COMMUNITY ROADMAP

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

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1. INTRODUCTION

1.1. PURPOSE

This Community Roadmap Report provides a strategic framework for advancing scientific activities and setting a research agenda to address gaps in the use of Earth Observation for multi-(hazard-)risk assessment and management. It is informed by more than 12 months of scientific engagement across the EO4MULTIHAZARDS project.

Over the last decades, natural hazards have become more frequent and intense (Poljansek et al., 2017; Cutter, 2018; IPCC, 2023). In 2023 alone, natural hazards caused an estimated $250 billion in global economic losses and over 74,000 deaths - well above the ten-year average (Munich Re, 2024). While many studies still focus on isolated events, it is increasingly evident that interacting hazards - those occurring simultaneously, cascadingly, or cumulatively - generate impacts that are more than the sum of individual effects due to complex, nonlinear dynamics (e.g., Kappes et al., 2012; Terzi et al., 2019; De Ruiter et al., 2020). As defined by the UNDRR (2017), multi-hazard risk involves considering the interactions and spatial-temporal dynamics of multiple hazard types. When interrelationships also span vulnerability and exposure dimensions, the term multi-risk becomes relevant. The term multi-(hazard-)risk is used collectively in this report to encompass these overlapping concepts (Ward et al., 2022).

The Sendai Framework for Disaster Risk Reduction (2015–2030) calls for integrated approaches to disaster risk reduction (DRR), climate change adaptation, and sustainable development. Earth Observation offers a powerful means to operationalize this vision - by providing consistent, scalable, and timely data to support risk assessment and decision-making.

EO data has long been recognized for their potential in monitoring hydro-meteorological and geophysical hazards (e.g., Novellino et al., 2024; Gosset et al., 2023). However, EO4MULTIHAZARDS moves beyond traditional hazard monitoring. It aims to harness the full potential of EO for integrated risk assessments, combining hazard indicators with dynamic representations of exposure and vulnerability. The project's science and demonstration cases - spanning Europe, the Caribbean, and Africa - have generated actionable insights into how EO data, when combined with in-situ information and stakeholder knowledge, can enhance the assessment, anticipation, and management of compound and cascading risks.

New methods such as impact chains, clustering algorithms, EO-informed crop stress indices, and AI-enhanced exposure mapping are now being piloted across diverse settings. Furthermore, stakeholder co-design and engagement activities have provided critical feedback loops to align scientific outputs with real-world decision needs.

This document builds on the insights of the Science Case Report (D3.1) and the Demonstration Case Report (D4.1), and updates the initial roadmap developed in the project's early stages. It identifies:

- Key research gaps and methodological challenges;
- Opportunities for integrating EO into multi-(hazard-)risk workflows;
- Strategies for enhancing uptake of EO-based risk information;
- Priorities for future science-policy-practice collaboration.

The roadmap is aligned with a forthcoming peer-reviewed article (van Maanen et al., *in Review*), which assesses the role of EO in multi-(hazard-)risk analysis and recommends a forward-looking research agenda. This document reflects the iterative learning emerging from pilot activities, scientific development, and stakeholder engagement.

1.2. DEFINITIONS AND ACRONYMS

1.2.1. 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, 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.

Table 1-1: Definitions

Concept / Term	Definition
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.
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)
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)
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)
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)
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)
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)
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.
Multi-(hazard-)risk	Term used when collectively referring to multi-hazard, multi-hazard risk, and multi-risk (Ward et al., 2020)
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 considering 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)
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)
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)
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)
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)

1.2.2. ACRONYMS

Acronyms used in this document and needing a definition are included in Table 1-2:

Table 1-2: Acronyms

Acronym	Definition
CERIS	Community for European Research and Innovation for Security
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici
DRR	Disaster Risk Reduction
EGU	European Geosciences Union
EO	Earth Observation
ESA	European Space Agency
ESRIN	European Space Research Institute
GDP	Gross domestic product
IPCC	Intergovernmental Panel on Climate Change
NHESS	Natural Hazards and Earth System Sciences
SDC	Science and Demonstration Case
UNDRR	United Nations Office for Disaster Risk Reduction
VUA	Vrije Universiteit Amsterdam

2. RECOMMENDATIONS FOR FURTHER SCIENTIFIC ACTIVITIES

To unlock the full potential of Earth Observation for multi-(hazard-)risk assessment and management, it is essential to reflect on research gaps and operational needs that have emerged over the course of the EO4MULTIHAZARDS project. The project's science and demonstration cases have moved beyond early conceptual framing, providing concrete illustrations of EO's role in capturing hazard dynamics, characterizing exposure and vulnerability, and supporting decision-making. This chapter presents updated recommendations for future scientific activities, informed by these advancements.

2.1. EO FOR EXPOSURE AND VULNERABILITY ASSESSMENT

EO is increasingly recognized not only for its capacity to detect hazards, but also for its underexplored potential to support dynamic assessments of vulnerability. Across demonstration cases - in Dominica, Senegal, and the Adige Basin - EO has been used to estimate building characteristics, crop sensitivity, infrastructure fragility, and ecological degradation. These applications demonstrate that EO can serve as a proxy for otherwise hard-to-capture vulnerability factors such as socio-economic exposure, infrastructure condition, and (potentially) adaptive capacity. However, significant gaps remain in operationalizing such approaches at scale. Future research should focus on developing standardized indicators for EO-based vulnerability assessment, integrating EO data with in-situ and participatory methods to ground-truth and contextualize vulnerability, and exploring the temporal dynamics of vulnerability, such as how it evolves before and after a hazard.

2.2. ADVANCING INTERDISCIPLINARY INTEGRATION AND CO-DESIGN

While a wealth of EO and non-EO datasets exists, they are often fragmented, inconsistently formatted, or misaligned across spatial and temporal scales. Demonstration cases highlighted the difficulty of linking Sentinel-derived indices with agricultural data on the ground or harmonizing population and infrastructure datasets for exposure analysis. There is a need for:

- Curated, open-access data repositories tailored to multi-risk applications.
- Improved metadata standards for documenting spatial resolution, update frequency, uncertainty, and usability.
- Semantic tools to enable cross-comparison and alignment of disparate datasets.

2.3. ENHANCING ACCESSIBILITY AND COMMUNICATION OF EO-BASED RISK INFORMATION

Effective decision-making hinges not only on data availability, but also on its interpretability. Project experiences from the UK, Dominica, and Senegal show that stakeholders - especially local planners and NGOs - require data visualizations and tools that are intuitive, actionable, and locally relevant. Scientific outputs must therefore be communicated using accessible formats such as story maps, dashboards, or visual platforms. They should be tailored to the needs of diverse audiences, ranging from national meteorological agencies to local risk officers. In addition, these outputs must be accompanied by capacity-building efforts that empower local users to interpret and apply EO insights effectively. The database developed by this project should be further refined, taking these components into account.

2.4. COMBINING BOTTOM-UP AND TOP-DOWN APPROACHES IN CASE STUDIES

The co-development of science and demonstration cases underscores the value of integrating top-down (EO-based) and bottom-up (in-situ, stakeholder-informed) methods. In the Adige River Basin, Sentinel-2 indices were validated against crop-level data; in Dominica, satellite-based exposure maps were ground-truthed with field surveys and co-design workshops. Such approaches ensure both accuracy and contextual relevance. Future scientific work should therefore prioritize multi-scalar case studies that combine EO with local knowledge and institutional data. It is also important to expand the coverage of data-poor regions, for example through transferability pilots such as the one in Senegal. Moreover, there is a need to promote longitudinal studies that span the full disaster risk management cycle - from preparedness to post-disaster recovery. Together, these recommendations provide a foundation for the next phase of EO-enabled multi-risk science. They also support the co-evolution of EO capabilities and disaster risk frameworks in line with global agendas such as the Sendai Framework, the Paris Agreement, and the Global Goal on Adaptation.

3. RESEARCH AGENDA

The EO4MULTIHAZARDS project is advancing the scientific state-of-the-art in multi-(hazard-)risk assessment by leveraging Earth Observation technologies to enhance the identification, characterization, and assessment of hazards, exposure, vulnerability, and their combined impacts on society and ecosystems. EO provides a unique capability to deliver timely, spatially explicit data that cannot be matched by in-situ measurements alone. As such, EO data serves as a crucial component in understanding and managing compound and cascading disaster risks.

A central ambition of the project is to bridge the gap between science and user-driven applications by developing operational tools informed by both cutting-edge research and real-world challenges. The integration of EO data with in-situ information and stakeholder expertise is being tested and refined across four diverse geographical demonstration areas - Northern Italy, the UK South Region, the Caribbean Island of Dominica, and Senegal - each characterized by different hazard types, institutional settings, and data availability.

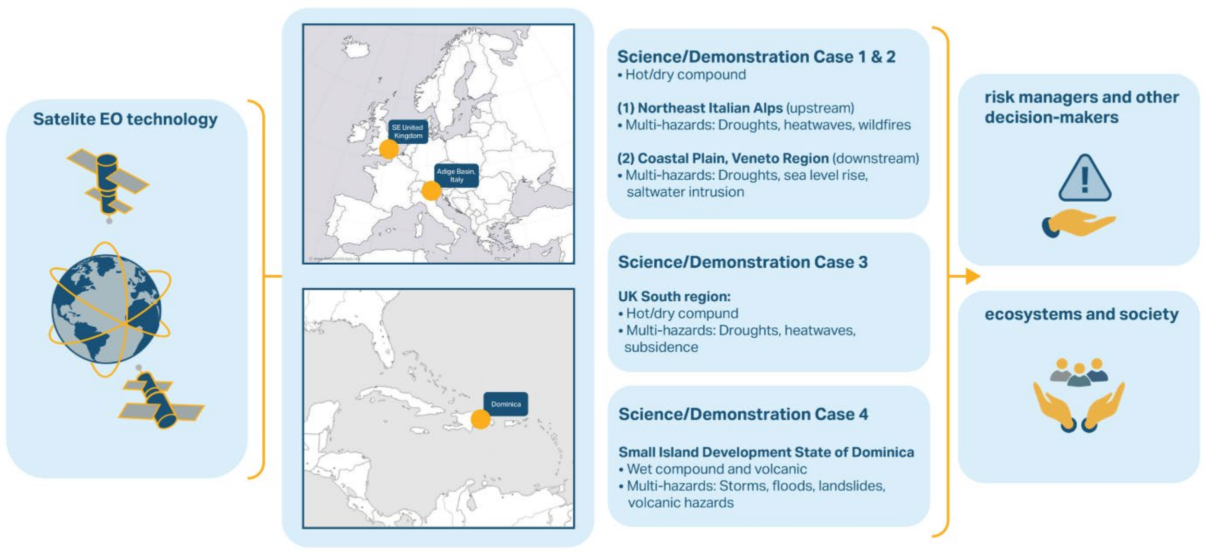

Figure 3-1 - Concept of the ESA-funded EO4Multihazards project including the introduction of the Science- and Demonstration Cases in the Northeast Italian Alps (Science/ Demonstration Case 1), the Coastal Plain of the Veneto Region (Science/Demonstration Case 2), the UK South Region (Science/ Demonstration Case 3) and the Small Island Developing State of Dominica (Science/ Demonstration Case 4).

To support a comprehensive and transferable approach to multi-risk analysis, the project uses a dual structure of Science and Demonstration Cases (SDCs). These cases allow for the joint development of methods and tools that are both analytically rigorous and grounded in local realities. The Science Cases initially focus on assessing hazard interactions - such as hot and dry extremes, floods, and seismic risks - while the Demonstration Cases integrate exposure and vulnerability data to evolve from multi-hazard to full multi-risk assessments.

In SDC 1 and 2, located along the Adige River in Northeast Italy, researchers analyze how hot and dry conditions influence water quantity and quality, crop health, energy generation, and socio-economic vulnerability. The upstream case explores risk interdependencies between heatwaves, droughts, and wildfires, while the downstream case focuses on agricultural vulnerability and changing hydrological conditions, including saltwater intrusion. SDC 3, in the Southeast UK, investigates how prolonged dry and hot events increase the likelihood of wildfires, subsidence, and extreme precipitation impacts, particularly in densely populated areas with complex infrastructure networks. SDC 4 centers on the island of Dominica, examining multi-hazard risks from tropical storms, floods, landslides, and volcanic activity, with a strong emphasis on asset vulnerability, infrastructure exposure, and community resilience.

An initial conceptualization of each SDC is conducted using the Impact Chains methodology (Zebisch et al., 2022), which maps causal relationships between hazards, exposure, and vulnerability to reveal systemic drivers of risk. This approach is followed by a structured data screening process to identify relevant EO and non-EO datasets, including climatic variables (e.g., precipitation, temperature), land surface data (e.g., soil moisture, land cover), socio-economic indicators (e.g., population density, building footprints), and observed or reported impacts (e.g., vegetation stress, health outcomes, infrastructure losses).

A broad range of analytical techniques is employed to support the risk assessment process. Network diagrams and impact chains are used to visualize causal pathways and cross-sector dependencies. Statistical techniques such as correlation analysis, multivariate regression, and distributional analysis provide insights into the relationships between hazards, exposure, and vulnerability. Where data density allows, machine learning and AI methods are used to weigh the importance of different indicators and improve predictive capacities. Generalized Additive Mixed Models (GAMMs) help explore non-linear relationships and manage variation across groups or regions, maintaining interpretability for end users (Zuur et al., 2009; Pedersen et al., 2019).

Narrative methods are also employed to capture the indirect and cumulative effects of multi-hazard events, helping to communicate complex system behavior in ways that are accessible to diverse stakeholders. In parallel, physical-based modeling and digital twinning approaches are used to simulate future scenarios under changing climate and socio-economic conditions. These simulations explore potential compound impacts, identify common points of failure, and support the development of vulnerability scenarios aligned with key literature on systemic risk and cascading effects (e.g., Pescaroli and Alexander, 2018).

The research agenda places a strong emphasis on transferability. Insights from the core science and demonstration cases are being applied in Senegal, where open-access EO and socio-economic datasets are used to replicate multi-risk frameworks in a data-scarce environment. This approach supports the project's commitment to scalability and global relevance.

Ultimately, the project promotes a holistic, data-informed approach to multi-(hazard-)risk assessment that spans all phases of the disaster risk management cycle - from preparedness and early warning to response, recovery, and long-term adaptation planning. While full operationalization for first responders may lie beyond the current project's scope, EO4MULTIHAZARDS lays critical groundwork for this next step by demonstrating how integrated EO-based methods can inform risk governance, spatial planning, and resilience strategies across diverse contexts.

4. STRATEGIC ACTIONS

This section outlines the strategic actions already undertaken by the EO4MULTIHAZARDS project to address the research gaps identified in its early stages, as well as key forthcoming steps within the scope of the project. It also offers broader recommendations for the wider EO and multi-risk research community, contributing to a sustainable and impact-driven research agenda.

4.1 Strategic Engagements and Networking Activities

To align EO4MULTIHAZARDS with other ongoing initiatives and foster cross-project collaboration, the consortium has actively participated in several key European and international events. In November 2023, team members attended the European Commission – European Space Agency Joint Earth System Science Initiative Workshop, held at ESA-ESRIN in Frascati, Italy. This high-level event gathered leading scientists and project consortia working on Earth Observation and Earth system science. The EO4MULTIHAZARDS team contributed both a keynote presentation (VU) and a poster (GMV) during the "Earth Observation for Multi-Hazards and Compound Events" session. The poster was further highlighted as a lightning talk in the session dedicated to setting research priorities for multi-hazard and extreme events, strengthening the project's visibility within the ESA community.

The project was also featured during the CERIS Disaster Resilient Societies (DRS) annual event in Brussels (4–7 December 2023). In the session on Societal Resilience and Risk Governance, a team representative (VU) participated in a panel discussion on connecting multi-hazard and compounding risk initiatives at the EU level. This event offered a valuable opportunity to engage with other Horizon Europe projects working on similar topics, creating space for strategic collaboration and data-sharing efforts. The VU will also attend this event again in late May 2025.

4.2 First Workshop: EGU 2024 and the Role of Multi-(Hazard-)Risk

To enable community dialogue on the role of EO in risk assessment, the project hosted a dedicated workshop at the European Geosciences Union (EGU) General Assembly 2024. Held on Wednesday, 17 April, the session brought together researchers and practitioners from Earth observation, disaster risk, climate science, and social science fields. It featured keynote discussions, thematic breakouts, and interactive polls focused on three guiding research questions:

1. What role do 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 scales?
3. What methods are necessary to integrate EO products with in-situ data to improve multi-(hazard-)risk assessment and management?

Informal networking, including a post-session gathering, fostered community building and helped identify collaboration opportunities for future EO and DRR efforts. Several consortium members also presented related research in scientific sessions throughout the EGU week.

4.3 Second Workshop: EO for Vulnerability Assessment

The second EO4MULTIHAZARDS workshop will take place on Wednesday, 30 April 2025, and will center on a key emerging theme: the application of EO in vulnerability assessments. Scheduled from 12:45–13:45 (location tba), the workshop will feature concise pitch talks, a panel discussion, and audience interaction. The session will open with a brief introduction by Philip Ward, covering the EO4MULTIHAZARDS project, the evolving definition of vulnerability, and key takeaways from the 2024 workshop. This will be followed by pitch presentations from three invited speakers - Ekbal Hussain, Jacopo Furlanetto, and Sophie Buijs (who will focus on post-disaster recovery). Each will respond to three questions:

1. Why is it necessary to use EO for vulnerability assessments?
2. What have they done in their work using EO for vulnerability assessments?

3. Where do they see new opportunities?

A moderated panel discussion, led by Marleen de Ruiter, will then explore:

- The current effectiveness of EO products for multi-risk scenarios Gaps in how EO assesses vulnerability, particularly in capturing socioeconomic indicators like poverty or health system access
- Future improvements and integration strategies, including the use of citizen science and stakeholder feedback interactive polls (via Menti) will be used throughout to engage the audience, followed by a Q&A session and a summary of takeaways and next steps.

Multiple members of the consortium will be at EGU 2025 and present their results in the context of the project (e.g., the database).

4.4 Towards Strategic Coordination and Long-Term Impact

Recognizing the proliferation of parallel efforts in the EO and DRR domains, EO4MULTIHAZARDS has introduced a Special Issue with iScience to consolidate fragmented outputs and promote synergies among related projects, including AI4Drought, Deep-extremes, and ExtrAIM. Coordination across these projects is essential to avoid redundancy, optimize data use, and inform both research and operational implementation.

Stakeholder engagement remains a cornerstone of the project. However, experiences from the demonstration cases and workshops highlight the need to avoid stakeholder fatigue, which can arise when communities are repeatedly approached by overlapping projects without seeing tangible outcomes (Canfield, Mulvaney, & Chatelain, 2022).

To address this, the project proposes several strategic recommendations:

- Extend project durations beyond the typical 2–4 year window to allow for deeper, more consistent stakeholder engagement.
- Simplify and increase flexibility in project extension mechanisms, particularly for initiatives with strong stakeholder buy-in and demonstrable impact.
- Match funding duration to research objectives, balancing the need for rapid funding in crisis response with the necessity of longer-term investment in systemic, participatory risk research.

The EO4MULTIHAZARDS project has laid the foundation for a more integrated, operational, and socially responsive EO research agenda. Through strategic partnerships, targeted workshops, and enduring stakeholder relationships, it is contributing not only to scientific progress but also aims to improve resilience and decision-making on the ground.

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