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Improving climate resilience of critical assets

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D2.3 ICARIA multi-hazards modelling tools and application guidelines

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D2.3 ICARIA multi-hazards modelling tools and application guidelines

Summary

Deliverable 2.3 of ICARIA defines and generalises an adaptable framework to be adopted within the project for the setup and simulation of a variety of compound hazard events. The work within this deliverable summarises developments as part of Task 2.3 "Coupled hazard models: methodology and tool".Within this task, a range of different multi-hazard scenarios have been assessed with details pertaining to how respective approaches and modelling tools can be utilised to model compound hazard scenarios. In addition this document also provides details on how climate data utilised within the compound hazard models can be assessed to derive joint probability distributions of compound hazard events.

The methodologies thus outlined within this document can serve as guidelines for the selection of input parameters and coupling of tools for multi-hazard assessment.

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List of Acronyms and Abbreviations

AMB	Barcelona Metropolitan Area
BUI	Buildup Index
CFFDRS	Canadian Forest Fire Danger Rating System
CI	Critical infrastructure
CMIP6	Coupled Model Intercomparison Project Phase 6
CS	Case study
CSO	Combined Sewer Overflow
DSS	Decision support system
FFMC	Fine Fuel Moisture Code
FWI	Fire Weather Index
HNMS	Hellenic National Meteorological Service
HW	Heat Waves
ISI	Initial Spread Index
LST	Land Surface Temperature
RAF	Resilience Assessment Framework
SAR	South Aegean Region
SLZ	Salzburg Region
SOLWEIG	SOlar and LongWave Environmental Irradiance Geometry model
SPI	Standardised Precipitation Index
SS	Storm Surge
SSPs	Shared Socioeconomic Pathways
SSO	Strategic Sub Objectives

Executive summary

This deliverable outlines approaches being adopted within the ICARIA project for the modelling of compound hazard events across the three case study regions.

With global temperatures rising, it is anticipated that the likelihood and severity of single and compound hazards are going to increase. To plan for and mitigate against such events, it is apparent that a multi-hazard and multi-risk assessment is needed. Previous deliverables within WP2 outlined models and tools used for single hazard assessment across the three case study regions addressing a variety of climate driven hazards. These are then expanded on this further providing generalised overview of methods used for multi-hazard assessment and means of assessing the joint probability of compound hazard events.

The main objectives of this document can be summarised as follows:

- Provide a generalised framework for the depiction and modelling of compound hazards that includes their:
    - Physical interactions and,
    - Joint probabilities

- Provide guidelines to serve as exemplar for the physical modelling of a variety of compound hazard combinations that includes both compound coincident and compound consecutive hazards.

1. Introduction

The number of climate-related disasters has been progressively increasing in the last two decades and this trend could be drastically exacerbated in the medium- and long-term horizons according to climate change projections. It is estimated that, between 2000 and 2019, 7,348 natural hazard-related disasters have occurred worldwide, causing 2.97 trillion US$ losses and affecting 4 billion people (UNDRR, 2020). These numbers represent a sharp increase of the number of recorded disaster events in comparison with the previous twenty years. Much of this increase is due to a significant rise in the number of climate-related disasters (heatwaves, droughts, flooding, etc.), including compound events, whose frequency is dramatically increasing because of the effects of climate change and the related global warming. In the future, by mid-century, the world stands to lose around 10% of total economic value from climate change if temperature increase stays on the current trajectory, and both the Paris Agreement and 2050 net-zero emissions targets are not met.

In this framework, **Project ICARIA** has the overall objective to promote the definition and the use of a comprehensive asset level modelling framework to achieve a better understanding about climate related impacts produced by complex, compound and cascading disasters and the possible risk reduction provided by suitable, sustainable and cost-effective adaptation solutions.

This project will be especially devoted to critical assets and infrastructures that are susceptible to climate change, in a sense that its local effects can result in significant increases in cost of potential losses for unplanned outages and failures, as well as maintenance – unless an effort is undertaken in making these assets more resilient. ICARIA aims to understand how future climate might affect life-cycle costs of these assets in the coming decades and to ensure that, where possible, investments in terms of adaptation measures are made up front to face these changes.

To achieve this aim, ICARIA has identified 7 Strategic Sub Objectives (SSO), each one related to one or several work packages. They have been classified according to different categories: scientific, corresponding to research activities for advances beyond the state of the art (SSO1, SSO2, SSO3, SSO4, SO5); technological, suggesting and/or developing novel solutions, integrating state-of-the art and digital advances (SSO6); societal, contributing to improved dialogue, awareness, cooperation and community engagement as highlighted by the European Climate Pact (SSO7); and related to dissemination and exploitation, aimed at sharing ICARIA results to a broader audience and number of regions and communities to maximise project impact (SSO7).

2. SSO1.- Achievement of a comprehensive methodology to assess climate related risk produced by complex, cascading and compound disasters

3. SSO2.- Obtaining tailored scenarios for the case studies regions

4. SSO3.- Quantify uncertainty and manage data gaps through model input requirements and innovative methods

5. SSO4.- Increase the knowledge on climate related disasters (including interactions between compound events and cascading effects) by developing and implementing advanced modelling for multi-hazard assessment

6. SSO5.- Better assessment of holistic resilience and climate-related impacts for current and future scenarios
7. SSO6.- Better decision taking for cost-efficient adaptation solutions by developing a Decision Support System (DSS) to compare adaptation solutions
8. SSO7.- Ensure the use and impact of the ICARIA outputs

2. Objectives of deliverable

Across the three case study regions a variety of hazards, risk receptors and cascading effects are being considered (Figure 1). As part of Work Package 2 (WP2) “Modelling and multi-hazard assessment”, the focus centres on the methodologies and tools used for the modelling of multi-hazard scenarios.

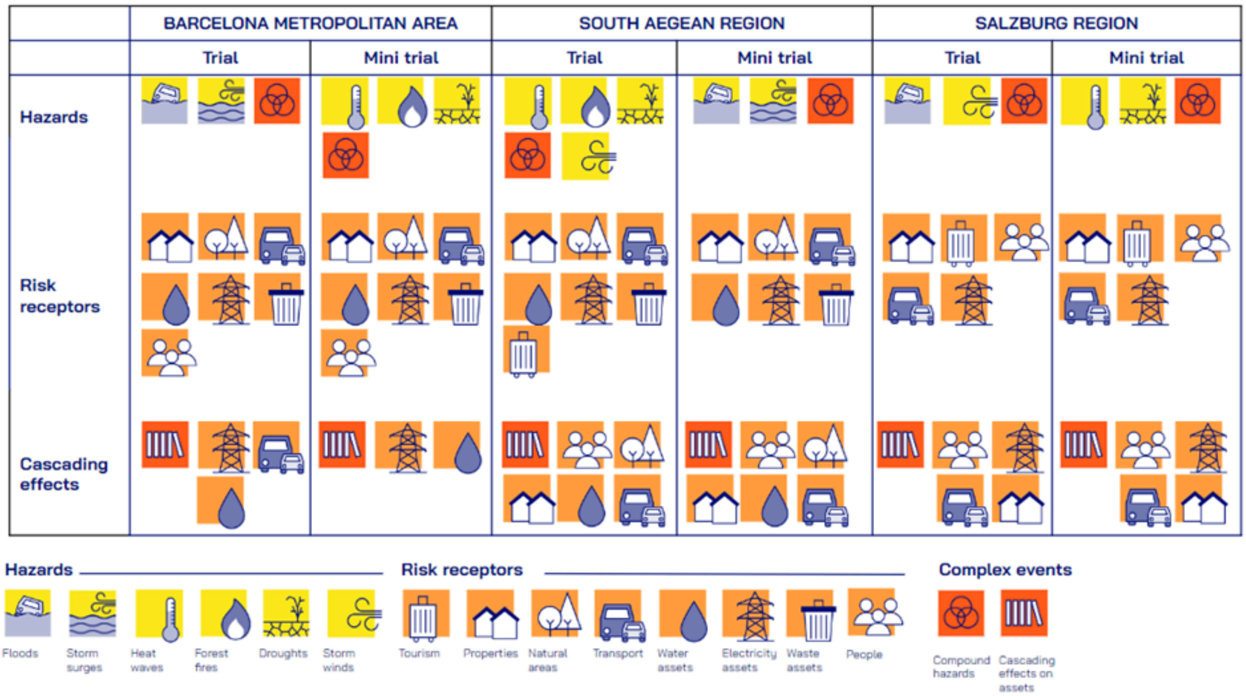

Figure 1. Summary of hazards and risk receptors considered in the different CS of ICARIA.

This deliverable, D2.3 “ICARIA Multi-Hazards Modelling Tools and Application Guidelines”, documents the developments from Task 2.3, “Coupled Hazard Models: Methodology and Tools”. Utilising the approaches outlined in previous tasks and deliverables within this WP a flexible modelling chain approach has been developed for the temporal and spatial coupling of different hazard combinations within the respective case studies.

The key objectives of this deliverable are thus summarised as the following:

- Provide a generalised framework for coupling of hazards and defining modelling chains for multi-hazard scenarios.
- Outline approaches for defining joint probability assessment of multi-hazard scenarios and means for selecting input parameters for multi-hazard modelling.
- Provide example guidelines for the spatial and temporal coupling multi-hazard models for:
    - Flooding (Pluvial) and Storm Surge,
    - Flooding and Extreme Wind,
    - Extreme Wind and Forest Fire,
    - Drought and Heatwave,
    - Drought and Forest Fire,

    - Heatwave and Forest Fire,
    - Heatwave, Drought, and Forest Fire.

The framework outlined here provides a basis for the production of compound hazard outputs that will subsequently be used within WP3 and WP4 to quantify the impact and its reduction caused by the adaptation solutions scenarios.

3. Generalised Compound Modelling Framework

For the modelling of multi-hazard scenarios, it is needed to consider events where different hazards have overlapping spatial extents and overlapping temporal extents (compound coincident hazards) or where the effects of one hazard may influence the magnitude and/or likelihood of subsequent hazards (compound consecutive hazards) within the same or part of the same region.

3.1 Physical Model Interactions

To facilitate the understanding of how different hazards can potentially interact with each other, their spatial and temporal extents should be defined. Figure 2 from Gill and Malamud, (2014) outlines 16 different natural hazards and their respective spatial and temporal scales. The figure highlights how certain hazards may be both spatially and temporally isolated such as ground collapse, avalanche and local flash flooding whereas other hazards such as droughts that can last for prolonged duration and affect large areas. From the compound analysis assessment, this depiction facilitates understanding of directions of interactions such as hazard A occuring during hazard B and whether hazard A is likely to occur within the region of hazard B.

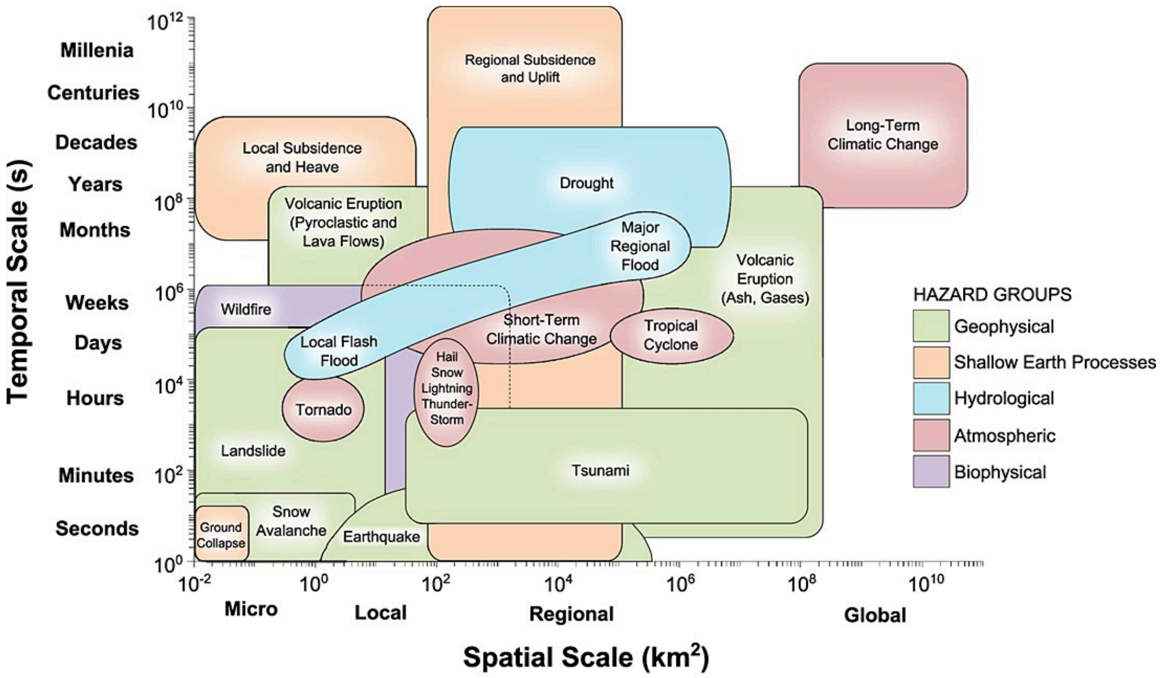

Figure 2. Spatial and temporal scales of 16 selected natural hazards, shown on logarithmic axes for spatial and temporal scales (Gill and Malamud, 2014).

Simplifying this depiction of spatial and temporal scales of hazards being modelled in ICARIA and referencing scales outlined in (Franzke, 2017) we identify the following scales (Figure 3).

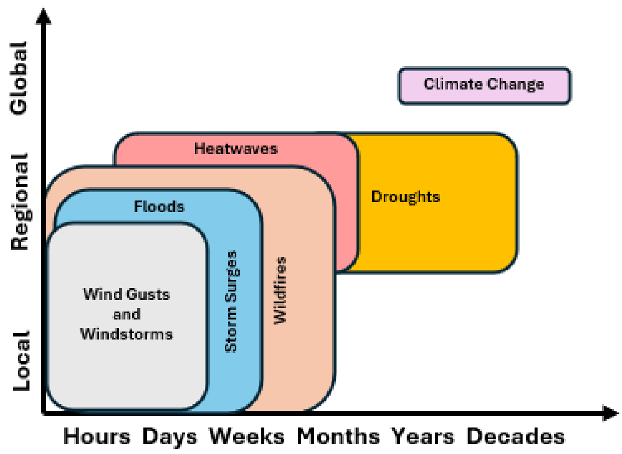

Figure 3. Spatial and temporal scales of modelled hazards within ICARIA (adapted from Franzke, 2017)

With spatial and temporal characteristics being considered for multi-hazard scenarios, consideration of cross hazard interactions is needed. These interactions include how the respective hazards interact with each other, how they relate to the vulnerability of the assets exposed to them, and any physical changes to the modelled extent via the hazards that could influence the behaviour of other modelled hazards. Hielkema et al, (2021) outlined four interaction pathways between two or more hazards that can be described as:

- **Independent**: hazards affecting the same region either simultaneously or in sequence, where there is no triggering relationship or dependence between them.
- **Triggering or Cascading**: The occurrence of one hazard results in the triggering of subsequent hazard/s. (e.g. earthquake triggering tsunami).
- **Change conditions**: The environmental conditions within a region are altered due to a hazard occurring that in turn changes the likelihood of a subsequent hazard occurring. For instance drought changing conditions of vegetation within landscape which in turn alters the likelihood of wildfire ignition.
- **Association**: Where two or more hazards are the result of the same triggering event. Such as an extreme rainfall event occurring in a region with sloped terrain leading to flooding and landslides.

To consider these aspects, a modelling chain can be plotted (Figure 4) whereby the time between Hazard 1 and Hazard 2 can range from 0 to *N* minutes/hours/days/months etc. depending on the interaction pathway of hazard 1, its effects on the regions and assets with the region and the recovery time of affected assets and regional characteristics.

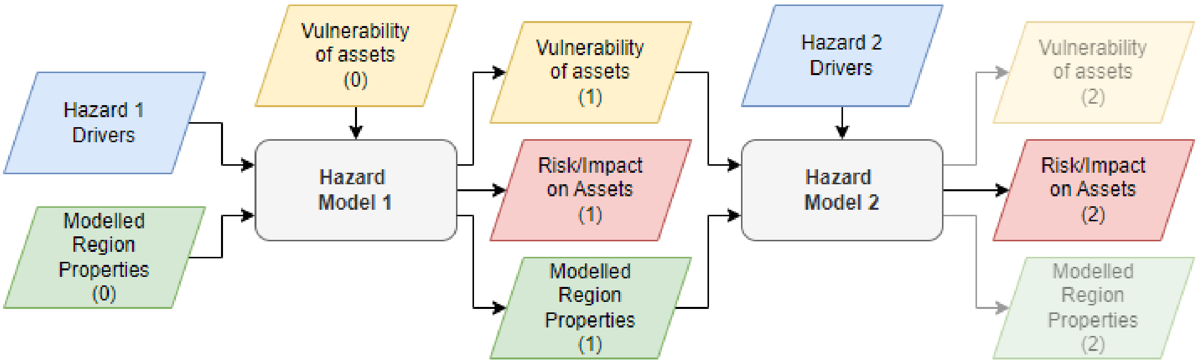

Figure 4. Physical interactions between hazards.

For the physical coupling of hazard models, Santiago-Collazo et al., (2019) outline 4 coupling approaches (Table 1). Within the multi-hazard modelling framework outlined within this deliverable, these 4 approaches are to be considered.

Table 1. Modelling approaches to coupling hazards (Santiago-Collazo et al., 2019).

Coupling technique	Definition
One-way	Computations that are transferred from one model and used as an input in another, often as boundary conditions
Loosely	Separately-running models are coupled using information exchange in an iterative manner
Tightly	Independent models are integrated into a single modelling framework by combining their source code
Fully	Governing equations of all the physical processes considered are solved simultaneously within the same modelling framework

3.1.1 Compound Coincident Hazards

Compound coincident hazards refer to two or more hazards that have both overlapping spatial extents and overlapping timeframes (Figure 5). For example, pluvial flooding occurring within the same coastal region being affected by flooding caused by a storm surge, or a wildfire occurring within a region currently experiencing drought would be defined as compound coincident hazards. Under such compound events the resulting impacts/risks are potentially greater than if they were to occur independently (Sutanto et al. 2020).

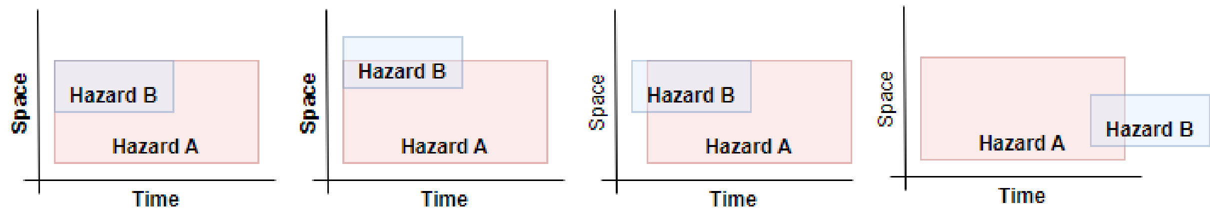

Figure 5. Compound Coincident Hazards

3.1.2 Compound Consecutive Hazards

In contrast to compound coincident hazard events, whilst compound consecutive hazards have overlapping spatial extents, they are temporally separated, occurring in sequence (Figure 6).

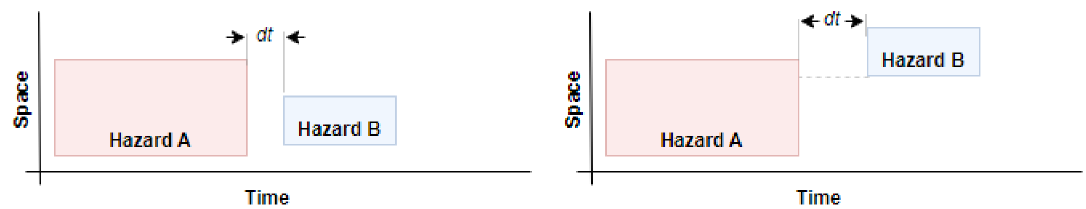

Figure 6. Compound Consecutive Hazards.

The occurrence of each hazard and time (dt) between them can influence the vulnerability of risk receptors in the region whilst also affecting the magnitude and probability of the following hazard occurring (de Ruiter et al., 2020). Figure 7 from de Ruiter et al., (2020) depicts a timeline of consecutive hazards and how these influence the risk receptor (represented by the quality of the built environment) and their recovery times (ΔR). Within this example the rate of recovery of the built environment can vary and the subsequent shock of an additional hazard before the built environment has fully recovered can result in greater damage to the built environment.

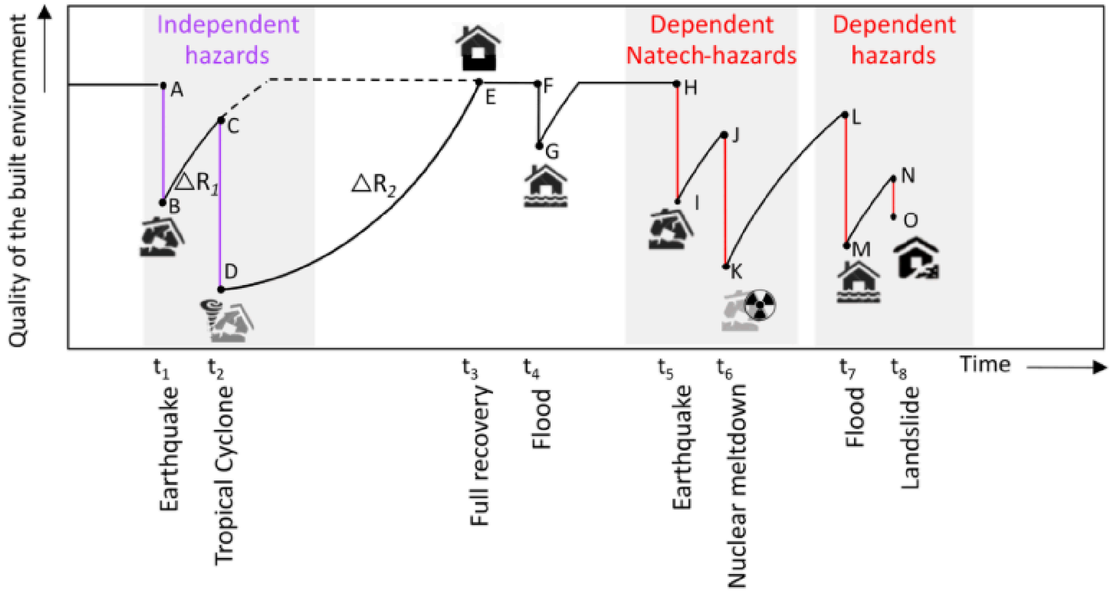

Figure 7. Schematic representation of consecutive disasters (de Ruiter et al., 2020)

These changes in the built environment and respective recovery rates are not limited solely to infrastructure but also to the environment itself as highlighted in Hielkema et al, (2021) relating to "change conditions" that can influence the magnitude and likelihood of proceeding events over time. Therefore when modelling compound consecutive hazards considerable effort is needed for determining the characteristics of the environment and recovery of assets change over time post-event. Whilst recovery times of asset and services with respect to a range of hazards may be available from literature, and insurance data for example information as to the specifics relating to the recovery of a region may not be readily available and as such local knowledge through stakeholder engagement could serve as a valuable resource for determining recovery timeframes and parameters that need to be considered when modelling compound consecutive hazards.

3.2 Joint Probability Assessment

When defining the modelling parameters for joint probability assessment, it must be considered that for specified return periods there can exist a range of potential compound hazard values. The climate data used within the hazard modelling framework within ICARIA comes from the CMIP6 models that considers historical data from 1950 to 2014 and 4 Tier 1 SSPs (ssp126, ssp245, ssp370 and ssp585) ranging from 01/01/2015 to 31/12/2100). The selected CMIP6 models being utilised within the hazard assessments are outlined in Table 2 with further details relating to the approaches used for downscaling and statistical analysis available in D1.2. "Climate Projections and Hazard Scenarios" (ICARIA 2023a).

Table 2. Information about the 10 climate models belonging to the 6 Coupled Model Intercomparison Project (CMIP6) corresponding to the IPCC AR6. Models were retrieved from the Earth System Grid Federation (ESGF) portal in support of the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (Deliverable 1.2).

CMIP6 MODELS	Resolution	Responsible Centre	References
ACCESS-CM2	1,875º x 1,250º	Australian Community Climate and Earth System Simulator (ACCESS), Australia	Bi, D. et al (2020)
BCC-CSM2-MR	1,125º x 1,121º	Beijing Climate Center (BCC), China Meteorological Administration, China.	Wu T. et al. (2019)
CanESM5	2,812º x 2,790º	Canadian Centre for Climate Modeling and Analysis (CC-CMA), Canadá.	Swart, N.C. et al. (2019)
CMCC-ESM2	1,000º x 1,000º	Centro Mediterraneo sui Cambiamenti Climatici (CMCC).	Cherchi et al, 2018
CNRM-ESM2-1	1,406º x 1,401º	CNRM (Centre National de Recherches Meteorologiques), Meteo-France, Francia.	Seferian, R. (2019)
EC-EARTH3	0,703º x 0,702º	EC-EARTH Consortium	EC-Earth Consortium. (2019)
MPI-ESM1-2-HR	0,938º x 0,935º	Max-Planck Institute for Meteorology (MPI-M), Germany.	Müller et al., (2018)
MRI-ESM2-0	1,125º x 1,121º	Meteorological Research Institute (MRI), Japan.	Yukimoto, S. et al. (2019)
NorESM2-MM	1,250º x 0,942º	Norwegian Climate Centre (NCC), Norway.	Bentsen, M. et al. (2019)
UKESM1-0-LL	1,875º x 1,250º	UK Met Office, Hadley Centre, United Kingdom	Good, P. et al. (2019)

With this range of models and SPPs being considered there is a need to adopt an approach to consider the various likelihoods and magnitudes of climate input data that will be generated for use within the hazard models and the subsequent uncertainties. To address these considerations from the hazard driver perspective, the proposed joint probability assessment within ICARIA is defined over 4 steps:

1. Consider all scenarios (40 statistical and 8 dynamical) for each climate variable produced that will be applied within the respective compound hazard models
2. Within each hazard model, select the SSPs for each variable and define the joint probability of compound events
3. Based on steps 1 and 2, 48 joint probability distributions are available for each time period considered
4. Sort all these probabilities by probability of occurrence so that, for each compound event, it is possible to select scenarios for modelling that correspond to the median (most likely) and 90th Percentile (for uncertainty assessment)

For compound coincident hazards, if they share common drivers, the probability of extremes affecting the same regions within the same timeframe may have some dependencies. For example, the climate conditions associated with a heatwave may also influence the magnitude of the Fire Weather Index (FWI) score (Figure 8a), or the climate drivers relating to a Storm Surge (SS) may also influence the magnitude and likelihood of heavy rainfall within the same region (Figure 8b) within their respective timeframes.

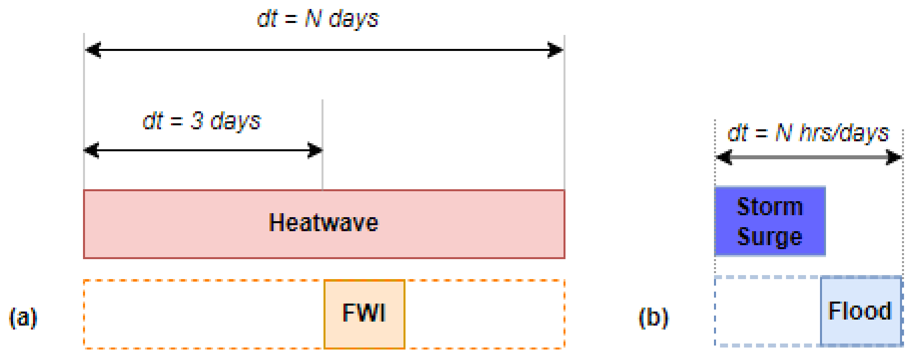

Figure 8. Temporal depiction of compound coincident hazards at different time scale ranges.

It is possible to visualise the relationship between different hazard drivers via plotting them together within a bivariate plot. Figure 9 shows variation in maximum wave height Vs maximum daily rainfall values and their respective marginal distributions) taken from respective wave buoy and rainfall sensors near the AMB region coastline. The figure shows wide variations in wave heights at low rainfall values (≤10mm/day). The historical data shows a limited number of recorded days where daily recorded rainfall is > 10mm with low maximum wave height values on these days.

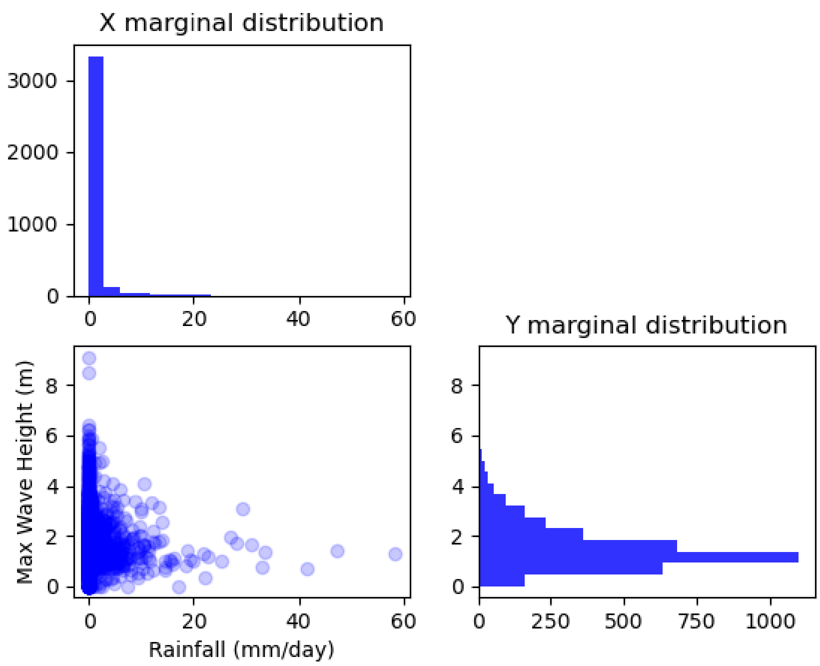

Figure 9. Cumulative rainfall (mm/dayt) Vs Maximum Wave Height (m) [*Historical Data*].

With the data being utilised to assess Joint Probability being at daily resolution, the probability of Hazard 1 occuring at same time, or within a specified timeframe of Hazard 2, would also be in terms of isidays. As such, to approximate return periods (RPs), it is necessary to convert from daily to annual probabilities. Once P (occuring in a day) is calculated, it is possible to follow the following 3 steps to convert to annual probabilities:

1. Determine probability of event not occurring on a single day

$$P(not\ occuring\ in\ a\ day)\ =\ 1\ -\ P(occuring\ in\ a\ day)$$

2. Probability of event not occurring on any day within a year

$$P(not\ occuring\ in\ a\ year)\ =\ P(not\ occurring\ in\ a\ day)^{365.25}$$

3. Probability of occurring at least once in a year

$$P(occurring\ at\ least\ once\ per\ year)\ =\ 1\ -\ P(not\ occuring\ in\ a\ year)$$

By calculating the daily probability distributions of these compound events and converting to yearly probability values we can visualise the probability of occurrence of compound hazard drivers (Figure 10). This figure highlights the relationship between maximum wave height on a daily basis and the corresponding daily rainfalls on those days. Here we see that there is a large range of wave heights extremes occurring on days with low daily rainfall values.

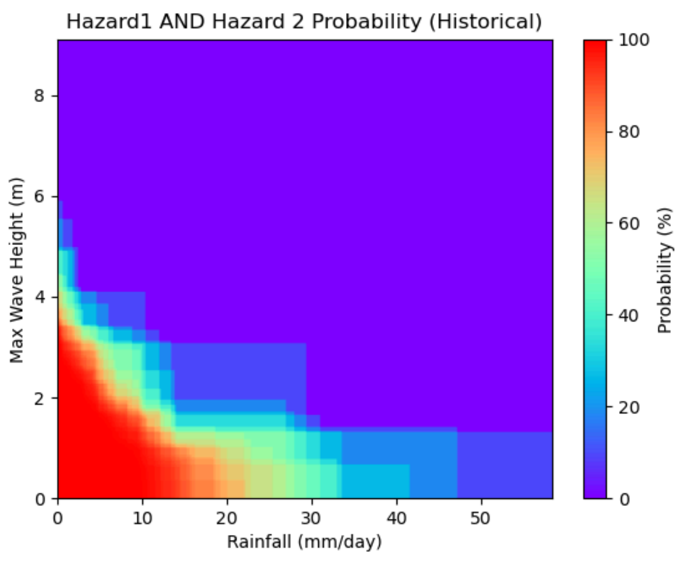

Figure 10. Joint Probability of cumulative rainfall (mm/day) Vs Maximum Wave Height (m) (*Historical Data*).

To further assess the relationships between bivariate data, Copulas that join/couples multivariate data together can be used. Copulas refer to a mathematical approach for modelling the dependence between two or more random variables (Schmidt 2006). Within the scope of multi-hazard modelling they have been used to define the joint probabilities of a range of hazard combinations including heatwaves and droughts (Ballarin et al., 2021, Páscoa et al. 2024), extreme wind and flooding (Bloomfield. et al., 2023), and Pluvial, Fluvial, and Storm Surge flooding (Ming et al., 2022).

Through utilising the Copulalib library within Python, it is possible to map the historical data to a copula and utilise this data to derive synthetic data based on the underlying correlation of the original dataset if present. Figure 11 shows synthetic data consisting of 10,000 data points derived via the use of a Clayton copula. By utilising a Copula based approach, it is possible to generate synthetic compound events that align with the marginal distributions of the original historical data previously generated. By doing so, it is possible to produce more data points representing extreme events to improve the understanding of the joint probabilities of the extreme values.

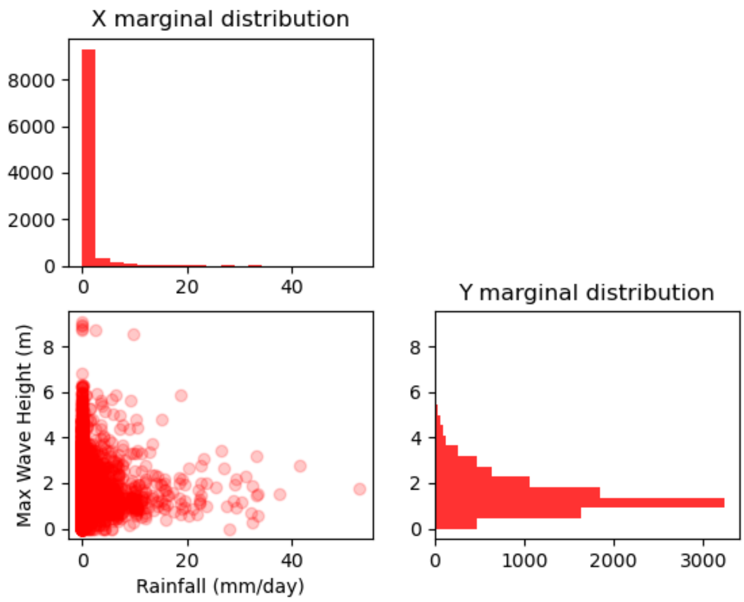

Figure 11. Cumulative rainfall (mm) Vs Significant Wave Height (m) (*Synthetic Data*).

Figure 12 shows the derived probability distributions for the synthetically generated bivariate data shown in Figure 11.

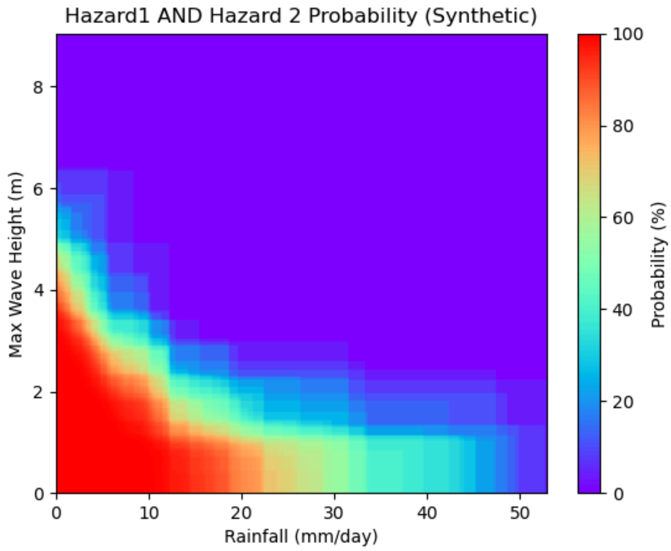

Figure 12. Joint Probability of cumulative rainfall (mm/day) Vs Maximum Wave Height (m) [*Synthetic Data*]

For the analysis of compound coincident events, firstly a leading hazard and then a secondary hazard that occurs within a given timeframe should be identified. Compound consecutive events can relate to different hazards (Figure 13a) and the same hazard type occurring in succession (Figure 13b).

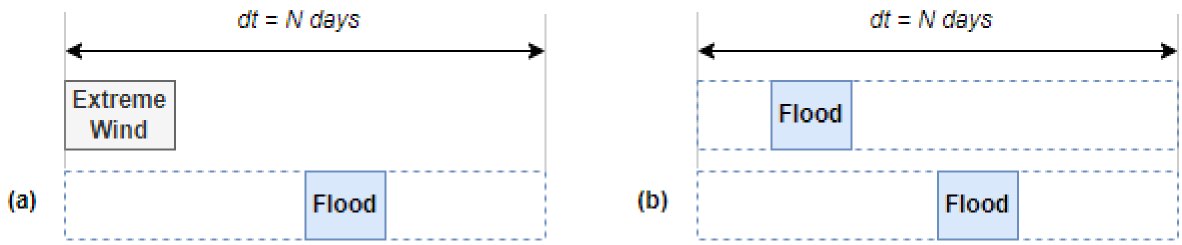

Figure 13. Temporal depiction of compound consecutive hazards.

To model these kinds of compound events we thus need to determine the limits for temporal duration (*N*) between events whereby the influence/effects of Hazard 1 still affect the effects of Hazard 2 within the modelled region. To plot this data a time window of duration *N* can be specified, and for each recorded value of hazard 1 (e.g. wind gust speed) the maximum value of hazard 2 (e.g. rainfall) that occurs within *N* days of hazard 1 is recorded. Figure 14 shows a comparison between probability distributions of wind gust speed and rainfall based on historical data from 1950 - 2014 for coincident (a) and consecutive (within a 30 day time window) (b) compound events. In this example for the compound coincident event we observe that there is a relationship between wind gusts and rainfall within the region where a day with wind gusts ~50km/hr and ~40mm/day rain occur almost annually. Analysis of consecutive hazards (for a 30 day timeframe) uplifts the probability of heavy rainfall (⩾20mm/day) such that there is a ~90% annual probability of heavy rainfall occurring within 30 days of an wind gust event (70km/hr), whereas the probability of heavy rainfall occurring on the same day is ~45% within this modelled region.

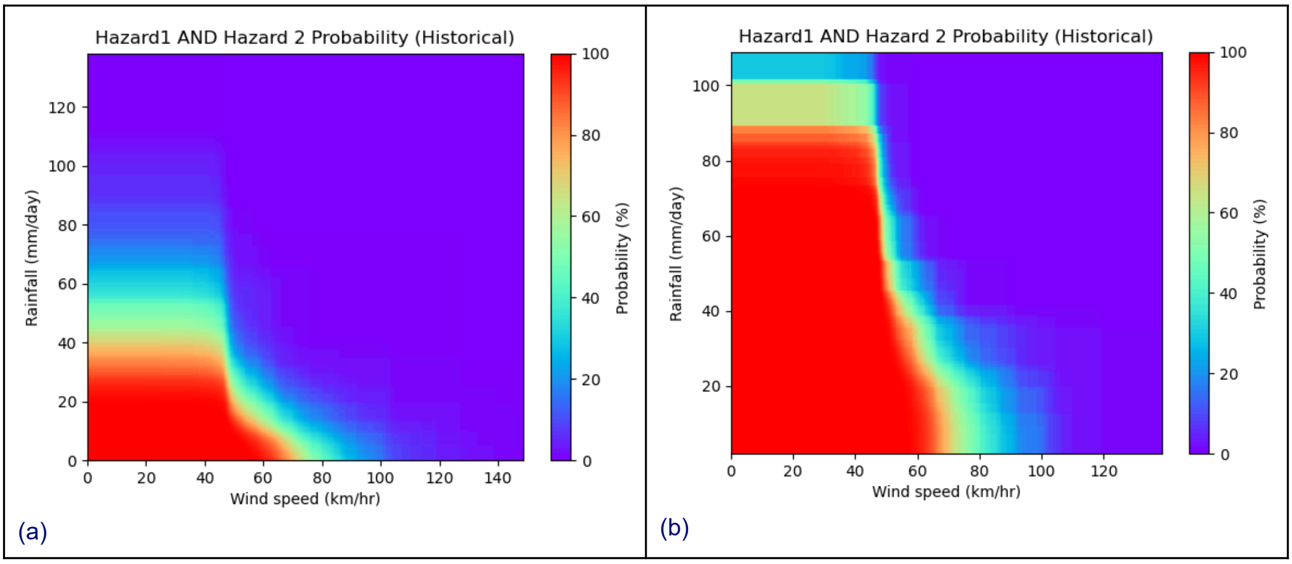

Figure 14. Joint Probability of historical data in Salzburg region for Wind Gust Speed (km/h) Vs cumulative rainfall (mm/day) for (a) compound coincident hazards and (b) consecutive hazards with 30 day window between wind gust and rainfall

Visualising the joint probability distributions of these compound hazard events highlights an additional challenge that for specified probabilities and respective return periods there exists a range of possible hazard combinations. Considering the example shown in Figure 14a we observe that for a joint probability of 10% (1 in 10-year event) there can be a wide range of respective wind speed and rainfall values. This poses a particular challenge in the selection of parameters to use within the compound hazard modelling framework. A potential means of reducing the modelling space for this could be via the selection of median and 90th percentile ranges that will reduce the parameters to a combination up to 4 per compound hazard scenario being modelled. Continuing with the example from Figure14a, for a 1 in 10 year return period event whereby the initial triggering wind speed is considered as ⩾70km/hr we have the following potential input parameters outlined in Tables 3 & 4. Here we observe three unique hazard combinations for consideration in the compound coincident hazard assessment which is further reduced to two if we omit the scenario where rainfall equals zero.

Table 3. Compound hazard combinations when deriving median and 90th percentile values from Wind speed and corresponding rainfall values

	Wind Speed (km/hr)	**Rainfall (mm/day)**
Median	109.25	13.14
90th Percentile	140.65	0.0

Table 4. Compound hazard combinations when deriving median and 90th percentile values from rainfall and the corresponding wind speed values

	Wind Speed (km/hr)	Rainfall (mm/day)
Median	109.25	13.14
90th Percentile	76.26	29.88

As outlined at the beginning of this section, the ICARIA project employs a variety of climate models, each coupled with several SSPs. Due to differences within these climate models, a range of distinct joint probability distributions are generated. Figure 15 presents a comparison of the joint probability distributions between the EC-EARTH3 model and the CanESM5 model. This comparison reveals a higher probability of increased daily rainfall events in the CanESM5 model compared to the EC-EARTH3 model. To consider these differences between the respective climate models, the derived joint probability hazard input values for modelled return periods will be considered from each model with the median and 90th percentile values being utilised. To account for the differences between the respective climate models, the derived joint probability distributions will be analysed for each model for selected return periods. Both the median and 90th percentile values from these results could then be utilised as input parameters for the physical modelling.

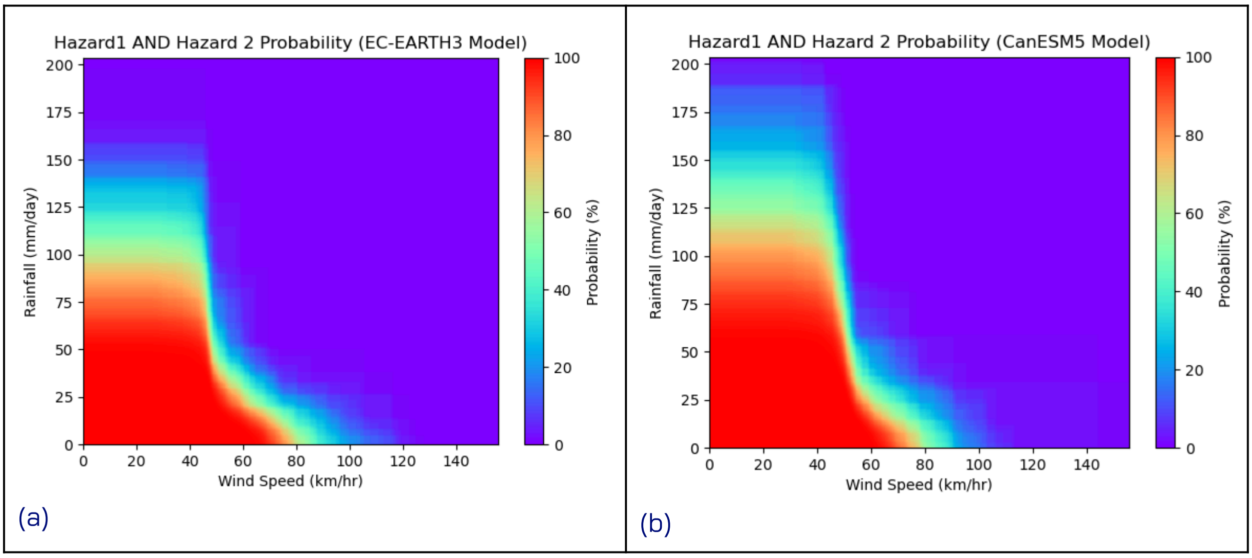

Figure 15. Combined Joint Probability of SSPs 126, 245, 370, and 585 for (a) EC-EARTH3 climate model and (b) CanESM5 climate model.

Through analysis of compound wind and rainfall events across 4 SSPs (126, 245, 370, and 585) and across 6 models where statistical downscaled wind and rainfall data are available (ACCESS-CM2, CanESM5, CMCC-ESM2, CNRM-ESM2-1, EC-EARTH3, and MRI-ESM2-0) we can examine the corresponding distributions wind speeds and rainfalls for different return periods (Figure 16). Here the joint probability values were derived for each model and their respective SSPs resulting in 24 joint probability distributions. Based on these distributions box plots were generated for three annual return periods (10, 30, 100). The results highlight that whilst the upper ranges of wind speed and rainfall values increase with more severe events the median rainfall value decreases highlighting the observation from Figure 14a that heavier rainfall events are less likely to occur at higher wind speeds. Though using this approach median and 90th percentile values for each return can be derived (Table 5) for use within the compound model setup to analyse the most likely compound hazard scenario for a given return period and uncertainty that considers potential extremes for this return period.

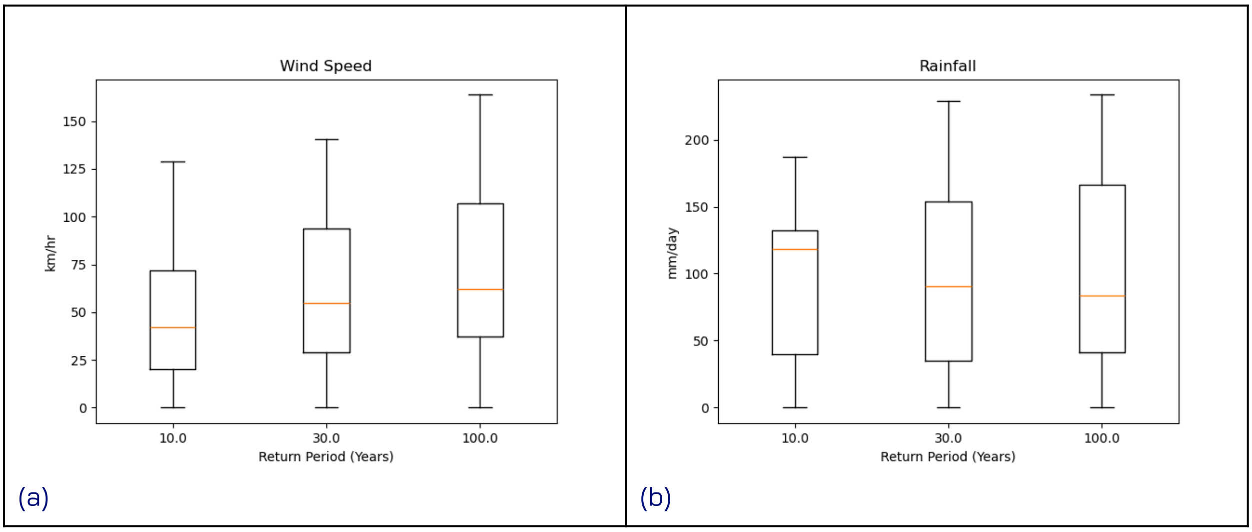

Figure 16. Wind Speed and Daily Rainfall distributions for compound events for 10.0, 30.0, and 100.0, year return periods using 4 SSPs (126, 245, 370, and 585) and 6 climate models (ACCESS-CM2, CanESM5, CMCC-ESM2, CNRM-ESM2-1, EC-EARTH3, and MRI-ESM2-0)

Table 5. Summary of Compound Hazard values for Wind Gust and Daily Rainfall within SLZ region derived from 4 SSPs (126, 245, 370, and 585) . and 6 climate models (ACCESS-CM2, CanESM5, CMCC-ESM2, CNRM-ESM2-1, EC-EARTH3, and MRI-ESM2-0)

Return Period (Years)	**Median**		**90th Percentile**	
	Wind Speed (km/hr)	**Rainfall (mm/day)**	**Wind Speed (km/hr)**	**Rainfall (mm/day)**
10	42.2	118	99.7	155
30	54.7	90.9	117.3	193.3
100	62.3	83.7	132.8	188.7

4. Single Hazard Models Overview

The multi-hazard scenarios being considered within the ICARIA across the three case studies are derived from combinations of six different climate driven hazard types (Figure 17), with different combinations of hazards being selected by respective case studies.

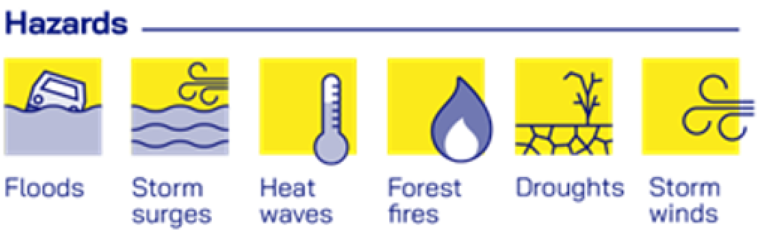

Figure 17. Hazard Classifications being modelled within ICARIA.

As an initial basis for selecting scenarios to be modelled as part of the multi-hazard assessment, it was defined what are the hazard drivers used within the hazard model and how extreme events are defined from a single hazard perspective (Table 6). This information will later be used to facilitate the derivation of joint probabilities of compound events and for the selection of multi-hazard scenarios that will be modelled.

Table 6. Extreme event definitions for modelled hazards.

Hazard Model	Hazard Drivers	Extreme Event Definition
Pluvial flood	Precipitation	Heavy to extreme rainfall days range from 20 mm/day to 100 mm/day. IDF curves used to simulate RPs of 2,10 and 100 years.
Storm surge	Significant Wave Height and Tide levels	90th percentile
Storm winds	Windspeed	Hazardous wind speeds > 70 km/hr are being considered
Drought	Precipitation	Standardised Precipitation Index (SPI) where: -1.00≥SPI>-1.50: moderate drought -1.50≥SPI>-2.00: severe drought -2.00≥SPI: extreme drought
Heatwave	Temperature	95th percentile of summer months for 3 or more days
Forest Fire	Temperature, Windspeed, Precipitation, Relative humidity	FWI where >= 70 would represent extreme fire danger ISI where >=13.4 windspeed >= 40km/hr

5. Model Setup Guidelines

5.1 Flooding (Pluvial) and Storm Surge

5.1.1 Compound Model setup

The occurrence of a compound event of storm surge and pluvial flooding generates challenging flood management scenarios in coastal areas due to the interactions established between both hazards. On the one hand, a storm surge entails a temporary rise of the mean sea level and maximum wave height. On the other hand, in an urban area, during rain events, the amount of water running through the sewer network increases due to the large volume of runoff generated, stressing drainage infrastructures.

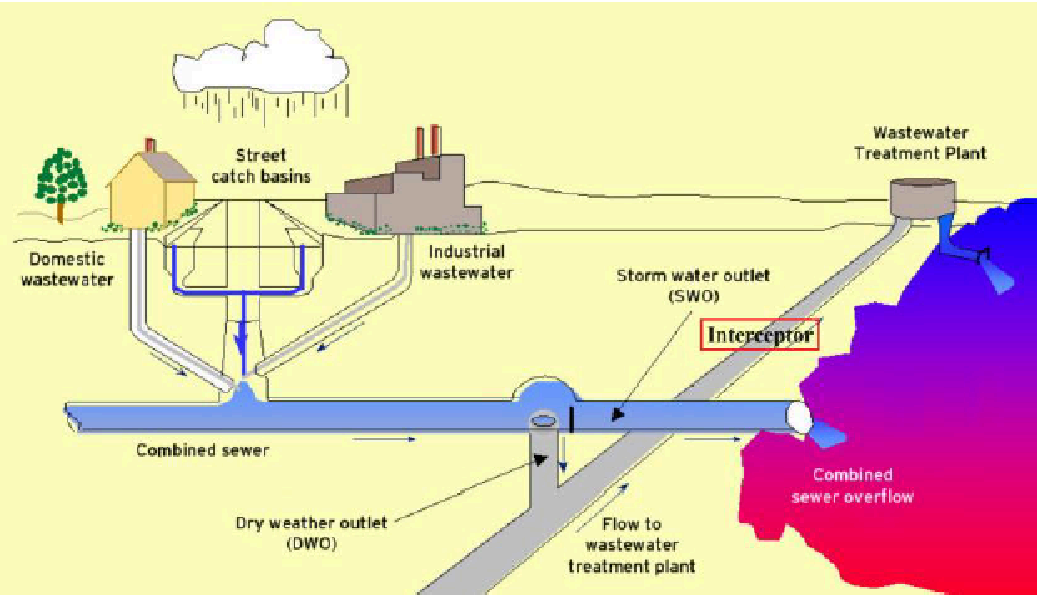

Figure 18. Scheme of a sewer system and the sewer interceptor

In case of combined sewer systems, under dry water conditions, the wastewater generated in a city is conveyed to the local wastewater treatment plant through sewer pipes. However, rain events above certain return periods, usually involving high rain intensities in short time periods, can generate a water flow above their maximum capacity. In these situations, the exceeding water is directly discharged from the surcharged pipes to the water receiving body (without previous treatment) through outfalls. In case of combined sewer systems, this phenomenon is known as combined systems overflow (CSO). In coastal areas, the receiving water body is often the sea. Outfalls that discharge water on the sea during CSOs are built at the shore line considering a safety height above the mean sea level to prevent sea water entering the drainage network.

However, during storm surge events, the mean sea level can rise to the point where this safety height is exceeded by a transitory extreme sea level. If this occurs, sea water is able to intrude the outlet of the urban drainage systems though the lowermost point of the outfall pipes. As a result, the drainage capacity of the whole network is reduced according to the degree of seawater intrusion. This situation, which corresponds to a backwater phenomenon, can lead to upstream saturation of the drainage network leading to flooding in upstream parts of the network drainage area (Figure 19) (Ming et al., 2022; Laster Grip et al., 2021; Bevacqua et al. 2019; Qiang et al., 2021a, Domingo et al., 2010).

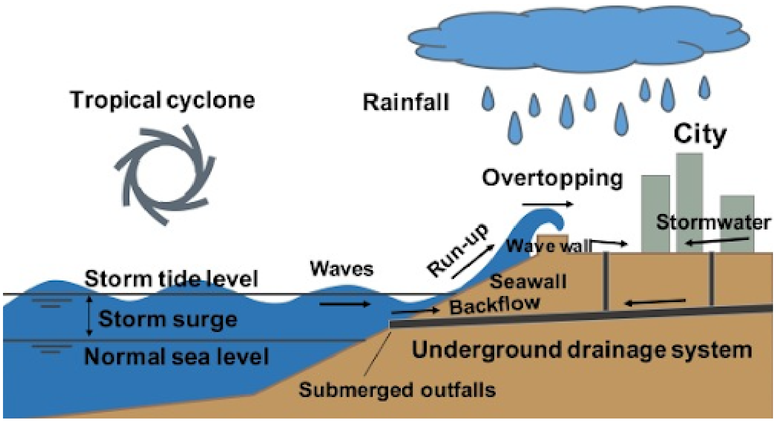

Figure 19. Conceptual model of the occurrence of backwater effect (Qiang et al., 2021a).

Furthermore, this kind of compound events have an important parallel effect on coastal low lying areas. A temporary sea level rise can lead to the intrusion of seawater as overland flow in low gradient terrain which are unprotected to this phenomenon. Just by itself, this can cause important floods. In combination with extreme precipitation, where extensive runoff circulates on the surface, the dynamics established between both floods can lead to more extensive flooded areas in the mentioned terrain (Santiago-Collazo et al., 2019).

Deliverable 2.1 of project ICARIA (Crisi-Adapt II 2020) presented a series of methodologies to develop hazard assessments of the different single hazard scenarios considered in the three case studies.

- Modelling of pluvial flooding with 1D/2D hydrodynamic model based on solving the free complete flow equations (mass and momentum equations), where the 1D and the 2D domains correspond to the sewer network and the urban surface respectively.
- Assessment of temporary extreme sea level with an hydrostatic model based on tides and wave height observations.

As mentioned earlier, the sewer network outfalls discharging water directly on the sea are the key structural element where pluvial water/wastewater and seawater interact during compound events. They are the entry points where seawater can intrude the sewer network, reducing surface drainage capacity and even leading to the direct flooding of coastal low-lying urban areas through inlets and manholes.

Despite being a well acknowledged problematic (Azevedo de Almeida et al., 2016; Meyers et al., 2021; Qiang et al., 2021; Kim et al., 2023), there are limited bibliographic references to modelling approaches to simulate the effect of the sea level - sewer network interaction at outfall level. The main reasons for this knowledge gap are various. Firstly, the limited general background on modelling of multi-hazard compound events, which has only gained attention in recent years (Zscheischler et al., 2018). Secondly, the intrinsic complexity behind the interaction between these two specific environments (the sea and the sewer network) requires knowledge on both maritime engineering and urban drainage science (Lee et al., 2020).

Santiago-Collazo et al., (2019) developed a comprehensive review of modelling approaches to simulate compound event floodings in low-lying coastal areas. Despite not considering the role of sewer networks in any of the reviewed approaches, this document provides a good insight on the efforts devoted to this specific field of multi-hazard modelling. Table 1 shown previously summarises the main modelisation approaches outlined by Santiago-Collazo et al., (2019) used to couple pluvial flooding and storm surge models.

The methodology proposed to assess the hazard posed by this specific multi-hazard event is based on a "one-way" coupling approach of a pluvial flooding and storm surge model.

It is articulated by defining abnormal boundary conditions in the outfalls of the urban drainage models, representing an increased water level in this point of the system during a storm surge. These conditions are determined with a hydrostatic extreme sea level model. Such approach allows to simulate key processes leading to floods during combined extreme rainfall and storm surge events.

1. Intrusion of seawater inside the pipes resulting in a partial or complete flooding of the downstream part of the sewer network reducing its drainage capacity.

2. Flooding of low lying coastal areas due to the temporary rise of the sea level.

The flowchart (Figure 20) represents the data flow between the coupled single-hazard models.

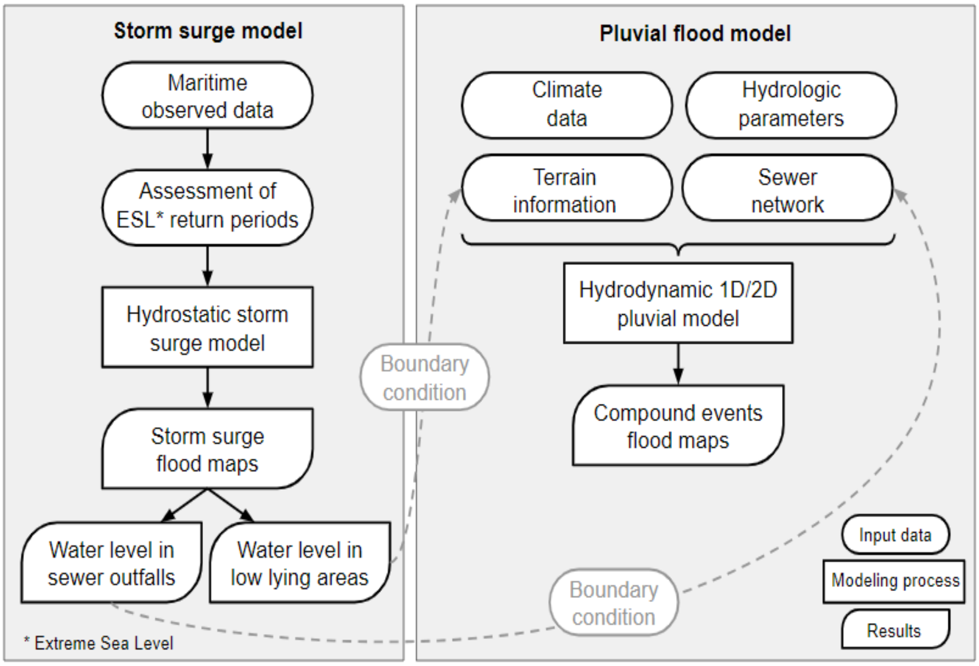

Figure 20. Flowchart of the one-way coupled approach to link pluvial flood and storm surge models.

The proposed approach allows a realistic modelling of the physical interaction between seawater and rain in the two key areas where they interact: the lower part of sewer networks whose outfalls have the sea as the water receiving body and low-lying coastal areas. However, it also requires specially accurate topographic surveys of the system outfalls and the overtopping height of the point where water is discharged to the sea as well as a high-resolution digital terrain model. Remarkably, information regarding the sewer network is often limited and/or inaccurate due to the usual data scarcity in the field of urban drainage infrastructure (Montalvo et al., 2024).

Similar approaches have been followed by other researchers like Lee et al. (2020), Jo et al. (2021), Qiang et al. (2021b) and Long & Gao (2023).

Figure 21 shows a conceptual model of an outfall connected to the sea under different rainfall and storm surge conditions to illustrate the mentioned interactions between wastewater and seawater sewer outfalls.

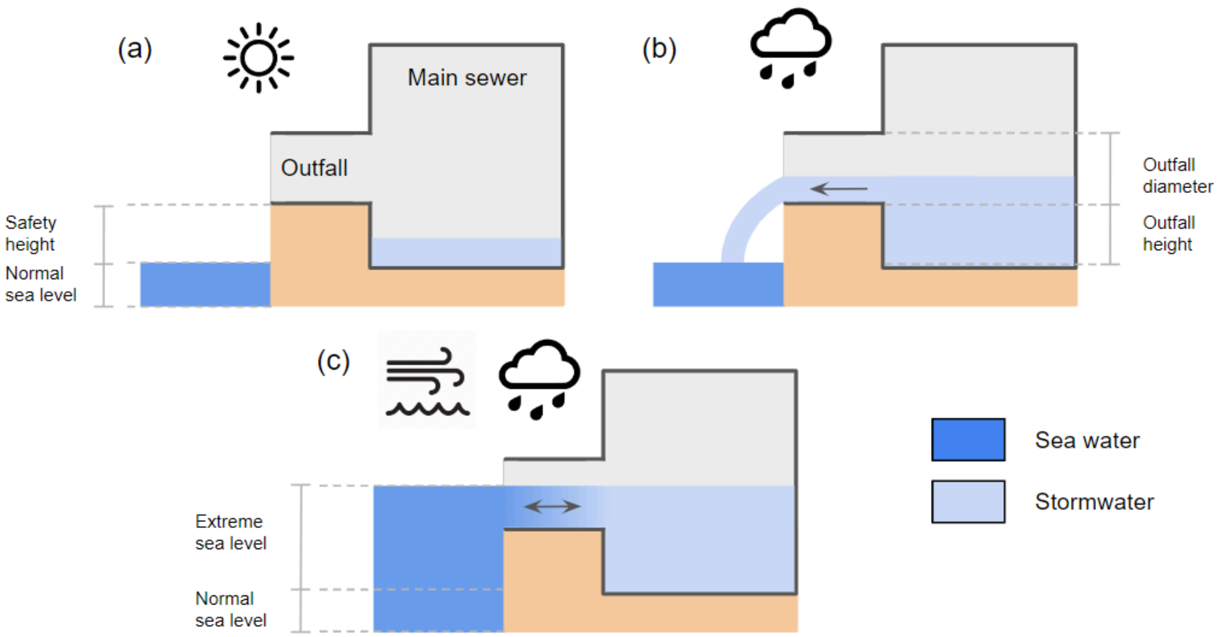

Figure 21. Scheme of an outfall connected to the sea under different conditions: (a) normal operation in dry weather conditions, (b) CSO due to an extreme rain event; (c) coincident storm surge and CSO.

Figure 22 shows another conceptual model reflecting the second key boundary condition to consider in this multi-hazard modelling approach. The three scenarios represented illustrate how low coastal low-lying areas can be affected by extreme rainfall events, storm surges and their combined occurrence.

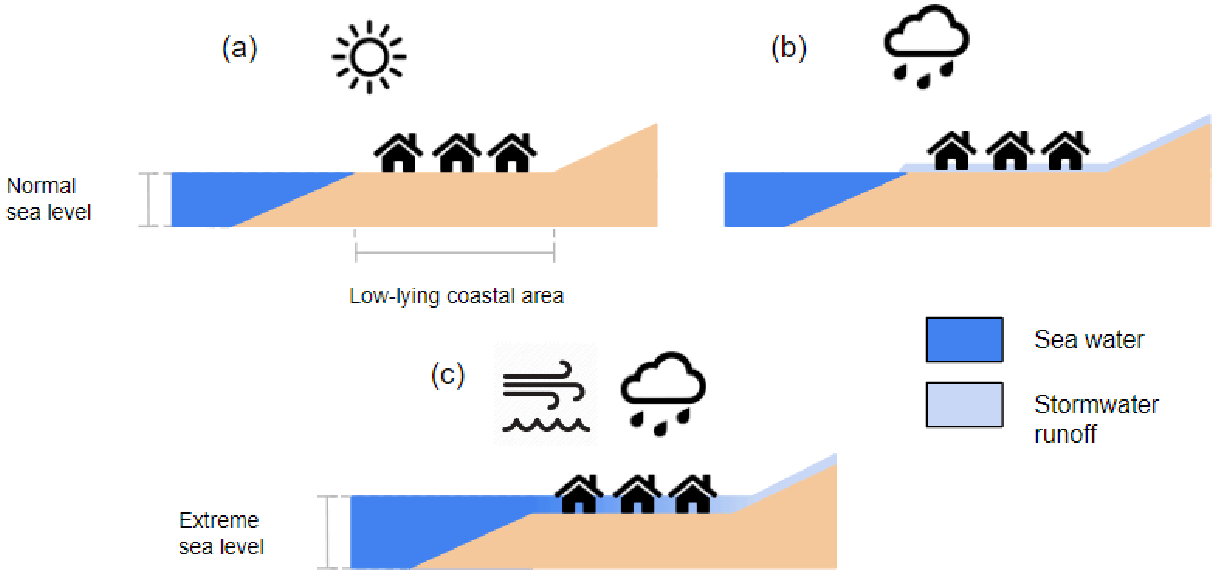

Figure 22. Scheme of a low-lying coastal area under different conditions: (a) dry weather conditions, (b) extreme rainfall conditions; (c) coincident coincidence storm surge and extreme rainfall conditions.

The following bullet points present the main steps to follow to set up the one-way coupled multi-hazard model shown in Figure 20 to simulate compound events combining pluvial flooding and storm surge. These should not be understood as a thorough step-by-step guide, but as a guide of the main processes to be followed.

1. Set up a hydrostatic storm surge model to assess the water height above the normal sea level reached during transitory extreme sea level events (Crisi-Adapt II 2020; ICARIA 2023b).
2. Extract extreme sea level values for different events of reference (corresponding to different percentiles of rainfall intensity associated to specific return periods)
3. Set up an hydrodynamic 1D/2D urban drainage model of the area of study (ICARIA 2023b).
4. Define the model boundary conditions based on the results of the previous step. These boundary conditions have to be defined at two levels (see Figure 20).
    a. Boundary condition for the 2D domain of the pluvial flooding level to represent the flooding of coastal areas due to the increased sea level.
    b. Boundary conditions in the sewer system outfalls to represent the backwater effect caused by the intrusion of seawater in the drainage network.
5. Simulate an extreme rainfall event with the 1D/2D hydrodynamic model considering the mentioned boundary conditions.

The results of the model correspond to a flooding map (showing water depth and velocity) resulting from the combined effect of the extreme rainfall and sea level.

The suggested approach presents a number of simplifications and data needs that generate uncertainty in the final results. Table 7 summarises them and suggests possible uncertainty reduction measures.

Table 7. Main sources of uncertainty in the one-way coupled pluvial flooding and storm surge multi-hazard model and possible improvements.

Source of uncertainty	Uncertainty reduction measure
The data of outfalls structure and actual height above mean sea level is often inaccurate	Carry fieldwork to accurately characterise the dimensions and height above mean sea level
A simplistic model to assess the hazard conditions of storm surges in coastal areas is used	Consider using a hydrodynamic storm surge model capable to simulate wave dynamics
The boundary conditions introduced to represent the ESL in the outfalls are stationary values, which do not account the dynamic nature of storm surges	Define time-varying boundary conditions to represent the short term fluctuations in the sea level at the sewer outfalls

5.1.2 Joint Probability Assessment

For the assessment of pluvial flooding and storm surge, compound coincident scenarios have been considered taking into account the influence of storm surge on the boundary conditions of the pluvial flood model. To assess the joint probability of these events, analysis will be undertaken on the correlation of days with extreme rainfall and that correspond to days where there are significant storm surge events. With these events being potentially correlated, the historical data relating to storm surge and extreme rainfall days will be analysed. Based on this assessment, probability of compound coincident events will be defined either relating to copula based derived return periods (where there is correlation) or as independent probabilities.

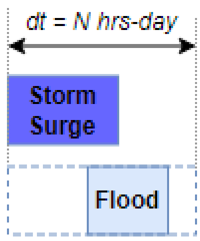

Figure 23. Temporal depiction of modelling of pluvial flood events during a storm surge.

5.1.3 Considered Risk Receptors and Cascading Effects

The outputs generated by compound flood scenarios will be utilised in the assessment of the following risk receptors.

Table 8. Modelled Risk Receptors for compound Flooding (pluvial) and Storm Surge hazards.

Risk Receptor		Hazard	
		Pluvial Flood	Storm Surge
	Properties	☑	☑
	Natural Areas	☑	☑
	Transport	☑	☑
	Water	☑	☑
	Electricity Assets	☑	☑
	Waste assets	☑	☑
	Tourism	☐	☐
	People	☑	☑
	Cascading Effects	☑	☑

5.2 Flooding and Extreme Wind

5.2.1 Compound Model setup

Compound events of flooding and extreme wind pose a risk to various types of natural and settlement areas. There are mainly two types of synoptic situations resulting in compound precipitation and storm events in Europe: (i) events that are caused by extratropical cyclones (Owen et al., 2021); (ii) summertime convective events (Pacey et al., 2021).

The recurrence time and magnitude of compound precipitation and wind extremes is predicted to increase under future conditions due to anthropogenic climate change (Ridder et al., 2022) and, especially, convective events will gain importance since warmer air can store more water, thereby causing increased precipitation intensities. At the level of physical interaction between hazards during coincident compound events, extreme rain events and wind storm do interact in the following ways:

1. Storms can increase the magnitude of flooding, trigger them through blocking the outflow of rivers and increase the probability of occurrence as storms alter the vulnerability of the surroundings towards extreme precipitation intensities.
2. In mountainous regions for instance, storms might lead to increased tree swamp, which causes increased inflow to the streams and decreased stability of the slopes. Both aspects affect flooding, the first one through blocked torrent barriers and therefore prevents the streams from flowing, the second increases the severity of extreme precipitation as destabilised slopes store less water, therefore increasing the runoff (Sebald et al., 2019).

It is important to note that flooding is considered as a hazard, not precipitation because extreme wind can trigger flooding, but can't trigger increased precipitation events.

Flooding can not trigger storms, yet, a storm occurring after a flooding event might hit the region harder as it is already dealing with the consequences of the flooding.

To capture the effect of compound coincident or consecutive wind storms and flooding, a one way coupling approach is taken (see Table 1) whereby the influence of wind storms in the region on the conditions in the environment are modelled. Thus the effect of the storm can be considered (depending on the type of stream, apparent flooding protection etc.) within the flooding model by:

- Adding a barrier within the stream downstream of a forest to represent the blocking due to trees
- Modelling the same precipitation event with a forested slope and a non-forested one to analyse the difference

These potential changes in conditions will thus be determined according to different wind speeds with flooding events of different intensities, that are associated to their joint probabilities.

To simulate the flooding, the SFINCS model is used and the precipitation rates based on the dynamical model (SSP126, SSP585, 2 regional climate models, 2 - 5km spatial and hourly temporal resolution) are taken as input.

The wind gusts are taken from one of the regional climate models (CLM) which has wind gusts as output parameter, as well as from the WRF regional climate model but after post-processing steps as wind gusts are only partly available, but mean wind as well as wind at different pressure levels are. However, it is important to note that the wind speed only indirectly affects the flooding model by defining the magnitude of broken trees.

5.2.2 Joint Probability Assessment

For defining the joint probability of Flooding and Extreme wind events within the Salzburg region, the probability of flood events occurring during (compound coincident) and after (compound consecutive) wind storm events are to be considered. To estimate the input parameters for respective return periods, both historical and future climate scenarios will be assessed.

For the compound consecutive hazard analysis the probability of extreme rainfall events that follow extreme wind events will be assessed over a various timeframes whereby assumptions will be required relating to recovery time of assets and the modelling environment based on expert knowledge and stakeholder discussions.

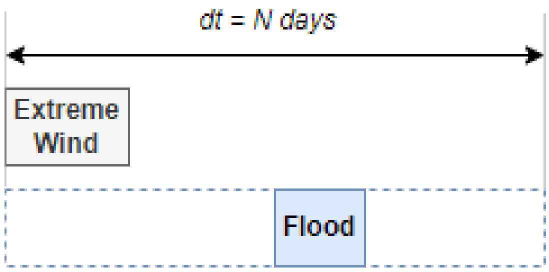

Figure 24. Temporal depiction of modelling of flood events during or following extreme wind.

5.2.3 Considered Risk Receptors and Cascading Effects

The outputs generated by compound wind and flood scenarios will be utilised in the assessment of the following risk receptors.

Table 9. Modelled Risk Receptors for compound Flooding and Extreme wind hazards.

Risk Receptor		Hazard	
		Flooding	Extreme Wind
	Properties	☑	☑
	Natural Areas	☐	☐
	Transport	☑	☑
	Water	☐	☐
	Electricity Assets	☑	☑
	Waste assets	☐	☐
	Tourism	☐	☐
	People	☐	☐
	Cascading Effects	☑	☑

5.3 Extreme Wind and Forest Fire

5.3.1 Compound Model setup

The investigation of compound hazard events in terms of extreme wind and forest fire is analysed in this section, as a notable association exists between high fire risk and the presence of strong winds. It should be mentioned that the main hazard driver of this compound model is the fire hazard, described by the Fire Weather Index (FWI) and derived by the Canadian Forest Fire Weather Index (FWI) System. FWI is a meteorologically based index used worldwide to estimate fire danger. It consists of different components that account for the effects of fuel moisture and wind on fire behaviour and spread. The higher the FWI is, the more favourable the meteorological conditions to trigger a wildfire are. Their analytical presentation of the system equations and numerical codes describing the structure and components of the FWI system can be found in Wagner and Pickett (1984) (Figure 25). Calculation of the components is based on consecutive daily observations of temperature, relative humidity, wind speed, and 24-hour precipitation.

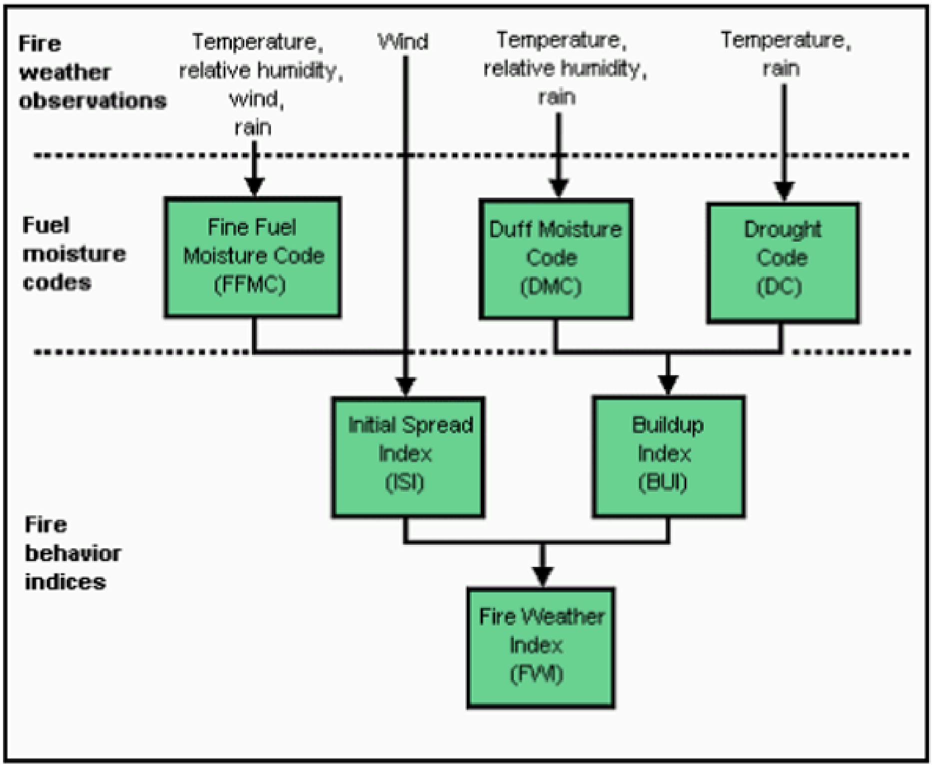

Figure 25. Structure of the FWI System (https://cwfis.cfs.nrcan.gc.ca/background/summary/fwi).

The first three components are fuel moisture codes, which are numeric ratings of the moisture content of the forest floor and other dead organic matter. Their values rise as the moisture content decreases. There is one fuel moisture code for each of the three layers of fuel: litter, represented by the moisture content of fine dead surface fuels (Fine Fuel Moisture Code, FFMC), loosely compacted organic material on the forest floor (Duff Moisture Code, DMC), and deep, compact organic soil layers (Drought Code, DC). The remaining three components are fire behaviour indices, which represent the rate of fire spread, the fuel available for combustion and the frontal fire intensity. The FFMC is combined with wind speed to estimate the potential spread rate of a fire (Initial Spread Index, ISI).

The Initial Spread Index (ISI) is a numeric rating of the expected rate of fire spread and one of the factors that hazard models have to take into consideration during extreme fire weather.

The classification of the FWI and ISI components according to EFFIS is presented in Table 10.

Table 10. Classification of values for the FWI and the ISI according to EFFIS (https://forest-fire.emergency.copernicus.eu/about-effis/technical-background/fire-danger-forecast)

Fire Danger Classes	FWI	ISI
Low	<11.2	< 5.0
Moderate	11.2 - 21.3	5.0 - 7.5
High	21.3 - 38.0	7.5 - 13.4
Very High	38.0 - 50	>=13.4
Extreme	50.0 - 70	
Very Extreme	>= 70	

Extreme Wind is a major controlling factor that determines rate and direction of spread, and shape of fire. The presence of strong winds plays a crucial role in determining wildfire behaviour by affecting their rapid spread, their intensity, turning the surface fires evolving into more severe crown fires with extreme fire behaviour and potentially making it more difficult to control fire (Zong et al., 2023, Richardson et al., 2022).

Within the ICARIA project, the compound hazard model will be set up for the selected area of study using the historical and future model datasets, which consist of 10 climate models each with 4 SSPs. The following description imposes the necessary steps for the definition of the coincidence of the compound events of forest fire and extreme winds:

- Calculation of daily FWI for fireseason of each year for a given time period.
- Definition of the extreme fire danger FWI values using percentile values (e.g., 90th percentiles) or selection from EFFIS extreme class threshold values for the selected location of interest for a given time period (e.g. for SAR region, FWI>70 is more representative for Greece as the extreme FWI is considered too low, and fire season spans from May to October).
- The daily coincidence of the selected FWI threshold with very high ISI (ISI >=13.4), along with extreme winds, exceeding the threshold 40km/h, in a daily time frame for each year for a given time period, represents the compound event of extreme winds and forest fire.
- Count of the annual number of days that fulfil the coincidence of the compound events.
- The results, as the median of ensemble models, are resumed to a table or a map that shows the number of days resulting from the combined effect of forest fires and extreme winds for the historical period and each climate change scenario for the selected case study.

5.3.2 Joint Probability Assessment

With wind being one of the components in deriving the FWI score, the analysis of influence of extreme wind and FWI scores will be based on compound coincident events. The joint probability assessment will be derived through the analysis of such events whereby days within wildfire season (June -

September) wil be considered and the relationship between FWI scores and along with extreme wind speed values of 40km/hr and above are considered.

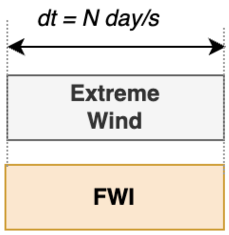

Figure 26. Temporal depiction of modelling influence of extreme wind on FWI scores.

5.3.3 Considered Risk Receptors and Cascading Effects

The outputs generated by compound extreme wind and FWI scenarios will be utilised in the assessment of the following risk receptors.

Table 11. Modelled Risk Receptors for compound Flooding and Extreme wind hazards

Risk Receptor		Hazard	
		Extreme Wind	Forest Fire
	Properties	☐	☑
	Natural Areas	☐	☑
	Transport	☑	☑
	Water	☐	☑
	Electricity Assets	☑	☑
	Waste assets	☐	☑
	Tourism	☑	☑
	People	☐	☑
	Cascading Effects	☑	☑

5.4 Drought and Heatwave

5.4.1 Compound Model setup

The effects of climate change are resulting in periods of higher extremes in relation to weather patterns. These extremes are reflected in the increasing occurrences of heatwaves and periods of drought. In the context of ICARIA, the combined effects of drought and heatwave will be assessed using a compound model set up whereby only events defined as heatwaves that occur within periods of drought (as highlighted in Figure 27) are considered for the model climate parameters. Moreover, within the ICARIA project, the compound hazard model will be set up for the selected study area using the historical and future model datasets, consisting of 10 climate models each with 4 SSPs.

a. SPI6 calculation

The SPI is calculated by fitting a probability density function to a given frequency distribution of precipitation (Faye Cheikh et al. 2019) and then the probabilities are transformed into a normalised distribution with a mean equal to zero and a variance of one, developed by Mckee et al. (1993). The distribution function used for computing SPI was the 'Gamma' as the most widely used in literature and recommended. Moreover, the SPI-6 was selected for drought hazard modelling, as in semi-arid and arid regions (as the study area), drought index computed at shorter accumulation periods could give unreliable estimates (Karavitis et al 2014). Drought classification is provided in Table 12. Moreover, drought conditions are indicated as SPI decreases below –1.0, while increasingly severe excess rainfall is indicated as SPI increases above 1.0.

Table 12. Drought classifications based on SPI

Classification	SPI	Drought classes
1	SPI≥2.00	extreme wet
2	2.00>SPI≥1.50	very wet
3	1.50>SPI≥1.00	moderate wet
4	1.00>SPI≥-1.00	normal
5	-1.00≥SPI>-1.50	moderate drought
6	-1.50≥SPI>-2.00	severe drought
7	-2.00≥SPI	extreme drought

The following description imposes the necessary steps for the definition of the coincidence of the compound events of drought and heatwave.

Definition of heatwave:

Within ICARIA and D1.2, a heatwave is defined as the period where the maximum daily temperature is equal to or exceeds the 95th percentile of summer (June, July, and August) temperatures for a duration of 3 or more consecutive days, for a given historical period.

Regarding the compound event drought and heatwave, the following approach will be used.

- Calculation of the monthly SPI6 as derived from the CMIP6 models for historical and future periods (for the selected SSPs) for the selected location.
    - Extraction of **SPI6 of September** values, for each year, which represent the drought conditions during the dry period in Greece.
    - Selection of drought years, based on the definition of drought conditions (-1.00≥SPI) of Table 12.
    - Statistical analysis and comparison of the number of heatwaves during these years in the historical and future period under the examined SSPs.

5.4.2 Joint Probability Assessment

The joint probability of these compound hazard events will consider the occurrence of heatwaves during periods of drought both in the historical context and range of future climate scenarios.

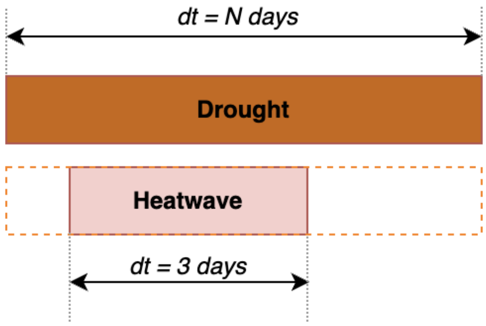

Figure 27. Temporal depiction of modelling heatwaves during periods of drought.

5.4.3 Considered Risk Receptors and Cascading Effects

The outputs generated by compound drought and heatwave scenarios will be utilised in the assessment of the following risk receptors.

Table 13. Modelled Risk Receptors for compound Drought and Heatwave.

Risk Receptor	Hazard: Drought	Hazard: Heatwave
Properties	☐	☐
Natural Areas	☑	☐
Transport	☐	☐
Water	☑	☑
Electricity Assets	☐	☑
Waste assets	☐	☐
Tourism	☐	☑
People	☑	☑
Cascading Effects	☑	☑

5.5 Drought and Forest Fire

5.5.1 Compound Model setup

Meteorological drought, which is generally defined as a period of unusual precipitation deficit, is not a necessary or sufficient condition for forest fire occurrence as fires also happen during conditions of normal seasonal aridity. However, when a drought occurs, both live and dead fuels can dry out and become more flammable and the probability of ignition increases along with rate of fire spread (Andrews et al., 2003; Scott & Burgan, 2005).

In the context of ICARIA, the combined effects of drought and forest fires will be assessed using a compound model set up. Moreover, within the ICARIA project, the compound hazard model will be set up for the selected area of study using the historical and future model datasets, which consist of 10 climate models each with 4 SSPs. For this compound model set up, it is primarily necessary the calculations of Standardised Precipitation Index (SPI) and Fire Weather Index (FWI) indices for the historical and future periods for selected locations, based on daily precipitation, maximum temperature, relative humidity and wind gust datasets.

The SPI is calculated by fitting a probability density function to a given frequency distribution of precipitation and then the probabilities are transformed into a normalised distribution with a mean equal to zero and a variance of one, developed by Mckee et al. (1993). The distribution function used for computing SPI was the 'Gamma' as the most widely used in literature and recommended.

Drought classifications for these compound scenarios are those that were previously defined in Table 12.

As outlined earlier in the Extreme Wind and Forest Fire Section, the fire hazard is described by the Fire Weather Index (FWI), derived by the Canadian Forest Fire Weather Index (FWI) System with components defined in Figure 25 with the corresponding Fire Danger Classes ranging from Low to Extreme (see Table 10).

The Compound hazard model is represented by the following steps:

1. Calculation of the monthly SPI6 as derived from the CMIP6 models for historical and future periods (for the selected SSPs) for the selected location. The SPI6 was selected for drought hazard modelling, as in semi-arid and arid regions (as the study area), drought index computed at shorter accumulation periods could give unreliable estimates (Karavitis et al 2014).
2. Calculation of the daily FWI for historical and future periods (for the selected SSPs) for the selected location.

After calculating both indices, it is important to define the common period for analysing the two indices in terms of compound hazards. This period is usually defined according to the fireseason period representing each location. Eg May to October for SAR case study.

3. For the same period, the definition of the coincidence of the compound events includes the following final procedure:
    a. Extraction of **SPI6 of October** values, for each year, which represent the drought conditions of the entire fireseason.
    b. o Selection of drought years, based on the definition of drought conditions (-1.00≥SPI) of Table 15.
    c. Statistical analysis and comparison of the extreme and mean values of the fire-related indices during these years in the historical and future period under SSPs:
        - Threshold of 90th percentile of FWI, ISI and FFMC
        - Number of very extreme fire days with FWI > 70.
        - Mean of FWI, FFMC and ISI

The output of the compound hazard model can be in the form of a table or map, depending on the type of datasets in point format or gridded.

5.5.2 Joint Probability Assessment

The joint probability of these compound hazard events will consider the probability distribution of fire danger weather during periods of drought.

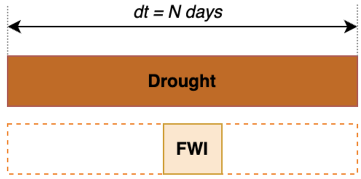

Figure 28. Temporal depiction of modelling FWI scores during periods of drought.

5.5.3 Considered Risk Receptors and Cascading Effects

The outputs generated by compound drought and FWI scenarios will be utilised in the assessment of the following risk receptors.

Table 14. Modelled Risk Receptors for compound Drought and Forest Fire

Risk Receptor		Hazard	
		Drought	Forest Fire
	Properties	☐	☑
	Natural Areas	☑	☑
	Transport	☐	☑
	Water	☑	☑
	Electricity Assets	☐	☑
	Waste assets	☐	☑
	Tourism	☐	☑
	People	☑	☑
	Cascading Effects	☑	☑

5.6 Heatwave and Forest Fire

5.6.1 Compound Model setup

Heatwaves and forest fires are hazards that are associated with each other, with their cooccurrence to have been increased the past decades, constituting in multi-hazard events. These events are mainly controlled by the duration and severity of the heatwaves. Prolonged high temperatures and dry conditions makes vegetation more susceptible to the ignition of forest fires. The compound Heatwave – Forest fire hazard model needs as input the number and the duration of heatwaves along with the quantification of fire hazard during these heatwaves, represented by the Fire Weather Index (FWI).

Within ICARIA and D1.2, a heatwave is defined as the period, where the daily maximum temperature is equal to or exceeds the 95th percentile of summer (June, July, and August) temperatures for a duration of 3 or more consecutive days, for a given historical period.

The fire hazard is described by the Fire Weather Index (FWI), derived by the Canadian Forest Fire Weather Index (FWI) System with components defined in Figure 25 with the corresponding Fire Danger Classes ranging from Low to Extreme (see Table 10).

For the quantification of coincidence of these events the following methodology is applied.

Within ICARIA project, the compound hazard model will be set up for the selected area of study using the historical and future model datasets, which consist of 10 climate models each with 4 SSPs. The common period for the specific compound event is summer months (June – July – August) for the given historical or future period. For each year, a heatwave event and its duration are estimated, during the given period. Respectively, for every heatwave event that occurs, FWI values equal or greater than 70 or exceeding the extreme 90th percentile (Varela et al 2018) of the historical period, are extracted. This approach is applied also during the summer future period to examine the effect of combined events of heatwave and fire danger under climate change.

5.6.2 Joint Probability Assessment

Within the joint probability assessment of high FWI scenarios coinciding with heatwaves we need to consider the duration of the heatwave and the likelihood of "fire danger" during this period.

Within the scope of ICARIA the definition of a heatwave event as defined in D1.2 is an event where the temperature is equal to or exceeds the 95th percentile of recorded summer (June, July, and August) temperatures during the period of 1981 - 2010 for a duration of 3 or more consecutive days.

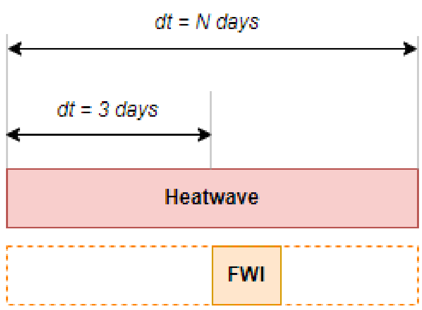

Figure 29. Defining compound Heatwave with Wildfire scenario

For defining “fire danger” weather, common practice is to consider FWI scores equal or greater than 50, however within the region of Greece this value is considered too low, with an alternative being 90th percentile within the modelled region. For consistency with the temperature metrics this 90th percentile is derived over the same time period 1981 - 2010 however the months analysed for defining this threshold span May - October.

5.6.3 Considered Risk Receptors and Cascading Effects

The outputs generated by compound heatwave and FWI scenarios will be utilised in the assessment of the following risk receptors.

Table 15. Modelled Risk Receptors for compound Heatwave and Forest Fire hazards

Risk Receptor		Hazard	
		Heatwave	Forest Fire
	Properties	☐	☑
	Natural Areas	☐	☑
	Transport	☐	☑
	Water	☑	☑
	Electricity Assets	☑	☑
	Waste assets	☐	☑
	Tourism	☑	☑
	People	☑	☑
	Cascading Effects	☑	☑

5.7 Heatwave, Drought and Forest Fire

5.7.1 Compound Model setup

The prolonged high temperature (heatwaves) and low precipitation periods (drought periods) increase the likelihood and magnitude of forest fire hazard.

Within ICARIA project, the compound hazard model will be set up for the selected area of study using the historical and future model datasets, which consist of 10 climate models each with 4 SSPs. The common period for the specific compound events is defined by the fireseason that spans from May to October, for the given historical or future period.

This compound model involves analysing the effect of coincidence of heatwave, drought and forest fire, as defined by the Standardised Precipitation Index (SPI), heatwave definition and the Fire Weather Index (FWI). The first step requires the extraction of dry years based on the definition of drought conditions (-1.00⩾SPI). For each dry year, a heatwave event is estimated, where the maximum temperature is equal to or exceeds the 95th percentile of summer (June, July, and August) temperatures for a duration of 3 or more consecutive days, for a given historical period. Respectively, for every heatwave event that occurs, FWI values equal or greater than 70 or exceeding the extreme 90th percentile (Varela et al 2018) of the historical period, are extracted. This approach is applied also during the summer future period to examine the effect of combined events of heatwave, drought and fire under climate change.

5.7.2 Joint Probability Assessment

Like that of the previous combinations of drought, heatwave and FWI scores, this joint probability assessment will assess the likelihood and influence of drought, heatwaves, and FWI scores occurring within modelled regions for both historical and future scenarios.

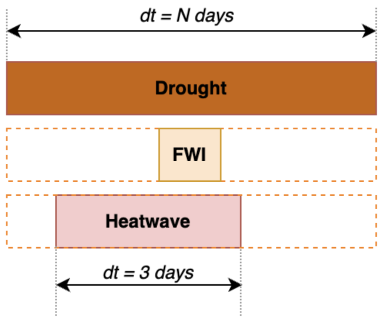

Figure 30. Defining compound Drought, Heatwave with Wildfire scenarios.

5.7.3 Considered Risk Receptors and Cascading Effects

The outputs generated by compound drought, heatwave and FWI scenarios will be utilised in the assessment of the following risk receptors.

Table 16. Modelled Risk Receptors for compound Heatwave, Drought and Forest Fire.

Risk Receptor		Hazard		
		Heatwave	Drought	Forest Fire
	Properties	☐	☐	☑
	Natural Areas	☑	☑	☑
	Transport	☐	☐	☑
	Water	☑	☑	☑
	Electricity Assets	☑	☑	☑
	Waste assets	☐	☐	☑
	Tourism	☑	☑	☑
	People	☑	☑	☑
	Cascading Effects	☑	☑	☑

6. Conclusions

The work undertaken within Task 2.3: "Coupled hazard models: methodology and tools", this deliverable outlines the approaches used across the three case study regions for modelling multi-hazard scenarios" has outlined approaches for the coupling and modelling of seven compound hazard scenarios:

- Pluvial Flooding and Storm Surge
- Flooding and Extreme Wind
- Extreme Wind and Forest Fire
- Drought and Heatwave
- Drought and Forest Fire
- Heatwave and Forest Fire
- Drought, Heatwave, and Forest Fire

Across these compound hazard scenarios two generalised modelling approaches have been highlighted with:

- **One-way coupling of models**: *Pluvial Flooding and Storm Surge* and Flooding and *Extreme Wind*.
- **Statistical analysis of hazard drivers**: *Extreme Wind and Forest Fire, Drought and Heatwave, Drought and Forest Fire, Heatwave and Forest Fire*, and *Drought, Heatwave, and Forest Fire*

Within the one-coupling models the influence of one hazard driver is considered when defining the modelling parameters of the other hazard. For the case of pluvial flooding with storm surge. The outputs from the storm surge model are utilised to define the boundary conditions for the pluvial flood model. Within the scope of the flooding with extreme wind model, potential effects of extreme wind events on surface flows will be considered such as how the accumulation of debris during or following an extreme wind event can block flow pathways resulting in greater risks of flooding.

For the statistical analysis of hazard drivers the climate data is analysed to select climate input parameters where the definition of one hazard occurs within the timeframe of another hazard. For instance, for the heatwave and drought model the selected scenarios for modelling within a region will first identify (from climate data) periods of time that a modelled region is within drought and then identify scenarios within these drought periods that can be defined as heatwaves as per the extreme event definitions in Table 6. For the other multi-hazard scenarios whereby Forest Fire is one of the featured hazards, as the FWI index shares climate input data that is a component of the other hazards to be modelled in combination such as Temperature, Precipitation and Wind (see Figure 25) a similar statistical approach is used such as extreme wind during forest, forest fire during drought, forest fire during heatwave, and forest fire during a heatwave that is occurring during a drought. Within each of these models the influence of the hazards with respect to the derived FWI scores is analysed.

For the Joint Probability assessment the work outlined within this deliverable highlights two main approaches for the quantification and visualisation of compound coincident and compound consecutive hazards.

The first approach highlighted is the use of statistical analysis of climate data whereby the probability of respective compound hazard drivers such as extreme wind and rainfall occurring either in the same place at same time or one within a pre-defined time frame of the other in the same location is assessed. By considering multiple climate models and SSPs the modelling framework defines a most likely compound hazard scenario for given return periods utilising the median values of the respective driver along with a degree of the uncertainty through the selection of the 90th percentiles to define more potential extremes for the selected return periods.

The second approach highlights the use of Copulas as a means of defining relationships between two or more independent variables. Through analysis of climate data and the use of python libraries such as Copulalib, large amounts of synthetic data can be generated that can be utilised to define the probability of compound events. This mathematical approach of generating synthetic data is of particular use when data relating to the extremes of compound scenarios is limited.

In summary the modelling approaches developed in task 2.3 and outlined within this document provide a guide/framework for setting up modelling tools for modelling multi-hazard scenarios and provide a basis for the selection criteria of input parameters required for the modelling of return periods that are of interest to the case studies.

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Annex 1: Data Management Statement

Table A.1. Data used in preparation of ICARIA Deliverable 2.3.

Dataset name	Format	Size	Owner and re-use conditions	Potential utility within and outside ICARIA	Unique ID
na	na	na	na	na	na

Table A.2. Data produced in preparation of ICARIA Deliverable 2.3.

Dataset name	Format	Size	Owner and re-use conditions	Potential utility within and outside ICARIA	Unique ID
na	na	na	na	na	na

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