multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

Codice progetto MUR: **PE00000005 – E63C22002000002**

Deliverable title: ***Large Plains: Rationale for trigger-based multiple geohazard severity mapping and zoning***

Deliverable ID: Deliverable 2.4.5

Due date: 30th November 2023

Submission date: 28th November 2023

AUTHORS
Giovanni Forte (UniNA); Rosa Colacicco (UniBA); Isabella Serena Liso (UniBA); Letizia Pace (UniBA)

1. Technical references

Project Acronym	RETURN
Project Title	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
Project Coordinator	Domenico Calcaterra UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II domcalca@unina.it
Project Duration	December 2022 – November 2025 (36 months)

Deliverable No.	DV2.4.5
Dissemination level*	PU
Work Package	WP4 - Trigger-based multiple geohazard scenarios
Task	Task 2.4.3 - Multiple geohazards for ground instabilities in large plains, sinkhole zones.
Lead beneficiary	Giovanni Forte
Contributing beneficiary/ies	Giovanni Forte, Rosa Colacicco, Isabella Serena Liso, Letizia Pace

* PU = Public

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

Document history

Version	Date	Lead contributor	Description
0.1	22/09/23	GF/RC	First draft
0.4	03/11/23	GF/RC/ISL/LP	Second draft
0.5	27/11/23	GF/RC/ISL	Critical review and proofreading
0.6	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	GF/RC/ISL	Final version

2. ABSTRACT

The present Deliverable shows the activities conducted under Task 2.4.3, with the objective of rationalizing trigger-based multiple geohazard severity mapping and zoning, in the context of large plains. The 13 Learning Examples identified were consistently implemented into worksheets, from which the necessary information was then extracted and turned into graphs. In order to build a common line with previous WPs, so-called 'tool chains' were created. These allow all factors to be understood, starting from predisposing, to preparatory, to triggering factors describing a particular process. The most represented process is subsidence, followed by sinkholes and finally liquefaction. In the analysis of the LE for subsidence, the geology and the geotechnical properties of the area represent the main predisposing factors in most of the cases, while the other predisposing factors observed in the LEs are the topography and the Land Use/Land Cover (LULC). On the other hand, the water pumping, and the water table fluctuations represent the main preparatory factors. In the sinkholes dataset, the main predisposing factors are geology structural elements, past events and geotechnical properties. The preparatory factors are represented by the water table fluctuations and rock strength degradation. In the liquefaction dataset, the predisposing factors are mainly represented by the geology, earthquakes with magnitude > 5, water table fluctuations, PGA, and geotechnical properties. In the case of liquefaction events, the collected LEs had no preparatory factors interacting with the process.

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4. First Section

4.1 Overview of task 2.4.3

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 December 31 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 focused 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 destressed glacial valleys, high-intensity erosion slopes, permafrost deglaciation areas, and thermally stressed rock walls.
- Task 2.4.3: Multiple geohazards for ground instabilities in large plains, sinkhole zones.
- Task 2.4.4: Reliability and uncertainness of statistical solutions. Uncertainty assessment methods, based on back analysis of event distribution, for ensemble and single process as well as for coupled/cascade multiple triggers.

This report summarized the scientific research activities carried out in the period January – November 2023 by the Task 2.4.3 "Multiple geohazards for ground instabilities in large plains, sinkhole zones" (hereinafter referred to as TK3).

The task is focused on ground instabilities in large plains, including soil subsidence and sinkhole zones. Objects of this task will concern multi-hazard effects and indicators in case of soil displacements in alluvial plains by combining process understanding (DV 2.4.5) and hazard mapping (DV 2.4.6) for multiple triggers and cascading effects. Processes to be considered include soil subsidence, sinkholes, river dynamics, and interactions with anthropogenic factors, including dikes, levees, and embankments along river corridors.

In particular, this deliverable (DV 2.4.5) focuses on Large plains: Rationale for trigger-based multiple geohazard severity mapping and zoning.

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);
- 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 multi-hazard:

- Inventory of Learning Examples (LEs).
- Individuation of LEs related to mapping methods, trigger and/or devoted to multi-hazard 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 TK1 to TK3, with a dominant number of triggers and processes related to the mountain and hilly environment (TK2). As regards the trigger of the ground instabilities, rainfall is the most frequent, followed by anthropic activities, earthquakes and water table variations.

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

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 2.4.3 prepared by the TK2. The processes that involve the plain areas, hence pertaining to the TK3 are **Subsidence**, which is only a slow-moving process, **Soil Liquefaction**, which is a process characterized by rapid occurrence and **Sinkholes**. These latter are divided into slow and rapid kinematics. In the former category, the "*Suffosion and Solution sinkholes*" are included, while the "*Collapse and cover-collapse sinkholes*" belong to the second category. The description of each process (subsidence, sinkholes, and liquefaction), and details about their predisposing factors, can be found within the DVs 2.2.3 and 2.2.5.

Ground Instabilities	Subaerial Landslides	Subaerial Slow Landslides Typologies	Slow Flows (Earthflows)
			Slow Slides (Rotational and Planar Slides, Soil slips)
			Slow Spread & Slow Slope Deformations (Spread (except Liquefaction), 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 Submarine Landslides (Creep, DsGSD)
			Rapid Submarine Landslides (Flows, Avalanches, Slides)
	Sinkholes	Slow Sinkholes Typologies	Slow Sinkholes (Suffosion Sinkholes, Solution sinkholes)
		Rapid Sinkholes Typologies	Rapid Sinkholes (Collapse Sinkholes, Cover-collapse Sinkholes)
	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

4.2 Analysis of collected LEs

The rationalization of the Learning Examples (LEs) assigned to the TK3, has been conducted 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 with the following labels:

- does not require modification
- requires integrations and/or translation
- new

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.

After the first phase, an internal recall has been useful to improve contents of the LEs suitable for the rationalization process and propose new ones that consider processes not properly addressed. In particular, an integration was requested concerning liquefaction and sinkholes processes, while subsidence was widely represented. After 2 rounds of recall, unfortunately only 2 new LE were integrated, one for liquefaction and one for sinkholes. The final count includes, in total, 13 LEs (Tab. 1). The distribution of the LE provided by the different involved institution is reported in Fig. 2. It shows that most of the cases are provided by UNINA, in particular as shown also in Figure 3, they encompass sinkholes and liquefaction processes. All the others contributed with LEs on subsidence and only UNIFI provided a sinkhole LE.

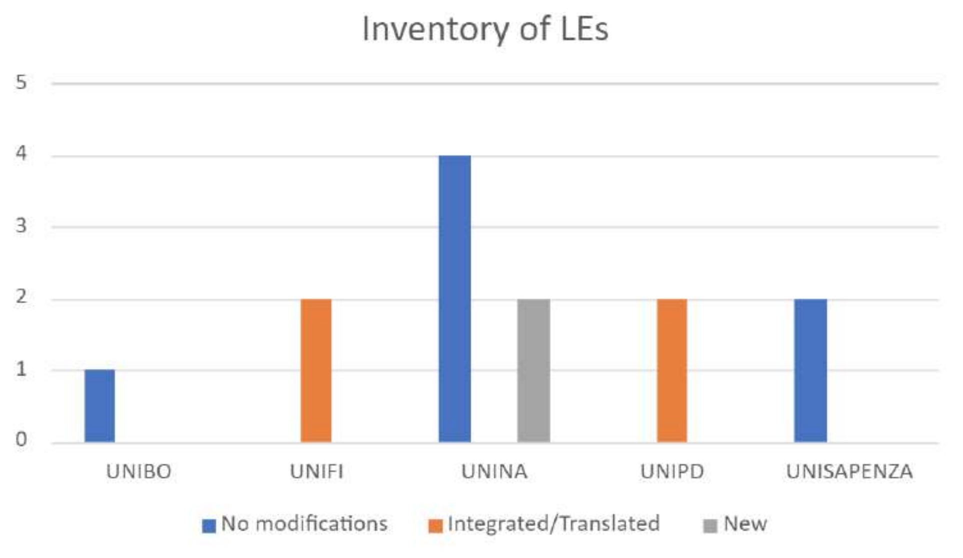

Figure 2: Inventory of LEs for WP4 – Number of LEs included with no modifications, integrated and/or translated and new derived from 2 rounds of recall.

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Table 1 – Final inventory of LEs for WP4 – Task 3.

Institution	LE ID	LE name	No modifications	Integrated/Translated	New
UNIBO	BO_4_WP4	Bologna area urbana	X		
UNIFI	FI_1_WP4	Regione Toscana		X	
	FI_4_WP4	Guidonia – Bagni di Tivoli		X	
UNINA	NA_1_WP4	Provincia Napoli Nord	X		
	NA_2_WP4	Emilia - Romagna	X		
	NA_3_WP4	Campania	X		
	NA_5B_WP4	Napoli	X		
	NA_S_WP4	Napoli			X
	UNINA_ML	Ischia			X
UNIPD	PD_2_WP4	Po delta		X	
	PD_3_WP4	Pianura Veneto - Friulana		X	
UNISAPIENZA	SA_6_WP4	Tivoli - Guidonia	X		
	SA_7_WP4	Fiumicino	X		

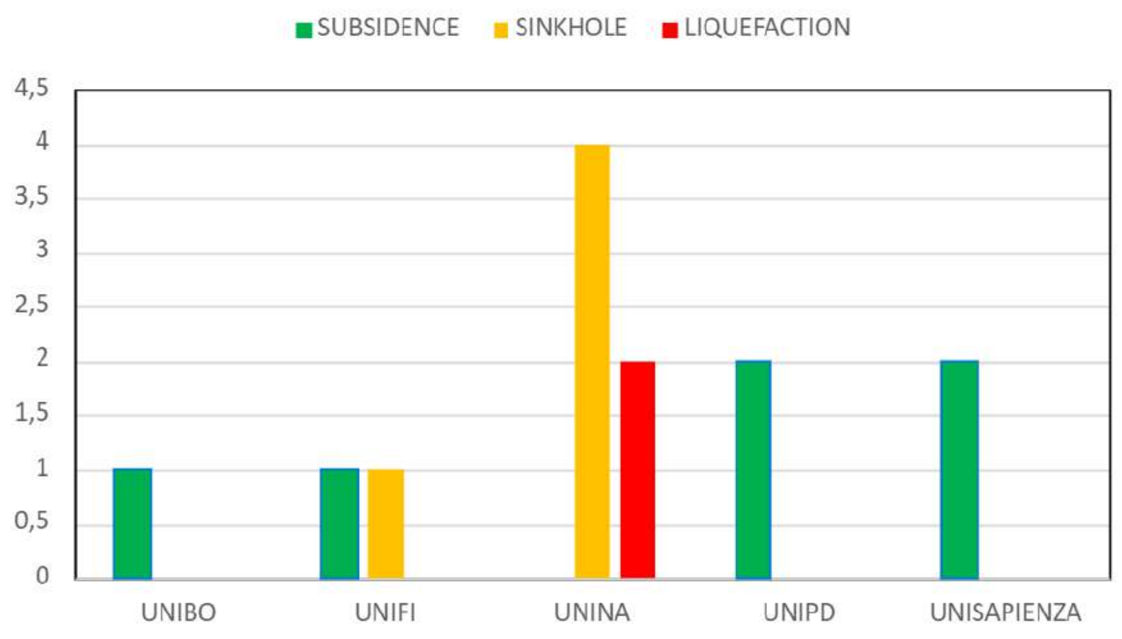

Figure 3: Inventory of LEs for WP4 – divided for process and contributing Institution

Furthermore, for each of the 13 LEs selected for the Task purpose, as a preparatory phase for the rationalization process, the following information has been extracted:

- Kinematics;
- type of process;
- control parameters;
- predisposing factors;
- preparatory factors;
- triggering factor(s);
- scale of validity;
- analysis log;

The dataset with all the collected information is reported in Table 2. It is composed of n. 13 ground instabilities case studies from different areas of Italy distributed as shown in Figure 4. Within the dataset, there are n. 6 case studies of subsidence, n. 4 of sinkholes (rapid sinkholes), and n. 2 of liquefaction (Figure 5).

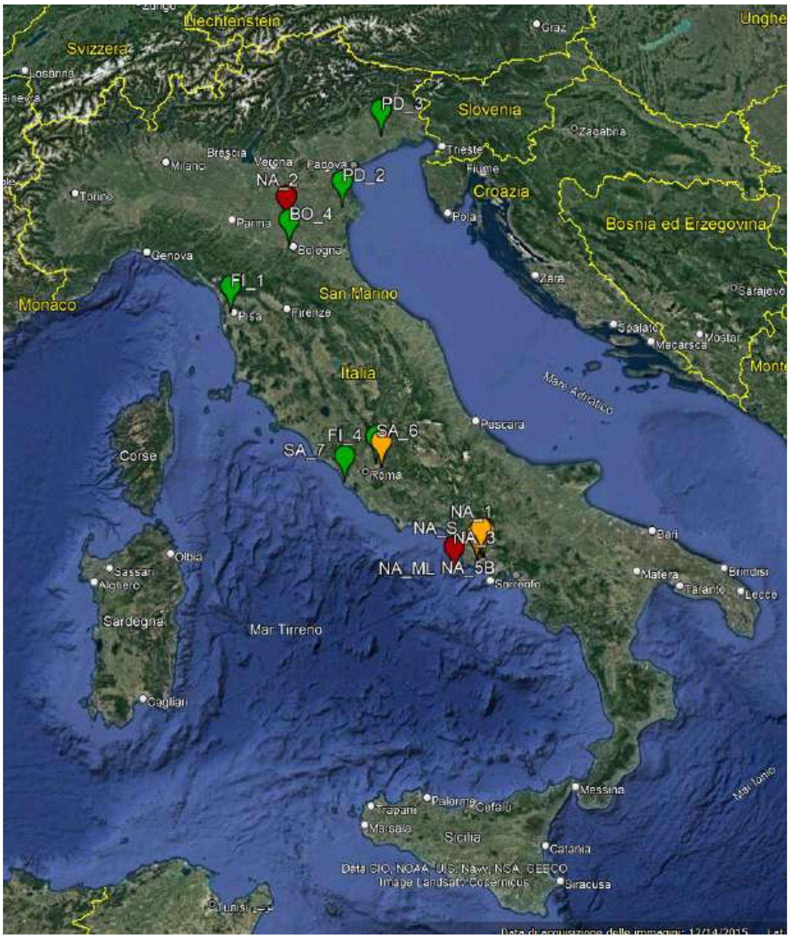

Figure 4: Location of the case studies composing the ground instabilities dataset (yellow: sinkholes; green: subsidence; red: liquefaction).

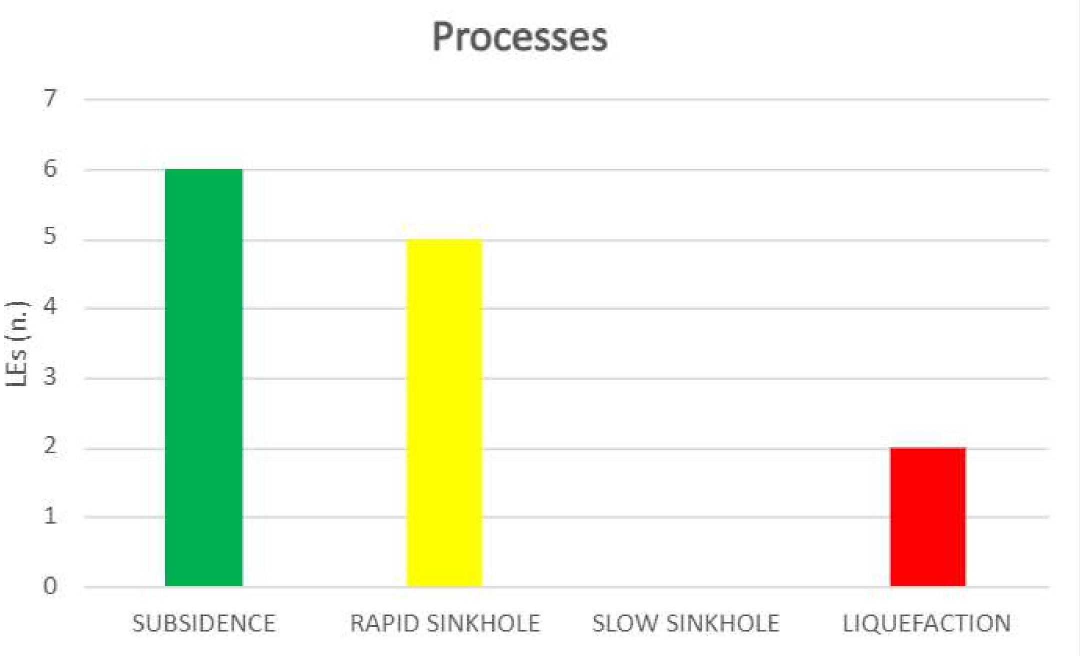

Figure 5: Graph showing the types of the case studies composing the analysed dataset (yellow: sinkholes; green: subsidence; red: liquefaction).

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. 9 LEs, at the basin scale in n. 10 LEs, and at the local scale in n. 5 LEs (Figure 6).

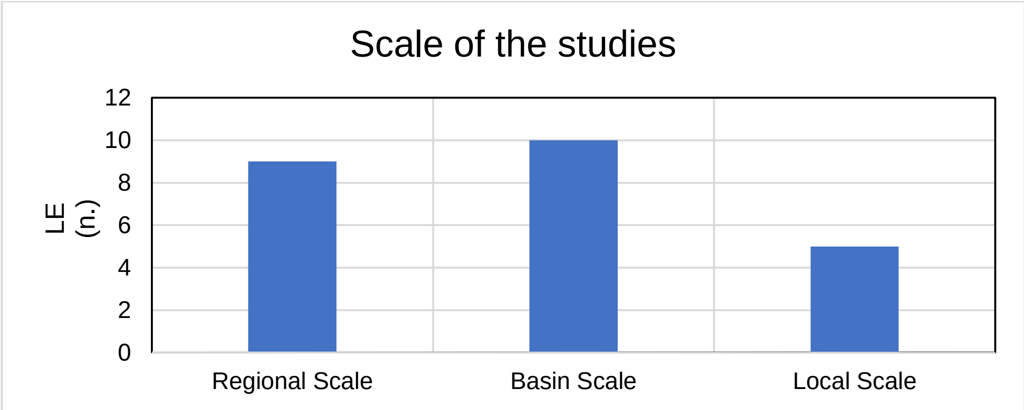

Figure 6: Graph showing the scale of the studies (regional, basin, or local scale) composing the analyzed dataset.

Table 2 – Summary table of information relating to each LEs

CA	Kinematics	Process	Trigger	Control parameters	Input data	Spatial scale	Analysis	LM	Applicability contrains	Outputs
BO_4_WP4	Slow	Subsidence	Water pumping	Geology; soil deformability modulus; permeability; water table level	Continuous coring; well drilling; penetrometric tests; piezometric levels; pumping data; topographic levels; GPS; Maps of surface deformation - PS InSAR (different resolutions)	100 km2	QL - SQL - QN	Statistical and susceptibility analysis	Sedimentary facies	Map of potential damage; Map of subsidence rate forecast
FI_1_WP4	Slow	Subsidence	/	Geology; water table levels; geothermal activity; anthropic influence; LU	DEMs; InSAR; Cartography; LU	10-1000 km2	QN	Identification of triggering processes; automatic procedure to distinguish area affected by subsidence or landslides	InSAR not for high velocity	Identification of subsidence area considering deformation velocity
FI_4_WP4	Rapid	Sinkholes	/	Geology; water table levels; distance from faults; LU	DEMs; InSAR; Cartography; piezometric levels; LU	Local scale	SQN	ML analysis (MaxEnt with cloglog)	With MaxEnt is considered only the locations; Only predisposing factors	Susceptibility maps of sinkholes (from 0 to 1); assessment of predisposing factors with response curves and jack-knife models; ranking of variables
NA_1_WP4	Rapid	Sinkholes	/	Geology; cavities; anthropogenic activity;	Historical data; Man-made caves; depths; geotechnical and geometrical properties; distance from aqueduct and pipeline	Small - Medium	SQN	2 - density distribution and assessment of safety factors	Man-made caves	Susceptibility classes (L,M,H); variations in Factor of Safety values (<1,3; 1,3 - 2,5; >2,5)
NA_5B_WP4	Rapid	Sinkholes	Rainfall	Geology; cavities; anthropogenic activity; rainfall	Aqueduct network data; water table levels; road, sewer system, cavity and underground railroad data	Local scale	SQN	Sinkhole map inventory; statistical methods for susceptibility assessment; InSAR	/	Inventory map; Susceptibility map with Natural Breaks classification model (1 = very low; 2 =low; 3 = medium; 4 = high; 5 = very high); Frequency Ratio approach (formula)
NA_3_WP4	Rapid	Sinkholes	Saturation	Rock resistance; Gravity load; Seismic load; Thickness of the rock in the vault; Vault span length; Existing cracks (orientation and distribution)	Uniaxial compression strength; Vertical "lithostatic" stress at the cavity roof; Thickness of the rock in the vault; Vault span length	Medium	SQL - QN	Finite different analyses executed through FLAC interpreted in the frame of a reliability-based method to estimate the safety conditions of the cavity roof including the uncertainties due to the presence of joints and variable rock strength.	Poisson coefficient = 0.3	Map and diagram distributions of the stability conditions of the cavity roofs.

UNINA_ML	Rapid	Liquefaction	Earthquake	Seismic load (amplitude Level 1: qualitative, provides 'attention zones'; Level 2: semi-quantitative, provides profiles of safety factors in terms of shear stress capacity/demand ratios, or liquefaction potential indexes (integrating them with depth); Level 3: quantitative, provides also strain values; Level 4: quantitative, provides also pore pressure ratios and may lead to settlement& duration)	Level 1 (screening criteria): Groundwater depth, lithology (if sandy), M and PGA; Level 2 (semi-empirical methods), plus field tests (SPT, CPT, VS) and static lab tests; Level 3-4 (simplified-advanced dynamic analysis), plus cyclic/dynamic lab tests and accelerograms	Multi-scale	SQN - QN - QL	Level 1: provides 'attention zones'; Level 2: provides profiles of safety factors in terms of shear stress capacity/demand ratios, or liquefaction potential indexes (integrating them with depth); Level 3: provides also strain values; Level 4: provides also pore pressure ratios and may lead to settlement	Lithology; individuation of seismic bedrock	Level 1: provides 'attention zones'; Level 2: provides profiles of safety factors in terms of shear stress capacity/demand ratios, or liquefaction potential indexes (integrating them with depth); Level 3: provides also strain values; Level 4: provides also pore pressure ratios and may lead to settlement
NA_S_WP4	Rapid	Sinkholes	Saturation	Rock resistance; Gravity load; Seismic load; Thickness of the rock in the vault; Vault span length; Existing cracks (orientation and distribution)	Uniaxial compression strength of the rock; Vertical "lithostatic" stress at the cavity roof; Thickness of the rock in the vault; Vault span length	Medium	SQL - QN	Finite different analyses through FLAC interpreted in the frame of a reliability-based method to estimate the safety conditions of the cavity roof including the uncertainties due to the presence of joints and variable rock strength.	Poisson coefficient = 0.3	Map and diagram distributions of the stability conditions of the cavity roofs
NA_2_WP4	Rapid	Liquefaction	Earthquake	Magnitude/PGA; Geology	Historical data; piezometric levels, PGA from shakemaps; SPT/CPT/Vs	Small - Medium	SQN	2 - density distribution and SPT/CPT/Vs	Lithology; groundwater; PGA and geotechinal parameters	Susceptibility classes (L,M,H); variations in Factor of Safety values (<1,3; 1,3 - 2,5; >2,5)
PD_2_WP4	Slow	Subsidence	Natural and anthropogenic causes	Geology; sea levels; piezometric levels; urbanization	Cartography; Geothecnical data; LIDAR; LU; infrastructures characteristics	10 - 10000 km2	QN	Numerical simulations; numerical modelling	Low rates of displacement	Numerical models; severity classes; correlation infrastructures/displacement data
PD_3_WP4	Slow	Subsidence	Natural and anthropogenic causes	Geology; sea levels; piezometric levels; urbanization	Cartography; Geothecnical data; LIDAR; LU; infrastructures characteristics	11 - 10000 km2	QN	Numerical simulations; numerical modelling	Low rates of displacement	Numerical models; severity classes; correlation infrastructures/displacement data
SA_6_WP4	Slow	Subsidence	Water pumping	Geology; water table leves	Piezometric levels; InSAR	Basin	SQN	Numerical model; correlations	/	Critical thresholds: the cumulative vertical displacement does not exceed 4 cm if the thickness of compressible deposits is less than 6 m and the drawdown less than 4 m, while higher vertical displacements occur.
SA_7_WP4	Slow	Subsidence	External loading	Geology; edification (age and type)	Urbanization phases; Geology; InSAR	Local scale	SQL	Supervised change detection; correlations	/	Correlation graphs of foundation types of the most relevant structures and infrastructures and the displacement velocity measured on PSs with different SAR datasets; correlation diagrams between the PS velocity and the soft-soil thickness; Comparison of theoretical settlements values with the corresponding COSMO-SkyMed

Table 2 possibly highlights a comparable amount of LE among the types of kinematics with n. 7 LEs focusing on rapid GI, n. 6 LEs on slow GI (Figure 7). As regards the triggering, it is quite variable, with n. 2 for groundwater pumping, n.2 for the rainfall, and n. 2 for the seismic input as well. Among the LEs, n. 3 are attributed to anthropic trigger or not specified and in 1 case only the rock degradation is assumed as trigger (Figure 8). The analysis log is represented by a high number of semi-quantitative outputs (n. 9), followed by quantitative one (n. 4) and only n. 2 developed on a qualitative basis (Figure 9). The complete sheets for each LE can be found at:

https://communitystudentiunina.sharepoint.com/:f:/s/PE3RETURN935/EjEstw5-tmJLsbx8xnhgPVsBwwY5H4VEvim-13MangcHVg?e=pwPYWa

The analysis of the preparatory and the predisposing factor is better highlighted in the next section, as they were used to define the parameters for running the tool chains that will be inserted in the simulator.

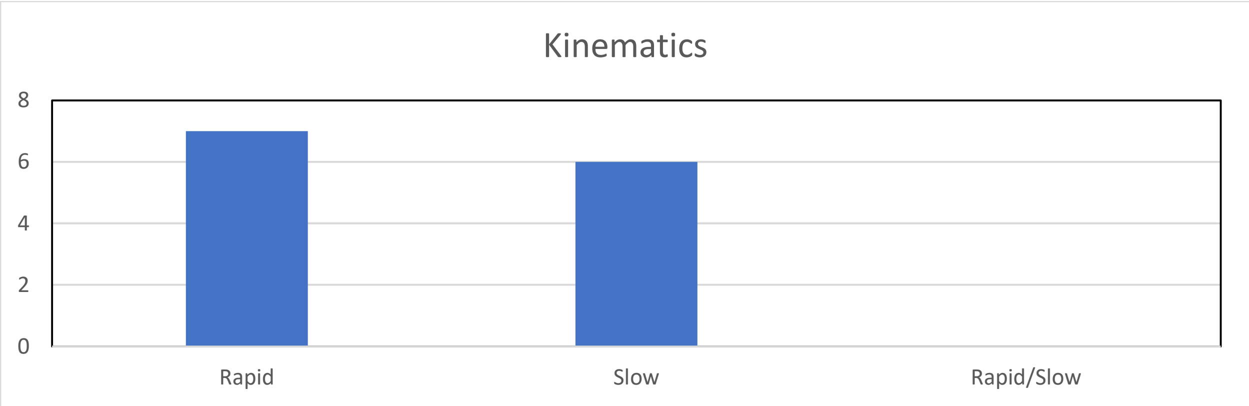

Figure 7: Graphs reporting the type of kinematics the LEs.

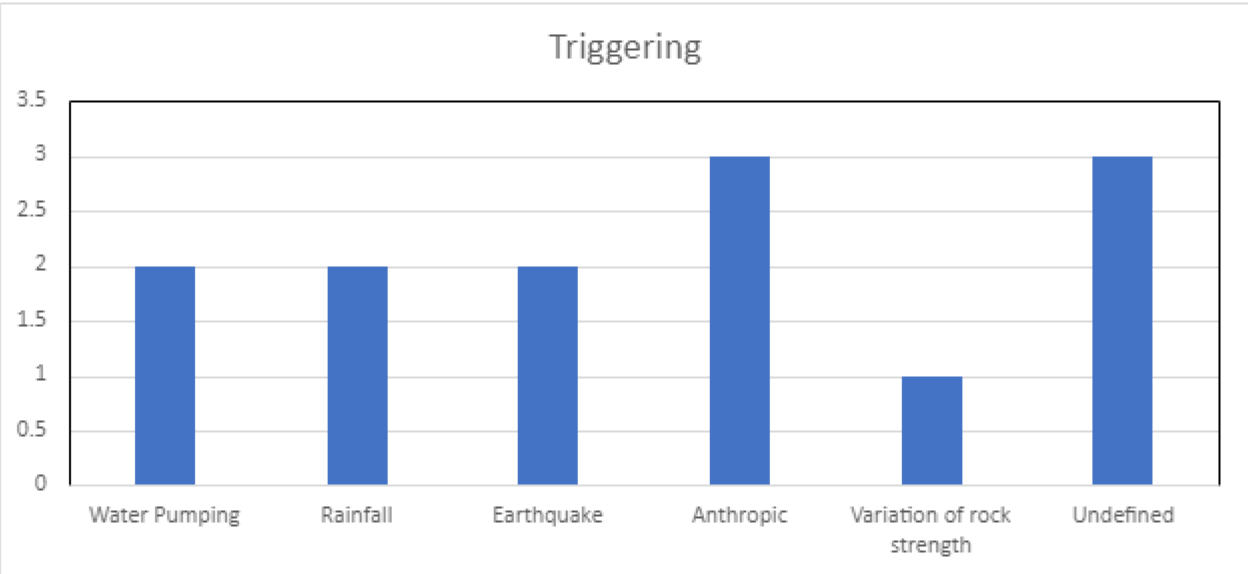

Figure 8: Graphs reporting the type of trigger of the LEs.

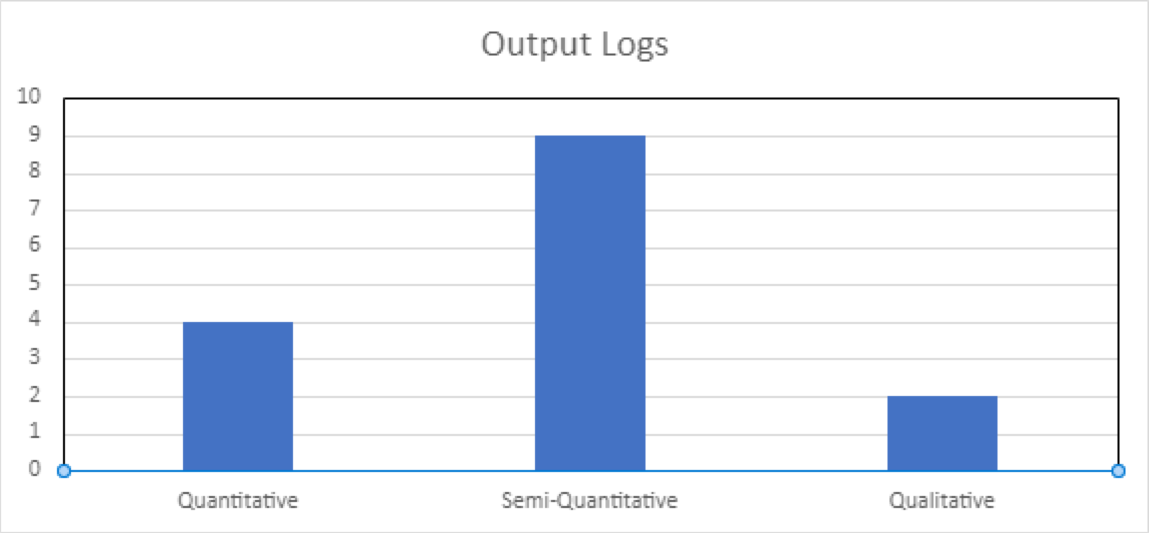

Figure 9: Graphs reporting the type of analysis log.

5. Second Section

5.1 Classification of the available LEs as tools

As discussed in the former section, upon completion of the review and recall activities, the number of Learning Examples (LE) included in Task 2.4.3 is equal to 13. One of the main purposes of this task is to define tools that can address issues related to the mapping and triggering of different types of ground instabilities in large plain areas, 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.

The output of the TK3, but in general of the whole WP4, should be the mapping of the identified phenomena, whose zoning expresses a specific parameter intensity variation. For rapid ground instabilities, these parameters are:

- displacement;
- velocity;
- kinetic energy;
- volumes of involved material.

Or, for slow ground instabilities:

- displacement and relative rate;
- area affected by deformation.

Possible occurrence of multiple geohazards that may affect a certain portion of the territory, in terms of:

- More than one hazard that can occur simultaneously over a certain portion of the territory;
- Cascading conditions in which the occurrence of one ground instability can be the trigger for a subsequent ground instability.

In order to build a chain of process 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 predisposing and preparatory factors that are needed to follow the tool chains.

In the analysis of the LE for **subsidence,** the geology and the geotechnical properties of the area represent the main predisposing factors (Figure 10) in most of the cases (n. 5 each), while the other predisposing factors observed in the LEs are the topography and the LULC (n. 3 each), while the tectonics (n. 2), and the rock permeability, geothermal activity, and sea level (n. 1 each). On the other hand, the water pumping, and the water table fluctuations represent the main preparatory factors (Figure 11) in n. 5 cases each, while the LULC in n. 3 case studies.

In the **sinkholes** dataset, the main predisposing factors (Figure 12) are: geology (n. 5 LEs), structural elements (n. 4 LEs), past events and geotechnical properties (n. 3 LEs each), man-made cavities and the distance from infrastructures (n. 2 case studies each), and the topography and LULC (n. 1 LE each). The preparatory factors (Figure 13) are represented by the water table fluctuations (n. 2 case studies), and rainfall events and rock strength degradation (n. 1 LE each).

In the **liquefaction** dataset, the predisposing factors (Figure 14) are represented by the geology, earthquakes with magnitude > 5, water table fluctuations, PGA, and geotechnical properties (n. 2 LEs each), and past events (n. 1 LE). In the case of liquefaction events, the collected LEs had no preparatory factors interacting with the process.

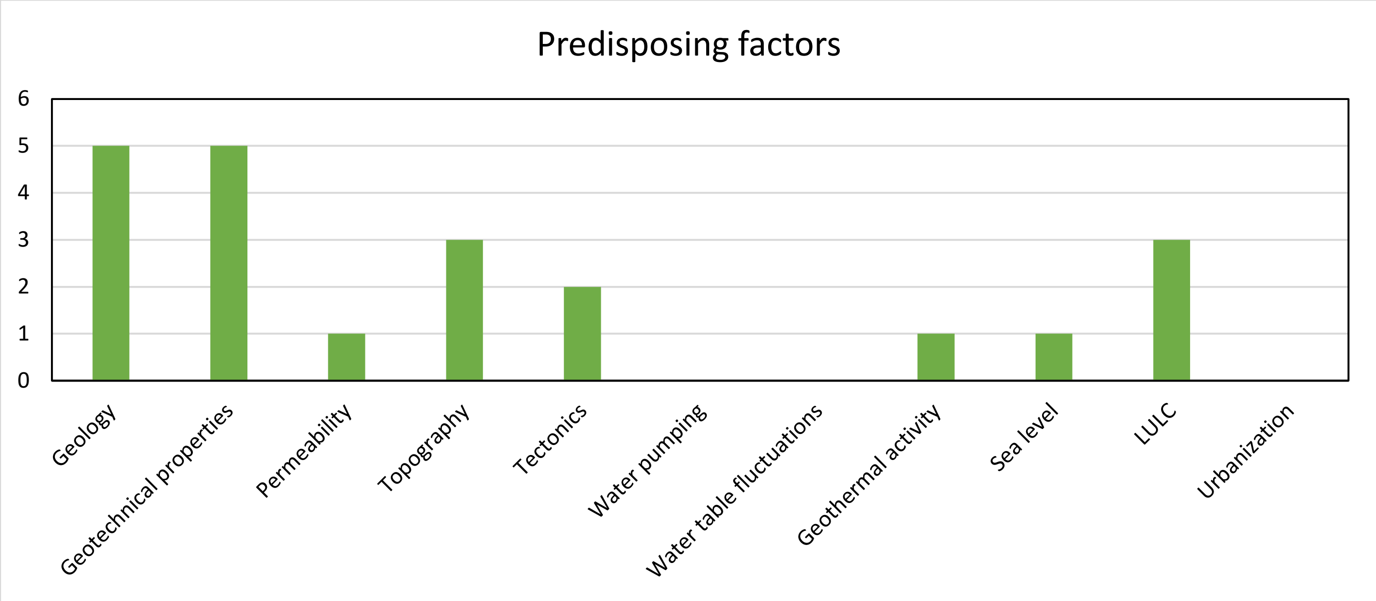

Figure 10: Graphs showing the predisposing factors characterizing the subsidence studies of the analyzed dataset.

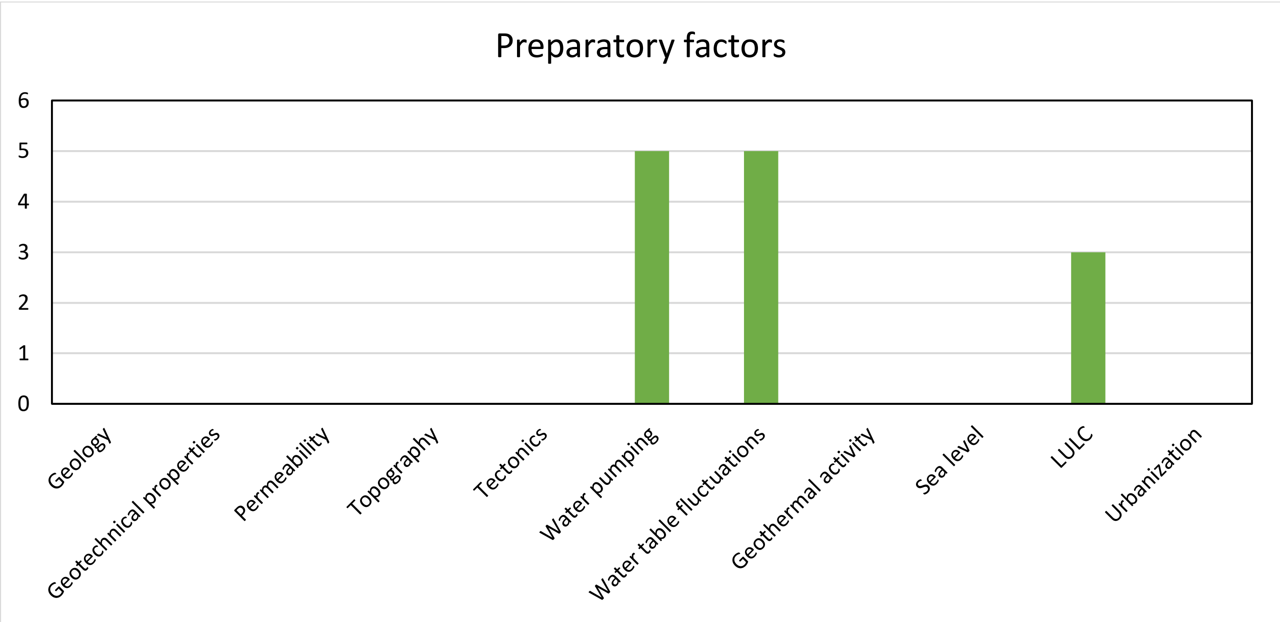

Figure 11: Graphs showing the preparatory factors characterizing the subsidence studies of the analyzed dataset.

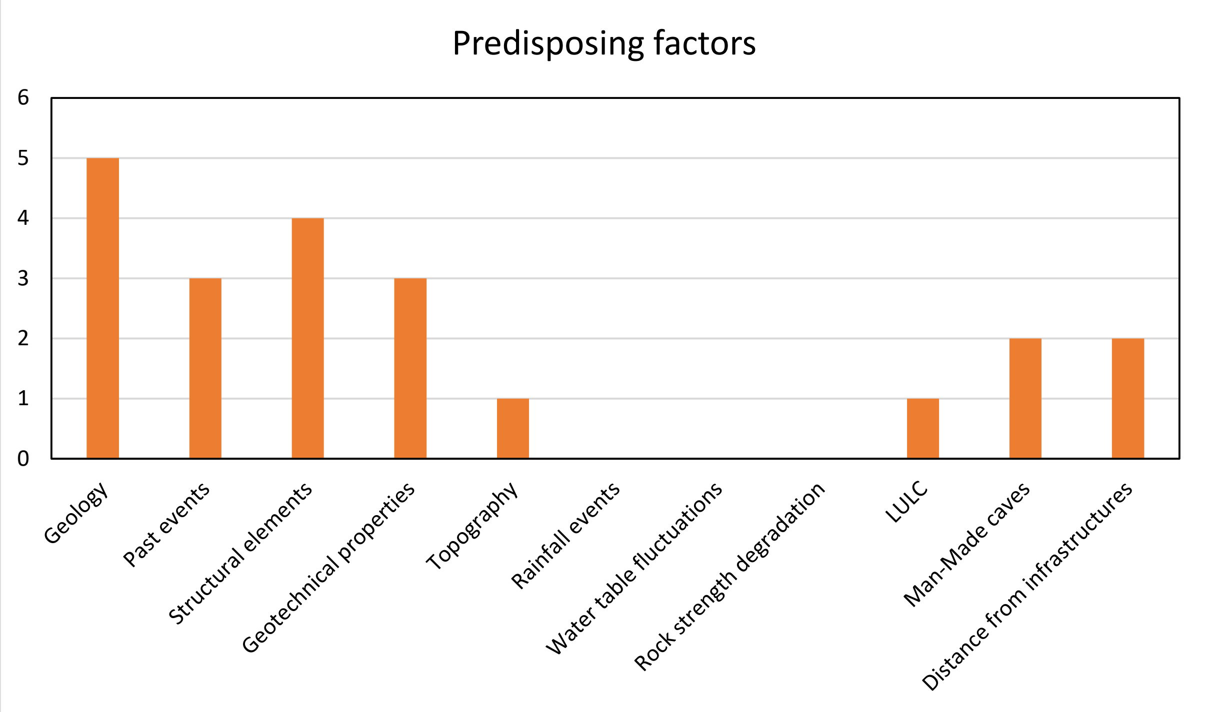

Figure 12: Graphs showing the predisposing factors characterizing the (rapid) sinkhole studies of the analyzed dataset.

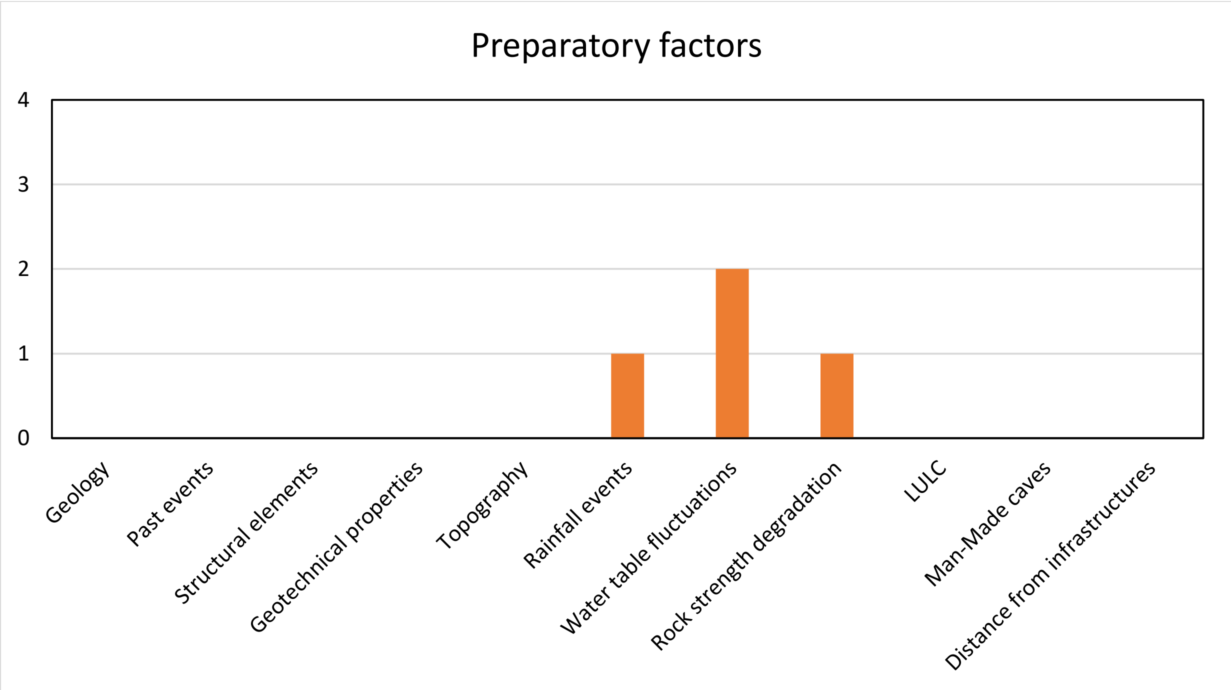

Figure 13: Graphs showing the preparatory factors characterizing the (rapid) sinkhole studies of the analyzed dataset.

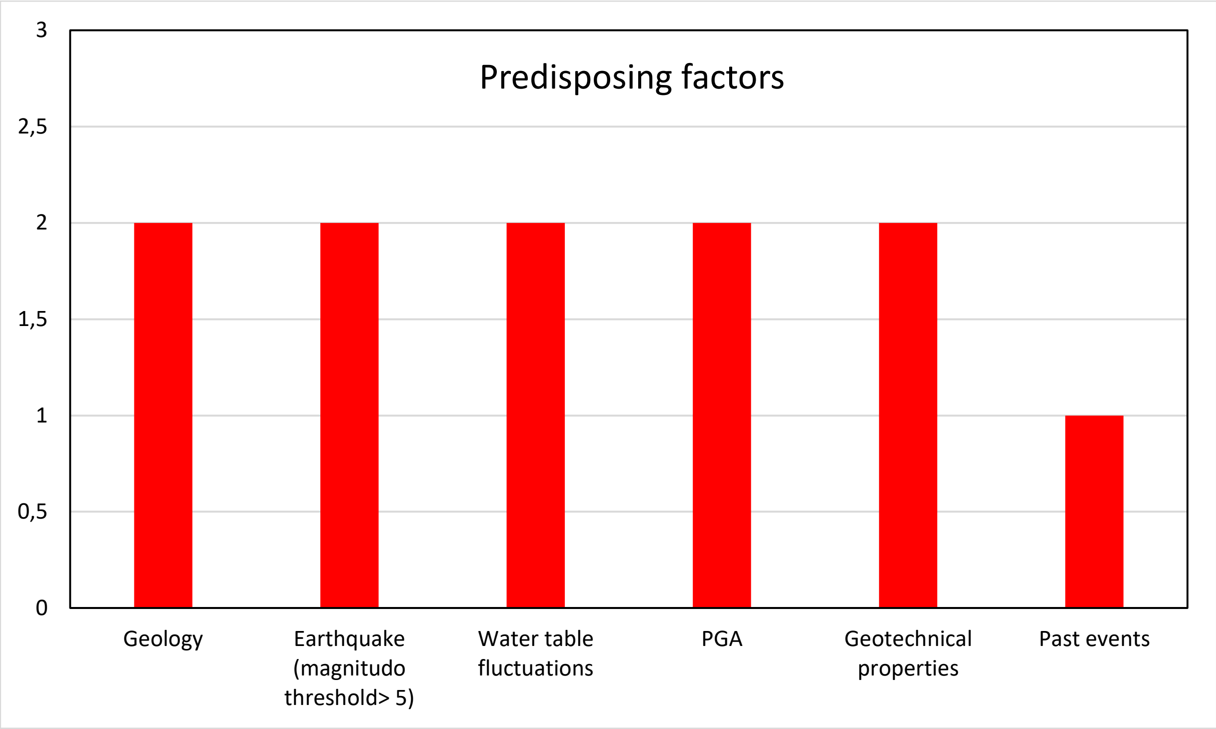

Figure 14: Graphs showing the predisposing factors for liquefaction studies of the analysed dataset.

5.2 Logical framework for building up the tool chains

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 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, passing through possible preparatory processes, up to the triggering. from the selected LEs.

Propaedeutically to the chain construction, each trigger / multi-hazard / 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, 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 shown in Figure 15:

- 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.

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Trigger category	
R Rainfall	
A/N Anthropic/Natural	
Rk Rock Strength Degradation	
WP Water Pumping	
N Not Specified	
Trigger category	
Triggers expected and addressed by tool(s)	
Triggers expected but not addressed by any tool	
Triggers rarely possible but not addressed by any tool	
Triggers not expected	
OUTPUT LOG	
QUALITATIVE	
SEMI-QUANTITATIVE	
QUANTITATIVE	
SCALE	
R= Regional	
B= Basin	
L= Local	

GROUND INSTABILITIES												
Process	Sinkholes											
kinematics	RAPID						SLOW					
Trigger category	E	R	A/N	WP	Rk	N	S	R	A/N	WP	RD	N
R						NA_1_WP						
						NA_5B_W						
B						FI_4_WP4						
						NA_1_WP						
						NA_5B_W						
L		NA_3_WP4			NA_S_WP	FI_4_WP4						
Process	Subsidence						Liquefaction					
kinematics	SLOW						RAPID					
Trigger category	S	R	A/N	WP	RD	N	S	R	A/N	WP	RD	N
R			PD_2_WP	BO_4_WP4		FI_1_WP4	UNINA_M					
			PD_3_WP	SA_6_WP4								
			SA_7_WP4									
B			PD_2_WP	BO_4_WP4		FI_1_WP4	UNINA_M					
			PD_3_WP	SA_6_WP4								
			SA_7_WP4									
L							UNINA_ML					
							NA_2_WP4					

Figure 15: Logical framework for branching the tools of TK 3

In the previous section, it was possible to identify the predisposing and preparatory factors that permits to analyse the processes of the plain areas in terms of mapping. Although, this approach highlighted the main triggers, it also showed a lack of parametrization, that prevent the implementation of a complete chain of events. For this reason, in the logical framework shown in Figure 15, the triggering factors were theoretically assumed, permitting to visualize both the available and the missing triggers. The latter can be furtherly implemented in a next stage of this Research.

The triggers that are considered relevant for the processes that can be found in the setting of this task are:

- Earthquakes (E)
- Rainfalls (R)
- Anthropic or Natural causes (A/N)
- Water Pumping (WP)
- Rock strength degradation (Rk)
- Not specified (N)

As already discussed, a complete missing of LEs describing some cases of slow sinkholes is obtained. Conversely, the **rapid sinkholes** are well represented in terms of scale of the analysis, but the trigger is seldom accounted. The only LEs that provide some zoning quantification are for the liquefaction and subsidence.

In summary, for the rapid sinkholes:

- The earthquake (E) and natural/anthropic (A/N) triggering is expected, but no LE is found;
- At the regional and basin scale, there are tools, but no quantification of the trigger is provided;
- At the local scale, the two characterized triggers are rainfall and rock strength degradation.

For the land subsidence:

- Local scale tools are completely missing;
- Mainly Regional and Basin scale tools are present;
- The seismic induced subsidence is not accounted.

For the liquefaction:

- The scale and the tools are covered, even if the LE are only two.

5.2 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.

With reference to the logical structure in which the extracted tools are placed, for each environment (plain areas for TK3) 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).

Going into the details of the proposed logical-operational scheme for sequentially composing the tools related to the macrocategories 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 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 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.

In the following paragraphs for each process, typical flowcharts are provided, see Figures 16 – 17 - 18. As regards predisposing factors, a relevance (weight) of the necessary factor is graphically attributed (Medal symbol), the three medals are the required parameters to at least provide a susceptibility study. The relative weights are derived from the frequency graphs reported in section 5.1. Please note that the complete fact sheets for each LE can be found at:

https://communitystudentiunina.sharepoint.com/:f:/s/PE3RETURN935/EjEstw5-tmJLsbx8xnhgPVsBwwY5H4VEvim-13MangcHVg?e=pwPYWa

5.2.1 Subsidence

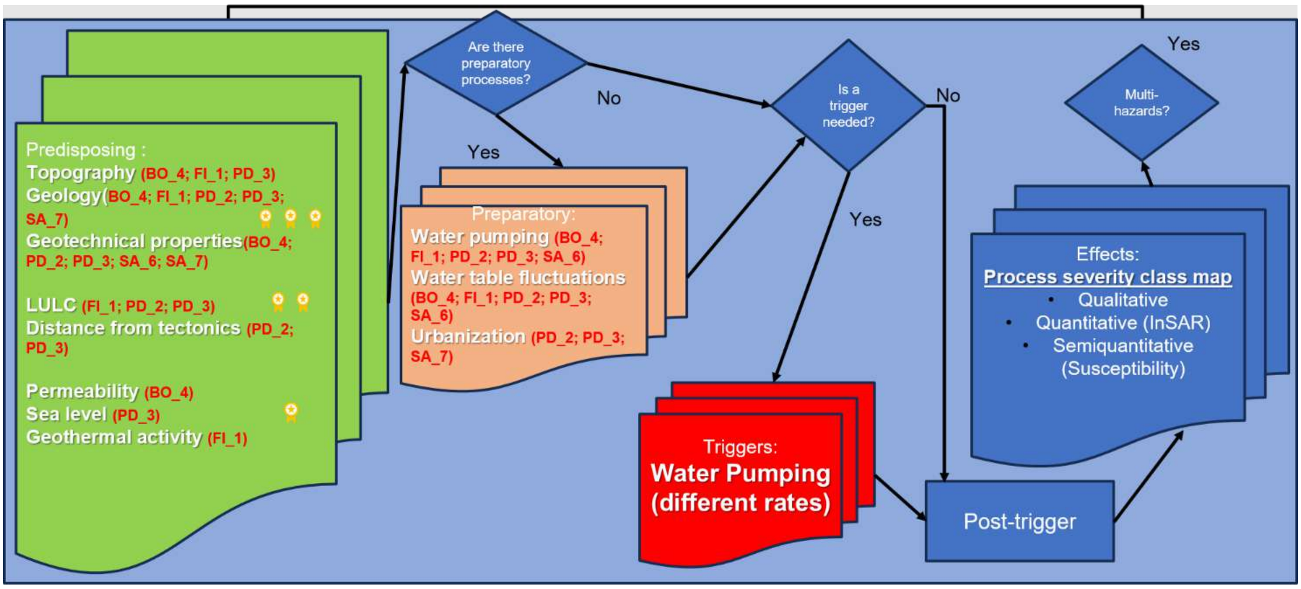

Figure 16 Tool chain for subsidence

Starting from case studies BO_4, FI_1, PD_3, PD_2, SA_7, SA_6 several predisposing factors are recognized with a weight that can be considered: high (3 stars: topography, geology, geotechnical properties), medium (2 stars: LULC, distance from tectonics), low (1 star: permeability, sea level, geothermal activity). To the predisposing factors can be possibly added the preparatory factors which are water pumping, water table fluctuations and urbanisation. An analysis of the above mentioned case studies shows that the trigger in cases of subsidence is water pumping. The effects of the post-trigger can be represented through process severity class maps that can be qualitative, quantitative (InSAR) and semi-quantitative (Susceptibility).

5.2.2 Sinkholes

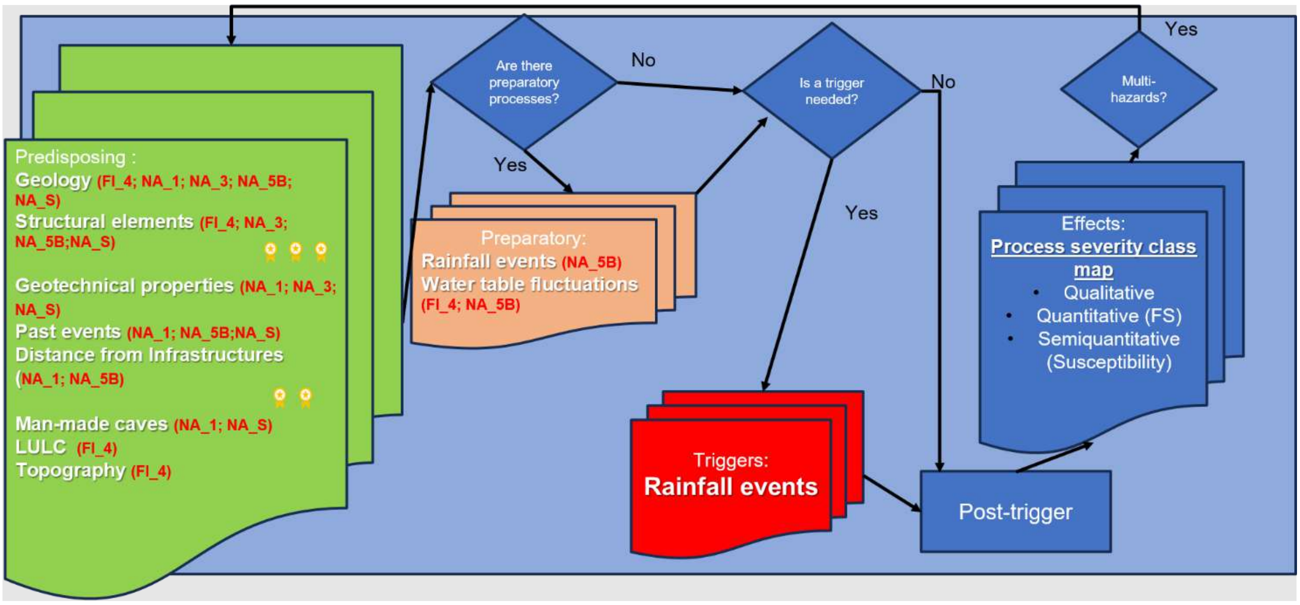

Figure 17 Tool chain for sinkholes

From case studies FI_4, NA_1, NA_3, NA_5B, NA_S, several predisposing factors are recognised with a weight that can be considered: high (3 stars: geology, structural elements), medium (2 stars: geotechnical properties, past events, distance from infrastructures), low (1 star: man-made caves, LULC, topography). To the predisposing factors can be possibly added the preparatory factors which are rainfall events and water table fluctuations. An analysis of the above mentioned case studies shows that the trigger in cases of sinkholes is rainfall events. The effects of the post-trigger can be represented through process severity class maps that can be qualitative, quantitative (FS) and semi-quantitative (Susceptibility).

5.2.3 Liquefaction

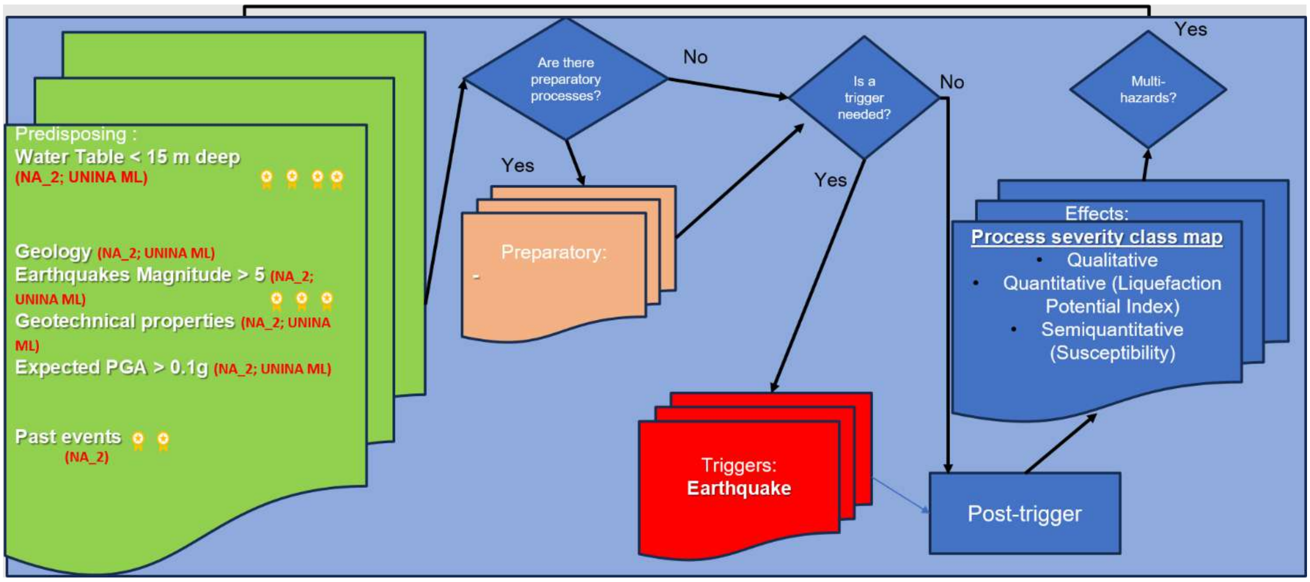

Figure 18 Tool chain for liquefaction

Starting from case studies NA_2 and UNINA_ML several predisposing factors are recognised with a weight that can be considered: very high (4 stars: water table < 15 m deep), high (3 stars: geology, earthquakes magnitude >5, geotechnical properties, expected PGA>0.1g), medium (2 stars: past events). To the predisposing factors can be possibly added preparatory factors. An analysis of the above mentioned case studies shows that the trigger in cases of liquefaction is earthquake. The effects of the post-trigger can be represented through process severity class maps that can be qualitative, quantitative (Liquefaction Potential Index) and semi-quantitative (Susceptibility).

In sandy soil deposits, the effective stresses may approach zero and consequently the soil behaviour switches from that of a solid to that of a fluid. Such a phenomenon is known as liquefaction. If the liquefaction phenomenon is attained, relevant vertical settlements of shallow-founded buildings and other engineering facilities occur. In many recent strong earthquakes (e.g. New Zealand, 2011; Japan, 2011; Emilia Romagna, 2012; Turkey, 2023) the liquefaction induced settlements have resulted in significant damages on the built environment. In practice the seismic induced building settlements are quantified via empirical procedures that were developed considering the one dimensional (1-D) volumetric consolidation settlements in “free-field” conditions, neglecting the presence of the structure at the ground level (e.g., Tokimatsu and Seed 1987; Ishihara and Yoshimine 1992). In other words, only the volumetric strains, mainly due to the dissipation of the excess pore water pressure accumulated during the seismic sequence, are considered. Settlements (w) can be estimated by the following equation:

$$w = \sum_{i=1}^{j} \varepsilon_{z,i} \cdot \Delta z_i \qquad (1)$$

where ε_{vi} is the post-liquefaction volumetric strain for the soil sublayer i; Δz_i is the thickness of the sublayer i; and j is the number of soil sublayers.

Ishihara & Yoshimine (1992) demonstrated that the volumetric strains induced by the dissipation of the excess pore water pressure induced by seismic event is linked to the safety factor (FS). In engineering practice, the safety factor against liquefaction in free field conditions is computed by comparing the "soil capacity" to resist liquefaction and the "seismic demand" generated by the earthquake (Seed & Idriss, 1971).

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6. Conclusions

In the period between January and July 2023, the research activities of WP4 were devoted to the definition of a Rationale for the processes preparing ground instabilities (GIs) and the trigger/multihazard events respectively. As already discussed, LEs describing the process of **slow sinkholes** is completely missing now. Conversely, the **rapid sinkholes** are well represented in terms of scale of the analysis, but the trigger is seldom accounted. The only LEs that provide some criteria for zoning quantification are **liquefaction** and **subsidence**.

In summary, **Slow sinkholes**

- No LE is collected, hence the chain for this process cannot be activated.

Rapid Sinkholes:

- The earthquake (E) and natural/anthropic (A/N) triggering is expected, but no LE is found;
- At the regional and basin scale, there are tools, but no quantification of the trigger is provided;
- At the local scale, the two characterized triggers are rainfall and rock strength degradation.

For the **Land Subsidence**:

- Local scale tools are completely missing;
- Mainly Regional and Basin scale tools are present;
- The seismic induced subsidence is not accounted.

For the Liquefaction:

- The scale and the tools are covered, even if the LE are only two.

Table 3 – Summary table of the critical points for TK3

Critical point	**Solution to be implemented**
Small Inventory of LEs	In the next months of the project, an implementation of the LEs could be done. In particular, as the inner recall did not provide meaningful results, an outside recall should be done.
Minor representation of liquefaction, subsidence and sinkhole effects with respect to landslide studies and LEs (WP3 and WP4)	
Lack of coverage of all processes at different scales	
Lack of WP4 LEs for multihazard	

7. References

Bianchini, S., Confuorto, P., Intrieri, E., Sbarra, P., Di Martire, D., Calcaterra, D. & Fanti, R. (2022). Machine learning for sinkhole risk mapping in Guidonia-Bagni di Tivoli plain (Rome), Italy. Geocarto International, 37, (27,), 16687–-16715. DOI: https://doi.org/10.1080/10106049.2022.2113455

Bozzano, F., Esposito, C., Franchi, S., Mazzanti, P., Perissin, D., Rocca, A, & Romano, E. (2015). Remote Sensing of Environment, 168, 219–238. http://dx.doi.org/10.1016/j.rse.2015.07.010

Bozzano, F., Esposito, C., Mazzanti, P., Patti, M., & Scancella, S. (2018). Imaging Multi-Age Construction Settlement Behaviour by Advanced SAR Interferometry. Remote Sensing, 10, 1137, https://doi.org/10.3390/rs10071137

Ceres, R., d'Onofrio, A., Gargiulo, F., & Silvestri, F. (2024). Inter-disciplinary and multi-level study of seismic liquefaction susceptibility in the coastal area of Casamicciola Terme (Ischia Island, Italy). Proceedings of the 8th International Congress of Earthquake Geotechnical Engineering (ICEGE).

De Silva, F., Lusi, T., Ruotolo, M., Ramondini, M., & Flora, A. (2023). Reliability-based roof stability charts for cavities in heterogeneous jointed rock masses. Rivista Italiana di Geotecnica, 2. https://doi.org/10.19199/2023.2.0557-1405.016

Fiaschi, S., Fabris, M., Floris, M., & Achilli, V. (2018). Estimation of land subsidence in deltaic areas through differential SAR interferometry: the Po River Delta case study (Northeast Italy). International Journal of Remote Sensing, 39, 23, 8724-8745. https://doi.org/10.1080/01431161.2018.1490977

Floris, M., Fontana, A., Tessari, G., & Mulè M.C. (2019). Subsidence Zonation Through Satellite Interferometry in Coastal Plain Environments of NE Italy: A Possible Tool for Geological and Geomorphological Mapping in Urban Areas. Remote Sensing, 11, 165; https://doi.org/10.3390/rs11020165

Guarino, P.M., Santo, A., Forte, G., De Falco, M., & Niceforo, D.M.A. (2018). Analysis of a database for anthropogenic sinkhole triggering and zonation in the Naples hinterland (Southern Italy). Natural Hazards, 91, S173–S192. https://doi.org/10.1007/s11069-017-3054-5

Modoni, G., Darini, G., Spacagna, R.L., Saroli, M., Russo, G., Croce, P. Spatial analysis of land subsidence induced by groundwater withdrawal. Engineering Geology, 167, 59–71. http://dx.doi.org/10.1016/j.enggeo.2013.10.014

Rosi, A., Tofani, V., Agostini, A., Tanteri, L., Stefanelli, C.T., Catani, F., & Casagli, N.International Journal of Applied Earth Observation and Geoinformation, 52, 328–337. http://dx.doi.org/10.1016/j.jag.2016.07.003

Santucci de Magistris, F., Lanzano, G., Forte, G., & Fabbrocino, GA peak acceleration threshold for soil liquefaction: lessons learned from the 2012 Emilia earthquake (Italy). Natural Hazards, 74, 1069–1094. https://doi.org/10.1007/s11069-014-1229-x

Santucci de Magistris, F., Lanzano, G., Forte, G. & Fabbrocino, G. (2013). A database for PGA threshold in liquefaction occurrence. Soil Dynamics and Earthquake Engineering, 54, 17–19. https://doi.org/10.1016/j.soildyn.2013.07.011

Scotto di Santolo, A., Forte, G., & Santo, A. (2018). Analysis of sinkhole triggering mechanisms in the hinterland of Naples (southern Italy). Engineering Geology, 237, 42-52. https://doi.org/10.1016/j.enggeo.2018.02.014

Tufano, R., Guerriero, L., Corona, M.A., Bausilio, G., Di Martire, D., Nisio, S & Calcaterra, D. (2022). Anthropogenic sinkholes of the city of Naples, Italy: an update. Natural Hazards, 112, 2577–2608. https://doi.org/10.1007/s11069-022-05279-x