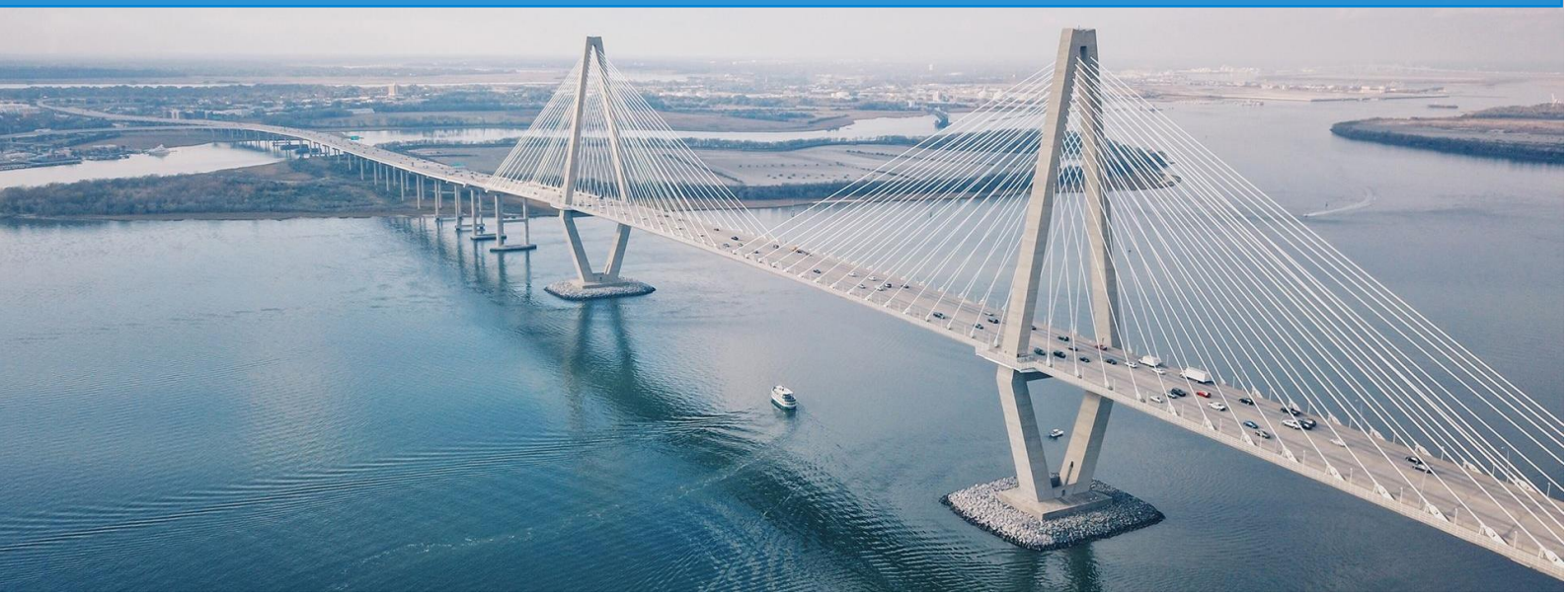
SIRMA

STRENGTHENING INFRASTRUCTURE RISK MANAGEMENT IN THE ATLANTIC AREA



Transportation infrastructure risk-based management

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SIRMA

STRENGTHENING THE TERRITORY'S RESILIENCE TO RISKS OF NATURAL, CLIMATE, AND HUMAN ORIGIN

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Transportation infrastructure risk-based management

WP 6 Risk & Resilience-Based Decision-Making procedure for Transportation Infrastructure

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SIRMA Project Synopsis

SIRMA aims to develop, validate, and implement a robust framework for the efficient management and mitigation of natural hazards in terrestrial transportation modes in the Atlantic Area, which consider both road and railway infrastructure networks (multi-modal). SIRMA leads to significantly improved resilience of transportation infrastructures by developing a holistic toolset with transversal application to anticipate and mitigate the effects of extreme natural events and strong corrosion processes, including climate change-related impacts. These tools will be deployed for critical hazards that are affecting the main Atlantic corridors that are largely covered by SIRMA consortium presence and knowledge. SIRMA's objectives will address and strengthen the resilience of transportation infrastructures by:

- Developing a systematic methodology for risk-based prevention and management (procedures for inspection, diagnosis and assessment);
- Implementing a decision-making algorithm for better risk management;
- Creating a hierarchical database (inventory data, performance predictive models, condition state indicators and decision-making tools), where information can be exchangeable between entities and across regions/countries;
- Developing a real-time process for monitoring the condition state of transportation infrastructure;
- Enhancing the interoperability of information systems in the Atlantic Area, by taking account of data normalization and specificity of each country.

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Executive Summary

This Deliverable report (D6.1), summarizes the work developed in the context of working package 6 “Risk & Resilience-Based Decision-Making procedure for Transportation Infrastructure”.

This WP aims to develop a resilience-based decision-making tool for transportation infrastructure in the Atlantic region. It is divided into three Actions:

(i) Risk-based model for transportation infrastructure;

(ii) Risk mitigation measures on transportation infrastructures;

(iii) Resilience-based decision-making.

Action 1 integrates data obtained from sensor system, developed at WP5. Additionally, the developed model considers the climate change effects on the likelihood and impact of extreme events, obtained from WP4.

Action 2 is divided into two parts: (i) collecting data about risk mitigation measures, not only in the Atlantic region but also out of it; (ii) incorporating such data on a risk-based predictive model (Action 1). In the end, a database with the most relevant risk mitigation measures will be obtained.

Action 3 addresses the development of a real-time decision-making framework, necessary to define: (i) risk-based predictive model (Action 1); (ii) risk mitigation measures (Action 2); (iii) optimization algorithm. In the end, a decision-making tool based on resilience will be delivered.

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1. Introduction and Context

The direct relationship between the social development of a region and its infrastructure requirements leads to an expansion of engineering knowledge. With population growth and changing climatic conditions, the challenge is proper infrastructure management that ensures optimal operation over time.

The present work develops in the context of transport infrastructure management. This infrastructure, due to its exposure to the natural environment, is especially susceptible to natural hazards. Threats are becoming more frequent due to worsening weather conditions. In the case of the transport infrastructure located in the Atlantic Area, which is the specific region of interest in the context of the SIRMA project, some of the natural hazards gain increased relevance.

Hence, working package 6 seeks to address the short, medium, and long-term decision-making, concerning the optimal planning of risk mitigation measures for transportation infrastructure. To achieve this goal, a risk-based framework for real-time decision-making is developed and summarized in the present document.

2. Theoretical Background

For Williams (1993) risk can be considered as a combination of individual uncertainties which have an impact on the overall objectives of the projects. Although there are several definitions for risk available in the literature, the broadest one, and the one being used in the present work (infrastructure project), the risk is defined using three variables as it appears in the following expression:

$$R = H \times V \times C \tag{1}$$

According to the previous expression, the value of risk (R) can be computed by multiplying the probability of a certain hazard (H) to occur, with the vulnerability (V) the asset being analyzed presents regarding that hazard, as well as, with the consequences (C) that asset's failure may originate.

The definition of each of the three components of risk definition is, in turn, also susceptible to several approaches. Depending on the context of analysis, several definitions can be found in the literature.

Perhaps the simplest approach to defining these components corresponds to the use of qualitative scales for each one. Illustrative examples of such qualitative scales can be found in Table 1 for hazard component, Table 2 for vulnerability component, and Table 3 for consequences component. Finally, in Table 4, one example of a risk score table can be found.

Table 1: Hazard qualitative scale (example).

Weight	Frequency of occurrence
Frequent (5)	1 or more events per year
Probable (4)	1 or more events per 10 years
Occasional (3)	1 or more events per 30 years
Remote (2)	1 or more events per 200 years
Improbable (1)	Less than 1 event per 200 years

Table 2: Vulnerability qualitative scale (example adapted from NIST (2012)).

Weight	Vulnerability severity
Very high (96-100)	The vulnerability is exposed and exploited, and its exploitation could result in severe impacts.
High (80-95)	The vulnerability is of high concern, based on the exposure of the vulnerability and ease of exploitation and/or on the severity of impacts that could result from its exploitation.
Moderate (21-79)	The vulnerability is of modern concern, based on the exposure of the vulnerability and ease of exploitation and/or on the severity of the impacts that could result from its exploitation.
Low (5-20)	The vulnerability is of minor concern, but the effectiveness of remediation could be improved.
Very low (0-4)	The vulnerability is not of concern.

Table 3: Consequences qualitative scale (example).

Weight	Public health consequences
Catastrophic (100)	Multiple fatalities and injuries
Major (60)	Single fatality, permanent total disability
Serious (25)	Major injuries (long term injuries)
Moderate (10)	Minor injuries (low severity impairment)
Minor (2)	Slight injury, first aid not required

Table 4: Risk qualitative scale (example).

Weight	Level	Action
>400	Extreme	Immediate action
100-400	High	Risk control measures
30-100	Moderate	Evaluate risk control in long term
<30	Low	Periodic evaluation of risk

Analyzing the above example tables, several comments can be drawn:

- Different rating scales, both in terms of scale limits (e.g., 1 to 5 continuous scale or 2 to 100 stepwise scale), scale rates (single value or interval values)
- Different levels of detail, both regarding each level description and designation
- Different input data is required to properly select one rate for each of the risk components. In some cases, this data can be quantified and measured (e.g., frequency of hazards occurrence) while others need to be defined based on the experience and expertise of the evaluator (e.g., vulnerability)
- Some could be used to quantify more than one risk component (e.g., vulnerability scale, as it is, somehow incorporates consequences concepts, and thus could be used as a replacement of consequences. In that case, R = H x V', where V' = V x C)

The approach presented above, using qualitative scales, is rather simplified. Ideally, this approach should be replaced by quantitative approaches in which risk may be given in terms of monetary units or other quantifiable metrics for a specific time. In that case, some or all the components of risk should also be evaluated using quantitative models. In practice, considering the difficulties associated with quantifying the three risk equation components, many studies make use of simplified risk analyses like those shown before.

In the next sections, different quantitative and semi-quantitative alternatives are presented to calculate risk in the infrastructure networks. Following the bibliographic references, the risk model presented in this work will be designed.

2.1 Illustrative examples of risk assessment

As mentioned above, there are several models of risk assessment proposed in the literature, many of them with a quantitative and semi-quantitative approximation for calculating hazard, vulnerability, and consequences.

One example of a risk model that involves the analysis of hazard, vulnerability, and consequences, explicitly is presented by Zhu & Frangopol (2013) for the risk analysis of bridges subjected to traffic and earthquake loads. With the calculated risk value, the authors establish optimal, essential, and preventive maintenance strategies for the studied bridge.

In this model, the authors propose an equation for risk as a result of multiplying the probability of occurrence of traffic and earthquake loads (hazard component), the probability of bridge failure in terms of its capacity (vulnerability component), and the estimated consequences in case of bridge's failure (consequences component).

For the seismic hazard, estimating the probability of occurrence of seismic events is done using earthquake probability mapping by USGS for probabilistic seismic hazard analysis in the United Stated (Zhu & Frangopol, 2013). With this information, they are comparing risk for numerous scenarios and then choose the worse earthquake occurrence probability applied to the bridge.

In the case of traffic load, the probability of traffic load occurrence was assumed to be 1.0 as it is expected that traffic is always present except when the bridge is closed.

Regarding vulnerability, the authors use some structural equations to determine if the bridge's capacity is exceeded for earthquake and traffic loads. The risk analysis model is finalized with a consequences evaluation by considering the costs of rebuilding, running, time-loss, removal, and safety, and a proposal for maintenance strategies.

At last, Zhu & Frangopol (2013) calculate the risk of the bridge, for the application case, analyzing the most critical conditions of hazard and vulnerability, and assessing some mitigation actions as a risk reduction strategy.

In the same way, Khelifa et al. (2013) presented a risk assessment, in which there is a direct relationship between the probability of failure of a bridge and the consequences of losing its main function, in face of a hazard.

The authors evaluated the scouring effect on a series of bridges in the United States. For the hazard, they analyze the precipitation intensity and the probability of overtopping and after determining a probability of failure, consider the capacity and resistance condition for each bridge.

The risk model presented by Khelifa et al. (2013) is based on the HYRISK methodology. This methodology has been used as a reference framework to calculate risk in several projects, and the main components are presented in Figure 1 with an adaptation of the process developed by the PEER - Pacific Earthquake Engineering Research Center (Ivey et al., 2010).

They analyze the increase of the effects of scouring produced by an increment in the intensity and frequency of rainfall (hazard), the number of bridge failures due to scour (vulnerability), and the economic losses (consequences) for the National Bridge Inventory of United State of America as application case.

In this approach, the authors also discuss the need for adequate policies for asset management to use this kind of information in agency investment decision-making in the future, lessening the negative effect of different hazards and climate change on the infrastructure.

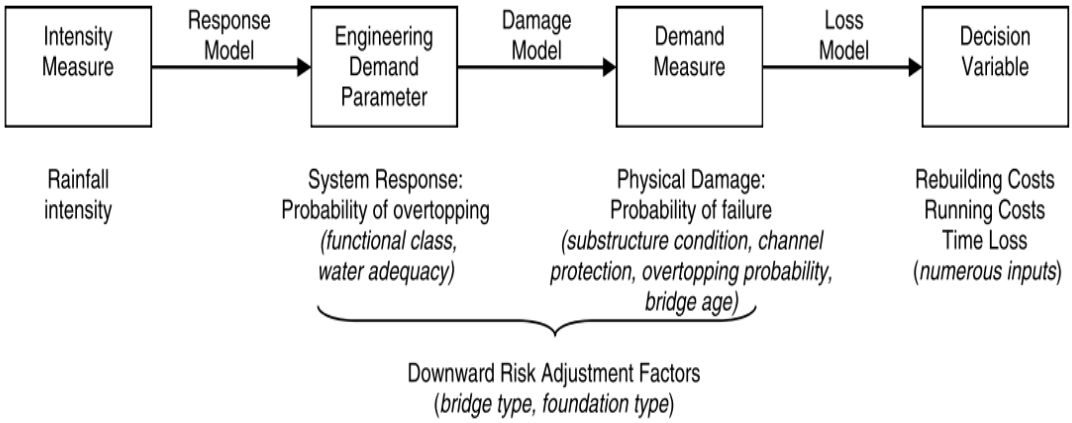

Figure 1 HYRISK model described using PEER risk framework (Khelifa et al., 2013)

Likewise, Carlos Lam et al.(2020) developed a flood risk model for the city of Citanova, Italy. This flood risk model was used aiming at mapping floods in the city to prevent damage and reduce risk and future losses.

The authors' proposal can be summarized in the diagram shown in Figure 2, with models to determine the probability of rainfall-runoff flood events. In addition to the identification of the threat with hazard maps for the urban center of Citanova, they monitored the vulnerability of the city with the evaluation of possible damages in each flooded area, considering parameters such as the number of inhabitants, environmental assets, and facilities, among others.

The model described by Carlos Lam et al. (2020) concludes with an evaluation of flood control alternatives to reduce the impact of floods on the population in the future.

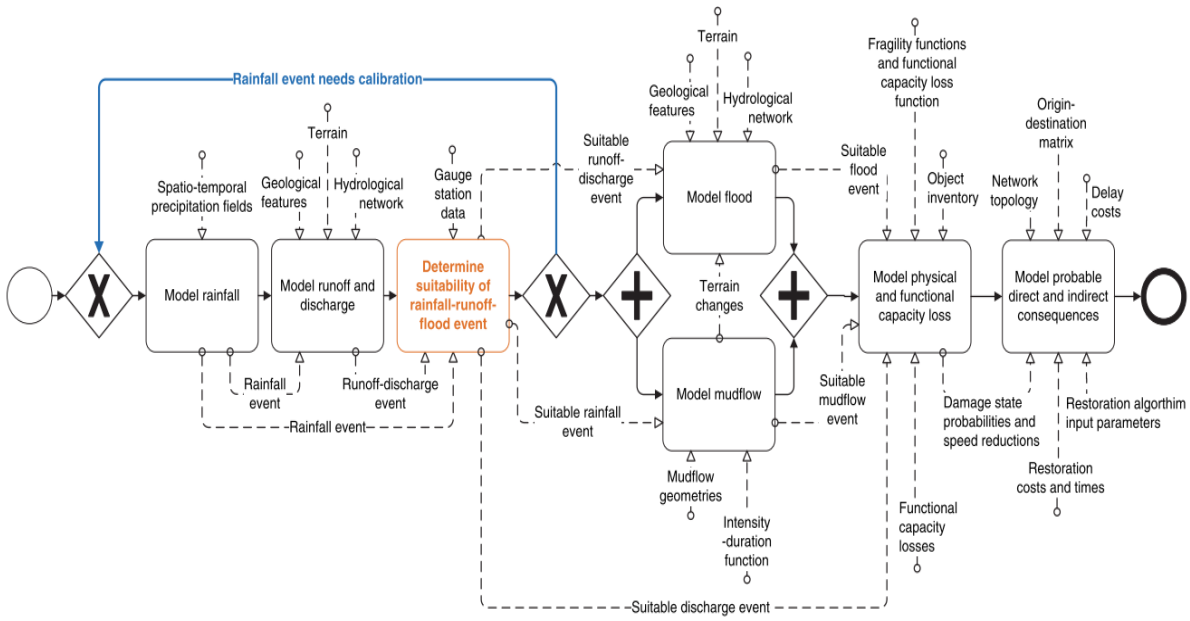

Figure 2 Process of simulation based modelling environment (Lam, Hackl, et al., 2020)

Even though there are several proposals to identify the risk and several case studies have already been applied, most of the authors, referenced in this document, agree on the challenges that exist when analyzing variables such as:

- The uncertainty in predicting the occurrence of each hazard that it's greater as climate change advances with the undeniable relationship between both.
- A large amount of information and mathematical models are needed to determine the vulnerability of assets and their real response to environmental threats.
- The estimation of consequences depends on some subjective parameters. Human losses, for example, are not easily quantifiable in economic terms, because there is not a global value for this parameter.

Finally, and although there are more questions than answers regarding the definition of a risk, it's clear that risk models allow the conception of control and resilience strategies to prioritize mitigation actions of the adverse effect produced by the different types of hazards. The main objective is to protect the population and optimize the use of economic resources.

2.2 Hazard

According to the United Nations International Strategy for Disaster Reduction (UNISDR), a *hazard is a natural process or phenomenon that may pose negative impacts on the economy, society, and ecology, including both, natural and human factors that are associated with the natural ones* (Shi, 2019).

Bibliographic references present classifications of the different hazards according to their origin. Some references associate the hazard with the intervention of human activities related to hazards like terrorism, accidents, explosions, criminal fire, among others. Those are not further developed herein, since the major concern of present work refers to natural hazards.

Around 1.875 trillion dollars cost of damage from weather and climate disasters in the U.S from 1980 to 2020 (NOAA, 2021), for each hazard that occurred in each year as shown in Figure 3.

These loss estimates reflect a direct effect of weather and climate events: physical damages to residential, commercial, and government/municipal buildings, material assets within a building, time element losses, vehicles, public and private infrastructure, and agricultural assets (buildings, machinery, livestock), and these losses assessment don't take in account losses to natural capital/assets and values associated with loss of life (Smith & Matthews, 2015)

The cost associated with disasters due to meteorological events in the United State increasing year-by-year as shown in Figure 3, and this isn't a good sign for the next years, in which the same trend of event's increasing, mainly due to climate change.

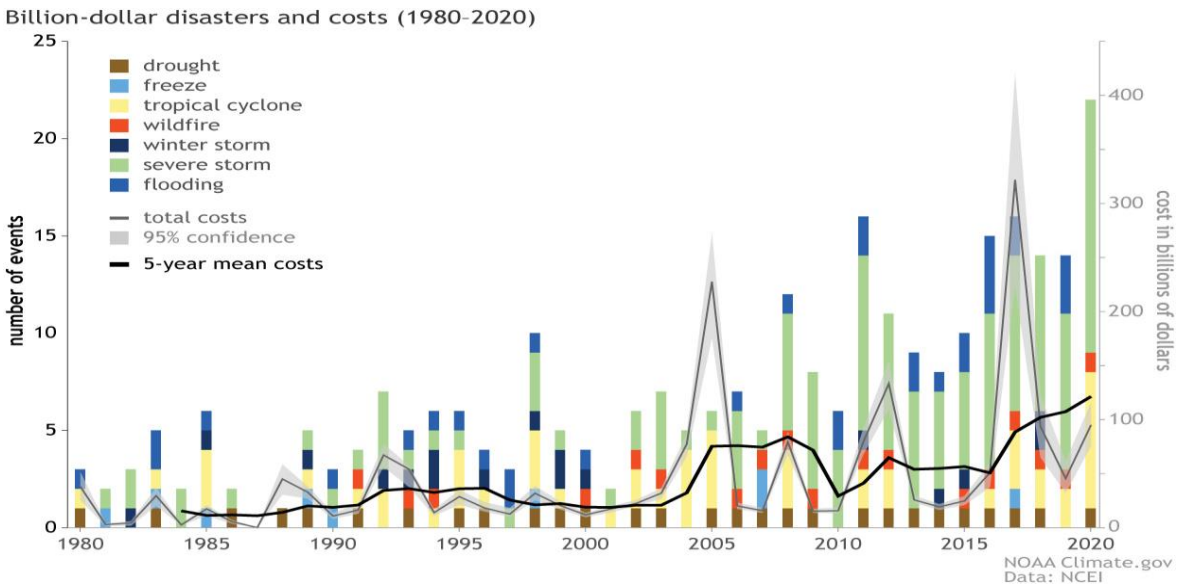

Figure 3 Billion-dollar disasters and costs (1980-2020) in the United States (NOAA, 2021)[1]

Certainly, knowing the lesson of each event in the past leads to a discussion about the need for risk and vulnerability assessment, and flexible response to disasters (Leavitt & Kiefer, 2006)

The following sections present some of the most important natural hazards and the corresponding effects on transportation infrastructures. Ultimately, we are concerned with effects more than with the hazard itself.

2.2.1 Earthquakes

This hazard is maybe one of the most studied around the world, due to its notable effects on lives and properties infrastructures on different populations located in high-risk areas, is considered as one of the most destructive natural hazards (Yön et al., 2017). The problem with this phenomenon is not in the movement of the ground itself but the damaging effect on the different construction and therefore on people who make use of them.

In the 20th century, earthquakes were the cause of more than 1.5 million deaths around the world (Spence et al., 2007), which motivated multiple investigations on this topic.

In addition, several other phenomena can be triggered by the earth's movements like tsunamis, soil liquefaction, structural damage, landslides as the most important. These events can maximize the devastation produced by earthquakes.

Although the relationship between multiple hazards is evident, the consideration of more than one hazard represents an important challenge due to the nature of the threats in terms of probability of occurrence, intensity, return periods, among others.

United Nations International Strategy of Disaster Risk Reduction (UNISDR) reveal according to the analysis of 281 events recorded by the Centre for Research on the Epidemiology of Disasters (CRED) in its EM-DA (International Disaster Database), earthquakes and tsunamis

[1] *Image taken from https://www.climate.gov/news-features/blogs/beyond-data/2020-us-billion-dollar-weather-and-climate-disasters-historical. 14.09.2021*

accounted for the majority of the 10.373 lives lost in disasters in 2018, while extreme weather events accounted for most of 61.7 million people affected by natural hazards around the world (UNISDR, 2019).

2.2.1.1. Soil liquefaction

Soil liquefaction is defined as the loss of soil stiffness and resistance due to a seismic movement that affects soils with a certain structure and composition. This effect can cause irreparable damage to the superstructures that are built on them just as suggested by Huang & Yu (2013) who reviewed soil liquefaction characteristics during major earthquakes of the twenty-first century.

The main locations of these earthquakes are India, Peru, China, Pakistan, Greece, Italy, USA, Chile, New Zealand, and Japan.

Furthermore, a large number of impacts that soil liquefaction on buildings and infrastructure have been reported by different researches, like Cubrinovski et al. (2012) with an estimation for economic losses in Christchurch, New Zealand by the earthquakes between 2010-2011, around 25 and 30 billion NZ dollars (or 15% to 18% of New Zealand's GDP) and Verdugo & González (2015) who describe damage during the 2010 Chile earthquake by liquefaction-induced ground, especially in the transport infrastructure (Figure 4).

Figure 4 Post-liquefaction settlements by 2010 Chile Earthquake. (a) Costanera route in Concepción and (b) near Concepción City (Verdugo & González, 2015)

Based on the results of much research on this topic, liquefied soil could be considered a hazard with potential damage to buildings and infrastructure. Therefore, research on liquefaction risk continues with the development of risk models that allow the identification of strategies to mitigate the impacts of this phenomenon.

2.2.1.2. Structural damages

In urban centers where the construction of buildings and infrastructure is carried out at a level of development proportional to the population and its needs, many codes, standards, and new technologies have been implemented. These contributions are related to the use of new materials and methods to design structures with better structural performance in the face of earthquakes. The seismic behavior of a structure is evaluated in terms of resistance, with the main objective of guaranteeing users' lives protection.

Over many years, highly relevant knowledge has been developed around this topic, and some authors highlight the continuous engineering challenge to improve the performance of buildings and bridges in the case of infrastructure, which are the main source of measurable damage, in case of failures (Housner & Thiel, 1995; Zelaschi et al., 2015).

The development of knowledge in the prediction of earthquakes and the effect on buildings and infrastructure leads to methods to mitigate the risk and reduce the unfavorable consequences of this phenomenon in the populations, especially in areas with high seismic risk (NIST, 2020).

2.2.1.3. Tsunami

A generalized definition of a tsunami describes it as a phenomenon that occurs in the sea, with the presence of large waves that are generated by seismic movements or volcanic activity underwater (Gill & Malamud, 2014; Vail, 1987).

These high-altitude waves affect populations in coastal areas, registering a large amount of loss of human life after each recorded event. For example, the Sumatra-Andaman earthquake of 26 December 2004, which generated probably the most lethal tsunami in the history of mankind, resulted in more than 225.000 deaths (Okal, 2015).

Figure 5 presents a global and regional hazard map to tsunami sources produced with the collaboration of ITIC and NOAA's National Centre for Environmental Information (NCEI), formerly NGDC, and ICSU World Data Service for Geophysics.

The information that appears in this Figure 5 directly relates to the areas where more seismic movements occur due to the convergence of tectonic plates, making the Pacific Ocean the main source of the largest generation of these waves with great destructive potential.

Although, a lower percentage of incidence in the coastal areas of the Mediterranean, Caribbean, Atlantic, and Indian oceans, can be found. In addition, other ways to generate tsunamis such as volcanic eruption, landslide, earthquake generated by a landslide, among others are summarized in Figure 6.

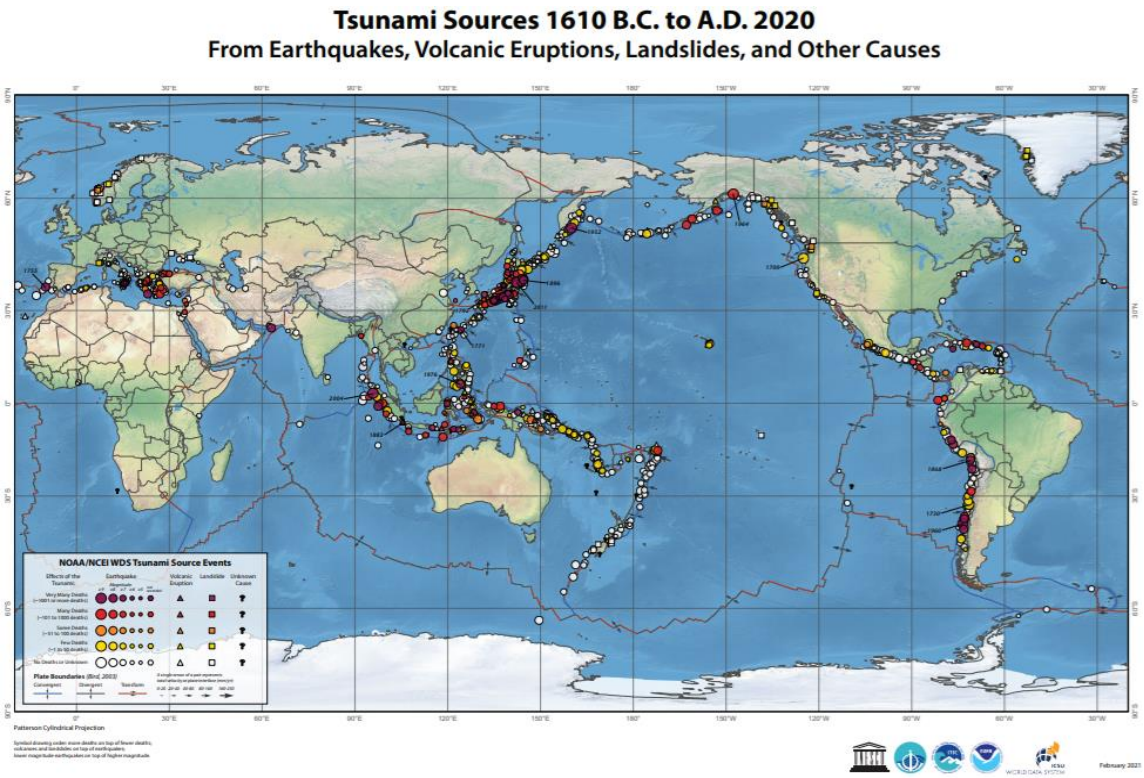

Figure 5 Tsunami Sources 1610 B.C. to A.D. 2020[2]

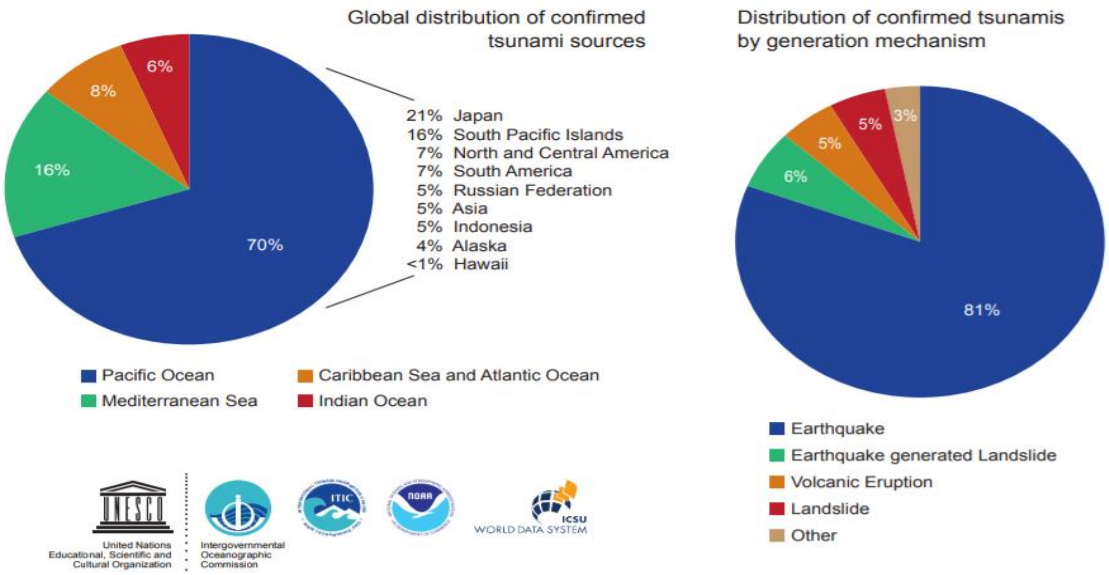

Figure 6 Global distribution of confirmed tsunami sources and generation mechanism[3]

[2] *Imagen copied from http://itic.ioc-unesco.org/images/stories/awareness_and_education/map_posters/2020_tsu_poster_20210304_a2.pdf 31.08.2021*
[3] *Ibid*

Previous data on the consequences of the earthquakes in 2018 suggest an exhaustive review of the effects of these movements on the different populations, it should be mentioned that the countries in which these effects were registered correspond essentially to those located in areas of convergence of tectonic plates. Figure 7 shows zones with strong earthquakes hazard in the south of Europe and the zone that separates the Euro-Asian plate from the African tectonic plate (Spence et al., 2007). This is the reason that this hazard isn't included in this project because there are other threats with more negative effects in the Atlantic Area. However, for the European Union earthquakes represent an important problem that requires special attention, working in policies for earthquake protection and strategies to reduce earthquake risk (Spence et al., 2007).

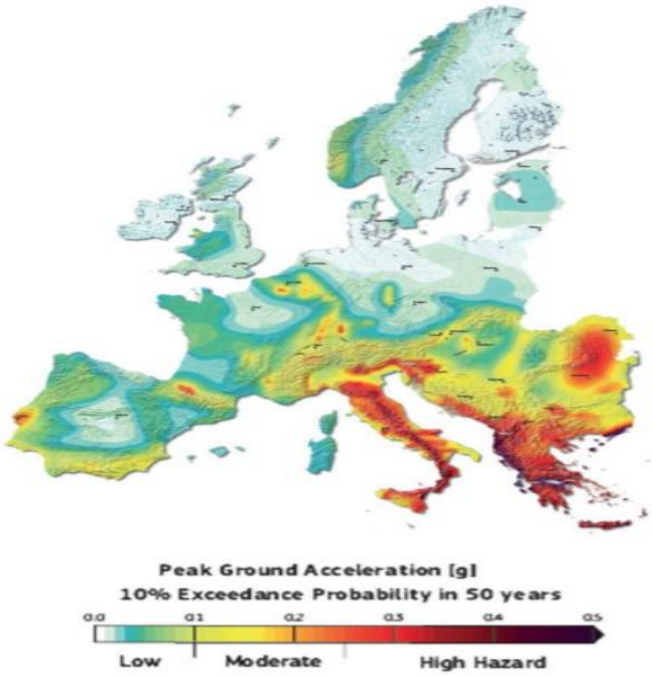

Figure 7 European Seismic Hazard Map showing the 10% exceedance probability in 50 years for Peak Ground Acceleration (Spence et al., 2007)[4]

2.2.2 Floods

According to the International Disaster Database (EM-DATA, 2021), floods correspond to a general term for the overflow of water from a stream channel onto normally dry land in the floodplain (riverine flooding), higher-than-normal levels along the coast and in lakes or reservoirs (coastal flooding) as well as ponding of water at or near the point where the rain fell (flash floods).

This increase in water levels can substantially affect areas with high population density, where there is also a greater susceptibility to flooding damage due to runoff caused by the growth

[4] *There is an special report for Earthquakes in Europe and EU response over 2000-2020 in https://erccportal.jrc.ec.europa.eu/ercmaps/ECDM_20201113_EQ_Europe_EUCPM.pdf in order to contrast the consequences of earthquakes in Europe.*

of impermeability layers, as the central axis of research for decades (Kim et al., 2019; Scionti et al., 2018).

Although a generalized view within the research suggests that climate change could increase the losses recorded by floods (Alfieri et al., 2016; Hajdin et al., 2018; Kim et al., 2019; Thornes et al., 2012). Some other authors highlight the relationship between economic and social factors such as those mainly responsible for flood disasters (Alfieri et al., 2016; Barredo, 2009).

The European Environment Agency (EEA, 2021) registered, between 1980 and 2019, climate-related extremes cause economic losses totaling an estimated EUR 446 billion in the EEA member countries. Figure 8 presents the economic damage caused by weather and climate-related extreme events in Europe between 1980 and 2019, divide into climatological, hydrological, and meteorological events.

Figure 8 shows the evaluation of economic losses estimated in millions of euros, with special attention in 1999, 2002 (the hydrological event was the major due floods along the Danube and Elbe rivers in summer) and 2013, as the years with the greatest economic losses in Europe (EEA, 2021) and with a probability of registering events with more frequency (Allen et al., 2014)[5].

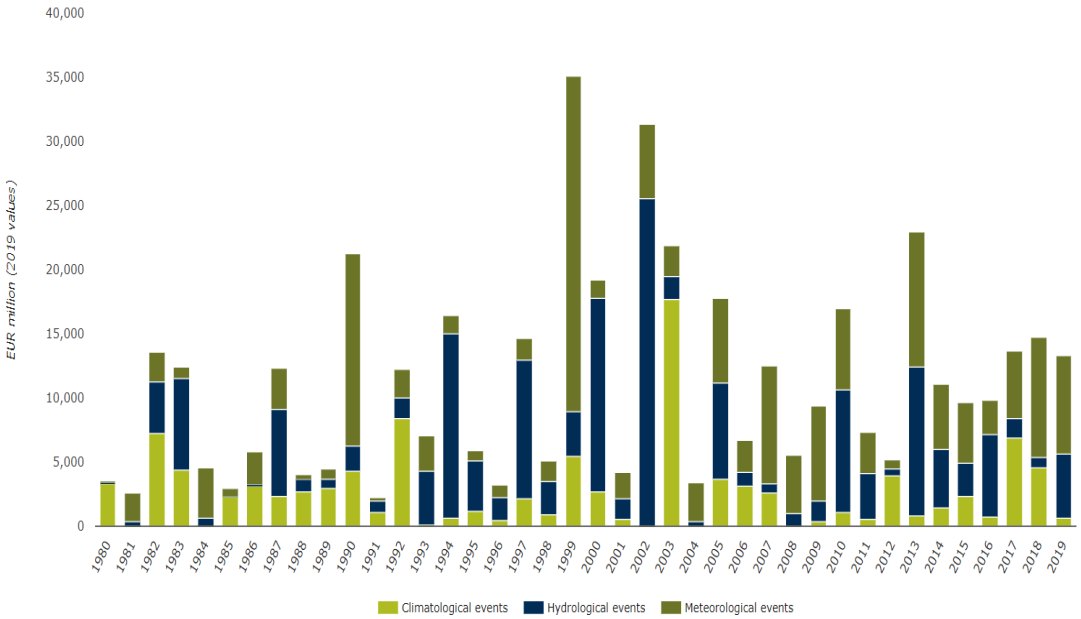

Figure 8 Economic damage caused by weather and climate-related extreme events in Europe (1980-2019)[6]

Several studies on flood risk analysis make it possible to identify flood prevention measures that mitigate the negative consequences on the affected populations (Kim et al., 2019) and propose an innovative solution to restore the natural water cycle with low-cost alternatives (Scionti et al., 2018).

[5] *The intergovernmental Panel on Climate Change https://www.ipcc.ch/. Reports. 01.09.2021*
[6] *Imagen copied from https://www.eea.europa.eu/data-and-maps/indicators/direct-losses-from-weather-disasters-4/assessment. 01.09.2021*

One example of the effect of river flood occurred in England between May and July 2007, with an estimate of total damage in £ 3.2 billion for direct damage and destruction by floodwater, disruption of traffic, cessation of services, among others (Groenemeijer et al., 2015).

2.2.3 Wildfire

From the several hazards described above, two of those that are expected to affect most of the Atlantic Region's transportation infrastructures are floods and wildfires. This aspect is highlighted by the European Environment Agency (see Figure 9). In the remaining of the present document, only those will be considered in the risk-based model.

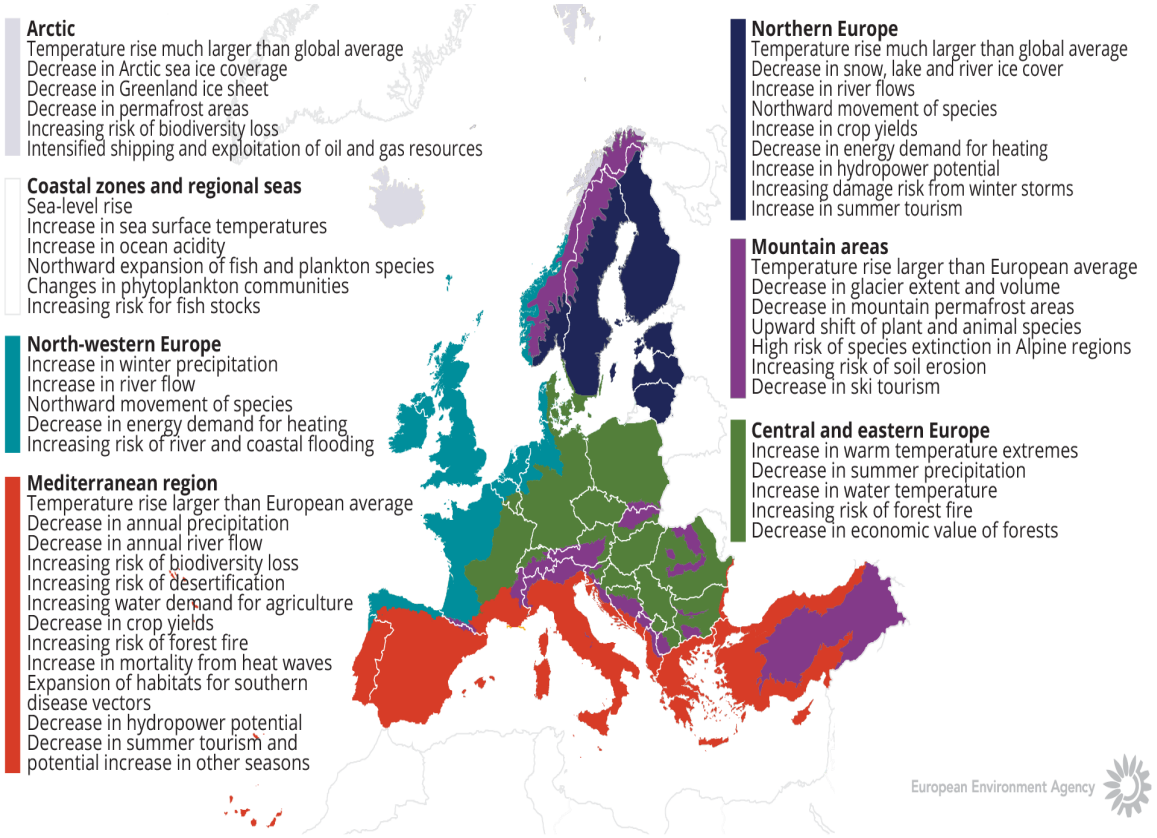

Figure 9 Climate change impacts in Europe[7]

Although Figure 9 show the projection of climate change in Europe, with a temperature rise and increasing risk of forest fire in Europe, Figure 10 present the burnt area of the Mediterranean region has decreased slightly since 1980 (except for Portugal).

[7] *Image copied from https://www.eea.europa.eu/soer/2015/europe/climate-change-impacts-and-adaptation/climate-change-impacts-in-europe/view 09.11.2020.*

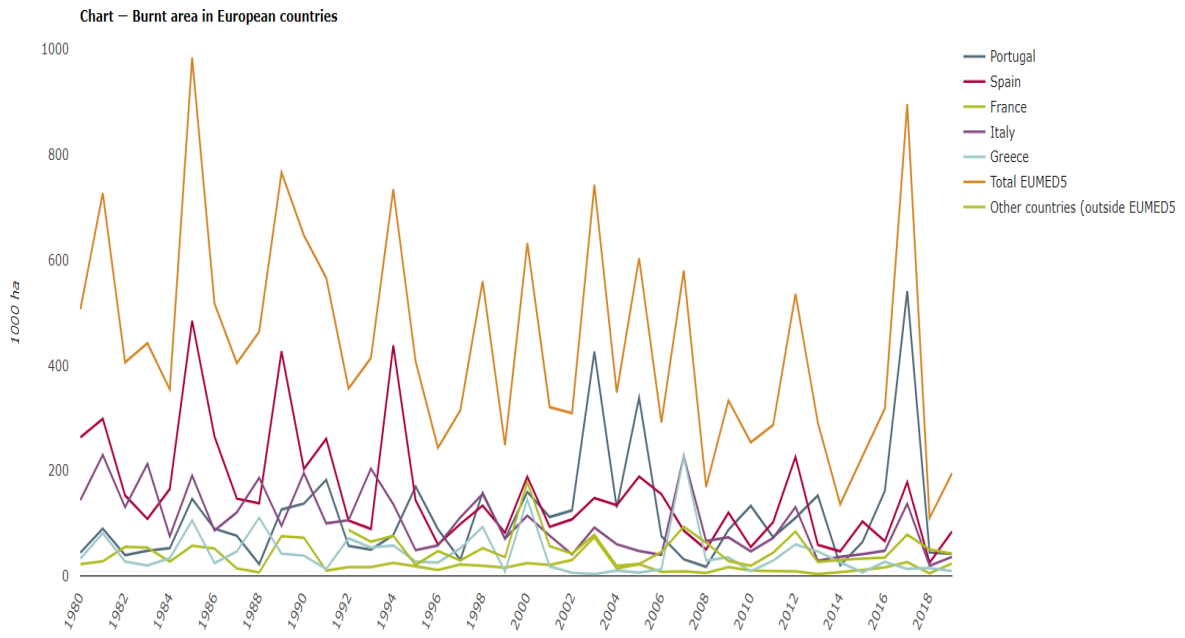

Figure 10 Burnt area in European countries (1980-2018)[8]

Several factors can affect fire propagation including temperature, soil moisture, and the presence of trees, shrubs, and other potential fuels[9]. Some changes in the use of land and climate increased fire risk and dangers (Moreira et al., 2011). These factors can be categorized into three groups: (1) forest fuels; (2) topography; and (3) meteorological conditions (Valentin & Stormont, 2019).

One of the most important wildfire events in modern times occurred in Sweden between 11 July 2014 and 11 September 2014, where around 1200 people were evacuated from their homes, 25 buildings were burned, one person died, several roads and railways were blocked, and other important economic consequences in the forest sector were registered (Groenemeijer et al., 2015).

2.3 Vulnerability

Vulnerability analyses are included in risk studies and there are many alternatives to understand it. Some authors define it according to the level of accessibility and function of the system (Berdica, 2002) and others highlight physical aspects of the system relating vulnerability according to the level of exposure and sensitivity to a specific event (JASPER, 2017).

Exist a relationship between the reliability and vulnerability concept, and some discussion about the little line that differentiates them has been addressed for some authors (Husdal, 2004), (World Bank, 2016). The differences and similarities between both allow proper use of

[8] *Imagen taken from: https://www.eea.europa.eu/data-and-maps/indicators/forest-fire-danger-4/assessment. 14.09.2021*
[9] *Taken textually from: https://www.c2es.org/content/wildfires-and-climate-change/. 14.09.2021*

different existing risk assessment methodologies or quality control plans as referenced in the Technical Report WG3- TU1406 Cost Action (Hajdin et al., 2018).

Although there are countless definitions of vulnerability, there isn't a universal definition of that concept or a single way to evaluate it in the risk analysis. Throughout this work, vulnerability is defined in terms of an asset's exposure and resistance in the face of a specific hazard.

In this way, it is expected to isolate the aspects specifically related to vulnerability than those related to either hazard or consequences since those would be considered twice when applying the risk formula defined in equation (1).

2.4 Consequence

The impact of a hazard is the result of damage and can be quantified in terms of monetary costs, lost lives, or any other way of identifying a loss. Many authors relate the consequences after a natural disaster as a monetary cost in most cases, and this cost is divided into direct and indirect costs as presented by Lam, Hackl, et al. (2020).

The direct cost could be evaluated as the sum of the direct cost of each intervention and restoration of damage to a specific asset produced by the hazard. This cost is mainly absorbed by asset or network managers (Lam, Heitzler, et al., 2020).

On the other hand, the indirect cost could include aspects such as the cost of time lost due to the closure or loss of an asset such as an extension of travel time (Hackl et al., 2018) and vehicle running cost (Khelifa et al., 2013), and finally, the costs absorbed by network users due to deficient deteriorated levels of services (Lam, Heitzler, et al., 2020) including the number of accidents caused (Hackl et al., 2018).

The projection of some climate change scenarios that include analysis of economic implications shows, for example, that it is less expensive to improve the bridge before than after the effect of climate change. In this way, it's important to consider adaptation or mitigation policies to the transportation sector, in sensitive areas to the effects of climate change (Neumann et al., 2015).

Working on the real knowledge of the consequences due to a natural hazard and the different ways of calculating them, is perhaps the fundamental pillar in the decision of network managers in infrastructure risk management. Estimating direct and indirect costs is important to support the decisions about alternative interventions to execute in the infrastructure network (Lam, Heitzler, et al., 2020).

2.4.1 Impacts of flooding on transportation infrastructure

Flood represents one of the higher threats for the transportation infrastructure due to the impact in the different elements such as bridges and roadways, among other assets. The knowledge of previous flood events and the recognition of the effect on the population allows preparing communities to better respond to this natural threat.

Some effects of the floods have been described in the literature, but the more common impacts can be summarized as the following:

- ✓ Bridges:
    - Debris flows that affect the embankments
    - Instability of the piers
- ✓ Roadway pavements:
    - Lost of subgrade layer
    - Erosion
- ✓ Railway track:
    - Closure and traffic effects
- ✓ Slopes:
    - Landslides
    - Erosion of embankments

2.4.2 Impacts of wildfire on transportation infrastructure

There is a direct relationship between forest fires and floods because forest fires can change the characteristics of watersheds, affecting bridges and drainage (Fraser et al., 2020; Valentin & Stormont, 2019).

The more common impacts of wildfires on transportation infrastructure can be summarized as the following:

- ✓ Roadway/railway closures due to fires threat or reduced visibility due to the smoke
- ✓ Create water-repellant soils resulting in increased surface runoff
- ✓ Lost in public and private property
- ✓ Bridges:
    - Structural damages, depending on the combustible material in which the bridge or any component thereof is built.
- ✓ Roadway pavements:
    - Degradation of the superficial surface: cracking of pavements due to high temperatures
    - Post-fire debris movements
- ✓ Railway track:
    - Railway lines damaged
- ✓ Slopes:
    - Increase susceptibility to mudslides due to the inexistence of vegetation to stabilize the soil

Thus, there are other events associated with wildfires such as debris flows, landslides, and erosions, being important to a multi-hazard analysis in the future process of decision making to reduce the risk.

3. Risk Models

Some risk models are presented in existing guidelines or research projects' reports, and they have been applied for many authors in some case studies like those presented previously. The relevant information about each reference risk model analyzed, methodologies for quality control, and other reference documents for this work are summarized in Table 5.

The information in Table 5 allows us to reflect on the different components of a risk model, and the way to propose a holistic way to evaluate it.

Table 5: Comparison between existing risk models/guidance/ methodologies

Guide/Methodology/ Document		Main Focus	Summary
JASPER	**Joint Assistance in Supporting Projects in European Regions.** Compilation of the Climate Change. Related Requirements for major projects in the 2014-2020 Programming Period. (JASPER, 2017)	Climate change adaptation	This guide addresses the climate change adaptation vulnerability and risk assessment considers adaptation measures to reduce the risk. The risk is evaluated in terms of severity and probability, where the severity represents the consequences or impact of the hazard. This guide presents four steps to evaluate the risk and the adaptation measures divided into three categories: -Structural measures -Non-structural measures -Risk management
TU1406	**WG3 Technical Report** Establishment of a quality control plan. (Hajdin et al., 2018)	Quality control plan	This technical report presents a methodology to evaluate the infrastructure (specifically bridges) according to key performance indicators (KPI). In this case, they use the reliability concept and define it in terms of the probability of structural and operational failure. The reliability is assessed with the exposure and resistance estimating the case with the worst reliability class. Although there is some difference between the concepts of vulnerability and reliability, the purpose of this technical report is to evaluate the

			reliability that will be taken as a reference in the vulnerability assessment that has been defined in this work.
FHWA (AASHTO)	**Federal Highway Administration** Incorporating risk management into transportation asset management plan. (FHWA, 2017)	Management Plan	This document refers a Risk-Based Transportation Asset Management Plans (TAMPs) - USA. The TAMP is one of a series of plans the State Department of Transportation is required to develop to achieve the Nation's transportation goals. The definition of risk is related to the likelihood and consequences and, they are singled out for accurate and sophisticated data collection, tracked with targets and measures, and supported with predictive modeling and risk analysis. FHWA defines transportation performance management as a "strategic approach that uses system information to make investment and policy decisions to achieve national performance goals."
THIRA	**Threat and Hazard Identification and Risk Assessment** (THIRA) and Stakeholder Preparedness Review (SPR) Guide. (Homeland Security, 2018)	Prepare the communities for the threats and hazards	The National Preparedness goal is: "*A secure and resilient Nation with the capabilities required across the whole community to prevent, protect against, mitigate, respond to, and recover from the threats and hazards that pose the greatest risk".* To achieve this goal, this document contains proposed strategies for prevention, protection, mitigation, response, and recovery. And three steps to face it: - Identify threat and hazard - Give threats and hazard context - Establish capability targets In this document, the possible impacts of a threat or a hazard are defined by the population, as capability targets according to their response capacity.

HYRISK	**Guidelines for Risk-based management of Bridges with unknown foundations. Appendix A** (Stein & Sedmera, 2007)	Asset´s prioritization strategy	The HYRISK methodology relates the probability of scour failure with the consequences associated with this failure on bridges. Originally, this methodology was used to prioritize bridges with unknown foundations.

Risk analysis must include a multi-hazard analysis due to the probability of two or more phenomena occurring at the same time, or cascade effect. For example, it is common for landslides to appear when a flood occurs or during an earthquake event. In this context, some algorithms to calculate the risk include this phenomenon in modeling functional capacity losses as presented by Lam, Heitzler, et al. (2020).

4. Risk Mitigation Measures

Risk mitigation measures are a set of activities that, if properly applied, can reduce the risk associated with a certain event. Following the risk basic expression presented in equation (1), it is expected that a specific measure will reduce risk if it can reduce any of the three components of the risk equation. Hence, in the following paragraphs, some risk mitigation measures are presented. Those are split by hazard type. Then, for each hazard type, different risk mitigation measures are listed per the risk equation component.

Researches about mitigation measures to reduce the risk show that to reduce the consequences of a hazard adaptation measures are the best option rather than trying to avoid its occurrence (Alfieri et al., 2016).

4.1 Flood hazard

The most commonly adopted mitigation measures regarding flood act upon the hazard component. In fact, for several millennium's humans have tried to control and modify flood's impact by controlling water movement.

Acting on the hazard, it is expected to change floodwater volume, maximum level, the velocity of occurrence, and total duration time[10]. This will also affect the extent of the flooded area and the speed and depth of the flood. These changes influence the volumes of debris, sediments, and pollutants carried by water during floods, which in turn may impact the actual consequences of a flooding event.

4.1.1 Hazard component

The characteristics of the flood hazard (its elevation, proximity to the river or coast, and susceptibility to fast-moving flows and surges, among others) can determine the necessary mitigation measures adopted.

- ✓ Construction of dam(s) and/or reservoirs to reduce flow speed
- ✓ Construction of dikes and flood containment structures
- ✓ Modification of riverbeds (water channel dimensions)
- ✓ Deviation of flood peak flows (water retention, tunnels, or other bypass strategies)
- ✓ Installation of flow dischargers

4.1.2 Vulnerability component

Regarding the vulnerability component of the risk equation, three types of mitigation measures can be considered. Firstly, there are preventive mitigation measures, which consist in avoiding or even prohibiting a dangerous use of land in areas susceptible to flood occurrence. This is more or less common sense nowadays but was not in the past. Hence, the second type of vulnerability mitigation measure includes reallocation of constructions and people to regions out of the flood-critical areas. In some cases, closure and dismantlement of constructions might also be considered.

[10] *Taken from https://www.nap.edu/read/18309/chapter/8. 15.11.2021*

The third type of vulnerability mitigation measures encompasses those interventions that can be done over specific assets to enhance their resistance and preparedness to flood events. As such, these sets of measures are asset dependent.

- ✓ Flood management plans with land-use restrictions
- ✓ Reallocation of existing construction in the dangerous zone
- ✓ Improvement of the river channel
- ✓ Bridges:
  - Optimal configuration of the fairing to improve hydrodynamic performance
  - For the Bridge abutments: embankment for slope erosion
  - Temporary Concrete Traffic Barrier
- ✓ Roadway pavements:
  - Bio-stabilization and chemical stabilization of subgrade/base
  - Geosynthetics (roadway foundation)
  - Permeable Pavements
  - More frequent paved roads to minimize erosion impacts
- ✓ Railway track:
  - Upgrade drainage culverts
- ✓ Slopes:
  - Drainage Systems
  - Surface protection

4.1.3 Consequence's component

Despite all the previous mitigation measures, it is known that floods continue to be one hazard that causes more losses to people and goods worldwide. To address this aspect, mitigation measures that consider the consequences components are quite important.

- ✓ Dissemination of adequate information and education to prepare populations for floods occurrence
- ✓ Governmental support in the post-flood period with credit lines, taxes, and fees adjustments to reduce economic impact over time
- ✓ Subscription of insurance plans and preparation of emergency plans
- ✓ Warning systems and evacuation plans to remove people within hazard impact time frame

4.2 Wildfire hazard

When it comes to wildfires, unlike floods, there is also a component that relates to human intervention. In other words, wildfires are not only produced by natural factors such as temperature increases but can also be the result of bad practices by populations near vulnerable places.

In this approach, the greatest number of fire mitigation measures have been adopted as emergency plans where the education and preparation of the population to face these events becomes the main objective. Acting on the hazard, it is expected to minimize potential fuels especially in areas close to the population.

4.2.1 Hazard component

The characteristics of the wildfire hazard (its burnt area, soil moisture, ignition density, among others) can determine the necessary mitigation measures adopted. Some of such measures include:

- ✓ Land-use planning
- ✓ Fuel management
- ✓ Burning and landscape fire management planning
- ✓ Forest monitoring and mapping

4.2.2 Vulnerability component

Regarding the vulnerability component, mitigation measures can be of two forms. First, and similar to flood hazards, land use in areas susceptible to wildfires could be the best strategy to reduce risk. However, as highlighted above, this is quite common sense today, but it was not in the past. And relocating existing communities and buildings near hazardous areas takes a lot of effort.

The second form refers to educating and preparing communities because a major of wildfire have a human origin.

- ✓ Land-use planning
- ✓ Vegetation management
- ✓ Reallocation of existing construction in the dangerous zone

4.2.3 Consequence's component

Unlike other threats, fires can be controlled in most cases, especially those that are the product of bad practices by humans. For that reason, education programs and evacuation plans aim to reduce the impact on the population and allow them to participate in the implementation of strategies for fire reduction and control (Fraser et al., 2020).

- ✓ Education to prepare populations for wildfires occurrence
- ✓ Emergency preparedness plans
- ✓ Evacuation plans
- ✓ Warning systems
- ✓ Fire danger prediction programs

5. Decision-making tool development

5.1 Implementation details

The programming language selected for the implementation of the tool developed within the scope of the SIRMA project was the Java language. This is an object-oriented programming language, interpreted by a virtual machine (Java Virtual Machine - JVM), whose portability allows the development of tools to be independent of the platform where they are executed. Additionally, this language has an extensive open source library of routines that facilitate cooperation.

For managing information,, the MySQL database system was used. MySQL is an open source relational database management system (RDBMS) that uses the SQL language as an interface and organizes data into one or more tables in which the data can be related to each other, helping to structure it. MySQL is free and open source software that has stand-alone clients that allow users to directly interact with a MySQL database using SQL.

5.2 User manual

The use of the tool consists, in a first phase, of introducing information about the network to be analysed, simply by entering its name and a description.

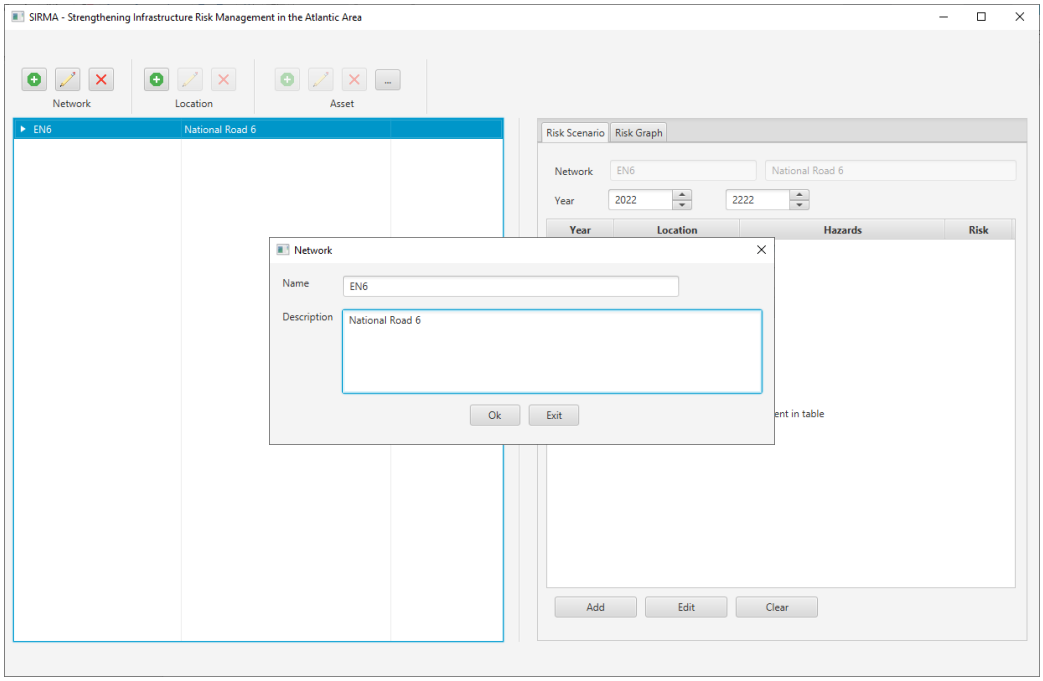

Figure 11 Network

After its creation, it will be possible to associate all the locations that constitute it. For this purpose, it will be necessary, in addition to a name, description and coordinates, to indicate which weather events affect each location and the probability of occurrence of these events (unlikely; remote; occasional; likely; frequent).

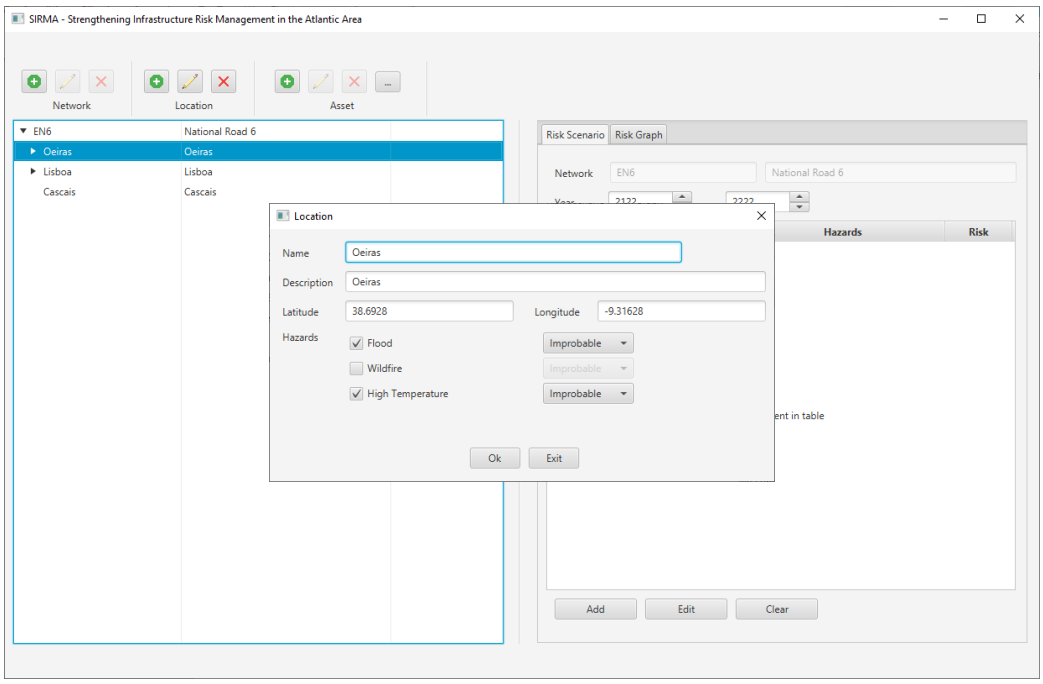

Figure 12 Location

Finally, and to complete the creation of the network, the assets that constitute them must be associated with each location. For the creation of each asset, it will be necessary to indicate a name, a description, the type of asset (bridge, road, railway or slope), its construction date, its condition status (CS1 - No or very slight damage; CS2 - Slight damage; CS3 - Moderate to severe damage; CS4 - Severe damage; CS5 - Extreme damage) and the date on which this status was determined.

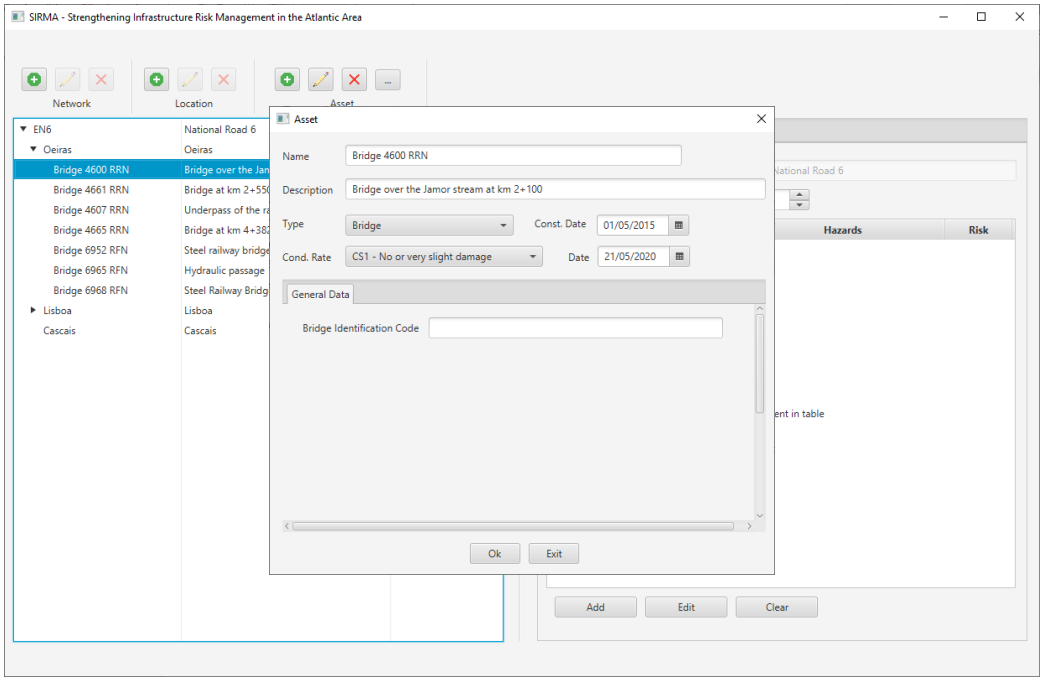

Figure 13 Asset

After creating the entire network, it will be possible to create risk scenarios over time. For this purpose, the analysis period should be indicated in the left part of the tool, and for each year under analysis, the scenario of occurrence of the events that affect each location of the network should be added.

In order to create a risk scenario in a given year, it will be necessary to indicate, for each event, whether that event should be considered in the analysis and, if so, the indirect consequence (negligible; minor; moderate; major; severe) for the location in question, as well as , for each asset that constitutes it, the foreseeable state of condition in which the asset will be, its vulnerability to the event (very low; low; moderate; high; very high) and what the consequence will be (negligible; minor; moderate; major; severe) that will result from the occurrence of that same event.

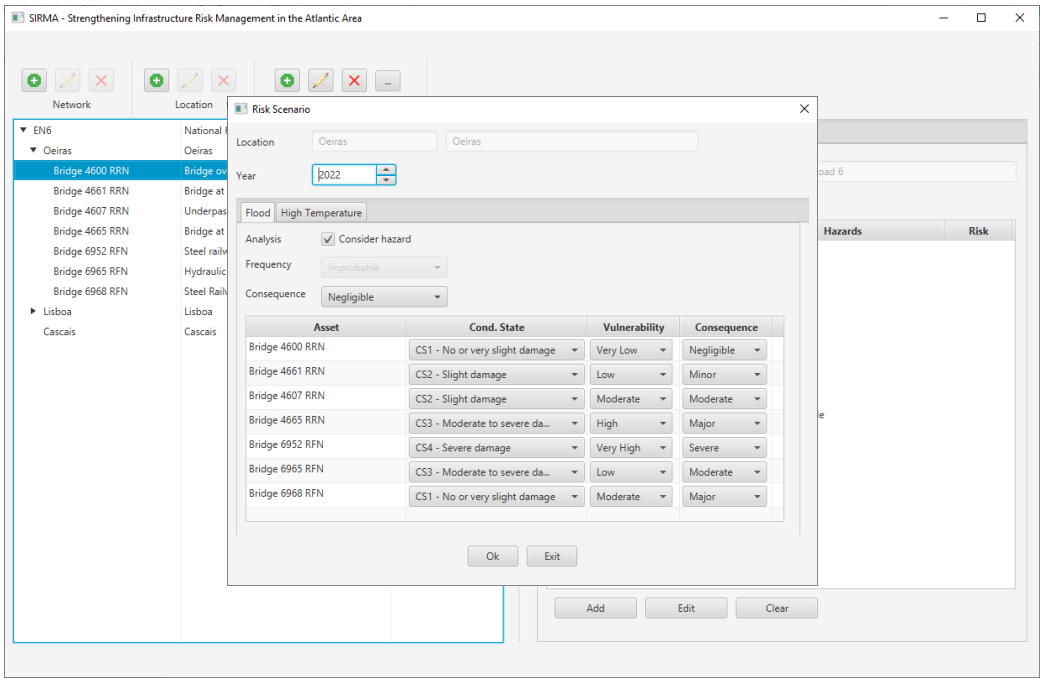

Figure 14 Risk scenario item

After introducing this information, by event and by asset, the tool will determine which risk the network will be subject to.

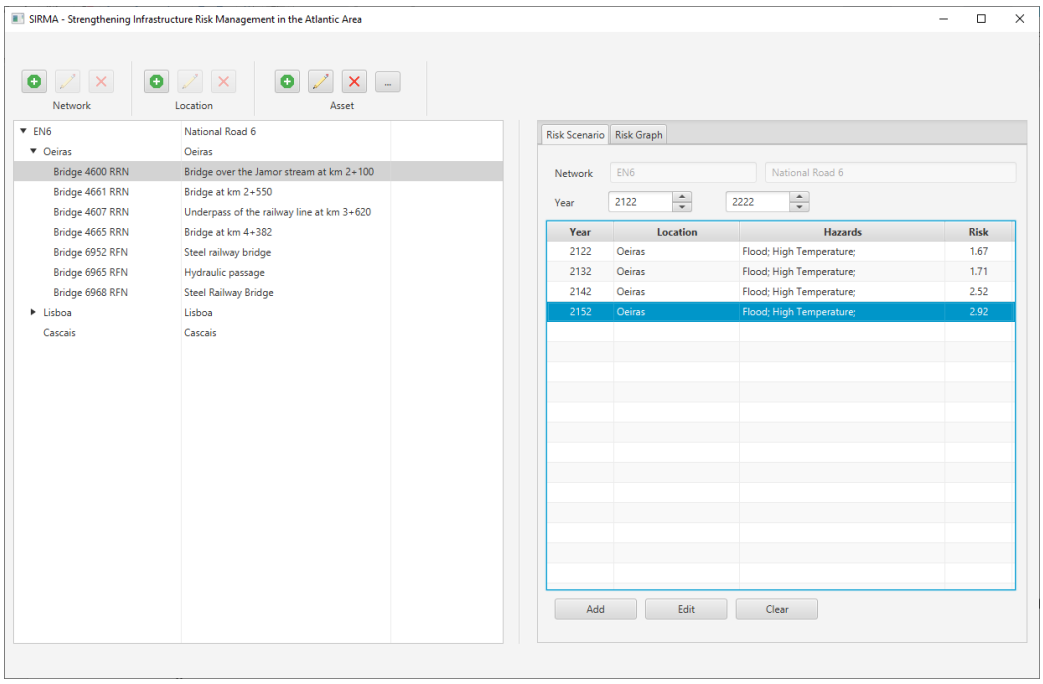

Figure 15 Risk scenario

By introducing different scenarios over the indicated period of time, it will be possible to visualize the evolution of risk over the time under analysis.

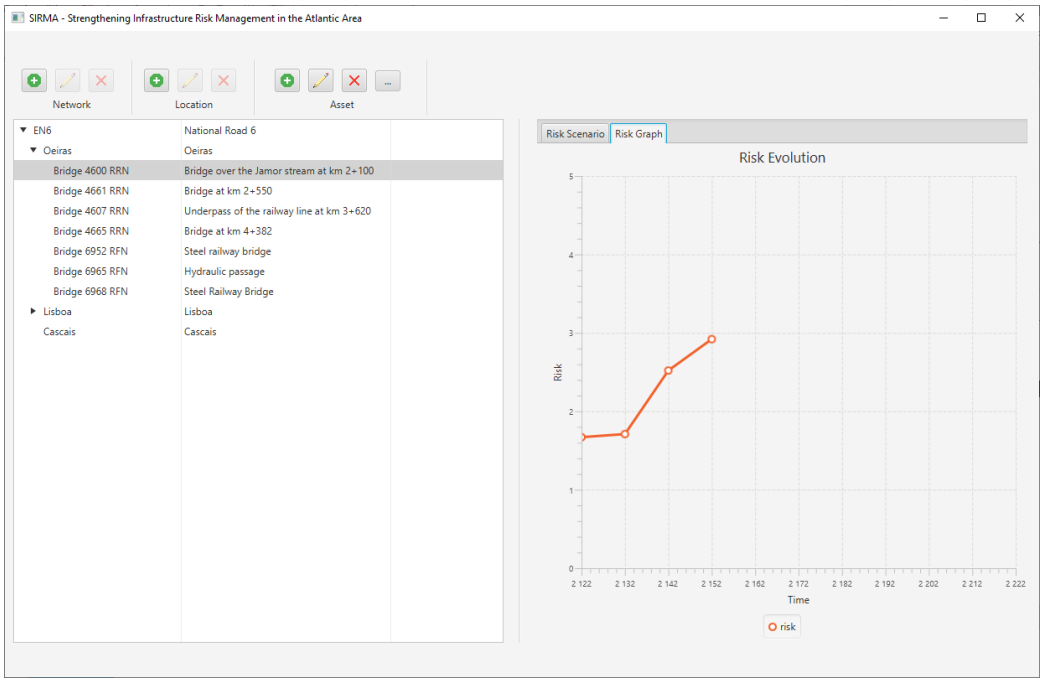

Figure 16 Risk evolution

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