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Concept design for risk analysis methods and components – Detailed concept design and documentation of methods on risk analysis - Draft

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List of Acronyms

ALS	Airborne Laser Scanning
AVA	Avanti Communications LTD
CA	Consortium Agreement
CIMA	Centro Internazionale in Monitoraggio Ambientale – Fondazione CIMA (CIMA Foundation)
CTTC	Centre Tecnològic de Telecomunicacions de Catalunya (Catalan Tecnological Telecommunications Centre)
CLC	Corine Land Cover
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DM	Disaster Management
DSM	Digital Surface Model
DTM	Digital Terrain Model
EC	European Commission
ESA	European Space Agency
FUA	Functional Urban Areas
GA	Grant Agreement
GBSAR	Ground-based Synthetic Aperture Radar
GHSL	Global Human Settlement Layer
GIS	Geographic Information Systems
GLOBC	Globcover
GUF	Global Urban Footprint
IAI	Impact Assessment Information
ICGC	Institut Cartogràfic I Geològic de Catalunya (Catalan Institute of Cartography and Geology)
IPCC	Intergovernmental Panel on Climate Cha
IPR	Intellectual Property Right
IPCC	Intergovernmental Panel on Climate Change}
IWG-SEM	International Working Group on Satellite-based Emergency Mapping
LULC	Land Use Land Cover
MoM	Minutes of Meeting
MMU	Minumum Mapping Unit
MOD50	MODIS map of global urban extent
NDVI	Normalized Difference Vegetation Inde

PB	Project Board
PC	Project Coordinator
PCF	Fundació d'Ecologia del Foc i Gestió d'Incendis Pau Costa Alcubierre
QRA	Quantitative Risk Analysis
QMR	Quarterly Management Report
RVA	Risk and Vulnerability Assessment
SP	Service Platform
SPH	Space Hellas S.A.
TDX	TanDEM-X
TL	Task Leader
TM	Technical Manager
ToC	Table of Contents
TSX	TerraSAR-X
TSYL	Tecnosylva S.L.
UNISDR	United Nations International Strategy for Disaster Reduction
VGI	volunteered geographic information
VHR	Very-High-Resolution
WP	Work Package
WPL	Work Package Leader

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Executive Summary

This document provides a detailed concept design and documentation of methods on risk analysis for the Risk and Vulnerability (RVA) module implemented in HEIMDALL. This deliverable is focused on the concept design of risk and impact assessment, the technical details regarding the communication interfaces, data formats and the design of the services are provided in [1]. First, a general introduction into the capabilities of remote sensing in pre- and post-risk assessment is provided. After listing the collected requirements, reference architecture (section 3) and the module functionality (section 4) are described.

The module is connected to various other services, providing the output over the HEIMDALL service platform (SP) in order to perform Impact Summary Generation, support the Situation Assessment (SA) processes and enable the Scenario Matching (SM) to identify similar scenarios in terms of expected impact on the affected elements at risk (section 3).

The module is composed by the hazard information, the exposure data set – comprised by physical and human exposure – and the impact assessment (section 4). First, the hazard information must be provided in order to identify the exposed elements within the hazard extent. The hazard information is either provided pre-event through the simulator modules, or post-event through the various earth observation modules within HEIMDALL. This results in different degree of detail in the hazard information provided and used during exposure and impact assessment. The identification of adversely affected elements based on the hazard information and the characterisation of those elements are performed in the exposure estimation process. This includes the generation of multi-source and multi-method exposure databases regarding physical elements such as building stock, transportation networks and critical infrastructures. By means of aerial interpolation techniques and the information generated on the physical elements, spatially refined human exposure information is generated.

Impact assessment is performed for each of the covered hazard separately, utilizing detailed information on the exposed assets and the hazard information. Because of different degrees of detail in hazard information two impact assessment approaches per hazard type are conceptualized. Impact assessment approaches based on simulated pre-event hazard information receive hazard forcings (e.g. simulated flood velocity and height) and can therefore feed hazard and asset specific damage functions in order to estimate the expected damage ratio. Impact assessment based on the observed post-event information are developed using the hazard specific semi-automatic mapping techniques, including mapping of hazard grading if applicable. Although the hazard information is generated with high and very high resolution earth observation data, information on hazard forcing can usually not be obtained. Therefore – in contrast to the simulation-based impact assessment -, the observation-based impact assessment is not integrating damage functions, thus rather provides an estimate of the observed direct impacts.

A multi-hazard concept is introduced, accounting for the assessment of effect due to spatio-temporal overlaps of the individual hazards covered within the project. A short introduction of each covered hazard, as well as the typical hazard interactions including the effects of anthropogenic interactions is provided.

1 Introduction

Severe geo-physical hazards become natural disasters, i.e. destroy people's lives and livelihoods, every year. In terms of an integrative and comprehensive risk analysis, the issue of an appropriate data collection is widely recognized [2–4]. In this context, remote sensing is generally perceived as a promising tool for an economical, up-to-date and independent data collection [5–9]. With regard to geo-risk research in particular, remote sensing is widely utilized as a contributing tool for hazard-related analysis [10–13].

In terms of pre-event risk assessment and management, remote sensing has its main share in the mapping of land cover and land use using multispectral data. For urban areas, this specifically relates to the capturing of elements at risk of the built environment such as buildings and infrastructures. In this context, the potential of remote sensing particularly lies in the generation of spatially accurate building inventories for the detailed analysis of the building stock's properties [5], [14–16]. Risk-related indicators have been derived in various landslide-related studies and include building footprint, height, shape characteristics, roof materials, location, construction age and structure type [2]. Especially last generation optical sensors featuring very high geometric resolutions are perceived as advantageous for operational applications, especially for small to medium scale urban areas in data poor countries [17]. These data are found to be suitable to quantify and characterize the building stock based on manual image analysis methods, statistical enumeration of samples [3] or automatic image information extraction methods [16], [18]. By the combination of optical sensors with digital elevation information from LIDAR measurements building characteristics can be determined with high accuracies [19]. Beyond, very high and high remote sensing data is suited to characterize homogeneous built-up areas. This capability in combination with information from a ground-based omnidirectional imaging system is used to determine the physical properties of the building inventory [20], [21]. With regard to the analysis of other risk components, remote sensing can deliver further multi-scale geo-spatial information. For the assessment of demographic vulnerability in particular, several regionalization and disaggregation approaches of census data based on remote sensing products are proposed [22], [23]. Furthermore, physical proxies for the approximation of socioeconomic vulnerability indicators can be retrieved from medium to high resolution optical and very high resolution LIDAR data [24–26].

Post-event risk assessments are mainly linked to tasks of damage mapping and assessment as well as the monitoring of the recovery phase and related [27] parameters in the aftermath of an event Investigations utilize remote sensing data and techniques for the identification of land cover/land use changes induced by forest fires, floods or landslides. Similar to pre-event studies, the focus of such applications is on the identification, description and assessment of the present and future conditions of the built and natural environment and hence the elements exposed, however, in the aftermath of an event when structural, demographic and socioeconomic vulnerability is significantly increased. In this context, remote sensing is a unique tool, capable of capturing the up-to-date large-scale damage situation of an affected area [27]. Thus, it has become an operational tool in emergency response, in particular for post-event rapid damage detection, mapping and assessment as well as the provision of crucial information for directing rescue and recovery [28–30]. Recovery-related parameters in this regard are for example the damage degree of individual and/or significant buildings or entire city blocks or roads and critical infrastructure affected [24]. This information helps emergency organizations in identifying severely impacted-areas and prioritizing response activities as decision support [31]. In this context, post-event rapid damage mapping uses mainly very high and high resolution (VHR1 to HR1) optical and SAR data as the best data source for damage assessment of buildings and infrastructure [28]. However, most operational applications are still limited to manual-visual interpretation techniques to enhance thematic accuracy compared to semi-automated approaches [32]. Moreover, even manually derived spatial information products for decision makers often underlie a certain degree of uncertainty due to visual misinterpretation since changes are often only detected for severely damaged structures [24]. Nevertheless, the use of change detection-based methods with multi-date imagery is still perceived to deliver more accurate and reliable results than automated approaches using solely post-event data [3], [33]. In this manner, applications are often enhanced by the employment of pre- and post-event LIDAR data to reach a higher level of morphologic detail and accuracy [33]. In the case of cloud coverage alternative approaches try to assess the damage situation by the combined use of pre-event optical and post-event SAR data [29]. In the broader context of post-event event applications, also other elements at risk of the built-environment are under investigation such as critical transportation networks, supply and lifelines by the employment of remote sensing datasets and products, in particular for the monitoring of post-event recovery and reconstruction activities [34].

This brief introduction highlights the capabilities of remote sensing systems and associated datasets with regard to particular applications in each phase of the disaster management cycle [35–39] i.e. pre-event reduction (mitigation) and readiness (preparedness) as well as post-event response and recovery.

2 Technical Requirements

This section describes the collected requirements that were gathered during the different end-user workshops (EUW) as well as the interface requirements that enable the module to communicate with the other HEIMDALL components. The collection and transformation of requirements has been performed in a hierarchical order: First, collection of User Requirements (UR) has been performed in order to create and overview of the most significant feature needs from an end-user perspective. Second, system requirements (SR) have been derived from UR, containing the requirements from a system point of view, describing the products that have to be created to fulfil a certain UR. Finally, the technical requirements (TR) transform the needed products into the necessary requirements from a technical point of view.

The following terminology has been agreed and used to define the time scope related to the fulfilment of the different requirements. Details about the timing of the below mentioned releases can be found in [40].

- Short term: ready for HEIMDALL Release A or B
- Mid-term: ready for HEIMDALL Release C or D
- Long term: nice to have after HEIMDALL project duration
- No applicable: out of scope of the planned system

In accordance with [40] the time frames presented in this document are a first estimation and will be revised after the system design has been done, which will allow a better overview about when and which component will be available.

The following terminology will be used to define the requirements, according to [41]:

"SHALL" – Requirements are demands upon the designer or implementer and the resulting product, and the imperative form of the verb, "shall," shall be used in identifying the requirement.

"Will" – A statement containing "will" identifies a future happening. It is used to convey an item of information, explicitly not to be interpreted as a requirement. "The operator will initialize the system by …" conveys an item of information, not a requirements on the designer of this product.

"Must" – "Must" is not a requirement, but is considered to be a strong desire by the customer, possibly a goal. "Shall" is preferable to the word "must," and only "shall statements are verifiable and have to be verified.

Other Forms – "To be." "is to be," "are to be," "should," and "should be" are indefinite forms of the verb, and they should be minimized when developing requirements. They are not requirements, but should be considered to be capabilities desired by the costumer.

2.1 Functional Technical Requirements

2.2 Short-Term Features

Table 2-1: Technical Requirement TR_Risk_01

Requirement ID:	TR_Risk_01
Related SR(s):	• Sys_Risk_9 • Sys_Risk_8
Description:	
The RVA module shall be able to extract built-up area from EO data for the exposure	

estimation.
Rational: Built-up area has to be extracted in order to perform impact assessment based on expected building damage and number of affected population.
Stimulus: The process will be triggered by the user.
Response: The RVA module will extract built-up area information from EO data.
Verification Criterion: The RVA is able extract built-up area from EO data.
Notes: The quality of the EO data (cloud cover, geometric resolution, number of points per unit) has to be sufficient.

Table 2-2: Technical Requirement TR_Risk_02

Requirement ID:	TR_Risk_02
Related SR(s):	• Sys_Risk_9
Description: The RVA shall be able to identify affected buildings and other infrastructure components based on hazard information.	
Rational: Identification of affected elements is the necessary input for the impact assessment.	
Stimulus: The process will be triggered by the user.	
Response: RVA module will perform geometric operations to identify the affected elements	
Verification Criterion: Given the necessary input affected/exposed elements can be identified by the module.	
Notes: Detected or simulated hazard extent must be provided in order to identify the affected/exposed elements.	

Table 2-3: Technical Requirement TR_Risk_03

Requirement ID:	TR_Risk_03
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to estimate the number of affected population based on hazard information regarding forest fires and population density products.	
Rational: Affected population shall be used as an impact indicator.	
Stimulus: The process will be triggered by the user.	
Response: The RVA module estimates the number of affected population.	
Verification Criterion: The RVA module provides an estimate of the affected population.	
Notes: In case no damage functions are available this indicator will serve as the impact assessment.	

Table 2-4: Technical Requirement TR_Risk_04

Requirement ID:	TR_Risk_04

Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to estimate the number of affected population based on hazard information regarding floods and population density products.	
Rational: Affected population shall be used as an impact indicator.	
Stimulus: The process will be triggered by the user.	
Response: The RVA module estimates the number of affected population.	
Verification Criterion: The RVA module provides an estimate of the affected population.	
Notes: In case no damage functions are available this indicator will serve as the impact assessment.	

Table 2-5: Technical Requirement TR_Risk_05

Requirement ID:	TR_Risk_05
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to estimate the number of affected population based on hazard information regarding landslides and population density products.	
Rational: Affected population shall be used as an impact indicator.	
Stimulus: The process will be triggered by the user.	
Response: The RVA module estimates the number of affected population.	
Verification Criterion: The RVA module provides an estimate of the affected population.	
Notes: In case no damage functions are available this indicator will serve as the impact assessment.	

Table 2-6: Technical Requirement TR_Risk_06

Requirement ID:	TR_Risk_06
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to integrate information on monetary values and based on this estimate the impact in flood prone areas expressed in loss of monetary values.	
Rational: Economic losses shall be used as an impact indicator.	
Stimulus: The process will be triggered by the user.	
Response: Using the hazard information and the information about the monetary values the RVA will provide an impact estimate expressed in monetary values.	
Verification Criterion: RVA can estimate loss of monetary values as indicator for the impact.	
Notes: Standardized information on monetary values of the affected areas must be present in	

an external data sources. The information on monetary values will be stored and on request used for the impact assessment as an indicator.

Table 2-7: Technical Requirement TR_Risk_07

Requirement ID:	TR_Risk_07
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to integrate information on monetary values and based on this estimate the impact in forest fire prone areas expressed in loss of monetary values.	
Rational: Economic losses shall be used as an impact indicator.	
Stimulus: The process will be triggered by the user.	
Response: Using the hazard information and the information about the monetary values the RVA will provide an impact estimate expressed in monetary values.	
Verification Criterion: RVA can estimate loss of monetary values as indicator for the impact.	
Notes: Standardized information on monetary values of the affected areas must be present in an external data sources. The information on monetary values will be stored and on request used for the impact assessment as an indicator.	

2.3 Mid-Term Features

Table 2-8: Technical Requirement TR_Risk_08

Requirement ID:	TR_Risk_08
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to estimate landslide impact based on the identified affected components, damage/vulnerability functions and the EO-products.	
Rational: Impact Assessment is the main output from the RVA module.	
Stimulus: The process will be triggered by the user.	
Response: The RVA module estimates the expected impact on the affected components based on EO-based hazard information.	
Verification Criterion: The RVA module provides the Impact Assessment product.	
Notes: With regard to specific hazards suitable vulnerability/damage functions must be available in order to calculate the expected damage.	

Table 2-9: Technical Requirement TR_Risk_09

Requirement ID:	TR_Risk_09
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11

Description: The RVA shall be able to estimate forest fire impact based on the identified affected components, damage/vulnerability functions and the EO-products.
Rational: Impact Assessment is the main output from the RVA module.
Stimulus: The process will be triggered by the user.
Response: The RVA module estimates the expected impact on the affected components.
Verification Criterion: The RVA module provides the Impact Assessment product.
Notes: With regard to specific hazards suitable vulnerability/damage functions must be available in order to calculate the expected damage.

Table 2-10: Technical Requirement TR_Risk_10

Requirement ID:	TR_Risk_10
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to estimate flood impact based on the identified affected components, damage/vulnerability functions and the EO-products.	
Rational: Impact Assessment is the main output from the RVA module.	
Stimulus: The process will be triggered by the user.	
Response: The RVA module estimates the expected impact on the affected components.	
Verification Criterion: The RVA module provides the Impact Assessment product.	
Notes: With regard to specific hazards suitable vulnerability/damage functions must be available in order to calculate the expected damage.	

Table 2-11: Technical Requirement TR_Risk_11

Requirement ID:	TR_Risk_11
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to estimate forest fire impact based on the identified affected components, damage/vulnerability functions and the simulation/modelling products.	
Rational: Impact Assessment is the main output from the RVA module.	
Stimulus: The process will be triggered by the user.	
Response: The RVA module estimates the expected impact on the affected components based on simulated hazard information.	
Verification Criterion: The RVA module provides the Impact Assessment product.	
Notes: With regard to specific hazards suitable vulnerability/damage functions must be available in order to calculate the expected damage.	

Table 2-12: Technical Requirement TR_Risk_12

Requirement ID:	TR_Risk_12
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to estimate flood impact based on the identified affected components, damage/vulnerability functions and the simulation/modelling products.	
Rational: Impact Assessment is the main output from the RVA module.	
Stimulus: The process will be triggered by the user.	
Response: The RVA module estimates the expected impact on the affected components based on simulated hazard information.	
Verification Criterion: The RVA module provides the Impact Assessment product.	
Notes: With regard to specific hazards suitable vulnerability/damage functions must be available in order to calculate the expected damage.	

Table 2-13: Technical Requirement TR_Risk_13

Requirement ID:	TR_Risk_13
Related SR(s):	• Sys_Risk_9 • Sys_Risk_11
Description: The RVA shall be able to estimate landslide impact based on the identified affected components, damage/vulnerability functions and the simulation/modelling products.	
Rational: Impact Assessment is the main output from the RVA module.	
Stimulus: The process will be triggered by the user.	
Response: The RVA module estimates the expected impact on the affected components based on simulated hazard information.	
Verification Criterion: The RVA module provides the Impact Assessment product.	
Notes: With regard to specific hazards suitable vulnerability/damage functions must be available in order to calculate the expected damage.	

Table 2-14: Technical Requirement TR_Risk_14

Requirement ID:	TR_Risk_14
Related SR(s):	• Sys_Risk_7
Description: The RVA shall be able to integrate preliminary risk information products provided by the end users based on their expert knowledge. For example, map products showing critical infrastructures and flood prone areas identified based on experience by the end-users and first responders should be integrated into the RVA module.	
Rational: Integration of preliminary risk information enables the RVA to assess risk without triggering the creation of simulation or observation products.	
Stimulus: The user has to import the products and request it.	

Response: The RVA module displays preliminary risk information products.
Verification Criterion: Preliminary risk information products can be integrated into the platform.
Notes: The preliminary risk information must be provided in a standardized format in order to be integrated into the platform.

Table 2-15: Technical Requirement TR_Risk_15

Requirement ID:	TR_Risk_15
Related SR(s):	• Sys_Risk_1 • Sys_Int_9
Description:RVA module shall be able to display the hazard extent without the generation of impact information.	
Rational: In case the necessary input data for detailed risk assessment is not available the module supports the user with hazard information.	
Stimulus: The user requests the hazard information.	
Response: RVA displays the hazard information provided by sensor or simulation data.	
Verification Criterion: Hazard information can be requested and is displayed by the RVA module without triggering of risk assessment information.	
Notes:	

Table 2-16: Technical Requirement TR_Risk_16

Requirement ID:	TR_Risk_16
Related SR(s):	• Sys_Risk_2
Description: RVA module shall be able to generate risk assessments for forest fires.	
Rational: Risk information products concerning the respective hazards are mandatory input for the situation assessment and the DSS component.	
Stimulus: The process will be triggered by the user.	
Response: Risk information products will be calculated.	
Verification Criterion: RVA module is able to estimate the risk concerning forest fires.	
Notes: Depends on hazard extent detected by analysis of sensor or simulations data.	

Table 2-17: Technical Requirement TR_Risk_17

Requirement ID:	TR_Risk_17
Related SR(s):	• Sys_Risk_2
Description: RVA module shall be able to generate risk assessments for floods.	
Rational: Risk information products concerning the respective hazards are mandatory input	

for the situation assessment and the DSS component.
Stimulus: The process will be triggered by the user.
Response: Risk information products will be calculated.
Verification Criterion: RVA module is able to estimate the risk concerning floods.
Notes: Depends on hazard extent detected by analysis of sensor or simulations data.

Table 2-18: Technical Requirement TR_Risk_18

Requirement ID:	TR_Risk_18
Related SR(s):	• Sys_Risk_2
Description: RVA module shall be able to generate risk assessments for landslides	
Rational: Risk information products concerning the respective hazards are mandatory input for the situation assessment and the DSS component.	
Stimulus: The process will be triggered by the user.	
Response: Risk information products will be calculated.	
Verification Criterion: RVA module is able to estimate the risk concerning landslides.	
Notes: Depends on hazard extent detected by analysis of sensor or simulations data.	

Table 2-19: Technical Requirement TR_Risk_19

Requirement ID:	TR_Risk_19
Related SR(s):	• Sys_Risk_4
Description: RVA module shall be able to consider cascading effects on vulnerability.	
Rational: In case of multi-hazard risk assessment the cascading effects on vulnerability have to be addressed by the RVA.	
Stimulus: Risk assessment process regarding multiple hazards is triggered by the user.	
Response: Cascading effects on vulnerability are estimated by the RVA during risk assessment.	
Verification Criterion: The cascading effects on vulnerability are taken into account during the risk assessment process.	
Notes:	

Table 2-20: Technical Requirement TR_Risk_20

Requirement ID:	TR_Risk_20
Related SR(s):	• Sys_Risk_5
Description: RVA module shall be able to integrate national datasets of critical, and if available significant, infrastructures that will be provided by the respective institutions over external data sources.	

Rational: National data sets of critical and significant infrastructures shall be integrated in order to further improve the exposure data set.
Stimulus: The process will be triggered by the user.
Response: The provided data set will be integrated into the exposure data set.
Verification Criterion: Critical, and if available significant, infrastructures from external sources can be integrated into the RVA exposure data set.
Notes: Critical infrastructure data sets have to be up-to-date and provided in a standardized format.

Table 2-21: Technical Requirement TR_Risk_21

Requirement ID:	TR_Risk_21
Related SR(s):	• Sys_Risk_5
Description: RVA module shall be able to identify the not affected and potentially affected infrastructures.	
Rational: Identification of not affected infrastructures shall be used for shelter identification.	
Stimulus: The process will be triggered by the user.	
Response: Location of potentially safe infrastructures.	
Verification Criterion: The RVA module identifies potentially safe infrastructures with respect to the disaster event extent.	
Notes:	

Table 2-22: Technical Requirement TR_Risk_22

Requirement ID:	TR_Risk_22
Related SR(s):	• Sys_Risk_6
Description: RVA module shall be able to estimate the vulnerability of the population.	
Rational: The assessment of the vulnerability of the population will lead to more precise risk assessment.	
Stimulus: The process will be triggered by either the user, exceedance of pre-defined threshold values or the generation of a new scenario.	
Response: Vulnerability assessment in the human domain will be performed by the RVA.	
Verification Criterion: RVA module provides an estimate of the vulnerability of the population.	
Notes:	

Table 2-23: Technical Requirement TR_Risk_23

Requirement ID:	TR_Risk_23
Related SR(s):	• Sys_Risk_10
Description: RVA module shall be able to share the risk assessment products with other services.	

Rational: Sharing of RVA information is mandatory for other services, e.g. during the situation assessment process.
Stimulus: RVA information is requested by the user.
Response: The created RVA information products are either provided or transformed to a standardized exchange format.
Verification Criterion: RVA information can be shared among other HEIMDALL services.
Notes:

2.4 Long-Term Features

Table 2-24: Technical Requirement TR_Risk_24

Requirement ID:	TR_Risk_24
Related SR(s):	• Sys_Risk_3
Description: RVA module shall be extendable to create information products for other hazards like e.g. earthquakes, storm events and man-made disasters.	
Rational: The user should have the possibility to extend the platform functionality.	
Stimulus: The process will be triggered by the user.	
Response: Respective RVA information products are created.	
Verification Criterion: RVA module can create information products for hazards other than forest fires, floods and landslides.	
Notes:	

Table 2-25: Technical Requirement TR_Risk_25

Requirement ID:	TR_Risk_25
Related SR(s):	• Sys_Risk_8
Description: RVA module shall be able to identify possible evacuation areas based on hazard information and exposure information.	
Rational: The end user shall be provided with possible evacuation areas to support tactical decisions.	
Stimulus: The process will be triggered by the user.	
Response: Evacuation areas are identified by the RVA module.	
Verification Criterion: The RVA module can identify evacuation area information products.	
Notes:	

3 Reference Architecture

This section outlines the overall architecture of the HEIMDALL platform and the schema of the RVA module. The relative position of the module in relation to other modules are described as well as the inputs and outputs expected from the RVA module. Communication interfaces are depicted in order to enable the exchange of information between the RVA module and other components and vice versa.

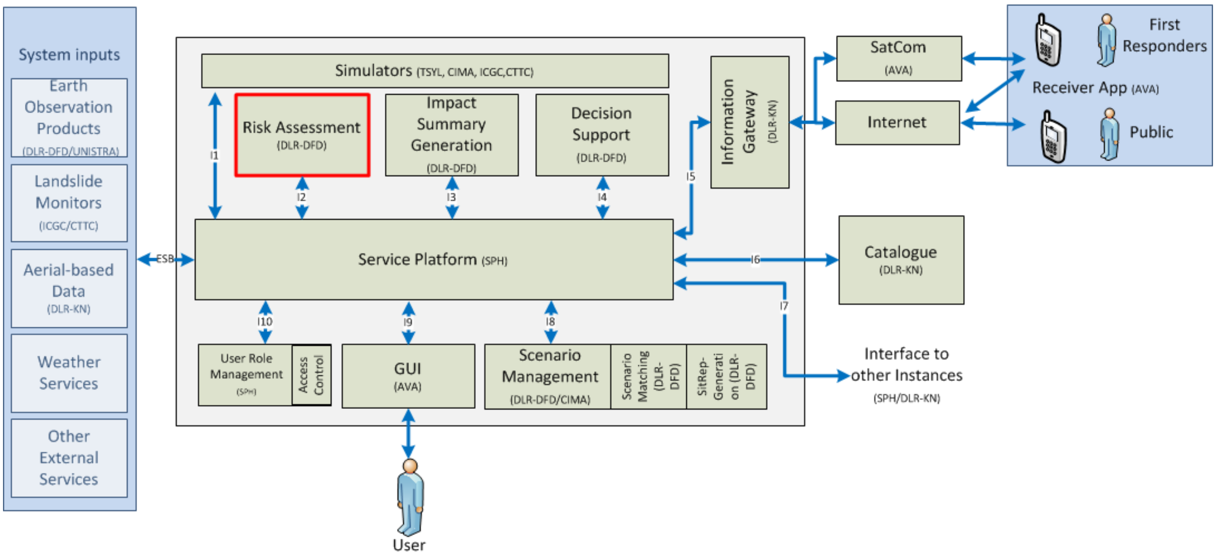

Figure 3-1: Overall architecture of the different HEIMDALL services and their connection with the RVA module.

Within HEIMDALL the RVA module is connected to the Service Platform (SP) and receives input from the Earth Observation and Simulation modules via standard RESTful services and the use of HTTP communication standards as well as FTP. As shown in Figure 3-1, other modules, such as the Impact Summary Generation (ISA), Decision Support (DS) and Situation Assessment (SA) modules, are using the output generated in the RVA module. The information provided is either aggregated, transformed into human readable text messages or used as additional parameter during the Scenario Matching (SMAC).

Table 3-1 is listing the input products consumed by the RVA module, including a short description and the expected product formats. Each input product will be used by the RVA module to generate exposure information and Impact Assessment products. Inputs are received by the Earth Observation modules (Figure 3-1) and the Simulators. Regarding Earth Observation, the following products that are specified in [42] will be consumed by the RVA module for risk analysis: flood extent, burn scar, landslide mask. The simulator products that are used during risk analysis comprise the fire perimeter, real-time flood extensions (simplified model), real-time water depth (simplified model), flood extensions (complete model), water depth (complete model), water velocity (complete model) and scenarios of potential landslide warning areas based on triggering conditions evolution. The simulation outputs differ in the level of detail depending on the hazard.

Table 3-1: Consumed inputs and generated outputs by the Risk and Vulnerability module (RVA).

Module	***Inputs***			***Outputs***		
	Product	**Short description**	**Format**	**Product**	**Short description**	**Format**
Fire Simulation	Fire perimeter	Represents the arrival time of the fire through isochrones, each line represents an hour of fire spread.	Vectorial output. In GML or GeoJSON (TBD)	Human Exposure	Quantities of the affected population dedicated to each fire perimeter.	Vector, Raster
				Physical Exposure	Location, height and function of the affected building stock, transportation networks, LULCs, CIs	Vector
	Forest fire impact relevance assessment	Relevance of the impact the fire will have on vulnerable areas	Vector or raster map of qualitative classes (low – medium – high).			
	Fireline intensity & Flame length	Fire intensity in kW/m. Flame lenght	Raster map of fire intensity and flame length.	Semi-quantitative impact assessment on population	Quantities of population within each hazard class	Vector, Raster
				Semi-quantitative impact assessment on buildings	Location, height and function of the affected building stock, transportation networks, LULCs, CIs within each hazard class	Vector
Flood Simulation	Real-time flood extensions (Simplified model)	Maps of flood maximum extensions at regional scale at coarse spatial resolution	Raster of binary values	Human Exposure	Quantities of the affected population in the flood extent.	Vector, Raster
				Physical Exposure	Location, height and function of the affected building stock, transportation networks, LULCs, CIs	Vector
	Real-time water depth (Simplified model)	Maps of maximum water depth in the flooded areas at coarse spatial	Raster of water depth	Flood Impact Assessment on buildings	Percentage damage and economic losses of building stock	Vector

Module	Inputs			Outputs		
	Product	Short description	Format	Product	Short description	Format
		resolution				
				Flood Impact Assessment on population	Number of people for different classes of water height (low, medium, high, very high)	Vector, Raster
	Flood extensions (Complete model)	Maps of flood maximum extensions at high spatial resolution	Raster of binary values	Human Exposure	Quantities of the affected population dedicated to each flood extent.	Vector, Raster
				Physical Exposure	Location, height and function of the affected building stock, transportation networks, LULCs, CIs	Vector
	Water depth (Complete model)	Maps of water depth in the flooded areas at high spatial resolution	Raster of water depth	Flood Impact Assessment on buildings	Percentage damage and economic losses of building stock	Vector
	Water depth and water velocity (Complete model)	Maps of water depth and water velocity in the flooded areas at high spatial resolution	Rasters of water depth and water velocity	Flood Impact Assessment on population	Number of people for different classes of water height and velocity combined (low, medium, high, very high)	Vector, Raster
Landslide Simulation	Scenarios of potential landslide warning areas based on triggering conditions evolution.	Terrain movement susceptibility map	Raster of landslide susceptibility classes	Human Exposure	Quantities of the affected population dedicated to each landslide susceptibility class.	Vector, Raster
				Physical Exposure	Location, height and function of the affected building stock, transportation networks, LULCs, CIs	Vector
				Qualitative impact assessment	Quantities of affected population per	Vector

Module	Inputs			Outputs		
	Product	Short description	Format	Product	Short description	Format
				on population	different level of relevance	
				Qualitative impact assessment on physical exposure elements	Location, height and function of the affected building stock, transportation networks, LULCs, CIs per different level of relevance	Vector
Fire Observation	Burn scar	Burnt areas binary mask	GeoTIFF and ESRI Shapefile	Qualitative impact assessment on population	Population density product, accounting for the number of people per grid cell dedicated to each fire perimeter	Raster
	Burn scar	Burnt areas binary mask	GeoTIFF and ESRI Shapefile	Qualitative impact assessment on physical exposure elements	Location, height and function of the affected building stock, transportation networks, LULCs, CIs per different level of relevance	Vector
Flood Observation	Flood extent	Flood binary mask	GeoTIFF / ESRI Shapefile	Qualitative impact assessment on population	Population density product, accounting for the number of people per grid cell dedicated to the flood extent	Raster
	Flood extent	Flood binary mask	GeoTIFF and ESRI Shapefile	Qualitative impact assessment on physical exposure elements	Location, height and function of the affected building stock, transportation networks, LULCs, CIs within the flood extent.	Vector
Landslide Observation	Landslide mask	Binary mask of abrupt landslide affected areas	GeoTIFF and ESRI Shapefile	Qualitative impact assessment on population	Impact on population (number of people per affected building)	Vector

Module	***Inputs***			***Outputs***		
	Product	**Short description**	**Format**	**Product**	**Short description**	**Format**
	Landslide mask	Binary mask of abrupt landslide affected areas	GeoTIFF and ESRI Shapefile	Qualitative impact assessment on physical exposure elements	Potentially impacted road network (inside / outside landslide affected area) Potentially impacted buildings (inside / outside landslide affected area, by function and number of stories) Impact on LULC classes (inside / outside landslide affected area) Impact on CI classes (inside / outside landslide affected area)	Vector

4 Module Functionality

This section outlines the module main building blocks which are depicted in Figure 4-1. Three main building blocks are defined within the module: Hazard information, exposure information and impact assessment. The hazard information products are generated either from the simulators or the earth observation modules. The extent can be derived by simulation of event propagation or observation using methods applied on earth observation data.

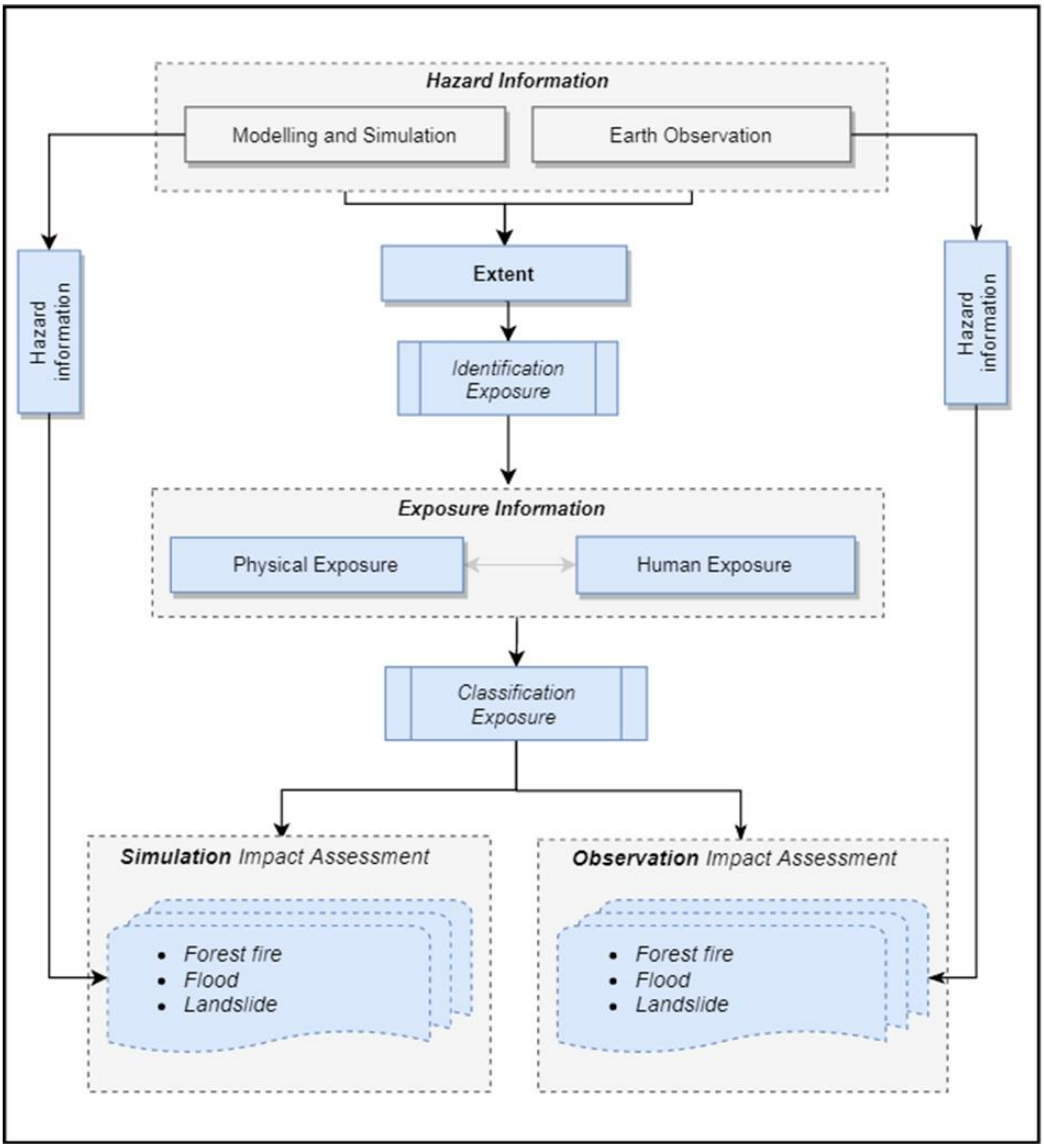

Figure 4-1: Overall risk assessment module functionality with the main building blocks and the internal interfaces.

This information is used as input for the identification of the exposed elements. Exposure information is composed of two sub-components: physical exposure and human exposure. Physical exposure is comprised by the physical elements, i.e. land use land cover (LULC) and the built-up environment. Human exposure describes the quantity and location of people, which are exposed to observed or simulated extent information. Classification of the exposed elements is performed in order to provide high detail inputs to the impact assessment block. This process includes information extraction using various sources, import of external data sources and based on that semantical categorization of the exposed elements. This information is crucial in order to apply suitable impact assessment procedures that are designed to estimate the impact on certain exposure classes.

Human exposure estimates are designed to provide a spatial-temporal assessment of the people present in hazard-prone areas. This information is created with exchange of physical exposure information, accounting for the presence of people mostly in places where built-up structure is present. Concepts on the spatial-temporal dynamics of population streams are integrated. In addition, human exposure products independent of the generated physical exposure information are integrated into the concept design in order to assure module consistency and stability.

Impact assessment concepts are designed separately for each of the hazards covered within the project. For each hazard different approaches were developed in the research community, accounting for a specific interrelation between available hazard information, the characteristics of the exposed elements and the expected damage ratio. This results in the application of hazard and exposure specific impact assessment approaches within the module. In addition, separation between simulation-based and observation-based impact assessment is performed, because the level of detail in hazard information is strongly dependent on the module generating the information.

In case of simulation-based hazard information, measures of the expected event intensity can be provided. This enables the application of functions that reflect the relation between simulated event intensity or magnitude (e.g. flood velocity or flood height), with the expected damage ratio for different exposure classes. Regarding observation-based hazard information, the observations are mostly done after the event and therefore the generation of intensity measures is not possible but the generation of post event hazard extent. This leads to different qualitative or quantitative metrics applied during impact assessment.

Disaster Management has been described for several decades as a “four phase” process involving:

- Mitigation
- Preparedness
- Response
- Recovery

These terms have been widely used by policy makers, practitioners, trainers, educators, and researchers. As illustrated in Figure 4-2 the four phases are often described as part of a continuous process. Other versions of the DM cycle involve five to eight phases [43], mostly in order to subdivide one or more of the phases mentioned above, or to stress the importance or further detail a specific phase. For this study, the classical four-phase approach has been used.

Figure 4-2: Four Phases of Emergency Management

The RVA module is one of the key components of the HEIMDALL platform, since it performs the Risk and Impact Assessment using the observed (DataEO) or simulated (SimU) hazard information. The capabilities of the module can not only be applied during monitoring, early warning and response tasks (by feeding actual data to the simulation that provides forecasts), but during all four phases of the DM cycle depicted in Figure 4-2 including training and planning activities (e.g., what-if scenarios).The impact assessment products are used during the response phase as well as for training purposes and generated fictional events during the preparedness and mitigation phases. During response phase, analysis products on post-event earth observation data, such as observed burn scar, observed landslide-induced terrain changes or observed flooded areas serve as input for the impact assessment. In addition, the simulation of incident evolution (e.g. the possible propagation of an ongoing fire during response phase) enables the module to perform What-If-Analysis with regard to the expected impact for a certain scenario. Besides the functionality during the response phase, the RVA module can be used as a platform for resource training during the preparedness phase. In training mode the RVA module is able to provide the expected impact in relation to the simulated hazard information in time in place. This enables the user to create completely fictional forest fire events, generate the likely propagation of the fire in time and place and assess the expected impact.

5 Risk Assessment Concept

This section will provide a detailed overview of the risk assessment concepts applied within the project. First, a general overview will provide insight into the common concepts in the risk community, including a definition of the terms and definitions of the underlying risk components (section 5.2). Second, the methods applied for the generation of the exposure information will be outlined in detail, including physical and human exposure information (section 5.3). In section 5.4 the concepts that are applied during impact estimation are outlined.

5.1 Overview

Reference [44] explained risk analysis, their underlying factors and the corresponding definitions. In short, risk is estimated with the following equation:

$$Risk = Hazard * Vulnerability \qquad (1)$$

Whereas hazard relates to external risk factors (probability, type, intensity and extent of an event), vulnerability represents internal factors like the capability to cope with the impacts of the hazard. The hazard is defined as the probability of a disastrous event happening in a certain period of time, with a particular intensity at a particular location. Vulnerability is the interrelation of the exposure and the susceptibility as stressor of the system with the coping capacity as the potential of the system to decrease the impact of the hazard.

$$Vulnerability = \frac{Exposure * Susceptibility}{Coping\ Capacity} \qquad (2)$$

The work by [45] further differentiated the human vulnerability dimension into a) adaptive capacity and coping capacity with regard to the human vulnerability. The adaptive capacity is the ability to anticipate and transform structure, functioning, or organization to better survive hazards, which is in line with the susceptibility from [44]. The coping capacity, defined as the ability to react to and reduce the adverse effects of experienced hazards, can been seen equivalent to the definition of [44] as they also emphasize the ability or the potential to decrease negative effects caused by impacts.

Within the project the different components needed for risk analysis is derived by the assessment of indicators since most of the factors involved are not directly measurable. According to [46] especially the vulnerability component can be assessed using indicators, which are described as “means of encapsulating a complex reality in a single measurable construct” [47] and can offer a systematic approach to discuss and quantitatively evaluate different root causes of risk and provide recommendations how to strengthen capacities for disaster risk and vulnerability reduction before an event occurs [48]. Therefore, proxies are the measurable counterpart to indicators and [24] defined them as “[...] measurable variables that can provide insight into phenomena that cannot be directly observed or measured, but which are conceptually linked.”

Within the risk analysis community the exposure is complemented by the human and the physical exposure and defines the degree of an element’s exposure according to the spatial and temporal setting. This includes physical elements such as lifeline, roads, land use land cover classes, building as well as other critical infrastructure components. In addition, the human exposure composes the human elements, i.e. the people. The degree of exposure can be inexistent, if there is no temporal and spatial overlap with the hazard information.

Reference [49] introduced the concept of Quantitative Risk Analysis (QRA) in the context of landslide impact assessment. To assess the vulnerability of the elements at risk they consider 1.) physical vulnerability and 2.) vulnerability of people, i.e. human vulnerability. In general, they defined vulnerability as the degree of loss of a given element. The IPCC defines vulnerability as "the propensity or predisposition to be adversely affected."[50]. In the agreed terminology regarding disaster risk reduction by the United Nations International Strategy for Disaster Reduction (UNISDR) [51], vulnerability is described as "[...] the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards." and therefore address the probability of loss.

Physical vulnerability refers to the direct damage to buildings, utilities and infrastructure. It can be expressed in terms of the extent of damage or the cost of recovery as a result of a given event. Human vulnerability or "Vulnerability of people" relates to whether or not a hazard will result in injury or fatalities. It can be expressed in terms of insurance value, cost of rescue, hospitalization and treatment, and the loss of earning potential.

5.2 Terms and Definitions

Within in the project at hand, the following definitions were agreed to be used. They are based on end-user expert knowledge and reflect the understanding from a practical point of view. Each of the terms will be defined and a short example will be provided.

Risk: The combination of the probability of a hazardous event and its consequences which result from interaction(s) between natural or man-made hazard(s), vulnerability (coping capacity, susceptibility) and exposure. Risk is either determined in a probabilistic assessment using simulation or modelling outputs or in a deterministic assessment implying a probability of 1, since it is based on post-event observations.

Hazard: A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. Examples for hazardous phenomena could be floods, forest fires, or landslides with adverse effects on people and properties.

Exposure: Exposure is defined by the UNSIDR ([51]) as: "… the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected." Other sources ([50]) describe exposure as: "…the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas." Since both definitions are in rather general terms, both physical and socioeconomic elements, including people, associated assets (property, infrastructure, agricultural land or economic goods) may be exposed [52], [53] through their existence in hazard prone areas [54].

Vulnerability: Vulnerability refers to the probability of the exposed elements (e.g. buildings, infrastructure, people) to take damage during an event. [14] further refined the concept of vulnerability with the susceptibility and coping capacity of the exposed elements. Therefore, vulnerability is defined as a complex interaction between physical, demographic, socio-economic, environmental exposed and susceptible elements having different levels of coping capacity. This implies that social groups with a certain combination of e.g. socio-economic and demographic features may be more vulnerable compared to other social groups. Within the project at hand, only physical vulnerability will be addressed through assessing the potential damage and loss of the physical elements [55].

Coping capacity: Ability of the system to decrease the impacts of the hazards. Coping capacity can be seen as the intrinsic vulnerability component.

Susceptibility: Likelihood of exposed elements that receive stress (hazards intensity) to be negatively affected. For example building susceptibility to landslide hazards could be estimated over structural building type (e.g. refined concrete) and the building age (30 years. Other analysis includes the analysis of landslide susceptibility that identifies areas most susceptible to landslides occurrence. The susceptibility can be seen as the extrinsic vulnerability component.

Cascading effects: Cascading effects are the dynamics present in disasters, in which the impact of a primary events trigger other secondary events or a sequence of events in human subsystems that result in physical, social or economic disruption [56]. Cascading effects can either trigger other events or increase/decrease the probability of occurrence [57].

5.3 Exposure Estimation

For comprehensive risk assessment, the identification of elements at risk, i.e. the elements exposed to hazard, have to be identified. This is usually done through geometric operations using geographic information systems (GIS) by intersecting the exposure data set with the hazard information. The hazard information relates to factors like type of event, intensity and extent of the event [44]. The exposure data set consists of the physical elements (building stock, transportation network, critical or significant infrastructure elements) and human elements, i.e. population. Both human exposure and physical exposure are closely related, since the building stock is used for the estimation of the human exposure estimation.

As a first step, the building stock information is generated by fusion of multi-sensor information, including high and very high resolution image data, Airborne Laser Scanning (ALS) and OpenStreetMap data. Building height and building function are the main characteristics used for the classification of the building stock. Building height can be extracted from earth observation such as Digitial Surface Models (DSM) following the concept of [58] or from joint use of earth observation data and VGI following the concept of [10]. Ancillary information on building function is usually derived from land use/land cover (LULC) maps, classifying buildings as residential, commercial or industrial buildings.

Second, statistical information regarding the total number of inhabitants per administrative unit is distributed on single buildings or building blocks depending on data quality and availability [46]. This method utilizes the concept of areal interpolation methods such as dasymetric mapping, i.e. disaggregate coarse population data to units where it is present at a finer resolution.

Generating the exposure information is performed using multi-sensor image data, OpenStreetMap data, land use/land cover information and socio-economic statistical data sets. First, physical exposure information has to be extracted from various data sources in order to identify the physical elements that could be adversely affected. The physical exposure data set consists of buildings, critical and significant infrastructure including for example educational and health facilities, as well as the transportation networks and other assets. Most importantly for the exposure workflow is the building stock information that is used during the human exposure estimation process (Figure 5-9). Detailed information on building function, building height and location are used as basis for the disaggregation of population counts from administrative level to finer scale population information on building or building block level [59].

5.3.1 **Physical Exposure Estimation**

The process of physical exposure estimation aims at identification and classification of physical elements at risk and elements affected by an incident. In general the workflow can be outlined as follows (also depicted in Figure 5-1):

1. Identification of the affected geographical area using hazard Information provided by simulation or observation products
2. Generation of multi-source physical exposure set containing building stock information, transportation networks, land use land cover information, as well as critical infrastructure for the area defined by observation / simulation.

With the hazard information (1) provided by simulation and earth observation services, the identification of exposed elements (2) can be performed. Therefore, for the geographical area that is subject of an hazardous situation, the exposed elements will be extracted from different data sources and through a wide range of remote sensing techniques, including OpenStreetMap data, analysis of VHR satellite and airborne data sets, as well as feature extraction from very high resolution DSMs obtained from LIDAR point cloud data.

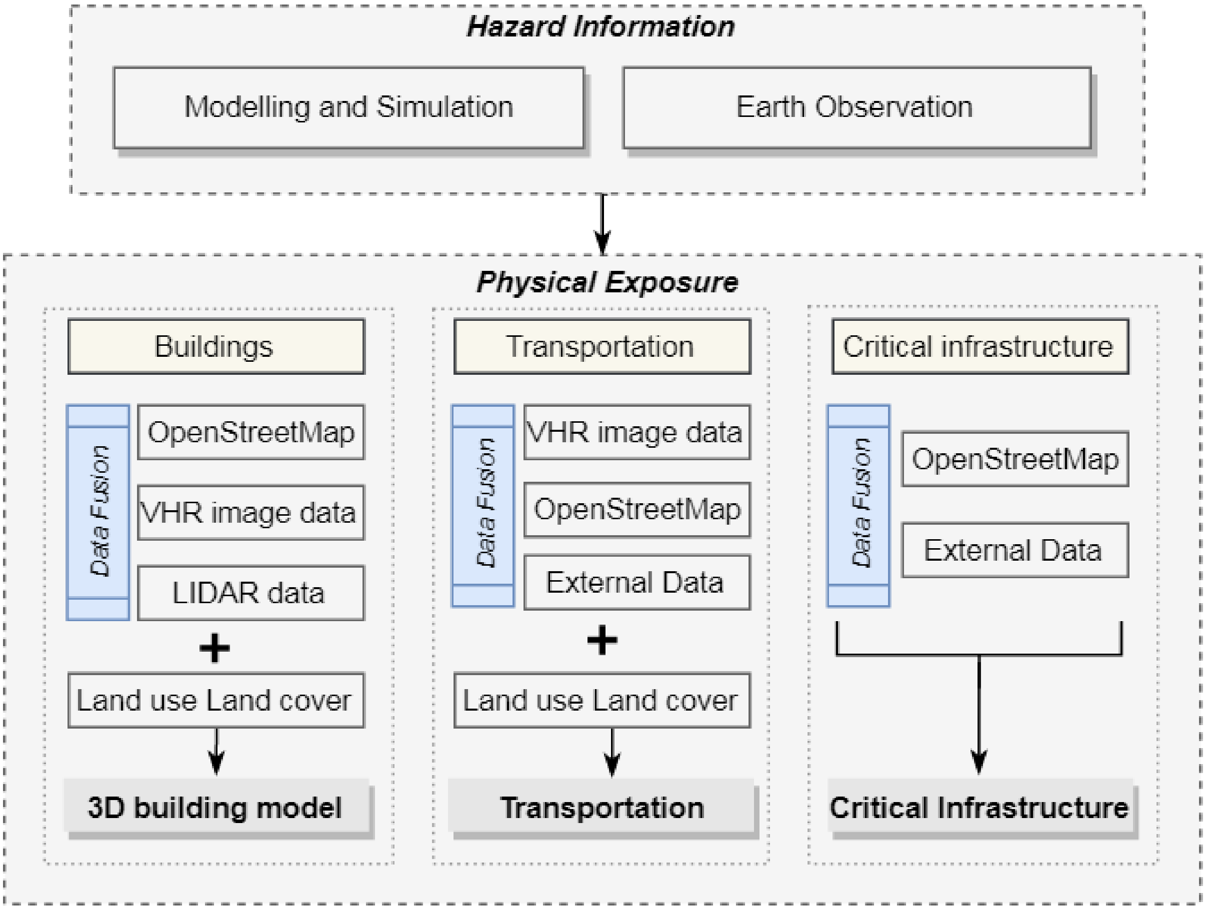

Figure 5-1: Concept design of the physical exposure estimation

The OpenStreetMap project (OSM) is a knowledge collective that provides user-generated street maps, building footprints, points of interest and other base-level geographic information objects. In the context of detailed urban mapping, crowdsourcing of geospatial data using informal social networks and web technology has gained attention in the past decade. Although the accuracy, availability, and completeness of volunteered geographical

Figure 5-2: Example of OSM building outline completeness at the City of Girona, Spain. Note the built-up area in the central area, which is not covered by OSM building outlines

information (VGI) depend on the individual mappers [60], stepwise improvement of the overall data quality is promoted by a self-controlling mechanism of mutual quality control and error reporting within the user community. Thus, OSM presents a valuable and cost-effective data source as an open source effort to map the world's streets, roads, railway, waterways, place locations and natural environment, especially in data-poor countries. Complete street maps can be used to weight population distribution within a given spatial unit- such as a postal code [60]. However, the streets in OpenStreetMap are rarely fully neither consistent nor complete due to local interest and activities of mappers. However, providing both land use and infrastructure information on building level a large global data basis has been compiled since 2004 [61]. Reference [60] attempts a first quality assessment of OSM road network data against Ordnance Survey data for the United Kingdom (England and Scotland) finding that OSM data can be fairly accurate with approximately 80 percent overlap with motorways. OpenStreetMap building outlines will be used as one source in the building bracket of the physical exposure workflow (Figure 5-1). When using volunteered geographic information (VGI) [62] data for geoinformation analysis, quality and completeness issues are the main challenges. Therefore, quality measures for OpenStreetMap data have been presented ([63], [64]) that assess the quality and actuality of the VGI data. Using quality measurement beforehand the OSM building outlines shall serve as one source for generation of the building stock information.

By employing an object-based, multi-level and hierarchical classification procedure using very high resolution optical satellite imagery, a high-detail building classification was generated to showcase the capabilities of remote sensing for semi-automatically mapping physical elements on building level [65]. Buildings not covered by the OSM buildings outlines, can be detected through the analysis of airborne or satellite sensor data and therefore complement the building stock information.

Airborne Laser Scanner utilize the concept of Light Detection and Ranging (LIDAR) creating point cloud datasets describing the physical features situated on ground. Depending on the point density per square meter, high - vey high resolution Digital Surface Models (DSM) can be extracted from point cloud data. The methodology of building extraction from DSM has been presented by [66] for TanDEM-X DSM. Similar concepts presented by [58] show the high capability of DSM analysis for the extraction of building height and building footprint using very high image data. Both works use Digital Surface Models (DSM) as basis for the identification of bare earth points and interpolation of the Digital Terrain Model (DTM). Terrain and Surface models are used to generate DSM information, normalized by the DTM information. Figure 5-4 exemplifies the generation of the nDSM, used for the extraction of height information for the 3D building model.

Classification of the building stock layer is done based on a hierarchical building function taxonomy developed within the project. The taxonomy was developed in order to provide a generic building function schema, which can be used to map the taxonomies used in external datasets to one generic schema. This allows the application of the developed methodological concepts using different building function taxonomies that may be present during a cross-border incident or through the integration of different building data sets. Within the taxonomy, four hierarchical building function levels with different levels of aggregation are defined. Figure 5-3 shows four levels of the taxonomy, with the first level (Level_1) holding generalized function information separating residential from non-residential buildings. The fourth level (Level_4) holds the highest degree of information available in the building stock layer, showing for example the location of critical infrastructures like educational buildings (e.g. schools, universities, adult education centres). Information regarding critical infrastructures that are typically linked with buildings is stored in the building stock layer using the developed taxonomy. Unlike in the third level (Level_3), buildings with unspecified function information may be present in the fourth level. For example main residential buildings (Level_3) might not be specified further (Level_4) with regard to differentiation in single family or multifamily housings and are therefore unspecified in the fourth level.

Figure 5-3: Example building stock product classified according to the developed hierarchical building function taxonomy. 4 levels of detail are holding information with increasing level of aggregation.

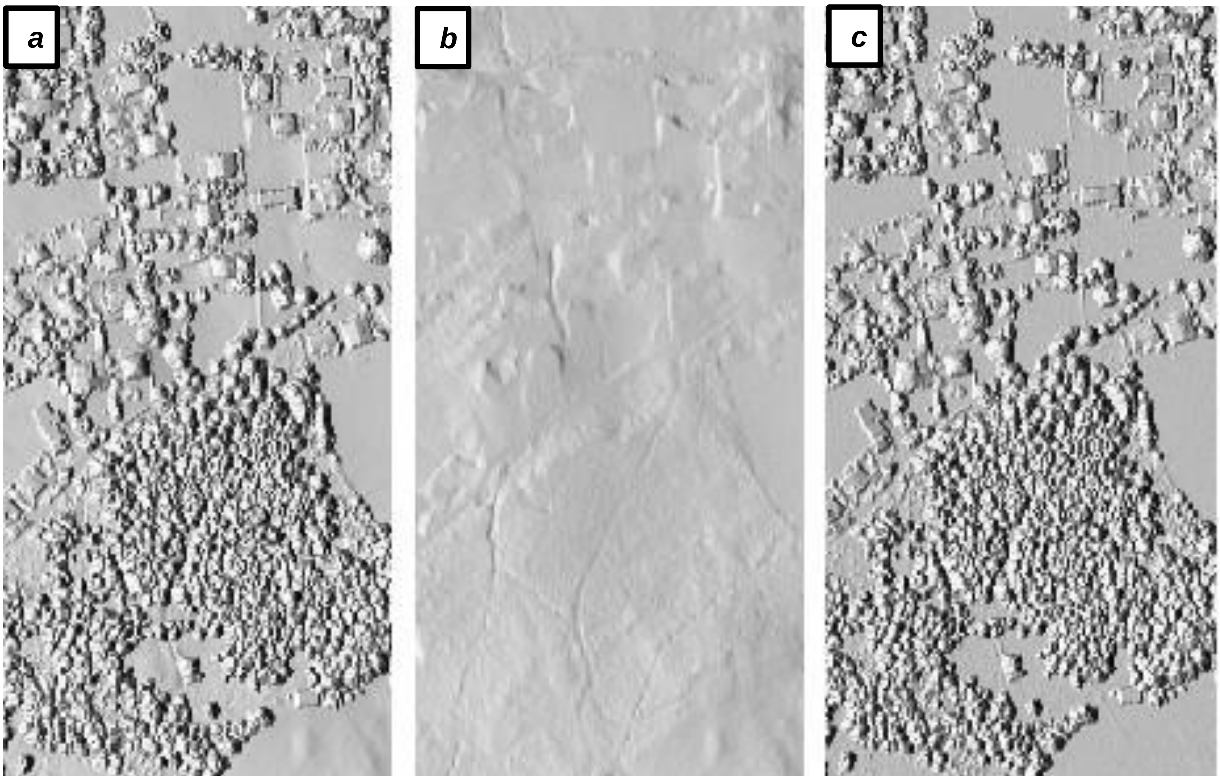

Figure 5-4: Steps for the creation of Normalized Digital Surface Models (nDSM). a) Extracted DSM from ALS point cloud data. b) Digital Terrain Model (DTM) created through identification of bare earth points. c) Normalized Digital Surface Models (nDSM) containing the normalized height value per cell [67].

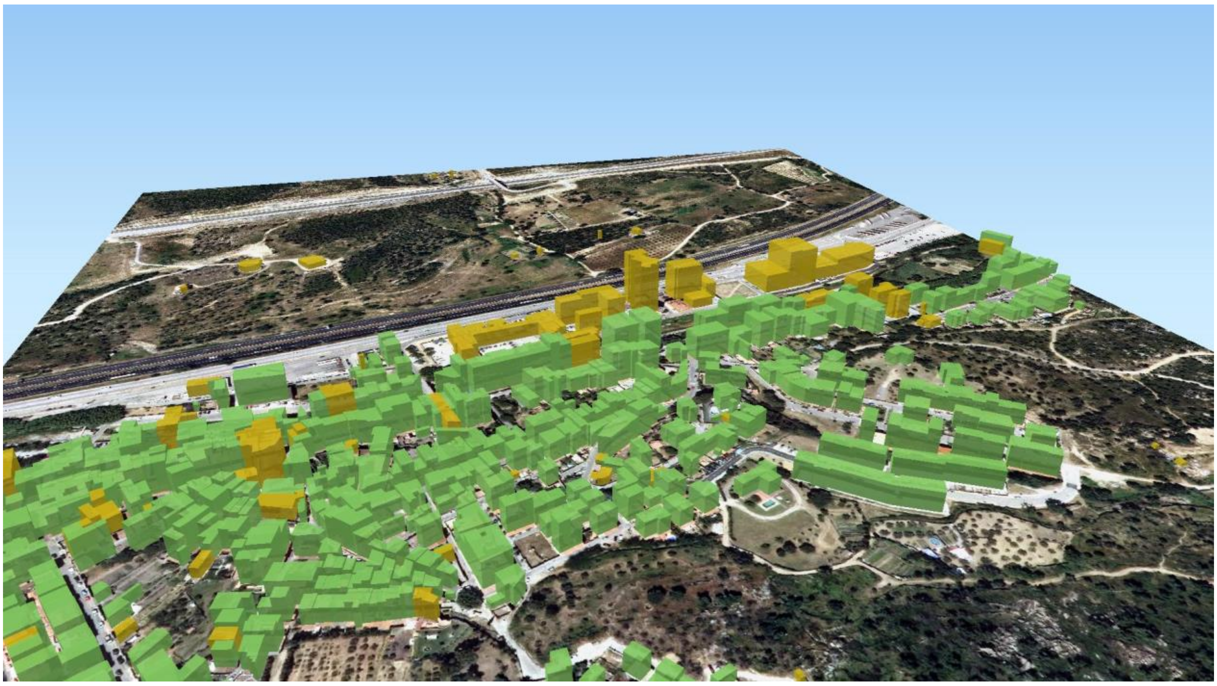

Figure 5-5: Example output of the 3D building model product showing the first level of the building function taxonomy (residential, non-residential) and the building height derived from the nDSM.

Figure 5-5 shows the first level of function information (residential vs. non-residential building function) present in the 3D building model. The figure uses 2.5D visualization techniques to represent the assigned ground-based height information, extracted from the generated nDSM. The building height is input for regression tasks, accounting for the relationship between building height and building storey number. Linear regression models were trained with ground truth building information in order to predict the building storey number from the assigned building height.

Transportation networks are complementing the physical exposure information, holding information on the location and type of roads and railways present in hazard-prone areas. Several data sources are investigated in order to provide the highest possible degree of geometric and semantic information. This includes the application of artificial neural networks (ANN) classifiers for the extraction of transportation networks from high and very high resolution image data [68]. Figure 5-7 shows the result of ANN based transportation network detection in multispectral IKONOS satellite imagery. The OSM transportation networks holds information on the road networks present, with different levels of importance. This information is queried and integrated into the physical exposure data set. In addition external data sources provided by external data providers are integrated if available. LULC products with a high thematic and geometric accuracy are another possible source for the complementation of the transportation network. Figure 5-6 shows the transportation network queried from the OSM database, with primary, secondary, tertiary and local roads present in the area of interest.

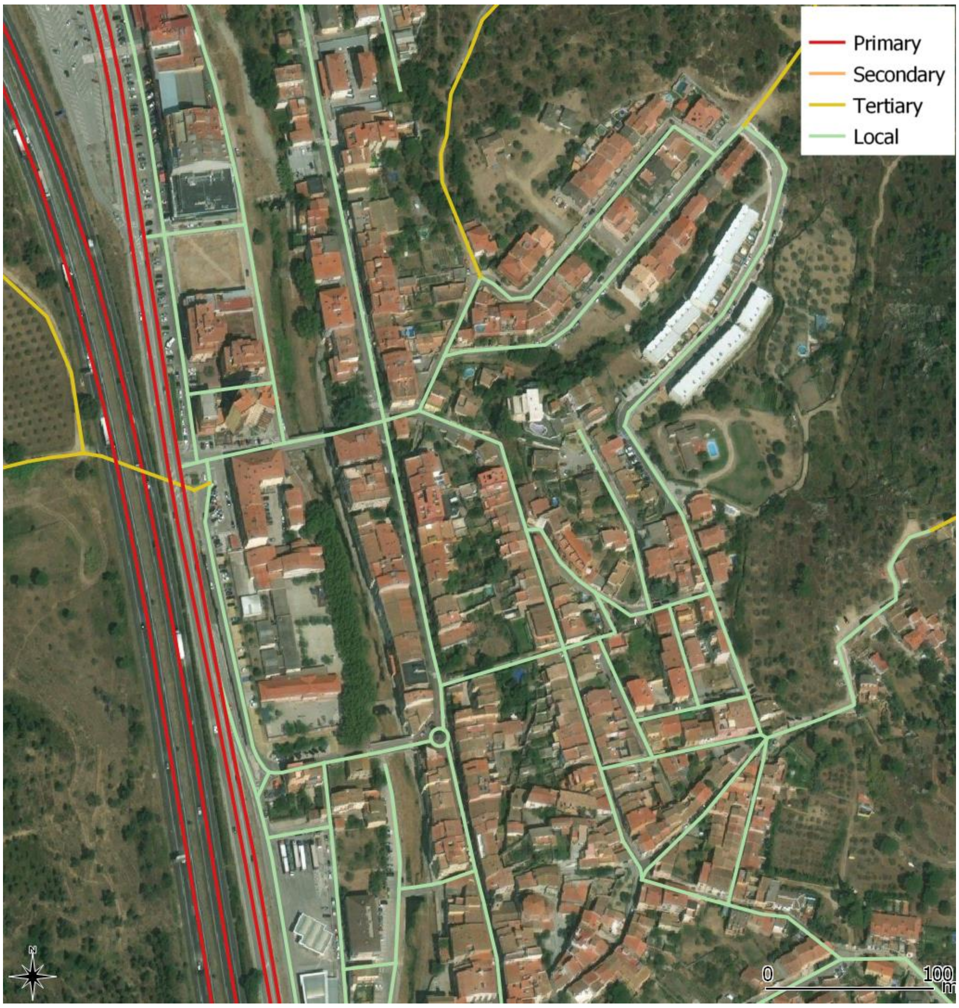

Figure 5-6: Example physical exposure output, showing the extracted transportation networks with the different road types primary, secondary, tertiary and local.

Figure 5-7: Road detection examples based on RGB Ikonos image data using artificial neural networks (ANN) presented by [68].

When a major disaster occurs, especially in remote parts of the world, knowing if the area is populated, and how densely, is crucial for the effective organisation of humanitarian interventions. This can help to reduce risks in areas that experience recurrent disasters and to focus post-disaster humanitarian interventions on the most likely populated places in disaster-affected countries and regions. In this context, global and regional land use land cover (LULC) data sets present a valuable basis for the analysis of large-scale human exposure and a first approximation of their spatial distribution. In order to obtain local- and regional-scale human exposure products, the integration of high-detail physical exposure information is necessary. Typically, the building stock information is used for the human exposure estimation. The thematic accuracy of the building function information may be very coarse of even inexistent. In this case, LULC map products shall be used to increase or complement the thematic accuracy of the extracted building outlines using hierarchical building function taxonomy (Figure 5-3). This step classifies the detected buildings by their predominant functions, providing separation in residential and non-residential buildings according to the first level of the building function taxonomy. In case suitable national LULC is available, the information can be mapped to higher levels in the taxonomy.

Subsequently two LULC products of regional European coverage as well as two LULC data sets of global coverage are presented, that could be used within the project for large-scale mapping of exposure.

The pan-European CORINE Land Cover (CLC) database provides a unique and comparable data base of seamless land cover and land use information for Europe based on satellite remote sensing images on a scale of 1:100,000 for the years 1990, 2000, 2006 and 2012. The most recent update was completed in 2012 and comprises 44 land use classes of which two correspond to urban fabric (continuous and discontinuous). With the regard to the multi-temporal approach, also area-wide regional land use change maps were obtained [69]. The main data source for the production of the dataset were three high-resolution satellite data sets (IRS Resourcesat-1/2, SPOT-4/5, RapidEye constellation) provided by ESA. Land cover derivation was based on techniques of computer-aided photointerpretation and manual digitizing with an overall thematic accuracy of above 85 % [70].

Featuring a more differentiated urban thematic detail, the Urban Atlas provides pan-European hot spot mapping of urban functional areas (FUAs), on the basis of repeatedly and homogenously processed data for larger European cities [71] and claims for itself to be the first large-scale geo-data set ever produced operationally from higher resolution optical satellite data. The European Environment Agency (EEA) produced the detailed database of maps and land cover information for 117 European cities. It encompasses 17 urban thematic classes with a minimum mapping unit (MMU) of 0.25 ha and 10 non-urban classes with a MMU of 1 ha. Information about impervious surfaces (IS), i.e. surfaces impenetrable by water such as side- walks, driveways, rooftops and parking lots as indicator for urban functional land use, are aggregated in five classes on building block level, ranging from discontinuous very low (<10% IS), low (>10-30% IS), medium (>30-50% IS) and dense (>50-80% IS) urban fabric to continuous urban fabric (> 80% IS) [72].

The Joint Research Centre’s (JRC) Global Human Settlement Layer (GHSL) is a planned globally available urban land cover dataset realized as an on-going by the European Commission (EC). For its derivation a novel approach has been developed to map, analyse and monitor human settlements and their spatiotemporal evolution in an automated manner [73]. The GHSL automatic image information extraction workflow integrates multi-resolution (0.5m-10m) multi-platform, multi-sensor (PAN, multispectral), and multi-temporal image data. Multi-scale urban parameters such as built-up area and density as well as average size and number of buildings will be derived on spatial units of 10m, 50m and 500m. The first release of data in 2012 builds on over 16,000 remote sensing datasets covering over 24,000,000 km² from 10 different satellite platforms and sensors.

Based on the German space missions TSX and TDX two coverages of the entire landmass for 2011 and 2012 have been acquired. In this context, DLR has developed a pixel-based classification approach aiming to globally extract urban and non-urban structures from single radar imagery. The intended “global urban footprint” will be a binary classification of urban and non-urban areas at global scale based on single polarized images acquired in Stripmap mode with a resolution of approximately 3 × 3 m. Considering the challenges of a global urban footprint production, the algorithm is currently further investigated for the potential to improve the classification performance by substituting the presented threshold-based technique by a machine-learning approach [74]. In a pilot study accuracy assessment for the test case Padang, Indonesia resulted in an overall classification accuracy of 77%.

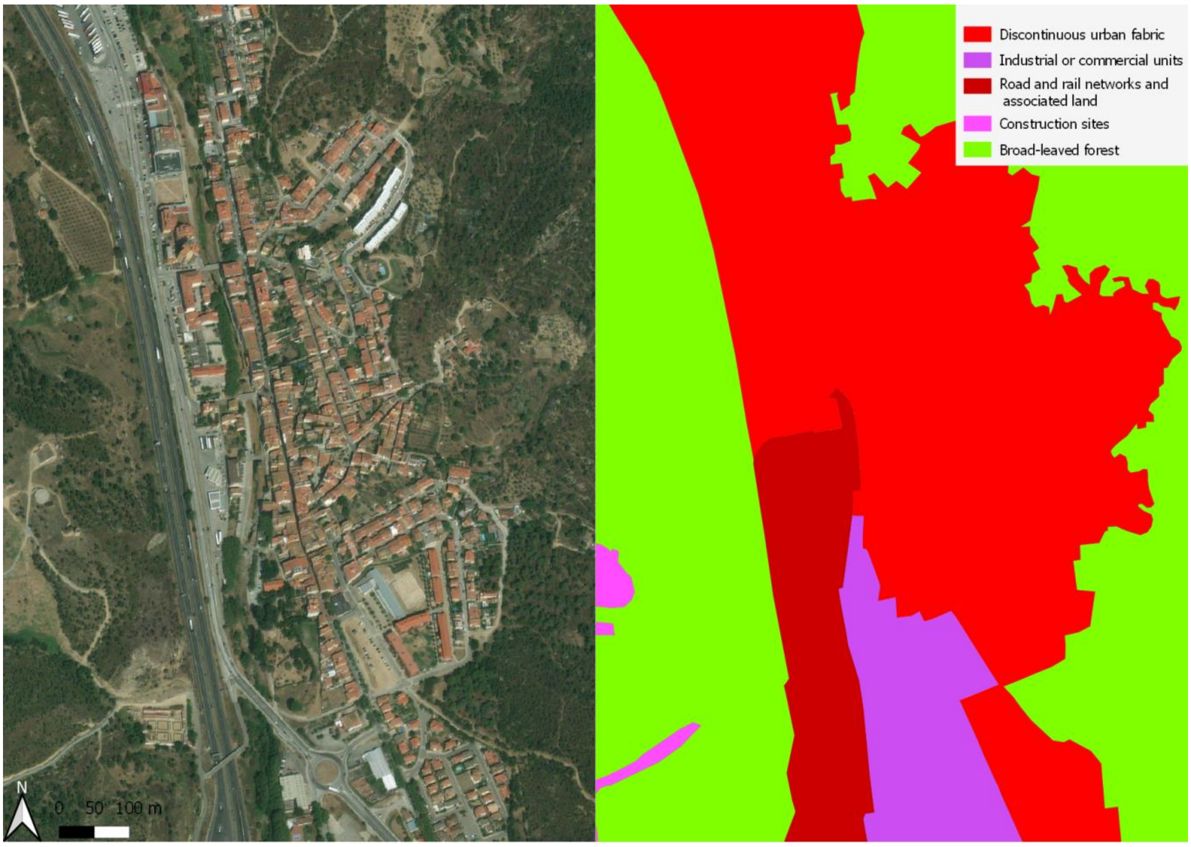

Figure 5-8: Example CORINE Land Use Land Cover map product holding the information on predominant land use.

The identification of exposed critical infrastructures will be mainly based on national external data sets, since the quality, completeness and reliability of critical infrastructure information plays an important role. The diverse definitions of critical infrastructures, lead to the here presented concept that will mostly rely on national datasets. Nevertheless critical infrastructures such as health and educational facilities extracted from OSM with the respective tags will complement the external dataset, if applicable.

The complemented multi-source physical exposure data set with information regarding the 3D building model, the transportation network and information on critical infrastructures will be utilized for the impact assessment and during the human exposure estimation integrating census data.

5.3.2 **Human Exposure Estimation**

Exposure estimation should not only consider physical assets situated in hazard-prone areas, but also the human exposure, i.e. population situated in hazard-prone locations. Besides the common datasets used in the disaster risk community (LandScan [22], GHSL Pop [75]) for the estimation of affected population, a high-resolution human exposure dataset will be generated on the basis of national census data and the building stock information provided by the physical exposure estimation.

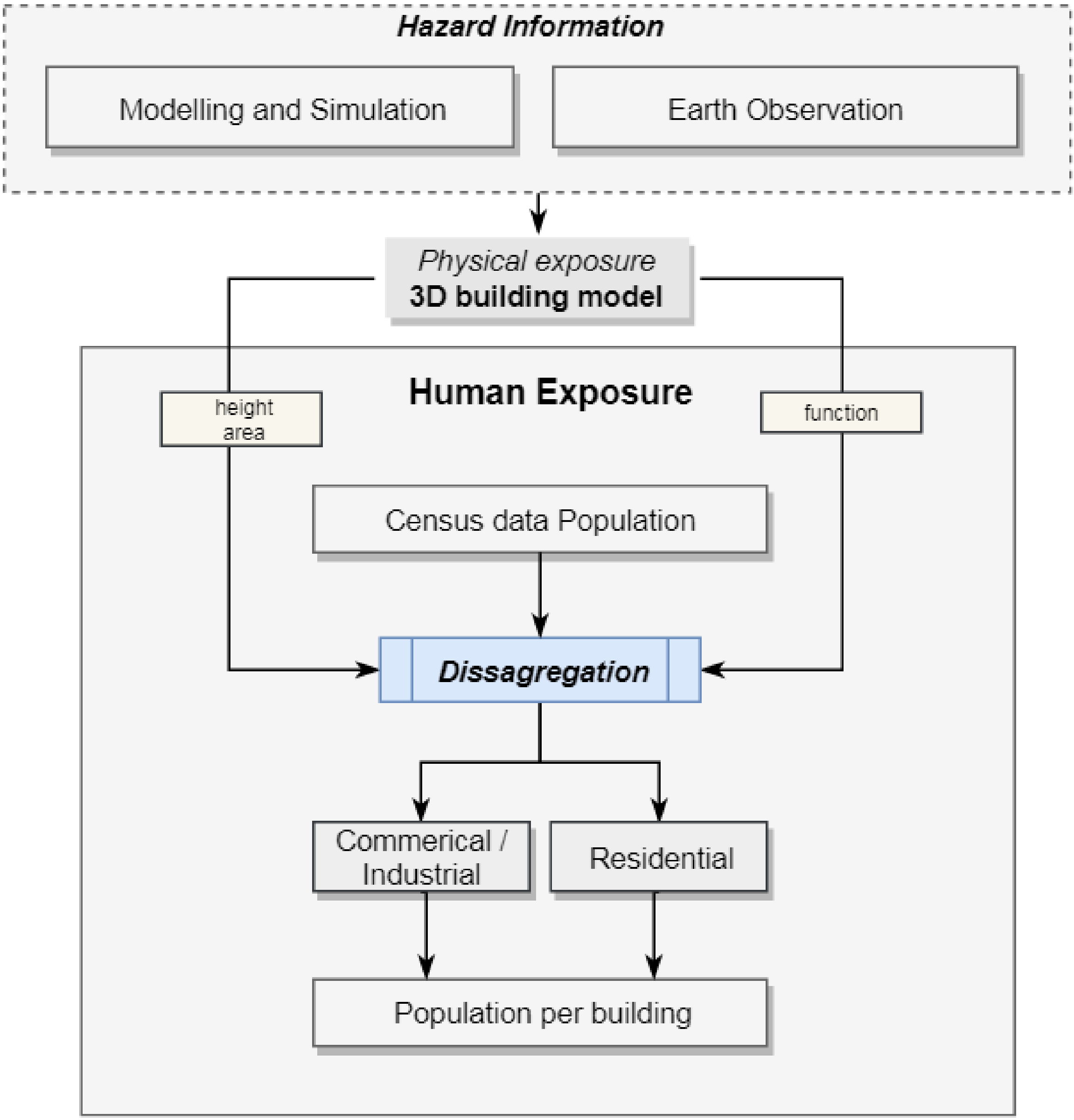

Figure 5-9: Concept design of the human exposure estimation using disaggregation methods for the generation of per building population product.

The quality and timeliness of the available census data as well as the thematic and spatial accuracy of the 3D building model are the main drivers for an accurate assessment of the human exposure. The disaggregation of population counts from administrative boundaries to buildings or building blocks requires areal interpolation methods such as dasymetric mapping [46], [76], [77].[59] reviewed common areal interpolation methods and concluded that among the different approaches available the dasymetric method is the most accurate and stable solution for disaggregated population estimation. Therefore, dasymetric mapping will be applied in order to retrieve a high spatial resolution human exposure product. As outlined in the concept designed in Figure 5-9, information about the building function (residential, non-residential) that is stored per building or building block and the information about the building height and area are used during the areal interpolation of the census population counts. For each of the affected administrative areas during an event, census counts holding information about the total population and the total share of unemployed citizens per area are used as source information. Within the designed approach, two target building groups are selected for the disaggregation method: residential and non-residential buildings. Using the information about the rate of unemployment within an area, the source information can be calculated for two groups: labour force and non-labour force. Using source and target information, necessary density measure for the disaggregation process can be obtained. Figure 5-10 shows two human exposure products, generated over specific density measures. During the daytime population estimation, the employed proportion of the total population is assumed to be situated in non-residential buildings. The unemployed proportion of the total population is assumed to be situated in residential buildings. In contrast, for the night-time population product, the majority of the total population is situated at their residence.

This disaggregation concept results in a shift of population density towards non-residential (commercial and industrial) buildings during the day in comparison to the population densities that can be observed during the night-time situation. This methodology ensures the consideration of spatial-temporal population dynamics as documented by [46], [76]. With increased level of detail in the census data provided (e.g. number of pupils, elderlies) and the available information on respective target groups (e.g. schools, stationary care) the disaggregation methodology will be further refined.

In case data quality is insufficient or the necessary data is unavailable, the GHSL Population raster product ([75], [78]) will be used. The product contains population counts on a regular grid with a pixel size of 250m.Even though, the level of detail for human exposure assessment on the local level might be too coarse, the dataset offers consistency and is therefore used as a fall back source the estimation of the affected people. While on supra-regional level coarse scale raster data on population are mostly sufficient, for risk analysis on smaller scales higher spatial resolution is required [46].

Figure 5-10: Example human exposure products showing the daytime and night-time product. The 3D building model (area, height and their predominant function) and the integration of census count data are the basis for the generation multi-temporal human exposure products.

5.4 Impact Assessment

Impact Assessment will be performed using the created exposure data and the hazard information provided by the Earth Observation module and Simulation modules. The expected impact will be addressed either by linking the intensity and/or the extent of the hazard. Depending on the hazard type, the level of detail in hazard information can be different and therefore hazard specific concepts will be outlined in the following sections either working with simulated or observed hazard information.

5.4.1 Simulation-based Impact Assessment

Simulation-based Impact assessment will be developed on the basis of the logical scheme adopted within the RASOR project.

From a general point of view, techniques for the estimation of risk linked to natural hazards are often grouped into three broad categories: qualitative (inventory and knowledge driven), semi-quantitative (partially data driven) and quantitative (data driven, deterministic, and probabilistic methods) [79–83], though the second technique tends to be a conjunction of the other two categories. The approach here adopted refers to the latter category; more specifically, deterministic/scenario-based analysis is performed. Such kind of analysis is usually applied at local scale due to the process complexity as well as to the required detailed data.

Direct impacts are evaluated through the use of vulnerability functions (also known as damage-state functions); such functions provide a relation in the form of a curve, with an increase in damage for a higher level of hazard intensity. Impact is thus evaluated as in the following:

$$I_a^s = f_a^h(w^s) * E_a$$

where:

E_a is the value of the asset a, typically expressed in monetary form;

w^s is the forcing (measure of the intensity of the hazard) acting in the location where the considered asset is placed in connection to the specific scenario/situation under evaluation;

$f_a^h(\cdot)$ is the vulnerability function for asset a in connection to hazard typology h; the domain of the function returns percentage values;

I_a is the direct impact connected to the specific asset (exposed element) a in scenario/situation s; it represents the damaged portion of the value of the asset E_a.

Different types of assets will show different levels of damage given the same intensity of hazard; this can be expressed by different shapes of the function $f_a^h(\cdot)$.

Two types of vulnerability functions can be found on literature, historical and synthetic curves. Historical curves are developed from historical loss data from actual events. Synthetic curves instead rely on the analysis of expected damage under certain hypothetical hazard conditions and are used when sufficient past events are not available.

Different functions exist for each couple type of hazard – type of asset, as they may derive from different studies, different geographic peculiarities, different level of detail of the analysis to be performed. In this context, asset-level functions will be preferred whenever possible. Furthermore, curves expressing the impact as a function of the detailed quantitative description of the hazard will be preferred whenever possible; i.e., whenever the simulation models integrated within HEIMDALL provide outputs that are suitable for the use in connection with such type of damage model. Such functions will be used for the development of the proper Impact Assessment.

Whenever this way can't be followed, a simplified approach will be adopted, using qualitative (or semi-quantitative) information for the description of the specific hazard situation to define intensity classes; such classes will be associated to exposure information in order to identify elements at different level of risk; obviously, the information connected to the level of risk will be qualitative in nature.

Despite the choice of specific curves to be used in connection to the specific output of the simulators, such curves will be organized in libraries (i.e., set of functions characterised by certain analogies) depending on the type of hazard considered and the information available on the spatial distribution of the forcing.

5.4.1.1 Forest Fire Impact Estimation

Forest Fire Impact Estimation will be performed through the use of semi-quantitative functions based on the approximate levels of damage for different thermal fluxes as reported in [84] and [52]. The combination of the information on fire-line intensity and flame length will be used to classify the exposed elements according to a semi-quantitative thermal flux scale. Typical damages described in the previously introduced works will be converted in hazard scales for specific categories of exposed elements (i.e. population and buildings). The output of the Impact Estimation module will be a vector or a raster file (depending on the nature of the exposure input) reporting the numerosity/location of the specific assets within the areas characterized by different hazard level.

Furthermore, the FFS simulator of the modelling and simulation module shall provide a functionality/service to estimate the impact relevance on the human and physical elements as described in deliverable D5.12 [85]. Based on the perimeter of an already existing simulation, this service identifies which are the elements (i.e. population, critical infrastructures, buildings in general) that are expected to be affected by the simulated fire, their typology, the time at which it is estimated that these elements are affected and the direction of the fire at the time of impact with the physical elements. Additionally, if economic values are provided, this service can also provide an evaluation of the estimated cost amount caused by the fire. In any case, this impact relevance service considers that in case an exposed element is affected by fire this element is completely damaged by this phenomenon not considering levels of damage the fire can cause in the considered element. The output of this service shall be a vector or raster file with the number and type of elements affected.

5.4.1.2 Flood Impact Estimation

The flood impact estimation sub-module in HEIMDALL integrates directly the one developed within the RASOR project, without introducing relevant modifications.

Most flood damage functions are based on the relationship between the type/use of the element at risk and the flood depth. The assumption that is implied is that a large hydrostatic pressure differential between the inside and outside of a building does not occur and the dominant effect of the flood is the slow-moving water that is at contact with buildings and objects [86], [87]. This is exactly the choice made for the structuring of the main library of vulnerability functions for the complete impact assessment that uses the building usage as key element for the assignment of the functions to the assets, together with the height of the buildings expressed in number of storeys.

For flood impact assessment on buildings, the vulnerability library developed within the RASOR project and based on the HAZUS MH Model [88], [89] will be used; such a library has been tested also in [90] and [91]. The library provides specific functions for different building usage and number of floors. The output will be a vector file describing, for each building, the percentage damage; if information on replacement costs is available, also the loss in monetary value will be provided. Such library will be applied to the output of both the simplified and the complete models.

Also the case of flood impact assessment on population is based on the work in the RASOR project, that embedded two vulnerability functions using as forcing the water depth in one case, and the product of water velocity and depth in the other; the latter is based on the work presented in [92], and it has been tested in [90]. In both cases, the quantitative information is used to obtain hazard zones; number of people in the different zones constitutes the output of such evaluation.

5.4.1.3 Landslide Impact Estimation

The output of the landslide simulator that may be used for impact estimation is the potentially affected area. The simulator will provide the area that may be affected by the propagation of a moving mass detached or failed in a source area, identified automatically or by the user through GUI. Whenever the user is able to define also a level of relevance (within a pre-defined qualitative scale) of the identified areas, these can be used as hazard zone analogously to the ones used in the impact assessment for forest fires and floods.

As for vulnerability, contrary to other natural hazards, the complexity and the wide range of variety of processes [93] make its assessment in case of landslides very difficult. There is no widely accepted and validated method in literature at present to assess landslide vulnerability [94].

Usually expert-based approaches are based on the use of tables and matrices, providing a qualitative description of vulnerability. Several qualitative approaches have been analysed inside the ENSURE project [95]. An analogous approach will be structured within the HEIMDALL system, starting from the data that will be provided by the landslide simulator.

The output of the model is a GeoTIFF file, that provides the susceptibility of each pixel of the DEM model, so each unit of the terrain (resolution depends on the DEM resolution), to become unstable and slide, given the conditions that the user provides to the simulators, with specific reference to the kind of output that can be provided for landslides, rockfalls and debris flows.

In case of landslides, the output of the model is a GeoTIFF file, that provides the susceptibility of each pixel of the DEM model, so each unit of the terrain (resolution depends on the DEM resolution), to become unstable and slide, given the conditions that the user provides to the simulator. Three susceptibility classes (plus the 0= no data) can be identified, starting from 1 (Low susceptibility) to 3 (High susceptibility). The level of susceptibility measures the likelihood of the area to become unstable and slide.

An analogous scale is defined in case of rockfall/ debris flow, in this case the susceptibility indicating the likelihood of the area to be reached by a rockfall or debris flow.

This information will be used as input for a matrix approach for the identification of risk associated to the given area; the other element necessary to use such matrix is linked to the potential damage. Due to the difficulties previously introduced regarding the evaluation of vulnerability to landslides, a conservative approach has been chosen, setting this parameter to 1; this equals to assume that an asset involved in an event is completely destroyed (or not functioning). Such assumption implies that the potential damage coincides with the exposure value, being it expressed in terms of number or (economic) value of the assets.

The output will be expressed in a 3-level qualitative scale.

5.4.2 Observation-based Impact Assessment

Observation-based Impact Assessment is performed using Earth Observation satellite images, acquired before and during / after a disaster event. The pre-event data, which should be as recent as possible, provides knowledge and overview of the territory and assets prior the disaster. This “reference” image is compared to crisis or post-event images in order to evaluate the disaster extent, and grade if possible, and then to assess the disaster impact. This Observation-based solution provides information at a certain date and time. Multi-temporal post-event satellite data can be used to give an assessment of the evolution of the event extent and impact.

The EO based impact assessment workflows are the fruit of close to twenty years of rapid mapping development dedicated to natural disasters management, within international and European frameworks. The actual Copernicus Emergency Management Service – Rapid Mapping [96] delivers standardised products, such as Delineation and Grading maps, providing an assessment of the event extent and of the damage grade, including information specific to affected population and assets, e.g. settlements, transport networks, industry and utilities. Moreover, the International Working Group on Satellite-based Emergency Mapping (IWG-SEM) has finalised Emergency Mapping Guidelines [29], specifying among other things the content and general workflow of impact assessment products.

5.4.2.1 Forest Fire Impact Estimation

Forest Fire Impact Estimation is built on Crisis and Situational data, coming from external databases and satellite imagery. The exploitation of these input databases leads to the set-up of an Exposure Database and a Fire Extent and Grade mapping. The impact assessment is generated by intersecting exposure and extent / grading information.

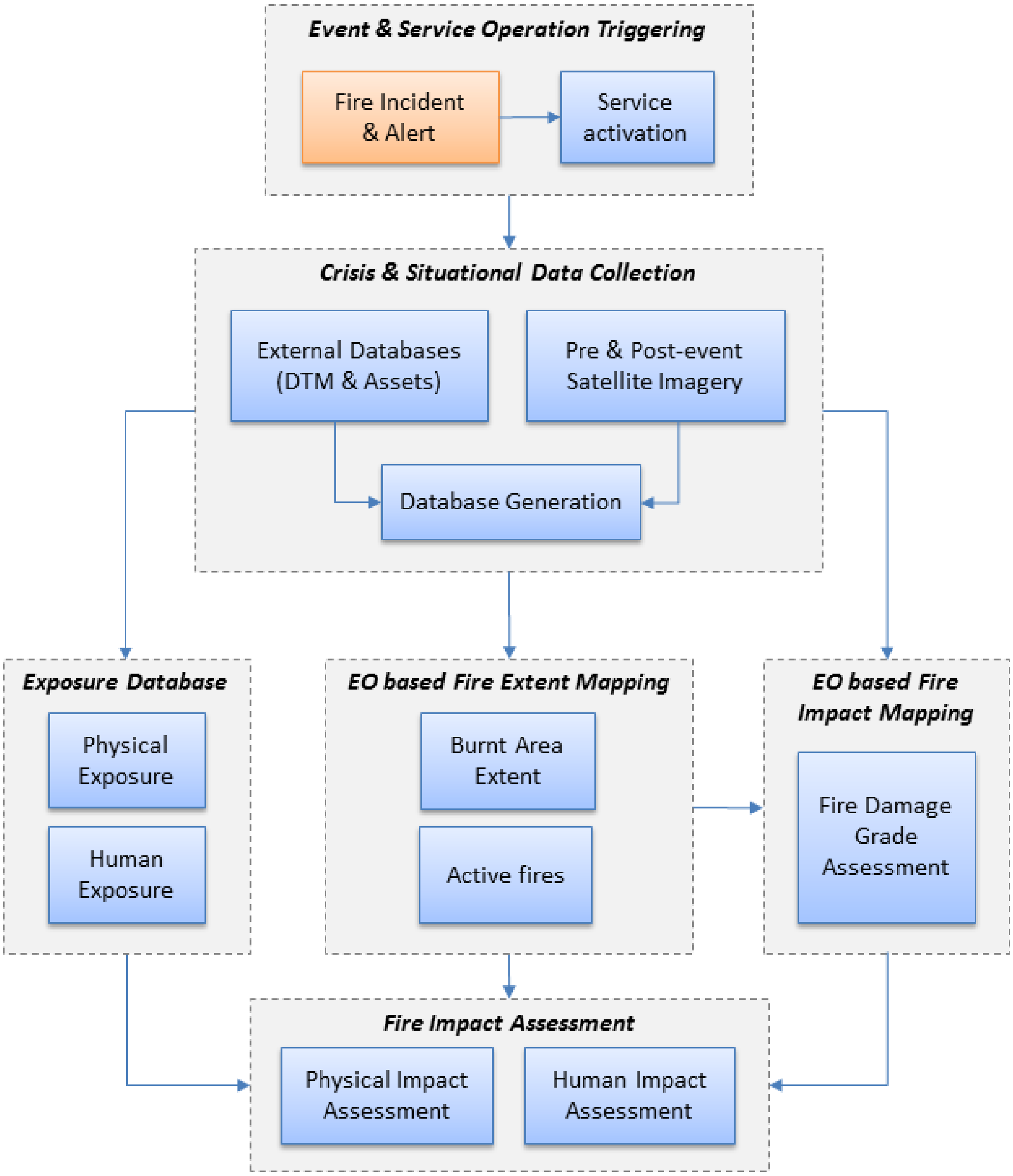

Figure 5-11: Concept design of the forest fire impact estimation using EO imagery

Forest fire impact assessment is a real case module, which depends on an event happening or, for simulation purposes, having happened (a past fire event can be chosen in order to demonstrate the impact assessment module). This entails an alert and an activation / incidence acceptance even if this is formal within a simulation / exercise. After the occurrence of a real fire event which has enough interest for crisis managers (affected assets and people), the EO-based Fire Impact Assessment process is triggered.

The first step of the process is the collection of pre and post-event satellite images covering the fire affected area, as well as of the external reference data concerning assets and terrain. This step only starts after a fire event of interest occurs. The data are then pre-processed and quality checked, before being integrated in a common geospatial database. The pre-event data are used to generate the reference layers whereas post-event satellite images are dedicated to the extraction of crisis fire extent and fire impact layers. The crisis layers can be generated from one to several acquisitions depending on cloud cover.

The second step of the process consists of generating the Burnt Area Extent derived from the post-event / crisis imagery compared with the pre-event one, removing any past fire extents. In parallel active fires or hot spots will be mapped if the satellite imagery allows.

The third step of the process consists of generating a fire damage grade assessment derived by change detection between the post-event / crisis imagery and the pre-event / reference imagery.

The Physical and Human Exposure database (if available: 3D building model, transportation, critical infrastructure, population per building), generated in parallel to the Fire Extent, is retrieved from their specific modules and integrated into the EO Fire Impact Assessment database as a key component of the EO Fire Impact Assessment workflow.

Physical and Human Exposure data are intersected with the EO based Fire Extent in order to derive EO-based Physical Impact Assessment and Human Impact Assessment products. These will be combined with the Fire Grade assessment.

The Forest Fire Impact Estimation product will be delivered through the HEIMDALL Service platform.

5.4.2.2 Flood Impact Estimation

Flood Impact Estimation is built on Crisis and Situational data, coming from external databases and satellite imagery. The exploitation of these input databases leads to the set-up of an Exposure Database and a Flood Extent mapping. The impact assessment is generated by intersecting exposure and extent information.

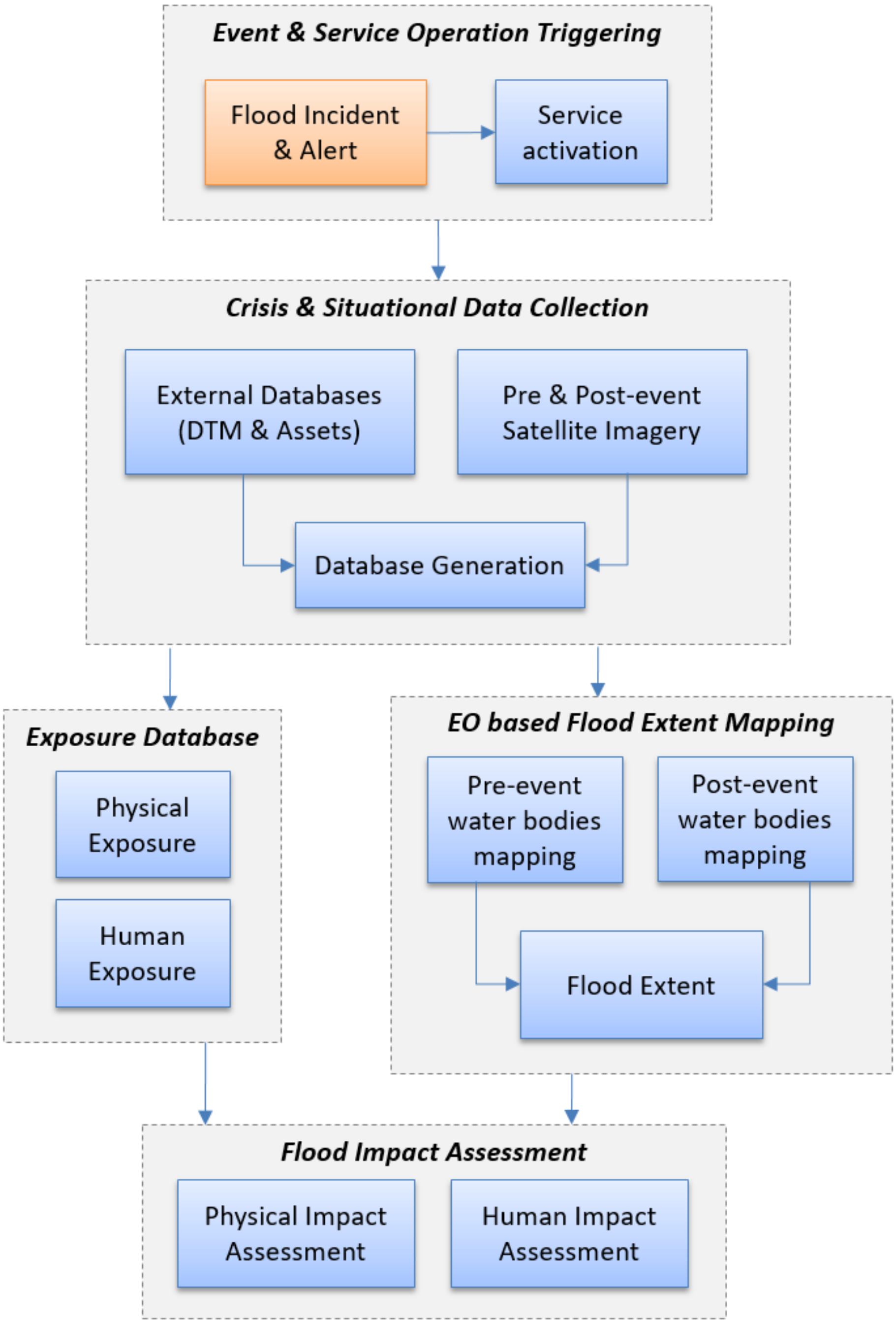

Figure 5-12: Concept design of the flood impact estimation using EO imagery

Flood impact assessment is a real case module, which depends on an event happening or, for simulation purposes, having happened (a past flood event can be chosen in order to demonstrate the impact assessment module). This entails an alert and an activation / incidence acceptance even if this is formal within a simulation / exercise. After the occurrence of a real flood event which has enough interest for crisis managers (affected assets and people), the EO-based Flood Impact Assessment process is triggered.

The first step of the process is the collection of pre and post-event satellite images covering the flood affected area, as well as of the external reference data concerning assets and terrain. This step only starts after a flood event of interest occurs. The data are then pre-processed and quality checked, before being integrated in a common geospatial database. The pre-event data are used to generate the reference waterbodies layer whereas post-event satellite images are dedicated to the extraction of crisis water bodies. The crisis layer can be generated from one to several acquisitions, according to the number of satellite images necessary to completely cover the flood affected area.

The second step of the process consists of generating the Flood Extent mapping derived from the removal of the previously elaborated pre-event / reference water bodies from the available post-event / crisis water bodies.

The Physical and Human Exposure database (if available: 3D building model, transportation, critical infrastructure, population per building), generated in parallel to the Flood Extent, is retrieved from their specific modules and integrated into the EO Flood Impact Assessment database as a key component of the EO Flood Impact Assessment workflow.

Physical and Human Exposure data are intersected with the EO based Flood Extent in order to derive EO-based Physical Impact Assessment and Human Impact Assessment products.

The Flood Impact Estimation product will be delivered through the HEIMDALL Service platform.

5.4.2.3 Landslide Impact Estimation

5.4.2.3.1 Satellite based approach

Landslide Impact Estimation is built on Crisis and Situational data, coming from external databases and satellite imagery. The exploitation of these input databases leads to the set-up of an Exposure Database and a Landslide Extent mapping. The impact assessment is generated by intersecting exposure and extent / grading information.

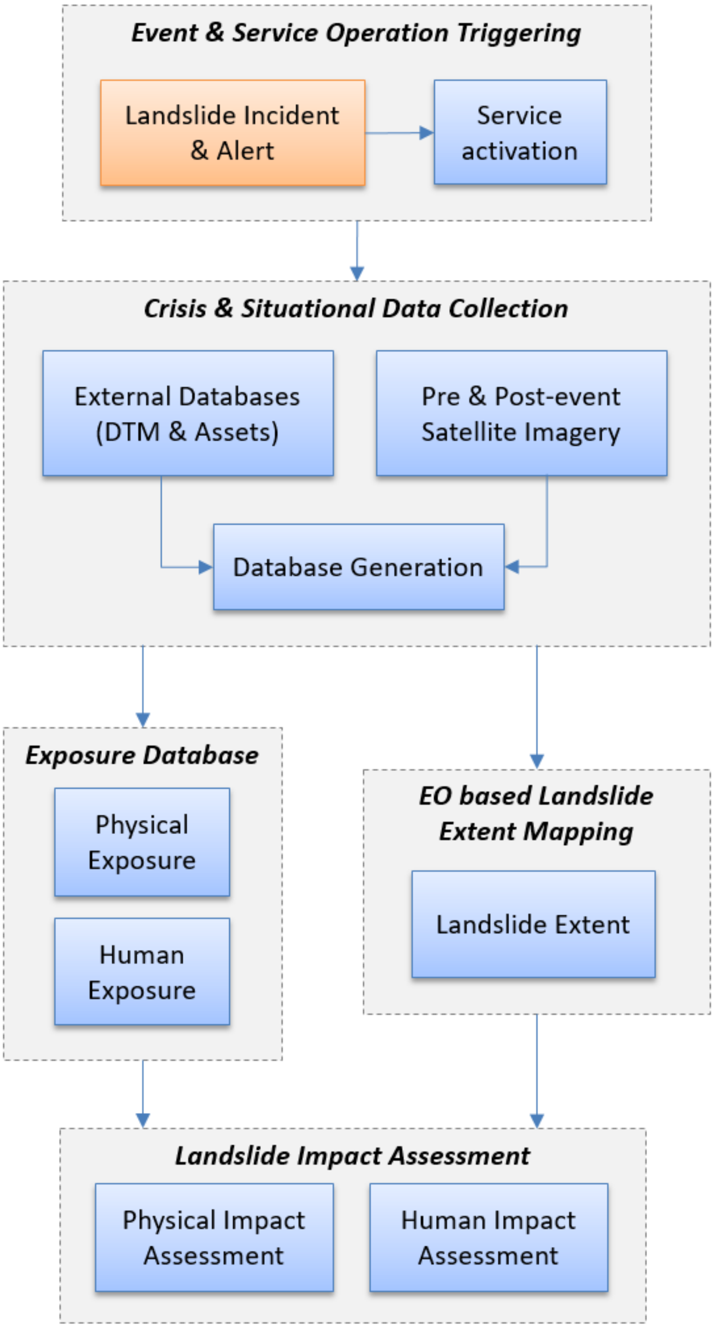

Figure 5-13: Concept design of the landslide impact estimation

Landslide impact assessment is a real case module, which depends on an event happening or, for simulation purposes, having happened (a past landslide event can be chosen in order to demonstrate the impact assessment module). This entails an alert and an activation / incidence acceptance even if this is formal within a simulation / exercise. After the occurrence of a real landslide event which has enough interest for crisis managers (affected assets and people), the EO-based Landslide Impact Assessment process is triggered.

The first step of the process is the collection of pre and post-event satellite images covering the landslide affected area, as well as of the external reference data concerning assets and terrain. This step only starts after a landslide event of interest occurs. The data are then pre-processed and quality checked, before being integrated in a common geospatial database. The pre-event data and post-event imagery are used to generate the landslide change detection layer. The crisis layer can be generated from one to several acquisitions depending on cloud cover.

The second step of the process consists of generating the Landslide Extent mapping derived from the change detection between pre-event / reference imagery and from the available post-event / crisis imagery.

The Physical and Human Exposure database (if available: 3D building model, transportation, critical infrastructure, population per building), generated in parallel to the Landslide Extent, is retrieved from their specific modules and integrated into the EO Landslide Impact Assessment database as a key component of the EO Landslide Impact Assessment workflow.

Physical and Human Exposure data are intersected with the EO based Landslide Extent in order to derive EO-based Physical Impact Assessment and Human Impact Assessment products.

The Landslide Impact Estimation product will be delivered through the HEIMDALL Service platform.

5.4.2.3.2 Ground-based SAR approach

Considering the observation-based impact assessment, a support can come from the use of in situ sensor, especially by the GB SAR monitoring products, thanks to its remote capability and to the characteristics of the provided products, which can be used for risk assessment. The system is installed in a safe and stable position and can provide information about the imaged zone in term of risk. Details about the system and the generation of the here used hazard information can be found in the specific deliverable concerned with in-situ sensors [97]. Here below, after recalling the feature of the GBSAR product, a feasible use of GBSAR data in risk assessment is shown. Two products will be available from the GBSAR, deformation maps showing the current situation and time series accounting for the observed trend within a several days. The deformation maps shown in Figure 5-14 are indicating four levels of deformation:

1) No data: pixels where the system cannot estimate the deformation or with insufficient accuracy. These points are generally not represented: the map is masked.
   Occupation of these areas demands evaluation based on other sensors, simulations, and/or expert support.
2) Stable Pixels. With a measured deformation within the error of the technique. This area can be considered stable, and its occupation recommended, provided that no close areas with high instability are identified. In this case expert support is mandatory.
3) Low deformation pixels. Those with a slow measured deformation. The occupation of these areas can be allowed for reduced time.
4) High deformation pixel. In this case the occupation of the area is not recommended at all.

The time series product consists of a plot of different temporal trend lines for some, selected, pixels over an interval of some days. Four each of the curves shown in Figure 5-15, a slope can be estimated which allows linear predictions based on the observed past trends. Three levels of velocity are indicated:

1) Stable trend. Velocity is equal to zero within the error of the retrieval technique. The area including these points can be considered stable, and its occupation recommended.

2) Low velocity. The velocity cannot compromise a safe occupation for short temporal interval, or can be occupied temporarily. Anyway expert support is of main concern for this decision.
3) High velocity. In this case the occupation of the area is not recommended at all.

It is mandatory that this information is processed by experts and final decision taken under their responsibility. The information on the deformation status will be intersected with the exposure information, indicating the estimated observed impacts.

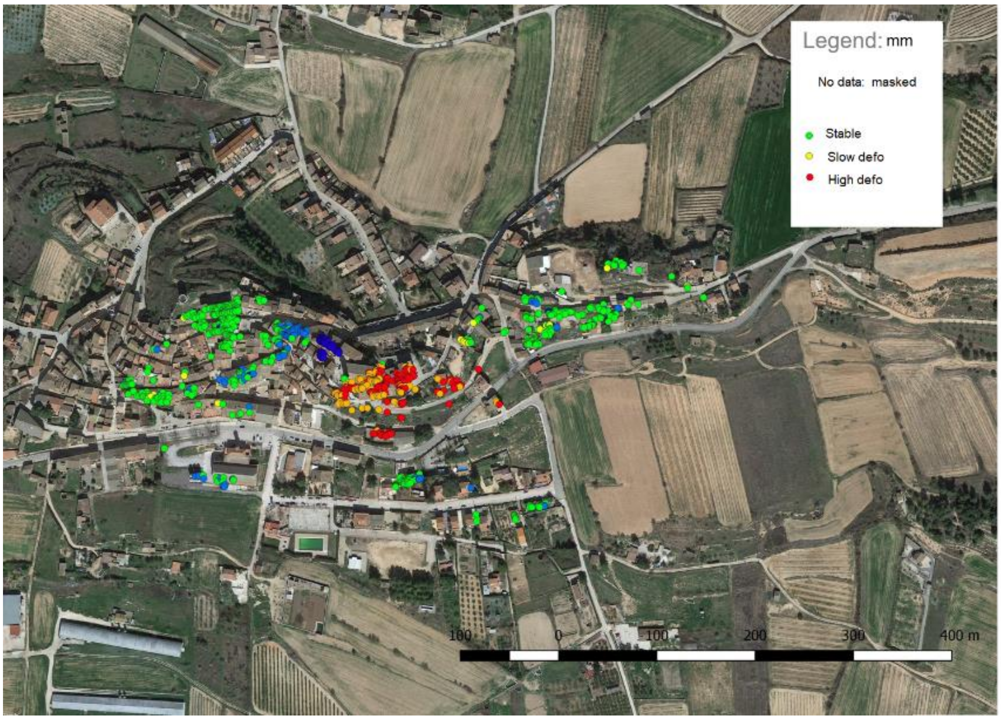

Figure 5-14: Deformation map product example from the GBSAR in-situ component. The levels of deformation are used within the impact assessment.

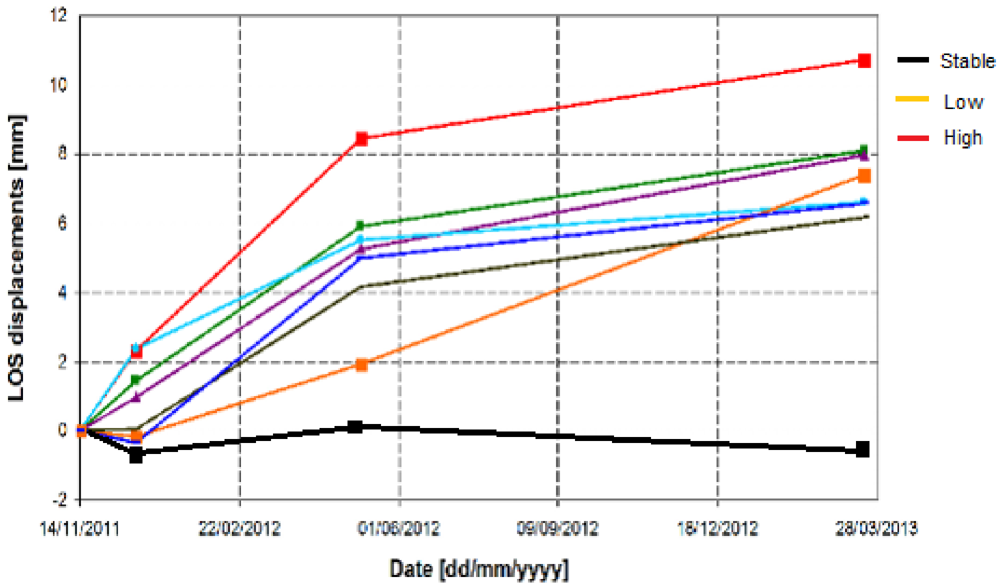

Figure 5-15: Temporal series product from the GBSAR in-situ component.

Figure 5-16

6 Multi-hazard Concept

Although the term *Multi-Hazard* is widely used, it lacks a common accepted definition. Multi-Hazard approaches are strongly encouraged on the international level for decades now (e.g. the United Nations International Decade for Natural Disaster Reduction IDNDR, the Hyogo Framework for Action [98] and the zero draft of the post-2015 framework for Disaster Risk Reduction/Sendai Framework 2015-2030 [99]).

The basic idea behind Multi-Hazard is to widen the scope of what processes are being considered, monitored or modelled (and on what level of detail, including side effects/impacts and interacting/cascading effects) when preparing for or coping with disasters, and to accept the challenge of increased complexity for the sake of a more holistic view, a better understanding, and a reduced risk of biased or under-informed decisions because of narrow approaches.

As [57] states, the failure to understand the whole natural system (rather than a small portion of it) can distort management priorities, increase vulnerability to other spatially relevant hazards or underestimate risk.

Therefore, Multi-hazard approaches are essential.

Among the different uses and interpretations of the term Multi-Hazard, two major groups can be identified [57]:

- The first group uses the term to describe the independent analysis of different hazards *relevant to a given area*. This approach can be understood as a collation of multiple single-hazard analysis or systems, where the results of the individual (single-hazard) assessments and analysis can be joined together/summed up (like a combination of different GIS layers, each describing a specific aspect of a (single) hazard). On a technical or DM system level, this equals to a number of single-hazard systems operating in parallel, where outputs can be combined and analysed.
- A second group considers single hazards, too, but also take into account that processes are not independent and hazards (and other natural or technical processes) interact, or may have cascading effects. This is an approach with much higher complexity on one hand, but with several synergy effects on different levels (see section 6.2.4) on the other hand.

The literature overview collected in [57] shows that triggering and increased probability relationships are widespread between natural hazards, with hazard cascades an important consideration for those interested in multi-hazards, and impacts deriving from the concurrence of two (or more) hazard events may be greater than the sum of components. Two examples are cited there:

- An earthquake may trigger hundreds of landslides, some of which may block rivers and result in flooding, causing erosion at the foot of slopes and triggering further landslides.
- Spatial and temporal overlap of a volcanic eruption and a tropical storm event may result in much more severe flooding than would have occurred otherwise, due to the blocking of drainage systems by volcanic ash.

A growing number of projects deal (at least partially) with multi-hazard aspects and the development of a consolidated terminology, but without a generally accepted version yet. The interactions between the hazards selected in this report are described in section 6.2. For HEIMDALL, we follow the second group and consider the term *Multi-Hazard* to be a holistic one, stressing the necessity for a broader approach (spatially, scientifically, technically), taking into account effects and relationships beyond the pure (limited) scope of a single hazard.

6.1 Multi-Hazard and related Terms

This section tries to describe the term Multi-Hazard and some of its related terms from the perspective of Disaster Management systems in general. The common prefix *multi-* in all the different terms addressed here denotes that the ability (or the options) of a system, its concept or approach are not limited to a single purpose or context, but can instead be applied in more than one context/for more than one purpose.

6.1.1 Multi-Hazard

As already noted in the previous sections, HEIMDALL follows the broader and more complex approach of Multi-Hazard and strives to cover multiple hazard types individually. This implies a number of requirements on the system and technical level, for which HEIMDALL has been designed from the beginning (e.g. openness of the HEIMDALL platform, extensibility and scalability of services, use of interoperability standards).

In section 6.2, additional hazard types are described and selected, and section 6.2.4 shows the interaction and cascading effects between them; the following chapters will analyse in what areas HEIMDALL needs to be extended in order not only to cover the additional hazard types in the single-hazard sense, but also to consider their potential interactions, thus complying with the HEIMDALL understanding of the term *Multi-Hazard*.

6.1.2 High Level Approach

Multi-hazard approaches and initiatives are promoted and encouraged on the international and political level, including multi-sector initiatives.

Multi-year programmes are developed at the UN level, and member state contributions are requested, serving as an overarching umbrella activity that fosters the definition of thematic focal points, the coordination of national programmes and the alignment of forces. However, apart from the important impulses set by these high level multi-hazard approaches, the context of HEIMDALL is a technical one on the local level upwards, which is described in the next section.

6.2 Hazard Types and Scenarios

The choice of hazards to exemplify the multi-hazard extension of the HEIMDALL system involved the consideration of several aspects and restrictions. First of all, due to time and resource issues, the number of hazards that could be considered has been limited to three hazards. A further criterion was to select hazards enabling the conjoint use of existing elements of the HEIMDALL system within all phases of disaster management (section 4). Respective hazards to be chosen should be assessable by means of satellite based as well as in-situ based earth observation (EO). Furthermore, the chosen hazards should serve for exemplifying possible interactions within a multi-hazard scenario. Figure 6-1 shows the spatial and temporal scales of 16 different types of natural hazards. Spatial scale refers to the area that the hazard impacts and temporal scale to the timescale that the single hazard acts upon the natural environment. Hazards are grouped into geophysical, hydrological, shallow earth processes, atmospheric, and biophysical.

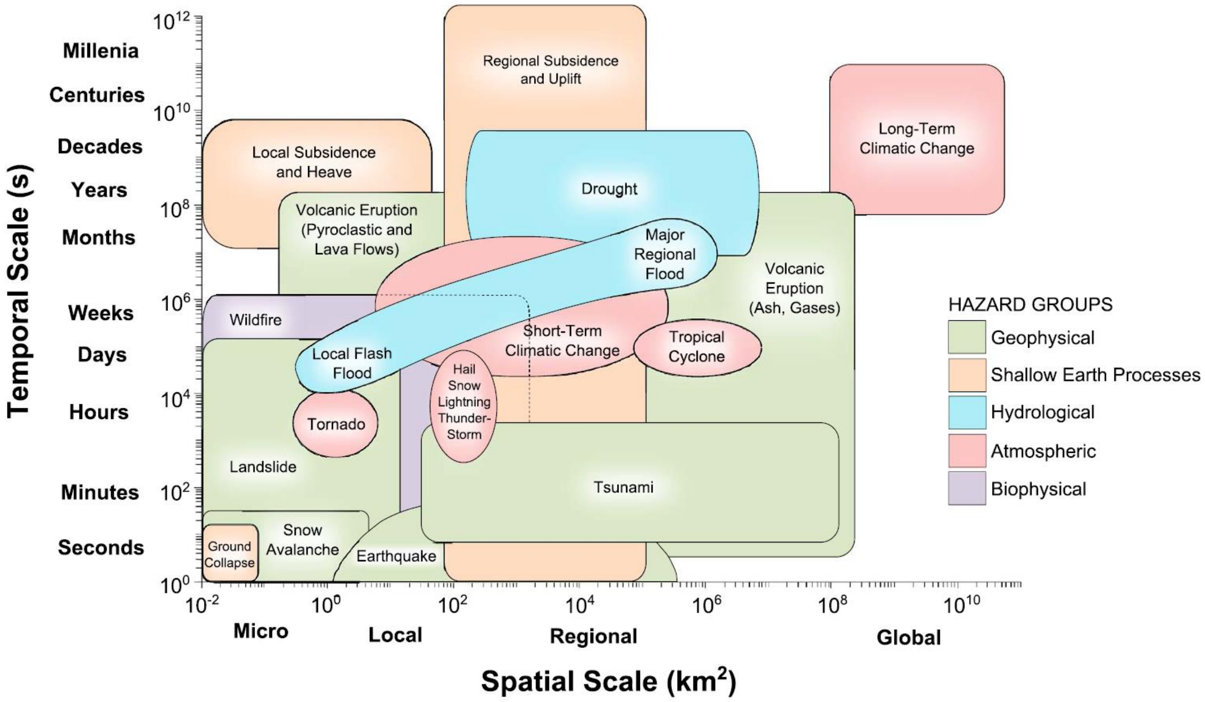

Figure 6-1: Spatial and temporal scales of 16 natural hazards shown on logarithmic axes (adopted from [100])

Another aim was to take a broad range of potential spatio-temporal scales into account and to consider different hazard groups (as in Figure 6-1), exemplifying the capability of the HEIMDALL system to cope with a multi-hazard scenario. Complying with the specified requirements, floods, forest fires and landslides were selected for demonstrating the multi-hazard capabilities of the HEIMDALL system.

6.2.1 **Forest fires**

Even if the level of forest fire preparedness and awareness is high, the consequences of forest fires can be dramatic. This is especially due to extreme weather conditions, in countries in which forest fires have not been a concern in past decades. In 2018 forest fires heavily affected Sweden, UK, Finland and Latvia. This implies that no longer only the EU member states in the Mediterranean region are affected by extreme weather conditions triggering forest fires. According to [101] in 2017 forest fires burnt over 1.2 million hectares of natural lands and 127 people including fire fighters and civilians were killed. 25 % of the burnt area was protected by Natura2000 legislation, minimising the outcomes of efforts to protect diversity and natural habitats within the EU.

6.2.2 **Floods**

Every year flood hazards cause enormous casualties and damage to structures, infrastructure, agriculture, eco-systems and economies all over the world. During the last decade of the 20th century, floods, directly or indirectly, affected about 1.4 billion persons. About 100000 were killed [102]. Flooding is the most frequent natural disaster in Europe [102]. In some areas of the world, at the same time, frequent flooding are wanted, being accompanied by positive side effects (e.g. floodwater containing nutrient-rich sediment fertilising floodplain soils or support of long term water supply and irrigation activities [103]).

A wide definition of flood was proposed by the European Commission (EC) [102]: ‘‘flood means temporary covering by water of land not normally covered by water’’. Due to the complexity of the interrelated processes that lead to flooding, however, it is not trivial to classify them [92], [104]. With regard to the region, scale and field of application, in literature several typologies are defined. Such typologies, in general, mainly refer to the types river floods, pluvial floods, flash floods and coastal floods ([50], [92], [104], [105], [106]):

- River (fluvial): overflowing of the normal confines of a stream or other body of water, resulting from intense and/or persistent rain for several days or even weeks over large areas (not necessarily in the flooded area). They are often related to seasonal regimes. In summer/autumn they are usually triggered by regional high rain quantities. The ground becomes fully saturated resulting in an increased overland flow and runoff. River floods in winter/spring can be influenced by snow and ice melt.
- Pluvial floods: “direct runoff over land causing local flooding in areas not previously associated with natural or manmade water courses”. Key aspect is the lack of proper drainage network in the area impacted by the flood [107].
- Flash floods: “a flood that rises and falls quite rapidly with little or no advance warning, usually as the result of intense rainfall over a relatively small area”. Key aspect is the time scale sudden hydrological response to the causative event [107].
- Coastal Floods (associated with high tides and storm surges): a flood that occurs in areas along the coasts of a sea or other large waterbodies. High on-shore wind storms (e.g. hurricane or cyclone) and low atmospheric pressure cause set-up of water levels on the coast. Coinciding with high astronomical tides this can be worsened.

6.2.3 **Landslides**

The definition of landslides introduced by [108] and adopted by UNESCO Working Party on Landslide Inventory (WP/WLI) [109]: “The movement of a mass of rock, debris, or earth down a slope caused” is simple but generally accepted. The IPCC defines landslides as “a mass of material (soil, rock or debris) that has moved downhill by gravity, often assisted by water […]”, setting an emphasis on hydrological influencing factors [50].

Landslides constitute a significant natural hazard, causing direct loss in terms of lives, damages to buildings, infrastructure, arable or habitable land and unpredictable changes in the local watercourse. Additionally, landslides produce relevant indirect cost for society due to long-term effects on the local economy ([110], [111]).

With regard to the establishment of a landslide typology many different approaches can be found in literature (e.g. [112–115]). Landslides can be classified according to geomorphological criteria, to the type of movement (kinematics) or to slope activity (rate of movement).

Table 6-1: Classification of slope movements [113]

Type of movement	Type of Material		
	Bedrock	Predominantly Coarse Soils	Predominantly Fine Soils
Fall	Rock fall	Debris fall	Earth fall
Topple	Rock Topple	Debris Topple	Earth topple
Slide - rotational	Rock slump	Debris slump	Earth slump
- translational	Rock block slide	Debris block slide	Earth slide, Earth block slide
Spread	Rock spreading	Debris spread	Earth spread
Flow	Rock flow	Debris flow	Earth flow

International efforts for a standardised definition of landslides and their characteristics were coordinated by WP/WLI and resulted in a process oriented classification scheme. These guidelines follow the typology elaborated and published by [113]. Herein slope movements are subdivided into 5 main single categories: Falls, topples, slides, spreads and flows (Table 6-1).

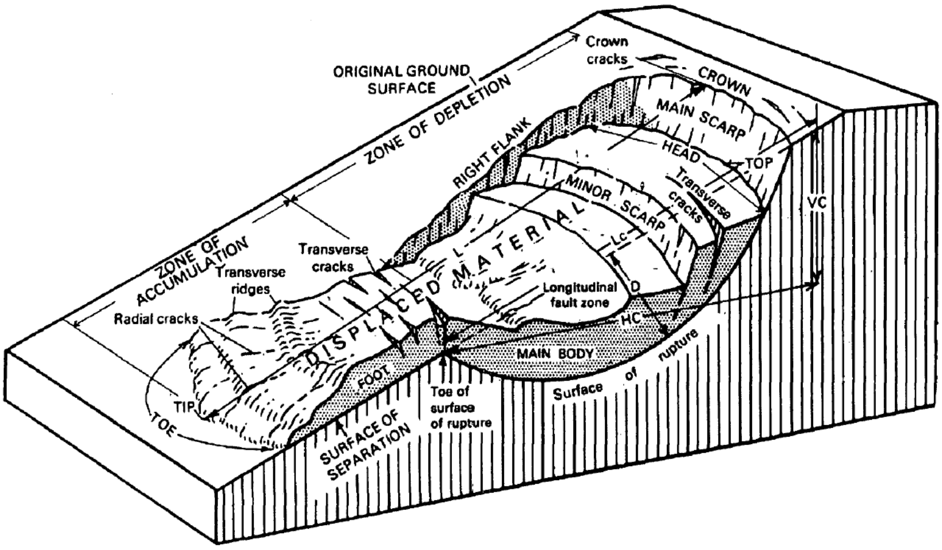

Figure 6-2: Main geometrical elements of a complex landslide [112]

Most landslides occur as a combination of at least two landslides, which might be of different types of movements. A complex landslide defines the case of various types of movement that occur in sequence. Further so-called styles of activity, which describe such combinations, are: composite, multiple and successive landslides [113]. Figure 6-2 shows a block diagram with the main geometrical elements of a rotational landslide that has evolved into an earthflow.

Table 6-2: Landslide velocity scale after Cruden and Varnes 1996 [113] and corresponding destruction potential (adapted from [115])

Class	Description	Velocity	Kinematics					Destruction potential
			Fall	Topple	Slide	Spread	Flow	
7	extremely rapid	5 m/s						very high destruction potential, many deaths, evacuation impossible
6	very rapid	3m/min						high destruction potential, some deaths, evacuation partially possible
5	rapid	1.8m/h						destruction potential, no deaths because evacuation possible, large physical damage
4	moderate	158m/a						physical damage to structures and infrastructure
3	slow	1.6m/a						physical damage to structures and infrastructure, renovation partially possible
2	very slow	16mm/a						physical damage to structures and infrastructure, structures may remain unaffected
1	extremely slow						Rock Flow, Soil Flow	not perceptible without instrumentation, construction with precautions possible

Regarding the rate of movement, 7 velocity classes from extremely rapid (<5m/s) to extremely slow (<16mm/a) can be differentiated. Table 6-2 shows the 5 main kinematic landslide types, their velocity ranges and their corresponding destruction potential. The destruction potential of landslides increases substantially with their velocity ([113], [116]).

Every slope features forces (shear stress) which tend to promote downslope movement and opposing forces (shear strength) which tend to resist movement along a known or assumed rupture surface. Hence, in a generalised manner, the safety of a slope (F) can be described by: F = shear strength/shear stress. Deterioration of slope safety, and the triggering of a landslide results from the interaction of several causal factors (Table 6-3) increasing shear stresses and/or reducing shear strength. Such factors are related to the ground conditions of a considered slope and the interaction of geological, morphological, physical or human processes.

Table 6-3: Landslide causal factors [113], [117]

a) Geological conditions	**b) Morphological processes**
- Weak materials - Sensitive materials - Weathered materials - Sheared materials - Jointed or fissured materials - Adversely oriented mass discontinuity (bedding, schistosity, etc.) - Adversely oriented structural discontinuity (fault, unconformity, contact, etc.) - Contrast in permeability - Contrast in stiffness (stiff, dense material over plastic materials)	- Tectonic or volcanic uplift - Glacial rebound - Fluvial erosion of slope toe - Wave erosion of slope toe - Glacial erosion of slope toe - Erosion of lateral margins - Subterranean erosion (solution, piping) - Deposition loading slope or its crest - Vegetation removal (by forest fire, drought)
c) Physical processes	**d) Human processes**
- Intense, short period, rainfall - Rapid snow melt - Prolonged exceptional precipitation - Rapid drawdown (of floods and tides) - Earthquake - Volcanic eruption - Thawing - Freeze-and-thaw weathering - Shrink-and-swell weathering	- Excavation of slope or its toe - Loading of slope or its crest - Drawdown (of reservoirs) - Defective maintenance of drainage system - Vegetation removal (deforestation) - Irrigation - Mining and quarrying - Artificial vibration - Water leakage from utilities

6.2.4 **Hazard interactions**

A multi-hazard scenario may comprise two different cases: (1) conjoint hazards**,** i.e. the simultaneous occurrence of two or more hazard events impacting the same area being independent from each other and (2) cascading hazards in the context of which one event (secondary hazard) occurs as a direct or indirect result of an initial event (primary hazard).

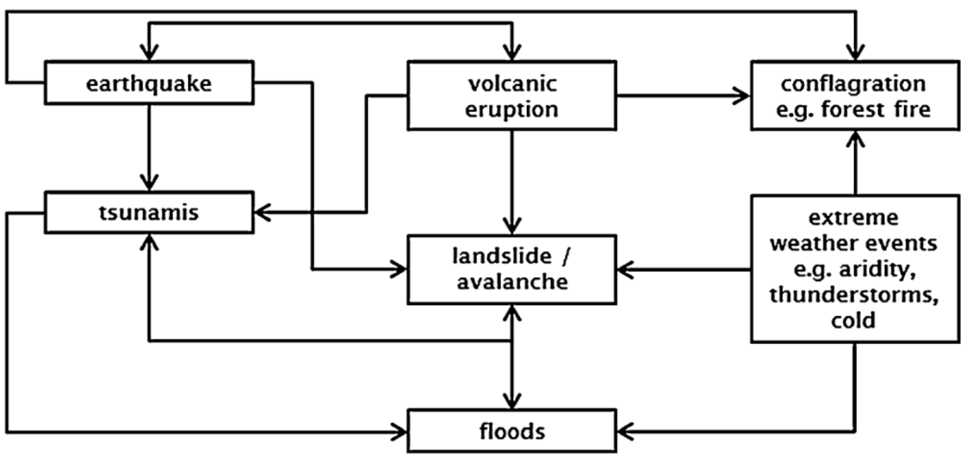

Figure 6-3: The interconnected network of natural hazard interaction relationships (adopted from [118])

Figure 6-3 depicts the scheme of an interconnected network of possible hazard interactions, where a series of hazards might be triggered one after another, or simultaneously, because of successive triggering processes [57].

Thus, the amplification of the respective overall hazard can be either a consequence of the spatial and temporal coincidence of two or more hazards or can be due to chaining, whereby one hazard triggers and increases the effect of the next hazard, i.e. a cascade or domino effect. Thereby, the overall hazard and risk of causally linked processes is amplified in comparison with the aggregation of presumed independent hazards ([79], [118], [119]).

In order to outline possible relations between natural hazards within a multi-hazard scenario more in detail, the following four adverse hazard interaction types can be differentiated [57], [120]:

1. **Interactions where a hazard is triggered:** Any natural hazard might trigger zero, one, or more secondary natural hazards where the secondary natural hazard might be of the same type as the primary hazard or different. These secondary natural hazards could then potentially trigger further natural hazards, thus resulting in a network of interacting hazards, which can dramatically escalate the accumulated hazard potential in a given region.
2. **Interactions where the probability of a hazard is increased:** This interaction type refers to the case, when a primary hazard not directly triggers a secondary natural hazard, instead it changes some aspect of the natural environment increasing the probability that another hazard will occur.
3. **Events involving the spatio-temporal coincidence of natural hazards:** For the case that more than one hazard is occurring within the same spatial extent, affecting this extent within a short timeframe, risks and impacts are likely to be different than just aggregating the risks and impacts of corresponding single hazards. The precise extent of the location as well as the spatial overlap depends on the considered hazard types and their magnitudes. The temporal overlap is influenced by the time the hazard event occurs but also largely relates to the impacts of the hazard event. Due to the spatio-temporal coincidence of natural hazards human populations, physical infrastructure and environmental assets may be placed under greater stress than if the hazards had occurred in different locations. The impact of one hazard on a location could increase its vulnerability to secondary or future hazard events and is therefore potentially amplifying the effects of a secondary or future hazard.
4. **Interactions with anthropogenic processes that catalyse or impede natural hazard interactions:** An example for this hazard interaction type is the vegetation removal by anthropogenic processes. Possible results in the hazard interaction domain include the catalysation, i.e. the enhancement of hazard interactions, and impedance, i.e. the increased resistance to hazard interactions. For example, tropical storms can often trigger floods. This triggering relationship can be catalysed by other specific anthropogenic processes (e.g. vegetation removal) through increased surface runoff.

Figure 6-4 shows possible interactions between 21 natural hazards covering geophysical, hydrological, atmospherical, biophysical, space hazards and shallow earth processes (considered hazards and hazard groups are listed in the “KEY” box in Figure 6-4). All in all, 90 hazard interactions are identified, including triggered relationships and relationships, where one hazard increases the probability of another. The primary hazards are depicted on the x-axis, the secondary hazards on the y-axis. Thereby, each secondary hazard can be thought of as the next primary hazard, having the potential to trigger further (tertiary) hazards. In addition, the effects of anthropogenic processes on the interaction intensity of two hazards are schematically depicted. Vegetation removal is used to exemplify either the impedance (decrease) of interaction processes (e.g. forest fire (WF) – forest fire (WF) interactions) or the catalysation (increase) of interaction processes (e.g. forest fire (WF) – landslide (LA) interactions).

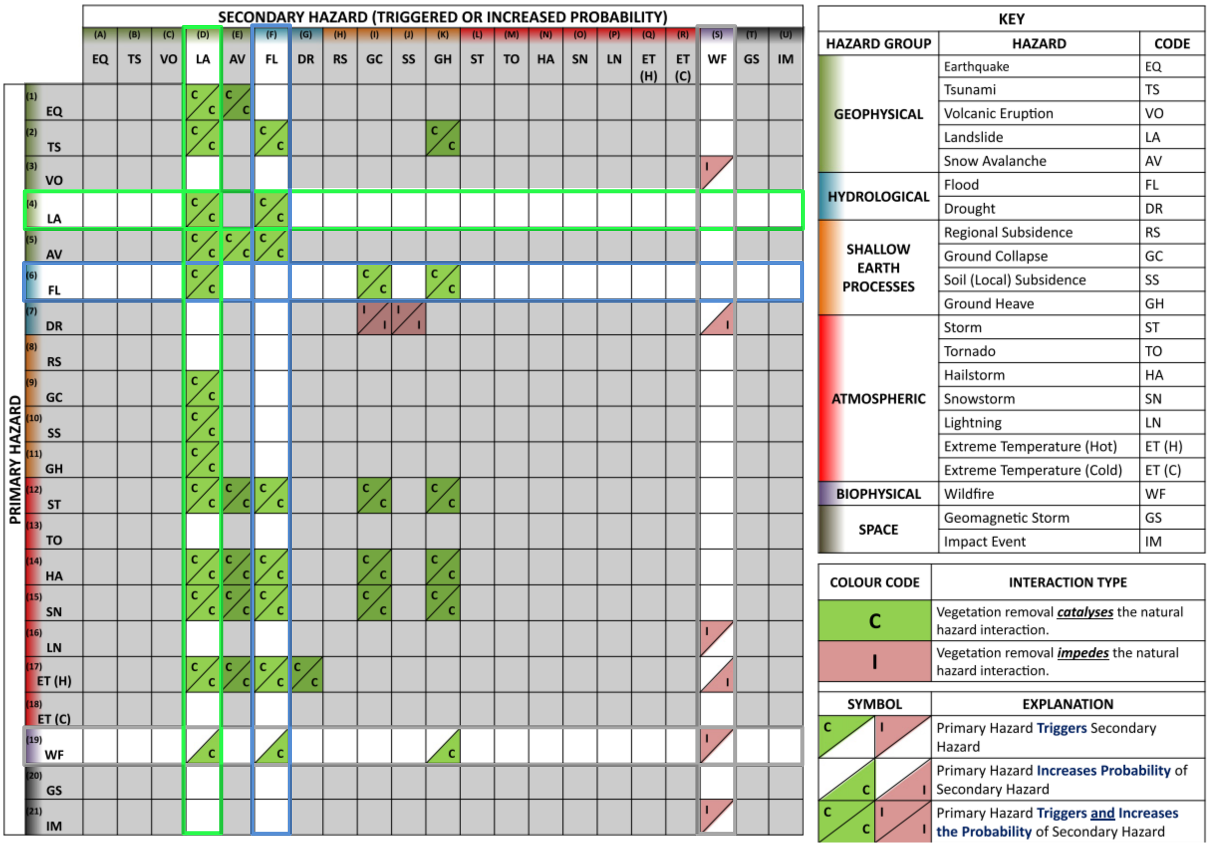

Figure 6-4: Hazard interaction matrix showing cases, where a primary hazard could trigger a secondary hazard and cases where a primary hazard could increase probability of a secondary hazard being triggered. Vegetation removal as one example for possible catalysis/impedance interactions with anthropogenic processes is depicted in different colours. Within HEIMDALL cascading effects regarding landslides (LA), floods (FL) and forest fires (WL) will be addressed (adopted from [120]).

Potential interaction scenarios between the natural hazards considered within this report, i.e. forest (wild) fires, floods and landslides are listed below. To exemplify the anthropogenic processes that could influence the interactions between hazards, the potential effects of vegetation removal is described:

- **Landslide (LA) – Landslide (LA) interactions**, where a primary landslide event could trigger and increase the probability of secondary landslides. The removal of vegetation catalyses the interaction through reduced slope stability.
- **Landslide (LA) – Flood interactions (FL)**, where a primary landslide event could trigger or increase the probability of secondary flood events, e.g. through the blocking of a river or the addition of significant quantities of sediment into the fluvial system. Through decrease of vegetation cover, surface runoff amount will enhance the interaction process.
- **Flood (FL) – Landslide (LA) interactions,** where a primary flood event could trigger or increase the probability of secondary landslides which then could trigger tertiary floods. The removal of vegetation catalyses the interaction through reduced slope stability.
- **Forest fire (WF) - Landslide (LA)-interactions**, where a primary forest fire could increase the probability of secondary landslides through vegetation removal, which acts as a water sink and promotes slope stability, increasing shear strength.
- **Forest fire (WF) - Flood (FL) interactions,** where a primary forest fire could increase the probability of future secondary floods, through the vegetation degradation and therefore increases surface runoff.
- **Forest fire (WF) – Forest fire interactions,** where a primary forest fire triggers secondary forest fires. The removal of vegetation is impeding the hazard interaction,

through missing or decreased fire fuels.

The outlined interactions between natural hazards implied the high importance of anthropogenic processes for a detailed overview of the situation. On the one hand anthropogenic processes could trigger or increase the probability of a hazard event (e.g. a socio-natural or technological hazard event), on the other hand, a natural hazard may impact on infrastructure, triggering or increasing the probability of new hazards ([57], [121]) Vegetation removal as one example for possible interactions with anthropogenic processes are depicted in Figure 6-4 with different colours, visualizing catalysis/impedance on the interaction processes.

At this stage of the project the very complex interactions between the analysed hazards accounting for cascading effects, are not fully integrated in the risk assessment concept. However, the theoretical basis of the multi-hazard interactions presented enable to identify the different interactions present between the hazards covered within HEIMDALL. In any case, the combination of single-hazard risk assessments, describing the exposure and impact in overlapping or independent regions, results in the description of the observed impact and calculated risk for multiple hazards.

7 Conclusion

The report at hand provides a first version of the risk assessment concept used within HEIMDALL. An introduction about the capabilities of remote sensing and Geographic Information Systems (GIS) to generate spatial information relevant in all four phases of the disaster management cycle is provided. Details about the methods utilized to generate exposure information from high to very high resolution earth observation data and statistical information are outlined. Two impact assessment approaches per hazard type are provided in order to reflect the differences in hazard information. Cascading effects and hazard interactions for a future multi-hazard risk assessment design are identified, including the effects of anthropogenic processes and the possible interactions within the hazards currently covered in the HEIMDALL project.

8 References

[1] C. A. (ICGC) Christian Knopp (DLR) Sandro Martinis (DLR) Roberto Rudari (CIMA) Eva Trasforini (CIMA) Stéphanie Battiston (UNISTRA) Stephen Clandillon (UNISTRA) Guido Luzi (CTTC) Miguel Mendes (TSYL), “D6.4 Technical Specifications on Hazard, Scale and User-Specific Risk Assessment Information, Products and Service Workflows- Draft,” H2020-Project HEIMDALL, 2018.

[2] C. Geiß and H. Taubenböck, “Remote sensing contributing to assess earthquake risk: from a literature review towards a roadmap,” vol. 68, no. 1, pp. 7–48.

[3] D. Ehrlich, G. Zeug, J. Gallego, A. Gerhardinger, I. Caravaggi, and M. Pesaresi, “Quantifying the building stock from optical high-resolution satellite imagery for assessing disaster risk,” *Geocarto International*, vol. 25, no. 4, pp. 281–293, 2010.

[4] J. Birkmann, “Indicators and criteria for measuring vulnerability: Theoretical bases and requirements,” *Measuring vulnerability to natural hazards: Towards disaster resilient societies*, pp. 55–77, 2006.

[5] M. Mueller, K. Segl, U. Heiden, and H. Kaufmann, “Potential of High-Resolution Satellite Data in the Context of Vulnerability of Buildings,” *Natural Hazards*, vol. 38, no. 1, pp. 247–258, May 2006.

[6] S. Dech, “Anwendung der Satellitenfernerkundung - Von der geowissenschaftlichen Forschung zum operationellen Einsatz,” 1997.

[7] L. Chiroiu, B. Adams, and K. Saito, “Advanced Techniques in Modelling, Response and Recovery,” *Assessing and Managing Earthquake Risk*, Jan. 2006.

[8] T. Esch, S. Dech, A. Roth, M. Schmidt, H. Taubenböck, W. Heldens, M. Thiel, M. Wurm, and D. Klein, “Monitoring and assessment of urban environments using space-borne earth observation data,” *Urban and regional data management. Taylor & Francis Group, London*, pp. 385–398, 2009.

[9] H. Guo, “Understanding global natural disasters and the role of earth observation,” *International Journal of Digital Earth*, vol. 3, no. 3, pp. 221–230, 2010.

[10] C. Geiß, A. Schauß, T. Riedlinger, S. Dech, C. Zelaya, N. Guzman, M. Hube, J. J. Arsanjani, and H. Taubenböck, “Joint use of remote sensing data and volunteered geographic information for exposure estimation: evidence from Valparaíso, Chile,” vol. 86, pp. 81–105, 2017.

[11] F. Dottori, M. Kalas, P. Salamon, A. Bianchi, L. Alfieri, and L. Feyen, “An operational procedure for rapid flood risk assessment in Europe,” vol. 17, no. 7, pp. 1111–1126.

[12] J. Wu, X. Wang, and E. Koks, “Building Asset Value Mapping in Support of Flood Risk Assessment: A Case Study of Shanghai, China,” vol. 2017, pp. 1–16.

[13] A. Twele and F. M. Hummel, “Combining automated satellite-based flood mapping with exposure mapping for flood risk assessment,” in *United Nations/Germany Expert Meeting on Space-based Information for Flood and Drought Risk Reduction*.

[14] H. Taubenböck, N. Goseberg, N. Setiadi, G. Lämmel, F. Moder, M. Oczipka, H. Klüpfel, R. Wahl, T. Schlurmann, G. Strunz, J. Birkmann, K. Nagel, F. Siegert, F. Lehmann, S. Dech, A. Gress, and R. Klein, “Last-Mile‘ preparation for a potential disaster â€’ Interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia,” *Natural Hazards and Earth System Sciences*, vol. 9, no. 4, pp. 1509–1528, 2009.

[15] S. P. French and S. Muthukumar, “Advanced technologies for earthquake risk inventories,” *Journal of Earthquake Engineering*, vol. 10, no. 02, pp. 207–236, 2006.

[16] B. Borzi, F. Dell’Acqua, M. Faravelli, P. Gamba, G. Lisini, M. Onida, and D. Polli, “Vulnerability study on a large industrial area using satellite remotely sensed images,” *Bulletin of Earthquake Engineering*, vol. 9, no. 2, pp. 675–690, 2011.

[17] U. Deichmann, *Using high resolution satellite data for the identification of urban natural disaster risk*. 2011.

[18] L. Sahar, S. Muthukumar, and S. P. French, “Using aerial imagery and GIS in automated building footprint extraction and shape recognition for earthquake risk assessment of urban inventories,” *IEEE Transactions on Geoscience and Remote*

Sensing, vol. 48, no. 9, pp. 3511–3520, 2010.
[19] M. Rutzinger, F. Rottensteiner, and N. Pfeifer, “A Comparison of Evaluation Techniques for Building Extraction From Airborne Laser Scanning,” vol. 2, no. 1, pp. 11–20.
[20] M. Wieland, M. Pittore, S. Parolai, J. Zschau, B. Moldobekov, and U. Begaliev, “Estimating building inventory for rapid seismic vulnerability assessment: Towards an integrated approach based on multi-source imaging,” *Soil Dynamics and Earthquake Engineering*, vol. 36, pp. 70–83, 2012.
[21] M. Pittore and M. Wieland, “Toward a rapid probabilistic seismic vulnerability assessment using satellite and ground-based remote sensing,” *Natural Hazards*, vol. 68, no. 1, pp. 115–145, 2013.
[22] J. E. Dobson, E. A. Bright, P. R. Coleman, R. C. Durfee, and B. A. Worley, “LandScan: a global population database for estimating populations at risk,” *Photogrammetric engineering and remote sensing*, vol. 66, no. 7, pp. 849–857, 2000.
[23] K. Chen, “An approach to linking remotely sensed data and areal census data,” *International Journal of Remote Sensing*, vol. 23, no. 1, pp. 37–48, 2002.
[24] A. Ebert, N. Kerle, and A. Stein, “Urban social vulnerability assessment with physical proxies and spatial metrics derived from air- and spaceborne imagery and GIS data,” vol. 48, no. 2, pp. 275–294.
[25] J. Zeng, Z. Zhu, J. Zhang, T. Ouyang, S. Qiu, Y. Zou, and T. Zeng, “Social vulnerability assessment of natural hazards on county-scale using high spatial resolution satellite imagery: a case study in the Luogang district of Guangzhou, South China,” *Environmental Earth Sciences*, vol. 65, no. 1, pp. 173–182, 2012.
[26] H. Taubenböck, M. Wurm, M. Netzband, H. Zwenzner, A. Roth, A. Rahman, and S. Dech, “Flood risks in urbanized areas–multi-sensoral approaches using remotely sensed data for risk assessment,” *Natural Hazards and Earth System Sciences*, vol. 11, no. 2, pp. 431–444, 2011.
[27] T. T. Vu and Y. Ban, “Context-based mapping of damaged buildings from high-resolution optical satellite images,” *International Journal of Remote Sensing*, vol. 31, no. 13, pp. 3411–3425, 2010.
[28] K. E. Joyce, S. E. Belliss, S. V. Samsonov, S. J. McNeill, and P. J. Glassey, “A review of the status of satellite remote sensing and image processing techniques for mapping natural hazards and disasters,” *Progress in Physical Geography: Earth and Environment*, vol. 33, no. 2, pp. 183–207, 2009.
[29] International Working Group on Satellite-based Emergency Mapping (IWG-SEM), “Emergency Mapping Guidelines, Version 1.0.” Dec-2015.
[30] F. Dell’Acqua, G. Lisini, and P. Gamba, “Experiences in optical and SAR imagery analysis for damage assessment in the Wuhan, May 2008 earthquake,” in *Geoscience and Remote Sensing Symposium, 2009 IEEE International, IGARSS 2009*, 2009, vol. 4, pp. IV–37.
[31] R. T. Eguchi, C. K. Huyck, B. J. Adams, B. Mansouri, B. Houshmand, and M. Shinozuka, “Resilient disaster response: using remote sensing technologies for post-earthquake damage detection,” *Research Progress and Accomplishments: 2001-2003*, pp. 125–137, 2003.
[32] K. Einzmann, M. Immitzer, S. Böck, O. Bauer, A. Schmitt, and C. Atzberger, “Windthrow Detection in European Forests with Very High-Resolution Optical Data,” *Forests*, vol. 8, no. 1, 2017.
[33] M. Li, L. Cheng, J. Gong, Y. Liu, Z. Chen, F. Li, G. Chen, D. Chen, and X. Song, “Post-earthquake assessment of building damage degree using LiDAR data and imagery,” *Science in China Series E: Technological Sciences*, vol. 51, no. 2, pp. 133–143, 2008.
[34] R. Huang, Li, and WL, “Analysis of the geo-hazards triggered by the 12 May 2008 Wenchuan Earthquake, China,” *Bulletin of Engineering Geology and the Environment*, vol. 68, no. 3, pp. 363–371, 2009.
[35] D. Mileti, *Disasters by design: A reassessment of natural hazards in the United States*. Joseph Henry Press, 1999.

[36] C. S. Prater and M. K. Lindell, “Politics of hazard mitigation,” *Natural Hazards Review*, vol. 1, no. 2, pp. 73–82, 2000.
[37] K. J. Tierney, M. K. Lindell, and R. W. Perry, “Facing the unexpected: disaster preparedness and response in the United States,” *Disaster Prevention and Management: An International Journal*, vol. 11, no. 3, pp. 222–222, 2002.
[38] S. Cartwright, “National civil defence emergency management plan order 2005,” *Published under the authority of the New Zealand Government, Wellington, New Zealand*, 2005.
[39] B. K. Paul, *Environmental hazards and disasters: contexts, perspectives and management*. John Wiley & Sons, 2011.
[40] A. M. (CIMA) Benjamin Barth Alberto Viseras Ruiz Monika Friedemann Martin Mühlbauer Christian Knopp Sandro Martinis (DLR) Alexandros Bartzas Spyros Pantazis Georgios Vamvakas (SPH) Miguel Mendes (TSYL) Diana Mathew (AVA) Stéphanie Battiston (UNISTRA) Guido Luzi (CTTC) Clàudia Abancó (ICGC) Javier Mulero Chaves, “D2.1 System Engineering Report Issue 1,” H2020-Project HEIMDALL, 2018.
[41] T. M. S. Garry J. Roedler Kevin J. Forsberg R. Douglas Hamelin David D. Walden, *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Version 4*. INCOSE, 2014.
[42] B. Barth, “D2.11 - Service Concept Specification.” HEIMDALL, 2018.
[43] D. M. Neal, “Reconsidering the phases of disasters,” *International Journal of Mass Emergencies and Disasters*, vol. 15, no. 2, pp. 239–264, 1997.
[44] H. Taubenböck, J. Post, A. Roth, K. Zosseder, G. Strunz, and S. Dech, “A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing,” vol. 8, no. 3, pp. 409–420, 2008.
[45] V. Mojtahed, C. Giupponi, C. Biscaro, A. K. Gain, and S. Balbi, “Integrated Assessment of Natural Hazards and Climate Change Adaptation: II - The Serra Methodology,” 2013.
[46] C. Aubrecht, D. Özceylan, K. Steinnocher, and S. Freire, “Multi-level geospatial modeling of human exposure patterns and vulnerability indicators,” vol. 68, no. 1, pp. 147–163, Jan. 2013.
[47] K. Vincent, “Creating an index of social vulnerability to climate change for Africa,” vol. 56, p. 41.
[48] J. Birkmann, “Risk and vulnerability indicators at different scales: Applicability, usefulness and policy implications,” vol. 7, no. 1, pp. 20–31.
[49] J. Corominas, C. van Westen, P. Frattini, L. Cascini, J.-P. Malet, S. Fotopoulou, F. Catani, M. Van Den Eeckhaut, O. Mavrouli, F. Agliardi, K. Pitilakis, M. G. Winter, M. Pastor, S. Ferlisi, V. Tofani, J. Hervás, and J. T. Smith, “Recommendations for the quantitative analysis of landslide risk,” vol. 73, no. 2, pp. 209–263.
[50] IPCC, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) [Field, C. B., V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. PLattner, S. K. Allen, M. Tignor, and P. M. Midgley (eds.)]*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2012, p. 582.
[51] UNISDR, “Terminology of disaster risk reduction,” United Nations International Strategy for Disaster Reduction, 2004.
[52] C. Aubrecht, P. Meier, and H. Taubenböck, “Speeding up the clock in remote sensing – Identifying the ‘black spots’ in exposure dynamics by capitalizing on the full spectrum of joint high spatial and temporal resolution,” vol. 86, no. 1, pp. 177–182, 2017.
[53] J. Birkmann, O. D. Cardona, M. L. Carreño, A. H. Barbat, M. Pelling, S. Schneiderbauer, S. Kienberger, M. Keiler, D. Alexander, P. Zeil, and T. Welle, “Framing vulnerability, risk and societal responses: the MOVE framework,” vol. 67, no. 2, pp. 193–211, Jan. 2013.
[54] UNISDR, “Global Assessment Report On Disaster Risk Reduction (GAR) 2015 -

Annex 1," United Nations Office for Disaster Risk Reduction, 2015.
[55] S. Wolf, "Vulnerability and risk: comparing assessment approaches," *Natural Hazards*, vol. 61, no. 3, pp. 1099–1113, 2012.
[56] G. Pescaroli and D. Alexander, "A definition of cascading disasters and cascading effects: Going beyond the 'toppling dominos' metaphor," *Planet@Risk*, vol. 3, no. 1, 2015.
[57] J. C. Gill and B. D. Malamud, "Hazard interactions and interaction networks (cascades) within multi-hazard methodologies," vol. 7, no. 3, pp. 659–679, 2016.
[58] M. Wurm, H. Taubenböck, M. Schardt, T. Esch, and S. Dech, "Object-based image information fusion using multisensor earth observation data over urban areas," vol. 2, no. 2, pp. 121–147, 2011.
[59] S. Wu, X. Qiu, and L. Wang, "Population Estimation Methods in GIS and Remote Sensing: A Review," vol. 42, no. 1, pp. 80–96, 2005.
[60] M. Haklay, "How Good is Volunteered Geographical Information? A Comparative Study of OpenStreetMap and Ordnance Survey Datasets," *Environment and Planning B: Planning and Design*, vol. 37, no. 4, pp. 682–703, 2010.
[61] OSM, "The Open StreetMap Project." 2018.
[62] M. F. Goodchild, "Citizens as sensors: the world of volunteered geography," vol. 69, no. 4, pp. 211–221, Jan. 2007.
[63] H. Fan, A. Zipf, Q. Fu, and P. Neis, "Quality assessment for building footprints data on OpenStreetMap," *International Journal of Geographical Information Science*, vol. 28, no. 4, pp. 700–719, 2014.
[64] J. J. Arsanjani, P. Mooney, M. Helbich, and A. Zipf, "An exploration of future patterns of the contributions to OpenStreetMap and development of a Contribution Index," *Transactions in GIS*, vol. 19, no. 6, pp. 896–914, 2015.
[65] H. Taubenböck, T. Esch, M. Wurm, A. Roth, and S. Dech, "Object-based feature extraction using high spatial resolution satellite data of urban areas," *Journal of Spatial Science*, vol. 55, no. 1, pp. 117–132, 2010.
[66] C. Geiß, M. Wurm, M. Breunig, A. Felbier, and H. Taubenböck, "Normalization of TanDEM-X DSM Data in Urban Environments With Morphological Filters," vol. 53, no. 8, pp. 4348–4362, 2015.
[67] Wichmann, "LiDAR Point Cloud Processing with SAGA." 2012.
[68] M. Mokhtarzade and M. V. Zoej, "Road detection from high-resolution satellite images using artificial neural networks," *International journal of applied earth observation and geoinformation*, vol. 9, no. 1, pp. 32–40, 2007.
[69] B. Mack, P. Leinenkugel, C. Kuenzer, and S. Dech, "A semi-automated approach for the generation of a new land use and land cover product for Germany based on Landsat time-series and Lucas in-situ data," *Remote Sensing Letters*, vol. 8, no. 3, pp. 244–253, Dec. 2017.
[70] EEA, "CLC 2012 — Copernicus Land Monitoring Service." 2016.
[71] EEA, "Urban Atlas 2012 — Copernicus Land Monitoring Service." 2016.
[72] C. Geiss, M. Wurm, H. Taubenböck, W. Heldens, and T. Esch, "Comparison of selected impervious surface products derived from remote sensing data—A case study for the city of Munich," in *Urban Remote Sensing Event (JURSE), 2011 Joint*, 2011, pp. 225–228.
[73] M. Pesaresi, G. Huadong, X. Blaes, D. Ehrlich, S. Ferri, L. Gueguen, M. Halkia, M. Kauffmann, T. Kemper, L. Lu, M. A. Marin-Herrera, G. K. Ouzounis, M. Scavazzon, P. Soille, V. Syrris, and L. Zanchetta, "A Global Human Settlement Layer From Optical HR/VHR RS Data: Concept and First Results," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 6, no. 5, pp. 2102–2131, 2013.
[74] T. Esch, M. Marconcini, A. Felbier, A. Roth, W. Heldens, M. Huber, M. Schwinger, H. Taubenböck, A. Müller, and S. Dech, "Urban Footprint Processor – Fully Automated Processing Chain Generating Settlement Masks from Global Data of the TanDEM-X Mission," vol. 10, no. 6, pp. 1617–1621, 2013.
[75] F. Sergio, K. MacManus, M. Pesaresi, E. Doxsey-Whitfield, and J. Mills, "Development of New Open and Free Multi Temporal Global Population Grids at 250

M Resolution," *Geospatial Data in a Changing World*, 2016.
[76] S. Freire and C. Aubrecht, "Integrating population dynamics into mapping human exposure to seismic hazard," vol. 12, no. 11, pp. 3533–3543, 2012.
[77] S. Freire, A. Florczyk, D. Ehrlich, and M. Pesaresi, "Remote sensing derived continental high resolution built-up and population geoinformation for crisis management," in *2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2015, pp. 2677–2679.
[78] S. Freire, K. MacManus, M. Pesaresi, E. Doxsey-Whitfield, and J. Mills, "Development of new open and free multi-temporal global population grids at 250 m resolution.," in *19th AGILE Conference on Geographic Information Science*, 2016.
[79] M. S. Kappes, M. Keiler, K. von Elverfeldt, and T. Glade, "Challenges of analyzing multi-hazard risk: a review," *Natural hazards*, vol. 64, no. 2, pp. 1925–1958, 2012.
[80] M. Coleman and H. Marks, "Qualitative and quantitative risk assessment," *Food Control*, vol. 10, no. 4–5, pp. 289–297, 1999.
[81] J. Schmidt, I. Matcham, S. Reese, A. King, R. Bell, R. Henderson, G. Smart, J. Cousins, W. Smith, and D. Heron, "Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling," *Natural Hazards*, vol. 58, no. 3, pp. 1169–1192, 2011.
[82] L. A. Cox Jr, D. Babayev, and W. Huber, "Some limitations of qualitative risk rating systems," *Risk Analysis: An International Journal*, vol. 25, no. 3, pp. 651–662, 2005.
[83] V. J. Davidson, J. Ryks, and A. Fazil, "Fuzzy risk assessment tool for microbial hazards in food systems," *Fuzzy Sets and Systems*, vol. 157, no. 9, pp. 1201–1210, 2006.
[84] J. Casal, *Evaluation of the effects and consequences of major accidents in industrial plants*. Elsevier, 2017.
[85] M. Mendes, "D5.12 Modelling and Simulation Services – Specifications – Draft." 2018.
[86] B. Merz, H. Kreibich, R. Schwarze, and A. Thieken, "Review article" Assessment of economic flood damage," *Natural Hazards and Earth System Sciences*, vol. 10, no. 8, p. 1697, 2010.
[87] I. Kelman and R. Spence, "An overview of flood actions on buildings," *Engineering Geology*, vol. 73, no. 3–4, pp. 297–309, 2004.
[88] C. Scawthorn, N. Blais, H. Seligson, E. Tate, E. Mifflin, W. Thomas, J. Murphy, and C. Jones, "HAZUS-MH Flood Loss Estimation Methodology. I: Overview and Flood Hazard Characterization," vol. 7, no. 2, pp. 60–71, 2006.
[89] C. Scawthorn, P. Flores, N. Blais, H. Seligson, E. Tate, S. Chang, E. Mifflin, W. Thomas, J. Murphy, C. Jones, and M. Lawrence, "HAZUS-MH Flood Loss Estimation Methodology. II. Damage and Loss Assessment," vol. 7, no. 2, pp. 72–81, 2006.
[90] F. Silvestro, N. Rebora, L. Rossi, D. Dolia, S. Gabellani, F. Pignone, E. Trasforini, R. Rudari, S. D. Angeli, and C. Masciulli, "What if the 25 October 2011 event that struck Cinque Terre (Liguria) had happened in Genoa, Italy? Flooding scenarios, hazard mapping and damage estimation," *Natural Hazards and Earth System Sciences*, vol. 16, no. 8, pp. 1737–1753, 2016.
[91] C. Arrighi, L. Rossi, E. Trasforini, R. Rudari, L. Ferraris, M. Brugioni, S. Franceschini, and F. Castelli, "Quantification of Flood risk mitigation benefits: A building-scale damage assessment through the RASOR platform," *Journal of environmental management*, vol. 207, pp. 92–104, 2018.
[92] S. Jonkman, J. Vrijling, and A. Vrouwenvelder, "Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method," *Natural Hazards*, vol. 46, no. 3, pp. 353–389, 2008.
[93] F. Leone, F. Lavigne, R. Paris, J.-C. Denain, and F. Vinet, "A spatial analysis of the December 26th, 2004 tsunami-induced damages: Lessons learned for a better risk assessment integrating buildings vulnerability," *Applied Geography*, vol. 31, no. 1, pp. 363–375, 2011.
[94] RASOR, "Deliverable 8.1: Definition of vulnerability functionality and criticality functions." CIMA.
[95] ENSURE, "Deliverable 1.1.1: Methodologies to assess vulnerability of structural

systems." CIMA, 2009.

[96] EC, "Emergency Management Service - Rapid Mapping Product Portfolio [http://emergency.copernicus.eu/mapping/ems/ems-rapid-mapping-products]." European Commission, 2015.

[97] C. A. (ICGC) Guido Luzi (CTTC) Alberto Viseras Ruiz (DLR), "D5.4 Drone Sensors and In-Situ Sensors," H2020-Project HEIMDALL, 2018.

[98] UNISDR, "Hyogo framework for action 2005-2015," *ISDR International Strategy for Disaster Reduction; Building the Resilience of Nations and Communities to Disasters*. United Nations Development Programme Geneva, Switzerland, 2005.

[99] UNISDR, "Sendai Framework for Disaster Risk Reduction 2015-2030," United Nations Office for Disaster Risk Reduction, 2015.

[100] J. C. Gill and B. D. Malamud, "Reviewing and visualizing the interactions of natural hazards," *Reviews of Geophysics*, vol. 52, no. 4, pp. 680–722, 2014.

[101] T. L. Tracy Durrant Roberto Boca Giorgio Libertà Alfredo Branco Daniele de Rigo Davide Ferrari Pieralberto Maianti Tomàs Artés Vivancos Hugo Costa Fabio Lana Peter Löffler Daniel Nuijten Anders Christofer Ahlgren Jesús San-Miguel-Ayanz, "Forest Fires in Europe, Middle East and North Africa," Joint Research Center, 2017.

[102] E. E. A. (EEA), *Impacts of Europe's changing climate-2008 indicator-based assessment*, no. 4/2008. European Environment Agency (EEA), 2008.

[103] C. Kuenzer, H. Guo, J. Huth, P. Leinenkugel, X. Li, and S. Dech, "Flood mapping and flood dynamics of the Mekong Delta: ENVISAT-ASAR-WSM based time series analyses," *Remote Sensing*, vol. 5, no. 2, pp. 687–715, 2013.

[104] S. N. Jonkman, "Global perspectives on loss of human life caused by floods," *Natural hazards*, vol. 34, no. 2, pp. 151–175, 2005.

[105] G. Berz, W. Kron, T. Loster, E. Rauch, J. Schimetschek, J. Schmieder, A. Siebert, A. Smolka, and A. Wirtz, "World map of natural hazards–a global view of the distribution and intensity of significant exposures," *Natural hazards*, vol. 23, no. 2–3, pp. 443–465, 2001.

[106] J. I. Barredo, "Major flood disasters in Europe: 1950–2005," *Natural Hazards*, vol. 42, no. 1, pp. 125–148, 2007.

[107] M. Brugioni, B. Mazzanti, and S. Franceschini, "Working Group F Thematic Workshop on FLASH FLOODS AND PLUVIAL FLOODING–Abstracts and Full Papers," *Istituto Superiore per la Protezione e la Ricerca Ambientale: Rome, Italy. Available online: https://circabc. europa. eu/d/a/workspace/SpacesStore/c9c5875a-5661-48a9-ac39-0065405672c2/10117_ATTI_WS_Cagliari_2010. pdf (accessed on 23 September 2018)*, 2010.

[108] D. M. Cruden, "A simple definition of a landslide," *Bulletin of Engineering Geology and the Environment*, vol. 43, no. 1, pp. 27–29, 1991.

[109] UNESCO, "Working Party for World Landslide Inventory - Multilingual Landslide Glossary," *BiTech Publishers*, 1993.

[110] F. V. De Blasio, *Introduction to the physics of landslides: lecture notes on the dynamics of mass wasting*. Springer Science & Business Media, 2011.

[111] M. Klose, L. Highland, B. Damm, and B. Terhorst, "Estimation of direct landslide costs in industrialized countries: Challenges, concepts, and case study," in *Landslide science for a safer geoenvironment*, Springer, 2014, pp. 661–667.

[112] D. Varnes, "Slope movement types and processes, Special report 176: Landslides: Analysis and Control: Washington, DC," *Transportation Research Board*, 1978.

[113] D. Cruden, D. Varnes, A. Turner, and R. Schuster, "Landslides, investigation and mitigation: special report 247," *Transportation Research Board, Us National Research Council, chap Landslides Types and Processes*, pp. 36–75, 1996.

[114] R. Dikau, D. Brunsden, L. Schrott, M. Ibsen, and A. Borgia, "Landslide Recognition, Identification, Movement and Causes," *Pure and Applied Geophysics*, vol. 151, no. 1, pp. 188–188, 1998.

[115] O. Hungr, S. Leroueil, and L. Picarelli, "The Varnes classification of landslide types, an update," *Landslides*, vol. 11, no. 2, pp. 167–194, 2014.

[116] C. Zangerl, C. Prager, R. Brandner, E. Brückl, S. Eder, W. Fellin, E. Tentschert, G.

Poscher, and H. Schönlaub, “Methodischer Leitfaden zur prozessorientierten Bearbeitung von Massenbewegungen,” *Geo. Alp*, vol. 5, pp. 1–51, 2008.

[117] M. Popescu, “A suggested method for reporting landslide causes,” *Bulletin of the International Association of Engineering Geology-Bulletin de l’Association Internationale de Géologie de l’Ingénieur*, vol. 50, no. 1, pp. 71–74, 1994.

[118] M. Budimir, P. Atkinson, and H. Lewis, “Earthquake-and-landslide events are associated with more fatalities than earthquakes alone,” *Natural hazards*, vol. 72, no. 2, pp. 895–914, 2014.

[119] M. Kappes, M. Keiler, and T. Glade, *From Single- to Multi-Hazard Risk analyses: a concept addressing emerging challenges*. 2010, pp. 351–356.

[120] J. C. Gill and B. D. Malamud, “Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework,” *Earth-Science Reviews*, vol. 166, pp. 246–269, 2017.

[121] G. Pescaroli and D. Alexander, “A definition of cascading disasters and cascading effects: Going beyond the ‘toppling dominos’ metaphor,” vol. 3, no. 1.