MINORITY REPORT

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DELIVERABLE 2.2

Methodology for Characterising Dynamic Multi-Hazard Social Vulnerability

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Executive Summary

The objective of this deliverable is to identify risk modelling techniques and to quantify how multiple hazards disproportionately impact different societal groups and sectors by linking risk models and their outcomes to socio-economic characteristics and interdependent infrastructure.

As a result, the deliverable provides a coherent taxonomy of various risk models, highlights important gaps in the literature that hinder operationalisation, and defines community- and expert-engagement methods that pinpoint risk modelling priorities for socio-demographic and economic characteristics together with personal needs during extreme natural events. Consequently, it establishes an overall people-centred risk modelling approach, which is at the heart of the Minority Report project.

In the project's pilot sites in Dublin and Patras, the previously mentioned engagement methods are applied to identify and prioritise differential risks. Additionally, for the Dublin pilot site, these differential risks inform the design of a modelling framework that combines impact models for people and infrastructure networks, taking socio-demographic and economic characteristics into account, as well as a detailed flood-impact model linked to housing of specific income groups. For the Wellington pilot site, the deliverable demonstrates how agent-based modelling techniques are currently applied to wild-fire scenarios, incorporating diverse socio-demographic characteristics. Within the broader context of this work, the pilot sites display a wide variety in how they prioritise differential risks and show differing levels of maturity in their model development.

This deliverable provides the analytical foundation needed to trace how socio-demographic and economic characteristics shape the distribution of loss across a population, thereby supporting the development of people-centred risk reduction strategies.

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List of Acronyms and Abbreviations

Term	Description
CFRAM	Catchment Flood Risk Assessment and Management
D1.1	Deliverable 1.1: Stakeholder Mapping Report

D1.2	Deliverable 1.2: Characterization of Stakeholder Behaviour & Identification of KPIs to Model
D1.3	Deliverable 1.3: Report on Outcomes & Learnings from Co-Design Process
D2.1	Deliverable 2.1: Methodology for Characterising Dynamic Multi-Hazard Physical Building Urban Infrastructure Vulnerability
D2.2	Deliverable 2.2: Methodology for Characterising Dynamic Multi-Hazard Social Vulnerability
D2.3	Deliverable 2.3: Multi-Hazard Risk and Resiliency Assessment Framework
D2.4	Deliverable 2.4: Integrated People-Centred Risk Modelling Framework
D4.3	Deliverable 4.3: Prototype Mobility & Behavioural Prediction Module Ready to Validate
DRR	Disaster Risk Reduction
LCC	Life Cycle Cost Analysis
LCA	Life Cycle Assessment
PCA	Principal Component Analysis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RoS	Rate of Spread
RHF	Radiant Heat Flux
SoVI	Social Vulnerability Index
T2.1	Task 2.1: Characterising Dynamic Multi-Hazard Physical Vulnerability
T2.2	Task 2.2: Characterising Dynamic Multi-Hazard Social Vulnerability
T2.3	Task 2.3: Multi-hazard Risk and Resilience Metrics
T2.4	Task 2.4: Developing an Integrated People-Centred Risk Modelling Framework
WP1	Work Package 1: Stakeholder Engagement and Co-Design
WP2	Work Package 2: Risk Assessment, Quantification & Mitigation
WP3	Work Package 3: Digital Infrastructure Specification
WP4	Work Package 4: Development of a People-Centric Resiliency & Adaptation Toolkit for the Urban Environment
WP5	Work Package 5: Demo Sites Implementation

List of Partners

Participant organisation name	Short Name
Integrated Environmental Solutions	IESRD
Stam Srl	STAM
Demo Consultants BV	DMO
B-Kode	BK
Urban Intelligence	UI
Trinity College Dublin	TCD
University of Canterbury	UoC
University of Auckland	UoA
University College London	UCL
University of Patras	UPAT
Prospex Institute	PI
La Sia Srl	LASIA
E2ARC Architecture & Research for Cities	E2ARC
Pilot site organisations	
Wellington City Council	WCC
Dublin City Council	DCC
Region of Western Greece	RWG

1 Introduction

1.1 Background

The deliverable D2.2 "Methodology for Characterising Dynamic Multi-Hazard Social Vulnerability" is prepared as part of the Minority Report project (*Minority Report Project*, 2025).

D2.2 is prepared as an outcome of T2.2 within WP2, the techno-scientific stream. WP2 develops and validates formal methods to assess natural hazard risks, including physical, social, and intangible impacts, by designing a people-centred risk modelling framework for use at the three project's pilot sites in Dublin (IE), Patras (GR), and Wellington (NZ). Task 2.2 contributes to WP2 by focussing on socio-physical aspects of natural hazard risks. D2.2 is closely linked to deliverable D2.1 "Methodology for Characterising Dynamic Multi-Hazard Physical (Building & Urban Infrastructure) Vulnerability," which focuses on physics-based aspects of the same stream (Valdivieso & Galasso, 2025). In the longer term, the insights generated by D2.1 and D2.2 will feed into deliverables D2.3 "Multi-Hazard Risk and Resiliency Assessment Framework" and D2.4 "Integrated People-Centred Risk Modelling Framework." Figure 1-1 shows the relationship between tasks of WP2.

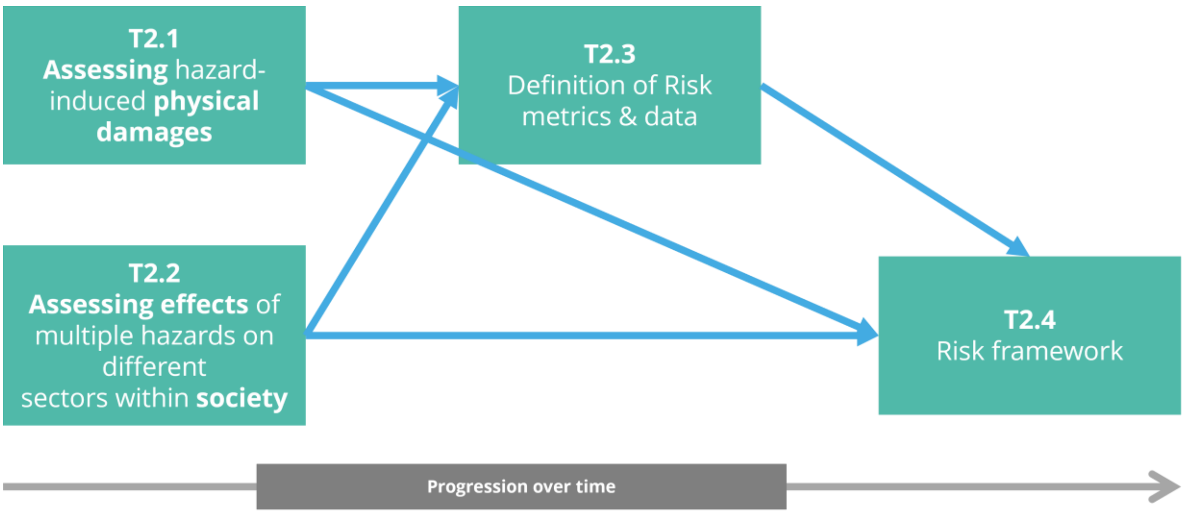

Figure 1-1: Relations between WP2 tasks in the Minority Report project.

The Minority Report project was conceived as a multidisciplinary effort. Consequently, a two-way exchange is embedded with the other work packages. There is a strong interrelationship between T2.2 and WP1, Stakeholder Engagement & Co-Design and their D.1. "Stakeholder Mapping Report" as well as D1.2 "Characterization of Stakeholder Behaviour & Identification of KPIs to Model" developing personas from engagements. But also, the collaboration with WP4 on the "Development of a People-Centric Resiliency & Adaptation Toolkit for the Urban Environment" is intensifying the further the results of WP2 progress.

1.2 Scope and objectives of the deliverable

The deliverable defines ways to identify the socio-technical assessment methods, using different risk modelling techniques and engagement methods to quantify how multiple hazards disproportionately impact different societal groups and sectors. Its scope also covers how risk models are linking people with socio-demographic and economic characteristics as well as interdependent infrastructures and their services. This work lays the foundation for a general methodological framework that links disaster impacts to the socio-demographic and economic profiles of affected people. The objective of the deliverable is to combine quantitative data supported modelling-driven techniques with simulation of human behaviour; to enable the identification of groups that experience disproportionate loss, to support the design of targeted mitigation measures and to feed the results into later risk management activities of the project.

In order to ease understanding of the subsequent chapters some key terminology needs to be defined:

- **Hazard** – refers exclusively to natural hazards, natural extreme events or natural disasters; man-made hazards are excluded from this project.
- **Multi hazard** – denotes the consideration of several distinct hazard types; it does not imply simultaneous, or compound occurrences as referred to in other scientific publications (de Ruiter, 2020).
- **Socio-demographic and economic characteristics** – attributes such as age, gender, income, education level or household composition, which describe the social and economic situation of individuals or communities as well as their demographic background.
- **Social vulnerability** – the degree to which socio-demographic and economic characteristics are connected to the likelihood of adverse outcomes when a hazard strikes. In this deliverable the two expressions are used interchangeably because the characteristics are examined solely for their influence on vulnerability.
- **Socio-physical vulnerability** - links social vulnerability, defined by socio-demographic and economic characteristics, with physical vulnerability, which captures hazard intensity and resulting functional impacts, to describe the combined "socio-physical" vulnerability to hazards.
- **Dynamic** – indicates that the analysis accounts for temporal changes, for example population growth, migration patterns or the changing climatic environment, rather than assuming a static snapshot.
- **Data-mining models** – statistical or machine-learning procedures that extract relationships between disaster impact records and socio-demographic and economic characteristics from existing databases. Within this work they are grouped under the broader label of disaster risk models (Xie et al., 2020).
- **Agent-based models** – computational simulations that represent individual or household agents, their movements and interactions with physical networks such as transport, to capture socio-physical interdependencies (Cho et al., 2012; Taillandier et al., 2021).
- **Socio-demographic and economically-centred risk models** – risk models that place emphasis on the socio-demographic and economic characteristics of potentially impacted people, communities, municipalities, etc., and include only a coarse consideration of physical aspects.
- **Socio-physical risk models** - have a balanced recognition of socio-physical vulnerability.
- **Differential risks** – allows to differentiate several risks as a variety of exposure and vulnerability categories, socio-demographic and economic characteristics of people, geographical areas and stages of the DRR management cycle.

By integrating risk modelling approaches such as data-mining models, agent-based models and others that are identified in this work, D2.2 will provide the analytical foundation needed to trace how socio-demographic and economic characteristics shape the distribution of loss across a population, thereby supporting the development of people-centred risk reduction strategies.

1.3 Structure of the deliverable

The document is divided into two major sections. The first section in Chapter 2 provides the conceptual and methodological basis for integrating socio economic characteristics into disaster risk models. The second section in Chapter 3 demonstrates how the concepts are applied in real-world pilot locations, showing the link between stakeholder input and model development. Below the subsections of each chapter are briefly introduced:

Theoretical Part – Foundations and Methodology

- Taxonomy of relevant risk models – A classification scheme is introduced that clarifies the terminology used throughout the work. It aligns the socio-technical perspective of D2.2 with the predominantly physical models developed in D2.1, creating a common language for socio physical risk modelling.
- Systematic literature review – Building on the taxonomy, a comprehensive review of peer-reviewed studies and grey literature is presented. The review highlights the current gap: existing socio-demographic and economic risk models do not place people and their personal needs at the core of the modelling process.
- Process for stakeholder-driven framework design – The final component translates the literature findings into a step-by-step procedure that engages both the public and domain experts. This process ensures that the resulting modelling framework centres socio economic characteristics and reflects the needs of the communities.

Pilot-Site Part – Practical Application and Stakeholder Engagement

- Site-specific engagement and risk metric identification – For each pilot location, the report describes how workshops, interviews and surveys were used to uncover differential risks. Emphasis is placed on socially focused themes such as income distribution, age structure and access to services, as well as on the broader people centred approach.
- Model selection and development – The section details which risk models and data inputs were chosen for each site, progressing from initial model identification to the construction of complete risk modelling frameworks where feasible.

Conclusions and Forward Integration

The closing section of Chapter 4 summarises the key insights obtained from both the theoretical and pilot-site work. It explains how these findings will be handed over to the upcoming tasks within WP2, namely D2.3 and D2.4, and how they may inform activities outside the current work package.

2 Integration of social vulnerability and related considerations in multi-hazard risk assessments

The opening of this chapter sets out the theoretical foundation that underpins the integration of social vulnerability into multi-hazard risk assessments within the Minority Report pilot sites. The risk-assessment process, in this context, is understood more broadly as the risk modelling process for multiple natural hazards that also incorporates stakeholder-engagement activities.

In this chapter three interrelated components are described.

1. The taxonomy of risk models is expanded to supply clear definitions, terminology and background needed to build a modelling framework that captures both physical and social dimensions of risk, the associated modelling techniques and the constituent parts of risk models.
2. A literature review is carried out to gauge how extensively social vulnerability and personal needs have already been incorporated into risk assessments that rely on risk models. The review highlights existing gaps and points to opportunities for deeper integration.
3. A participatory engagement method is devised and presented. This method brings together the terminology refined in the taxonomy with the insights uncovered by the literature review, enabling the explicit consideration of socio-demographic and economic characteristics, forming vulnerability, and personal needs before selecting or constructing risk models.

Together, these three strands create a coherent pathway for embedding social vulnerability into multi-hazard risk assessments across the project's case studies.

2.1 Taxonomy of risk models including social and physical dimensions

This risk model taxonomy is used to standardise terminology so that models can be compared, selected, and combined consistently; it is used to highlight methodological gaps (Subsection 2.1.3.4) , enable seamless integration of diverse models into practical applications, and provide a clear vocabulary for communicating risk concepts to communities, experts and decision-makers (Subsection 2.3). The present taxonomy builds on the taxonomy published by ARUP, adapting its structure to the specific needs of the Minority Report project and the needs of T2.2 (Almufti et al., 2024). The work is still being drafted for a peer-reviewed publication; the material presented here therefore represents a condensed version of the forthcoming article (Valdivieso et al., 2025).

The taxonomy is made of various classes and categories. Class 0 till class 3 are distinguished primarily by the type of purpose they address. The categories are defined as four exposure-vulnerability categories: Social - people centred, physical – building, physical – infrastructure and socio-physical (Subsection 2.1.2)

While all categories are relevant for a complete picture of natural hazard risks, the deliverable places particular emphasis on the social category, which is described as a people-centred exposure and vulnerability category. The socio-physical category is focus of the upcoming D2.4 and therefore is also only briefly touched. Figure 2-1 shows the methodological flowchart visualising the generation of the taxonomy.

Beyond the exposure-vulnerability category, the taxonomy incorporates a set of model-characteristics that further separate the classes and categories, each elaborated in the taxonomy as a whole table in Figure 2-1. The multitude of tables collectively captures the matrix of class-category pairings for each model characteristic. Among these model characteristics, the modelling approach receives special attention because it clarifies how each model is constructed and how it can be applied in the pilot-site contexts. Detailing the modelling approach makes the current state of work in the selected sites more transparent and supports stakeholders in understanding the methodological choices that underpin the risk assessments.

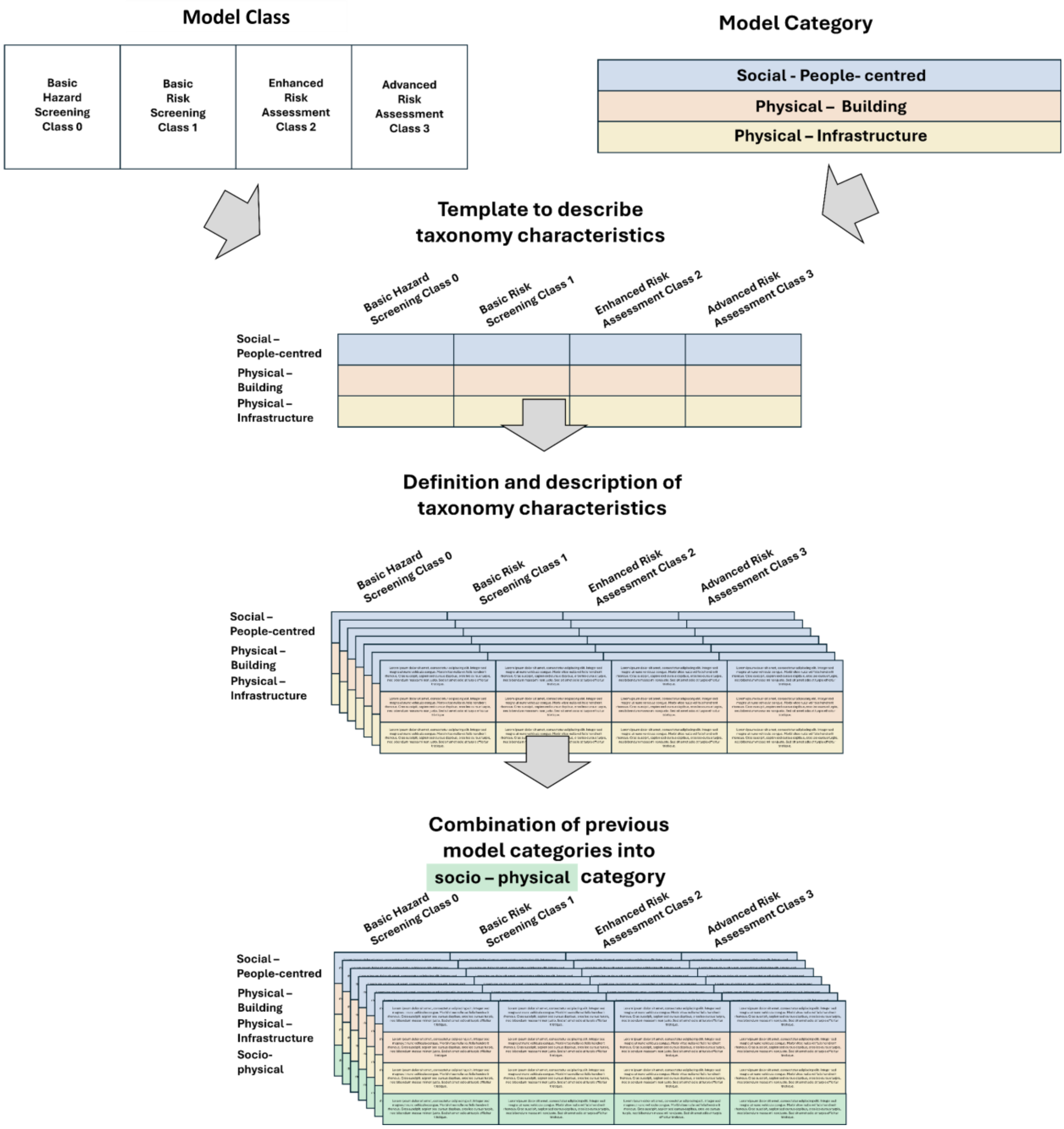

Figure 2-1: Flow chart of the methodology to determine the taxonomy for socio-physical risk modelling frameworks.

2.1.1 Risk model classes

The taxonomy distinguishes four model classes that correspond to the purpose each model serves. The classes are applicable across all exposure-vulnerability categories (physical building, physical infrastructure, social, socio-physical) and are framed by a series of guiding questions.

Class 0 asks whether assets are exposed to a hazard. This foundational class determines if any further analysis from Class 1 to Class 3 assessments are required.

Class 1 evaluates whether the current level of risk warrants an intervention. It moves the assessment from mere presence of exposure to a judgment about the necessity for risk reduction measures through intervention and adaptation measures.

Class 2 identifies the specific locations or assets where interventions should be directed. At this stage the model pinpoints the spatial or functional zones that demand attention.

Class 3 explores how the identified risk reduction measures can be operationalised. It provides guidance on implementation pathways, resource allocation and monitoring mechanisms.

These classes form a logical progression from detection of exposure to the planning of concrete risk reduction measures, ensuring that each model is aligned with the decision-making needs of the project.

2.1.2 Exposure and vulnerability categories

The taxonomy distinguishes four exposure-vulnerability categories that are used throughout the deliverable.

Social - people-centred – captures the direct exposure of individuals and households to hazards together with the socio-economic traits (age, income, health status, access to services) that shape their sensitivity. This is the primary focus of D2.2 (Cutter et al., 2003).

Physical – building – concerns the structural characteristics of residential, commercial or public edifices and the way they respond to hazard loads (Valdivieso et al., 2024).

Physical – infrastructure – covers non-building assets such as bridges, water-distribution networks, power grids and transport corridors (Schotten & Bachmann, 2023).

Socio-physical – recognises that people's vulnerability is mediated by their dependence on physical systems (e.g., road networks, water supply) as considered by Brower et al. (2023) or Wang et al. (2025)

The need to combine social and physical components is a conclusion of the presented work detailed definition and examination is forthcoming as part of D2.4.

2.1.3 Model characteristics

The taxonomy groups risk models by a set of characteristics that together describe how a model is built, what information it consumes, the spatial and temporal grain at which it operates, and the way it expresses risk. These attributes are elaborated below and illustrated with the social - people-centred and the socio-physical perspective that drive Deliverable D2.2.

2.1.3.1 Risk modelling techniques with relation to social vulnerabilities

All techniques placed in this category concentrate on the individual, the household, the community or the municipality. As the model class moves from 0 to 3, the modelling techniques become progressively finer. The taxonomy distinguishes several families of modelling techniques. Each family can be adapted to a people-centred perspective by inserting socio-economic attributes, demographic breakdowns or behavioural rules that describe how individuals, households or even bigger administrative units such as municipalities are exposed to or related to a hazard. The following paragraphs summarise the main modelling technique families and illustrate how they can be employed to capture what is referred to as social vulnerability in the context of the Grant Agreement.

Empirical statistical studies: These techniques exploit observed data to quantify the strength of relationships between hazard exposure and empirically derived risk metrics usually addressing Class 0 or Class 3 risk models. By adding variables such as income level, age group or housing quality, the statistical model can reveal which social groups experience more severe impacts. To provide a Social - *People-centred category example*: a logistic regression that predicts the probability of flood-related injury for households, with predictors that include median neighbourhood income and proportion of elderly residents.

Geographical models: This modelling technique maps hazard footprints and exposure layers on a cartographic grid and is usually associated with Class 0 or Class 1 risk models. When the exposure layer is replaced by a population density raster that is further disaggregated by census tract characteristics, the spatial model begins to reflect social disparity. A Social - *People-centred example* would be a flood inundation map overlain with a map showing the distribution of households lacking indoor plumbing, highlighting areas where lack of basic services increases vulnerability and therefore amplifying potential impacts through potential diseases.

Linear models: Linear formulations combine hazard intensity, exposure quantity and vulnerability weightings in a summed expression referring to Class 1 risk models. By assigning higher vulnerability weights to groups identified as socially fragile, the linear model produces a risk surface that mirrors social inequality. A Social - *People-centred example* could be a risk map calculated as hazard magnitude multiplied by population count multiplied by a vulnerability coefficient derived from unemployment rate.

Index models: Composite indices aggregate a suite of socio-economic and environmental indicators into a single score that can be compared across administrative units, serving as a Class 3 risk model. When the index includes variables such as literacy, access to health care and building age, it becomes a direct measure of social vulnerability to a given hazard. To provide a Social - *People-centred example*: a “Community Resilience Index” that ranks municipalities resilience by combining flood depth, proportion of low-income households and distance to emergency shelters.

Non-linear models – tagged *Network system flow non-linear models*. These approaches capture feedback loops, threshold effects and cascading pathways that cannot be represented by simple additive formulas and can span all classes from Class 0 - 3. By modelling the interdependence between utility networks, transportation links and population clusters, non-linear models expose systemic weaknesses that disproportionately affect vulnerable groups. A Social - *People-centred example* could be an input-output simulation that tracks how a landslide blocks a road, causing delayed medical aid for patients in remote villages, thereby quantifying indirect health impacts.

Human-behaviour models and data-mining models - these modelling approach are elaborated in more detail in Subsection 2.1.3.2 and Subsection 2.1.3.3 since they are specifically highlighted in the Grant Agreement and partially applied in the context of the Wellington case study in detail.

2.1.3.2 Human behaviour models

The human behaviour models have been designed to assess how the exposure of hazards to individuals can affect their mobility and potentially endanger their wellbeing by the risks these hazards pose to them. To analyse this, human behaviour model assessment is comprised in two parts:

1. Physical risk posed to individuals
2. How risks affect individuals’ mobility

Within these two parts considerations are also made in relation to human responses to hazards that govern the actions people take within hazard scenarios. These behavioural characteristics and how they're integrated into the models are available in more detail within Deliverable 4.3 "Prototype Mobility & Behavioural Prediction Module Ready to Validate".

Physical risks posed to individuals: The assessment of physical risks posed to the local population is assessed both at the property and the transport level. At the property level the risk assessment considers the level of direct and indirect impacts (such as loss of key services such as electricity and water supply) to a property that would result in the increased likelihood that the person would need to vacate their property. For example, Figure 2-2 shows the Radiant Heat Flux (RHF) levels at the building level along a section of the Wildland Urban Interface during a simulated 6-hour wildfire event. Depending upon the building characteristics/vulnerability there is the potential for ignition and therefore would require evacuation.

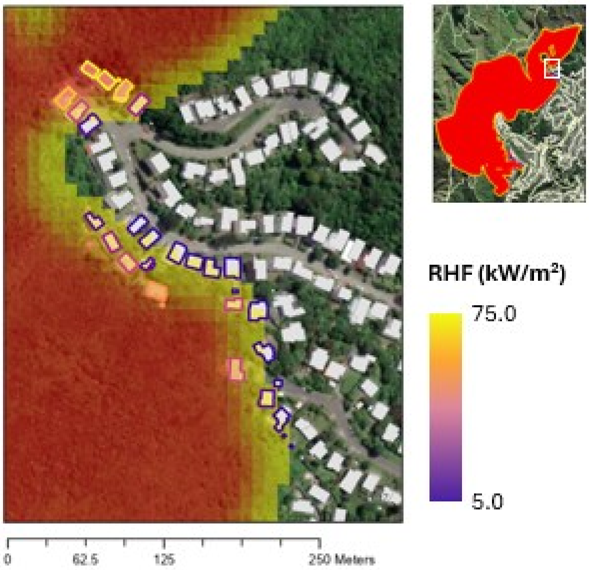

Figure 2-2. RHF Exposure at the property level for a 6-hr simulated wildfire scenario

How risks affect individuals' mobility: Once a property is evacuated, considerations need to be made as to the potential risks the evacuees are exposed to in the network.

From the evacuation and mobility perspective, evacuees may tend to relocate either by foot or by vehicle. The effect of the hazard will also vary according to transport method available/selected by the evacuees. To quantify the risks posed to those within the transportation network and the potential disruption to mobility, we can thus consider risks posed to vehicle occupants and individuals moving on foot.

Within the context of flood risk assessments, previous work by Pregnolato et al. (2017) reviewed a number of studies analysing the influence of weather on vehicle mobility with the research highlighting the relationship between flood depth and vehicle speeds and the variations associated with vehicle types. In this study an upper threshold of approximately 30 cm was identified as a maximum traversable flood depth for vehicles that corresponds to approximate tailpipe clearance heights.

Research by Martínez-Gomariz et al. (2016) and Martínez-Gomariz et al. (2017) expanded on the depth-disruption based risk assessment by including flow velocities into their assessments in the context of how moving flood waters can affect the stability of people (Figure 2-3a) and vehicles (Figure 2-3b). This approach highlights that vehicles are more susceptible to flood depths due their buoyancy whereas people are more susceptible to flow velocities. For the generation of the graphs in Figure 2-3a a range for medium risk is suggested because also a range of different population groups exhibiting differing capacities to stand stable have been considered.

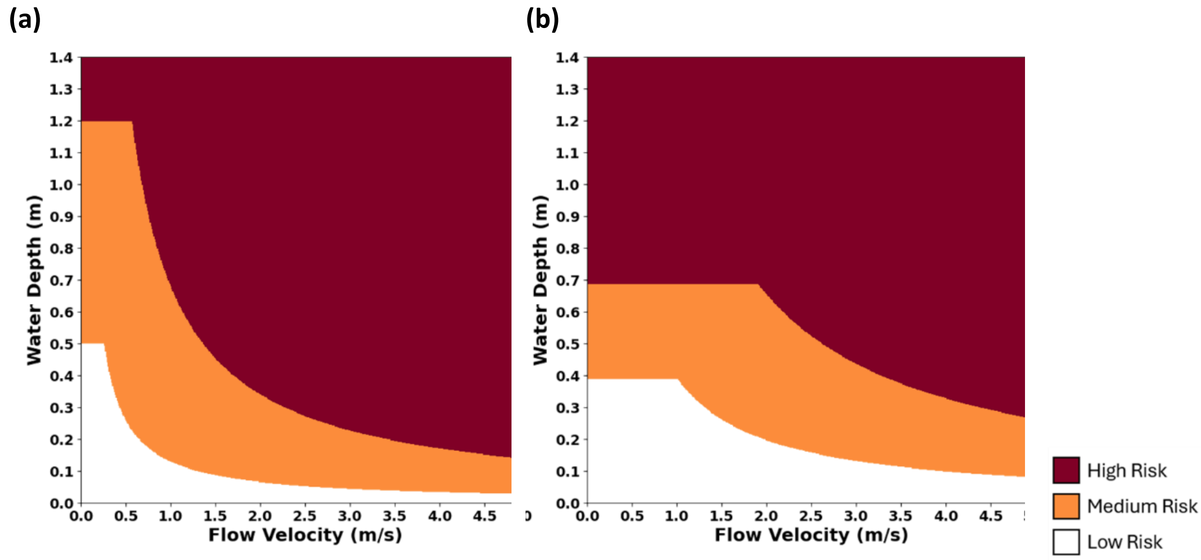

Figure 2-3. Pedestrian (a) (Martínez-Gomariz, Gómez and Russo 2016) and vehicle (b) (Martínez-Gomariz, et al. 2017) flood depth and velocity stability curves

Within the wildfire modelling, the applied thresholds for vehicles and people are kept the same using the values/data associated with the tolerances related to RHF values that people can withstand. Table 2-1 outlines the respective RHF tolerance levels defined in Zarate et al. (2008), and the risks classifications assigned for assessment within the wildfire case study.

Table 2-1. Radiant Heat Flux safety thresholds (Zárate, Arnaldos and Casal 2008) with appended risk classification

Wildfire Risk	Radiant Heat Flux (kW/m^2)	Effects on individuals
Low	1.4	Harmless for person without any special protection
Medium	1.7	Minimum required to cause pain
	2.1	Minimum required to cause pain after 60s
	4.0	Causes pain after 20s exposure (first degree burns)
High	4.7	Causes pain in 15-20s and burns after 20s
	7.0	Maximum tolerable value for firefighters completely covered and protected by specialist protective clothing

The risk metrics defined for both flooding and wildfire are used within the mobility and evacuation models to influence and constrain movements within the transportation network (Figure 2-4). As part of the network constraints, we can close off road and sidewalk access over time to people and/or vehicles when risk scores are high or greater than medium. With these closures in place, accessibility assessments can be carried out to analyse how such closures impact mobility.

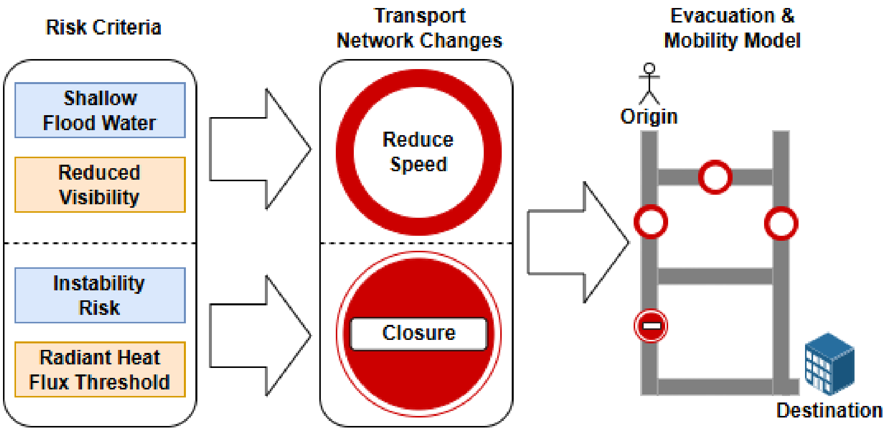

Figure 2-4. Example linking hazard outputs to mobility and evacuation assessment models

For the risk assessment in the context of mobility and evacuation, each persona class defined in D1.2 of WP1 Has an associated risk awareness metric that is defined in WP4 (D4.3). This awareness score can be utilised to determine whether a modelled persona will traverse a section of the transportation network that is still theoretically passable based on its risk score e.g. low up to medium risks values. Using a micro-scale modelling approach observation will be made as to the level of risk individuals are exposed to as they traverse the network.

2.1.3.3 Data-mining models

The complex dependencies that individuals have on the built environment is often limited by the purpose with which risk models are assembled. To overcome this limitation, a data mining simulation-based framework for characterising relationships between people and the built environment that can be directly integrated into a conventional natural-hazard risk model by Wang et al. (2025) is introduced in detail.

The proposed simulation-based framework (Figure 2-5) is designed for application across a self-contained geographical extent (e.g., a city). The framework captures people's dependencies on a set of $z_{(res)}$ residential and $z_{(tot)} = \sum_t z_{(t)}$ non-residential buildings within this extent that are important to their daily lives.

The definition of the variables mentioned in Figure 2-5: X_{pop}: a list of variables that each represent a socio-demographic or household characteristic of a real population; $X_{control}$: a subset of X_{pop} that are chosen as 'control variables'; Y_{phy}: physical vulnerability characteristics of buildings; Y_{occ}: high level occupancy information for buildings; $Y_{phy,res}$: a subset of Y_{phy} included in "population housing" samples; X_{res}: a subset of household-level characteristics in X_{pop} that are included in population-housing samples; Dres: designated home locations of each individual; $Y_{phy,t}$: a subset of Y_{phy} included in "population-asset-distance" samples associated with service type t; X_t: a subset of individual-level characteristics in X_{pop} that are included in population-asset-distance samples associated with service type t; distance_r travel distance via the shortest route; D_{t_time}: designated buildings for each individual for service type t for a prescribed time (time) of the day

The types of non-residential buildings considered (e.g., workplaces, health-care centres, recreational facilities) depend on the goals of the risk analysis (i.e., which $z_{(tot)}$ service types are of interest to stakeholders) and on the data available (discussed further in a subsequent section).

The framework comprises three calculation modules:

1. **Population Synthesis** – Generates a synthetic population that reproduces the joint distributions of key attributes observed in a real population (Sun et al., 2018).

2. **Building Data Fusion** – Spatially merges data detailing the physical characteristics of buildings with high-level information about their occupancy.

3. **Population Spatialisation** – Assigns the synthetic population from Module 1 to specific residential and non-residential buildings, using the information stored in Module 2 and human-building linkage models that rely on additional data samples.

The outcome is a synthetic-population dataset containing the spatial dependencies of each person (organized into households) on the built environment. Monte Carlo sampling is integrated throughout the framework to account for uncertainty at various calculation stages.

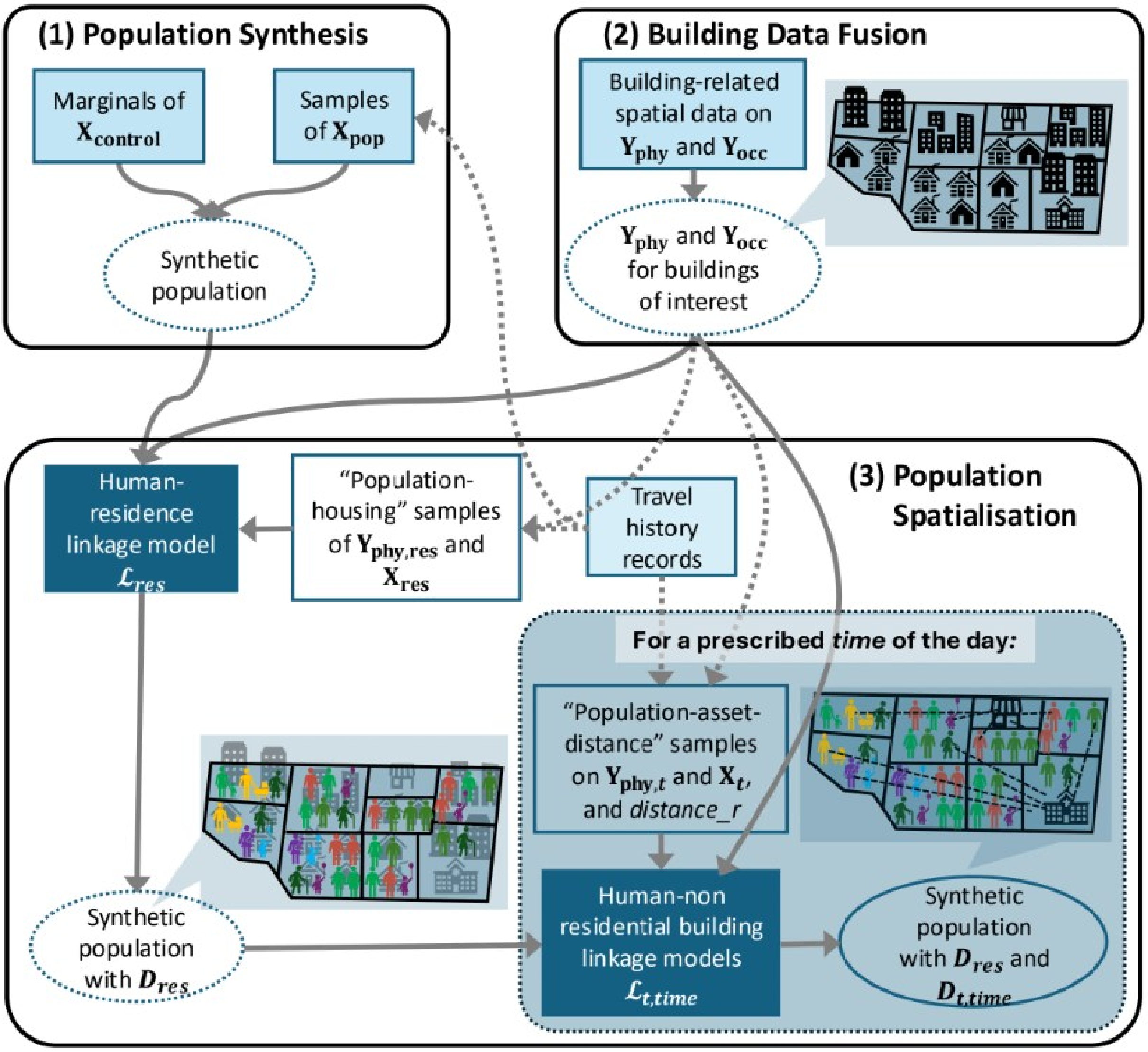

Figure 2-5: Simulation-based framework for characterising detailed human dependencies on the built environment (Wang et al. 2025)

2.1.3.4 Other model characteristics

Data types

The data used to support these techniques evolve in parallel with the model class. Early-stage models rely on binary presence/absence layers (population counts per administrative unit). Mid-stage models require disaggregated socio-economic tables, often broken down by scenario (future climate, land-use change) or by time of day (night versus daytime activity patterns). The most advanced models integrate dynamic datasets such as real-time mobility traces, energy consumption logs or health-service utilisation records, thereby linking individuals and communities to their evolving characteristics. The examples previously elaborated are concentrating on exposure data only, but also vulnerability data is considered in the taxonomy for the social – people centred category.

Resolution and typical scale

People-centred risk models are typically anchored to administrative boundaries at multiple spatial scales, ranging from a micro- scale for individuals or households, through meso- scales such as census blocks and neighbourhoods, to medium-area units like census tracts or sub-districts, and finally to large-area units such as municipalities or districts. Socio-economically centred risk models refer to these units because these are the units in which demographic statistics are collected, and policy decisions are made. Some applications adopt a grid-based representation that aligns with the spatial footprint of the hazard (e.g., a flood depth raster); this approach yields a more physically oriented view of risk but can be intersected with administrative layers to retain the social dimension. The typical spatial grain ranges from a few hundred metres in dense urban settings to several kilometres in rural catchments, while the temporal horizon spans from near-term forecasts (hours to days) to long-term scenario analyses (decades).

Model purpose

In addition to a general definition of the model's purpose (as outlined in Subsection 2.1.1), the purpose of a model can also be mapped onto the four risk model classes focussing on the social - people-centred exposure and vulnerability category.

- Class 0 – Determine whether people are exposed to a natural hazard.
- Class 1 – Assess whether the magnitude of that exposure justifies an intervention.
- Class 2 – Identify who and where the at-risk population is located.
- Class 3 – Analyse how people are affected and design risk-reduction measures that address their specific needs.

Risk metrics

Risk metrics translate the output of a model into quantities that can be communicated to decision-makers. In the social – people centred category they are built incrementally along the model classes and serve as a bridge to the concept of *differential risks* – the notion that risk is not uniform across a population but varies according to socio-economic attributes.

- Class 0 – Count of people exposed to flooding within a catchment.
- Class 1 – Annual number of people at risk of being harmed by flooding (Jonkman, 2007).
- Class 2 – Percentage of exposed individuals possessing a specific set of socio-economic characteristics that amplify vulnerability (e.g., low income + elderly).
- Class 3 – Number of people who could lose power because of cascading flood impacts and who depend on electricity for life-sustaining functions (e.g., medical equipment).

By moving from a simple exposure count (Class 0) to a nuanced assessment of cascading service failures (Class 3), the taxonomy captures increasingly detailed differential risks, enabling planners to target interventions where they are most needed.

2.2 Literature review of socio-economically centred risk models

The systematic review builds directly on the terminology defined in the preceding chapter: The taxonomy's exposure and vulnerability categories (social – people centred risk models, and socio-physical risk models), are used as a perimeter for the literature that has been investigated in the literature review. In this chapter these are also being referred to as socio-economically centred risk models or only risk models. The model characteristics outlined in the taxonomy are used to categorise the literature that is studied and assign the literature to different types of details that they consider. The literature review is currently undergoing peer-review, and an excerpt of the draft is included in this deliverable to illustrate the emerging contribution (Schotten & Cremen, 2025).

Determining the type of detail that risk model studies consider is the focus of the literature review. This type of detail relates to the class definitions used in the taxonomy work. Because the literature review must assign categories, subcategories, and tags to each piece of literature sharply, it cannot be as continuous as the classes defined in the taxonomy. Consequently, the levels of detail are closely linked to, but not synonymous with, the taxonomy classes. Table 2-2 is showing the similarities and differences of classes from the taxonomy and types of detail for the literature review.

Risk models first type of detail is to focus on binary exposure maps coupled with demographic aggregates. Other risk models combine potential impacts with probabilities for risk-based models. More advanced contributions enrich the exposure layer with income brackets, age cohorts, health status and access to critical services. The most sophisticated papers combine dynamic mobility patterns with cascading infrastructure failures to capture indirect impacts on vulnerable groups. In the course of this work, it is suggested to refer to people-centred socio-physical risk models as a combination of all of these previously outlined levels of detail (Figure 2-6).

The synthesis of the reviewed publications reveals a clear gap: most of the analysed literature describing risk models either concentrate on physical hazard dynamics or treat socio-demographic and economic characteristics as an afterthought. Few studies present a structured risk model process that starts from data on socio-demographic and economic characteristics, proceeds through calibrated vulnerability functions and ends with actionable risk metrics that can guide mitigation planning that are able to address a purpose adhering to Class 2 and Class 3 of the taxonomy.

To address this gap for Class 2 and Class 3 risk models the final part of the review proposes a generic modelling process. The process begins with a baseline exposure assessment, adds a layer of socio-economic weighting, incorporates behavioural modifiers where data permit, and finishes with scenario-based risk outputs. By following this sequence practitioners can construct genuine people-centred risk models that qualify as socio-economically risk models in the sense defined by the taxonomy.

Table 2-2: Difference of risk model classes from taxonomy and type of details of risk models for literature review.

Taxonomy - Classes	Literature review – Type of detail
Class 0 - Exposure	Exposure
Class 1 – Risk and impact	Risk and impact
Class 2 – Locating the need for risk reduction interventions	Social vulnerability characteristics
Class 3 – Comparison of intervention measures	Personal needs level

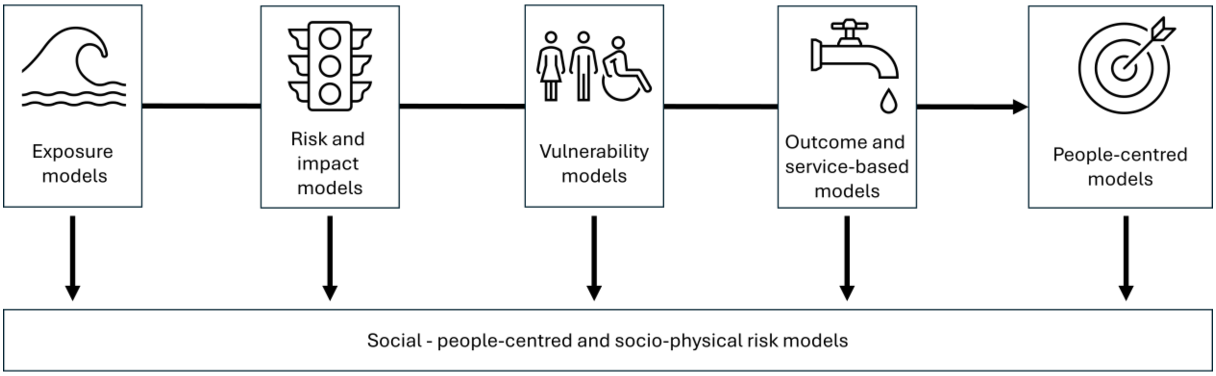

Figure 2-6: The type of details contributing to social – people centred and socio-physical risk models.

2.2.1 Methodology of the literature review

The prepared systematic literature review is classified as a meta-analysis literature review (Ralph & Baltes, 2022) which is combined with a rapid review (Pizard et al., 2024) and has been executed in a process shown by the flowchart in **Error! Reference source not found.** as also used by Kitchenham & B rereton (2013). At the end of the literature review, the findings are presented as results and challenges and recommendations are derived from those as done by Cremen & Galasso (2020). The dataset gathered during the preparation of the literature review is shared in the publication currently being prepared (Chapter 6 Appendix).

The first step of the literature review is stating the research question and specifying the scope of the review. The main research question guiding this study is: "How and to what extent do social – people-centred and socio-physical risk models represent the impacts that people experience during disasters?". The scope is structured using the framework proposed by (Booth et al., 2012), which addresses three core elements: "Who is being studied?" For this study only publications describing technical natural hazard risk models or as defined in the taxonomy social – people-centred and socio-physical risk models also referred to in this chapter as socio-economically centred risk models are considered. "What is being investigated?" It is studied which type of detail is considered in different socio-economically centred risk models and how this relates to the model purpose or the modelling technique that is being used as well as other supportive categories complementing the answer to the lead question. The final question structuring the literature review "How does the literature review answer the research question?" is addressed by developing a first-version categorisation of risk model characteristics and assessing how each modelling technique performs in relation to the central research question.

In the second step a first informal literature review showed that the scope of the study opened by the research question is a relevant question currently being discussed in other publications. Additionally, a scoping of literature has shown that sufficient material is available for a literature review.

In the third step publications were screened subjectively by the authors to assess their value in addressing the research question. In total 14 publications were selected as key literature of this literature review to form the categories and subcategories of the literature review (Agrawal et al., 2024; Burton, 2010; Cremen et al., 2022; Fekete & Nehren, 2023; Iannacone et al., 2024; Joint Research Centre (European Commission) et al., 2019; Kantamaneni et al., 2024; Kind et al., 2020; Maharani & Lee, 2017; Otárola et al., 2024; Sutley et al., 2017; Tocchi et al., 2024; Wang & Logan, 2025).

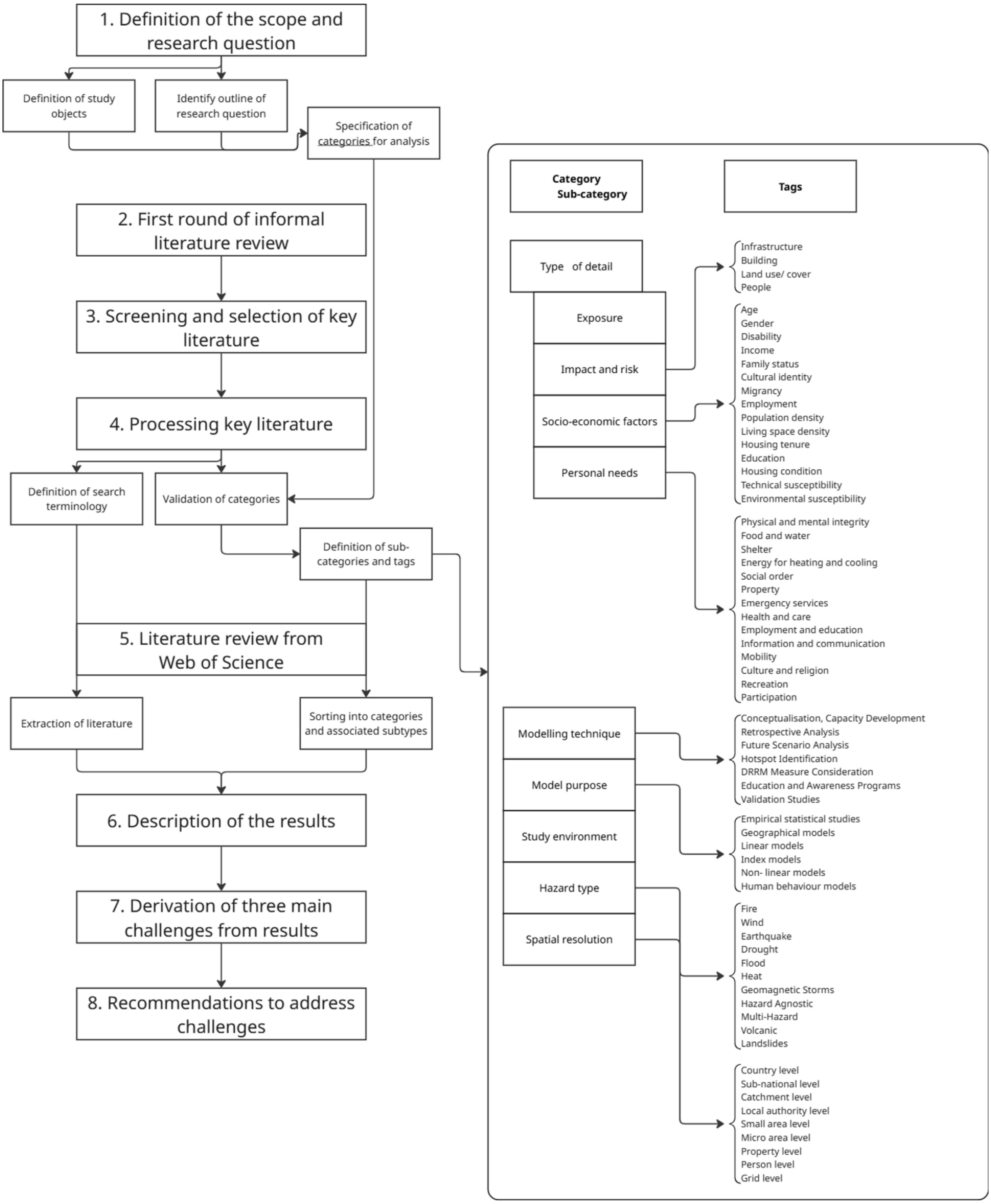

Figure 2-7: Process flow chart of systematic literature review including the categories, sub-categories and tags used to characterise the identified literature.

In a fourth step this literature was analysed to derive key terminologies for a search query in the library Web of Science (Clarivate Analytics). Figure 2-8 shows the chosen combinations of key words necessary in the title of publications. Another part of this step was the review of categories, subcategories as suggested in the first step and shown in Figure 2-7. Each of the categories and subcategories then were further classified in tags that would describe the different options that a risk model can have to fall into the categories and subcategories. The category “type of detail” is split into the subcategories: “exposure”, “impact and risk”, “vulnerability” and “personal need”. The tag for a vulnerability

(((TI=(risk OR disaster OR hazard OR flood OR earthquake OR storm OR hurricane OR typhoon OR wind Or extreme Or heat OR drought)) AND*

TI=(Model OR simulation OR framework OR index OR quant)) AND*

TI=(Social OR socioeconomic OR socio OR poor)) AND*

TI=(human-cent OR people-cent* OR equity OR vulnerability OR consequences OR community OR impact)*

Figure 2-8: Key terminology to search for relevant literature in the Web of Science (Clarivate Analytics).

subcategory is then for example "age", "income" or "education" which if assigned to a publication means that these risk models would consider "vulnerabilities" as a type of detail and specifically people of certain age, income or educational status. Additionally, **Error! Reference source not found.**Appendix 6-1 provides a detailed description of these model characteristics, along with the naming conventions used for these attributes in the dataset generated during this literature review.

The fifth step is the actual reviewing of literature based on the PRISMA methodology (Moher et al., 2009). For that the literature is first identified using the search query in Figure 2-8. After screening and checking for eligibility, 96 out of 290 publications were included in the detailed review. In the detailed review tags were assigned to the publications for each category and subcategory.

In the sixth step, the results of the literature review were described by compiling graphics that summarize the total number of tags assigned to the 96 studies but also relate the occurrence of certain tags to each other. As done in the bar charts of Figure 2-9-F which relate the used modelling technique with the model's purpose.

In the last two steps the results are investigated for the challenges they surface and subsequently recommendations are made to address these.

2.2.2 Literature review results

A selected excerpt from the results of the literature review of the 96 relevant publications is summarized in Figure 2-9. The methodology provides a comprehensive account of the process by which the publications are identified and how these were assigned to categories subcategories and tags, the results of which are presented herein Subsection 2.2.1.

The literature review indicates that the highest number of publications addressing socio-economic risk models, which consider only one of four in the category "types of detail", pertains to the *exposure* and *vulnerability* subcategories (Figure 2-9-A). *Risk and impact* as well as *personal needs* are only considered in ~30% of all publications.

When categories are further broken down into subcategories, it becomes clear which aspects receive particular attention. The *risk and impact* subcategory, the distribution is even across the tags *buildings, infrastructure, land use/land cover* and *people* (Figure 2-9-B). In the subcategory *vulnerability characteristics* especially the tags *age* and *income* but also *gender* are considered most (Figure 2-9-C). The most tagged *personal needs* in the analysed publications consider *physical and mental integrity* as well as damages to own *properties.* Other personal needs such as *food and water* or the availability of *shelter* are only scarcely considered (Figure 2-9-D).

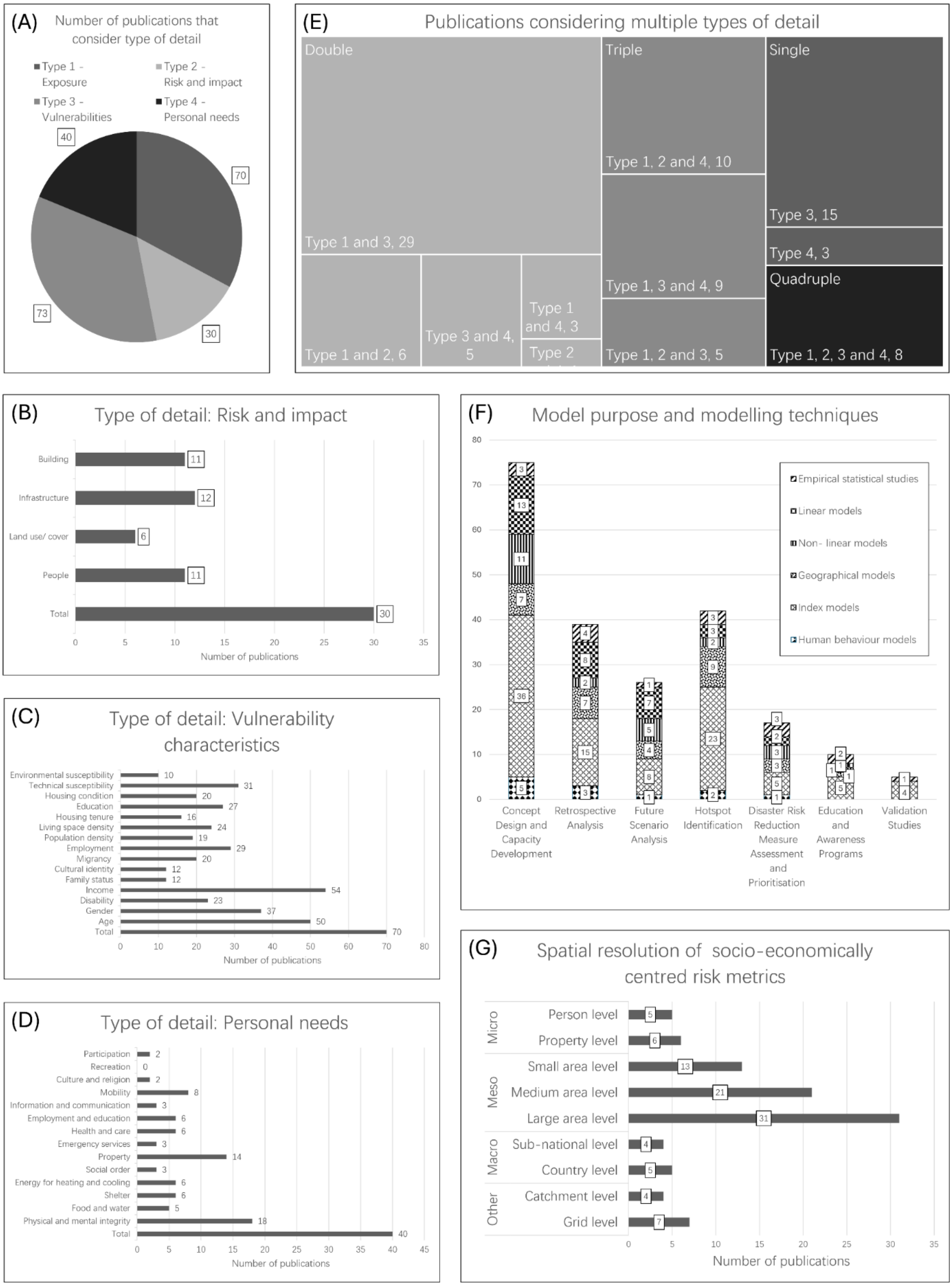

Figure 2-9: Results of the literature review on socio-economically centred risk models

In addition to evaluating which subcategories of the category "type of detail" were considered in how many publications, the results also provide insight into how many of these subtypes were considered in combination (Figure 2-9-E). A representation of two types of detail within a single study was the most common finding, appearing in 44 publications; of these, 29 examined the "exposure" and "vulnerability" details, which are closely associated with vulnerability indices. A triple application of *types of detail* was identified in 24 publications. The consideration of a single *type of detail* was only identified in 18 publications. But most scarce was the application of all four *types of detail* in one study with only eight studies -referred to as quadruple in Figure 2-9-E.

Figure 2-9-F shows which *model purpose* was addressed using which *modelling techniques (Subsection 2.1.3)*. Most publications served the purpose of the *concept design and capacity development* with half of that category utilising index models. Also, the second largest model purpose category of *hotspot identification* is addressed by utilising index models. Less than 20% of the studies addressed the purpose of *disaster risk reduction measure assessment and prioritisation*.

The last category introduced in the results of this literature review is assigning tags based on how the publications spatially resolve the resulting socio-economically centred risk metrics (Figure 2-9-G). The majority of the publications are applying a spatial resolution on the meso scale. The macro and micro scale are only represented by a small number of publications.

2.2.3 Challenges derived from the literature review

Most socio-economically centred risk models concentrate on vulnerability and exposure utilising index models.

Most literature identified in the literature review concentrate on exposure and vulnerability as level of detail (Figure 2-9-A).

These two types of detail are most commonly found in studies that use Social Vulnerability Indexes (SoVIs), which tend to oversimplify real-world experiences of natural-hazard risk by aggregating socio-demographic and economic characteristics into a single composite index. In addition, other focal points—such as environmental, hazard-centric, or infrastructure-related aspects—can be incorporated by index-based approaches, although these dimensions play only a minor role in this deliverable and are considered alongside the primary focus on social vulnerability.

SoVI have established themselves as a solid method to acknowledge that vulnerability itself is not only an outcome of extremes in intensity measures such as temperature, flood depths wind speeds and so on but that it is being "produced in and by society" (Ellena et al., 2020)." Since the first production of a SoVI by (Cutter et al., 2003) the number of articles utilizing this methodology has increased exponentially from 2001 till 2022 with more than 160 references in publication titles in 220 (Painter et al., 2024).

The index model process usually consists of three main steps: identification and validation of spatial input data on socio-economic characteristics (e.g. hierarchical segmentation analyses (Aroca-Jimenez et al., 2017)); reduction of redundant correlated socio-economic factors (e.g. principal component analysis (PCA) (Guillard-Gonçalves et al., 2015)); and finally, the index generation and analysis (Cutter et al., 2003). There are other manifestations of this methodology that, for example, additionally incorporate environmental or technical factors or focus on processing the index results to generate local vulnerability islands.

What the literature review frames as "vulnerability characteristics" cannot automatically be taken as normative factors that increase vulnerability; each characteristic must be evaluated in the context of the specific type of impact and hazard to which it relates. Their aggregation into a single index amplifies this inaccuracy even further, since vulnerability is assumed to be uniform and independent of the dynamics introduced, for example, by different types of hazards or the personal needs of the individuals behind socio-economic characteristics. PCA as the main tool is used to reduce correlations and redundancy among the socio-economic variables in each statistical unit (e.g. regions, census tracts, small areas) which are selected for constructing SoVI. While the choice of input characteristics can be expert-driven, PCA itself does not provide an interpretation of what the resulting components mean for vulnerability. Blackwood & Cutter (2023) also note that social vulnerability indexes are inadequate in capturing individual realities due to their reliance on aggregated data.

As an example, to underline this point, an empirical study of the 1995 Chicago heat wave demonstrated that certain socio-economic characteristics, such as ethnicity, could enhance resilience rather than increase vulnerability, contrary to how some vulnerability indices might interpret them (Klinenberg, 2015).

Risk metrics for socio-economically centred risk models are mostly resolved on administrative boundaries and less on community and individual level affecting the granularity of potential methods.

The findings of the literature review show that the spatial resolution of socio-economically centred risk models concentrates on the meso-scale and less on the micro-scale, which impairs the ability to identify detailed risks and make decisions at the individual level.

The spatial resolution of the socio-economically based risk metrics is resolved in more than 2/3 of the publication on the meso scale which includes small area units (e.g. census blocks to neighbourhoods), medium area units (census tracts to sub-districts) and large area units (e.g. municipalities to districts) (Figure 2-9-G). This approach organizes individuals into groups ranging from ~100 to ~100,000, thereby consolidating the needs associated with these population clusters. Moreover, the micro-scale level of resolution, encompassing both property and individual levels, examines individuals and groups comprising fewer than 100 individuals.

A finer spatial resolution is not only sharpening the resolution in a geographical dimension but also allows much more nuanced and diverse understanding of personal needs within study areas. As an example, a risk metric such as the economic damage or costs associated with the impact of an extreme event will shine a different light when expressed on district level compared to an individual level. On district level it would lead to a generalisation of individuals and impede the consideration of varying coping capacities present.

One effect of generating risk metrics at a higher resolution is the production of higher numbers, which lead to a phenomenon known as compassion fade, thereby reducing the likelihood of individual-level reaction to information and call to action along the whole DRR management cycle (Jenni, 1997; Vastfjall & Slovic, 2015). One effective strategy to mitigate compassion fade is the singularization of impacts, as demonstrated by psychological studies that show an increase in donations compared to fundraisers that didn’t make use of this technique (Hsee et al., 2013). Singularisation refers in this case to breaking down impacts on an individual or household level. This concludes the challenge for risk models to represent consequences in their singularity, which is particularly important when considering individual vulnerabilities The resolution of a risk model is constrained by both the granularity of the available input data and the model’s intended purpose, and because detailed socio-demographic and economic data—as well as fine-scale hazard intensity-impact-vulnerability relationships for those characteristics—are scarce, the model’s spatial and thematic detail inevitably remains limited.

Socio-economically centred risk models don’t propagate to the purpose of considering specific risk management measures.

The purpose of socio-economically centred risk models rarely extends into DRR management measure assessment and prioritisation. Their potential to equitably reduce the consequences of extreme events for people is not evaluated, yet.

The literature review shows that most socio-economically centred risk models concentrate on concept design and capacity development, retrospective analysis and hotspot identification (Figure 2-9-F). The model purpose is derived from the conclusion of the investigated literature and some literature reviews addressed multiple purposes. In addition to education and awareness, as well as validation studies, risk models considered risk reduction measures in only 12 out of 96 studies, highlighting the need for their prioritisation.

A key obstacle to advancing risk models towards the appreciation and prioritisation of risk reduction measures stems from the inherent limitations of the modelling techniques themselves. For example, social vulnerability indexes, although some account for technical or environmental deprivation as contributors to vulnerability (Figure 2-9-C), cannot represent technical measures that lead to small-scale changes in risk metrics. As an example, non-linear modelling techniques such as flow-based or topology-based network models which have better capability to consider measures often lack the differentiated input data to represent relate physical intensity measures using vulnerability information of certain population groups to direct impacts (flood depth, wind speed) or indirect impacts here referred to as consequences.

Additionally, it remains challenging to differentiate between vulnerability as understood in socially oriented risk studies and the terminology used by risk modellers not only for the risk reduction measure consideration. Vulnerability indexes typically frame it as a characteristic of certain population groups which is being referred to here as social vulnerability. By contrast, risk modelling often interprets vulnerability in quantitative terms, linking hazard intensity measures (e.g. flood depth, wind speed) to exposed elements (e.g. infrastructure, buildings, people) through for example flood-depth–damage functions. This latter interpretation is accurately described as physical vulnerability. Closer interlinking of these vulnerability concepts is necessary in order to leverage the full potential of risk models for equitable DRR management.

2.2.4 Recommendations for future risk modelling

Initial stakeholder engagements then development of socio-economically centred risk models

The primary recommendation of this literature review is to first conduct community and expert engagements that explore the socio-economic contexts and prioritise differential risks and then develop risk models to evaluate the potential impacts of natural extreme events and support the DRR measure development associated with Class 3 risk models.

The guiding question for socio-economically driven risk modelers is recommended to be: “Why am I building a risk model, and what type of decision do I want to enable?” Otherwise, socio-economically centred risk models will continue to focus on technology-centric development rather than supporting DRR management (Figure 2-9-F). The emphasis should shift toward solution-oriented applications that improve living conditions, especially in communities most vulnerable to extreme weather events.

The challenges of designing Class 3 risk models that improve the real-life circumstances of affected individuals and communities with diverse vulnerability profiles can be addressed through early and structured participation. Early participation in modelling efforts is established for e.g. flood models (Gebremedhin et al., 2020), water resources management (Basco-Carrera et al., 2017) or earthquake induced land-slide models (Miles, 2011). Such participation can be distinguished by the level of engagement, ranging from merely consulting experts to actively co-creating with community members, and by the phase of involvement, which may span setting objectives, collecting input data, designing the model, developing scenarios, and ultimately interpreting decisions.

For socio-economically centred risk models it is recommended to engage with experts and communities early on, before selecting the modelling technique, spatial resolution, or hazard types (Subsection 2.1.3.1) and instead collaborate on these decisions. This strategy can effectively address the limitations associated with employing modelling techniques that are restricted to the stages of concept design, capacity development, or hotspot identification.

Socio-economically centred risk models should combine several types of detail to represent socio-demographic economic characteristics and personal needs.

It is recommended that socio-economically focused risk models integrate both individual needs and vulnerabilities as a type of detail, because the combination of personal-needs dimensions with socio-demographic characteristics constitutes a people-centred risk modelling approach that can capture lived experiences within Class 3 risk models. This enables disaster-risk-reduction measures that improve those lived experiences to be tested and quantified, thereby facilitating people-centred decision-making and ultimately enhancing the everyday safety of those at risk from natural hazards. In addition, all types of detail identified in the literature review—exposure, impact and risk, vulnerabilities, and personal needs (Figure 2-9-D) should be addressed in parallel.

The consideration of the type of detail about vulnerability helps to expand on the question "who is affected?" and "what their ability/capability is to deal with certain impacts. Whereas the utilisation of Maslow's personal needs concept (Maslow, 1943) adapted to the needs in DRR management as done by (Wang et al., 2024) allows for more precision to answer the question "how are people impacted".

Combining the questions "who is affected?" and "how they are affected?" yields a people-centred risk modelling technique that can operate at a finer, micro-scale resolution (Subsection 2.1.3.4).

Socio-economically centred risk modelling techniques are diverse and already have the capability to address aspects of people-centred risk modelling. Especially, agent-based models have shown promising approaches combining personal needs and vulnerability characteristics as done by (Evans et al., 2025) for evacuation modelling considering movement restrictions and evacuee behaviours. Indexes are well suited for summarising vulnerability, but they require a stronger link to the question of "how people are actually affected" as done by (Alem et al., 2021). Non-linear modelling techniques are well equipped to address the "how are people affected" but lack the representation of vulnerability characteristics or socioeconomic factors as done by (Huang & Wang, 2024) for the restoration of interdependent infrastructure systems. Non-linear modelling approaches necessitate a foundational dataset that integrates diverse vulnerability characteristics to represent people-centred impacts, linking them not only to direct and indirect impacts but also to subsequent restoration and recovery processes.

People-centred risk models need more socio-physical vulnerability data and information.

People-centred risk models that support DRR management should be informed qualitatively by information on social and physical vulnerabilities and quantitatively by data on those same vulnerabilities, while also accounting for the socio-physical interconnections between them. Incorporating both the qualitative information and quantitative data on socio-physical vulnerabilities in this way yields truly socio-physical, people-centred risk models.

An example of what this means for floods and their impact on physical integrity and health is elaborated further on. Flood depths, velocities, energy heights or the rate of water levels rising are used as a physical vulnerability threshold to determine whether people are endangered. The social vulnerability in this example relates to which type of people are living in the areas that are investigated and which socio-economic characteristics they have, potentially making them more vulnerable to health impacts of flooding. The socio-physical vulnerability then refers to a set of physical vulnerability thresholds which consider different type of people and their socioeconomical backgrounds, such as kids, elderly, wheelchair users or people with an intellectual disability. Another example for the intersection of social and physical vulnerability is illustrated by the cascading impacts of hazards—such as flood-induced power outages—on individuals whose well-being depends on critical infrastructure. Beyond the general population, those relying on electrically powered medical devices (e.g., artificial respirators) or mobility aids (e.g., wheelchair lifts) are more vulnerable and therefore at higher risks, underscoring the need for more differentiated risk metrics. The resulting recommendation is a linkage of the concept of social vulnerability and physical vulnerability towards socio-physical vulnerability or colloquially speaking, a vulnerability function for the vulnerable.

Next to highly resolved and accurate hazard information it is fundamental for the application of socio-physical vulnerability to have access to well resolved exposure and vulnerability data that can represent the social vulnerabilities identified as relevant in the physical risk model domain. One potential source of data is well-resolved census datasets. In the absence of such datasets, synthetic datasets offer the potential to serve as complementary resources (Wang et al., 2025).

2.2.5 Other research gaps and limitations

Other research gaps identified in the literature are also acknowledged in this work, but are only referenced through other publications that highlight them:

- A grey literature study by Soden et al. (2023) has shown that equity in disaster risk assessments is not sufficiently addressed therefore highlighting another argument that risk models don't propagate to Class 3
- A few studies of the literature review considered more than one hazard, but a consideration of multi-hazard assessments as proposed by (Haer & Ruiter, 2024) could not be identified in the context of socio-economic risk models. Therefore, these multi-hazard risk models are discarded in this literature review.
- Hazard types and multi-hazard situations exhibit fundamentally different vulnerability profiles across population groups, which in turn shape the dynamics of impacts, consequences, and the measures adopted for their reduction. For instance, seismic risk models often concentrate on structural, non-structural, content, and fatality impacts (Aljawhari et al., 2022), while flooding follows distinct impact pathways (Kutschera, 2008).
- Correspondingly, risk-reduction strategies differ. Seismic hazards are mitigated through both soft measures—such as insurance—and hard measures—such as retrofitting (Wang et al., 2023). In contrast, flood risk is typically managed primarily with soft measures such as financial-protection instruments, including insurance, social-protection schemes, and self-protection measures (Kind et al., 2020).
- This study deliberately focuses on social vulnerability, acknowledging that other research has aimed to integrate social, ecological, and technical vulnerabilities (Chang et al., 2021), or has emphasized an industrial perspective (Khazai et al., 2013). It is arguable that all these dimensions ultimately converge on influencing individual personal needs in conjunction with their vulnerability characteristics.

The methodology chosen for this literature review does come with uncertainties:

- The sorting of literature describing the application of risk models into categories is subject to uncertainties. As an example, in the spatial resolution category studies are categorized by their names and not their absolute numbers introducing uncertainty: The subdistrict in one study might have a higher absolute number in one case study compared to another study where even though higher on the resolution scale the absolute number in the district of another case study is smaller.
- The presented recommendation emphasizes a people-centred perspective that integrates personal-needs considerations with socio-demographic and economic characteristics; a comparable approach could be applied to other microscale units—such as households or entire communities—which could highlight different priorities. Therefore, focusing on people as the unit of resolution introduces an additional source of uncertainty.

2.2.6 Conclusion

The literature review concludes that most socio-economically centred risk models concentrate on social vulnerability characteristics that are aggregated in social vulnerability index models. The resulting risk metrics derived from these risk models are mostly resolved on administrative boundaries and units and less on community and individual level. Both trends tend to simplify real world circumstances of people impacted by natural extreme events. Another logical conclusion evidenced by the literature review is that socio-economically centred risk models do not propagate from the purpose of Class 0 till 2 to the consideration of specific DRR management measures in Class 3. Therefore, it is required to evaluate how socio-economically risk models support the identification and development of DRR management measures that improve real-life circumstances.

The main concluding recommendations of this work is to identify and prioritise collaboratively the socio-economic consequences of natural extreme events prior to developing risk models. People-centred risk modelling is defined as an option of socio-economically centred risk models which manages to address multiple type of details. It is recommended to choose modelling techniques, model purpose and resolutions considering the people-centred risk as a combination of site-specific personal needs and socio-economic characteristics. This is expected to help create more people-centred measures and ultimately advance equitable well-being for the risk of natural extreme events. A technical necessity to pave the way for this development is to better inform risk modelling processes with quantitatively and qualitatively on social, physical, and socio-physical vulnerabilities.

The response dimension as defined by Simpson et al. (2021) considers the reaction that certain approaches to risk management might trigger. A people-centred approach will spark a response from individuals by confronting them with the potential consequences they may have to face. In a tense societal atmosphere these responses can lead to an overreaction, negatively influencing trust between experts, communities and their representatives. Therefore, an open communication informing about what we know and do not know is important to build and maintain trust in this process.

2.3 Participatory engagements for the prioritisation of differential risks

The approach and understanding of this deliverable acknowledge that the concept of risk, as a combination of consequences and their probability, is not a singular entity, but that risk must be differentiated along certain dimensions into a differential risk. For example:

- Personal needs: Such as access to healthcare, safe shelter, stable food and water supply, or mental well-being support.
- Individual vulnerabilities and characteristics: Including age, gender, socioeconomic status, disability, or pre-existing health conditions.
- Time stages defined in the DRR management cycle: For instance, preparedness, response, recovery, as well as protection and mitigation stages, each elevating different risks and priorities.

For the course of the participatory engagements introduced in the following sections, the dimensions, personal needs, individual vulnerabilities and characteristics, as well as the time stages defined in the DRR management cycle, are chosen as focal points. Ultimately, this will help articulate which risks will be prioritised in the ongoing work of this deliverable in each pilot site. Further on this is being referred to as differential risk.

The engagements described here were organised and conducted under WP1, but they also complemented and provided mutual benefits for WP2, which is documented in this chapter. For further details, readers are referred to D2.1 (Valdivieso & Galasso, 2025) and D1.1 and D1.2.

For the pilot sites of Dublin and Patras, engagements were carried out as described in the following sub-chapters. For the Wellington pilot site, engagements were executed in a slightly different manner due to pre-existing activities at the time of project initiation. The Wellington-specific findings are documented in a separate report (Logan et al., 2025) and are not part of this deliverable.

2.3.1 Theoretical basis for the engagement

The theoretical foundation underpinning the engagement activities is rooted in three interconnected components Figure 2-10. First, the conceptual framework of the pyramid of personal needs, as articulated by Maslow (1943), provides a basis for understanding how individuals prioritise their personal psychological requirements. The psychological perspective is condensed to the personal needs during extreme natural events as shown on the top right of Figure 2-10. This especially emphasizes the hierarchical nature of human needs and their influence on behaviour and risk assessment.

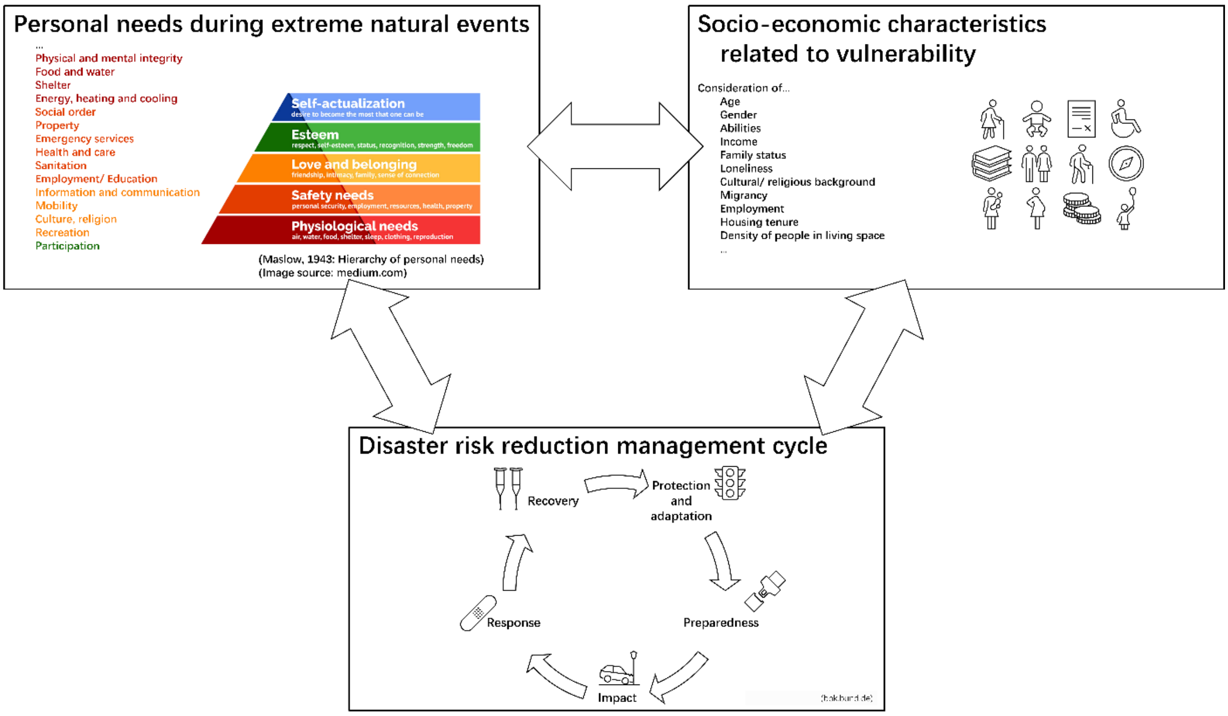

Figure 2-10: Theoretical components of engagement activities

Second, the relevance of socio-demographic and economic characteristics is examined as a critical determinant of individual and community vulnerability during extreme natural events. When integrated with Maslow's hierarchy of needs, these socio-demographic and economic characteristics contribute to a people-centred approach to risk perception. This approach underscores the importance of personal and socio-demographic and economic characteristics in communicating how risks are perceived, interpreted, and responded to by affected populations.

Third, the DRR management cycle is employed to identify key temporal phases where targeted engagement and DRR management measures are essential. This framework ensures that the needs of communities and individuals are addressed at critical junctures during and after extreme events, thereby enhancing resilience and preparedness.

The integration of these three components into the engagements serves a dual purpose. Firstly, they aim to communicate risk-related elements in an accessible and actionable manner to diverse stakeholders, including communities, flood management practitioners, and risk modellers. Secondly, the engagements seek to bridge the gap between theoretical risk modelling and real-world applications, fostering closer collaboration between risk modellers field experts and communities in natural hazard risk management. By doing so, the framework not only enhances the practical relevance of risk modelling but also ensures that interventions are grounded in both empirical evidence and community-specific needs.

2.3.2 Setting and conducting engagements

For the setting and conducting of the engagement the following normative points are elaborated:

- Slight variations in engagements with experts and communities.
- The concept needs explanatory and contextual moderation for participants.
- Moderation needs to place disclaimers.

The engagement materials are intended for two main audience groups. First, community-based stakeholders: These are community members and their representatives who draw knowledge from personal experience in everyday life or during natural extreme events, as well as from their sense of belonging and rootedness in the community. Second, expert stakeholders: These participants are defined by their professional background, whether it comes from their current role in the DRR management process or from prior professional experience. Although the categories of community- and expert-based help tailor content, they are not mutually exclusive; an individual may display characteristics of both groups. The community engagement should take place in a location that residents pass through every day, such as a community centre or a shopping centre, so participation feels natural and convenient. Expert engagement is best organised in a venue that is easy to reach and kept brief, focusing on concise formats that respect busy schedules.

The concept of these engagements needs clear explanation and contextualisation for engagement partners. First, posters were used to serve as visual guides that illustrate the key concept behind the engagement process (Subsection 2.3.3). But these will have to be moderated with explanations to simplify the accessibility of the posters for the users. This moderation requires dedicated staff who can answer questions, point out relevant details and ensure that everyone interprets the material in the same way.

Moderation also calls for a set of carefully crafted statements that prevent misunderstanding and manage expectations. One disclaimer reminds participants that the goal is to identify people-centred outcomes that can be prevented, not to accept those outcomes as inevitable. Another clarifies that vulnerability does not reside in individuals themselves. Rather, it arises from the surrounding environment and conditions as stated in the definitions of Subsection 1.3. By stating these points openly, moderators reduce the risk of mistrust, avoid creating false hopes and keep the conversation focused on practical solutions.

A feedback process is optional, but every engagement should verify that the material is understandable to its engagement partners. Ideally, the concept is refined iteratively after each application, for example by using a short feedback form that lets engagement partners comment on what worked well and what could be improved.

2.3.3 Engagement materials

The materials necessary for the engagements are comprised of the following:

- Three posters for each question with site and engagement specific framing for the
  - Hazard type
  - Spatial boundary
  - DRR management cycle stage time steps
- A set of unique stickers for each engagement partner to differentiate their voting behaviour from each other.

The three posters cover (1) personal needs, (2) relevant socio-economic characteristics, and (3) the key temporal instances of the DRR management cycle. Each poster must state clearly which type of natural-hazard event is being addressed and the spatial boundary of interest to the engagement organiser. Language considerations include both the language spoken by the engagement partners and the use of simple, comprehensible wording so that partners understand precisely what each option means. For the personal-needs poster, key terms have been rephrased for this purpose (see Table 2-3). It is worth noting that the time frames for each stage of the DRR management cycle vary according to the hazard type and need to be adjusted accordingly in posters. For example, in the preparedness stage of flooding a warning is usually expected within a few days, whereas earthquake warnings can be valuable in the seconds and minutes preceding an event. This hazard-specific timing also applies to the other DRR management stages. Examples of the expert and community-engagement posters for Dublin are shown below (Figure 2-11).

Each stakeholder should receive a unique set of stickers that distinguish their voting patterns from those of other participants. The stickers are used only to track voting behaviours across posters and questions; they are not intended to link specific individuals to their responses, preserving anonymity so that voting behaviour is not influenced.

Table 2-3: Rewording of description of personal needs for personal needs answering options.

Key word	Accessible description of personal need
Civic participation	Having a say in decisions and being involved in society
Internet and communication tech	Accessing news and being able to communicate
Transportation	Being able to travel and move around freely
Governance	Living in stable social order organized by authorities
Property integrity	Minimising damage to homes and personal belongings
Emergency services	Having emergency services available if needed
Physical integrity	Remaining unharmed physically
Food and water security	Getting a stable supply of water and food
Mental health	Being able to relieve stress and maintain well-being
Cultural heritage	Ensuring the integrity and availability of cultural and religious institutions
Water and sanitation	Accessing water and sanitation services
Healthcare systems	Being able to make use of medical care and health services
Education and employment	Accessing workplaces and schools
Housing and shelter	Having safe shelter and temporary housing available when needed
Energy and utilities	Being able to use electricity, heating, or cool

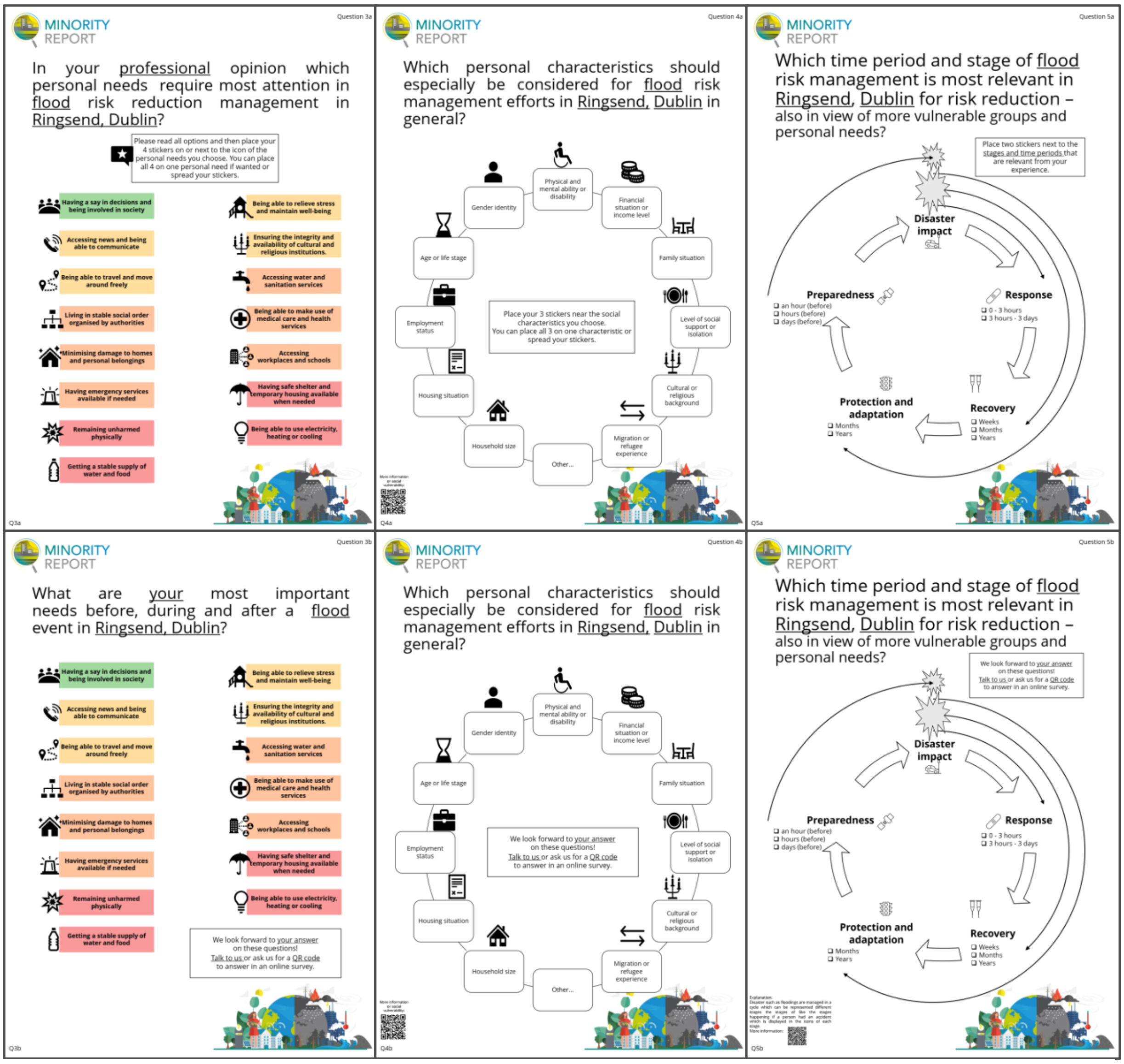

Figure 2-11: Exemplary poster design for expert (top) and community (bottom) engagements with slightly adapted wording in the lead questions.

2.3.4 Processing of engagement output, translation to differential risks and risk model priorities

The first step in processing the engagement output is to aggregate the answers from each poster and extract the most selected options. By combining the responses that describe personal needs with the socioeconomic characteristics, the analysis can rank the differential risks that require investigation using risk models as well as give an idea which modelling techniques are most appropriate (Subsection 2.1). Likewise, the votes on the disaster-risk-reduction cycle reveal the engagement partners' perspective on the most relevant future scenarios and point out the time dimension of potential risk-reduction measures that should be examined (Subsection 3.1.2 (Dublin, IE) and Subsection **Error! Reference source not found.**(Patras, GR).

The second step involves tracing the individual polling patterns using the unique sticker identifiers assigned to each participant. Although the stickers do not reveal personal identities, they allow risk modellers and user experience designers to follow each participant's sequence of choices across the three posters. Linking the patterns of personal-need and vulnerability responses creates a user-experience profile that highlights the specific risk metrics that need to be derived (T2.3).

Participatory engagements that combine personal needs, socioeconomic characteristics and the selected DRR management cycle stages create a clear picture of which risk models and associated risk metrics are most relevant. By mapping these community inputs onto the components of the overall risk modelling framework (hazard, exposure, vulnerability and scenario components) the identified models and metrics become directly informed by lived experience.

The next chapters detail how the above has been applied in the project's pilot sites.

3 Applications in pilot sites

This chapter describes how the modelling framework is assembled for the three pilot locations, linking the input data streams to the methodological steps outlined in Section 2. The pilots operate at different stages of model maturity and integration. In Dublin the work progressed to the design of modelling techniques and the selection of data inputs that constitute the core of the modelling framework, illustrating a mid-level development where the structure is defined but full automation is not yet achieved. In Patras the process began with stakeholder engagements that identified prioritisable differential risks, providing the first set of socially relevant hazard-exposure pairs. Wellington represents the most advanced case: a completely defined modelling framework has been implemented, allowing the generation of people-centred risk outputs that feed directly into the downstream analysis planned for T2.3. The actual risk metrics themselves are not reiterated here because they are documented in detail in D2.3.

3.1 Dublin, Ireland

This sub-chapter concentrates on the pilot site in Dublin, Ireland. It provides a brief introduction of the pilot study area in Dublin and a concise overview of the participatory engagements undertaken, the site-specific differential risks of flooding identified during the pilot phase, and the underlying modelling framework together with its constituent components.

3.1.1 Pilot site introduction

The pilot site in Dublin has repeatedly been exposed to natural hazards. In the past there have been intense coastal flooding and fluvial flooding. Dublin experienced severe tidal flooding in 2002, especially affecting the communities of Ringsend and Irishtown (Office of Public Works, Ireland, 2025). Past experiences and future projections have led to a 2024 newspaper article whose headline proclaimed "… Dublin among the world's most at-risk cities from rising sea levels" (Burke, 2024). Fluvial flooding driven by the city's rivers, namely the Liffey, Dodder, Camac, Tolka and Santry, also plays a significant role in risk assessment and management (Figure 3-1). The River Liffey burst its banks during the widespread November 2009 floods, affecting counties beyond Dublin (Sun et al., 2009). Flash-flooding and heavy-rain episodes in December 2015 and July 2021 produced street-level inundation. In addition, high-speed winds from storms can amplify flood depths, erode embankments, and trigger cascading failures in drainage and energy infrastructure, making wind-driven events a critical component of Dublin's disaster-risk-reduction management. These recurring events underscore the need for a coordinated risk modelling effort that integrates both riverine and coastal processes.

The project's organisational framework for the pilot site in Dublin is anchored by Dublin City Council (DCC), which serves as the primary stakeholder linking municipal authorities, community groups, and public-sector experts. In addition, the initiative engages commercial partners, including property developers, to ensure that risk assessments reflect both public safety priorities and private-sector development interests.

While hazard-centric risk assessments traditionally delineate catchment boundaries for each river, the collaborative nature of this work with DCC necessitates a broader focus that aligns with the administrative limits of Dublin City Council Figure 3-1. Consequently, the study area encompasses the full jurisdiction of the council, integrating hydrological, socio-economic, as well as infrastructural dimensions to produce a comprehensive, city-wide flood risk evaluation. It is noted that Ringsend and Irishtown possess a distinctive social fabric, situated between a rapidly gentrifying, high-income neighbourhood and a sprawling industrial-port district that shapes the everyday lived experience of their residents.

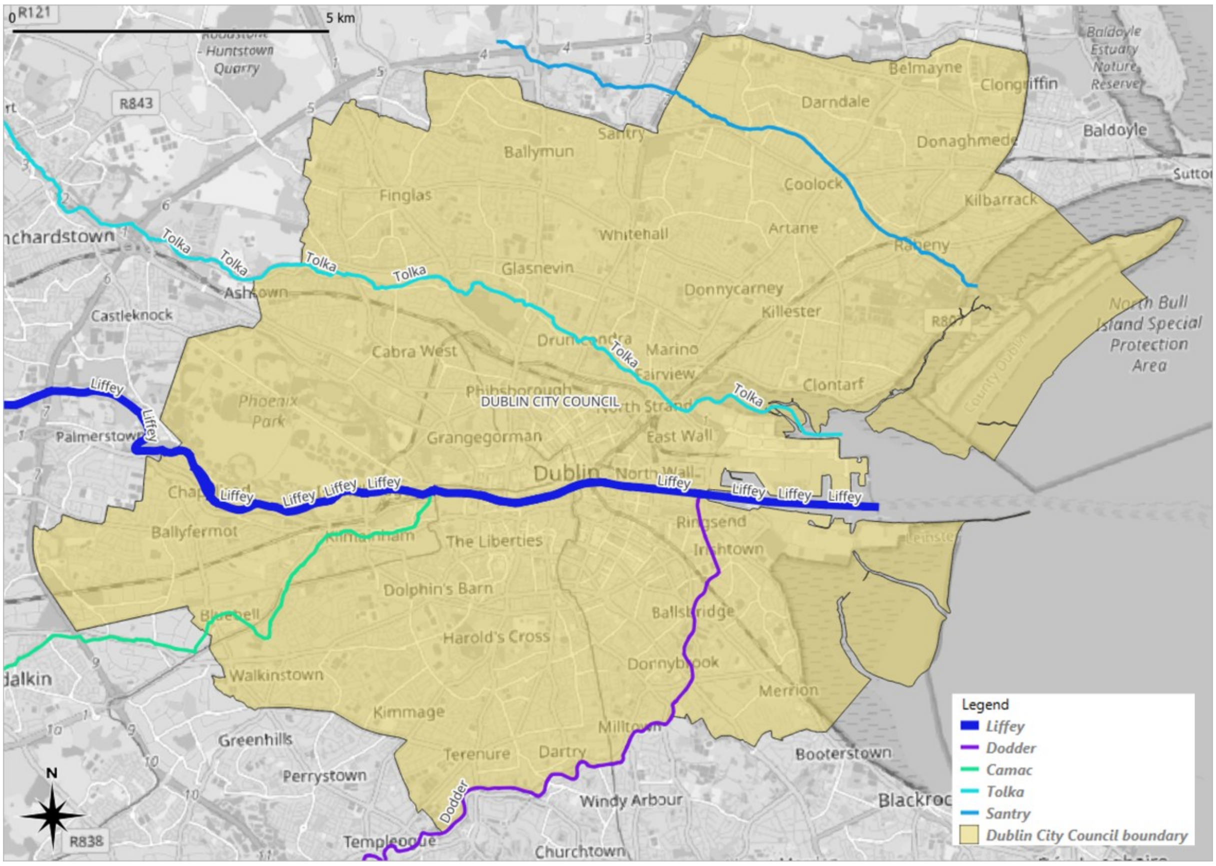

Figure 3-1: Overview of pilot site area in Dublin along the administrative boundary of the Dublin City Council and including the most relevant flowing waterbodies. Background map: (OpenStreetMap contributors, 2017).

3.1.2 Participatory engagements

3.1.2.1 Setting

The execution of the engagements in Dublin focused on flooding. Expert sessions were held as a workshop, while community sessions took place at a local community fair. For the workshop, eight experts participated, representing three public sector organisations labelled as "government" in the three figures below, three firms from the built environment sector and two specialists from other fields. Thirteen community members were engaged during the fair. Details of the methodology, questionnaire design and raw results are documented in a separate report (Froes & Faradsch, 2025). The engagement materials asked participants to identify personal needs that would arise during a flood event, providing the foundation for subsequent risk model prioritisation. The results of the engagements are presented in bar charts combining the votes of the three different expert engagement groups and the community members.

3.1.2.2 Engagement findings

Figure 3-2 highlights which personal needs were considered most and least relevant for differential risks across all engagement groups. The most frequently identified needs include physical integrity, food and water security, and water and sanitation, indicating strong recognition of the importance of basic survival and safety requirements. Housing and shelter and property integrity also feature prominently, reflecting concerns related to protection and stability. In contrast, areas such as education and employment, governance, and cultural heritage were mentioned far less often, suggesting they are perceived as less immediate or pressing personal needs compared to those directly tied to health, safety, and essential services.

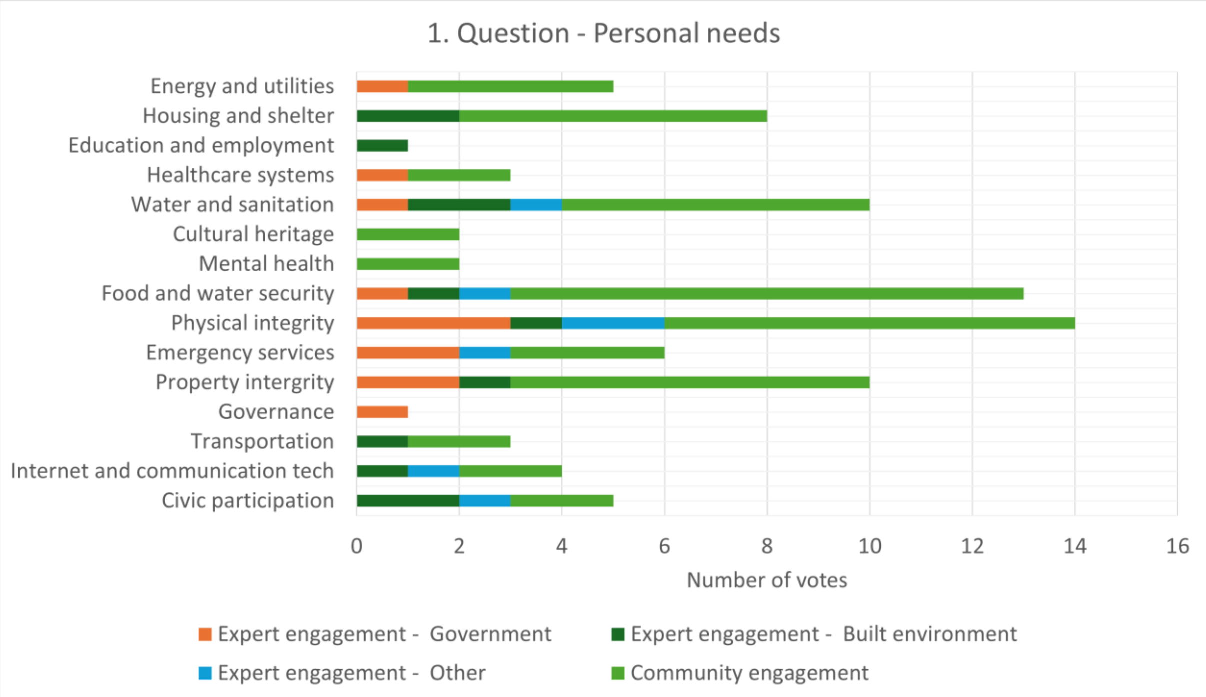

Figure 3-2: Responses from expert and community engagement on the question which personal need is most relevant based on their professional (for experts) and their personal (for community members) experience.

Figure 3-4 shows which socio-economic characteristics were viewed as most and least relevant for differential risks across all engagement groups. The most frequently mentioned factors are physical and mental ability or disability, age or life stage, and level of social support or isolation, indicating a strong emphasis on individual vulnerability, wellbeing, and social connectedness. Housing situation and financial situation or income level were also highlighted as important determinants of people's circumstances. In contrast, aspects such as gender identity, employment status, household size, and cultural or religious background received comparatively few mentions, suggesting they are considered less influential in shaping socio-economic vulnerability or resilience in this context.

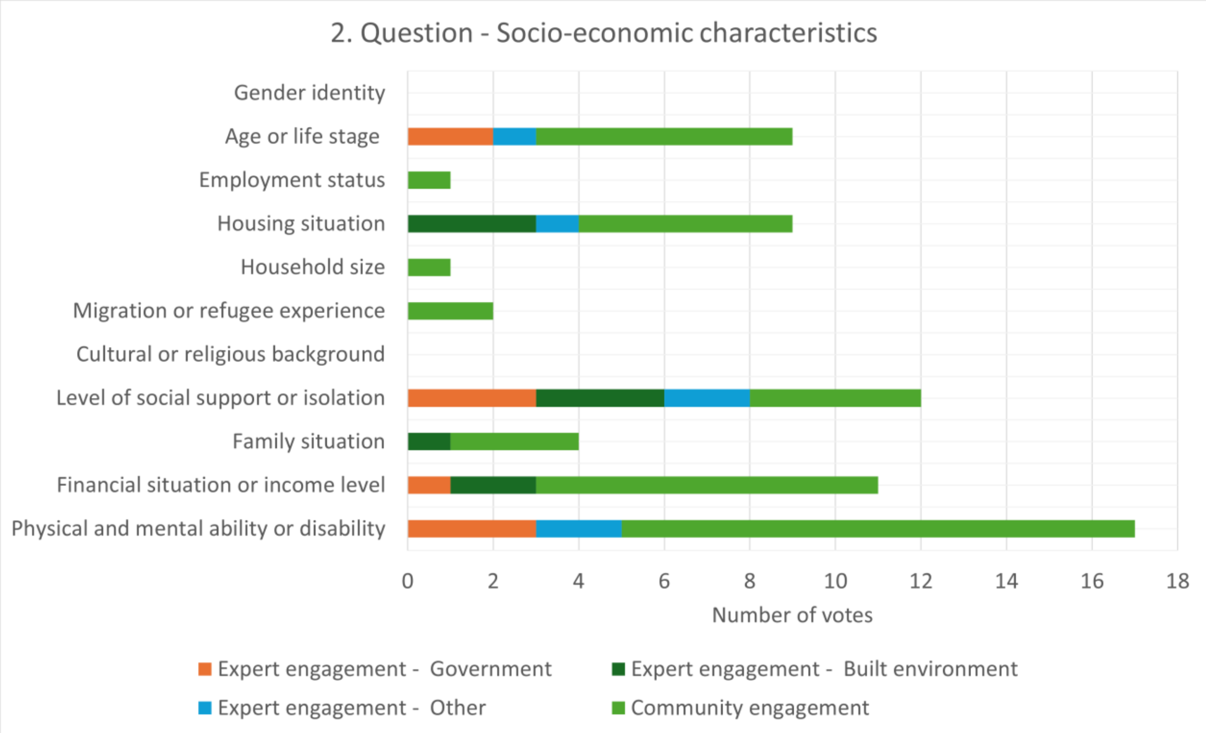

Figure 3-4: Responses from expert and community engagement on the question which socio-economic characteristics are most vulnerable during flooding events and therefore relevant for differential risks in Dublin based on their professional (for experts) and their personal (for community members) experience

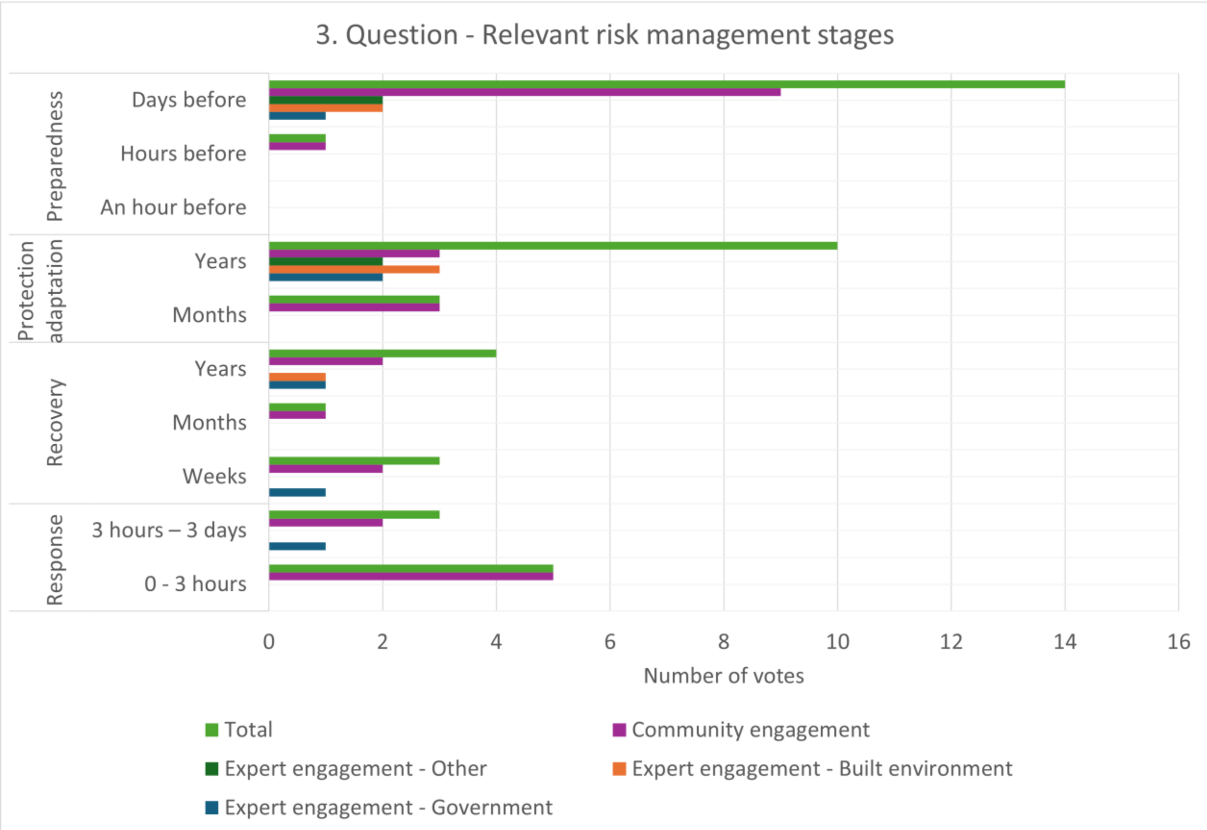

Figure 3-3: Responses from expert and community engagement on the question which stage of the DRR management cycle requires most attention as differential risk in Dublin based on their professional (for experts) and their personal (for community members) experience

Figure 3-3 illustrates which risk management stages were considered most relevant, with bars grouped by engagement type rather than stacked. The results show that preparedness, particularly actions taken days before an event, was regarded as the most important stage overall, followed closely by long-term protection and adaptation measures spanning years. These findings highlight a strong emphasis on preparedness and protection approaches. Recovery phases, especially those occurring weeks or months after an event, were less frequently prioritised, while immediate response actions within the first few hours or days were also relatively less emphasised. Overall, the data suggest that participants see greater value in anticipatory and long-term planning rather than short-term recovery and response measures.

3.1.3 Pilot site specific differential risks and user experience scenarios

3.1.3.1 General differential risks

The analysis highlights that the most pressing concerns for the Dublin pilot revolve around personal safety, basic necessities and property protection, shaped by individuals' physical and mental abilities, the strength of their social networks, and their financial resources. Participants emphasized the importance of preparing several days before a flood and implementing protection and adaptation measures during the event. Below examples are shown on how the previously outlined differential risk components are merged into general differential risk profiles:

1. Immediate danger to bodily safety and difficulty accessing food, water and sanitation, particularly for people with limited physical or mental capacity.
2. Greater vulnerability of low-income households or those with weak social support, which may hinder access to temporary shelter, recovery funds and essential services.
3. Elevated exposure of properties situated in flood-prone areas, where damage to structures can amplify threats to personal safety and disrupt essential utilities.

These three general differential risk profiles inform the selection of flood-risk models that account for rapid onset hazards, resource-distribution constraints and the effectiveness of early-stage preparedness and protective actions (Subsection 3.1.4).

3.1.3.2 Specific differential risks

The second part of the engagement analysis examines the voting behaviour of individuals anonymously but across the three questions and posters (Subsection 2.3.3). This allows to derive specific differential risks that are specific to each respondent of the expert engagements.

Figure 3-5 illustrates the response pattern of a specific government representative as expert stakeholder. This case was selected because the participant's answers align closely with the overall most-frequent selections identified in Subsection 3.1.3.1, providing a clear example of typical voting behaviour.

The expert stakeholder specifically highlighted the following priorities:

- Personal needs – civic participation, property integrity, personal physical integrity and food and water security.
- Socio-economic characteristics – physical and mental abilities, financial situation or income level, and level of social support or isolation.
- Risk-management stages – preparedness days before the event and recovery years after the event.

By linking these answers across the three posters, the analysis reveals how individual perspectives combine personal, socio-economic and temporal dimensions into coherent specific differential risk

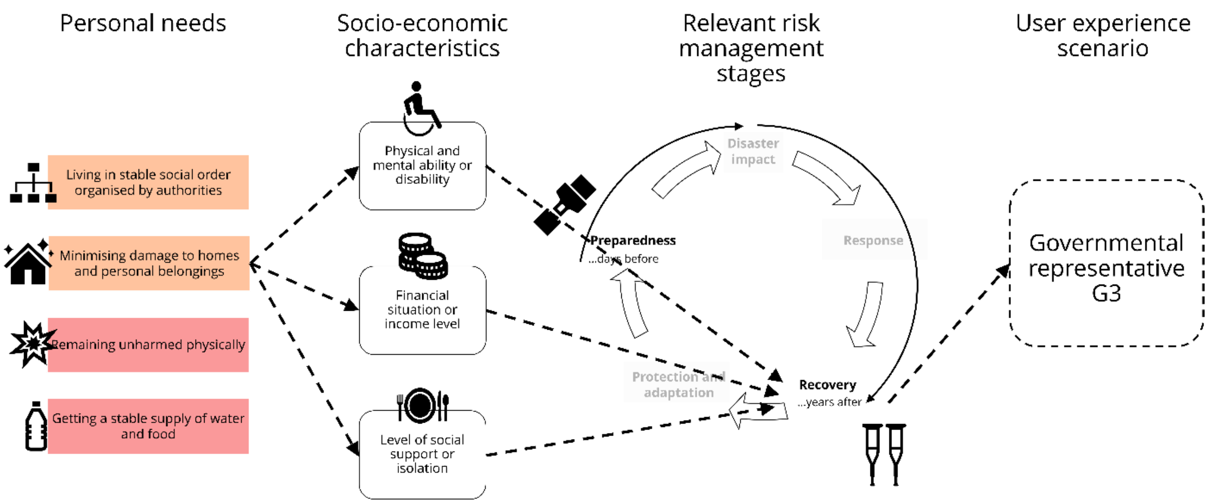

Figure 3-5: Engagement feedback of a governmental representative highlighting the four most relevant personal needs, the three most relevant socio-economic characteristics and the two most relevant DRR management cycle stages summarising differential risks. The dotted line highlights a potential user experience scenario.

profiles. Based on the previously chosen priorities the following specific differential risk profiles can be derived next to the previously already identified general differential risk profiles:

Specific differential risk profile 1 – Elderly resident with limited mobility

The expert stakeholder places the highest priority on personal physical integrity and on having reliable water and food supplies. Because physical and mental abilities are reduced, evacuation and self-care during a flood are challenging. The user's limited financial resources restrict the ability to purchase emergency kits or pay for temporary housing. In the preparedness stage, the user needs clear, early warnings delivered days before the event and assistance with securing the home. During recovery, the user will require long-term support to restore safe living conditions, making the recovery phase a critical risk period for this profile.

Specific differential risk profile 2 – Low-income family living in a flood-prone neighbourhood

Civic participation and property integrity are the main personal needs, while financial situation and level of social support are the key socio-economic factors. The family cannot afford extensive home reinforcement and depends on community networks for assistance. Early-stage preparedness messages must reach the household days before flooding, and the family should be guided on low-cost protective measures. After the flood, the recovery phase stretches over several years, during which the family needs sustained financial aid and access to rebuilding programmes to regain stable housing.

Specific differential risk profile 3 – Young professional with strong social ties but limited experience in disaster response

The expert stakeholder values civic participation and food and water security, and benefits from a high level of social support. Physical and mental abilities are adequate, but the user lacks practical experience with flood emergencies. The preparedness stage should provide detailed, actionable steps a few days ahead of the event, leveraging the user's network to coordinate mutual aid. In the recovery stage, the user's strong social connections facilitate quicker reintegration, yet the user still requires guidance on restoring property integrity and securing long-term food and water supplies.

Similar profiles like these have been derived in other deliverables of the Minority Project in D1.3 with more detailed interviews on daily behaviours resulting in personas.

3.1.4 Modelling framework and components

Based on the findings of the previous subchapters and the model characteristics in Subsection 2.1.3 a model framework for Dublin is suggested that combines the following risk modelling components:

Hazard

The hazard component uses two CFRAM (catchment flood risk assessment management) flood-model inputs: the CFRAM coastal model, which simulates coastal flooding, and the CFRAM fluvial model, which addresses riverine flooding. Both models generate flood-depth maps within the Dublin City Council boundary at a 5 m resolution (Office of Public Works, Ireland, 2025). The yearly return periods associated with each model are specified as T10, T200 and T1000 for the coastal model, and the same three return periods for the fluvial model. For each return period the flood-depth maps are made available by Dublin City Council.

Exposure

The exposure components of the modelling framework incorporate several data layers. Population density maps (Meta - Data for Good, 2023) are combined with census data so that people can be distinguished by physical and mental abilities, by financial situation or income level, and by the level of social support or isolation (Central Statistics Office Ireland, 2025). Another exposure component are infrastructures that are directly or indirectly connected to the provision of food and drinking water. In addition, residential buildings located in low-income neighbourhoods with high exposure to coastal and fluvial flooding are mapped, allowing the model to assess how these households are affected by flood events, see also D2.1 (Valdivieso & Galasso, 2025).

Spatial boundary

The primary spatial boundary for the modelling effort follows the administrative limits of the Dublin City Council. Within this area a finer scale focus is placed on individual properties and buildings that were highlighted during earlier stakeholder engagements. These detailed zones allow the model to produce results at a resolution that is suitable for property level risk assessment and planning.

Vulnerability

Vulnerability modelling components are split into physical components and social components. Physical components include threshold values for people being directly affected, flood-depth damage curves for economic land uses, flood-depth functional relationships for infrastructure elements (Koks et al., 2022) and highly detailed residential fragility curves for buildings as described by D2.1 (Valdivieso & Galasso, 2025).

Social vulnerability components complement the physical vulnerability side by incorporating information on the capacity of people and communities, such as physical and mental abilities, income level and the degree of social support or isolation. These social variables are woven into the other modelling layers: they refine the exposure classification of the population and drive the rescaling of spatial boundaries from the Dublin City Council extent to the smaller areas where social vulnerability is pronounced.

Scenarios

One type of input for the scenario stems from the CFRAM flood model programme. In the CFRAM programme flood scenarios are developed to assess not only the current but also future flood hazards, taking into account the impacts of climate change and other environmental changes (Office of Public Works, Ireland, 2025). Two future scenarios are defined which are introduced to the fluvial and coastal flood hazard components:

1. Mid-Range Future Scenario: This scenario incorporates moderate projections of climate change impacts, including a 20% increase in extreme rainfall depths and peak flood flows, a 500 mm rise in mean sea level, and adjustments for land movement and changes in land use such as forestation.

2. High-End Future Scenario: This scenario reflects more severe climate change projections, with a 30% increase in extreme rainfall depths and peak flood flows, a 1000 mm rise in mean sea level, and further adjustments for land movement and land use changes.

Other scenario options on for example population or infrastructure developments are not considered at this stage.

Potential measures
Potential measures are developed in Work Package 4 “Development of a People-Centric Resiliency & Adaptation Toolkit for the Urban Environment” and Work Package 5 “Demo Sites Implementation”, building on the previously identified approach and information.

3.2 Patras, Greece

3.2.1 Pilot site introduction

The pilot site of Patras, located in Western Greece, represents a coastal–urban environment that has increasingly faced climate-related hazards, primarily flooding, coastal erosion, and wildfires alongside the ever-present risk of earthquakes. The area combines densely built residential zones, academic institutions, and key transport infrastructure, all situated within a complex topography that channels runoff towards the coastline of the Gulf of Patras.

The case study area (Figure 3-6) comprises the University of Patras campus, surrounding schools, and the residential district of Rio, extending from the campus to the coast. Several nearby zones, including *Kato Kastritsi* and *Sichena*, are prone to forest fires — the most recent of which, during this summer, led to evacuation orders (ekathimerini, 2025), while the *Charadros river* occasionally overflows during intense rainfall (mainly due to the narrowing of riverbed in the recent decades, Papadopoulos et. Al, 2025) producing localized flooding. Along the Rio coastline, recurrent wave action and extreme storms has led to annual erosion and flooding of the coastal road, a persistent issue identified by local stakeholders.

The Patras pilot site was selected as it encapsulates many of the environmental and social challenges that Mediterranean coastal cities experience: rapid urban expansion, pressure on natural drainage systems, and exposure of critical infrastructure to multiple hazards. Within the *Minority Report* framework, it provides a testbed for evaluating how digital twin technologies and people-centred modelling can enhance the city’s preparedness and response capacity.

Given the city’s blend of academic, residential, and transport infrastructures, the Patras pilot site integrates hydrological, environmental, and behavioural components. The pilot aims to identify critical and vulnerable infrastructure, assess social and behavioural characteristics, and verify technical requirements of the *Minority Report* tool in WP4 through continuous collaboration with end-users and citizens.

Figure 3-6: Overview of pilot site area in Patras.

3.2.2 Participatory engagements

3.2.2.1 Setting

The participatory engagements in Patras were designed to capture both community and expert perspectives on climate-related risks, focusing primarily on flooding, coastal erosion, wildfires and earthquakes—the most pressing hazards for the region. All activities were conducted on 26 May 2025 and combined interactive public sessions with a structured expert workshop, ensuring a comprehensive representation of views across stakeholder groups.

Two community interventions were organized in the University of Patras campus (“Parko Eirinis”) and at the entrance of the AB Vasilopoulos mall. These open events invited citizens to join at their convenience and participate in a short questionnaire and creative mapping and daily-clock exercises, illustrating their personal routines, exposure points, and coping strategies during high-risk events.

A total of 70 community members participated, 64 of whom completed the personal-needs and behaviour questionnaire. In addition, 45 daily clocks, 23 maps, and 3 weekly diaries were collected.

Later the same day, an expert stakeholder workshop was hosted at the RWG headquarters between engaging 13 participants from the government, built environment, and emergency & security sectors. Following short presentations on the technology platform, participants joined two thematic sessions:

1. Minority Report Technology Platform, examining data inputs, desired outputs, and functional expectations; and
2. Critical Infrastructure and Social Vulnerabilities, validating hazard maps and identifying local risk hotspots.

During both sessions, experts used numbered stickers to express their views on personal needs, socio-economic characteristics, and risk-management stages, applying the same questions as the community participants to ensure comparability across stakeholder groups.

Collectively, these engagements produced quantitative and qualitative data reflecting local perceptions of vulnerability, resilience, and preparedness in the Patras case-study area. The following section presents the aggregated results from these activities.

3.2.2.2 Engagement findings

Community Activities

Figure 3-7 presents the *personal needs* that community participants in Patras considered most relevant for the DRR management. Responses reveal strong convergence around health, safety, and essential-service continuity. The top-ranked needs were access to medical care and health services (49 votes), availability of emergency services (38), and secure food and water supply (37). These priorities highlight the population's concern for the *maintenance of basic survival systems* under crisis conditions.

Secondary needs included safe shelter or temporary housing (28) and physical integrity (31), indicating that protection and stability of households are also viewed as critical. Needs linked to *governance, mobility, or cultural life*—such as participation in decision-making or access to schools—received very few mentions, suggesting that, in Patras, citizens perceive disaster resilience primarily through the lens of immediate physical safety and service reliability.

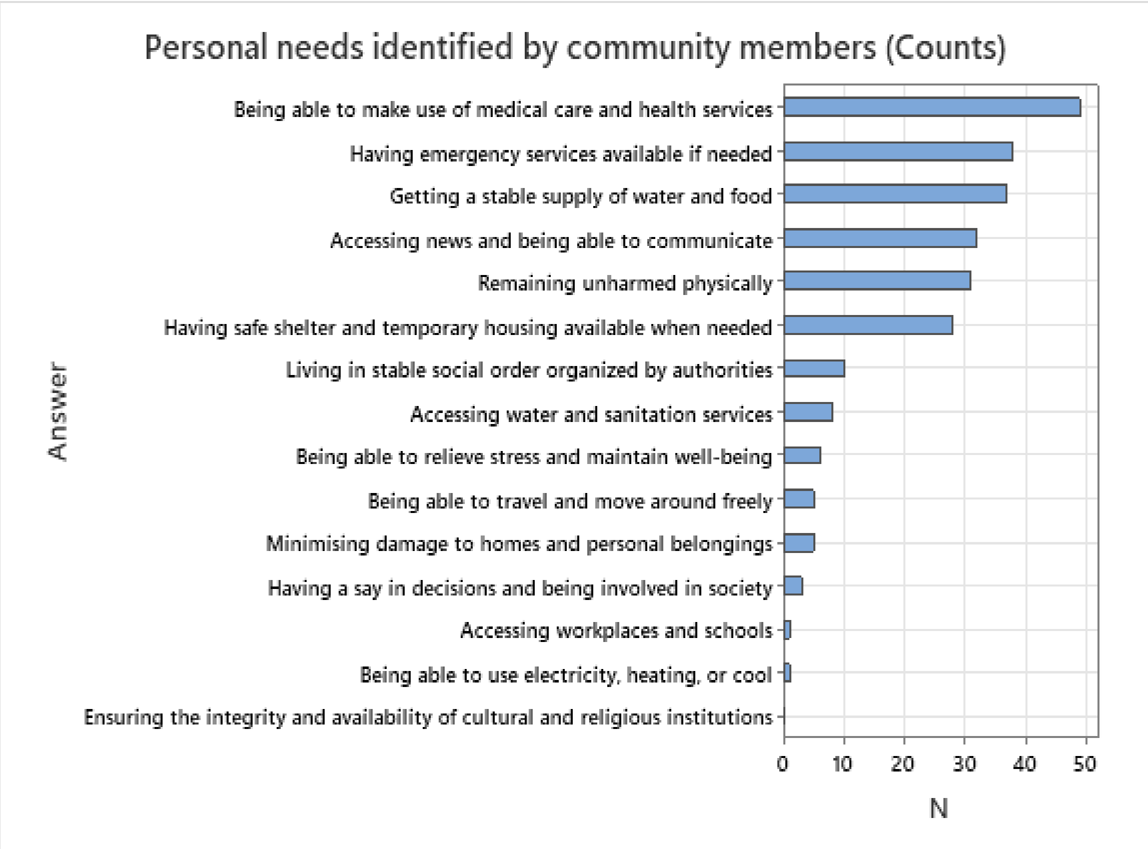

Figure 3-7: Responses from community engagement on the question which personal need is most relevant based on their personal experience.

Figure 3-8 shows which socio-economic characteristics were viewed as most and least relevant for differential risks across the engagement group. The most frequently cited factors were physical and mental ability or disability (60) and age or life stage (40), confirming that residents recognize physical capacity and generational status as key determinants of vulnerability. Housing situation (25) and financial situation or income level (18) were also emphasized, underscoring the influence of material conditions on preparedness and recovery potential. Far fewer participants selected *gender*, *employment status*, or *cultural background*, indicating that local perceptions of vulnerability focus mainly on functional and economic constraints rather than on broader social dimensions.

Table 3-1 illustrates which *time stages of an extreme event (flood-risk) management* were judged most relevant for reducing vulnerability. The community expressed the greatest interest in preparedness actions months before an event (31 votes) and long-term protection and adaptation measures extending over years (21), reflecting a forward-looking orientation toward prevention. Immediate response activities within the first 0–3 hours (24) were also valued, while *recovery phases* occurring weeks or months afterward received little attention. Overall, the findings suggest that citizens in Patras prioritise anticipatory and proactive measures over post-event recovery efforts.

Complementary *lived-experience activities* provided additional insights into daily exposure and behaviour. A total of 41 daily clocks, 23 community maps, and 3 weekly diaries were collected across both locations. These visual and narrative materials captured the rhythms of everyday life—where people spend time, how they move, and which spaces they perceive as safe or at risk.

Together, the community engagement results point to a population that equates resilience with health security, service availability, and proactive preparedness. They also reveal how socio-economic vulnerability is locally understood in *practical and bodily terms*—age, ability, housing, and income—rather than through abstract social categories.

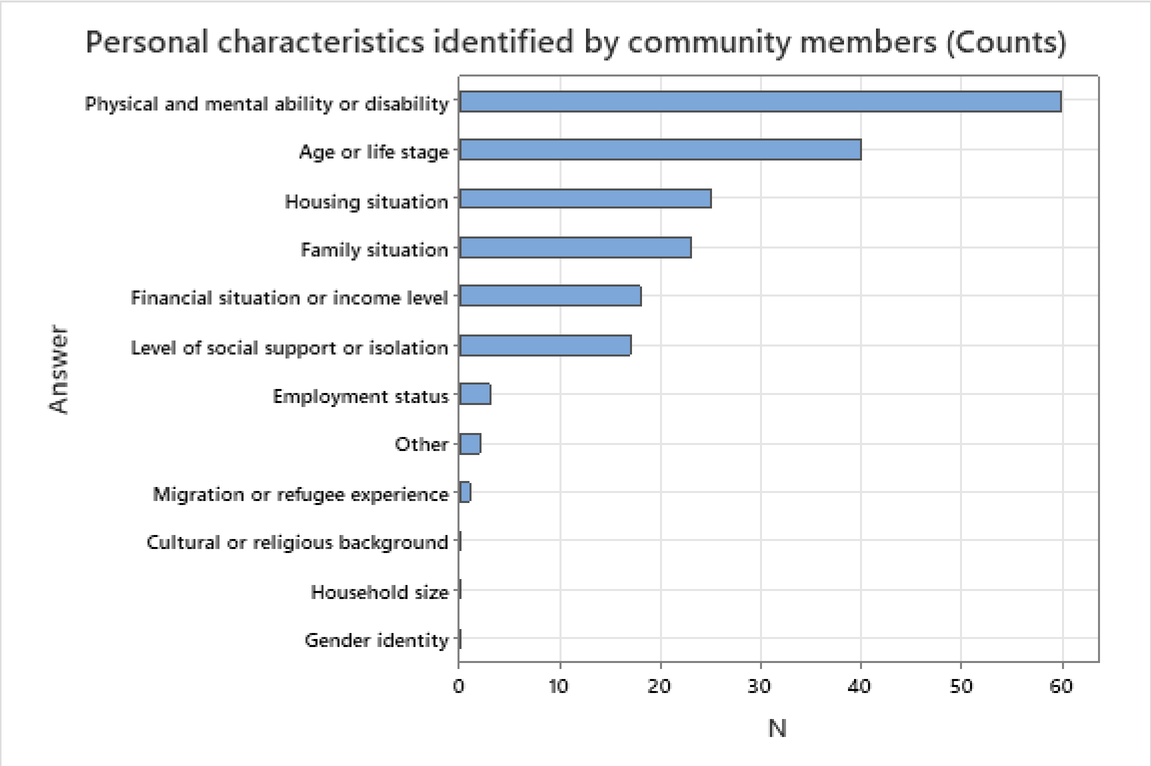

Figure 3-8: Responses from community engagement on the question which socio-economic characteristics are most vulnerable during flooding and wildfire events and therefore relevant for differential risks in Patras based on their personal experience

Table 3-1: Responses from expert and community engagement on the question which stage of the DRR management cycle requires most attention as differential risk in Patras based on their professional (for experts) and their personal (for community members) experience

Answer Options		University of Patras	AB mall	TOTAL
Response	0 - 3 hours	10	14	24
	3 hours – 3 days	5	3	8
Recovery	weeks	5	13	18
	months	3	-	3
	years	-	-	-
Protection and adaptation	months	1	6	7
	years	17	4	21
Preparedness	An hour before	-	3	3
	Hours before	-	4	4
	Days before	5	1	6
	Months before	9	22	31

End-user engagement

The end-user engagement in Patras brought together thirteen participants representing the government, built environment, and emergency and security sectors. The discussions and interactive exercises revealed consistent priorities across professional groups, centring on health, safety, and service continuity during extreme events.

The personal needs most frequently identified as requiring attention in extreme events (like flood-risk) management were access to medical care and health services, the availability of emergency services, and the secure supply of water and food. These priorities clearly reflect an emphasis on essential life-support systems and immediate safety concerns. Participants also gave importance to the provision of temporary shelter and psychological well-being, acknowledging the need to address both physical and emotional resilience during disasters. In contrast, needs related to mobility, property protection, or access to education and culture were rarely mentioned, suggesting that professional stakeholders view resilience primarily through a lens of human safety and functional continuity.

When asked which socio-economic characteristics should receive particular consideration in an extreme event (flood-risk) management, participants emphasized physical and mental ability, age or life stage, and housing situation. These responses show a strong awareness of how vulnerability is shaped by physical capacity, dependency, and living conditions. By comparison, characteristics such as financial status, gender, or migration background were rarely selected, indicating that experts in this context tend to interpret vulnerability mainly in terms of functional and infrastructural exposure rather than social identity.

Participants also discussed which stages of the DRR management cycle are most critical for reducing risks. Their responses concentrated on immediate response actions during the first few hours of an event, alongside long-term protection and adaptation measures that extend over several years. Preparedness activities taking place months before an event were also viewed as important. This dual emphasis reflects both the operational realities faced by emergency services and the strategic priorities of regional authorities—combining rapid intervention capacity with long-term adaptation planning. Recovery stages, by contrast, were considered less central to effective risk reduction.

Beyond the voting exercises, discussions provided deeper qualitative insights. Participants recognized the complex interplay of hazards in the Patras area—particularly floods, wildfires, earthquakes and coastal erosion—and viewed the Minority Report digital-twin platform as a valuable tool for improving evacuation planning, training, and coordination among agencies. They identified specific data needs for the platform, such as detailed information on building occupancy, access points, and construction year, and expressed interest in incorporating multi-hazard scenario modelling. Key challenges highlighted included ensuring data availability and real-time updating, building user trust, and maintaining institutional collaboration after the project's completion.

Feedback from participants was highly positive. On a scale from 0 (very poor) to 5 (very good), the overall quality of the workshop was rated 4.8, and the achievement of objectives 4.6. Participants appreciated the diversity of stakeholder representation, the opportunity to contribute to discussions, and the knowledge gained through the exchanges. Logistical arrangements were rated slightly lower, at 4.2, with suggestions to expand future events to include more public bodies and to circulate preparatory material beforehand. Several participants described the workshop as the beginning of a constructive and long-term cooperation between regional institutions engaged in resilience planning.

Overall, the end-user engagement in Patras confirmed the strong institutional interest in digital-twin modelling and integrated risk management. The findings align closely with those from the community engagements, underscoring shared priorities around health, safety, and proactive preparedness. At the same time, professionals highlighted the importance of data reliability, coordination mechanisms, and trust-building as essential preconditions for embedding digital resilience tools into routine practice within the Region of Western Greece.

3.2.3 Pilot site specific differential risks

The analysis of participatory engagements in Patras—covering both community and end-user activities—indicates that the most pressing risks concern personal safety, health service continuity, and access to essential resources during flood or heat-related emergencies. These priorities are shaped by participants' recognition of the area's combined exposure to fluvial and coastal flooding, forest fires, coastal erosion and earthquakes, as well as by the local population's age structure, physical ability, and housing conditions.

Community respondents placed highest importance on the availability of medical care, emergency services, food and water security, and temporary shelter, signalling that the city's resilience is viewed primarily through the lens of survival and continuity of care. End-users—representing government, emergency, and built-environment sectors—echoed these priorities and highlighted the importance of long-term adaptation and rapid response capacity as complementary needs. Both groups identified physical or mental disability, old age, and poor housing quality as key vulnerability drivers, suggesting that residents with limited mobility or those living in inadequate dwellings face heightened risk when evacuation or service disruption occurs.

Three distinct differential risk profiles emerge for the Patras pilot site:

- Health and mobility-related vulnerability – Individuals with reduced physical or mental capacity are at highest risk from rapid-onset floods or heat events, given possible delays in evacuation and dependence on functioning health infrastructure.
- Housing and infrastructural exposure – Residents in low-lying or poorly maintained dwellings, particularly along the Rio coastline and near the Charadros river, face repeated flooding and fire hazards. Structural damage to homes can compound personal safety threats and disrupt essential utilities.
- Socio-institutional fragility – Households with limited income or weak social networks may struggle to access emergency assistance, temporary shelter, or recovery funding, amplifying post-event inequality and slowing recovery.

Collectively, these risk profiles underscore the need for integrated risk models that capture both rapid-onset events and long-term degradation processes, while accounting for spatial differences in building quality, service accessibility, and social support structures. Also, they deliver the basis for the ongoing work to derive a modelling framework as done for Dublin in Subsection 3.1.4.

3.3 Wellington, New Zealand

The participatory work and the identification of differential risks for Wellington began before the conceptual framework described in Chapter 2.3 was formalised. Therefore, the structure of this section differs from the one established in 3.1 for Dublin and for 3.2 for Patras. The engagement activities executed for Wellington are documented by Logan et al. (2025).

The following subsections summarise the Wellington case study and introduce the setting in Wellington with its hazard dynamics. Further the wildfire-evacuation modelling framework is introduced, which relies on an agent-based approach to simulate population movement during fire events.

3.3.1 Pilot site introduction

The Wellington pilot site focuses on a coastal-urban region that is exposed to multiple natural hazards, chiefly severe windstorms, fluvial and coastal flooding, and frequent wildfire events. In this subsection the initial hazard-modelling framework is introduced and how that underpins the subsequent risk modelling.

Figure 3-9: Map showing the impacts to residential properties from a 0.2% AEP flooding event in Wellington. Screenshot from Resilience Explorer

The hazard layers for flooding and wildfire hazard models have been analysed and integrated into the risk analysis visualization platform, Resilience Explorer (Urban Intelligence, 2025). Alongside these hazards, several infrastructure and community layers have been sourced and uploaded to the platform for analysis, including residential properties and essential amenities. These layers have far-reaching implications when assessing societal impacts and community vulnerability to natural hazards.

We first consider how the residents themselves are impacted through a flooding event. A**Error! Reference source not found.** severe, 0.2% AEP flood at current climate conditions impacts several asset types (Figure 3-9). Our analysis shows that about 12% of the residential properties in Wellington may be affected by this event. Beyond these direct impacts, people's access to essential amenities is relevant for social vulnerability. When looking at this specific event, all the supermarkets, schools, and hospitals in the central Wellington area have been flooded, leading to an increased burden on the residents living in this area. Not only might the people in this area have flooded houses, but those who live there (flooded or not) are potentially left without access to food, medical services, and schooling.

This leads to a wider disruption in livelihood following an event, and highlights some of the broader implications that flooding may bring.

We can also consider wildfire spread and the potential impacts that could bring to the electricity network. For example, if the electrical transmission system were exposed to a wildfire (Figure 3-10), there could be a cascading failure throughout the electricity network. This could mean that the nearby residents could lose access to electricity, along with the school, supermarket, and hospital facilities in the valley below to the left. Taking this cascade one step further, this could also mean that water and wastewater pumps in this catchment lose power and also disrupt those services. These concepts of indirect impacts and burden will be explored through further engagement with the Wellington stakeholders throughout the project.

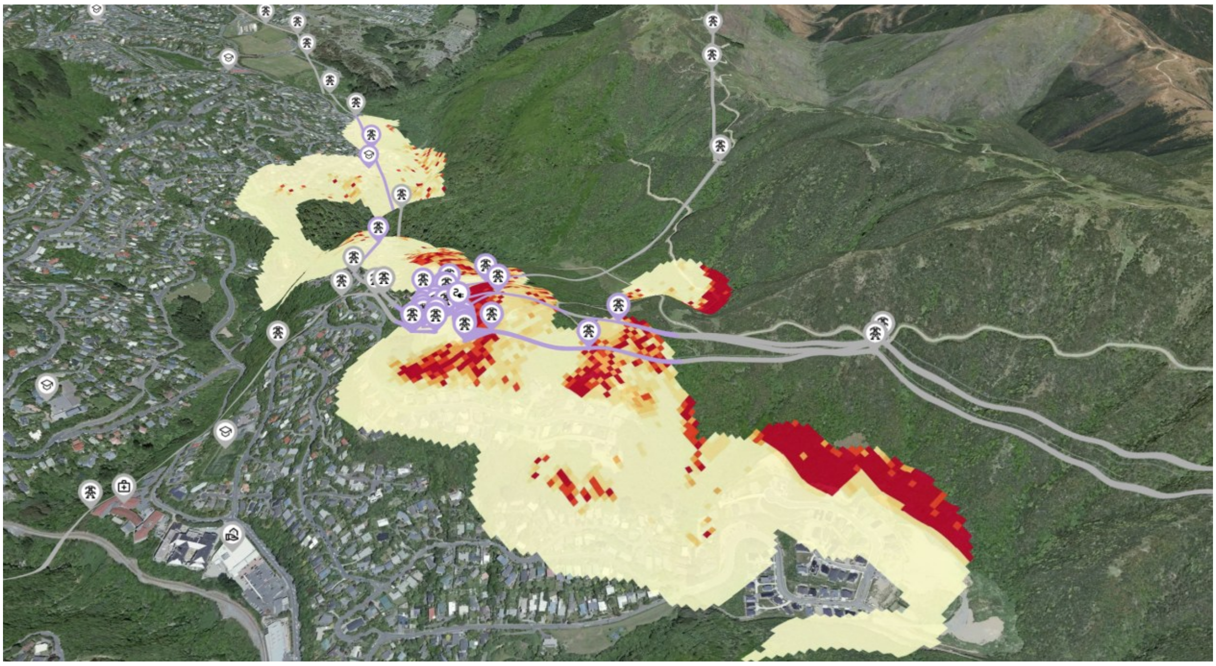

Figure 3-10: Map showing schools, supermarkets, hospitals, transmission structures, transmission lines, and grid exit points, along with a hazard scenario showing radiant heat flux of wildfire. Screenshot from Resilience Explorer

3.3.2 Wildfire modelling framework

To simulate the risks posed by wildfires within the Wellington region the wildfire modelling software Inferno is being utilised. Inferno is a semi-empirical based model that simulates fire behaviours across different land classes/fuel types whilst considering weather-based variables such as windspeed and wind direction that influence the rate of spread (RoS) and fire intensity. As outlined in Subsection 2.1.3.2 the key hazard metric for utilised for risk assessment is the RHF values. As part of the Inferno software RHF values can be calculated at user defined time intervals (Δt) and translated to both building and network level features such as roads/sidewalks and powerlines. For the mobility risk assessment, the RHF values at the transport network level are defined for each Δt with their respective risk classifications outlined as in Figure 3-11. Agents (vehicles and/or pedestrians) traversing the network will assume roads/sidewalks with "High" risk classification are closed whereas roads/sidewalks with risk classification ranging from "Very Low" to "Medium" maybe avoided depending on the agents' risk awareness levels (as defined in D4.3).

The agent-based representation of vehicles and pedestrians provides a robust foundation for people-centred risk modelling, yet the approach would benefit from finer distinctions among the agents. For example, pedestrian agents could be differentiated by mobility capacity—such as elders, children, or people with mobility impairments—while vehicle agents could reflect socio-economic traits by assigning distinct car types (e.g., SUVs versus compact cars). Incorporating these additional layers of heterogeneity would enhance the realism and explanatory power of the model, and this refinement work is still ongoing.

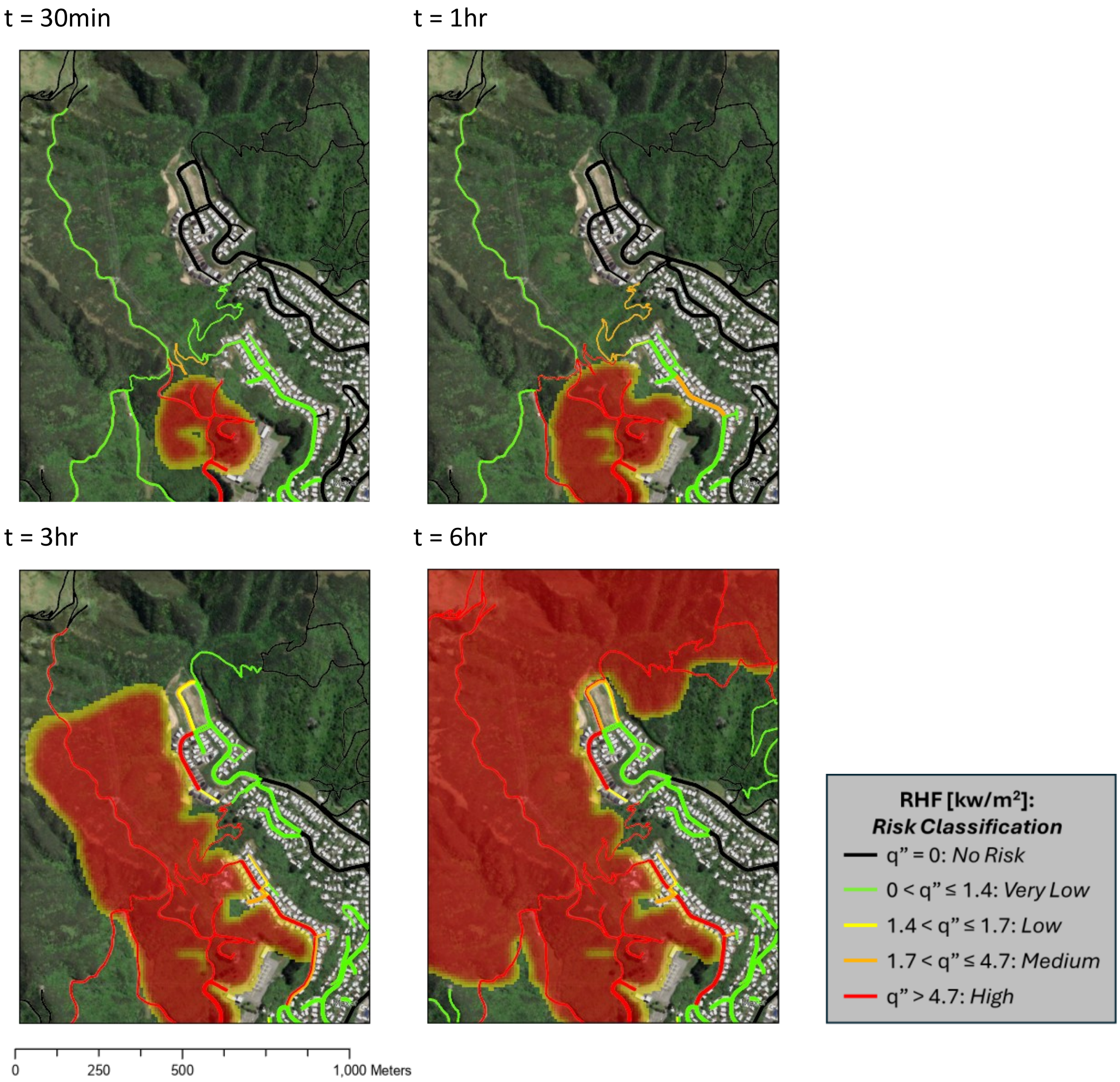

Figure 3-11. Example 6hr wildfire scenarios with road network risk classifications

4 Conclusion and outlook

The deliverable provides a coherent taxonomy for different versions of risk models, identifies important gaps in the literature towards operationalising these models, and then discusses how some of these gaps can be addressed through applications in the pilot sites.

A coherent taxonomy was developed to separate four purpose-driven classes of socio-demographic and economic risk models. Risk models were characterised by its modelling technique, spatial and necessary input data.

A literature review based on the terminology shows that (1) most socio-economically centred risk models rely on aggregated social-vulnerability indices; (2) the resulting risk metrics are typically resolved at coarse administrative boundaries rather than at community or individual scales, thereby simplifying real-world conditions; and (3) the progression from generic purpose classes (Class 0-2) to concrete DRR management measures (Class 3) is rarely realised, indicating a gap in translating socio-economic risk insight into actionable interventions.

Consequently, the work recommends that socio-economic consequences of natural extreme events be identified and prioritised collaboratively before model construction, adopting a people-centred approach that connects site-specific personal-needs data with socio-demographic and economic characteristics. Selecting modelling techniques, and resolution with this combined perspective is expected to generate more equitable, people-focused risk DRR management measures and improve well-being under extreme-event exposure. A technical prerequisite for this evolution is to enrich risk modelling workflows with both quantitative data and qualitative information on social, physical, and socio-physical vulnerabilities.

Guided by the literature-review recommendations, an early-stage engagement process was devised specifically to feed a socio-physical, people-centred risk modelling pipeline; it produces differential-risk descriptions rooted in community and expert consultations and has been documented as a reproducible workflow.

The practical implementation followed a four-step workflow: engagements, identification of differential risks, selection of risk model classes and data inputs, and risk model set-up with preliminary results. This workflow was applied in the three pilot locations. Dublin has progressed to the third stage of risk model selection, where a fully defined modelling framework and initial outputs are currently defined. Patras is currently processing the differential risks to identify potential risk modelling techniques, resolutions and input data sets. Wellington has reached the last stage where risk models are set up and refined to address people-centred risk modelling, featuring a complete, integrated modelling system that directly supplies the risk-metric analysis described in T2.3. Table 4-1 gives an overview of the current progress of the pilot sites.

Overall, the study delivers a scalable, people-centred modelling pipeline that can be replicated across diverse contexts and continues to reveal how hazard impacts are distributed among population groups, thereby supporting more equitable risk-reduction strategies.

As mentioned in the Subsection 1.3 the outcome of this deliverable will feed into the progress of WP2 namely D2.3 and D2.4. Outside of this WP another round of engagements is planned in the surrounding of WP1 indicated by the empty brackets in the second column of the table. Additionally, WP4 and WP5 will benefit from the findings presented here in the future.

Table 4-1: Overview on how far pilot sites have progressed in the suggested methodology to address social vulnerability in their modelling framework. Green checkmarks indicate fully addressed aspects and yellow work in progress.

Pilot site	Engagements	Identification of differential risks	Identification of risk models and data inputs	Risk model set up and results
Wellington, NZ	✓ (green) ( )	✓ (green)	✓ (green)	✓ (yellow)
Patras, GR	✓ (green) ( )	✓ (green)	✓ (yellow)	
Dublin, IR	✓ (green) ( )	✓ (green)	✓ (yellow)	

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6 Appendix

Appendix 6-1: Additional explanations of the review categories, subcategories and tags that were systematically collected.

Name	Review category, subcategory and tag as named in the supporting dataset	Description
Type of detail	**Review category: (1) Type**	**This literature review category describes the aspect of people-centred risk models in four different types of details that can potentially be addressed.**
Exposure type	**Subcategory: Type 1**	**Exposure defined as the occurrence of natural extreme +events and human activity.**
Type of impact and risk	**Subcategory: Type 2**	**Type two is defined by the consideration of physical vulnerability that are used to derive impacts and risk for different dimensions.**
Infrastructure	Tag: L2_impact_infrastructure	Impact and risk to infrastructure are determined by assessing vulnerability in relation to hazard intensity, and, for example, specific functional relationships relevant to infrastructure assets.
Building	Tag: L2_impact_building	For buildings, the assessment combines vulnerability and fragility information to relate hazard intensity directly to the likely damage state of the structures.
Land use/ cover	Tag: L2_impact_landuse	Impact on land use and land cover, often expressed as economic impact, is related through intensity-measure damage relationships that quantify the extent of damage caused by varying hazard intensities.
People	Tag: L2_impact_human	Human impacts are represented in a simplified manner by defining thresholds of hazard intensity that determine whether people are affected or not.
Type of socio-economic factors	**Sub-type: Level 3**	**Type three that considers of socio-economic factors in risk models.**
Age	Tag: L3_age	The age of a person.
Gender	Tag: L3_gender	A person's gender which is differentiated in the investigated study as male or female.
Disability	Tag: L3_abilities_health	Disability does not refer to disabled people, but people are disabled by barriers in society, not by their impairments, and the CRPD frames disability as arising from interaction with barriers.
Income	Tag: L3_income	Considering income both as an absolute resource measure (e.g. per capita income) or as a deprivation threshold measure (e.g. poverty)
Family status	Tag: L3_family_status	The family status considers the composition of households and clusters them into categories considering caregiving status, marital status or the composition of people at different stages of life
Cultural identity	Tag: L3_cultural_religion_ethnicity	This characteristic refers to the shared identity, traditions, beliefs, practices, and social norms associated with a group of people connected by

		common ethnicity, religion, language, or heritage.
Migrancy	Tag: L3_migrancy	This characteristic refers to people that have moved from one place to another and also includes connected characteristics such as language barriers.
Employment	Tag: L3_employment	It refers to an individual's employment status or, in some studies, to whether there is at least one income-earner present in a household.
Population density	Tag: L3_population_density	The density of people on a wider spatial scale beyond the household.
Living space density	Tag: L3_living_space_density	The density on a smaller scale.
Housing tenure	Tag: L3_housing_tenure	This characteristic categorizes whether the dwelling is owned outright, owned with a mortgage, rented privately, or rented through social or public housing
Education	Tag: L3_education	These characteristic highlights whether people were able to visit educational facilities. The intensity of educational background can vary from study to study. (e.g. Yes/no or Education of at least 4 years)
Housing condition	Tag: L3_housing_material_condition	This characteristic refers to the condition and housing material in which people or households are living.
Technical susceptibility	Tag: L3_technical_suseptibility	This cluster of characteristics highlights attributes that reflect the lack of technical infrastructure on a bigger scale and the resulting increased vulnerability to hazard events.
Ecological and environmental susceptibility	Tag: L3_ecological_susceptibility	This clustered characteristic highlights attributes that reflect ecological and environmental conditions increasing susceptibility to hazard events, such as ecosystem fragility, resource depletion, and exposure to environmental stressors.!
Personal needs type	Sub-type: Level 4	**Type four considers people-centred consequences by addressing one or more personal needs in the risk model.**
Physical and mental integrity	Tag: L4_p_a_m_integrity	Physical and mental integrity refers to protecting an individual's body and mind from harm or unwanted interference, ensuring safety and psychological wellbeing during natural hazard events.
Food and water	Tag: L4_food_water	Access to sufficient food and clean water is often disrupted during natural disasters, impacting survival and health.
Shelter	Tag: L4_shelter	Safe and stable emergency housing is necessary to protect individuals from environmental hazards and provide security.
Energy for heating and cooling	Tag: L4_energy_heating_cooling	Reliable energy supply for heating and cooling is critical to maintain safe living conditions.
Social order	Tag: L4_social_order	Maintaining social order supports community stability and reduces the risk of chaos following a disaster.
Property	Tag: L4_property	Natural hazards can damage personal belongings and homes, cause loss and hindering recovery efforts.
Emergency services	Tag: L4_emergency_services	Emergency services provide rapid medical care, rescue, and coordination during natural hazards,

		playing a crucial role in saving lives and managing disaster response.
Health and care	Tag: L4_health_a_care	Health and care services treat injuries and illnesses caused by natural hazards, while maintaining ongoing healthcare support despite strained resources.
Employment and education	Tag: L4_employ_educ	Employment and education systems support economic stability and social continuity, although they may be disrupted by hazard impacts, affecting livelihoods and learning.
Information and communication	Tag: L4_info_comm	Information and communication networks are vital for disseminating warnings, coordinating responses, and keeping communities informed and connected during emergencies.
Mobility	Tag: L4_mobility	Mobility ensures people can evacuate affected areas, access aid, and restore normal activities by maintaining transportation routes during and after hazards.
Culture and religion	Tag: L4_culture_religion	Culture and religion can be disrupted or damaged during natural hazards, affecting community identity and spiritual wellbeing.
Recreation	Tag: L4_recreation	Opportunities for recreation are often reduced or unavailable during and after disasters, impacting mental health and social cohesion.
Participation	Tag: L4_participation	Participation in community decision-making may be limited during hazard events, hindering inclusive recovery and resilience.
Modelling technique	**Review category: (2) Model complexity**	**This literature review category describes the type of modelling approach that has been chosen to at least partially represent human-centred consequences.**
Empirical statistical studies	Tag: Statistical models	This category of risk model applies statistical techniques to examine correlations in empirical datasets.
Geographical models	Tag: Spatial	This type of risk model refers to methods that consider only the geographical representation of hazard and exposure.
Linear models	Tag: Process model/ linear model	A linear natural hazard risk model is defined here as a weighted linear combination of hazard, exposure, and vulnerability indicators, assuming proportional and additive relationships between each component for an overall risk more extensive than geographical models.
Index models	Tag: Index	Indexes are defined as composite indicators that integrate socio-economic and environmental variables into a single aggregated score to quantify and compare social vulnerability to hazards across geographic units.
Non- linear models	Tag: Network/ system/ flow/ non-linear models	Non-linear risk models capture complex, non-proportional relationships and interdependencies, using methods such as network analyses, input–output frameworks, or topology-based simulations to assess cascading effects and systemic vulnerabilities.
Human behaviour models	Tag: Agent-based individual / community / social	This type of risk model centres on human behaviour, modelling the decisions and interactions of individuals or groups—examples include agent-based network models, social network models, and microsimulations.

Model purpose	Review category: (3) Model purpose	This review category groups the risk models according to the objectives addressed in the publications describing them.
Concept Design and Capacity Development	Tag: concept design/ capacity development	This tag covers publications that focus on methodologies and frameworks for risk modelling, emphasising tool or capacity development.
Retrospective Analysis	Tag: retrospective analyses	Focuses on analysing past hazard events to evaluate impacts, and lessons learned.
Future Scenario Analysis	Tag: (future) scenario analyses	Clusters publications exploring potential future hazard events and their impacts using hypothetical or projected scenarios.
Hotspot Identification	Tag: hotspot identification	Highlights publications identifying geographic areas or sectors with elevated risk or vulnerability to hazards.
Disaster Risk Reduction Measure Assessment and Prioritisation	Tag: DRR measure assessment/ prioritisation	Focuses on evaluating, comparing, and prioritising disaster risk reduction measures to inform decision-making and resource allocation.
Education and Awareness Programs	Tag: education and awareness	Addresses publications that concentrate on enhancing the understanding of hazards for public awareness initiatives and education.
Validation Studies	Tag: validation study	Evaluates the accuracy, reliability, and applicability of risk models by comparing predictions against observed data or established benchmarks.
Study environment	**Review category: (4) study environment**	**This review category collects the geographic references of case study sites used in data processing.**
Hazard type	**Review category: (5) hazard**	**The types of natural hazards addressed by the risk model or case study.**
Fire	Tag: fire	Wildfires and urban fires
Wind	Tag: wind	High wind events, storms, hurricanes
Earthquake	Tag: earthquake	Seismic activity causing ground shaking
Drought	Tag: drought	Prolonged periods of abnormally low rainfall
Flood	Tag: flood	Overflow of water onto land
Heat	Tag: heat	Extreme temperature events
Geomagnetic Storms	Tag: geomagnetic storms	Disturbances in Earth's magnetosphere
Hazard Agnostic	Tag: hazard agnostic	General hazard or multi-risk perspective
Multi-Hazard	Tag: multi-hazard	Events involving multiple hazard types simultaneously considering the interplay of different hazards.
Volcanic	Tag: volcanic	Volcanic eruptions and related phenomena
Landslides	Tag: landslides	Movement of rock, earth, or debris down slopes
Gender sensitivity	**Review category: (6) gender**	This review category checks whether gender has been considered as a social characteristic.

Spatial resolution	Review category: (7) spatial resolution	This review category clusters models according to the resolution with which the social dimension of consequences is represented.
Macro level	Country level; Tag: national	The highest administrative level, representing an entire sovereign state or nation. (millions and more)
	Sub-national level; Tag: state/ province/ region	High administrative divisions within a country, such as states, provinces, or regions. (millions)
Meso level	Large area level; Tag: county / district / municipality	Administrative areas responsible for local governance. (hundreds of thousands)
	Medium area level; Tag: census tract / ward / sub district	Smaller statistical or administrative units used for detailed demographic and socio-economic analysis. (tens of thousands)
	Small area level; Tag: census block / census sector / group level / neighbourhood level	The smallest standard geographic units for census or administrative purposes (hundreds to thousands)
Micro level	Property level; Tag: household / building level	The level of individual households or buildings (~ 1 to hundreds)
	Person level; Tag: individual	The most granular level, referring to data or analysis focused on individuals. (1 person)
Other levels	Catchment; Tag: catchment-level	Geographic areas defined by drainage basins or catchments, where all water flows to a common outlet.
	Grid-based; Tag: raster-based (1km, 250m, 100m)	Geographic areas defined by a regular grid (e.g., 1 km, 250 m, 100 m squares) and
Unit of impact metrics	**Review category: (8) unit of impact metrics**	This review category gives a short summary of the metrics that are presented at the end of the analysed publications.

Appendix 6-2: Dataset generated during the literature review.

RawData.zip

Mitigating environmental disruptive events using people-centric predictive digital technologies to improve disaster and climate resilience

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