REQUIREMENTS BASELINE

EARTH OBSERVATION FOR HIGH IMPACT MULTI-HAZARDS SCIENCE (EO4MULTIHAZARDS)

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1. INTRODUCTION

1.1. PURPOSE

The aim of this report is to provide a baseline for the identification, consolidation, and implementation of the scientific requirements in the EO4Multihazards project (Deliverable D1.1 – Requirements Baseline). The deliverable is associated with WP100 Scientific Requirements Consolidation and developed with contributions from all partners: BGS (lead), CMCC, EURAC, GMV, UT-ITC, UCL, and VU. The objectives of WP100 are to:

- Consolidate the scientific background of the project.
- Define the science cases and goals of the activities involved in each case.
- Perform a risk analysis and propose solutions.
- Deliver a complete set of scientific and operational requirements.

This Deliverable D1.1 represents an agreed-upon, reviewed, and approved set of scientific requirements that set the expectations among the consortium and project stakeholders regarding the project outputs, outcomes, and impact. It also helps establish a baseline against which the consortium can evaluate the progress of the project. The consortium aims to pursue its projects objectives collaboratively with stakeholders including scientific organizations, NGOs, operational agencies, public institutions, practitioners, economic operators, and relevant projects networks (a list of stakeholders and potential contributors to the multi-hazard scientific community is listed in Annex 1, section 2.2 of the Technical Proposal).

1.2. SCOPE

Aligned to the objectives of WP100, Deliverable D1.1 introduces in **Section 2.** a state-of-the-art review of approaches, scientific results, analytics, and models relevant for the characterization, detection, and prediction of multi-hazard (compound and cascading) events and quantification of multi-hazard risks. In **Section 3.** , the project work plan and major scientific goals are presented. **Section 4.** describes the planned science and demonstration cases by EURAC and CMCC (Science Case 1-2), BGS (Science Case 3), and UT-ITC (Science Case 4) including the methodologies to be implemented, data needs, and the role of EO in each science case. The expected scientific impact and publication plan for the project is described in **Section 5.** **Section 6.** highlights possible synergies with relevant ongoing projects and initiatives. Finally, the project risk assessment and associated mitigation actions are introduced in **ANNEX A.**

1.3. DEFINITIONS AND ACRONYMS

1.3.1.DEFINITIONS

Concepts and terms used in this document and needing a definition are included in Table 1-1. Other relevant concepts and terms can be consulted in the glossary of the Disaster Risk Gateway (www.disasterriskgateway.net), an online crowdsourced platform for sharing existing approaches for understanding, analysing, and managing multi-hazard and multi-hazard risks and definitions, adopted by the EO4Multihazards project. The consortium agrees that the definition of 'high impact multi-hazards' is context-specific and a universally applicable characterization of such events is unhelpful. What constitutes high impact for a receptor (element at risk) can be a low or medium impact for another due to a complex interplay of environmental, socio-economic, cultural, and institutional factors that vary from one location to another and across scales. Nevertheless, any novel terminology and definitions proposed in this project will be disseminated through existing multi-(hazard-) risk platforms, conferences, workshops, and publications (e.g., see Table 5-1). We will strive to ensure acceptance in the scientific community and alignment with established international glossaries.

Table 1-1 - Definitions

Concept / Term	Definition
Hazard	Potentially dangerous phenomenon, process or activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation (UNDRR, 2017).

Exposure	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. Measures of exposure can include the number of people or types of assets in an area. These can be combined with the specific vulnerability and capacity of the exposed elements to any hazard to estimate the quantitative risks associated with that hazard in the area of interest (UNDRR, 2017).
Vulnerability	The conditions determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards (UNDRR, 2017).
Disaster Risk	The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society, or a community in a specific period, determined probabilistically as a function of hazard, exposure, vulnerability, and capacity (UNDRR, 2017).
All hazards approach	To strengthen technical and scientific capacity to capitalize on and consolidate existing knowledge and to develop and apply methodologies and models to assess disaster risks, vulnerabilities, and exposure to all hazards.
Multi-Hazard	Multiple major hazards that an area faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects (UNDRR, 2017).
Multi-hazard risk	Risk generated from multiple hazards and the interrelationships between these hazards (but not considering interrelationships on the vulnerability level) (Zschau, 2017).
Multi-risk	Risk generated from multiple hazards and the interrelationships between these hazards (and considering interrelationships on the vulnerability level) (Zschau, 2017).
Multi-(hazard-)risk	Term used when collectively referring to multi-hazard, multi-hazard risk, and multi-risk (Ward et al., 2020).
Compound (hazard) relationship	Two different natural hazards that impact the same period and spatial area. Compound hazards can have a footprint with spatial and temporal characteristics that differs from the component single hazards (Tilloy et al., 2021, Zscheischler et al., 2018).
Triggering relationship	One hazard causing another hazard to occur. Any natural hazard might trigger zero, one, or more secondary natural hazards, with these being either the same or different from the primary hazard (Ciurean et al., 2018, Tilloy et al., 2021).
Amplification relationship	The occurrence of one hazard can increase the likelihood and/or magnitude of additional hazards in the future (e.g., forest fires can amplify the triggering of debris flows during heavy rain) (Ciurean et al., 2018).
Cascading hazard	Cascading hazard processes refer to an initial hazard followed by a chain of interrelated hazards (e.g., earthquake triggering landslide, landslide triggering flooding, flooding triggering further landslides) (Adapted from UNDRR, 2019).
Interacting risk	A general term to indicate that several hazardous events worsen the impact on society. The term interacting risk is used to highlight the importance of hazard interactions, in terms of their causal mechanisms and effect they have on other hazardous processes.
Interconnected risk	Used to highlight the importance of interconnected causality networks that generate and amplify disasters, and the interlinkages between human, environmental and technological components (Helbing, 2013), which can be analysed using network analysis.
Cascading risk	Cascading risk is used to highlight the progressive impact of disaster events in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events distinguished by increase in progression over time and secondary events that spread from one component to the others. Cascading risk is complex and is associated more with the magnitude of the impact than with that of hazards. Low-level hazards can generate broad chain effects if vulnerabilities are widespread in the system or not addressed properly in sub-systems. These subsequent and unanticipated secondary crises can be exacerbated by the failure of critical infrastructure, and the social functions that depend on them (adapted from Pescaroli and Alexander 2015,2016, 2018). This can also include so-called NaTech disasters, where extreme events with a natural origin (e.g. earthquake) cause a secondary technological disaster chain (Krausmann et al., 2011).
Systemic risk	Risk of a 'system' due to interaction effects of elements of a system (Gill et al., 2022). Systemic risk refers to those impacts that may impede the functioning of a system. For example, the cascading impacts of one or more interacting extreme events may pass over to other sectors of society and to other regions, causing cross-boundary effects that may lead to the collapse of the functioning of a part of society, or event extending to several geographical areas (Silmann et al, 2022).

Scenario	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Scenarios are neither predictions nor forecasts but are used to provide a view of the implications of developments and actions (IPCC, 2023).

1.3.2.ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-2 - Acronyms

Acronym	Definition
AISCC	African Island States Climate Commission
AI/ML	Artificial Intelligence/Machine Learning
ASTAT	Instituto Provinziale di Statistica ASTAT (Alto Adige)
BGS	British Geological Survey
BIGF	British Isles GNSS Facility
CCI	Communications Control Interface
CDEM	Caribbean Disaster Emergency Management Agency
CEMS	Copernicus Emergency Management Service
CERIS	Community for European Research and Innovation for Security
CLMS	Copernicus Land Monitoring Service
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici
CMEMS	Copernicus Marine Environment Monitoring Service
CMINE	Crisis Management Information Network Europe
CORINE	Coordination of Information on the Environment
CRED	Centre for Research on the Epidemiology of Disasters
DAT	Digital Audio Tape
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DEM	Digital Elevation Model
DRM	Digital Rights Management
DRMKC	Disaster Risk Management Knowledge Centre
DRS	Disaster Resilient Societies framework
ECA	Error Characterisation Approach
ECWMF	European Centre for Medium-Range Weather Forecasts
EDF	European Defence Fund
EDO	European Drought Observatory
EFAS	European Flood Awareness System
EFFIS	European Forest Fire Information System
EGU	European Geosciences Union
UNU-EHS	United Nations University Institute for Environment and Human Security,
EO	Earth Observation
ESA	European Space Agency
ESWD	European Severe Weather Database
EWS	Early Warning Systems
GDACS	Global Disaster Alert and Coordination System
GDO	Global Drought Observatory
GDP	Gross domestic product
GFM	Global Flood Monitoring
GLOFAS	Global Flood Awareness System

GLOMOS	Global Mountain Safeguard Research
GWIS	Global Wildfire Information System
HOC	HydRON Operation Centre
IEEE	Institute of Electrical and Electronics Engineers
IJDRS	International Journal of Disaster Risk Science
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IRDR	Institute for Risk and Disaster Reduction
ISTAT	Instituto Nazionale di Statistica
LiDAR	Light Detection and Ranging
LULC	Land Use Land Cover
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multi-Spectral Imager Instrument
NDMI	Normalized Difference Moisture Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NGO	Non-Governmental Organization
NHESS	Natural Hazards and Earth System Sciences
NTL	Nighttime Light
SAR	Synthetic Aperture Radar
SIDS	Small Island Developing States
SMCE	Spatial multi-criteria Evaluation
SPEI	Standardised Precipitation-Evapotranspiration Index
SPI	Standardised Precipitation Index
SRC	Societal Resilience Cluster
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial System/Vehicle
UCL	Use Case Leads
UCPKN	Union Civil Protection Knowledge Network
UHI	Urban Heat Island
UNDRR	United Nations Office for Disaster Risk Reduction
UNU-EHS	United Nations University Institute for Environment and Human Security,
VCI	Vegetation Condition Index
VHI	Water Holdings Index
VUA	Vrije Universiteit Amsterdam
WCRP	World Climate Research Programme
WWRP	World Weather Research Programme

2. STATE-OF-THE-ART REVIEW

2.1. APPROACHES FOR THE CHARACTERIZATION AND DETECTION OF MULTI-HAZARD (COMPOUND AND CASCADING) EVENTS

The impacts of natural hazards have increased over the last decades (Poljansek et al., 2017, Cutter et al., 2018 and IPCC 2023). Interactions between hazards can cause the impacts to be larger than the sum of the individual events (Kappes et al., 2012, Terzi et al., 2019). Following the extensive impacts of multi-hazard events, recent years have seen a call for a shift from a predominantly single hazard paradigm towards a comprehensive understanding of multi-hazards (including from the international community, e.g., UNDRR 2019, IPCC 2014, Ward et al., 2022, De Angeli et al., 2022, AghaKouchak, et al., 2020). This shift is characterized by several challenges, amongst which the lack of a common understanding of multi-hazard, multi-risk terminology and concepts is highlighted in recent multi-hazard reviews (Ciurean et al., 2018 and Gill et al., 2022).

Another challenge is the collection and storage of multi-hazard data. Development and relief agencies have long recognized the crucial role played by data and information in mitigating the impacts of natural hazards on vulnerable populations. Systematic collection and analysis of these data provides invaluable information to governments and agencies in charge of relief and recovery activities. They are also crucial in the integration of health components into development and poverty alleviation programs. Yet there is still no consensus regarding good practices for collecting multi-hazard event data. One reason for this is the difficulty in identifying such events due to the complex nature of hazard interactions and the limited availability of multi-hazard observations. Recent studies explored the utility of existing single hazard datasets and databases for the identification and classification of multi-hazard events. For example, Lee et al. (2024) present a framework for classifying and assessing multi-hazard events in relation to their frequency, impact on human lives and assets, and reporting trends, using the global disaster database EM-DAT (over 123 years, 1900–2023). Their findings highlight the design limitations and biases stemming from the database's single-hazard focus: hazard sequencing, attribution of losses and fatalities exclusively to a single hazard, inaccurate definition of hazards, temporal biases, and inherent biases due to its inclusion criteria.

Claassen et al. (2023) developed a method for compiling global multi-hazard event sets from single hazard datasets, the MYRIAD—Hazard Event Sets Algorithm (MYRIAD-HESA) and applied the method to compile the first global multi-hazard event set database (MYRIAD-HES). The database can be used to identify global hotspots of hazard pairs, which hazard pair occurs most frequently in different regions, and unique multi-hazard groups with and without time-lag. Whilst this approach extends the possibility to investigate the frequency and location of past multi-hazards hotspots, the findings are limited by the source data coverage (i.e., scale, resolution) and assumptions used to define the hazard events from reanalysis data, resulting in an over or underestimation of the number of events.

These state-of-the-art approaches are valuable steps forward and serve as a guide to identifying events with severe consequences, which is a key first step in understanding the complex multi-hazard interactions that drive impacts. However, they also underscore the imperative need to create a dedicated multi-hazard database that integrates local and regional hazard observation data. In this project, we will develop a common framework for a multi-hazards database using established definitions of hazard interactions and the spatial and temporal relation between hazard events with a national and sub-national coverage. This resource will be and available for other EU project dealing with multi-hazards (e.g. MYRIAD-EU, PARATUS, the HUT, MEDIATE, AGILE, C2IMPRESS united in the CMINE SRC cluster (https://www.cmine.eu/topics/20936/feed).

2.2. ANALYTICS, MODELS, AND METHODS FOR MULTI-HAZARD RISK

Although the number of publications on multi-hazard risk assessment has greatly increased over the past decades, there is still a bias towards landslide-related applications in Europe (Owolabi & Sajjad, 2023). Many methods for multi-hazard risk assessment have been outlined in literature (Delmonaco et al., 2006; Garcia-Aristizabal and Marzocchi, 2011., Kappes et al., 2012; Gallina et al., 2016). These have advantages and disadvantages, as summarized in Table 2-1. One of the most common approaches for multi-hazard risk assessment linked to spatial planning is the application of weighting methods, such as Spatial Multi-Criteria Evaluation (SMCE) or the Delphi-method, which are used to compare the impact of different hazards in a region by applying weights given by experts (Olfert et al., 2006). The INFORM method is such a method which has become one of the most popular methods where a range of indicators are weighted for exposure, vulnerability, and capacity. The method has been applied at national and sub-national scale in many countries.

Impact chains are analytical concepts, usually represented in the form of network diagrams, used to better understand, systemise, structure, and prioritise different factors and processes causally linked and contributing to the risk (Zebisch et al., 2022). They are a useful tool to visualise and understand cascading impacts and their drivers in a given context. Impact chains can be created through participatory approaches or literature research resulting in structured information about the risk drivers, and disaster risk reduction and adaptation options. The impact chain concept has been employed successfully in Climate Risk Assessments and is one tool to visualise multi-hazard/ multi-risks scenarios. In addition to helping us understand what is driving the risk, impact chains engage stakeholders and experts in the development phase as well as communication phase. Impact chains allow to visualise the complexity of risk in one figure. The elements of an impact chain may be represented by indicators, which when quantified could be aggregated, allowing to compare the risk and risk components of regions and/or sectors. In this project we envisage to use the impact chain approach to identify EO datasets that can be used to quantify the different factors.

With respect to scales of analysis, approaches have been developed ranging from a global scale to a local level. Ward et al. (2022) provides an overview of risk assessment methods at the global scale and conclude that the interactions between hazards and the dynamic nature of exposure and vulnerability are difficult to incorporate at such general level. This is also the case when dealing with regional scale analysis, such as trans boundary analysis of multi-hazard risk for the Hindu Kush Himalayas (Rusk et al., 2022). At the European level, many countries have developed their national multi-hazard risk assessment, which have often not kept pace with the risk management practices (Bossong and Hegemann, 2015; Hochrainer-Stigler et al., 2023). This is even more so in many developing countries where international donor agencies often facilitate the generation of national risk assessments, led by external consultants, without a real uptake of the results in the country itself (Van Westen et al., 2020). Developments at more local administrative level have shown good example of integrated multi-(hazard-)risk assessment (e.g., Bell and Glade, 2004; Marzocchi et al., 2012; Chen et al., 2016; van Westen et al., 2014; Di Angeli et al., 2022).

Increasing complexity as demonstrated by real world examples of multi-hazards events, requires major improvements of our current multi-hazard scientific modelling capabilities (De Ruiter et al., 2022, Simpson et al., 2021). In the compound events research field, there has been a growing attention to quantify the co-occurrence of climate drivers and hazards (Cutter et al., 2018, Leonard et al., 2014, Ridder et al., 2020, and Zscheischler et al., 2018). While several quantitative methods exist for the analysis of compound and multi-hazard risk (Tilloy et al., 2019), traditional risk assessments and models continue to have a predominant single hazard focus and often do not account for dynamics and feedbacks of multiple hazards and between risk components (Simpson et al., 2021, Ward et al., 2022, De Ruiter et al., 2022, Matano et al., 2022). This is in large part due to a lack of sufficient, high-quality empirical data (Kreibich et al., 2022, Tilloy et al., 2019, Ward et al., 2022, De Ruiter et al., 2022), but also a lack of in-depth case studies (Ward et al., 2022). Kreibich et al. (2022) argue that to better understand the effects of risk management measures, requires extensive empirical data analysis.

Similarly, scenarios have been used in teaching emergency management, in running exercises and in conducting national risk assessments because they can help “anticipate the unforeseen” and reveal possible impact and limitations inherent in sudden evolution of the emergency (Alexander, 2000). In the last ten years, qualitative or semi-qualitative methodologies have been used for understanding hidden vulnerabilities, recording bottom-up perspectives, and developing tabletop exercises on complex emergencies. These approaches are easy to replicate and can be used complementary to quantitative assessment for training purposes to provide in-depth interpretation of existing challenges for operational capacity and support decision making (Pescaroli et al., 2018), while they can be integrated in more holistic approaches to methodologies such as stress testing (Linkov et al., 2022).

High-quality satellite imagery has the potential to contribute to addressing this data and subsequent knowledge gap (Abbasi and Nawaz, 2020, Van Westen, 2000). As outlined by some of the previous references, data gaps are one of the main reasons behind the limited knowledge and understanding of multi-hazard phenomena. Even though modelling capability improves, the access to reliable data (freely, if possible) is not evolving at the same pace. Data sources can be diverse, from Unmanned Aerial Systems (UAS) or satellites to social media. Up to now, there have been limited attempts to include satellite imagery into the workflow of multi-(hazard-)risk analysis, modelling, forecasting, and added-value generation. One of the main reasons is the limited historical archive with competitive spatial and temporal sampling in relation to the requirements of hazard modelling. The scenario that Sentinel missions proposed some years ago is changing the paradigm, and now we are in a position to start deeply analysing the topics within the multi-(hazard-)risk domain in which EO can take a relevant role. The current project will analyse the potential use of these kinds of analysis in the multi-(hazard-)risk domain.

Table 2-1 - Approaches used for multi-(hazard-)risk assessment, with indication of the main advantages and disadvantages

	Method	Description	Advantages	Disadvantages
Quantitative approaches	Probabilistic risk assessment	Calculates losses of all possible hazard interaction scenarios, and include uncertainties of risk components.	Provides complete analysis of average annual losses as basis for financial decision-making.	Requires specialized software and is not applicable for all types of hazards (e.g., landslides, volcano, flooding). Very data demanding. The analysis requires specific software tools.
	Artificial intelligence	Predict the losses of hazard interactions based on a large training dataset, using AI, with relevant covariates.	No need to develop datasets on risk components, no hazard, exposure, or vulnerability assessment needed.	There are only few examples where loss datasets were large enough to be able to do this. The analysis requires high level of expertise, and programming skills.
	Event-tree Analysis / Bayesian networks	Hazard interactions and impacts are structured into a tree structure and the probability of each branch is calculated.	Allow modelling of a sequence of events and works well for domino effects.	The probabilities for the different nodes are difficult to assess, and spatial implementation is very difficult due to lack of data. The method requires specific expertise and tools.
	Scenario-based Quantitative Risk assessment	Losses are calculated for specific combinations of hazard scenarios with their return period and exposure. Risk is calculated from 4 or more loss scenarios by calculating the area under the curve.	This approach requires a limited number of hazard interaction scenarios. It is important to have these for a range of frequencies (both frequent and infrequent).	It can be difficult to determine the specific frequency of certain hazard interactions. It can work well with trigger coupled events, and independent event, by taking the frequency of the trigger. Not all possible scenarios are evaluated.
	Impact-Based Forecasting	This is a near real-time estimation of expected losses, considering the forecasted hazard trigger (e.g. rainfall, storms, drought).	The approach can be based on actual continuous modelling of hazards, exposure, vulnerability, and losses, or based on machine learning approaches.	For the process-based modelling, the models should be fast enough to run in real-time. The method requires a direct coupling with real-time hazard forecasting. For AI based approach enough training data is needed.
Semi-Quantitative approaches	Individual scenario analysis	Losses are calculated for specific hazard interaction scenarios without considering their frequency. It can be simplified by calculated only exposure or using Vulnerability=1 approach.	This method is ideal as the basis for disaster preparedness actions, for instance for the modelling of population exposure as the basis for Early Warning. It is also helpful for validating with historical events.	The scenarios are generally limited, and other events might occur as foreseen. The frequency is not considered in this approach. The method is often applied in data scarce regions where data on elements-at-risk are lacking.
	Risk Matrix Approach	A simplified method where risk classes are defined based on frequency classes and loss classes into a matrix, which can be used for zoning.	This method is a good basis for land use planning and doesn't require very detailed quantified data. The method is worked out in many countries as the basis for and use in planning.	The method is not often applied in a multi-hazard context. The same area might be falling under various combination of frequency and losses. Only the highest is considered.
Qualitative approaches	Descriptive analysis	Basic description of the hazard interactions and the impact sequence.	This is the most logical first step to develop the scenarios as a narrative.	The problem is that the scenarios are not spatially represented and cannot be directly quantified.
	Impact-chain analysis	Co-development of visual representation of hazard interactions, and direct	This method is a good approach to understand the multi-hazard interactions and	The method doesn't quantify the losses. Even though also the indirect losses are included, the

		and indirect impacts for different sectors.	cascading impacts and can be used as a basis for the quantification using other methods.	quantification of these is extremely complicated and often very case specific. Impact-chains can be very complicated.
	Multi-Criteria Evaluation	Method in which the risk components (hazard, exposure, vulnerability, capacity) are represented by a series of indicators, which are combined by giving them a weight.	The method can be standardized (as in the case of the INFORM Risk method), and can be carried out without extensive hazard modelling, by planning experts.	The method does not provide actual values of frequency of losses, but merely scores per administrative unit that can be used to prioritize them for risk reduction actions.
	Qualitative or semi-qualitative scenario building	Qualitative or semi-qualitative methodology relies on interviews, focus groups, reviews, and surveys. Scenarios of this type can identify cascading effects that in complex events may lead to increased demand for assistance and coordination.	This method can be used to explore the concurrent, compound, and cascading drivers of the escalation process while maintaining a focus on capacity of the stakeholders. It can help to derive common vulnerabilities and point of failures across organisations and operational areas. It can integrate holistically the data derived from quantitative approaches, such as event tree analysis, and qualitative approaches. It can be easily integrated into stress testing, exercises, and training for civil protection actors among other.	This approach has limited ability to integrate quantitative information and can be influenced by the cultural context where it is adopted. Other forms of biases need to be considered in the limitations, such as for example political agenda or lack of access to confidential information.

Methods, tools, and approaches considered in the EO4Multihazards project are:

- Impact chains / network diagrams (Science cases 1, 2, 3 and 4)
- Descriptive analytics (Science cases 1, 2 and 4)
- AI and ML algorithms (Science cases 1 and 2)
- Narrative descriptions (Science case 3)
- Multi-(hazard-)risk indicators (Science case 3)
- Physically based modelling (Science case 1) and digital twinning combined with scenario-based Quantitative Risk assessment (science case 4)
- Vulnerability scenarios and common point of failures (Science cases 1, 2, 3 and 4)

2.3. THE GENERAL ROLE OF EO DATASETS IN THE MULTI-(HAZARD-) RISK DOMAIN

Earth Observation (EO) from satellite, airborne or UAS-based sensors provide data and products that can be used to monitor physical processes in many hazard-prone areas around the world. EO sensors capture timely large-scale environmental data over a range of spatial, spectral, and temporal resolutions, and provide long time series of homogeneous and accurate environmental information, which, when combined with socioeconomic data can give unique insights into assessing risks. Both data from passive sensors, through visible and near-infrared (optical instruments) to thermal infrared, and microwave systems, and from active sensor, including radar and LiDAR, can support hazard and exposure monitoring, impact evaluation and risk assessment for a great range of hazards, from climate-induced hazards like droughts or floods, to geo-hazards such as landslides, mudslides, or terrain subsidence.

The importance of EO data for improving our knowledge of hazards and risks is well-recognized in the science community, and many studies have demonstrated the unique capabilities of satellites for characterising hydrometeorological and geological hazard events (Novellino et al., 2024, Gosset et al., 2023, Kruczkiewicz et al., 2021, Le Cozanet et al., 2020). EO is particularly important in regions where in-situ measurements are limited or where on-the-ground infrastructure assessments are not possible due to safety concerns (Kirschbaum et al., 2019). However, these are key to feed the modelling community with systematic input data to scale up the spatial results from single or multi-hazard models. For example, EO has been used for landslide hazard assessment, including landslide mitigation and monitoring through the mapping of landslides (Ambrosi, et al., 2018) using simple spectral analysis, i.e. NDVI (Phakdimek et al., 2023), NDWI (Singh et al., 2021), to more complex AI or Machine Learning approaches (Kabiru et al., 2023). The application of active and/or passive radar (Phakdimek et al., 2023) with related research on potential landslide activity through land cover change analysis (Psomiadis et al., 2020) or through estimates of variables such as soil moisture (Ramsauer & Marzahn, 2023) is well established. EO techniques have been employed for slope stability (Aldiansyah & Wardani, 2024) and the generation of landslide susceptibility products (Dashwood & Ciurean, 2020) into risk assessments.

EO products can be used by modellers and assist them to setup different hazard scenarios. For example, EO-derived indices such as SPEI, VCI, NDVI or NDWI can be used to assess drought conditions and to define the event onset and end date, or to determine the burned area in a wildfire. For instance, in the case of droughts, EO has been used to inform the assessment of drought-vulnerable areas and for the monitoring of drought through determination of drought indices (Chanyang Sur et al., 2021; Su et al., 2017); through the assessment of stresses and the extraction of measures of soil or vegetation moisture (Massart et al., 2024) and vegetation condition (De Luca et al., 2022); and have been coupled with an assessment of the meteorological impact on drought (Bergonse et al., 2021; Marumbwa et al., 2021) or the early detection of drought (Behrangi et al., 2016). EO data has further been integrated with forecasting or modelling with AI (Heydari et al., 2018).

EO products can also support model validation and assess the accuracy of their results by estimating, for instance, the extent of the flooded area in a flood driven by heavy rains over a previously deforested or burned area. For example, EO has been applied to wildfire research (Szpakowski & Jensen, 2019) through detection and mapping of burned area using multispectral datasets (Han Zhang et al., 2023; Amos et al., 2019) and/or radar datasets (Radman et al., 2023). They have also been used to assess factors such as fire intensity or burn severity (Chatzopoulos-Vouzoglanis et al., 2024), the estimation of fire spread rates (Humber et al., 2022), research on potential markers for fire occurrence from land surface temperature change (Waring et al., 2023), or as a proxy for soil moisture (Dadap et al., 2019) in addition to assessing atmospheric consequences from burn emissions (Shikwambana et al., 2019).

Whilst the use of EO data and products for single-hazard and risk assessments is well established, their use for the identification, characterisation, and assessment of multi-(hazard-)risk only recently started to build momentum. Examples include characterisation of cascading hazards impacting high mountain regions in Asia (Kirschbaum et al., 2019) and modelling of hazard interactions such as in wind-induced storm-surge events (Wei Zhang et al., 2017; Brun & Barros, 2013; Kiage et al., 2005), water-induced mass movement events (Zhang et al., 2022; Kirschbaum & Stanley, 2018; Kniveton et al., 2000), and drought induced wildfire (Yong Piao et al., 2022). EO datasets have also been used to study the relationship between wildfires and rainfall-driven mass movement hazards, including the seasonality and location of mass movements at burned and unburned locations (Peduto et al., 2022; Culler et al., 2021; Rengers et al., 2020).

Finally, EO-based information can also be incorporated into models through data assimilation to improve the accuracy and robustness of model outputs. In this way, EO data can be used to constrain state variables (e.g., soil moisture) setting boundary conditions. The resulting outputs benefit from the spatial and temporal information provided by the EO measurements, while enhancing their ability to simulate the output variables.

2.4. IDENTIFICATION OF KNOWLEDGE GAPS, CHALLENGES, AND OPPORTUNITIES FOR EO APPLICATION

EO technology has contributed substantially to the generation of relevant information for hazard risk assessment and management. Satellite observation data is an indispensable source of information for weather prediction models and forecasting (including impact-based), disaster risk response, recovery, and preparedness activities. Drawing on the previous sections, the following gaps, challenges, and opportunities in the application of EO in the multi(-hazard)-risk domain are summarised:

- The lack of a common understanding of multi-(hazard-)risk terminology and concepts as highlighted in recent multi-(hazard-)risk reviews → *there is an opportunity to use EO data to analyse spatial-temporal relationships between hazards and contribute to the definition of (high-*

impact) multi-hazard events. This may consider the attribution of direct and indirect impacts to different sectors.

- The lack of a framework for the collection and storage of multi-hazard data in a database that integrates local and regional multi-hazard observations → *the current project will develop a framework for a multi-hazards database using established definitions of hazard interactions and the spatial and temporal relation between hazard events with a national and sub-national coverage. Such a database can be used for scenario-based multi-hazard impact assessments.*
- Bias towards particular hazards combinations and their spatial coverage → *satellite-based imagery can support the rapid development of reference baseline datasets in areas with limited coverage and to better understand the underlying mechanisms of hazard interactions with a positive effect on modelling.*
- Insufficient, high-quality empirical data and in-depth multi-hazard case studies, particularly for understanding the effects of risk management measures → *the combined use of ground-based observations and in-situ data with satellite imagery and monitoring can provide a more complete understanding of multi-hazard impacts in a given environmental context. EO technologies can also be used for monitoring reconstruction and recovery after an event.*
- Traditional risk assessments and models often do not account for dynamics and feedbacks between risk drivers → *through the analysis of multi-temporal EO datasets there is an opportunity to identify antecedent conditions leading to changes in vulnerability and exposure through time and how these changes respond to or connect with hazard dynamics.*

3. WORK PLAN AND MAJOR SCIENTIFIC GOALS

3.1. PROJECT AIMS AND SCIENTIFIC GOALS

The overarching goal of the EO4Multihazards project is to leverage advancements in satellite EO technology, such as Sentinel missions and Earth Explorers, to deepen our scientific understanding of high-impact multi-hazard events. This effort aims to refine our ability to identify, characterize, and assess associated risks, vulnerabilities, and impacts on both society and ecosystems.

Following the science meeting in Amsterdam (January 2024), the following three main research questions were identified by the consortium in this project:

1. **What role do Earth Observation (EO) technologies, methods, data, and tools play in advancing our understanding of multi-(hazard-)risk (scenarios)?**
2. **What specific EO products are currently absent or needed to enhance our understanding of hot/dry and wet multi-(hazard-)risks across diverse spatial and temporal scales?**
3. **What methods are necessary to integrate EO products (with in-situ) data and advance our understanding of multi-(hazard-)risk?**

The project encompasses eight main science objectives:

- Assessing science needs for multi-(hazard-)risk scenarios, expanding reviews on terminology and methods, particularly focusing on the role of Earth observation in enhancing disaster risk assessment. This involves engaging with a diverse scientific community and deriving research questions based on key drivers such as science suitability and impact on risk assessment.
- Enhancing foundational scientific understanding of multi-hazard events through geographically diverse science cases. This includes addressing hot/dry and wet compounds, various interactions like cascades, and incorporating additional drivers such as regional model scale and replicability.
- Improving the ability to assess exposure, risks, and vulnerabilities by defining practical science cases, leveraging developed scientific knowledge, bridging the gap between scientific and practical realms, and showcasing impact through demonstration cases in high-risk, low-resilience locations.
- Collaborating closely with end-users and practitioners within the first responder domain to ensure that the project results can effectively support timely actions.
- Focusing on designing an Open Multi-Hazard Events Database, including efficient tools to interact with the stored data. This involves establishing a tabular-driven database for gathering events to build a reliable reference dataset.
- Establishing a Community Roadmap, including organizing two workshops through connections with communities like Risk-KAN and CERIS, as well as relevant international events (e.g., EGU).
- Contributing to the establishment of coordinated European research on multi-(hazard-)risk by fostering collaboration, creating synergies at the European level, and actively involving practitioners from NGO and public service throughout and beyond the duration of the project to ensure impactful societal outcomes.
- Disseminating project results through scientific peer-reviewed publications and accessible materials, with an emphasis on exploring and exploiting novel capabilities in the latest Earth observation satellite systems.

The project focuses on enhancing modelling frameworks, integrating Earth Observation into forecasting and risk assessment, and evaluating their potential benefits. Theoretical science cases, validated through tests (i.e., demonstration cases), provide a functional framework with input from the scientific community. These demonstration cases bridge scientific findings to practical applications, refining workflows for end-users in forecasting and early warning.

This project serves as an effort to identify key topics that could significantly improve the assessment and management of high-impact multi-hazard events. The results of the project should empower stakeholders to prioritize relevant services and advocate for implementing projects to ensure operational effectiveness. The overall outcomes of the project, consolidated in scientific papers and a white paper report, create a scientific roadmap that guides recommendations for future initiatives.

3.2. RATIONALE AND ADVANCES BEYOND THE STATE-OF-THE-ART

The scientific literature underscores the relevance of EO data in disaster risk management across and among various hazards. Researchers highlight the prevailing focus on hazard assessments and crisis management in space-based EO, advocating for improved vulnerability and exposure mapping and disaster risk reduction and adaptation planning, with a call for multi-risk approaches (Le Cozannet et al., 2020; Elliott, 2020; Tomás and Li, 2017; Schumann et al., 2018; Oddo and Bolten, 2019; Schumann et al., 2018). The literature also acknowledges the significant advancements in satellite observations of solid earth processes and increased accessibility of EO data, especially through initiatives like the Copernicus Sentinels. The versatility of EO products, encompassing different sensor types and platforms for monitoring and modelling geohazards, is emphasized. Existing studies already delve into earthquake hazard assessment using EO data, the role of EO in assisting flood disaster response, the use of Nighttime Light (NTL) data to assess both exposure (e.g., Mard et al., 2018) and post-disaster recovery (e.g., Andersson et al., 2015), and the social value of near real-time EO for disaster response or quantifying economic benefits (Elliott, 2020; Tomás and Li, 2017; Guy J.-P. Schumann et al., 2018; Oddo and Bolten, 2019; Schumann et al., 2016). For example, the Texas flood disaster in 2015 underscored the potential of EO, calling for stronger collaboration, proactive assimilation of methodologies, and managing expectations in EO data use among relevant stakeholders (Schumann et al., 2016). The critical role of EO in disaster risk management is underscored in the literature, ranging from earthquake assessments to flood response, with a strong call for multi-risk approaches, collaboration, and proactive assimilation of EO methodologies. The literature collectively emphasizes the need for evaluating where space based EO can best support disaster risk management and highlights its potential societal benefits.

There are still several major challenges that should be addressed before the hazard interactions can be fully integrated in multi-risk studies:

- There is still no uniform understanding on the concept of multi-(hazard-)risk: what they are in terms of hazard interactions, and spatial/temporal evaluation.
- There is no standard methodology which has been tested in different environments and scales of analysis. Most of the papers on the topic remain at a rather conceptual level, although there are some good examples with applications.
- Although the number of publications on multi-(hazard-)risk assessment has greatly increased over the past decades, there is still a bias towards landslide-related applications in Europe.
- It is still very difficult to model possible hazard interactions at the local level, due to the lack of appropriate hazard models that take these hazards into consideration. Although there is a rapid development in the use of Artificial Intelligence in the field of hazard and risk assessment, the number of training samples needed to properly model the specific interactions are a limitation. The application of physically-based multi-(hazard-)risk models is hampered by the large number of input parameters needed for such models and the difficulty to calibrate them. Rapid multi-(hazard-)risk modelling tools are needed to can be used in combination with tools to represent the uncertainty of the input data.
- The probability of occurrence of multi-hazard events in space and time is still a major uncertainty. For many hazard types, the historical records are too limited to form a sound basis for such analysis. For hydro-meteorological events the use of climate models (e.g., CMIP6) offers a good alternative for regional scale analysis, but for local scale analysis this remains problematic.
- The inclusion of modified elements-at-risk datasets to analyse the effect of consecutive events in future requires the inclusion of the damage caused by earlier events in the assessment of future events, as well as the results of the recovery efforts. Very few studies have been able to make such analysis.
- The joint vulnerability assessment of several hazardous phenomena has not been studied in detail, and there is a lack of appropriate vulnerability curves that consider the impact of several types of events simultaneously, or consecutively.

The EO4Multihazards project aims to enhance preparedness for high-impact multi-hazard events, by leveraging EO for improved forecasting, risk quantification, and vulnerability assessment. The objectives above align with calls from the literature on the critical role of data and information in disaster risk management, and the emphasis on a collective and accessible database. The project contributes by advancing the scientific state-of-the-art in the multi-(hazard-)risk domain. It adopts an agile approach, addressing gaps, and aligning with ongoing initiatives. Workshops provide a platform for diverse scientific contributions from various disciplines.

3.3. PROJECT PLAN

The project will be implemented following the work logic depicted in Figure 3-1. The primary phases encompass the establishment of the scientific context and the creation of a robust database (WP100 and WP200), serving as the technological backbone for delivering key project outputs. This database structure is conceived to manage diverse data types and documentation. Simultaneously, two tasks are executed in parallel: dynamic dataset gathering (WP200) and consolidation of baseline scientific framework (WP100). The former involves ongoing efforts to identify and gather crucial datasets, with a focus at the project's initiation and ongoing dynamics to incorporate newly generated datasets during demonstration cases. The latter task entails assessing the current state-of-the-art, identifying significant gaps, and targeting impactful advancements in scientific and practical domains.

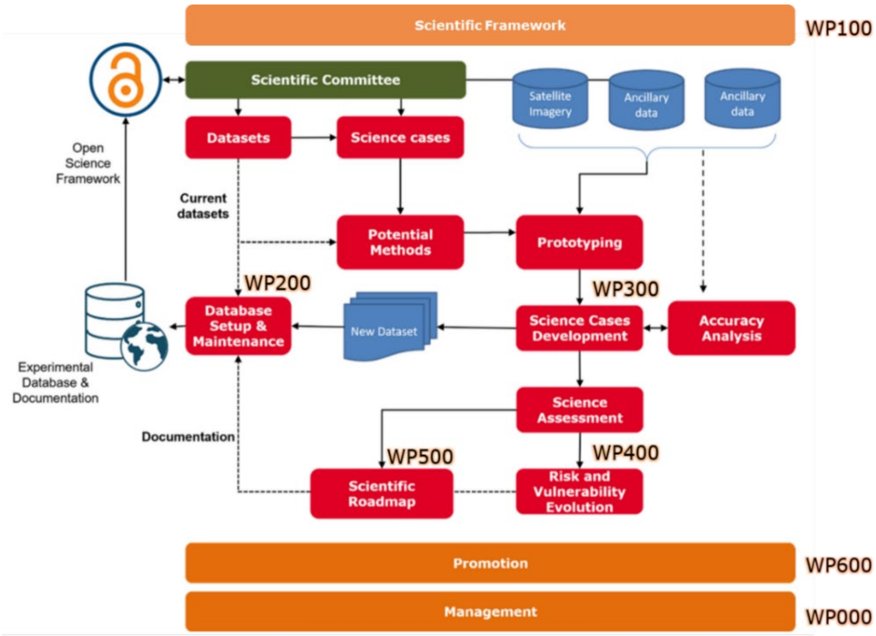


Figure 3-1 Project work logic for the EO4Multihazards project

Following the consolidation of the scientific framework, a comprehensive multi-hazard events database is populated with preliminary data from WP300, WP400, facilitating efficient exploration of events and the development of science and demonstration cases. At the end of the project, this database will be openly available for the broader scientific community as well as civil protection agencies, first responders and other decision-makers. The definition of the target user may evolve as the project develops. The subsequent project phases involve the development and implementation of science and demonstration cases (WP300, WP400). Specifically, WP300 focuses on multi-hazard analysis (including spatial distribution and frequency, underlying processes and drivers, attribution, early warning, onset, and magnitude), while WP400 addresses multi-risk assessment (integrating multi-hazard information with exposure and vulnerability). The consortium agreed at the science meeting in Amsterdam (January 2024) that the work in WP300 and WP400 will be seamless. This is to account for the conceptualisation of multi-hazard events (via impact chains, for example) which necessitates a preliminary good understanding of causal links between hazard interactions and their impacts across different sectors. This approach will also enhance the use of existing resources and account for different boundary conditions between science/demonstration cases. The results associated with WP300 and WP400 will be reported in separate deliverables which will be updated for consistency as the research progresses and new results become available.

Throughout this process, transversal tasks such as Project Management (WP000), Scientific Community Roadmap (WP500), and Coordination, Promotion and Outreach (WP600) play an integral role. Project Management ensures precise execution of WPs within budget margins and upholds quality in deliverables. Scientific Community Roadmap engages stakeholders for feedback and strategic actions, aligning with larger scientific and operational activities. Coordination, Promotion, and Outreach manage dissemination activities, participation in events, and coordination of workshops, with varying work intensities over the project's duration. Figure 3-2 illustrates the breakdown structure of work per packages and tasks.

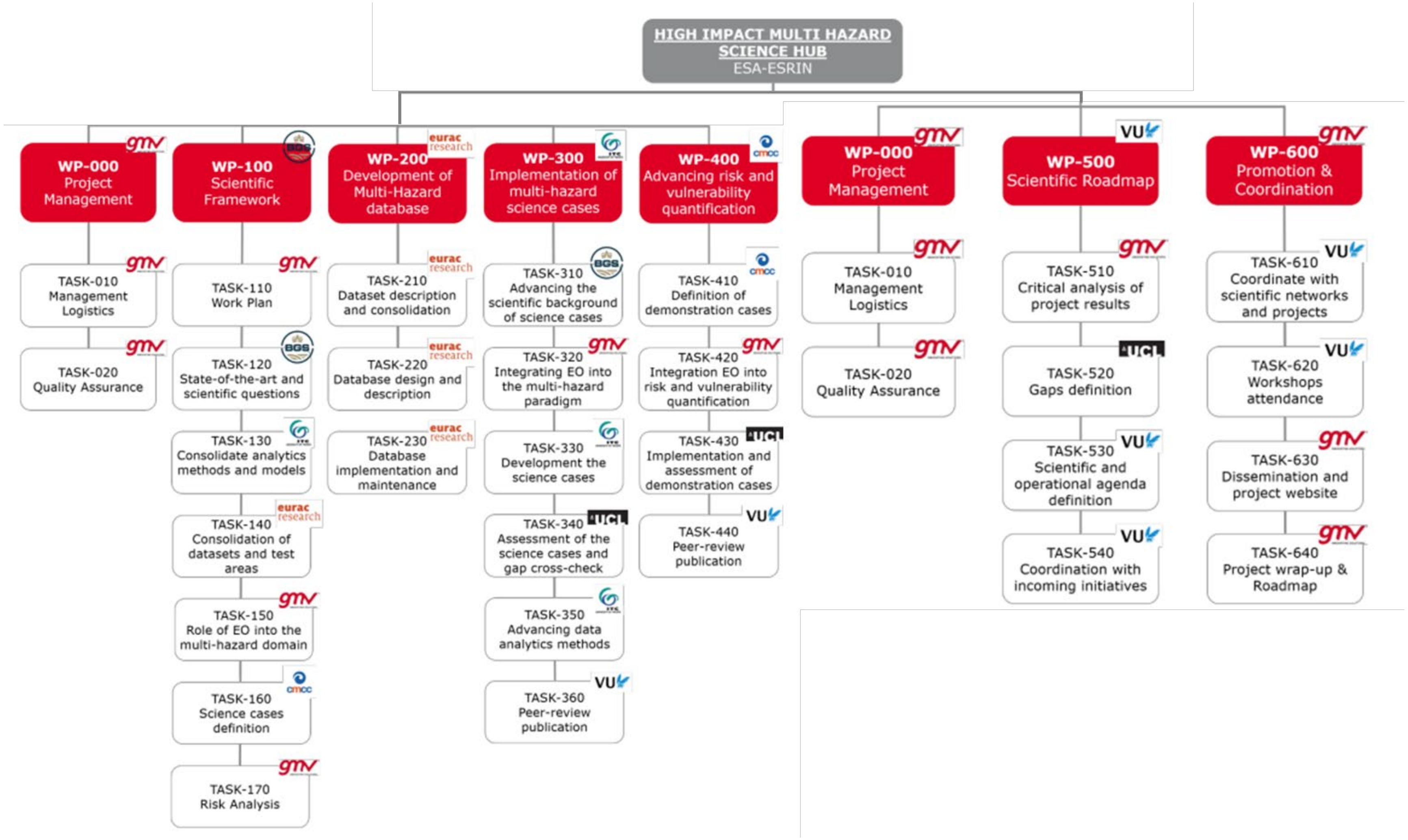


Figure 3-2 Breakdown structure of work per packages and tasks for the EO4Multihazards project.

4. PLANNED SCIENCE AND DEMONSTRATION CASES

4.1. INTRODUCTION

A set of science cases were identified to bridge the science domain towards the user-driven domain: the science cases provide the working framework to integrate inputs from the scientific community, and once the science cases are considered mature, connected demonstration cases will be defined to showcase the benefit and impact of the scientific progress.

Science cases are geographically distributed areas or regions characterised by hot/dry and/or wet events, as well as different types of hazard interactions. Science cases are focused on the latest impacts that climate change is forcing in different regions but also consider other types of hazards, such as volcanic eruptions and earthquakes. They were selected to showcase different spatial scales, geographical locations, socio-economic characteristics, and a range of hazards (droughts, heatwaves, wildfires, coastal flooding, saltwater intrusion, earthquakes, volcanic, floods, landslides, storm surges and sea level rise) and their interrelated effects (cascading, compounding, amplifying, etc.).

Demonstration cases are geographically distributed areas or regions where the results obtained from the multi-hazard assessment (in the science cases) are integrated with exposure and vulnerability data to assess multi-risk. A demonstration case can be an area or region within the boundaries of the science case (e.g., a sub-catchment within a hydrological basin) or a distinct geographically entity (e.g., a separate island or region) with similar multi-hazard characteristics as its corresponding science case. The selection or definition of demonstration cases will be concluded after the science cases are mature enough to allow their selection (e.g., there is a clear understanding of existing data, methodological approaches, and system boundary analysis).

Findings from each science and demonstration case should be scalable and transferable. It is expected science case leads will approach the development and selection of tools, models, and approaches for vulnerability and exposure assessment according to their specific science and demonstration case goals and objectives. For this purpose, science case leads and UCL/ CMCC will have a joint meeting early in the project to decide the best way forward. However, a common approach for stakeholder engagement in the demonstration cases was proposed and could consider as a minimum: (i) an early communication about the project goals, objectives, and expected outcomes; (ii) a provisional timeline of planned engagement activities and the expected stakeholder contributions, and (iii) an opportunity to provide feedback on outcomes and impact towards the end of the project.

The proposed science cases are:

- **Science/Demonstration Case 1 and 2:** These science cases are focused on the analysis of hot/dry compound and cascading events along the Adige River, considering the interactions between the upstream and the downstream parts of the river, and on the effects of these hazards on water quantity and quality and on their consequences on surrounding vegetation. Science case 1 will focus on the upstream part of the river and Science case 2 on the downstream part.
- **Science/Demonstration Case 3:** the Southeast region of UK is selected to evaluate the impact of hot/dry compound in a scenario of sustained high temperatures and how this affects the stability of the terrain and potential geologically driven events.
- **Science/Demonstration Case 4:** the Caribbean Small Island Development State of Dominica (comparable to other SIDS in other regions) is considered to evaluate multi-hazard scenarios mainly from a wet compound and volcanic perspective.

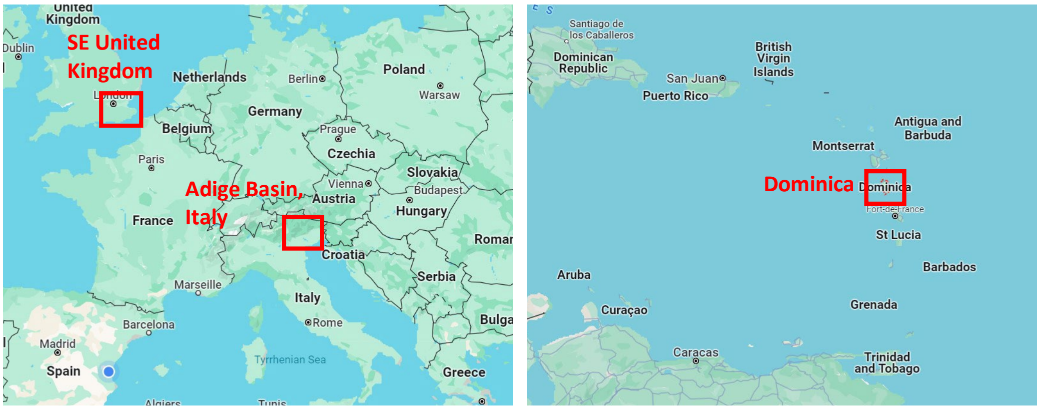


Figure 4-1 Location of science/demonstration cases in the EO4Multihazards project.

4.2. OVERVIEW OF METHODOLOGIES TO BE IMPLEMENTED IN THE SCIENCE CASES AND DEMONSTRATION CASES

4.2.1. SCIENCE CASES 1-2 (EURAC - CMCC)

4.2.1.1. RATIONALE

The Adige River basin in the North-East of Italy (SC1-2) experienced multiple past drought events that compounded with other hazards such as heatwaves, wildfires, and salt intrusion. Multi-hazard conditions impacted on different sectors (e.g., water management, agriculture, and forestry) from upstream in the Alps to the coast downstream.

4.2.1.2. SCIENCE CASE DEFINITION

SC1-2 focuses on the Adige River basin, the second longest river in Italy which covers an area of 12 100 km² with heterogeneous landscapes and socio-economic characteristics, from the mountainous Autonomous Provinces of Bolzano-Bozen (62% of the overall basin) and Trento (29%) to the more densely populated pre-alpine, hilly, and flat Provinces of the Veneto region (Verona, Padova, Rovigo and Venezia, 9%).

SC1-2 is composed of two parts within the same catchment, exploring hot/ dry events, and their impacts along the river. One describes a typical case of Alpine River dynamics, affected by winter snow and summer rainfall drought conditions compounding with elevation-dependent intensification of wildfire risk and heatwaves. The second focuses on the downstream and coastal area, impacted by drought, salt-water intrusions, heatwaves, and freshwater quality risks.

The acquired knowledge and good practices can be transferred to other glacierised river catchments in Europe or in the world (e.g., the Rhine) experiencing hot-and-dry events affecting water resources.

4.2.1.3. SCIENTIFIC GAPS ADDRESSED, QUESTIONS AND OBJECTIVES

While methods and models for assessing and predicting single hazards, such as droughts, heatwaves, or wildfires, are already in place, the complex interactions among multi-hazard events and their potential chains of impacts across interconnected and vulnerable sectors and areas are still underexplored and require further investigation. An emerging issue is the need to better address the impacts of these events on water availability and quality that may cascade from the mountains to the sea, and how they may compound downstream with intensive anthropogenic land use, and coastal hazards such as saltwater intrusion and sea level rise.

SC1-2 will try to fill these gaps by advancing the understanding, characterization, and quantification of hot and dry multi-hazard risks from the mountainous water sources to the sea at different spatial and temporal scales along the wide and diverse territories of the Adige River catchment. Focus will be put on the multi-hazard nature of the hot and dry hazards, the cascading effects from the mountain to the coast, and the analysis of the impact of events across multiple sectors (e.g., human health, water management and agriculture) and scales.

- **SC1 (upstream)**:

The goal of SC1 is to advance the understanding and quantification of hot and dry events in the upper mountainous part of the Adige River Basin. The analysis will focus on the recent drought events investigating drivers and factors compounding with heatwaves and wildfires which led to severe impacts, particularly on water resources management.

- **SC2 (downstream)**:

The goal of SC2 is to estimate the effects of hot and dry events on water quality and vegetation along the plain part of the Adige catchment. Input of the analysis will be the hazards, vulnerability, and exposure indicators; hazard indicators will include river discharge, atmospheric variables like temperature and precipitation, sea level; vulnerability and exposure indicators will include land use, land cover, population density and possibly soil characteristics. The assessment endpoints will be water quality parameters, such as salinity and turbidity, and vegetation stress level. Some indicators and assessment endpoints will be retrieved from satellite images. The system dynamics between indicators and assessment endpoints will be analysed by means of ML techniques such as artificial neural networks.

4.2.1.4. MULTI-HAZARD ASSESSMENT

- **SC1 (upstream)**:

The first step developing SC1 will be the creation of a database containing information about past hot and dry events as well as wildfires in the study area, including monitoring of snow cover in the mountainous regions. Once this dataset will be available, a multi hazard analysis will be conducted. Several different meteorological datasets covering the Adige catchment will be collected, such as temperature, precipitation, wind speed, snow cover, soil moisture. Statistical methods will be applied to identify and characterise heatwaves compounded by drought and wildfire conditions. Outcomes of the analyses will be meteorological indicators describing hot and dry events for the Adige catchment as well an improved methodology to detect hot and dry hazard detection and modelling. Outcomes of the meteorological analysis will be used both as an input of a physically based hydrological model able to describe snow drought conditions and its effects on river streamflow at different spatial and temporal scales leading to hydrological droughts. For the wildfire modelling in addition to the meteorological data, information on topography, hydrography, land cover, forest types and management plans will be gathered and analysed in a statistical model.

- **SC2 (downstream)**:

Data related to atmospheric indicators linked to hot and dry events, such as precipitation, temperature, humidity, number of consecutive tropical nights, number of consecutive dry days, etc. will be collected from local measurements, reanalysis datasets and EO data. Estimates of the river discharge along the river, and the related soil moisture in the surrounding area will also be considered in the input database, as well as the sea level values near the river mouth.

Multi-hazard footprint tools, based on statistical methods and Unsupervised Machine Learning algorithms (DBSCAN) for clustering will be tested to identify the hotspots of hot and dry events along the Adige lower basin and the most frequent hazard combinations in the last 30 years.

4.2.1.5. MULTI-(HAZARD-)RISK ASSESSMENT

In SC1-2, multi-hazard risk approaches, which consider the interactions between multiple natural hazards, vulnerability, and exposure factors of different natural and socio-economic systems, will be adopted. The impacts of hot and dry events will be characterised through different methods using qualitative and quantitative risk approaches. The selection of tools and methods for multi-hazard risk assessment will be mainly determined by the scientific questions and objective of the two parts composing the IT-SC, and the characteristics of the available data.

Both in SC1 and SC2 an initial conceptualization will be based on the development of impact chains. Impact chains provide a general assessment framework, consistent with the IPCC AR6 concept on climate risk, to understand and visualize complex cause-effect relationships in climate change impacts and risks (Zebisch et al., 2022). Impact chains are an important tool to support the system definition, and hence the characterization of the interrelations between hazards, vulnerability, and exposure, as well as the potential direct and indirect risks to be considered for a systemic multi risk assessment and management (Hochrainer-Stigler et al., 2023).

- **SC1 (upstream)**:

Specific applications in SC1 will involve the use of a physically based hydrological model able to describe drought conditions and cascading effects on water management, agricultural withdrawals, and hydropower production in the upper part of the Adige River basin. In addition, indices will be developed starting from model data from the latest meteo-reanalysis products to identify and characterise heatwaves occurring in the upper part of the catchment and impacting urban vulnerable population (such as elderly people), but also compounding with other hazards, such as wildfires that threaten the extended forest ecosystems in the mountainous area. Moreover, eexplainable data-driven multi-(hazard-)risk models are developed and used to analyze existing spatial-temporal dynamics and patterns between hazards, exposure and vulnerability indicators and impacts. Flexible and interpretable approaches (e.g., Generalized Additive Mixed Models) that allow to account for spatial and temporal data dependencies, for higher level interactions (e.g., non-linear tensor functions) and for hierarchically nested data (e.g., via random effects) will be tested, for example to investigate wildfires overlapping with heatwaves or drought periods.

An impact database will be created, and different methodologies will be used to describe the relationship between hazards and impacts. The analysis of these relationships will create an insight into the underlying processes and drivers.

- **SC2 (downstream)**:

To evaluate the risk, hazard information will be integrated with vulnerability and exposure indicators, such as land use and crop type, which will be estimated from regional databases and available EO. Assessment endpoints, such as water quality indicators and vegetation stress will be estimated using local measurements and available EO.

To describe the relationships between hazards, vulnerability, exposure, and assessment endpoints, SC2 will consider the application of the following tools and methods:

- Indices and indicators (which are respectively proxies for the hazards, vulnerability, and exposure characteristics, Mysiak et al., 2018), collected from available in-situ and EO measurements, will be analysed to guide the initial scoping phase, as well as to screen and prioritize areas with higher propensity to be adversely affected by multi-hazard events. This information will be stored in a database, that will be then used as input for multi hazard and multi risk assessment.
- Impact chains and conceptual diagrams, which describe the causal relationships between hazard, vulnerability, exposure, and assessment endpoint.
- Risk assessment approaches based on machine learning techniques, which have gradually emerged in recent years due to their ability to model non-linear relationships (e.g., Zennaro et al., 2021), will be implemented to unravel multi-hazard risk and multi-scale hazard dynamics across the Adige River basin.

4.2.1.6. ROLE OF EO DATASETS IN THE SCIENCE AND DEMONSTRATION CASES IMPLEMENTATION

- **SC1 (upstream)**:

For the mountainous part of the river basin, EO data will be used to identify the presence and extension of wildfires, to estimate the winter snow coverage as well as to investigate indicators of vegetation cover as well as impacts, such as vegetation stress and degradation.

- **SC2 (downstream)**:

EO measurements will be used to derive information about hazard, exposure, and vulnerability indicators with better spatial and temporal resolution. In particular, the indicators that will be retrieved by EO measurements will be, if possible: surface temperature, crop type (by the comparison of images in different months of the year), vegetation stress level, and, if the resolution allows, water quality parameters like water turbidity and salinity. The advantage of the use of EO with respect to in situ measurements are the temporal and spatial resolution. Water quality measurements along the river in most stations are sampled every 3 months, only few ones are sampled monthly, making the development of data driven models very challenging.

4.2.1.7. EXPECTED SCIENTIFIC IMPACT

The developments and results from SC1-2 will contribute to advance the scientific understanding of complex multi-hazard risk conditions through the development of a scientific framework, consisting of a conceptual diagram to visualise and pinpoint the main multi-hazard risk elements to be analysed and to highlight the important regional multi-hazard processes and direct and indirect environmental and societal impacts.

- **SC1 (upstream)**:

  Moreover, the conceptualisation from the science case will inform and prepare for the creation of the first multi-hazard event database for the analysed watershed. The creation of an open first-of-this-kind database will make information on specific events and their main properties and their spatial and temporal settings available to the scientific community as well as to local practitioners and decision-makers.

- **SC2 (downstream)**:

  The main goal of SC2 will be the creation of a framework that describes the relationship between the river conditions, the sea level, the water quality and the stress level of crops and natural vegetation. SC2 will highlight the connection between hot and dry events along the whole river path on water quality and vegetation downstream.

4.2.2. SCIENCE CASE 3 (BGS)

4.2.2.1. RATIONALE

Unprecedented hot, dry conditions in the past 10 years resulted in hazards and multi-hazard interactions that have not previously been experienced in the UK (SC3). This expression of high temperature induced multi-hazards in novel geographical areas along with more commonly seen weather induced hazards, such as storms and flooding, is largely attributed to climate change. The predicted long-term increase in the frequency of hotter, dryer summers and wetter winters in northern European areas, such as South-East UK, will lead to higher exposure to such hazards in the future. It is therefore essential to understand how multi-hazard events resulting from sustained high temperatures can amplify the occurrence of other hazards, what is their impact in areas with pre-existent environmental or societal vulnerabilities, and how can we better monitor and forecast their occurrence for enhanced decision-making and risk management.

4.2.2.2. SCIENCE CASE DEFINITION

SC3 focuses primarily on the South-East UK region, including the Greater London Authority, the most densely populated (more than 19 million people) and largest region in UK (>8% of total UK area). SE UK is also serviced by the densest network of transportation and energy infrastructure covering large urbanised and agricultural areas. Changing environmental conditions and continued urbanisation have an impact on resources and natural habitats across the South-East UK as vital water resources are under pressure from climate change. The area also needs to accommodate more than 600 000 new homes by 2026, with forecast population growth of half a million over the next six years (Environment Agency, 2010). It is projected that river flows could fall by as much as 35% by 2050 and there are still 400 000 properties at risk of river and sea flooding in the South-East, more than any other region of the UK, despite recent adaptation efforts.

In the past four years, the region suffered from sustained complex interacting hazards associated with sustained high temperatures. These include:

- Drought, resulting from the decrease in rainfall and the subsequent drying of the ground; this in turn can lead to subsidence as clay rich soils shrink.
- Shrink-driven subsidence has created unprecedented insurance claims and damage to infrastructure including road, rail, and water defence structures in the UK. The drying of the soil

and lack of water can also have a negative effect on crop yields, increasing the cost of food both for people and animals. The high temperature also increases the likelihood of wildfire and the removal of vegetation (adding to the cost of food).

- The drying of the soil and incidence of wildfires decrease the infiltration rate of natural ground surfaces. This means that when rain does occur, intense rainfall flows over the now bare ground. As a result, water takes longer to be absorbed into the ground, increasing the risk of a flash flood or debris flow response. This can put pressure on the weakened, aging water defence and dam structures as well as major road and rail networks.
- Wider flooding, perhaps later in the year when the warmer, wetter winter starts, exerts pressure on sewerage systems, exceeding the capacity of treatment plants and therefore resulting in discharges of sewage into rivers and sea. The drought decreases the water supply in the system but does introduce pollution.
- Intense rainfall can also trigger landslides, especially following periods of dry weather. Such landslides further impact vulnerable, aging infrastructure such as road and rail networks. Other mass movements such as rock falls can be triggered by the mechanical effects of the high temperatures within the rock itself. At the same time, the infrastructure itself is put under pressure by sustained high temperatures: rail tracks buckle, roads melt, electrical grids can fail (Chapman et al., 2019 and Stone Jr. et al., 2021), and water defence and dam structures are put under further stress.
- Finally, localized effects, such as Urban Heat Island (UHI), which occurs when natural vegetation is replaced by built structures that absorb and retain heat, can affect vulnerable people such as the elderly and the ill, as heat concentrates within urban centres. This can lead to increased death rates, which can be further compounded by other hazards, such as the COVID pandemic that had already stretched national health and emergency services to their limit in the UK and worldwide.

Natural hazards can also combine with critical infrastructure failures, creating higher impact secondary crisis thorough pre-existing organizational and societal vulnerabilities (Pescaroli and Alexander, 2018). For example, the 2021-22 high temperatures leading to drought and heatwaves in the UK highlighted the stress that could potentially be placed on the electrical grid and causing power outages. Changes in consumption patterns such as a peak in demand due to increased use of fans and air conditioning, decrease in electric plant production, and price fluctuations on the energy market can combine, creating the conditions for power outages. The UK grid had a near miss for a power outage in the summer of 2022; similar scenarios ("reasonable worst-case") are identified in national risk registers and emergency energy plan for other compound events such as cold weather and gas shortages. The guidelines developed by UCL, and the Greater London Authority suggested the need for improving training to mitigate the cascading effects of events such as power outages happening because of, or simultaneously with, weather extremes. This implied a better use of tabletop scenarios inclusive of both cascading effects and concurrencies for vulnerability assessment (Pescaroli et al., 2017).

4.2.2.3. SCIENTIFIC GAPS ADDRESSED, QUESTIONS AND OBJECTIVES

The interrelated effects of multiple hazards described above present obstacles for risk managers and other decision-makers, largely due to the limited understanding of how one hazard can trigger or amplify the likelihood of another. Hazards (including drivers and modulators) can interact over several time and spatial scales influencing the overall impact of the compounding event. Moreover, the lack of data has been one of the main constraints in better understanding systematic, cascading, and complex risks in new regions. The use of high-quality satellite data and EO technologies in conjunction with in-situ datasets can make a difference in this context. Lastly, due to pre-existent environmental or societal vulnerabilities, measures to reduce risk associated with one hazard may result in exacerbating the risk to another. As such, it is important to understand how changes in observable environmental conditions leading to cascading or compounding events are exacerbating the risk of already weakened infrastructure, agriculture, or social systems. Therefore, the UK-SC will address the following research questions:

1. How do spatially and temporally compounding events, such as droughts and heatwaves, lead to or else amplify the occurrence and impact of other types of hazards? (This question will be explored in a region not previously associated with such types of hazards, for example in the UK, to highlight the potential impacts of climate change).

2. Can EO products help identify trends and tipping points leading to cascading or amplifying effects in a multi-hazard event? Can we use this information to develop tools and methods for monitoring and early warning?

3. Is it possible to identify thresholds in observable environmental changes that indicate the onset of compounding or cascading multi-hazard events? If so, can these changes be linked to the increased probability of the failure of engineered structures (such as critical infrastructure) or severe impact on agricultural production?

The overarching aim of this case study is to better understand the relationships, thresholds, and trigger points that allow us to use EO observations coupled with in situ data to monitor the state of an area and generate early warning of impending hazard and multi-hazard events. SC3 is built around hot and dry compound events that lead to or else amplify the occurrence and impact of other types of hazards, such as wet events (e.g., extreme precipitation, flooding, etc.). However, in this science case, wet events are not the primary driver but considered in the impact chains and modelling of multi-hazard events, where possible. Understanding the 30-year timeline of satellite data and its application to earth/environmental science allows us to have a better understanding of the baseline of multi-hazard events prior to the onset of accelerated climate change. As the timeline of available satellite data increases, the statistical robustness of these events will improve with each passing year, allowing for improved forecasting of the impacts of changing climate on multi-hazards.

4.2.2.4. MULTI-HAZARD ASSESSMENT

We propose to create a detailed case study addressing a high sustained temperature event in SE UK. We will develop a time series of EO data from the last 30 years to analyse both the 2018 and 2022 high sustained temperature events in the UK, using the satellite data most relevant to each specific secondary or tertiary hazard component. For example, understanding shrink swell induced subsidence will involve an analysis of soil moisture and ground deformation data from Sentinel–1 integrated with the in-situ geotechnical information. In the case of drought, we will look at reservoir levels and vegetation health derived from Sentinel-2 and Sentinel-3 integrated with meteorological and climate data. By pulling together all these time series we will be able to assess the trends of change over varying time periods, providing information on whether the high sustained temperature event was a short, sharp shock or whether it was part of a wider more sustained trend potentially linked to long-term climate change. We will also identify, where possible, any observable tipping points that indicate the onset of a hazard. The overall compound and cascading events analysis will be complemented by the investigation of a selection of smaller/ less extended case studies from other areas around the world (e.g., California, US, and Australia, Greece, NE Europe – exact location to be decided) via network diagrams, narrative descriptions, and/or multi-hazard, multi-risk indicators. These will be used to demonstrate a particular multi-hazard event in the overall mapped multi-hazard network. Such cases will strengthen our understanding of the events that occurred in the UK (either through testing or validation of the methodology) and enable us to bridge any gaps relating to data paucity or where the events have not progressed beyond a certain point due to the shorter relative timeline of available data. It is beyond the scope of this work to explore these smaller demonstrator cases to the same detail as the overarching case study.

4.2.2.5. MULTI-(HAZARD-)RISK ASSESSMENT

In SC3, the risks associated with hot and dry multi-hazard events (including secondary hazards) will be assessed using qualitative and quantitative method approaches, such as impact chains/network diagram, narrative descriptions, multi-hazard, multi-risk indicators. Impact chains/network diagrams are graphs that describe the relationships between all the factors that will play a role in the multi-risk analysis, like hazards, vulnerability and exposure factors, and assessment endpoints; they are useful to try to understand which are the causality relationship that are present in the system, and hence to depict compound and cascading links between risks. Narrative descriptions provide a valuable source of evidence for better understanding previous multi-hazard and multi-risk events and informing scenario planning in data scarce environments. For example, investigating the effects of functionality reduction or failure of a system (e.g., infrastructure) due to the spatial or temporal interaction (triggering, amplifying, compound) of different hazards and correlating that back to a given hazard intensity or magnitude might be more appropriate in contexts where physical modelling is not an option due to data availability. The expansion of this qualitative method can lead to the development of multi-hazard, multi-risk indicators, which in turn can be used to identify hazard combinations that have the greatest influence on hazard impacts. Indicators relating to multiple weather-related hazards (coastal flooding, fluvial flooding, water scarcity, heat stress, and wildfire) can be determined, standardised, and aggregated into a multi-hazard impact index, with the ability to explore how interactions between indicators influence this index.

4.2.2.6. ROLE OF EO DATASETS IN THE SCIENCE AND DEMONSTRATION CASES IMPLEMENTATION

SC3 is underpinned by 30 years of research at BGS. This research is grounded in geological mapping, deployment of sensor networks, routine engineering lab testing resulting in the generation of extensive databases, datasets, modelled outputs, and understanding of multi-hazards within this setting. To advance the research proposed in this study EO-based input data is complemented by local, regional, national, and global models and in-situ data (see Section 4.3). Within this science case we will use evidence from the 2022 UK and other global heatwaves to map their occurrence, distribution, and interrelated effects. Tracking through space and time will allow us to document how hazards are migrating to areas which were previously less susceptible. This, together with weather information and climate projections, will enable forecasting of their future impacts.

4.2.2.7. EXPECTED SCIENTIFIC IMPACT

We will advance the state-of-the-art by using long-term EO satellite data to identify thresholds, triggers, and tipping points within time series of established environmental metrics which indicate the dynamic evolution of a multi-hazard event. This information will be complemented by in-situ observations and local, regional, and global models to identify environmental precursors, shocks, and chains of events that may be suggestive of multi-hazard event onset conditions.

Proposed advancements linked with the scientific goals: (i) Mapping of hazard interactions/ interrelationships considering secondary and tertiary hazards associated with environmental and/or societal impacts from sustained hot dry compound events. These events are likely to increase in both frequency and magnitude due to the impact of climate change and so there is a pressing need to fully map the network of potential interactions. The outputs for this study could then be used for the creation of policies and strategies to mitigate the impacts of such events in the future. (ii) Demonstrate that EO data can be used to derive environmental indicators that reveal the complex causal relationships and underlaying mechanisms which lead to cascading or compounding multi-hazard impacts. (iii) By identifying these trends and critical tipping points from EO data it would be possible to establish Early Warning Systems (EWS) to indicate the increased probability of hot dry compound events. This would allow for increased preparedness for those most at risk and the ability for decision makers to enact protocols ahead of time to limit the impact (human, infrastructure, and economic) of these events. We intend to use small user cases where necessary to test and validate these tipping points.

4.2.3. SCIENCE CASE 4 (UT-ITC)

4.2.3.1. RATIONALE

Small island development sates (SIDS) are among the most vulnerable environments related to climate change and multi-hazards. The Caribbean region is considered as one of the most hazard-prone regions due to the combination of frequent tropical storms, increasing drought severity, combined with the occurred of geological hazard events (volcanic eruptions, earthquakes). The region has many SIDS which have a limited capacity in terms of disaster risk management, and dependence on limited resources and services (e.g., tourism). Small volcanic islands in tropical environments are and could be particularly affected by these types of events and as such constitute an important case study to test, validate and implement efficient and comprehensive approaches to tackle multiple and complex hazards in a geographically well constrained environment. The occurrence of extreme events such as volcanic eruptions has led to devastating impacts, leading to partial abandonment of islands (e.g., Montserrat), and consecutive events have had large impacts on society, such as the 2011 earthquake/ tropical storm Grace sequence in Haiti, or the volcanic eruption/tropical storm sequence in Saint Vincent in 2022.

4.2.3.2. SCIENCE CASE DEFINITION

The science case 4 (SC4) will focus on the Small Island Development State (SIDS) of Dominica, located in the Eastern Caribbean, in between two islands that are part of the EU (Martinique and Guadeloupe).

The Commonwealth of Dominica, with a population of around 73 000, has a surface area of 750 km^2, and is densely vegetated with tropical rainforest. The island has a high volcanic hazard, with nine active volcanos with a maximum elevation of 1 477 m, seven of which are located within 10 km from the capital of Roseau. Although there have been no recent volcanic eruptions, the most likely next eruption is expected to be a lava dome-forming eruption in southern Dominica. Dominica is prone to tropical depressions, which may evolve into full-scale hurricanes. Some of the largest historical impacts were from Hurricane David in 1979, and Hurricane Dean in 2007. Recently the island was affected by a sequence of events, starting with tropical storm Erika, which hit the island on 27 August 2015, with high intensity rainfall of 500 mm within 10 hours, and resulted in flash flooding in several watersheds on the island. The capacity of many bridges and culverts of the road system was insufficient, resulting in the interruption of several critical road sections. Also, the airport was flooded during this event, and recovery lasted several months. The estimated damage and loss by Erika were about 483 million US Dollar, equivalents to 90% of Dominica's GDP, of which 89% in the transport sector and 11% in the agricultural sector (Kambon et al., 2019).

Two years later, while still recovering from the impact by Erika, the island was hit by hurricane Maria, which was a category 5 event. Maria was the deadliest Atlantic hurricane since Mitch in 1998, and the tenth most intense Atlantic hurricane on record. Maria was accompanied by extreme wind, damaging roofs of most of the buildings, and stripping the island of its vegetation. All agricultural areas were destroyed. The extreme precipitation caused thousands of landslides on the volcanic soils of the island, which turned into debris flows, which destroyed several settlements located on alluvial valley floors close to the coast. The storm surge destroyed coastal villages in the Southwest of the island. Vegetation debris blocked culverts and caused more flooding. The sedimentation associated with the debris flows and flash floods resulted in a reduction of the capacity of the river systems, and a threat of severe flooding in a next event. Therefore, massive sediment removal activities were undertaken in the years after Maria. Maria destroyed the water supply and energy sector on the island, and drinking water had to be brought to the island for a considerable amount of time. Due to the destruction of tourist facilities and harbour facilities for cruise ships, the tourism industry collapsed. The Post-Disaster Needs Assessment concluded that Hurricane Maria resulted in 64 casualties, total damages of US$931 million and losses of US$382 million, which amounts to 226 percent of 2016 GDP. The estimated recovery needs for reconstruction and resilience interventions were US$1.37 billion (Government of the Commonwealth of Dominica, 2017).

4.2.3.3. SCIENTIFIC GAPS ADDRESSED, QUESTIONS AND OBJECTIVES

The science case will study the interconnections between successive compounding events and complex cascading multi-hazard events. Past events will be analysed with the help of forensic analysis, and three different and complex multi-hazard impact scenarios of future events will be considered, which are by themselves three different case studies within the same context. The study of these scenarios is relevant for many other islands in the Caribbean and for other small islands affected by storms and in volcanic active area. For this reason, the case study constitutes a benchmarking analysis that has wider implications than the reduction of risk of Dominica.

Tropical storms are complex combinations of interacting simultaneous phenomena, including wind, storm surge, vegetation removal, pluvial flooding, flash flooding, landslides, debris flows and obstruction of bridges and culverts by vegetation debris. The damage cause by them creates major failure in the transportation system, as roads are blocked, and airports and harbours are out of service for quite some time. Lifelines such as electricity supply, water supply and telecommunication services are obstructed as leading to systemic failure in different sectors. This case study evaluates the systemic risk resulting from such a major impact.
Recovery from major impacts can be slow, as the economy is badly affected, and loans are needed for reconstruction planning. Subsequent impacts of major events during the recovery process are another major aspect that will be studied in the case study.

4.2.3.4. MULTI-HAZARD ASSESSMENT

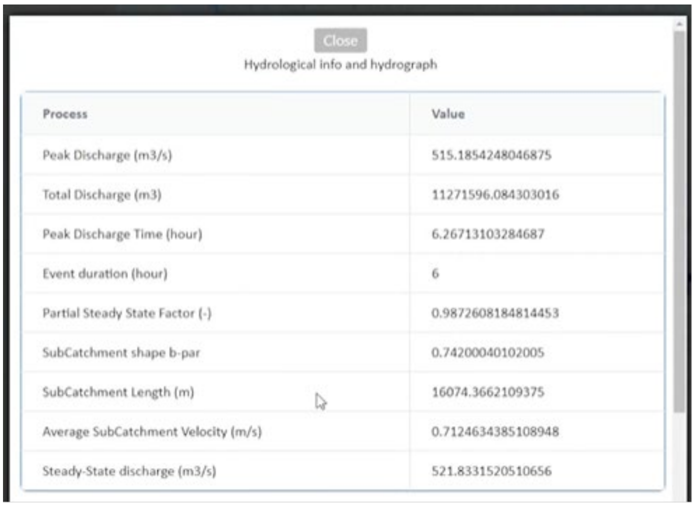
The analysis of compounding hydro-meteorological and geophysical events requires more in-depth approaches, resulting in impact chains that can also be quantified in terms of direct and indirect impacts in various sectors, i.e., land use, population, agriculture, environment, and biodiversity.

The relationship between the intensity of the triggering precipitation and hazard interactions such as landslides, flash floods, and debris flows will be modelled using integrated physically-based modelling approaches, which model all processes that take place simultaneously, and allows to model their interactions , such as the contribution of sediments from landslides towards debris flows and flash floods, and the sedimentation of channels leading to increased flash flooding in next events. We will develop and apply multi-hazard models that are running very fast and that can be used with globally available datasets, which are derived from EO data (van den Bout et al., 2022). One of these is called Fastflood.org and the version for landslide initiation and runout is currently under development. The fast nature of the models allows them to be used in a probabilistic mode, where the parameters uncertainty can be tested, and the sensitivity of the model evaluated. When available the global data can be substituted by higher resolution data. The models also use weather prediction data from ECWMF models and will be used as also an approach to develop an impact-based forecasting tool. The validity of this assumption of complex multi-hazard events has not been thoroughly investigated.

We will use UAV data that was taken before and after Hurricane Maria to calculate the changes due to erosion and sedimentation, to validate the multi-hazard model. We will simulate different scenarios of successive events, with and without removal of stream sediment, to model the differences in flooding. We will learn from the sequence of latest events since 2015, in order to describe the impact chains of successive multi-hazard events under the new conditions, with impacts on different sectors, and to use this knowledge in developing impact scenarios of future events, which are combinations of tropical storms, occurring in succession or in combination with volcanic eruptions, either on the island, or on a nearby island (e.g., Guadeloupe, Martinique) and the associated secondary hazards and impact chains. We will use data for climate models (Using CMIP6) to estimate multi-hazard processes for different combinations of rainfall events in future. To achieve our scientific goal, we will tackle three main challenges, 1) analysing historic hazard events with the help of forensic analysis, 2) developing multi-hazard scenarios under new conditions (including changes in land-use, population, and emerging risks that have not yet been observed), 3) quantifying uncertainties and displaying them.

4.2.3.5. MULTI-(HAZARD-)RISK ASSESSMENT

EO data will be used in combination with UAV datasets to characterize the elements-at-risk, focusing on buildings, transportation infrastructure and land use. Field surveyed damage data will be used in combination with the modelled and mapped hazard footprints, to derive vulnerability curves for different processes simultaneously (e.g., windspeed and impact pressure by sediment laden flood). Building data will be used in combination with the modelled hazard scenarios to develop state of the art 3D models in the form of Digital Twins. The aim is to develop it in a collaborative mapping environment using tabletop screens so that first and second responders can use the tools interactively. Current results include simultaneous view of multiple scenario outputs which allows for visual interpretation and comparison of different scenarios. The different scenario outputs can be exported and analysed using GIS tools.


Close
Hydrological info and hydrograph

Process	Value
Peak Discharge (m3/s)	515.1854248046875
Total Discharge (m3)	11271596.084303016
Peak Discharge Time (hour)	6.26713103284687
Event duration (hour)	6
Partial Steady State Factor (-)	0.9872608184814453
SubCatchment shape b-par	0.74200040102005
SubCatchment Length (m)	16074.3662109375
Average SubCatchment Velocity (m/s)	0.7124634385108948
Steady-State discharge (m3/s)	521.8331520510656

Figure 4-2 Hydrological info and hydrograph already generated as part of fast flood for every simulation. This would also be reflected in the 3D view for each scenario.

In the case study, we will use a transdisciplinary approach to reconstruct impact chains for the historical events and adapt them to possible future scenarios. We will use a Spatial Decision Support Tool for modelling changing multi-hazard risk, called RiskChanges (www.riskchanges.org) which is an open-source web-based tool, for reconstructing the losses by historical events (Erika and Maria), which are used for validating the loss estimation method with historical damage data. The tool will then be used for modelling losses from future events, following several future scenarios.

Three main scenarios will be investigated, which are:

- The occurrence of successive high intensity tropical storms under climate change scenarios.
- The occurrence of a tropical storm during a large eruption of a nearby Caribbean Island with significant tephra accumulation, disruption on aviation and other transports and tsunamis waves generated by PDCs and flank collapses during the eruption.
- The occurrence of a tropical storm during a large magmatic eruption of the Plat Plays complex accompanied by PDCs, surges, flank collapses and tsunamis wave generated by them.
- These three scenarios have a decreasing probability of occurrence, in particular scenario 3 has a low probability but the impacts caused could be devastating and it has a higher probability of occurrence in other Caribbean Islands and so it cannot be ruled out and need to be considered.

4.2.3.6. ROLE OF EO DATASETS IN THE SCIENCE AND DEMONSTRATION CASES IMPLEMENTATION

EO-based Digital Elevation Models (e.g., Copernicus30) will be used to test the difference with the use of more detailed DEMs derived from LiDAR data. Optical (very) high resolution data will be used for mapping hazardous phenomena (e.g., landslides, flash floods) for different time periods, especially after the occurrence of major events. Optical data will also be used to monitor vegetation differences, and the recovery of vegetation after the passing of a major Hurricane. High resolution imagery in combination with radar satellite data (Sentinel-1 and -2) will be used to characterize building heights. We also aim to use EO data for monitoring the recovery after a major event, by mapping differences in buildings, bridges, roads, and other infrastructure, indicative of recovery.

4.2.3.7. EXPECTED SCIENTIFIC IMPACT

We will advance the state-of-the-art by using long-term EO satellite data in combination with drone data to extend and operationalize the ”multi-hazard impact chains’’ approach considering the dynamic risk environment. We will develop worked out impact-chains of the various impact scenarios, with links to the metadata and spatial modelling components. We will be able to better quantify the impact of trigger-coupled events and develop a method that can be used to estimate direct and indirect losses of such events. We will also develop an approach to evaluate the impact of two successive events, in the form of two tropical storms or rainfall events that occur relatively close to each other in time. Our approach will consider the recovery of one event in the loss estimation for the next event, depending on the severity of the impact and the time between two successive ones.

We will also develop an approach to use EO data in combination with rapid multi-hazard modelling and loss estimation tools as a basis for impact-based forecasting.

We will also produce open-source online tools for multi-hazard modelling and subsequent multi-hazard risk assessment that can be applied in other areas.

4.3. OVERVIEW OF NECESSARY DATA TO BE USED IN THE SCIENCE AND DEMONSTRATION CASES

The selection of the necessary data to be used in the science and demonstration cases is carried out in synergy with an initial conceptualization of the specific multi-hazard risk conditions investigated in each case study. In particular, the use of conceptual diagram such as the impact chains (Zebisch et al., 2022) allows identifying the biophysical and socio-economic factors involved in specific compound and cascading multi-hazard risks in each science and demonstration case. Based on the initial conceptualization, a screening on data available, covering the identified factors, provides an overview on quantitative information necessary to describe specific conditions.

For example, data on atmospheric and meteorological conditions (e.g., precipitation, temperature), biophysical elements (e.g., topography, land cover and soil type), socio-economic factors (e.g., population density, land use) and recorded impacts (e.g., forest fires, vegetation/crop damage and water quality) are information required for developing science and demonstration cases.

4.3.1.NON-EO DATASETS IN THE SCIENCE CASES

The following table reports the non-EO variables and datasets identified for the science and demonstration cases to be developed in this study.

Table 4-1 Summary of non-EO datasets required for the science cases

Science/ demonstration case	**Non-EO products and datasets** (not exhaustive)
Italy	• Drought parameters: SPI, SPEI, snowpack anomalies (ERA5-derived), river discharge and water level data from the Alpine Drought Observatory project. • Updated high resolution observation grids of daily temperature and precipitation since 1980 for Trentino-South Tyrol (Crespi et al., 2021) • Emergency interventions data by national and local responders (e.g., Italian Red Cross, Terzi et al., 2022) • Population and their characteristics (e.g. population density from national datasets, such as ISTAT; and provincial, such as ASTAT). • Air temperature from CMEMS or CMCC reanalysis (mixed in-situ/EO) or regional/provincial environmental agency observations (e.g., ARPAV) • Precipitation data from CMEMS or CMCC reanalysis (mixed in-situ/EO) or regional/provincial environmental agency observations ((e.g., ARPAV) • Snow cover from CMCC, CERRA or CEMS-Flood reanalysis (mixed in-situ/EO) • River discharge from CEMS-Flood. • Soil moisture from CMCC, CERRA or CEMS-Flood reanalysis (mixed in-situ/EO) • Fresh water salinity and turbidity from regional environmental agency observations (ARPAV) • Drought indices (footprints) from MYRIAD-EU analysis (recalculation)
United Kingdom	• Volume changes potential lab test of shrink-swell soils (underpins Geosure shrink-swell model) • BGS GeoSure models – shrink-swell, compressible ground, landslides, soluble rock, geological indicators of flooding. • BGS Geo-scour model. • Soil moisture measurements coupled to weather stations (existing BGS shrink-swell observatory research) • Stream gauge measurements. • Meteo data (CO2 levels, temperature, precipitations, climate projections) • Infrastructure failure report (events, damages, impacts) • Insurance data (ABI) • Census data (including household level statistics) • Ordinance Survey maps. • GNSS data for 106 continuously monitored permanent GNSS stations.
Dominica	• Topography. • ERA5 Wind speed. • ERA5 Soil moisture. • ERA5 Precipitation. • ECMWF high-resolution forecast precipitation or DestinE high-resolution forecasts (if available). • Hydrogeological and geological data. • Physical and networks vulnerabilities data from field collection. • Building damage survey, carried out for all the island by trained personnel, indicating the level of damage for buildings. • Coastal boundary conditions for the model, representing storm surge induced by the tropical cyclones.

	• Multi-hazard intensity maps: landslides, debris flows, flash floods, vegetation debris, wind speeds, storm surge height, sediment thickness for different scenarios. • Elements-at-risk maps (of building stock, land use, transportation facilities, and essential facilities) • Spatial measures for dynamic risk reduction and climate adaptation focusing on the systemic risks. • Map of the impact on agriculture and vegetation. • Population census data.

Moreover, information on specific multi-hazard events in the selected cases is gathered by using data coming from the existing international disaster portals on specific hazard events, such as their spatial-temporal features. These data will be made available in the event database providing open-source information for further analysis and research activities on multi-hazard risk dynamics and impacts.

4.3.2. EO DATASETS IN THE SCIENCE CASES

The analysis of compound and cascading hazards will be conducted by utilizing available EO datasets from international agencies, or by creating tailored EO-based products using data from the current satellite constellations.

Table 4-2 - Summary of EO datasets required for the science cases.

Science/ demonstration case	**EO products and datasets** (not exhaustive)
Italy	• Drought indices (VCI and VHI) from the Alpine Drought Observatory project. • Land Use Land Cover (LULC) from Copernicus Land Monitoring Service (CLMS). • Imperviousness from the Copernicus Land Monitoring Service (CLMS) • Vegetation stress indices (e.g., NDVI, NDMI, fAPAR anomaly) from either Sentinel-2, Landsat 5-9 or Sentinel-3, to be calculated (AD-HOC) or from already existing products (fAPAR Sentinel-3 or EDO) • Turbidity monitoring using reflectance data to potentially detect water colour changes using either Sentinel-2, Landsat 5-9 (AD-HOC) • Crop type (winter/summer crop) from NDVI time series data from Sentinel-2 or Landsat 5-9 (AD-HOC) • Sea level from CMEMS reanalysis • Land use/land cover from ESA CCI or CORINE LULC
United Kingdom	• Air quality (stagnant air) from Sentinel-5P L2 products • Soil moisture from the Copernicus Land Monitoring Service (CLMS). • Shrink swell from Sentinel-1 (AD-HOC) • Drought indices from Sentinel-2 and Landsat imagery (AD-HOC) • European Ground Motion Service (InSAR data) • Landsat imagery (back to 1972) • Aerial photography for Great Britain • Environment Agency LiDAR DEM • Reservoir levels and volume from Sentinel-1 SAR • Land Use Land Cover (LULC) from Copernicus Land Monitoring Service (CLMS). • British Isles GNSS Facility (BIGF) • Vegetation stress indices (e.g., NDVI, NDMI, fAPAR anomaly) from either Sentinel-2, Landsat 5-9 or Sentinel-3, to be calculated (AD-HOC) or from already existing products (fAPAR Sentinel-3 or EDO)
Dominica	• Sea level from the Copernicus Climate Change Service (C3S) • Land Use Land Cover (LULC) from Copernicus Land Monitoring Service (CLMS). • Disaster information from GDACS (https://www.gdacs.org/) • Elevation data from COPERNICUS 30 (https://spacedata.copernicus.eu/collections/copernicus-digital-elevation-model) • Global Flood Awareness System (GLOFAS) • Global Wildfire Information System (GWIS)

	• Global Drought Observatory (GDO) • UAV data sets • LIDAR data sets • Orthophotos images

5. EXPECTED SCIENTIFIC IMPACT AND PUBLICATION PLAN

5.1. EXPECTED SCIENTIFIC OUTPUTS

It is expected that the project will produce new scientific knowledge and carry the multi-hazard research beyond the state of the art by combining various quantitative and qualitative methods. These results have a large value beyond their use within the project consortium, and active and continuous dissemination will entice uptake of results and magnify the reach and impact of the project. Specifically, this will be achieved through two channels: publications in scientific journals and presentations at scientific conferences. Significant scientific results (when they are not to be exploited commercially) will be published, some of which potentially contributing to a special issue in an open-access scientific journal and presented at international scientific conferences to share the advances with the scientific community. Open-access EO-focused journals with a large readership will be targeted as well as those centred around hazards, disaster risk science and remote sensing and innovation to encourage interest in and diffusion of multi-hazard model and EO applications into risk management applications. A preliminary publication plan is presented in Table 5-1 below.

Table 5-1 - Tentative publication plan

WP	Tentative title	Short description	Lead	Potential journal	Estimated submission date
200	The EO4MULTIHAZARDSdata portal: a collaborative platform to explore and assess multi-hazard events	The platform focuses on collecting and making available relevant data to explore and assess multi-hazard events. It will describe the methodological flow and required data as well as the architecture of the underlying portal. A detailed description on tagging multi-hazard events and the openly available datasets covering hazard, exposure and vulnerability information will be make available for other researchers. Finally, "Geostories" to combine different data and narratives to describe relevant high-impact multi-hazard events.	EURAC	Big Earth Data	1 December 2024
300 (SC1)	The compound hot and dry conditions of summer 2022 in the Adige River catchment (north-eastern Alps): event detection, understanding and attribution	Focuses on the reconstruction and analysis of the hot-dry event of summer 2022 over the Adige River basin by integrating observations and model reanalyses. Based on a compound indicator for the event detection, the spatial and temporal patterns of the event in terms of start, intensity and persistency of hot and dry conditions and their mutual contributions to recorded impacts in the upper and lower parts of basin are assessed. Then, the weather circulation type leading to this compound event is identified and based on a flow-analogue approach the role of human-induced climate change is investigated.	EURAC	Weather and climate extremes. (Elsevier)	20 December 2024
300 (SC1)	Assessing water scarcity in the upper Adige River basin within the context of climate change	Focuses on modelling water scarcity conditions by coupling a glacier and snow modules into a physically based hydrological model to simulate and investigate low flow conditions at different spatial and temporal	EURAC	Natural Hazards and Earth System Sciences (Copernicus)	1 September 2024

	and receding glacier volumes	scales within the upper part of the Adige River basin (Italy)			
300 (SC2)	Assessing multi-hazard hot and dry-related events through impact chains and machine learning in the Adige River Basin, Italy.	Focus on the identification and the assessment of the spatiotemporal patterns of drought occurrences. First, impact chains were developed to identify main drivers, hazard combinations and potential cascading effects across systems and sectors. Then, percentile analysis and DBSCAN clustering techniques were used to identify extreme climate events and single-hazard clusters from climate indicators. Finally, single hazard clusters were combined to analyse compound events, considering their spatial and temporal overlaps. Overall, this study contributes to a better understanding of hot and dry hazard dynamics through the application of machine learning techniques.	CMCC	Weather and climate extremes. (Elsevier)	20 December 2024
300 (SC3)	Characterisation of hot and dry multi-hazard events in the UK through integrated EO and in-situ technology and datasets	Focuses on the characterisation of multi-hazard events in SC3 (underlying processes and drivers, attribution, onset, magnitude, early warning), the analysis of changes in environmental conditions over varying time periods (identifying trends, thresholds, and tipping points), and testing and validation in areas outside UK	BGS	Remote Sensing of Environment (Elsevier)	20 December 2024
300 (SC4)	Multi hazard perspective by modelling the interactions between the triggering events: The Case of Dominica	Focuses on multi hazard events to consider the compound effects by modelling the interactions between the triggering events in Dominica Island. The publication will bring together the results of various complementary methods to assess the impact that will carry the multi-hazard risk research beyond the state of the art.	UT	Progress in Disaster Science (Elsevier)	20 December 2024
400 (SC2)	A data driven approach to multi risk analysis of the effects of hot and dry events on the vegetation and water quality in the lower Adige River catchment.	Focuses on the effects of hot and dry events on the vegetation and on the water quality along the course of the Adige River. EO measurement will be used to retrieve impact data and vulnerability indicators with fine temporal and spatial resolution. Machine learning techniques will be used to unravel the multi – risk dynamics that determines the impacts.	CMCC	International Journal of Disaster Risk Science (IJDRS)	1 November 2025
400 (SC3)	Multi-hazard risk assessment associated with hot and dry compound and cascading events in the UK	Brings together the theoretical scientific advancements with the user needs in the Science Case. It will focus on the use of EO technologies and data in better understanding the impacts and consequences of multi-hazards, the multi-hazard risk drivers and how decision-makers and other stakeholders can use the tools and methods developed in the project.	BGS	International Journal of Disaster Risk Science (IJDRS)	1 November 2025

400 (SC4)	Qualitative analysis of the multi-hazard risk assessment: The case of Dominica	Brings together the theoretical scientific advancements with the user needs in the Science Case. The focus will be on the qualitative analysis of the developed tools.	UT	International Journal of Disaster Risk Reduction (Elsevier)	1 October 2025
500	Role of Earth Observation in multi-(hazard-)risk assessment and management	Provides an overview of the current status and recent advancements in Earth Observation (EO) for disaster risk, explores the relevance of EO data for multi-(hazard-)risk assessment, discusses how EO can practically enhance our understanding of multi-hazard risk through science cases and identification of research gaps, and addresses the accessibility and practical use of EO information for relevant stakeholders, concluding with a discussion on research gaps, project aims, recommendations, and an outlook.	VUA	NHESS Special Issue: https://nhess.copernicus.org/articles/special_issue1277.html	1 March 2024

Any further publications developed by the consortium team and aligned to the scientific goals and objectives of the project will contribute towards its scientific impact. The consortium will strive to identify opportunities for co-authorship of publications across science cases, where possible, and capitalize on common research goals and questions to achieve a join vision of the project's legacy.

5.2. EXPECTED OUTCOMES AND IMPACTS

The EO4Multihazards project will establish an Open Multi-Hazard Events database. Relevant data will be consolidated within a reference multi-hazard database. Beyond documentation, the database will also feature exposed data encompassing both the reference baseline characterizing all possible events and various input datasets crucial for conducting analyses and extracting value-added information. The dynamic design of the database ensures continuous improvement and enhancement of information and content throughout the project duration. Furthermore, in a subsequent phase extending beyond the current duration, there is a vision for the database to evolve into a service that empowers the scientific community to use tools for manipulating data, experimenting with new methodologies, and exploring the available datasets.

Two workshops will be organized in the context of the EO4Multihazards project, involving a broad scientific community to accelerate scientific knowledge progress. Workshops are organized to facilitate discussion, formulate key scientific questions, and confirm science cases, leveraging opportunities to maximize audience attendance. Diverse channels, including peer-review journals, workshops, and collaborative meetings with key stakeholders and initiatives and networks, are utilized for this purpose.

The current project serves as a precursor for multi-hazard events and marks the initial step in a long-term path, establishing the scientific foundation for subsequent activities aimed at enhancing on the ground assessment and management of high-impact multi-hazard events. Together, these deliverables capture the dynamic and collaborative essence of our scientific pursuit within the project.

The project aims to collaborate with other international projects (e.g. EU Horizon PARATUS project) and initiatives (e.g., UNU-EHS/EURAC GLOMOS) in the use of EO data in multi-hazard risk assessment in Small Island Development States (SIDS) in the Caribbean, Indian Ocean and around Africa. Initial contacts have been made and a first workshop is planned in Barbados in Feb 2024 where representatives of the three regions will meet with participants from CDEM, UNDRR, IOC and UN-ECA, AISCC.

6. POSSIBLE SYNERGIES WITH RELEVANT ONGOING PROJECTS AND INITIATIVES

The project seeks to make a meaningful contribution to the activities outlined in the EC Horizon Europe initiative, specifically those centred around "Science for climate adaptation, extremes, and natural hazards" scheduled for the period 2023-2025. To achieve this objective, it is crucial to actively coordinate and collaborate with both existing and upcoming EC-funded projects and activities. There are several key initiatives and databases that play a crucial role in disaster risk management and response. Some of these initiatives include:

- **EM-DAT and EM-DAT Atlas**: Developed by the Centre for Research on the Epidemiology of Disasters (CRED), EM-DAT provides an objective foundation for vulnerability assessment and decision-making during disasters. It offers insights into historical impacts, human casualties, economic damages, and international aid contributions. The EM-DAT Atlas, a georeferenced database, visually represents disaster data for twelve countries, enhancing visibility and complementarity.
- **Disaster Risk Management Knowledge Centre (DRMKC)**: The European Commission DRMKC integrates multidisciplinary scientific knowledge and develops innovative solutions. It translates complex scientific data into usable information, offering science-based advice for Disaster Risk Management (DRM) policies.
- **International Charter "Space and Major Disasters"**: This worldwide collaboration facilitates the sharing of satellite data for disaster management. The Charter coordinates Earth observation assets from various space agencies, enabling rapid response to major disasters across cyclones, earthquakes, fires, floods, and more.
- **Copernicus Emergency Management Service (CEMS)**: CEMS includes early warning systems and rapid mapping services like EFFIS, GloFAS, EFAS, and EDO. These services operate in near real-time, providing actionable information for decision-making, forecasting, and risk quantification in multi-hazard scenarios.
- **Global Flood Monitoring (GFM) service**: Integrated into Copernicus, GFM utilizes Sentinel-1 Synthetic Aperture Radar satellite data for continuous global flood monitoring. Its automated system ensures high timeliness and quality of flood and water extent maps.
- **Global Disaster Alert and Coordination System (GDACS)**: A collaboration between the United Nations, the European Commission, and global disaster managers, GDACS improves alerts, information exchange, and coordination after sudden-onset disasters. It covers earthquakes, tropical cyclones, volcanoes, floods, droughts, and forest fires.
- **European Severe Weather Database (ESWD)**: Operated by the European Severe Storms Laboratory, ESWD collects detailed and quality-controlled information on severe convective storm events over Europe. It involves networks of observers, meteorological services, and the public, accumulating tens of thousands of reports.
- **MYRIAD-EU**: This EU Horizon-2020 funded project develops forward-looking disaster risk reduction pathways that consider interrelationships between different hazards, sectors, and regions. Several of the consortium members are also involved in the MYRIAD-EU project (and VUA is coordinating), ensuring strong links.
- **PARATUS-EU**: This EU Horizon Europe funded project will perform in-depth assessments of complex hazard interactions and their resulting impacts and study how future scenarios could change impacts. These scenarios of multi-hazard impacts will be co-designed with stakeholders and developed in four case study areas (including the Caribbean, Romania, Istanbul, and Alpine areas). UT-ITC is the coordinator of this project, which has strong links.
- **CMINE – SRC Cluster**: The **SRC - Societal Resilience Cluster of Projects** within the platform of the Crisis Management Information Network Europe. CMINE is the hub for crisis management professionals in the EU and beyond. It aims to foster innovation and research uptake in crisis management through cross-sector, multi-stakeholder dialogues around capability gaps and potential solutions Clusters are constituted as informal, voluntary, and free subsets of the Community for European Research and Innovation for Security (CERIS). Made-up of projects working on thematic and related research areas under the Disaster Resilient Societies (DRS) framework and, increasingly, of other programmes such as the Union Civil Protection Knowledge Network (UCPKN) and European Defence Fund (EDF).
- **Knowledge Action Network on Emergent Risks and Extreme Events (RiskKAN)**: RiskKAN functions as an extensive hub, bridging various disciplines. It brings together scientists,

experts, and communities to focus on multi-hazard risks, disaster risk reduction, and the management of extreme events. As an integral part of the Future Earth Global Research Network, and a collaborative effort of Future Earth, IRDR, WCRP, and WWRP programs, the Risk KAN is dedicated to fostering the sharing of information, insights, and data across these critical fields. The network consists of 9 working groups, including those on compound events and early warning systems for multi-risk events.

An extended list of relevant past and on-going projects, initiatives, and programs is presented in Annex 1 of the Technical Proposal. Further to this, other relevant projects were highlighted more recently at the EC-ESA joint Earth System Science Initiative 2023, Climate adaptation – Extremes, multi-hazards, and compound events theme (Figure 4), where synergies with the EO4Multihazards project were identified and priorities for a better understanding and assessment of extremes using EO technologies were discussed.

Figure 6-1 EO4Multihazards project amongst synergistic projects and initiatives at the EC-ESA joint Earth System Science Initiative 2023

ANNEX A. RISK ASSESSMENT AND MITIGATION

The implementation of the EO4Multihazards project could face several challenges. Below we list potential risk areas and their respective mitigation measures:

- **Limited Reference Baseline:** insufficient access to relevant and accurate baseline information poses a risk to accuracy and data quality. The impact is deemed high, with a low likelihood of occurrence. To mitigate this risk, the project will actively engage with key users responsible for critical datasets. Additionally, alternative communities and contacts from parallel projects will be mobilized to address potential gaps in information.
- **Uncertainty of Scientific Work:** the inherent uncertainties in scientific work present a risk of investing efforts in unproductive study lines. This risk is considered to have a medium impact with a high likelihood. Mitigation strategies include adopting an agile working strategy for early evaluation of study lines. The team will iteratively assess and adapt approaches to minimize the investment in unsuccessful paths.
- **Transferability of the developed approaches:** challenges in testing algorithms over different regions associated with each science case due to the absence of open representative reference baselines data are identified as a potential risk. The impact is considered low, with a low likelihood of occurrence. To mitigate this, science cases will either integrate the demonstration cases within their boundary conditions (administrative, geographical, socio-economic, etc.) or similar use cases will be selected for testing outside. Scaling up will be approached cautiously, evaluating the feasibility of a more generalized model.
- **Variability of Input Datasets:** high variability in content and format of input datasets poses a risk to the design of the technical and technological solution of the multi-hazard database. The impact is high, with a medium likelihood. Mitigation involves designing the database to be agnostic regarding data type and defining distinct data management schemes for various data formats.
- **Lack of Support from Stakeholders and Scientific Community:** potential disengagement and fatigue among stakeholders pose a risk with a high impact and medium likelihood. Mitigation strategies include leveraging existing cooperation and robust relationships among engaged scientists. The project will sustain active involvement through collaborative efforts and consistent communication.
- **Limited Impact of the Approaches and Models developed into practice:** the high scientific content may lead to no uptake of research lines into practice, with a medium impact and high likelihood. The project will concentrate on defining a scientific roadmap with a comprehensive database. Efforts will be redirected from research lines supporting evidence-based practice to building a solid knowledge foundation for future research applications and activities.
- **Complexity in Organizing Workshops:** challenges in organizing workshops with limited resources for ad-hoc events are acknowledged as a potential risk. The impact is high, with a low likelihood. Mitigation involves proposing a flexible approach by aligning workshops with events of opportunity. Priority will be given to larger impact events like EGU to maximize engagement.
- **Delays in the submission of publications during project's lifetime:** delays in peer-review journal publications may impact project timelines and payments, with a low impact but high likelihood. Mitigation strategies include considering the submission of manuscripts as proof of completion and ensuring commitment to the peer-review process beyond the project lifetime.

The methodological approach for calculating a risk index for the above challenges and a description of mitigation measures for all science cases is presented in A.1The effectiveness of the risk mitigation actions will be monitored monthly and consequently risks will be re-assessed until their full mitigation, risk index reduction in accordance with the established procedure. Where necessary, case by case risk matrices can be created and updated accordingly.

According to this methodology, most of calculated risk indices, except for one which is under the green category, fall within the severe (orange) category, which means controls are in place but may be ineffective; mitigation/ contingency plans should overcome worst results; some action required immediately/ further action later; and status of risk should be managed continuously.

A.1. PROJECT RISK ASSESSMENT

Risks are a threat to project success because they have negative effects on the project cost, schedule, and technical performance, but appropriate practices of controlling risks can also present new opportunities with positive impact.

The objective of project risk management is to identify, assess, reduce, accept, and control risks in a systematic, proactive, comprehensive, and cost-effective manner, considering the project's technical and programmatic constraints. Risk is considered tradable against the conventional known project resources within the management, programmatic (i.e., cost, schedule) and technical (i.e., mass, power, dependability, safety) domains. The overall risk management is an iterative process throughout the project life cycle, with iterations being determined by the project progress through the different project phases, and by changes to a given project baseline influencing project resources.

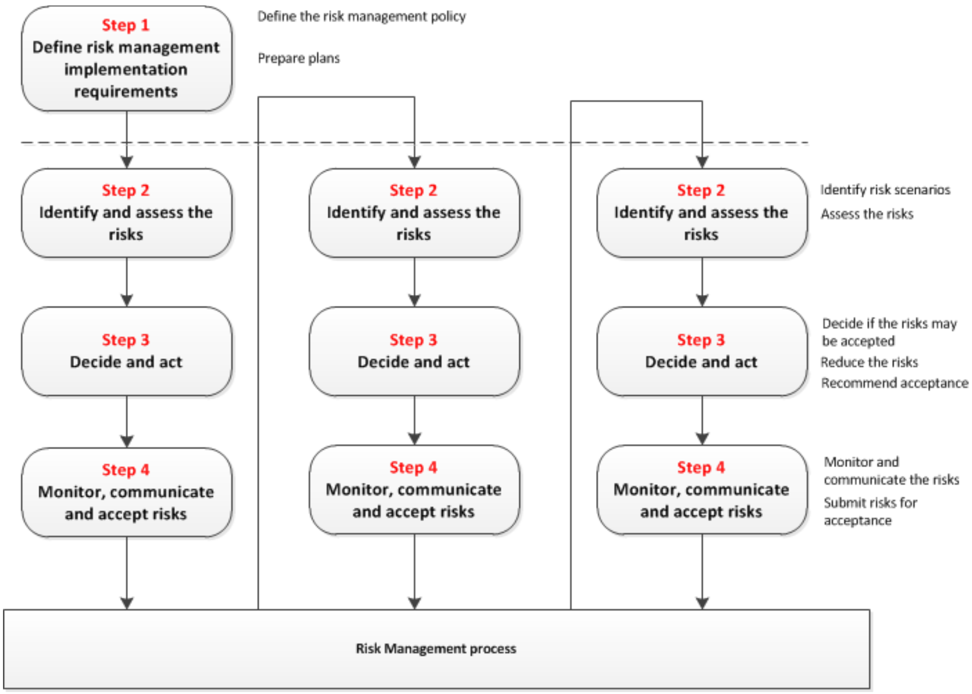


Figure 6-2 Risk management approach

Within the risk management process, available risk information is produced and structured, facilitating risk communication and management decision making. Risks are scored according to the index derived from the combination of its likelihood and severity:

Table A-1 Risk Index Scheme

Risk Index			Severity				
			1 Low	2 Moderate	3 Significant	4 Damaging	5 Catastrophic
Likelihood	5	Very likely					Unacceptable
	4	Likely					
	3	Possible			Severe		
	2	Unlikely					
	1	Remote	Controlled				

According to this scheme, the obtained risk index falls under three possible risk categories (**Unacceptable**, **Severe**, **Controlled**), which give the qualitative results of the risk. Risks are scored according to their risk index and commensurate actions are defined to handle them in an effective manner up until risk is considered acceptable and not further action is required:

Table A-2 Risk acceptance and action criteria

Risk Index	Reduction Action(s) Required	Meaning
Unacceptable	YES	• Most concerning • Controls are insufficient or ineffective. • Unrecoverable damage to reputation, finances, or business continuity • Action required immediately
Severe	YES	• Controls in place but may be ineffective. • Mitigation / contingency plans should overcome worst results. • Some action required immediately / further action later. • Status of risk should be managed continuously
Controlled	NO	• Comfortable with the risk • Controls are sufficient and already in place. • Consequences can be managed or are relatively unimportant. • Status of risk should be reviewed periodically

Science case risks will be scored including a colour code (**red**, **orange** and **green**) according to their index (function of its severity and probability).
Actions effectiveness will be monitored monthly and consequently risks are re-assessed, new ones might be opened, new actions might be launched up until their full mitigation or associated risk index is decreased up until acceptance and associated actions closure in accordance with the established procedure.

Table A-3 Risks impact and mitigation plan

Risk Id. and Description	Science Case	Likelihood 1…5	Severity 1…5	Index 0…25
R-01. Limited Reference Baseline	**All**	2	3	6
	Proposed Risk Mitigation Details (Actionee, Action): Insufficient access to relevant and accurate baseline information poses a risk to accuracy and data quality. **The impact is deemed high, with a low likelihood of occurrence**. To mitigate this risk, the project will actively engage with key users responsible for critical datasets. Additionally, alternative communities and contacts from parallel projects will be mobilized to address potential gaps in information.			
R-02. Uncertainty of Scientific Work	**All**	4	2	8
	Proposed Risk Mitigation Details (Actionee, Action): The inherent uncertainties in scientific work present a risk of investing efforts in unproductive study lines. **This risk is considered to have a medium impact with a high likelihood.** Mitigation strategies include adopting an agile working strategy for early evaluation of study lines. The team will iteratively assess and adapt approaches to minimize the investment in unsuccessful paths.			
R-03. Transferability of the developed approaches	**All**	2	1	2
	Proposed Risk Mitigation Details (Actionee, Action): challenges in testing algorithms over different regions due to the absence of open representative reference baselines are identified as a potential risk. **The impact is considered medium, with a low likelihood of occurrence.** To mitigate this, science cases will either integrate the demonstration cases within their boundary conditions (administrative, geographical, socio-economic, etc.) or similar use cases will be selected for testing outside. Scaling up will be approached cautiously, evaluating the feasibility of a more generalized model.			
R-04. Variability of Input Datasets	**All**	3	3	9
	Proposed Risk Mitigation Details (Actionee, Action): high variability in content and format of input datasets poses a risk to the design of the technical and technological solution of the database. **The impact is high, with a medium likelihood.** Mitigation involves designing the database to be agnostic regarding data type and defining distinct data management schemes for various data formats.			
R-05. Lack of Support from Stakeholders and Scientific Community	**All**	3	3	9
	Proposed Risk Mitigation Details (Actionee, Action):			

	potential disengagement and fatigue among stakeholders pose a risk with a **high impact and medium likelihood**. Mitigation strategies include leveraging existing cooperation and robust relationships among engaged scientists. The project will sustain active involvement through collaborative efforts and consistent communication.			
R-06. Limited Impact of the Models in practice	**All**	4	2	8
	Proposed Risk Mitigation Details (Actionee, Action): the high scientific content may lead to non-profitable research lines, with a **medium impact and high likelihood**. The project will concentrate on defining a scientific roadmap with a comprehensive database. Efforts will be redirected from non-profitable research lines to more promising topics.			
R-07. Complexity in Organizing Workshops	**All**	2	3	6
	Proposed Risk Mitigation Details (Actionee, Action): challenges in organizing workshops with limited resources for ad-hoc events are acknowledged as a potential risk. The **impact is high, with a low likelihood**. Mitigation involves proposing a flexible approach by aligning workshops with events of opportunity. Priority will be given to larger impact events like EGU to maximize engagement.			
R-08. Delays in the submission of publication during project's lifetime	**All**	4	1	4
	Proposed Risk Mitigation Details (Actionee, Action): delays in peer-review journal submission may impact project timelines and payments, with a **low impact but high likelihood**. Mitigation strategies include considering the submission of manuscripts as proof of completion and ensuring commitment to the peer-review process beyond the project lifetime.			

Table A-4 Summary of EO4Multihazards Science Cases Risks

Risk Index			Severity				
			1	2	3	4	5
			Low	Moderate	Significant	Damaging	Catastrophic
Likelihood	5	Very likely					
	4	Likely	R-08	R-02, R-06			
	3	Possible			R-04, R-05		
	2	Unlikely	R-03		R-01, R-07		
	1	Remote					

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