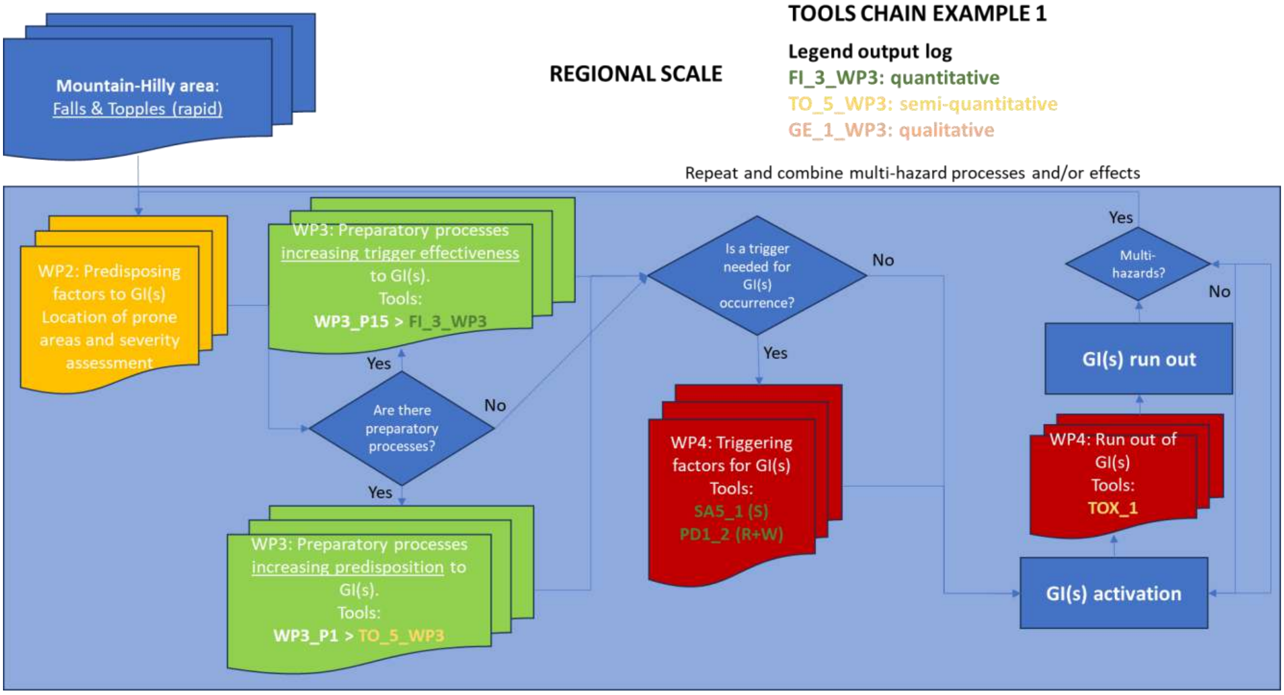

Figure 13: Tools chain example 1 (Falls & Topples at regional scale of analysis).

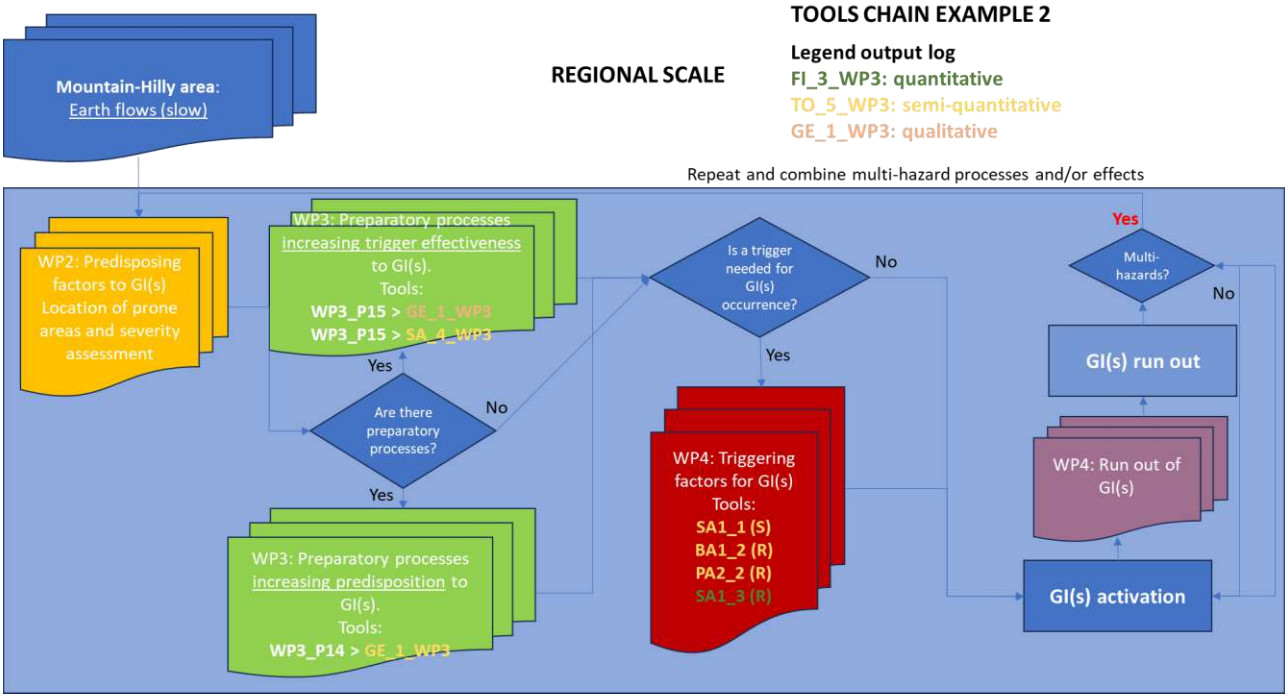

Figure 14: Tools chain example 2 (Earth flows at regional scale of analysis).

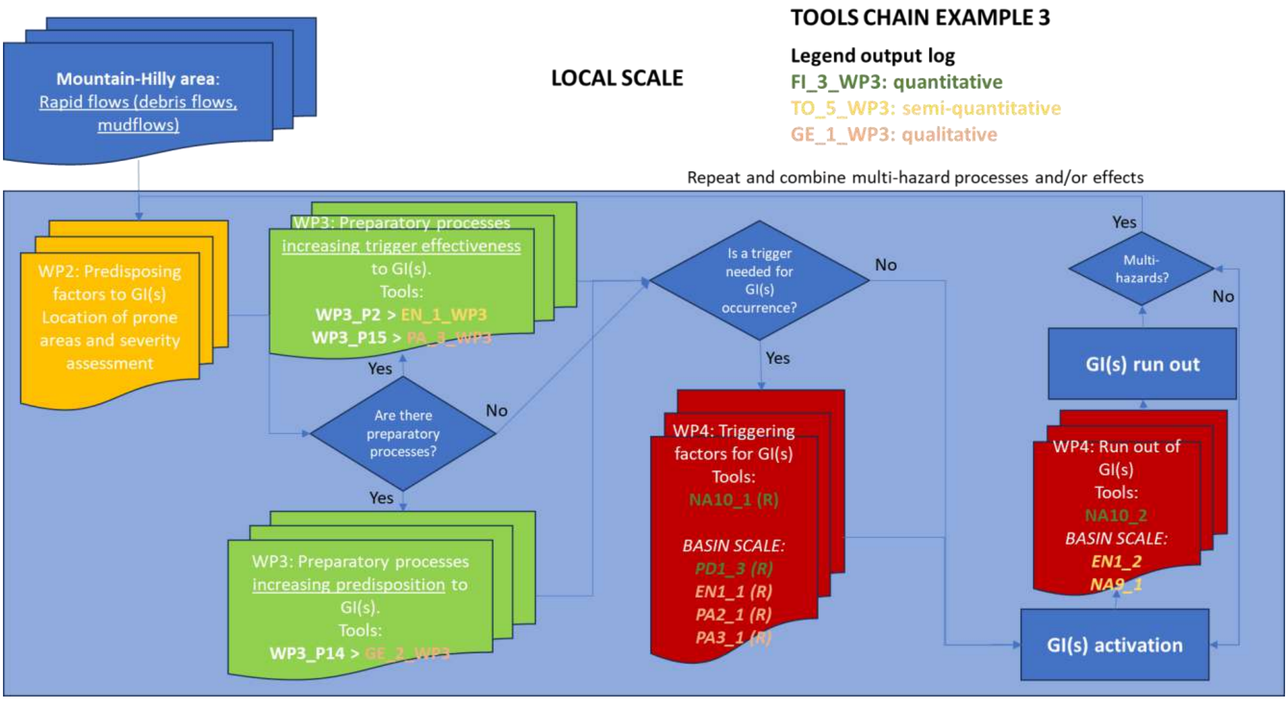

Figure 15: Tools chain example 3 (Rapid flows at local scale of analysis).

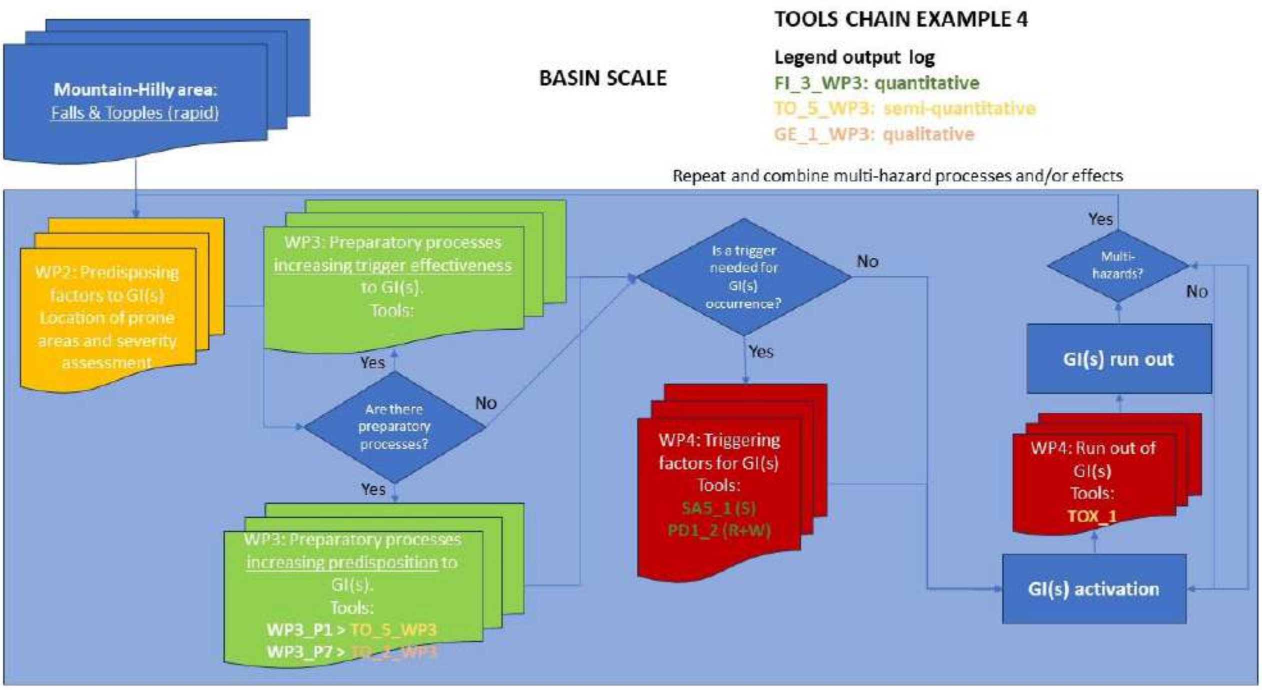

Figure 16: Tools chain example 4 (Falls and Topples at basin scale of analysis).

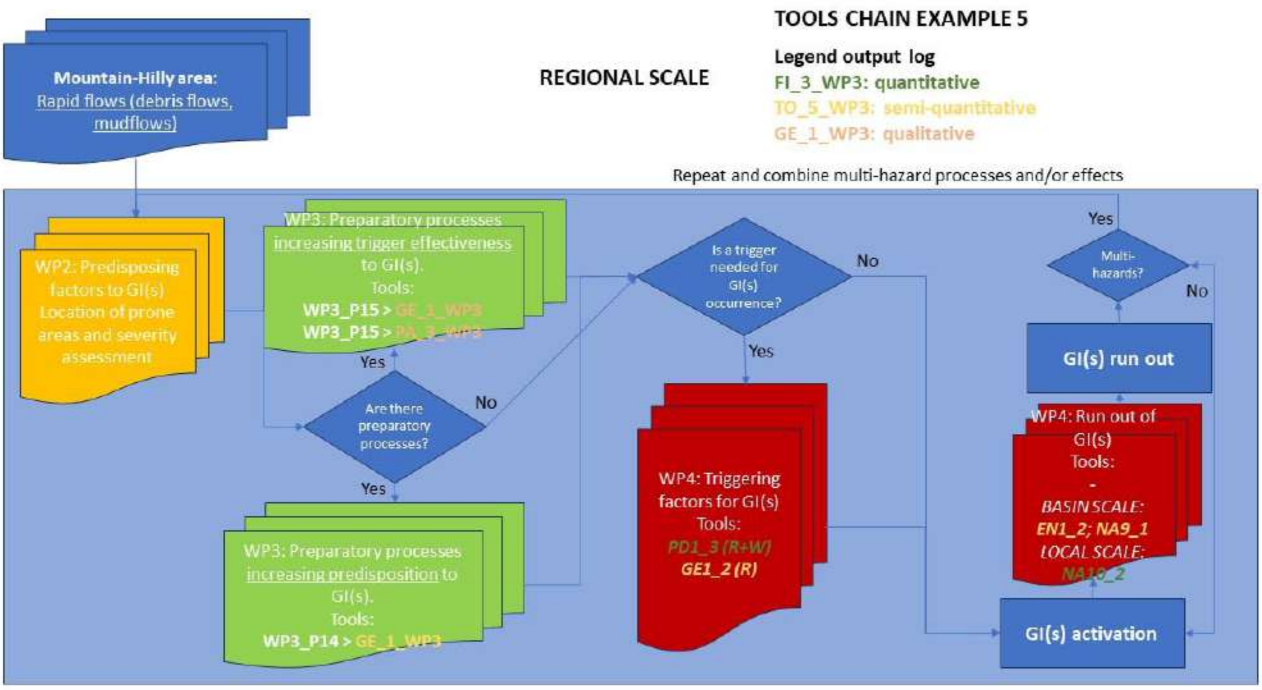

Figure 17: Tools chain example 5 (Rapid flows at regional scale of analysis).

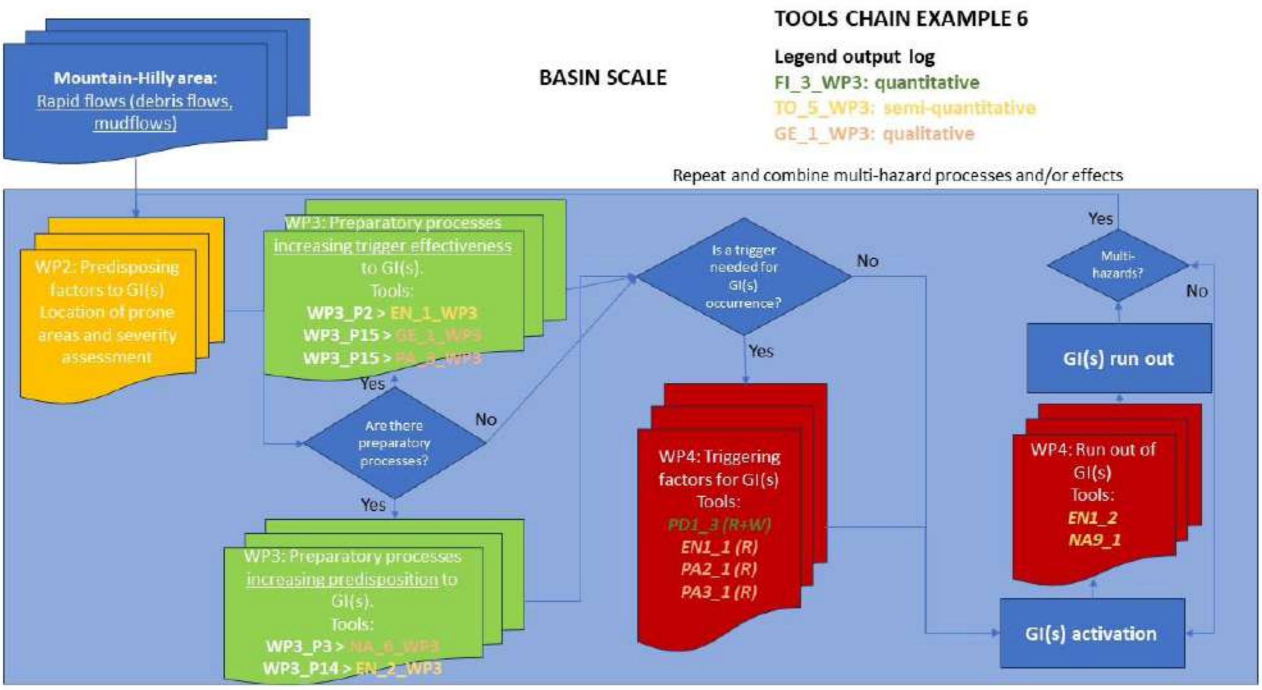

Figure 18: Tools chain example 6 (Rapid flows at basin scale of analysis).

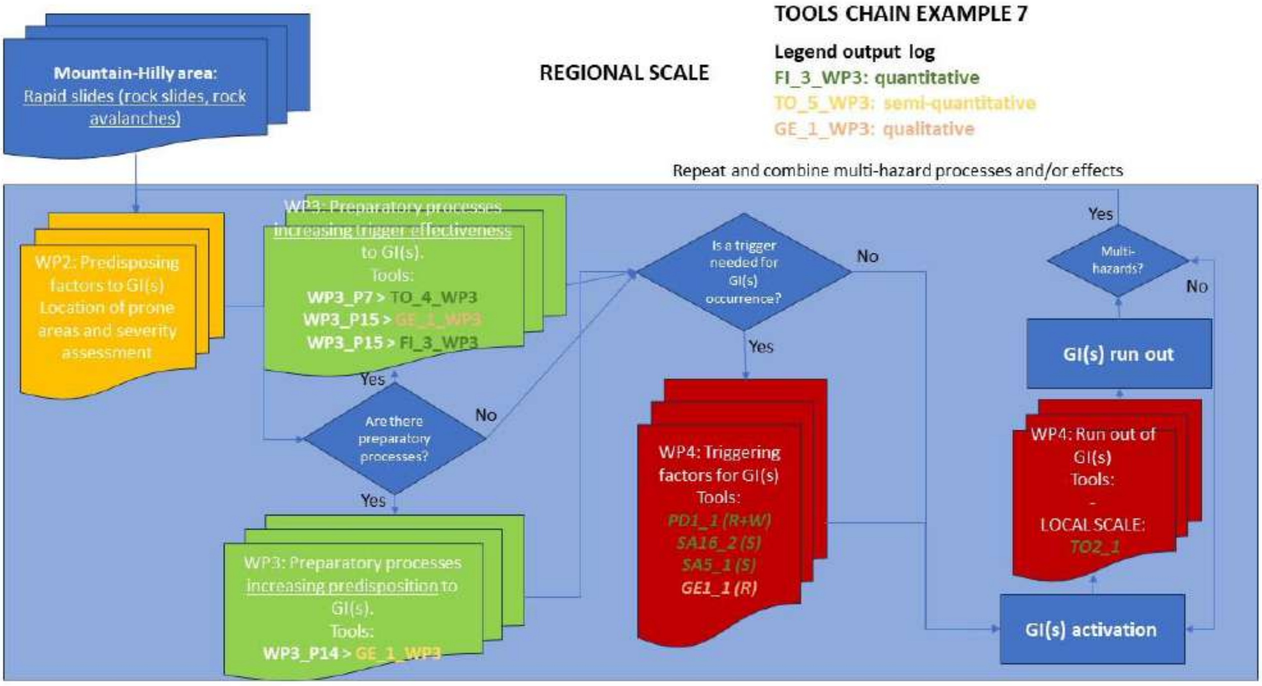

Figure 19: Tools chain example 7 (Rapid slides at regional scale of analysis).

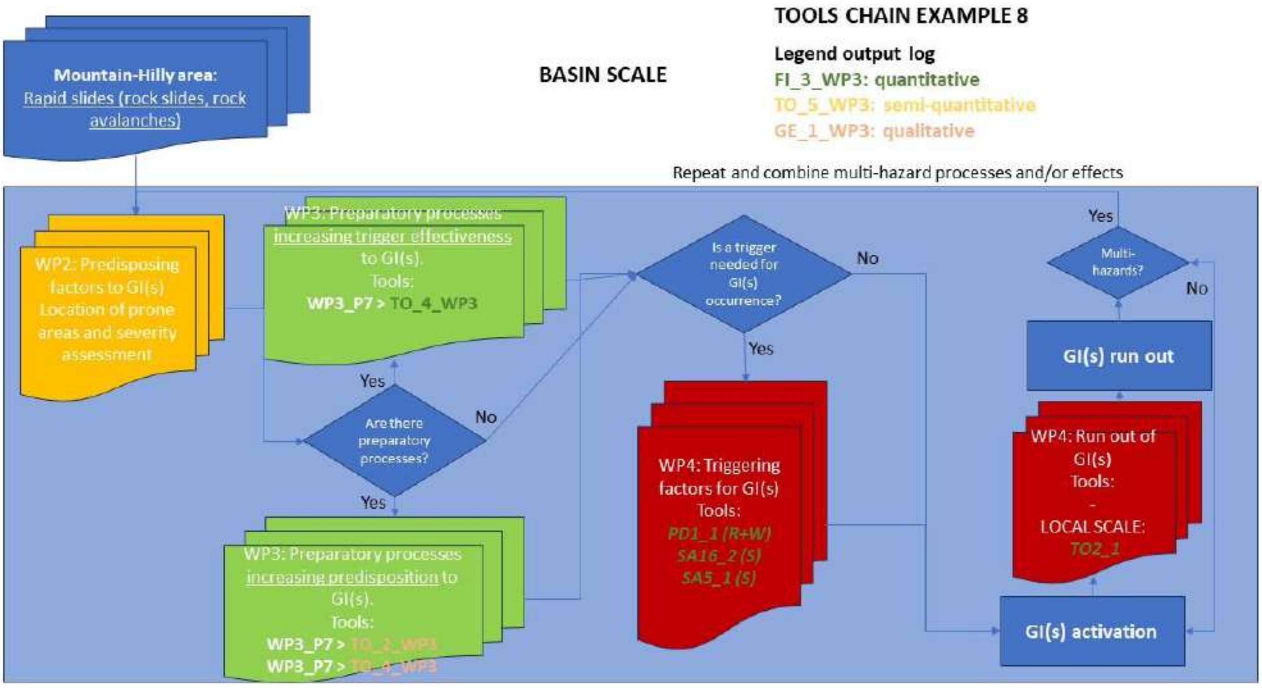

Figure 20: Tools chain example 8 (Rapid slides at basin scale of analysis).

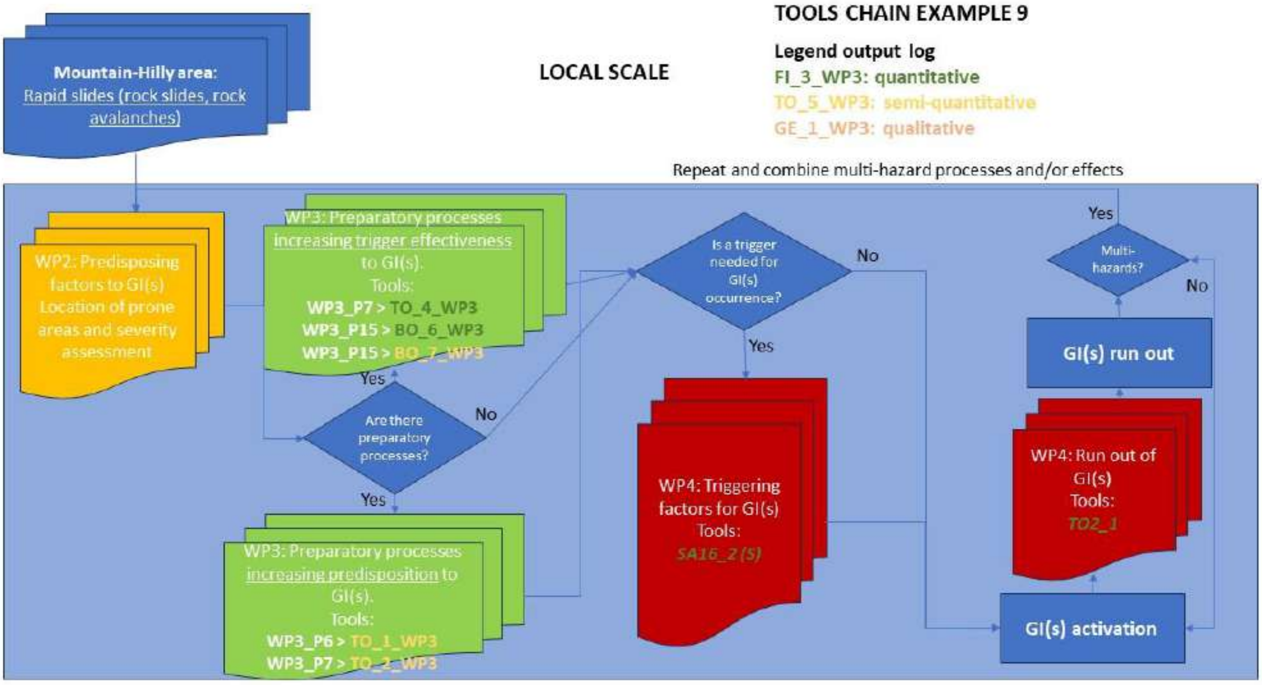

Figure 21: Tools chain example 9 (Rapid slides at local scale of analysis).

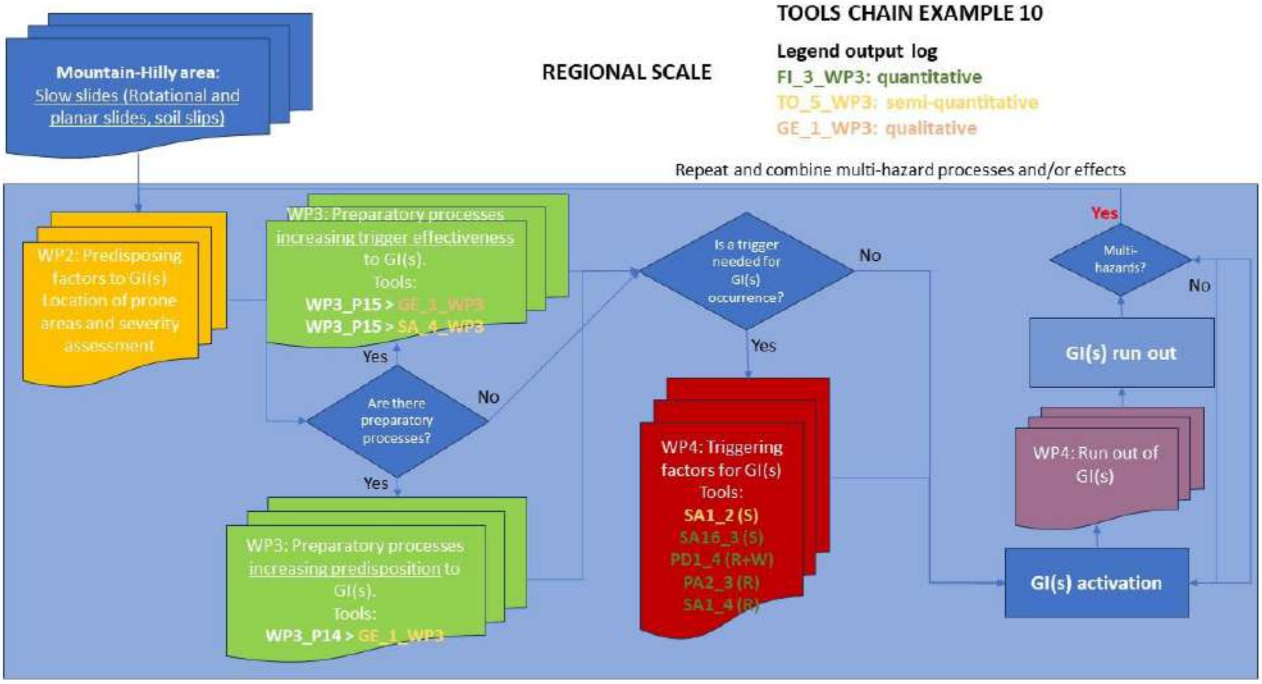

Figure 22: Tools chain example 10 (Slow slides at regional scale of analysis).

5. Conclusions

Concerning T 2.4.2, the activities carried out to date allow some considerations in view of the project's planned future developments.

First, after the in-depth analysis of proposed LEs, it has been possible to draw an overall picture of the knowledge acquired and exploitable for the PoC, regarding the effects of triggering processes, in terms of their ability both to activate paroxysms of GI processes and to return related intensity scenarios. For the hilly-mountainous environment, a picture emerges in which slope instabilities are definitely the most represented, as indeed is to be expected for that environment.

Then, the extraction of single operational tools from the LEs allowed to better delineate the framework actually available for the construction of the PoC. This more in-depth analysis highlights that not all landslide types are analyzed with the same degree of detail in terms of triggering processes; furthermore, analysis tools are not available at all spatial scales for some landslide types. The most obvious gap, however, remains the scarce presence of operational tools for the analysis of fluvial dynamics and accelerated erosion processes, although they are present and impacting the Italian territory. To conclude the examination of weaknesses, another critical issue concerns the relatively small number of tools available to analyze the instability processes in terms of the areal extent of the effects and the related descriptors or metrics of intensity.

Beyond these limitations, it is worth highlighting that the overall framework is satisfactory in terms of covered topics to the extent that most of the relevant GIs for the hilly-mountainous environment are addressed at least by one tool at one scale. As a final step of the work carried out so far, the collected tools and related information have been organized in a hierarchical tree structure as to get insights into the possible concatenation of operational tools, inferred from the different WPs and which can be synthetized to simulate instability processes starting from the intrinsic predisposition of the territory (predisposing factors) and going through the preparatory and triggering processes and the related scenarios of potential impact. As a result, it has been possible to conceptualize a workflow of tool chains and provide, by its implementation on actually available tools, hints for the implementation of such a stepwise procedure in the PoC.

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