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Multi-hazard and risk informed system for Enhanced local and regional Disaster risk management

MEDiate

Deliverable D2.1

A generalised framework for the assessment of current and future multi-hazard interactions

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DEL	Deltares	Netherlands
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BRGM	Bureau de Recherches Géologiques et Minières	France
EUC	Fondazione Eucentre	Italy
IMO	Icelandic Meteorological Office	Iceland
IMT	Institut Mines-Telecom	France
UIce	University of Iceland	Iceland
R2M	R2M Solution	France
RINA-C	RINA Consulting	Italy
IUSS	Istituto Universitario di Studi Superiore Pavia	Italy
OSL	Oslo kommune	Norway
NICE	Metropole Nice Cote d’Azur	France
AUS	Austurbru	Iceland
UStr	University of Strathclyde	UK
UCL	University College London	UK
ARU	Anglia Ruskin University	UK
ECC	Essex County Council	UK

GLOSSARY

Acronym	Description
CCC	Committee on Climate Change (now Climate Change Committee)
CISI	Critical Infrastructure Spatial Index
DEM	Digital Elevation Model
D.	Deliverable
EM-DAT	Emergency Events Database
ENSO	El-Nino Southern Oscillation
GIS	Geographical Information System
IbF	Impact-based Forecasting
IPCC	Intergovernmental Panel on Climate Change
ISC	International Science Council
LISI	Landslide Intensity Spatial Scale Index

PAR	Participatory Action Research
ROC	Relative (or Receiver) Operating Characteristics
SCAI	Seed Cell Area Index
SPI	Standardised Precipitation Index
SSI	Standardised Streamflow Index
UNDRR	United Nations Office for Disaster Risk Reduction
UNSEEN	Unprecedented Simulated Extremes using Ensembles
WHO	World Health Organisation
WMO	World Meteorological Organisation
WP	Work Package

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1 INTRODUCTION

The MEDiate project aims to develop a decision support system for disaster risk management by considering multiple interacting natural hazards and cascading impacts, It will use a novel resilience-informed, service-oriented and, people-centred approach that accounts for forecasted modifications in the hazard (e.g. climate change), vulnerability/resilience (e.g. aging structures and populations) and exposure (e.g. population decrease/increase), building on the consortium's existing strengths in this domain. This will be undertaken and developed through a number of work packages (WP).

This is the first deliverable of WP2 of the MEDiate project. The purpose of this deliverable is, firstly, to review approaches proposed in the literature to model and assess multi-hazard interactions and cascading impacts. The second objective is to use this review to propose a framework to analyse multi-hazard interactions and cascading impacts under current and future climate change scenarios for use in the MEDiate project. This deliverable assists in defining the research that will be taken forward through Tasks 2.2, 2.3 and 2.4.

1.1 Typical multi-hazard scenarios for the MEDiate testbeds

A multi-hazard event is one where a number of hazards can affect a location either spatially or temporally, with the order of hazard occurrence and their relationships being defined. The order in which a hazard's effects are felt leads to the definitions of *primary hazard* (i.e. the first hazard causing an impact) followed by *secondary* or *tertiary hazards* and so forth. They may have different relationships between them, for example triggering or hazard cascades (one causes another), (de-)amplification (one decreases or increases the probability or magnitude of another) and compound (multivariate events and unrelated hazards that overlap spatially and/or temporally). To give an idea of the importance and type of multi-hazards for the four MEDiate testbeds (locations shown in Figure 1), historical events that took place in the testbeds can be considered. These events indicate the types of multi-hazards that need to be able to be modelled within the platform being developed in MEDiate. The framework proposed in this deliverable is a basis of this platform.

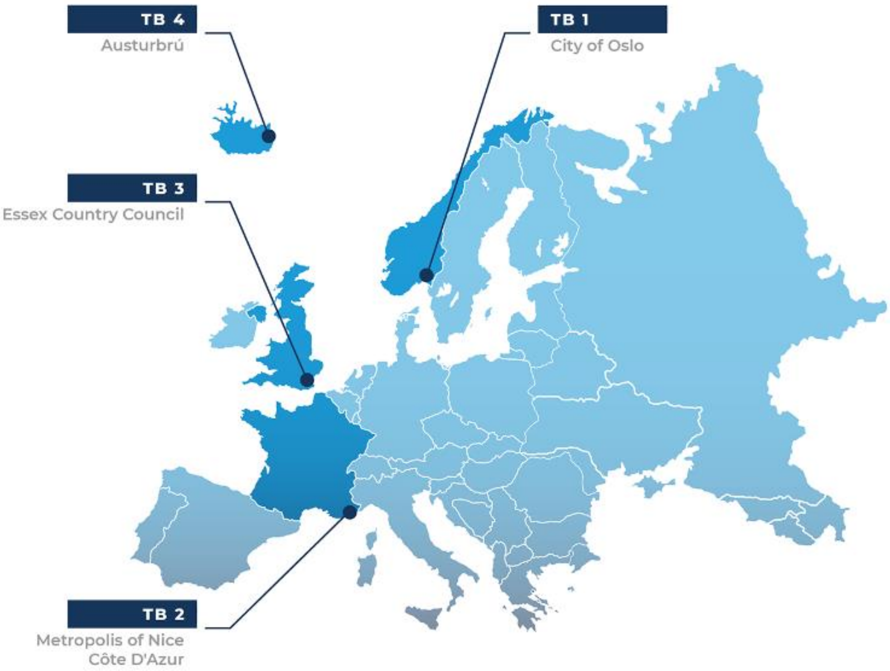


Figure 1: The location of the four MEDiate testbeds, TB1 – Oslo (Norway), TB2 – Nice (France), TB3 – Essex (United Kingdom) and TB4 – Austurbrú (Iceland)

For Testbed 1 (Oslo, Norway) the October 1987 storm is informative of the type of event that could occur in the future, and one that could be made worse by climate change. On the 15th and 16th October 1987 an extratropical cyclone passed over northern Europe, causing destruction in Ireland and the UK. It then reached southern Norway, including Oslo, where it led to extreme rainfall of 11cm in 48 hours and a storm surge in the Oslo fjord. These two occurrences caused fluvial and surface flooding (from the extreme rainfall), and sea water levels more than 2m higher than normal (from the storm surge). These separate flooding mechanisms led to damage to property in the Oslo area. Although this is an important and destructive event, there is surprisingly little information available in the literature. The reports of Risk Management Solutions (2007), Roald (2008) and Oslo Kommune (2020) provide some information on the 1987 storm and its impacts.

For Testbed 2 (Nice, France) the extratropical cyclone known as Storm Alex, which occurred in early October 2020, shows the sequencing of events that can occur at this testbed and which climate change can make even more extreme. Storm Alex brought extreme rainfall of 45cm in 24 hours to the region surrounding Nice. This extreme rainfall led to fluvial flooding that caused damage to properties. The rainfall also caused landslides that also damaged properties and infrastructure, such as mountain roads. The impacts of the hazards resulted in 21 deaths and 9 missing persons in the affected areas. The recentness of this event means that there is little information yet available in the literature but the webpages: https://climate.copernicus.eu/esotc/2020/storm-alex and https://www.bbc.co.uk/news/world-europe-54402096 provide basic information and images of the effects of this event.

For Testbed 3 (Essex, United Kingdom) the mid-August 2022 heatwave, which was followed by thunderstorms is an indicative example of a recent multi-hazard event. From 9th to 15th August 2022, there were sustained high temperatures above-30 degrees Celsius in southern England, including Essex. This extreme heat led to ill health and increased mortality. The heat also contributed to wildfires that damaged crops and the natural environment, and caused smoke that further exacerbated health conditions in the local population. Finally, the heatwave ended with thunderstorms that brought extreme rainfall causing surface flooding, which damaged property and led to traffic disruption. Again, references in the literature on this event are limited but the report of Office for National Statistics (ONS) and UK Health Security Agency (UKHSA) (2022) and the webpages: https://www.bbc.co.uk/news/uk-england-essex-62532722 and https://www.bbc.co.uk/news/uk-england-essex-62584821 provide some information.

For Testbed 4 (Austurbrú, Iceland) the events of 18th December 2020 in Seyðisfjörður, a settlement in this region, present a useful example of the type of events that can occur. There was extreme rainfall (in terms of duration and quantity) in the days running up to the 18th December (about 75 cm in the two weeks prior to the 18th), which triggered a landslide on the hill overlooking Seyðisfjörður. This landslide destroyed some properties, leading to an evacuation of the town, and when it entered the sea, the landslide triggered a small tsunami. Limited information on this event is available on these webpages: https://www.bbc.co.uk/news/av/world-europe-55389821, https://en.vedur.is/about-imo/news/the-landslide-in-seydisfjordur-is-the-largest-landslide-to-have-damaged-an-urban-area-in-iceland and https://icelandmonitor.mbl.is/news/news/2020/12/19/seydisfjordur_evacuated_landslide_causes_major_dama/ .

1.2 Objectives of this deliverable

This deliverable has two main objectives:

1. Reviewing and summarising quantitative methods for the assessment of multiple hazards that have been proposed and applied in the literature. A focus is on the methods applied within the past decade (i.e. approximately since 2013) as these will likely be most applicable for MEDiate and will not have been superseded. The focus is on those methods that allow the assessment of multi-hazard interacting relationships and cascading impacts.

2. Proposing a framework to analyse multi-hazard interactions and cascading impacts under current and future climate change scenarios.

When proposing this framework, the ambitions of MEDiate to go beyond the state of the art need to be considered. These ambitions include:

- Moving beyond a siloed approach, in which hazards and their impacts are analysed through a broad perspective;
- Considering multi-hazard interactions through a number of relationships and the potential for cascading impacts;
- Considering both the future and present conditions in multi-hazard interactions and impacts;
- Assessing ‘cascading’ effects, using multiple methods and data sources;
- Focus on general procedures with wide applicability;
- Understanding the potential spatial and temporal evolution of multi-hazard and multi-sectoral cascading effects
- Considering hazards that are applicable to the whole of Europe rather than a specific location;
- Going beyond susceptibility maps; and
- Producing multi-hazard intensity measures to support risk assessments and decision making.

It is also useful to clarify here what this deliverable is not aiming to do. Firstly, we are not reviewing approaches for assessing *individual* hazards (e.g. seismic hazard assessments) as methods for such assessments are well established and numerous reviews are available for specific hazards. Next, we are not reviewing or quantifying any one hazard at any one place – instead what methods these assessments used is the focus. Due to a lack of resources and because that level of detail is not necessary, we are also not providing a historical narrative or detailed description of all previous methods in the literature. This has also been done by other researchers for example through the MYRIAD-EU project in their *Handbook of Multi-hazard, Multi-Risk Definitions and Concepts* (MYRIAD-EU, 2022), Gill and Malamud (2014), and Tilloy *et al.* (2019). Finally, only those hazards that are relevant to MEDiate testbeds are being considered explicitly, although it is expected that the proposed framework will also be applicable for other hazards beyond those present in the testbeds.

1.3 Structure of the deliverable

The next section of this deliverable provides an overview of the topics covered as well as a set of definitions of the key terms used within the report. Section 3 provides a summary of previous approaches to multi-hazard analyses describing their aims and objectives. The methodologies used in these approaches to quantitatively assess multi-hazards, which will also be followed in MEDiate, are discussed in Section 4. All hazard assessments require input data so the main sources of these data are summarised in Section 5. The penultimate section then uses the proceeding sections to propose a framework to be followed within MEDiate for multi-hazard assessments. The deliverable ends with some brief conclusions and introduces the following deliverables within WP2 (D2.2, D2.3 and D2.4), which will be completed in the next 18 months of the project.

2 SCOPE OF THE REPORT AND DEFINITIONS

2.1 Scope of the report

This report collates and reviews existing hydrological, meteorological, climatological and geophysical resilience projects, initiatives and, publications globally to provide baseline evidence of existing multi-hazard approaches, methods and, applicable data including multi-hazard interacting relationships and cascading impacts. The report also proposes a high-level flexible multi-hazard framework suitable for assessing current and future multi-hazard interactions and cascading impacts.

To remain relevant and current, a historical review or examination of documents more than ten years old is not undertaken. Documents older than ten years are only included if they are important and foundational to the research. This report also does not review the approaches for assessing individual hazards or provide a quantification of any one hazard at any one place, but rather focusses on the multi-hazard context. A compilation of existing research is reviewed, but an exhaustive review is beyond the scope of this research.

Due to the emerging nature of research on multi-hazard interactions and cascading impacts, few standard approaches can be readily applied to capture the key characteristics and dependencies of these. This report collates and reviews previous approaches to identify gaps and to create a standardised approach in multi-hazard assessment and cascading impact evaluation that can be used throughout WP2. Although a review of approaches is undertaken, a detailed description of every approach is not provided. Overall, this component of the work looks at hazards and their impacts and, although may briefly discuss risk, it is not intended to provide a multi-hazard risk assessment, which would be more than just an evaluation of the natural processes in hazard and impact assessment.

Interactions between the hazards and their cascading impacts to be investigated are natural hazards that are relevant to Europe and in particular the variety of interacting natural hazards experienced at the four testbeds. These include the following:

- Hydrological (e.g. surface water, flash and fluvial floods)
- Meteorological (e.g. storms and wind)
- Climatological (e.g. heatwaves, forest fires and droughts)
- Geophysical (e.g. landslides, and earthquakes)

Hazards that are not relevant to the project and/or the testbeds are not covered.

The relationship and interactions between hazards have been defined differently across the literature and over time. In the case of this report, there are three relationships between hazards that are used, these are triggering or hazard cascades (one or more hazards cause another), (de-)amplification (one hazard increases the probability or magnitude of another hazard, this can also be viewed as a negative amplification, i.e. where the probability of a hazard is decreased) and compound (multivariate events and unrelated hazards when two or more independent hazards coincide spatially and/or temporally). The reader is referred to Section 2.2 for more details on the definitions.

Multi-hazard interactions can occur across the different type of hazards to create a hazard chain and cascading impact. For example, geophysical hazards that originate from internal earth processes, such as an earthquake or hydrological hazards, associated with the occurrence, movement and distribution of water such as heavy rains may cause a chain of events. A commonly used example of such a chain is the triggering of landslides (geophysical), that may cause damming and dam breach of a natural river leading to flooding (hydrological), and contributing to debris flow (geophysical and hydrological) that may have a vast range of impacts on roads, transmission networks, infrastructure and vegetation. It is therefore also of importance to understand what is meant by impact, and in the context of this report and WP2, this refers to the total effect, either negative or positive that a hazard may have on the economy, the environment and the community in the affected area.

2.2 Definitions

As multi-hazard and risk research is a multi-disciplinary community and a relatively new area of research, there is a need to build consensus on the terminology used. There have been a number of endeavours to create a common understanding of terminologies various intergovernmental bodies, including the United Nations Office for Disaster Risk Reduction (UNDRR), International Science Council (ISC), Intergovernmental Panel on Climate Change (IPCC), World Health Organisation (WHO) and the World Meteorological Organisation (WMO).

The MYRIAD-EU project has also gone to great lengths to establish working definitions in their project, through in person and online consultations with both internal and external experts in the field. Additionally, a literature review was also undertaken to determine terms and their definitions, whether these are self-generated or based on existing glossaries, and definitions and how these terms are used. This work produced deliverable *D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts* (MYRIAD-EU, 2022). As an extensive review of definitions has already been undertaken for a recent EU project this report will utilise the relevant definitions defined in this handbook which also draws on those defined elsewhere including intergovernmental bodies and literature (MYRIAD-EU, 2022). In the event that a definition is not provided by MYRIAD-EU this is indicated by an asterisk (*), while any edits to a MYRIAD-EU definition are noted using square brackets []. Additions to the definitions are from the RESILOC (n.d.) glossary, and Zscheischler *et al.* (2020). A number of key definitions required for the multi-hazard and cascading impacts analyses that are relevant to WP2 of MEDiate are provided in Table 1 below.

Table 1: List of definitions related to multi-hazard interactions and cascading impacts

Characteristic	
Event Characteristic*	A parameter that is used to characterise a certain hazard event
Site Characteristic*	A relevant parameter of the site that is impacted by the hazard/multi-hazard event
Event*	Something that occurs or takes place such as the occurrence of a hazard or a combination of hazards
Extreme Event	A time and place in which weather, climate, or environmental conditions—such as temperature, precipitation, drought, or flooding—rank above a threshold value near the upper or lower ends of the range of historical measurements
(Hazard) Forecast	Hazard forecasts provide information on the physical event characteristics, such as the location, timing, and magnitude of a potentially damaging event. [These can be determined through probabilistic or deterministic methods]
Hazard	A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.

Hazard relationships / inter-relationships	The mode in which one hazard affects another hazard
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).
External Hazards	Hazards originating from sources located outside the site area of interest
Natural Hazards	Hazards that are predominantly associated with natural processes and phenomena [caused either by rapid or slow onset events]
Hydrometeorological Hazards	Hydrometeorological hazards are of atmospheric, hydrological, or oceanographic origin
Climatological Hazards*	These originate from changes in the weather and climate
Geological / Geophysical Hazards	Geological or geophysical hazards originate from internal earth processes
Hydrological Hazards*	These are associated with the occurrence, movement and distribution of water both from oceanographic and surface water sources
Meteorological Hazards*	These originate from atmospheric changes
Impact	The total effect, including negative effects (e.g. economic losses) and positive effects (e.g. economic gains), of a hazardous event or a disaster. The term includes economic, human and environmental impacts, and may include death, injuries, disease and other negative effects on human physical, mental and social well-being.
Cascading Impact	Cascading impacts are those in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that results in physical, social or economic disruption. Thus, an initial impact can trigger other phenomena that lead to consequences with significant magnitudes.
Indicators	Indicators are observable and measurable characteristics that can be used to simplify information to help understand the state of a concept or phenomenon, and/or to monitor it over time to show changes or progress towards achieving a specific change
Multi-hazard	1) The selection of multiple major hazards that the country faces, and 2) the specific contexts where hazardous events may occur simultaneously, cascadingly [sic] or cumulatively over time, and taking into account the potential interrelated effects.
Multi-hazard event*	

Multivariate*	This refers to the co-occurrence of multiple drivers and/or hazards of the same geographical region causing an impact.
Preconditioned*	Where one or more hazards can cause an impact, or lead to an amplified impact only because of a pre-existing, climate driven condition
Spatially compounding*	These occur when multiple connected locations are affected by the same or different hazards within a limited time window thereby causing an impact.
Temporally compounding*	This refers to a succession of hazards that affect a given geographical region, leading to, or amplifying, an impact when compared with a single hazard.
Multi-Layer Single Hazards	More than one hazards are considered, but not the interrelationships between these (i.e. they are treated as discrete and independent).
Multi-Hazard Event Sets	A list of multi-hazard events over a given time period
Relationship	
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. Related concepts include domino or cascades, chains, causation and, consecutive disasters
(De-)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). [This can also be viewed as a negative amplification or de-amplification, i.e. where the probability of a hazard is decreased]. Related concepts include alteration of the disposition, change conditions, association and, amplification.
Compound Relationships	Two [or more] different natural hazards that impact the same time period and spatial area. Compound hazards [multi-hazards] can have a footprint with spatial and temporal characteristics that differs from the component single hazards. Related concepts include compound events, coinciding hazards, coupled hazards, compound hazard, independence and, consecutive disasters.
Scenario	A plausible description of how [a future event] 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.
Current Scenario	A hazard or risk scenario using the historical baseline or current data, for the current conditions
Future Scenario	A hazard or risk scenario using the historical baseline or current data, and/or modelled climate change metrics presented in the future (after present day), for example for 2050 or 2080.

The term compound hazard is often used as an alternative or is near synonymous to the term multi-hazard and therefore these terms are adopted in this report as having the same definition. Throughout the report it is attempted to consistently use the term multi-hazard unless referring to or quoting existing studies using the term ‘compound hazard’.

3 OUTLINE OF PREVIOUS APPROACHES

Natural hazards and their impacts have typically been analysed as a single-hazard and impact approach rather than looking at them through the multi-hazard/cascading impact lens. This results in a siloed approach where each individual hazard is assessed separately making it difficult to allow for a comparison of hazard types and their impacts. It is important to acknowledge that multi-hazard events and impacts are more than just the sum of their parts and applying a siloed or single hazard methodology will not account for the true event or extent of impact. MEDiate WP2 intends to focus on a range of natural hazards and their effects in order to allow for a cross boundary approach in terms of natural hazard assessments to ensure the evaluation of multi-hazard interactions and cascading impacts.

3.1 General approaches to multi-hazards

Different approaches have been applied to analyse and assess multi-hazard interactions and cascading impacts over the years. The approaches can be categorised either as qualitative or quantitative methods or a combination of both. Qualitative approaches are more frequently used compared to quantitative methods primarily due to a lack of measurable data or access to the necessary data, and knowledge gaps in understanding how natural physical processes interact with each other or with infrastructure (Ciurean *et al.*, 2018).

A breakdown of the different methods applied to evaluating multi-hazards and cascading impacts in terms of their nature as qualitative or quantitative was undertaken by the British Geological Survey and Natural Hazard Partnership in 2018 for the Natural Environment Research Council (Ciurean *et al.*, 2018). This report undertook a scoping review to determine projects and literature that investigate existing environmental multi-hazard approaches. It mostly focused on the UK but did include some international practice. A high level description of the approach is shown in Table 2 (Ciurean *et al.*, 2018), with figures that describe some of the methodologies provided in Figure 2 and Figure 3.

Table 2: General methodologies used to assess multi-hazard interactions and cascading events from qualitative to quantitative, through a range of both

Qualitative methodologies	
Narrative descriptions	A narrative methodology makes use of case studies that allow for a characterisation of the event and to describe its occurrence and effects.
Hazard wheels (Graphical example provided in Figure 2)	Hazard wheels are used to characterise an area in terms of its hazard profile and then provide potential management options, thus analysing the hazard and level of vulnerability of the system. They have typically been developed for coastal systems of differing typologies. This methodology can be used in areas with limited data and thus assists in screening for hazards and identifying areas of risk and can include multi-hazard events.
Qualitative or semi-quantitative methodologies	
Hazard matrices (Graphical example provided in Figure 3)	Hazard matrices can be used in a multi-hazard context and are used to examine the relationship between hazards. Hazards relevant to a spatial region are identified and then used to assess how these may interact with other hazards in various relationship styles such as triggering. They can be adapted to the amount of information or data within a spatial location and are a valuable tool in identifying secondary hazards. They can also be used to link likelihoods of occurrence and consequences.

Network diagrams (Graphical example provided in Figure 2)	Network diagrams, typically more qualitative but with the potential to include quantitative data, allows for a diagram that shows the interconnection and relationships between hazards to demonstrate the potential multi-hazard events.
Hazard maps (Graphical example provided in Figure 2)	Hazard maps utilise a cartographic approach to represent hazards across a spatial region and are able to demonstrate areas that are susceptible to multiple hazards utilising an overlay. Other factors can also be accounted for such as vulnerability to evaluate overall risk.
Semi-quantitative methodology	
Hazard/risk indices	This process determines indicators related to hazard types and how likely the occurrence of an impact may be. It is then possible to examine the interactions between the indicators.
Quantitative methodology	
Systems-based or physical modelling (Graphical example provided in Figure 3)	Process-based models are able to analyse more complex relationships in the multi-hazard environment and look at the interactions of these. Systems based or physical models simulate the real or physical environment in a model by creating a construct of the actual characteristics within the model environment.
Probabilistic and statistical approaches (Graphical example provided in Figure 3)	Probabilistic and statistical methods can characterise events through modelling of relevant parameters, as random variables, through appropriate probability distributions.
Hybrid approach	A hybrid approach uses a combination of systems-based or physical modelling and statistical and probabilistic methods to determine multi-hazard interactions and cascading impacts.

Although qualitative analysis is of value in assessing multi-hazards and cascading impacts, this review will focus on the quantitative approaches as the other work packages of MEDiate will use this approach as they allow for long-term assessment and planning against multi-hazards. One of the main concerns around quantitative methods, particularly probabilistic models, is that the output quality may vary based on data availability and computational power (Ciurean *et al.*, 2018). Although advancement in computing technologies enables higher resolution assessments, it is still important to select the right approach based on the hazards being assessed and the quality or quantity of the available data. The following section and Section 4 provide an overview of the various methods and models that are used in assessing multi-hazards and cascading impacts, with the framework providing some guidance on the model choice.

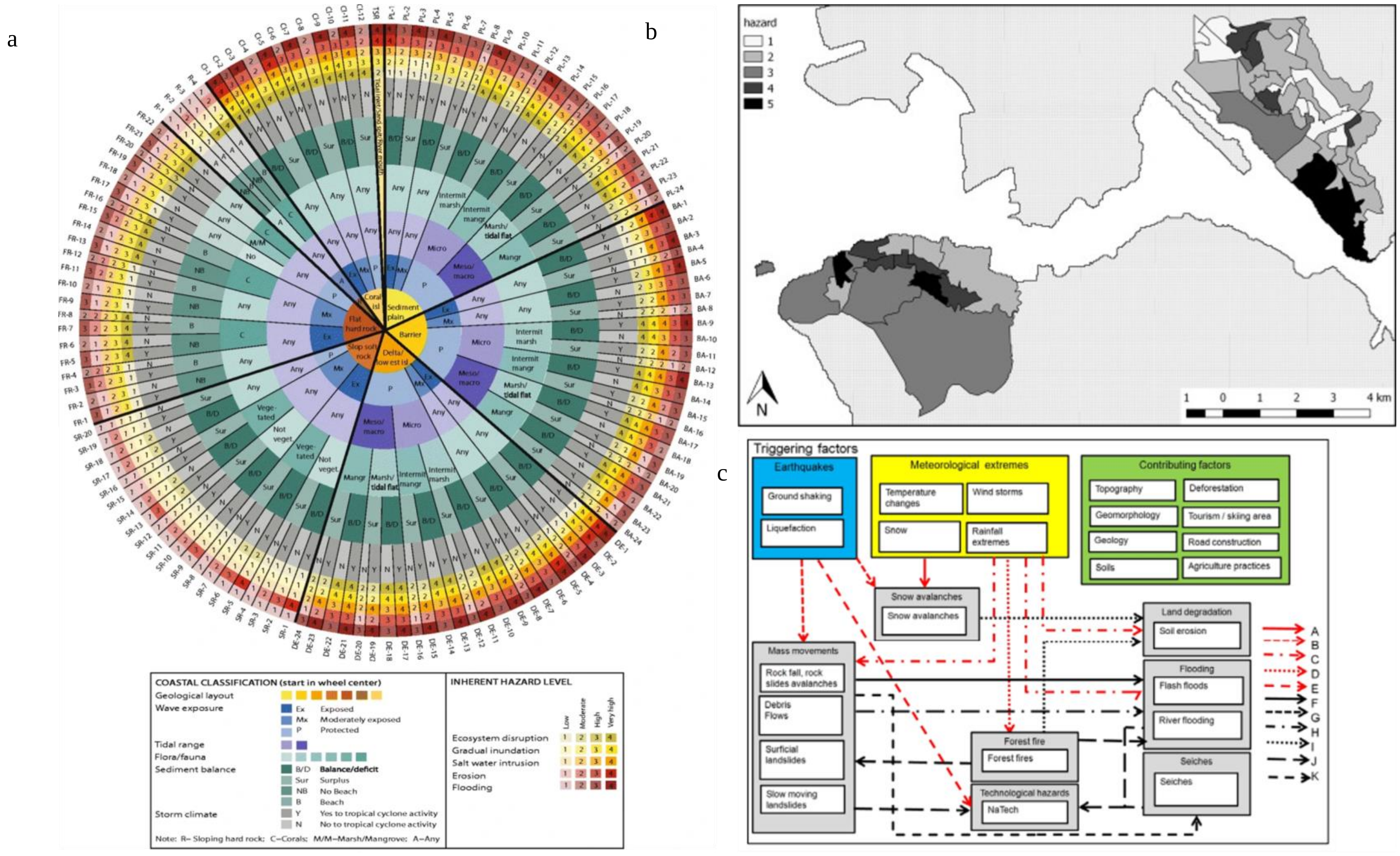
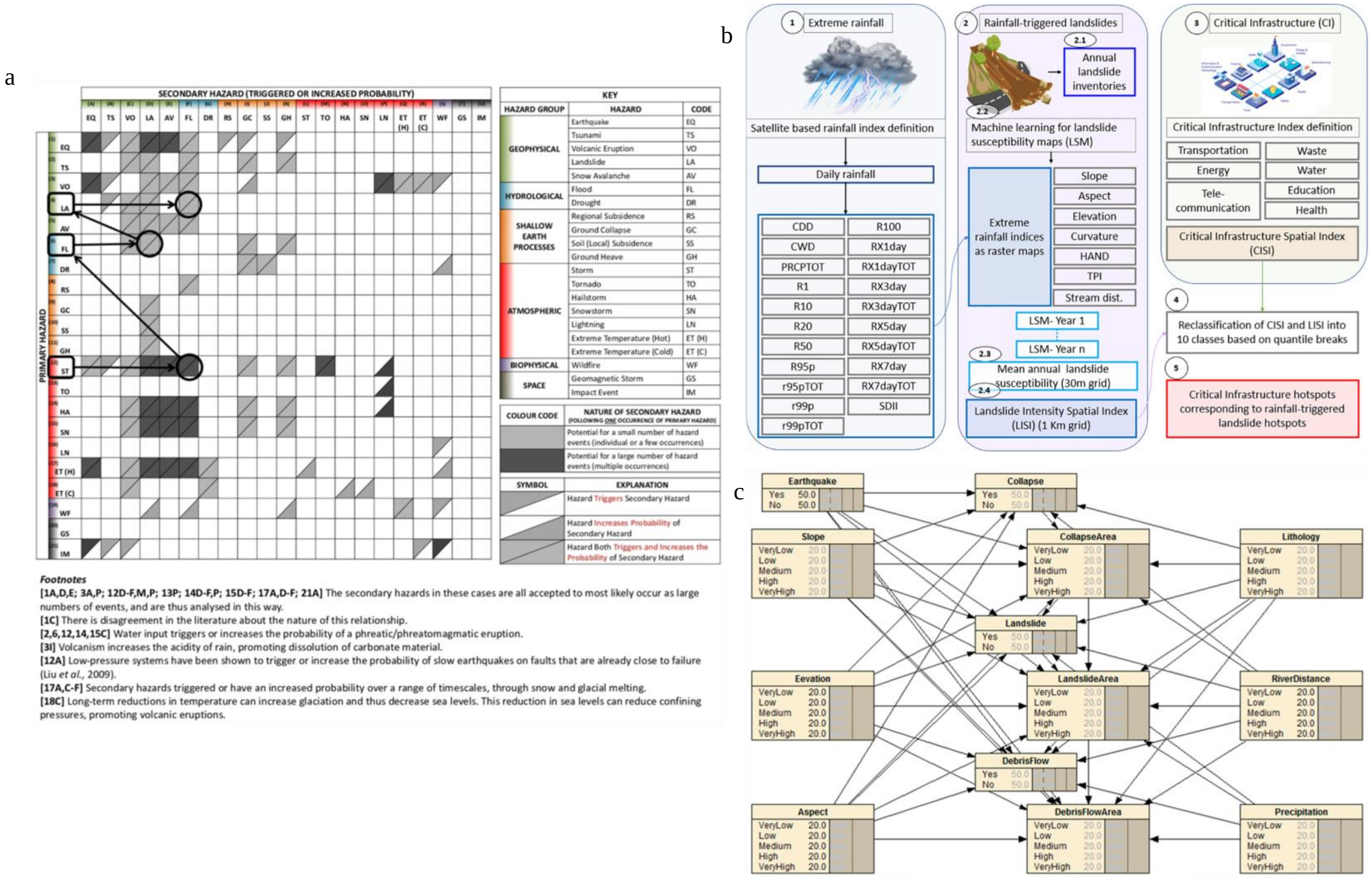


Figure 2: Graphical representation of general multi-hazard analyses: a) Hazard Wheel (Rosendahl Appelquist and Halsnæs, 2015), b) Hazard Map (Johnson *et al.*, 2016) and, c) Network Diagram (Van Western, 2012)



KEY		
HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche	AV
HYDROLOGICAL	Flood	FL
	Drought	DR
SHALLOW EARTH PROCESSES	Regional Subsidence	RS
	Ground Collapse	GC
	Soil (Local) Subsidence	SS
	Ground Heave	GH
ATMOSPHERIC	Storm	ST
	Tornado	TO
	Hailstorm	HA
	Snowstorm	SN
	Lightning	LN
	Extreme Temperature (Hot)	ET (H)
	Extreme Temperature (Cold)	ET (C)
BIOPHYSICAL	Wildfire	WF
SPACE	Geomagnetic Storm	GS
	Impact Event	IM

COLOUR CODE	NATURE OF SECONDARY HAZARD (FOLLOWING ONE OCCURRENCE OF PRIMARY HAZARD)
▨	Potential for a small number of hazard events (individual or a few occurrences)
■	Potential for a large number of hazard events (multiple occurrences)

SYMBOL	EXPLANATION
◤	Hazard Triggers Secondary Hazard
◢	Hazard Increases Probability of Secondary Hazard
▨	Hazard Both Triggers and Increases the Probability of Secondary Hazard

Footnotes

[1A,D,E; 3A,P; 12D-F,M,P; 13P; 14D-F,P; 15D-F; 17A,D-F; 21A] The secondary hazards in these cases are all accepted to most likely occur as large numbers of events, and are thus analysed in this way.

[1C] There is disagreement in the literature about the nature of this relationship.

[2,6,12,14,15C] Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption.

[3I] Volcanism increases the acidity of rain, promoting dissolution of carbonate material.

[12A] Low-pressure systems have been shown to trigger or increase the probability of slow earthquakes on faults that are already close to failure (Liu *et al.*, 2009).

[17A,C-F] Secondary hazards triggered or have an increased probability over a range of timescales, through snow and glacial melting.

[18C] Long-term reductions in temperature can increase glaciation and thus decrease sea levels. This reduction in sea levels can reduce confining pressures, promoting volcanic eruptions.

Figure 3: Graphical representation of general multi-hazard analyses: a) Hazard Matrix (Gill and Malamud, 2014), b) Systems based model approach (Gnyawali *et al.*, 2023) and, c) Probabilistic model – Bayesian Network (Han *et al.*, 2019),

3.2 Quantitative approaches: aims and objectives

A number of quantitative approaches that examine hydrological, meteorological, climatological and geophysical hazards have been evaluated. This section provides a summary of these studies in terms of their aims and objectives. The methodologies applied to the studies are provided in Section 4. These approaches are discussed under the type of quantitative methods described in Section 3.1 above, namely systems-based or physical modelling, and probabilistic and statistical approaches or a hybrid of the two.

3.2.1 Systems-based or physical modelling

Systems-based or physical models simulate the real or physical environment by creating a representation of its characteristics within the model environment. These models use real case studies or data to validate their performance and estimate prediction accuracy. Several studies (described below) have utilised systems-based or physical modelling to analyse multi-hazards and/or cascading impacts, with later studies starting to incorporate a machine learning-based approach. These studies have compared the impacts of multiple hazards being applied independently or using a true multi-hazard analysis with cascading impacts to prove that multi-hazard events are more than just the sum of their parts. They have also investigated the likelihood of a multi-hazard event (landslide initiation in the studies below) occurring due to contributing, or triggering factors such as rain-related parameters.

Chen *et al.* (2016) developed a physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows to provide a real-time warning system for these events. The model was developed on a case study that evaluated the risk to road users of a highway in Sichuan Province, China. The model was validated against an observed storm event that triggered slope failure and debris flows in this area. It considered the combined impact of a slope failure contributing to debris flow as well as analysing them separately in order to determine if the sum of the individual impacts is equivalent to that of the combined effect. Scenarios of an individual slope failure as well as multiple slope failures and debris flows were considered with the model predicting the impact area and the runout distance (Chen *et al.*, 2016). It is intended that the method would be used in real-time warning systems. The results indicated that the risk to lives is underestimated if the interaction between slope failure and debris flow are not considered or if the risk from each hazard is considered individually and summed together (Chen *et al.*, 2016).

In landslide prone areas the potential for landslides to create a hazard chain of natural dams and dam breaches is a common phenomenon. The 2018 Baige landslides in China are one such example that demonstrates a triggering multi-hazard event propagating over large distances (Fan *et al.*, 2020) that may result in a more severe impact than the initial landslide. Fan *et al.* (2020) used an integrated numerical simulation approach to model and predict a multi-hazard chain due to landslides causing a river to dam and subsequent flooding at downstream locations when they are breached. This study was able to predict future cascading hazards through the analysis of seven scenarios and to predict the flood extent if a breach of the landslide-induced dam were to occur as well as the depth, velocity and peak arrival time at chronological locations downstream. The methodology applied in this study has the potential to be replicated in similar landslide-induced hazard chains in other locations. It provides a methodology and insight into the interactions amongst landslide probability, landslide runout, natural dam creation and breaching and then the subsequent flood propagation, utilising hypothetical scenarios.

A framework that links the changes in rainfall extremes due to climate change and landslide susceptibility to protect vital infrastructure at a national level (with Nepal as the case study) was developed by Gnyawali *et al.* (2023). Landslides can be triggered by extreme heavy rainfall events as well as continuous localised rainfall, and areas can be impacted on a temporal scale as well as spatially. It is important to differentiate areas that are regularly affected from those that experience events only on occasions (Gnyawali *et al.*, 2023). Previous studies have utilised rainfall statistics such as mean annual rainfall; however, Gnyawali *et al.* (2023) note that these do not account for localised subtleties of rainfall extremes and therefore more rainfall parameters are required, such as those that describe the frequency, quantity, intensity, thresholds, percentiles and consecutive occurrences. Machine learning can be used to determine the susceptibility of areas to landslides and typically require data on past occurrences of landslides and static or dynamic descriptors such as topographical and rainfall parameters. The machine learning approach is then able to learn from past events and their triggering conditions to generate susceptibility scores (i.e. the spatial probability of a landslide occurring) for map grids or pixels (Gnyawali *et al.*, 2023).

3.2.2 Probabilistic and statistical approaches

Probabilistic and statistical approaches are a commonly applied methodology to assessing multi-hazard interactions and cascading impacts as they typically rely on the use of historical data to determine future scenarios. Probabilistic and statistical methods are able to characterise individual hazards and their interactions by modelling relevant parameters as random variables through appropriate probability distribution These can be defined based on available data and an understanding of the phenomena. A common type of probabilistic model is a Bayesian Network that is valuable for determining hazard chains and interactions.

Wang *et al.* (2013) used Bayesian Networks to analyse earthquake disaster chains, i.e. triggering relationships of hazards with the starting event being a strong earthquake. This study summarised 23 common earthquake chains, with the event process being defined into four types: serial (a chain event from the input through other hazards to the impact), parallel (the initial hazard can result in one of a number of secondary hazards to produce an impact), parallel-serial (the initial hazard causes one of a number of secondary hazards but will still result in the occurrence of a tertiary hazard leading to the impact) and dendroid disaster chains (this is a kind of parallel-serial disaster chain that spreads out into multiple hazard options) (Wang *et al.*, 2013). This study developed a theoretical Bayesian Network model for a chain event comprising earthquake-landslide-barrier lakes-floods that allows for quantitative evaluation of the probability of such triggered hazards occurring, with the added benefit of having a graphical model.

Han *et al.* (2019) also used a Bayesian network to model a volcanic earthquake-collapse-landslide-debris flow disaster chain to assess their probabilities and intensities for the Changbai Mountain in China, an active volcano. In this approach, they also incorporated ArcGIS to produce the chain event hazard map. The Bayesian Network provides a means of dealing with the uncertainty in hazard chains initiated by earthquakes so as to model the event and predict the probability of occurrence of the subsequent hazards. ArcGIS then allows the results from the modelling process to be incorporated into mapping software to generate a map-based hazard intensity. The methodology allows the integration of the Bayesian Network and ArcGIS mapping software so that data, analysis and, outputs can be assessed using both tools.

An analysis of compound drought events was undertaken by Wu *et al.* (2022). This multi-hazard event is defined as when two droughts of differing propagation perspectives occur simultaneously. It is an example of an amplification hazard relationship. The two droughts analysed are meteorological drought, characterised by a deficit in precipitation during a period of time, and a hydrological drought, which results when the precipitation deficit affects surface water runoffs causing deficits in streamflow of rivers (Wu *et al.*, 2022). The study uses a standardised precipitation index to define the meteorological drought and a standardised streamflow index to represent the hydrological drought. It is able to characterise droughts based on duration, severity and intensity and to determine their return periods. The methodology of this study allows for a statistical assessment of compound droughts through propagation and a comparison of compound drought events over multiple areas.

The World Meteorological Organisation (WMO) proposed using multi-hazard impact-based forecasting (IbF) in order to improve prediction and management of impacts from multi-hazards events. As droughts are an example of a hazard that may be influenced by other hazards they are deemed one of the events that could utilise an IbF; however, there are challenges to implementing this in the current environment. Boult *et al.* (2022) therefore proposes an intermediate approach that assesses real-time dynamic vulnerability in the context of a drought based IbF while the development, leading to the adoption of an IbF is undertaken (Boult *et al.*, 2022). As droughts are an event that happens over a period of time they allow for early actions to be incorporated. There are, however, challenges involved in developing an IbF for droughts as determining the relationship between the hazard and the impact can be difficult. This is because impact data may not be available or that aid and development in regions may have masked the true impacts of a drought. Other challenges are the trade-off between creating a system that is pre-defined or one that allows for live decision-making inputs and the practicalities of a multi-hazard IbF.

With the aim of assessing the impacts of multi-hazard events De Angeli *et al.* (2022) developed a five-step conceptual framework that can be used to assess a variety of hazards and their interactions on the built environment (1 – hazard identification, 2 – multi-hazard modelling, 3 – spatial and temporal evolution analysis, 4 – identify type of impact interaction, 5 – risk or impact assessment). It is anticipated that the framework would be able to assist practitioners and researchers in determining the impacts of multi-hazards, their interactions and impacts and can be applied to their areas of interest (De Angeli *et al.*, 2022). The steps of the framework allow for the determination of potential hazard/s and their interactions or dependencies with other hazards and the potential impacts that may result due to these circumstances over spatial-temporal conditions.

Although the review by Domeisen *et al.* (2023) does not provide a methodology of how to predict and project heatwaves, it does provide detail on knowledge that needs to be improved upon in order to allow these predictions to be undertaken with better lead times. There are indications that heatwaves are becoming more frequent and more extreme and will continue to do so in the future due to human influence on the climate. These events may be accompanied by soil drying or humid conditions (a combination of temperature and specific humidity) and may result in compound events such as drought and heat or wildfires. In order to ensure preparedness and the ability to cope with impacts, better predictions are therefore needed at various reference points as well as changes in frequency at specific locations (Domeisen *et al.*, 2023). As it is difficult to predict the occurrence of a heatwave more than a few weeks in advance, the tendencies of a heatwave to occur can rather be estimated (Domeisen *et al.*, 2023).

3.2.3 Hybrid approaches

A hybrid approach uses a combination of systems based or physical modelling and statistical and probabilistic methods to determine multi-hazard interactions and cascading impacts. These models are commonly used to understand the changes that may be induced due to climate change, as done by WSP for the Committee on Climate Change (2020) (CCC), now Climate Change Committee, in the United Kingdom. They are also used to develop more hypothetical but probable scenarios of climatic conditions that could have occurred, than what is available through actual events as undertaken by Thompson *et al.* (2017).

Thompson *et al.* (2017) used climate simulations to understand the probability of extreme rainfall events and to show that these events should be anticipated even if they exceed observed monthly rainfall records (Thompson *et al.*, 2017). This study was undertaken after the UK experienced a number of successive storms in the winter of 2013/2014 with unprecedented rainfall that caused widespread flooding. Observational records have a limited length. Therefore, the use of them as indicators of future events are constrained in terms of the timeframes as well as previous quantities that may not recognise the likelihood of exceedance. The modelling approach allowed for the development of many more events that could be probable based on a combination of existing climatic causes such as pressure systems and ocean currents.

The CCC developed a dependency model (Bayesian belief network) to demonstrate and quantify interacting risks across three sectors, infrastructure, the built environment and the natural environment, as described in the report *Interacting risks in infrastructure and the built and natural environments* (2020) focussed on the United Kingdom. The model looked at the impacts climate change would have on hydrological, meteorological and climatological hazards and their impacts at two temperature increases (2 and 4ºC) at 2050 and 2080 (WSP and Committee on Climate Change, 2020), compared to a baseline 2020 scenario. The hazards included are precipitation and flooding, sea level rise, temperature, drought, storms and wildfires. Although the model evaluated single hazard events it did allow for cascading or interacting events to be visualised and assessed. The results of the model could be used to determine linkages between policy management teams to enable collaboration, to identify areas where there is a lack of understanding by evaluating the length of connected nodes, determine areas where there is insufficient inputs and where further knowledge may allow better confidence in policy development and to understand where resilience measures may be built upon in the natural environment pathways. The visualisation of the pathways through the interconnected nodes demonstrates the connection of cascades, from hazards to impacts, and overall risk can be used to better understand interdependencies.

To produce a multi-hazard probability assessment using a case study location of the Fars Province in Iran, Pourghasemi *et al.* (2020) analysed the susceptibility of the area to flood, forest fires and landslides. The objective of the study was to understand what areas could be impacted by one or more of the hazards so as to allow for risk reduction measures to be implemented. The study highlights that it is of importance to produce a universal set of multi-hazard assessment techniques that can be shared amongst practitioners and stakeholders that will allow for better understanding of multi-hazards and therefore contribute to disaster risk reduction (Pourghasemi *et al.*, 2020).

A methodology that integrates modelling and multivariate analysis was developed by Tanim and Goharian (2021) to evaluate urban coastal flooding. The study aims to better understand the causes of coastal urban flooding as a consequence of multi-hazards in the form of storm surges and heavy rainfall (Tanim and Goharian, 2021), utilising the city of Chittagong, Bangladesh as a case study. It was found that the flood intensity and duration is influenced by changes in the tidal phase and that this event is both a compound and amplification relationship in that the flooding intensity is higher with the co-occurrence of the events rather than them occurring in sequence (Tanim and Goharian, 2021). There are also external factors that may play a role in the formation and extent of the event such as urbanisation, climate change and sea level rise. The methodology coupled a hydrological model with a hydrodynamic model to assess both the rainfall and coastal interaction after which the uncertainty of the flood depth prediction was analysed using the multivariate Gaussian Copula (Tanim and Goharian, 2021).

Ming *et al.* (2022) utilised a hybrid approach to analyse multi-hazard flooding events of heavy rainfall, extreme river flow and storm surge (i.e. pluvial, fluvial and coastal processes) in a compound hazard relationship. The driving factors of these events may all be driven by the same weather system and thus are spatially and temporally concurrent. This quantitative study utilises a copula statistical tool to determine the joint probabilities and the return period distributions of the hazards, while a 2D hydrodynamic model is used to produce inundation maps and frequency-inundation curves that are then used in a risk assessment (Ming *et al.*, 2022). This study provides a framework for multi-hazard flood events from the multi-hazard analysis to the hazard risk assessment through four stages; hazard frequency analysis, hydrodynamic flood simulation, (the hazard component) vulnerability analysis and multi-hazard risk calculations (the impact and risk components) (Ming *et al.*, 2022) and is tested through a case study in what is defined at the Greater London catchment, which covers part of the Thames catchment from Kingston to the coast.

4 REVIEW OF METHODS USED FROM PREVIOUS APPROACHES

This section of the report provides a brief overview of the steps undertaken in the methodologies of the different quantitative approaches provided in Section 3. It also provides a list of the outcomes of the studies demonstrating what information of interest or value has been determined through the processes undertaken. This assists in developing the framework provided in Section 6 that can be applied to the other tasks of WP2.

4.1 Systems-based or physical modelling

The studies that utilise a system-based or physical modelling approach all require physical data such as terrain conditions, and hydrometeorological parameters. In the examples used in this section, it can be seen that there is a steady progression in the ability of the models over time, with machine learning technologies being used in the later years. Chen *et al.* (2016), Fan *et al.* (2020) and Gnyawali *et al.* (2023) all analyse landslides or slope failures as part of the chain event. These landslides are either rainfall-induced or earthquake-induced with various secondary hazards and impacts such as debris flows (Chen *et al.*, 2016), and damming of a river and subsequent downstream flooding as a result of dam breakage (Fan *et al.*, 2020).

All the studies require observed or recorded data to undertake the modelling, through the construction of realistic scenarios and/or to analyse the results of the models against actual values to ensure concurrence with the real event and validate the accuracy of the models.

Table 3: Methodology and output of various systems based or physical modelling of multi-hazard analyses

Study	**Key components / methodologies**	**Outputs**
Chen *et al.* (2016)	The following steps were used to develop the physically-based multi-hazard risk assessment: 1. Develop a digital terrain module using a gridded approach to the study area, by dividing it up into a number of cells and assigning them properties including geology, topography, soil properties, hydrological parameters and groundwater table. 2. Create a spatial rainfall distribution module where monitored rainfall data is discretised across the cells using universal kriging interpolation (a method that allows for spatial interpolation if there is missing data). 3. A slope failure prediction module assesses the runoff and infiltration processes to determine the spatial and temporal pore-water pressure profiles of each cell. The instability and movement and deposition location of unstable cells is then determined using slope failure prediction module with the failure probability calculated using first-order-second-moment method (an uncertainty analysis method the relates input variables and parameters to the output).	• Ability to detect the location, volume, and movement of material due to slope failures as well as where and how this material is being deposited. • Identify locations that may potentially be impacted by multiple hazards. • Analyse the interaction effects between slope failure and debris flows. • A qualitative tool that can undertake risk assessments for regional slope failures and debris flows.

	4. A debris flow simulation module is used to determine the occurrence probability, volume of material moved and the impacted area of rainfall-induced debris flows. The vulnerability of road users is assessed based on the total depth of the runout material in comparison to the height of a car. 5. The risk of slope failure and debris flows is assessed through a multi-hazard quantitative risk assessment module accounting for the contribution of rainfall-induced slope failures to debris flows and the scenario of a location impacted by multiple slope failures or debris flows.	
Fan *et al.* (2020)	A numerical simulation approach (used to solve complex mathematical or physical problems by running an algorithm on a computer that breaks it up into smaller components) was used for the prediction of a multi-hazard chain allowing for the entire disaster chain to be viewed as separate interacting parts and as a whole. A number of different physically based numerical models were used for the different hazard simulations, (FLAC3D and RocPlane for landslide initiation, MassFlow for landslide runout and damming, DABA for dam breach, and HEC-RAS for river flooding) with the parameters used in each of the steps and the required results fed into the next step to allow for a systematic prediction of the entire chain. 1. Identify the probability of future landslides – undertake field and remote sensing investigations in order to determine the potential for future landslides, e.g. unstable rock masses and major discontinuities that could be mapped. 2. Simulate landslides and evaluate how the river will dam and subsequently breach – empirical and numerical quantification is used to determine the probabilities of landslides and then evaluate how the river will dam and the breach may occur. 3. Analyse the dam breach flood in terms of extent and peak arrival time at downstream locations.	• Utilises a set of numerical modelling approaches through pre-existing programs. • Demonstrates that current models can work well for different types of input boundary conditions, so they can be linked or connected to each other. • Demonstrates hazard triggering effect, where one hazard may be caused by another. • The maximum values of the extent of the dam breach flood, depth, velocity, and peak arrival time are predicted at sites downstream.

Gyawali *et al.* (2023)	A machine learning approach, the random forest approach (the use of multiple decision trees to determine a likely prediction) was used to develop a means of linking landslide susceptibility to rainfall extreme, from which a landslide susceptibility map to determine critical infrastructure in rainfall-induced landslide susceptibility zones can be produced. 1. Define extreme and localised rainfall indices to generate an Extreme Rainfall Index definition using Integrated Multi-satellitE Retrievals for GPM (IMERG) indices for 21 rainfall parameters that define extreme and local annual rainfall patterns e.g. consecutive wet days and number of heavy precipitation days. 2. Develop an inventory of annual landslides to produce a Landslide Intensity Spatial Scale Index (LISI) for the period 2016-2020 by plotting annual landslides onto a satellite image which was used along with the rainfall parameters to train and validate the machine learning software to produce a mean annual landslide susceptibility map. 3. Construct a gridded critical infrastructure spatial density map (Critical Infrastructure Spatial Index (CISI) using OpenStreetMaps, the density of critical infrastructure at grid locations was determined. Infrastructure deemed critical are those of transportation, energy, water, waste, telecommunications, education and health. 4. Reclassification of the CISI-LISI, after ensuring that both maps are using the same grid size, they were reclassified into ten classes based on quantile breaks. 5. Scenario analysis determining critical infrastructure that needs mitigation measures determined on a 1 km grid, by overlaying the landslide susceptibility map and the gridded critical infrastructure spatial density map.	• Develop a link between landslide susceptibility and changing rainfall extremes as well as critical infrastructure. • Define a set of 21 unique rainfall indices that describe extreme and localised rainfall. • Create a landslide susceptibility map through machine learning that combines existing landslide data and the rainfall indices.

4.2 Probabilistic and statistical approaches

Bayesian networks, a probabilistic graphical model consisting of nodes (variable) and edges (conditional probability) are a commonly used approach to analysing multi-hazard events as it allows relationships among variables to be visualised and quantified. Both Wang *et* al (2013) and Han *et al.* (2019) use this approach to analyse earthquake chain events and determine the probability of the chains occurring. Another methodology that is popular in the multi-hazard context is that of the copula models [a mathematical function that expresses the joint cumulative probability distribution of multiple variables (Tootoonchi *et al.*, 2022)] as used by Wu *et al.* (2022) for compound drought assessments. These tools are useful for statistical assessments in quantifying the cause and effect of multi-hazards and cascading impacts. The probabilistic and statistical approaches applied by Boult *et al.* (2022) and De Angeli *et al.* (2022) have some commonality in their approach to creating a multi-hazard framework, and, in the case of Boult *et al.* (2022), using this as a process towards developing an IbF methodology. Both studies try to determine the hazards or multi-hazards that may occur in the area through an assessment approach and how they may progress through the impact and risk to an area. Domeisen *et al.* (2023) makes an imperative point in highlighting the importance in understanding the processes that lead to the development of a hazard (in this case a heat wave), how this may differ across geographic areas and incorporating that into the models allowing for long range predictions, which is a necessary component across all the studies.

Table 4: Methodology and output of various probabilistic and statistical multi-hazard analyses

Study	**Key components / methodologies**	**Outputs**
Wang *et al.* (2013)	1. Develop all individual disaster event nodes comprising of input, state and output variables. 2. Set up the directed acyclic graph (a way to represent the relationships between the different factors or variables that contribute to the occurrence of the disaster) for each disaster (sub-model) according to the dependencies between the nodes. 3. Develop the conditional probability table for each node that defines the likelihood of occurrence. This can be done using expert judgement, actual events data and data training or machine learning. 4. Once the sub-model of each disaster chain is known, the total Bayesian Network model can be developed by combining them through their linkages and adjusting the probabilities in overlapping nodes. 5. Run the model with the probabilistic reasonings to determine the probability of a hazard in the chain occurring. 6. Uncertainties can be studied and mitigated at a global scale through statistical data and at a local scale with site specific information.	• 23 common earthquake disaster chains. • Determining that there are 4 types of disaster chains starting with a strong earthquake; serial, parallel, parallel-serial and dendroid. • Establishing a Bayesian model that analyses the earthquake-landslide-barrier lakes-floods disaster chain. • Establishing the most critical links in the chain that will have the most impact, these were determined to be population density, loose debris volume, flooded area, and landslide dam stability.
Han *et al.* (2019)	1. Establish the components of the volcanic earthquake chain by defining	• A quantitative hazard assessment – showing the chain probability and

	the system and determining the factors of the event as input, state and output elements 2. Collection of data from field survey data, remote sensing and digital elevation models (DEMs) to get topographical conditions and disaster points (training and verification points) 3. Construct a hazard assessment model with Bayesian Network representing the cause and effect relationships between the nodes (i.e. hazards). 4. A gridded view of the study area is created with data assigned to each in GIS and fed into the Bayesian Network (using Netica software) so that occurrence probability can be determined. 5. The results of the assessment are converted back to ArcGIS to develop a hazard map. 6. Validation of the model using relative operating characteristics (ROC) (a graphical plot that illustrates the performance/accuracy of a binary classifier system) and seed cell area index (SCAI) (a value that demonstrates susceptibility through the classification of variables as seed cells)	hazard intensity of chain events that is mapped within ArcGIS. • An earthquake-collapse-landslide-debris flow disaster chain hazard zoning map. • An assessment of the conditioning factors and inter-relationships between them to assess the likelihood of a disaster chain occurring.
Wu *et al.* (2022)	The framework development of analysing compound droughts is done in three steps: 1. Define compound drought in terms of drought propagation as the meteorological and hydrological drought events. As hydrological drought events follow on from meteorological drought they do not overlap the whole time therefore compound drought event begins when a hydrological drought starts and ends when the meteorological drought ends 2. Identify the compound drought using standardised drought indices as standardised streamflow index (SSI) (streamflow refers to the rate of flow in a watercourse over a period of time) and standardised precipitation index (SPI) at a monthly scale, by using the Pearson correlation coefficient to assess SPI timescales from SSI.	• Determined the relationship between the drought duration and drought severity of a compound drought. • Utilises standardised drought indices that are unitless and therefore allows these characteristics to be comparable in time and space. • Quantitively determines the joint return period of compound droughts.

	3. Assess the progression of a compound drought characteristics of duration, severity and intensity using run theory (a probabilistic method to determine the duration of an event) as well as their return period through Copula functions.	
Domeisen *et al.* (2023)	- To develop better understanding of physical processes (drivers and feedbacks) that lead to the occurrence of heatwaves. - Noted that atmospheric processes are a key development in heatwave generation and can be categorised as horizontal advection of air from warmer regions, adiabatic warming (due to subsidence of air) and diabatic heating (due to radiation) and, surface sensible heat fluxes (transfer of heat between the earth's surface and the atmosphere). Drivers associated with the land and ocean surfaces can impact heatwave development including soil moisture deficits that may reduce the impacts of evaporative cooling, land cover conditions, cloud cover and sea surface temperatures. - Anomalies in the sea surface temperatures can influence atmospheric circulation and drive heatwaves over adjacent continents. Examples of these include Pacific Ocean and Atlantic Ocean sea surface temperature anomalies and El-Nino Southern Oscillation (ENSO)	How far in advance heatwave occurrence and intensity can be predicted if certain information can be better understood and modelled: - two to three days ahead of the event can be predicted with confidence, provided surface sensible heat fluxes and upstream diabatic processes and anticyclonic flows (atmospheric circulation patterns characterised by high-pressure systems in which air flows outward) can be understood, - up to 10 days with Rossby wave packets (large-scale atmospheric waves that travel in a wavelike pattern across the globe), wave trains (a series of atmospheric waves that are organised in a particular pattern and move together as a group) and atmospheric blocking (a weather phenomenon in which a high-pressure system becomes "stuck" in one place for an extended period of time) - beyond the traditional limit of 10-15 days, up to two months means forecasts have to be expressed probabilistically using remote forcings from climate patterns e.g. ENSO and soil moisture/land surface conditions.
Boult *et al.* (2022)	The interim approach allows for droughts to be considered in the context of other (concurrent) hazards, i.e. multi-hazard events by developing a hybrid framework of a predefined system that incorporates real-time expert judgement. The system allows for a pre-defined action-based forecasting system to initially be used by: 1. Predicting the occurrence of a drought using hydrometeorological forecasts to which a static vulnerability matrix is applied to assess the risk.	- Provides an interim approach to multi-hazard IbF. - Includes the opportunity to incorporate real time judgement to account for other hazards.

	2. Thresholds for action are determined through stakeholder involvement to determine the lead times willingness to act. 3. The risk component is compared to the threshold for action to decide if early action is required. If the risk is greater than or equal to the threshold then early action is prompted to mitigate against impact. Additional components can be incorporated that allow for dynamic vulnerabilities and concurrent hazards to be included: 4. Expert judgement determines if there is dynamic vulnerabilities to be included such as "conflict, pest outbreaks, or recent hydrometeorological events" (Boult *et al.*, 2022 p. 5) etc. allowing the system to be subjective to actual events. 5. If vulnerabilities are higher, the threshold can be adjusted (lowered) to accommodate those susceptible to greater impacts and trigger action for less severe droughts. The opposite can also be applied to prevent false alarms. 6. In comparing the new risk and thresholds matrices the need for action can be determined. Early actions can also be adapted to account for multi-hazards	
De Angeli *et al.* (2022)	The multi-hazard framework for spatial-temporal impacts analysis incorporates two phases to assess the impacts of multi-hazards. Phase 1 steps look at causal dependencies and how the hazards interact: 1. Identification of all possible hazards that may occur in an area and how they may interact based on six basic interaction mechanisms (parallel hazards, cascading hazards, disposition alteration [one hazard changes the possibility of another occurring], additional hazard potential, coincident triggering, and cyclic triggering) to determine their causal dependencies. 2. Multi-hazard modelling utilising the most suitable model type.	• A framework application that allows the identification of important elements for multi-hazard impact modelling. • Creates a standardised approach to evaluate multi-hazard impacts.

	Phase 2 examines the spatial and temporal progression of the impacts caused by the hazards. 3. Determining the extent of impact of the hazards and their progression to assess if there are any spatial-temporal overlaps. 4. Determine the type of impact interactions as one of four categories (spatial-temporal overlap impact, temporal overlap impact, spatial overlap impact and independent single hazard impacts) using Boolean decisions (based on Boolean logic, a type of algebra that uses two values (true or false) and logical operators (e.g. "AND," "OR," and "NOT")). 5. Assess the impact or risk of the multi-hazard.	

4.3 Hybrid approach

The hybrid approaches to multi-hazard assessments use a combination of statistical and probabilistic models along with a physical model. This is a common approach when quantifying the impacts of climate change on hazards and impacts or analysing the more complex interaction of hazards. Thompson *et al.* (2017) state that using a climate model in the prediction of extreme rainfall allowed for a greater number of plausible meteorological events to be analysed than what would be possible through observational records only. The methodologies allow for the incorporation of existing data along with the model/s to quantitatively assess the susceptibility of an area to a hazard as done by Pourghasemi *et al.* (2020), Hasan Tanim and Goharian (2021) and Ming *et al.* (2022).

Table 5: Methodology and output of various hybrid modelling multi-hazard analyses

Study	**Key components / methodologies**	**Outputs**
Thompson *et al.* (2017)	Employed the Unprecedented Simulated Extremes using Ensembles (UNSEEN) method 1. Multiple simulations of the current climate were produced using the Met Office's near-term climate prediction system (a high-resolution climate model) that uses the Hadley Centre global climate model and input data of observed atmospheric, oceanic and sea-ice data along with anthropogenic and natural forcings (the various external factors or drivers that influence the climate system). 2. Model fidelity tests were applied using observed data to ensure that the model simulations are accurate enough to look for rainfall extremes.	• The simulations provided a hundred times more winter conditions than observation records available and therefore also contained more extreme events. • Assessing the model simulations of atmospheric circulations showed that a number of conditions can lead to high rainfall events and a probability of rainfall events that exceed the current observational record can be determined. • This study is able to show that in current climate conditions, extreme events can be anticipated with the timing and occurrence determined through natural variability.

	3. Estimate the probability of extreme events from the dynamical model rainfall data with a ranking method and an extreme value theory (a statistical theory that deals with the probability of extreme events).	
WSP and Committee on Climate Change (2020)	1. Literature review evaluating the various model options to identify risks (starting with the hazard) and interactions. A systems map or Bayesian Belief Networks (dependency models) was chosen. 2. Nodes were defined as climate drivers (hazard event) and impacts allowing for the relationship between the two to be created. The nodes have two classifications, event based (i.e. present or absent) or continuous (i.e. there can be incremental changes in an event) and are connected with conditional probabilities. 3. Systems maps were developed to allow visualisation of the dependency model and to describe the relationships between hazards and impacts along the pathway. In total 12 maps showing the climate drivers and the propagation of hazards and impacts were developed. 4. OpenMarkov, an opensource probabilistic graphical modelling software, was used for the model. The model developed chains of events containing nodes that represented climate hazards and impacts. The nodes incorporated data that determined the likelihood and effect of interactions, allowing for the calculation of a value of overall risk at the end of the network. An impact-based magnitude was assigned to provide a consistent unit. 5. Integrating findings into the CCRA3 (Third Climate Change Risk Assessment) urgency framework (HM Government, 2022).	• Two different models were created as Model 1: The risk pathways associated with increased summer temperatures and heat waves combined with the potential for lower summer rainfall and drought, and Model 2: The risk pathways associated with increased winter rainfall and sea level rise combined with the potential for extreme rainfall events. • The results of the model were able to demonstrate how the different climate hazards could be compounded through the chain of events and showed where significant impacts were shared between sectors (infrastructure, the built environment and the natural environment). • It also allowed for future scenarios to be evaluated over timescales and with different emission scenarios by allowing the impacts to be scaled using macro-economic growth (i.e. GDP and population growth). • Creates an overarching view of cascading hazards and impacts but does have its limitations in that it is not location specific, and does not allow for the modelling of a sequence of events such as consecutive dry years.
Pourghasemi *et al.* (2020)	• Data preparation by plotting locations of previous events of three defined hazards (floods, forest fires and landslides) and the values of the	• Determined the top three factors of importance for the hazard to propagate using the Boruta algorithm as quantitative results:

	parameters leading to the events were also determined. - Determine the critical parameters / conditioning parameters that contribute to the development of the hazard. Categorised into two main groups; biophysical and anthropogenic. The biophysical category was further subdivided into atmospheric parameters and topographical factors. The Boruta algorithm (a feature selection method used in machine learning that helps to identify which variables in a dataset are the most important for making accurate predictions) was used to determine and rank the order of importance of factors leading to the development of the hazard. - Develop individual and combined susceptibility maps for floods, forest fires and landslides using the random forest tree machine learning model based on the historic data locations and the triggering parameters. Part of the data set was used for training with the remaining data used in the validation of the model.	○ Floods: land use, drainage density, and topographic wetness index ○ Forest Fire: distance from urban areas, slope, and aspect ○ Landslides: slope, distance from rivers, and lithology - Produced susceptibility maps as individual maps for each of the hazards as well as a multi-hazard probability map by combining the three individual maps.
Tanim and Goharian (2021)	The methodology encompassed three stages: 1. Using a coupled coastal hydrodynamic model, i.e. the combination of two coastal model (SWAN and Delft3D) with various data inputs e.g. bathymetry (seafloor depth), land use, tidal harmonic constituents (periodic components that make up tidal variations), cyclone data (to represent storm surges) etc., the boundary conditions of surge height and tide were determined that are then used as input to the second stage. 2. The hydrological model (SWMM) is run to determine the compound flood depth and duration utilising the drainage layout of the case study city. 3. The Copula function is run to adjust the uncertainties and biases in the model to produce a bias adjusted compound flood model.	- In the case of a tidal surge the surge height is inversely related to the water depth, i.e. the surge height during low tides is higher than those during high tide. - Each cyclone can produce spatially varied surge maxima in different places and times as their wind speeds, intensity and, track are variable. - Flood response is correlated with the rainfall intensity and tidal phase, with temporal correlation of rainfall intensity and surge peak dominating the intensity of compound floods.

Ming *et al.* (2022)	Only the methodology for the hazard analysis is discussed: 1. The hazard frequency analysis allows for estimations of the joint probability distributions of the hazards through stochastic analysis using dependence and Copula functions. 2. Joint return periods and hazard scenarios (recurrence intervals) are determined and used to produce randomly generated extreme events and frequencies. 3. The events are used as boundary conditions in the 2D hydrological model to develop inundation and velocity maps. The model is driven by river flows and tidal boundary conditions and is able to predict flooding from multiple sources. 4. Model calibration and validation was done using historic data to test the model performance.	• Assesses the interdependencies and influences of the various hazards on each other. • Quantitative results of multi-hazard flood risks of high rainfall, high river flow and surge. • Provides inundation maps for the case study area. • Produces inundation depth-return period curve, that defines the relationship between the two.

4.4 Summary

This section has identified several existing ways of analysing multi-hazards and cascading impacts. This is perhaps understandable given the number of hazards that are assessed and the cross-disciplinary work involved in them. According to the methodology applied, multi-hazard events can be categorised into three classes: statistical and probabilistic approaches, physical or systems approach, or a hybrid approach – as shown in Figure 4. This figure solely classifies the hazards in the provided literature and some hazards may be analysed by other means elsewhere. Hazards overlap the boundary lines when more than one approach is used for them; however, they fit mostly within the cell in which they are mainly analysed.

There is no singular framework defined and/or adopted for the analysis of multi-hazard assessments and cascading impacts. From Figure 4, it can be seen that it would be challenging to utilise any single methodology for all hazards as there are also a plethora of conditioning parameters across spatial and temporal areas. In order to develop the next stages of WP2, a high-level flexible framework is developed that allows for subjective expert decisions in model selection. This is detailed further in Section 6.

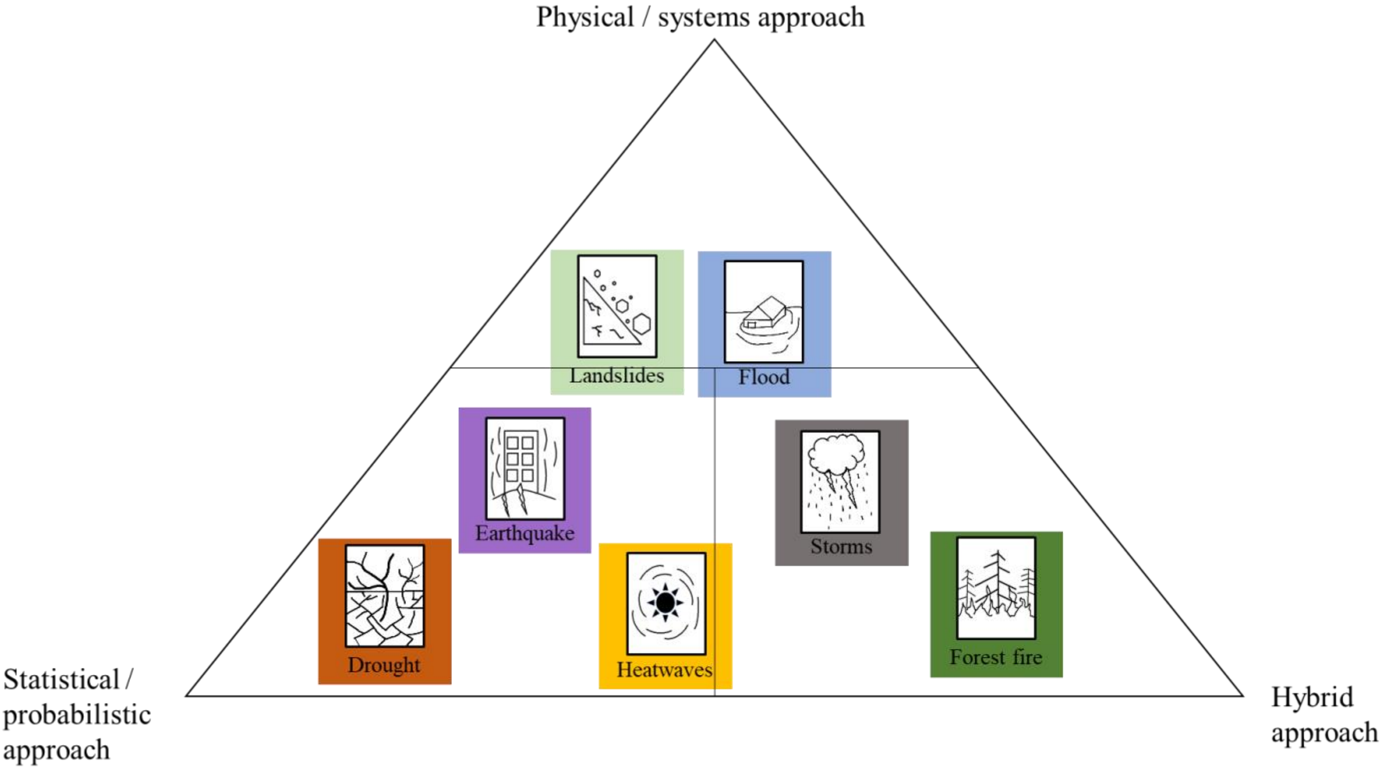


Figure 4: Classifications of hazard types in terms of the commonly used methodology for their assessment

5 DATA AND SOURCES

The data types and sources detailed in this section (Table 6) are based on available sources of data used in the literature review or from other recommendations. In addition to the EU Copernicus data (https://www.copernicus.eu/en), many of the sources of data listed in the literature are country specific – these are, simplified in this section for clarity. This list is not prescriptive for all tasks of WP2, nor is it exhaustive. It is, however, simply a collection of data sources that may be of value for future analyses. Data from the testbed locations will also be utilised and may include some of those listed in Table 6; however, exactly what data is needed from the testbeds will be determined through the Participatory Action Research (PAR) process.

Table 6: Overview of data used in previous quantitative studies for multi-hazard assessment and cascading impacts

Data type	**Data source**
Hazard identification • Geological • Hydrological • Climatological • Meteorological	• Hazard Databases ○ EM-DAT – The International Disaster Database (https://www.emdat.be/) ○ HANZE - Historical Analysis of Natural Hazards in Europe ○ ThinkHazard (https://thinkhazard.org/en/) • Satellite imagery e.g. ○ SPOT5 satellite ○ Landsat8 satellite • Extreme events records ○ Copernicus data (extreme precipitation, heat waves etc.) (https://www.copernicus.eu/en)
Impacts	• Hazard Databases ○ EM-DAT – The International Disaster Database • INFORM Climate Change Tool (https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Climate-Change/INFORM-Climate-Change-Tool) • Existing risk assessment literature • Insurance records • Industry reports • Newspaper articles • Estimated with expert judgement • Inputs from government agencies, business organisations, critical infrastructure providers and civil society organisations
Rainfall data • Observed rainfall totals (precipitation data) • Precipitation index forecasts • Daily rainfall records • Average annual precipitation maps • Extreme rainfall index • Monthly precipitation	• Meteorological Offices, e.g.: ○ UK Met Office National Climate Information Centre datasets ○ European Meteorological Departments • Environmental Agency's gauge stations • Automatic rain gauges • Copernicus data • Integrated Multi-satellitE Retrievals for GPM (IMERG) daily rainfall estimates
River flow data • Daily average flow discharge • Water level records • Streamflow	• Environmental Agency's river gauge stations • National River Flow Achieves e.g. ○ UK National River Flow Archive • Copernicus data

Ocean data
• Tidal and surge records
• Daily maximum surge
	• Tidal station data e.g.
	  ○ British Oceanographic Data Centre
	  ○ European Commission - World sea levels

Temperature • Air temperature • Land surface temperature	• Copernicus data • Historical weather records

Climate projections
• Estimations of the changes in different climate variables
	• Climate datasets e.g.
	  ○ UKCP18 probabilistic projections
	  ○ Copernicus data
	  ○ Evidence from peer-reviewed studies that captured projected changes in these variables
	  ○ Stakeholder engagement and/or expert judgement

Socio-economic projections	• Population data e.g.
	  ○ Office for National Statistics (UK)
	• GDP Projections e.g.
	  ○ Office for Budget Responsibility (OBR) Fiscal Sustainability Report (UK)
	• Inputs from government agencies, business organisations, critical infrastructure providers and civil society organisations

Topographical data
• Elevation
• Slope
• Slope aspect
• Horizontal curvature
• Vertical curvature
• Height above the nearest drainage
• Topographic position index
• Bathymetric data
	• DEMs e.g.
	  ○ Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM (ASTER-GDEM)
	  ○ Shuttle Radar Topography Mission (SRTM) DEM
	  ○ Advanced Land Observing Satellite (ALOS) Global Digital Surface Model
	• Topographic maps
	• Environmental Agencies
	• Online map and data delivery services e.g.
	  ○ Digimaps

Aerial imagery	• In-situ aerial imagery • Satellite data e.g. ○ Sentinel 2 satellite imagery

Lithology	• Geological surveys:
	  ○ Lithology maps
	  ○ Geological maps

Land use	• Satellite data e.g. ○ Google maps • Urban areas map • Copernicus data
Critical infrastructure	• Government departments • Land use maps • Mapping services ○ OpenStreetMaps
Location data: • Distance from rivers • Distance from roads	• Topographical Maps • Drainage line distribution dataset • Estimated from river and road network
Vegetation • Vegetation cover	• Copernicus • Sentinel-2 10-Meter Land Use/Land Cover (ESRI)

• Vegetation condition index forecasts • Land cover • Vegetation index	
Soil moisture • Soil water index • Forecasts	• Copernicus data • TAMSAT-ALERT • Soil surveys
Fire • Burnt area • Fire danger metrics	• Copernicus data
Measured empirical data	• In-situ sensors

6 PROPOSED FRAMEWORK

Analysing multi-hazard interactions and cascading impacts is not as simple as summing the single hazard components. It requires careful consideration of various magnitudes and probabilities that must be harmonised to facilitate accurate comparisons. The methodologies discussed in Section 4 demonstrate the various approaches for hazard characterisation and impact assessment and provide guidance in developing the framework proposed here for use in the rest of WP2. Many of the studies and models discussed in the preceding sections have been undertaken to assess multi-hazard interactions and cascading impacts and, although improvement has been made over time to include multi-hazards, these are still limited in the number of hazards that are assessed in a particular study.

Within WP2, Task 2.2 will utilise and build on the framework to identify and assess the primary interacting hazards at the testbed locations that are applicable to the whole of Europe for current conditions and into the future. Task 2.3 will then build on Task 2.2 to evaluate the cascading impacts across Europe, after which Task 2.4 will use all the information from the previous tasks to develop and test multi-hazard indicators suitable for risk-based assessments and decision-making that will be further developed in WP3. The MEDiate project needs to analyse a wide range of hazards that may occur at the testbed locations, as well as develop a method that allows for an integrated approach. It is important to understand the interactions of hazards and the potential cascading impacts to model the interacting physical parameters and events in order to better quantify them. As such the framework provided here is a high-level flexible framework to assist in the guidance of the other tasks within WP2 and to provide a guide for assessing multi-hazards and developing multi-hazard intensity measures, cascading impacts and multi-hazard indicators for the later risk-based assessment processes, i.e. to provide an initial direction for the WP2 task to follow and develop as the project progresses.

The framework for analysing multi-hazard interactions and cascading impacts in the MEDiate WP2 tasks is shown in Figure 5Figure 6and is described in the following steps. The framework demonstrates the multi-hazard assessment process by identifying the hazard and the plausible hazard interactions that may occur by first understanding what the modulators are (e.g. sea surface temperature, regional climate) that lead to the drivers and conditioning parameters that will allow the development of a particular hazard (Step 1). This component also considers how climate change may influence and alter the drivers of a hazard, whether in terms of regularity of occurrence, intensity, or other influences. The second step (Step 2) of the framework is to then collect the relevant data that will be needed to undertake a hazard assessment (Step 3). The hazard assessment will result in multi-hazard intensity measures, describing the extent or magnitude of the hazard. This step will investigate multi-hazard interactions in the form of compound events, triggering events or hazard cascades, and (de-)amplification of hazards, that can then also feed into and possibly change the multi-hazard intensity measures. This component of the framework provides a guideline to the work to be undertaken by Task 2.2 where the hazard analysis and generation of the multi-hazard intensity measures is the output. Based on multi-hazard intensity measures, the multi-hazard cascading impacts that may be applicable to sectoral assets and infrastructure and, network and supply chains can be determined (Step 4), which is the work of Task 2.3. The final component (Step 5) of WP2 is the development of multi-hazard indicators (Task 2.4), which uses the information on multi-hazards compiled in Task 2.2 and cascading impacts, from Task 2.3, to develop and test multi-hazard indicators suitable for use in risk-based assessments and decision-making.

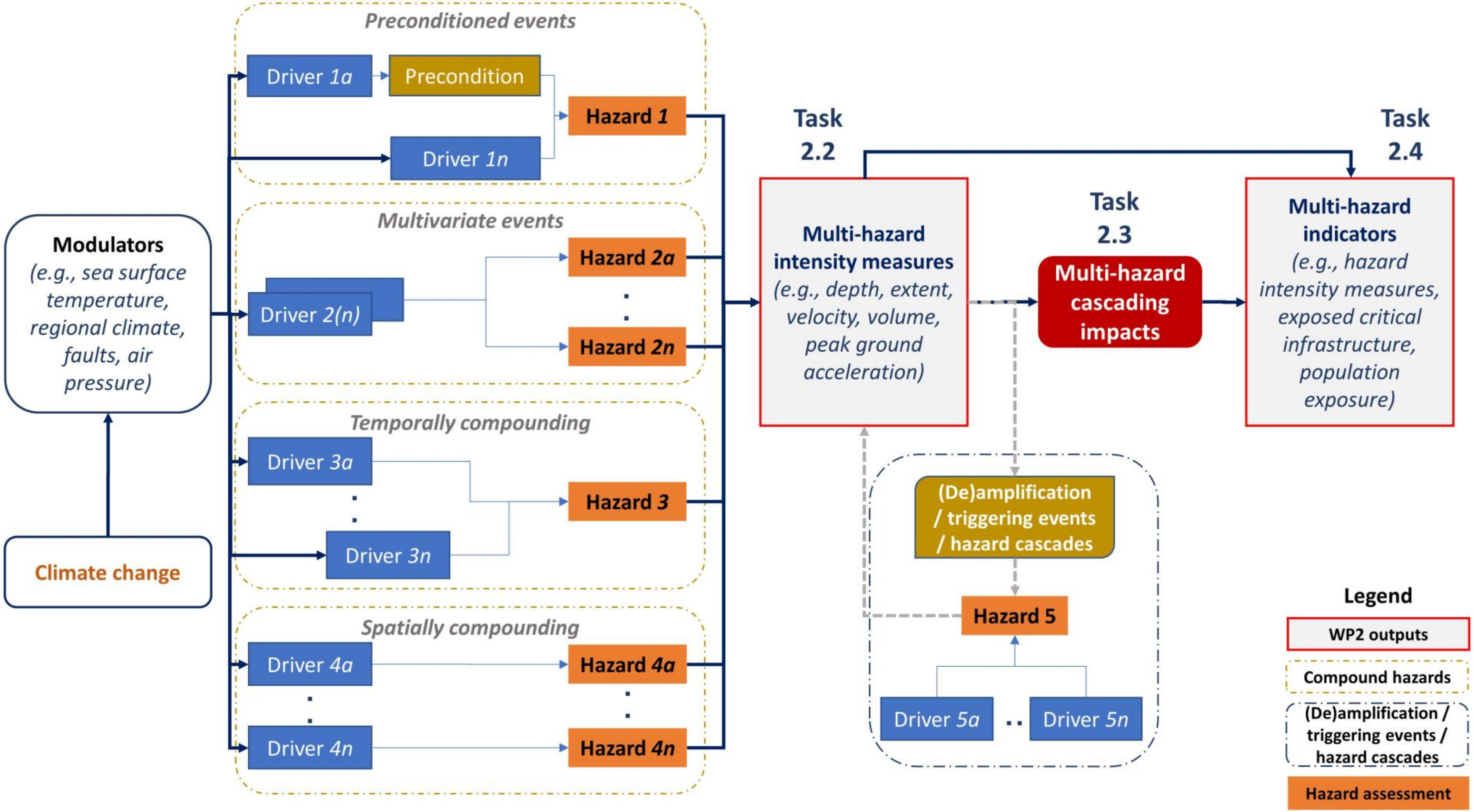


Figure 5: Framework for analysing multi-hazard interactions and cascading impacts

Figure 6 demonstrates an exploration of the framework in Figure 5 through an analysis of some examples in assessing multi-hazards and determining the intensity measures. This figure does not encompass all situations but provides a deep dive into potential combinations of a few multi-hazards. Figure 6 exhibits the overall hazard assessment approach showing the inner layer, the physics that may cause an event to occur. These are defined as the drivers and conditioning parameters and are shown as rectangular textboxes. The middle layer is the hazard assessment accounting for the interactions between the driver and the conditioning parameters, shown in oval textboxes. The orange lines show what drivers and conditioning parameters may influence the occurrence of a certain hazard. The green lines between the hazards provide the interaction between them, one or more of those relationships defined in Section 2 may be described as triggering or hazard cascades, (de-)amplification, and compound. The outer layer aims to capture the impact of the hazard or multi-hazard scenario through a set of intensity measures, provided in trapezoidal textboxes. The blue lines connect the different hazards to potential intensity measures used to characterise them.

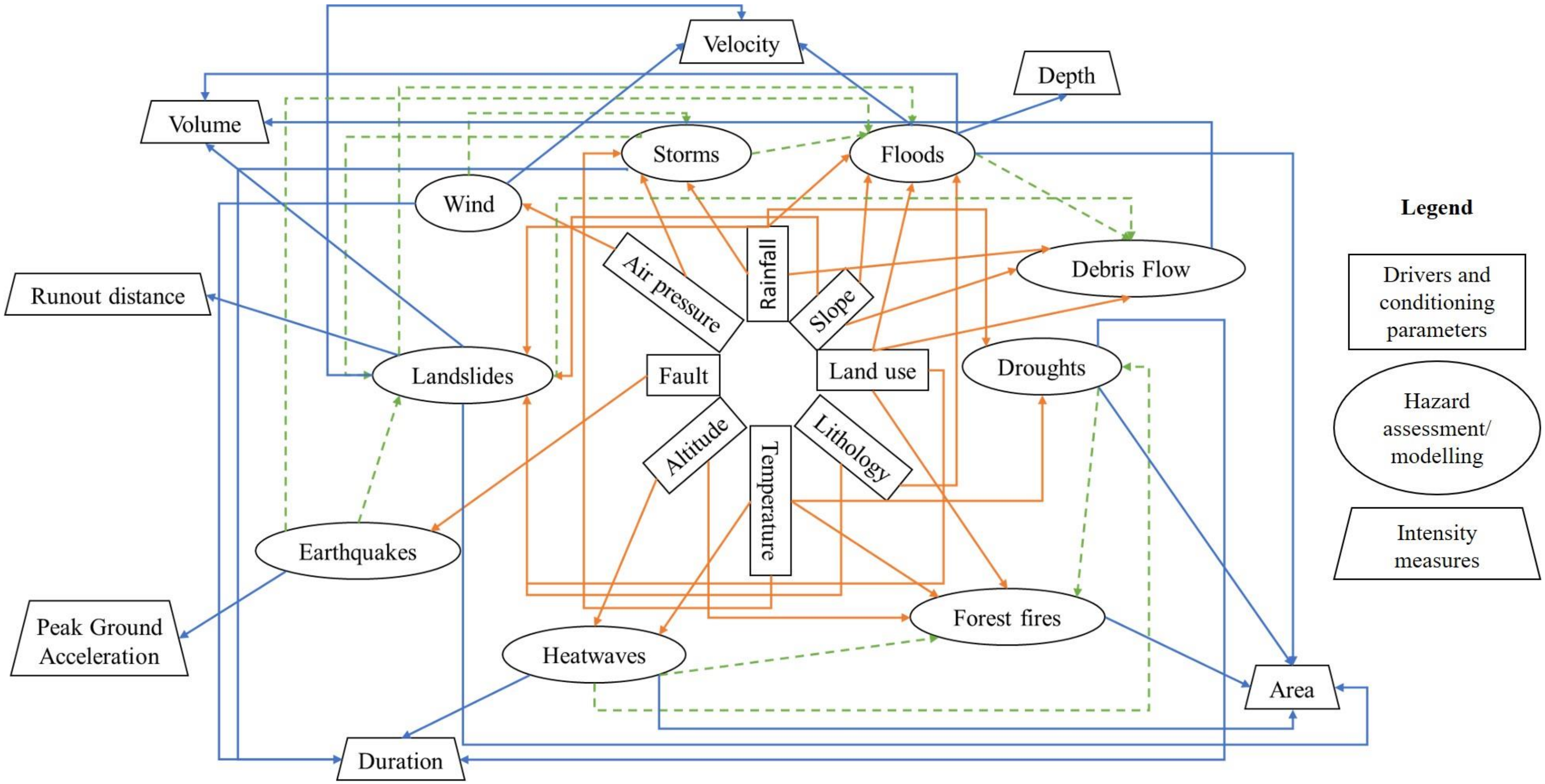


Figure 6: Exploration of examples utilising the multi-hazard analysis framework

6.1 Step 1: Establishing plausible multi-hazard interactions

This step requires investigating all interacting hazards (e.g. compound, triggering or hazard cascades, and, (de-)amplification) that occur at the particular location (e.g. the testbeds) and establishing alternative hazard chains. These should be plausible events that may occur at that particular location and these should be ranked using a hierarchical approach. A single hazard of importance (i.e. one that is prominent in an area of study) may be used as the starting point for developing the chain. Establishing these chains can be undertaken through a review of hazard databases [e.g. EM-DAT (Centre for Research on the Epidemiology of Disasters - CRED, 2023) or ThinkHazard (Global Facility for Disaster Reduction and Recovery, 2020)], literature review, historic hazard occurrences, or discussions with expert stakeholders living at the location. It would be useful to review the hazard matrices from Gill and Malamud (2014), provided in Figure 3, and Tilloy *et al.* (2019), provided in Figure 7, that show potential interacting relationships between the hazard groups. Both of these matrices demonstrate triggering or hazard cascades, and amplification hazard relationships, with only Tilloy *et al.* (2019) showing that compound relationships may occur between any of the hazards. This is where site-specific historic hazard data would be of value in determining potential interactions between non-influencing hazards in a multi-hazard context.

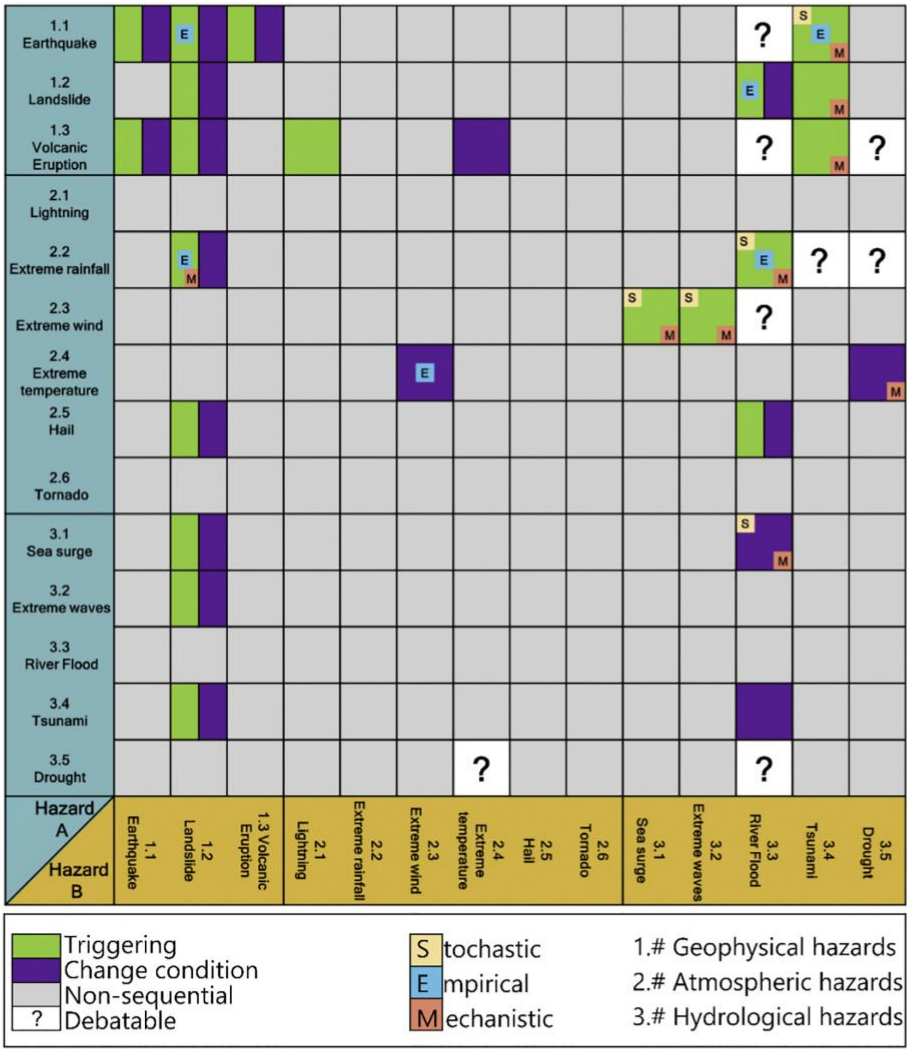


Figure 7: Multi-hazard interaction matrix from Tilloy *et al.* (2019)

6.2 Step 2: Data collection and data processing

Any available data from the study area (e.g. the testbeds) that pertains to the drivers and conditioning parameters of the hazard should be collated. Data could be related to the topographical, hydrological, geological, anthropogenic, and climatic conditions of the area. Figure 6 provides some examples of drivers and conditioning parameters that may be of value for establishing whether a hazard will occur. For example, rainfall-triggered landslides are dependent on the amount of rainfall, the slope angle, land use and lithology, and so forth. As described in Section 5, there are many locations where this data may be recorded, such as country meteorological offices, satellite imagery, maps, and geographical information systems. These sources and others (such as necessary data provided by the testbeds) can be used to collect data relevant to the hazard and the area.

In some instances, the available data may be observational data that is incomplete or limited, and there may also be uncertainty in projecting the data into the future as well as what the future conditions (social or climatic) may be. Therefore, within WP2, there should be a focus on trying to extend the observational database and to get the most benefit out of the records that do exist. This can potentially be undertaken through climatic or other relevant models. The accumulated data should be checked to determine its quality as well as to understand the resolution provided. This may require the alignment of different data types and is important for feeding into the chosen model.

6.3 Step 3: Multi-hazard assessment / modelling

6.3.1 Determining spatio-temporal scales

To undertake the hazard assessment, the geographic extent or spatial scale as well as the duration or temporal conditions of the hazard need to be defined based on the stakeholders and their needs as an end user. It may also be restricted based on the information available. Both scales need to consider the multi-hazard event and not just the singular occurrence, as this will influence the extent and duration thereof, which may cover many orders of magnitude difference (Gill and Malamud, 2014). It should also be chosen based on the extent of the hazards and their relationship to each other as triggering or hazard cascades, (de-)amplification, or compound as the area of impact and overlap as well as time lag may vary. This may mean that the extent and duration boundaries of the hazard can vary or that there may be several requirements throughout the analyses if multiple stakeholders are involved or if the relationship between the hazards extends or changes the conditions.

Gill and Malamud *et al.* (2014) provide a graphic demonstrating the spatial and temporal scale for various single hazards based on the literature, as shown in Figure 8. This figure provides the spatial and temporal scale of 16 natural hazards but does not cover all those that may be experienced by the testbeds of the MEDiate project. It is, therefore, provided only as a guide, and the specific multi-hazard events being analysed should be considered in this context.

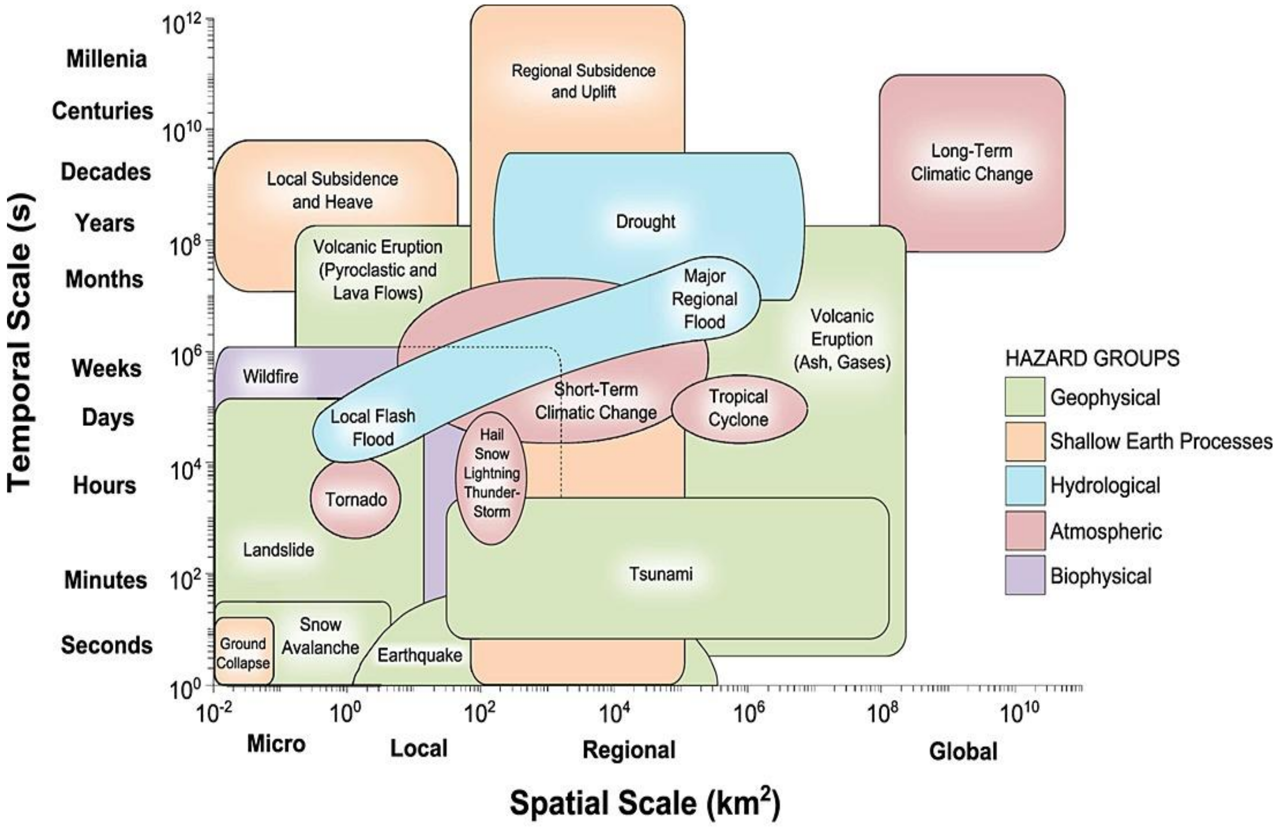


Figure 8: Spatial and temporal scale examples of 16 hazards on logarithmic axes, taken from Gill and Malamud (2014). The spatial scale is the area of impact while temporal scale is the timeframe that the individual hazard will act upon the environment. The hazards are grouped and those of interest to the MEDiate project are geophysical (green), hydrological (blue), atmospheric (meteorological) (red) and biophysical (purple)

A means of defining the temporal overlap of hazards may be to break it down into three relevant time frames as defined by De Angeli *et al.* (2022) as:

1. The hazard time – this is where the natural hazard evolves and affects the area of impact.
2. The exposure time – this accounts for the direct and indirect exposure of the area of impact to the hazard.
3. The resulting damage time – the duration of time in which the area of impact remains significantly damaged.

Having a breakdown of the timeframes allows for assessing any temporal overlap of hazards and to determine the end of one hazard and the beginning of another, determining the hazard relationship. An example of this is defining the timeframes of a multi-hazard drought as described by Wu *et al.* (2022) as a meteorological drought followed by a hydrological drought.

The spatial extent of hazards can be defined in a number of ways depending on the area of impact, such as localised, municipal, regional or extended (as they may extend beyond international boundaries), intercontinental to global. Knowing the spatial extent of the hazard/s will also help to identify instances of multi-hazard events. This can have an influence on impact identification as well as on other stages of the MEDiate project, such as determining the risk and stakeholder involvement.

6.3.2 Model selection

The manner in which the modelling takes place depends on the availability of data. In situations where there are a lot of historical data records, it may be more suitable to use a probabilistic or statistical approach, whereas in the event that there is minimal data available, a system-based or physical approach may be preferred. There is also the option of using a hybrid approach making use of both model types depending on data and output requirements. The type of hazards and their drivers and conditioning factors that are being analysed may also play a role in the decision-making of what model to use (Figure 4 provides a graphic demonstrating what hazards are analysed with a particular model type based on common use within the literature). It may be feasible to couple different models together to analyse the multi-hazard situation where the conditions or outputs of one feed into another. An example of this is the use of hydrological models for flood analysis coupled with hydrodynamic models that are able to evaluate storm surges in multi-hazard flood events.

The advancement in complex models and computing power allows for higher resolution data to be utilised for better analysis of the hazard processes. The advancement of machine learning is also a valuable tool in hazard prediction and evaluating cascading impacts as it can be used in a variety of application contexts and hazards. Various machine learning algorithms can help merge different parameters in the modelling of extreme events to examine complex hazard interactions. Such algorithms enable estimating the probability of certain hazards occurring, based on conditioning factors, to be determined through training with historical data. There are a number of machine learning algorithms that can be utilised in the multi-hazard context such as artificial neural networks, k-nearest neighbour, random forest, and support vector machine. The choice of which methodology to use depends on the ease of use as well as data quality as these may influence the accuracy of the results. It may also require comparing the results of different algorithms in order to select the best performing model.

Utilising the historic records of hazards at the testbeds is a valuable resource that can be used for the calibration of models that are used for predicting future multi-hazard and impact scenarios.

6.3.3 Impact and magnitude

The output of the multi-hazard assessment is the generation of multi-hazard intensity measures which provide a metric of measurement for characterising the extent and/or intensity of a hazard. Based on the literature above, Table 7 below provides some examples of units of measurement of the intensity measures that can be used to capture the impact of the multi-hazard scenario. In deciding what is needed for the requirements of the risk assessment in the following stages to be evaluated, the necessary parameters or outputs from the modelling process can be decided.

Table 7: Examples of intensity measures for various hazards

Hazard	Intensity measures	Unit
Landslides	Runout distance	m
	Velocity	m/s
	Landslide area	m^2
	Thickness	m
Debris	Runout distance	m
	Thickness	m
Flood	Flood area	km^2
	Velocity (mean)	m/s
	Flood depth	m
	Peak flow/discharge	m^3/s
Earthquake	Peak ground acceleration	g
	Peak ground velocity	m/s
Heatwave	Temperature	ºC

	Duration	days
Storms e.g. storm surge /cyclones	Water level	m
	Wind velocity	m/s
	Air pressure	Pa
Wind	Wind speed	m/s or km/hr
Forest Fires	Area	km^2
Droughts	Duration	Months
	Standardised precipitation index (SPI)	unitless
	Severity	unitless
	Intensity	unitless

As the intensity parameters and their quantification vary across hazards, it may be necessary to develop a unified consequence scale that will allow for the comparison of the effects of the different hazards in terms of their economic, human, and environmental impacts.

6.4 Step 4: Multi-hazard cascading impacts

Utilising the output of the multi-hazard intensity measures, the multi-hazard cascading impacts can be evaluated. This will assess the possible ‘knock-on’ effects due to the hazard on sectoral assets and infrastructure (e.g. transport, energy, water) as well as networks and supply chains to understand the potential spatial and temporal evolution of multi-hazard and multi-sectoral cascading effects.

While Step 3 focuses on hazard-to-hazard interactions, Step 4 focuses on the hazard to exposure interactions and the type of impact interactions. The analysis of spatial and temporal evolution of the hazards can be obtained from the hazard assessment and modelling performed in the area of interest (Figure 8). Starting from the area of spatial and temporal overlap of hazards identified in Step 2, different types of impact interactions may be generated for specific areas. The areal or spatial extent of the hazard influences the impact assessment, as they relate to the spatial scale of direct impacts, which can range from municipal to intercontinental levels. It is also important to acknowledge that in some cases even a very localised hazard can result in consequences (indirect impacts) at a larger scale (De Angeli *et al.*, 2022).

6.5 Step 5: Multi-hazard indicators

The output of Step 3 and Step 4 will be used to develop multi-hazard indicators. The indicators will include various scenarios of multi-hazard intensity measures (e.g. depth, extent, velocity, volume, and peak ground acceleration) and their cascading impacts resulting in exposed critical infrastructure and population. These indicators will contribute to multi-hazard risk assessments, which will aid in the development of decision support systems.

7 CONCLUSIONS

This deliverable (D2.1), the first of WP2, introduces the topics that will be covered in more detail in future deliverables (D2.2 and D2.3, due in M20, and D2.4, due in M24). Firstly, we provided, in Section 2, some key definitions of key hazard-related concepts, which are proposed to be used throughout the project. Next, the general approaches to the assessment of multiple interacting and compounding natural hazards are summarised and examples from the literature provided (Section 3). Because they are most closely aligned to the aims of MEDiate, in the next section (Section 4), we provide a more detailed description of quantitative approaches, which are separated into those based on systems or physical modelling, those based on probabilistic or statistical analyses, and finally, those combining aspects of both these methods (hybrid). All quantitative multi-hazard assessments require extensive input data, so Section 5 provides an overview of data that has been used in previous studies and a list of sources of such data for Europe. Section 6 proposes a general framework to assess multiple interacting and compounding hazards and to provide potential scenarios for use in the rest of the project, most specifically in WP3 and WP4. This framework is the key output of this deliverable. Because MEDiate is still in its early stages, the framework will be further refined over the course of WP2 based on work undertaken in Tasks 2.2, 2.3 and 2.4.

The proposed framework in Figure 5 is based on a five-step process. In Step 1, plausible hazard interactions are identified based on single-hazard assessments (either from the literature or specifically conducted for the study). In Step 2, relevant data is collected from various sources to provide information on the drivers and conditioning parameters of the hazard. Step 3 is primarily concerned with multi-hazard assessment and modelling. Therefore, the spatial and temporal scales of the multi-hazard assessment are defined based on the needs of the end users and available information and the hazard assessment technique is undertaken. The most appropriate method to assess the multi-hazards is chosen, again based on the needs of the end users, availability of the data, and existing hazard models for the region. This hazard assessment should account for potential interactions between the drivers and conditioning parameters. The extent and magnitude of the relevant key parameters/indicators are evaluated over the geographical area of interest and for the time period chosen for the scenarios and should be incorporated into the hazard assessment. Step 3 results in multi-hazard intensity measures, providing a metric for evaluating the extent and/or intensity of a hazard. The parameters/indicators chosen and the intensity measures obtained at this step are those that are relevant for multi-hazard risk modelling (covered by WP3). In Step 4, the cascading impacts that result from the multi-hazard interactions are evaluated to understand possible “knock-on” effects on sectoral assets and infrastructure resulting from multi-hazard exposure. Finally, in Step 5, the multi-hazard indicators are determined by combining multi-hazard intensity measures (Step 3) and cascading impact evaluation (Step 4).

WP2 will continue with Tasks 2.2, 2.3 and, 2.4 over the next 18 months, with the aim of generating evidence and knowledge relating to multi-hazard interactions and cascading impact with relevance to the European context. Task 2.2 will assess the multi-hazard interactions to generate relevant intensity measures, Task 2.3 will then use this to understand and measure the cascading impacts with Task 2.4 developing multi-hazard indicators that will be suitable for use in the multi-hazard risk assessment component of WP3.

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