RAIN – Risk Analysis of Infrastructure Networks in Response to Extreme Weather

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Technical Impact Matrices

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Executive Summary

The RAIN project aims to provide an operational analysis framework which minimises the impact of extreme weather events on critical components of EU infrastructure. Work Package 7 of the project considers mitigation strategies with a focus on measures that can be adopted to improve the resilience of the existing infrastructure network. These measures include physical adaptations and changes to management strategies. This deliverable follows directly from D7.1 which focused on the identification of engineering solutions which increase the level of redundancy and prevent cascading effects. The aim of this deliverable is to outline the Technical Impact Matrix (TIM) approach developed as a method for assessing the advantages and disadvantages of various maintenance strategies for reducing the impact of extreme events on infrastructure systems

The report is divided into seven sections, each briefly describing the specific impacts of severe weather hazards on elements of critical infrastructure. A complete TIM is developed for each asset. The assets examined include; Bridges for road and rail networks, Road Pavements, Cutting and embankment slopes (both natural and manmade), Rail Tracks (including Switches and Crossings), Tunnels, Electrical and Telecommunications Networks (energy lines, cables, pylons) and Dams which form parts of the Energy Infrastructure network and energy networks.

The appropriate remediation/mitigation strategies for each of the critical infrastructure assets were identified and discussed in detail as part of Deliverable 7.1. The TIM method outlined in this report allows asset managers to assess the impact of different maintenance strategies for reducing the impact of extreme weather events on infrastructure systems. This will facilitate decisions on how to invest limited funding to increase the safety and reliability of the network while considering such factors as; the available budget, political focus, technical, societal and environmental factors. The results of the TIM are used in the form of expert judgement to adjust probabilities of failure (to account for mitigation measures) in Work Package 5 of the RAIN project.

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1 Introduction

1.1 Background

The elements of infrastructure considered in this report include; bridges, pavements, slopes, rail tracks, tunnels, energy lines, pylons and dams. Incidents of failure of these elements of infrastructure has increased in recent years due to more frequent and extreme weather events, largely due to the effects of climate change. The hazards considered in this report are in keeping with those identified in WP2 of the RAIN project, e.g. heavy rainfall, windstorms, coastal floods, river floods, lightning, tornadoes, hail, snow, ice, forest fires and freezing rain. Certain elements of infrastructure are particularly susceptible to failure due to particular hazards, e.g. heavy rainfall can cause slope instability, river floods can result in bridge scour and windstorms can affect overhead cables. In this report each element of infrastructure is first briefly outlined, examples of typical failures are presented and the impacts described. Methods of remediation and preventive measures relevant to infrastructure types are discussed. Remediation methods involve the repair of damage caused due to climatic behaviour. Preventative measures are to be applied to increase the resilience of the element of infrastructure to the climate hazards. These topics analysed and the effectiveness is quantified using a Technical Impact Matrix (TIM) approach. The TIM allows the user to assess the various mitigation measures available and rank them in order to determine the optimum solution.

1.2 Technical Impact Matrices

This section gives a brief description of the Technical Impact Matrix procedure and how it can be used as a decision support tool for infrastructure managers.

1.2.1 TIM rationale

The TIM approach developed was developed by WP7 participants using the following three stage approach:

Defining the Problem

- Outline a goal statement by brainstorming among the group members
- Outline the relevent structural elements

Choosing Influence Factors

- The goal statement was used to guide the selection and influence of model factors. If there is more important factors the key ones must be identified and the rest grouped according to their significance.
- Outline the Envoirnmental risks to each structural element

Ranking the Impact Matrix

- Complete the TIM that represents the qualitative assessment of the strength of the impact that exists between the given factor and every other factor in the matrix
- A two stage ranking system is then completed for each hazard

1.2.2 Ranking System

A two-stage ranking procedure was developed to populate the TIM. Critical analysis from experienced professionals has been used to develop a relative ranking system. Each rank is colour coded so that the greatest impact can be easily identified.

In the first stage, the effect of the weather hazards identified in the RAIN project was considered on the performance of an asset (considering different failure modes for a given asset) or a component (e.g. for a bridge the deck, foundation etc.) using a number between 1 and 5 depending on their impact (according to the scoring table: see Table 1).

Table 1 Scoring Table for Weather Hazard Impacts Ranking

0	No impact
1	Low impact
2	Low to medium impact
3	Medium impact
4	Strong impact
5	Very strong impact

In the second stage the different remediation strategies available for each element or component are considered. Different remediation strategies are ranked (according to the scoring tables presented in each section – see Table 2 for an example) in terms of technical effectiveness, cost, human and financial loss and environmental impact. When the effectiveness is 0 (not useful), the next factors (cost, environmental impact, human impact) are not analysed.

Table 2 Scoring System for Remediation Strategies Ranking

0	Not useful
1	Negative impact
2	Low to medium impact
3	Medium impact
4	Positive impact
5	Very positive impact

In the second stage the various remediation strategies possible for each bridge component are considered. Different remediation strategies are relatively ranked (according to the scoring tables presented from **Error! Reference source not found.**Table 3 to Table 6 in terms of technical effectiveness, cost, human and financial loss and environmental impact.

Table 3 Scoring System for Technical Effectiveness Ranking

Score	Technical Effectiveness
0	Not useful
1	Negative impact
2	Low to medium impact
3	Medium impact
4	Positive impact
5	Very positive impact

Table 4 Scoring System for Cost Ranking

Score	Cost of Measure
0	Very Expensive
1	Expensive
2	Expensive to Medium price
3	Medium price
4	Cheap
5	Very Cheap

Table 5 Scoring System for Human and Financial Loss Ranking

Score	Human and financial loss if mitigation measure adopted
0	Very High
1	High
2	High to Medium
3	Medium
4	Low
5	Very Low

Table 6 Scoring System for Positive Environmental Impact Ranking

Score	Positive environmental impact
0	Very Low
1	Low
2	Low to Medium
3	Medium
4	High
5	Very High

In regards to the scoring system for:

- Technical effectiveness- The highest mark suggests that the solution is the most effective.
- Cost- The highest mark suggests that the cost is the lowest of all the proposed solutions, therefore has a very positive impact.
- Human and financial loss- The highest mark reflects the best protection of human lives and properties.
- Positive environmental impact- Relates to the impact that a specific solution installation has on the environment and its aesthetic benefit.

The scoring system is a relative analysis, and the effectiveness of each remediation strategy for any given structural element is summarised on a final table to determine which strategy provides the optimum remediation solution.

2 Bridges

2.1 Introduction

As a key component of infrastructure, the failure of bridges greatly affects the general public, and raises concern in terms of safety, transport and commerce. Bridges are designed to resist extreme weather and loading effects, and this has become more important in recent years due to an increase in extreme weather events.

Bridges are vulnerable to extreme weather hazards such as floods, tornadoes and wind storms. In particular scour during flood events, extreme wind and increased lateral loading during flood are common causes of bridge failure.

Several remediation measures were also outlined in D7.1 to mitigate the effects of extreme weather events on bridges, these include: scour protection, upstream debris traps, erosion protection, lifting the bridge deck, provision of additional stiffeners, wind deflection devices and vibration dampeners.

2.2 Technical Impact Matrix for Bridges

For each component of a typical bridge (Abutment, Deck, Drainage, Footing/Foundation, Piers and Wing walls), different natural hazards considered in WP2 of the RAIN project, have been analysed and ranked (Table 7) depending on their impact (according to the scoring table: see Table 1).

Table 7 List of weather hazards and their impact on Bridge components

Bridge Components	**Wind-storms**	**Heavy rainfall**	**Floods**	**Thunder-storm gust**	**Tornado**	**Hail**	**Lightening**	**Snow & Ice Loading**	**Freezing rain**	**Wildfire**
Abutments	0	0	**3**	0	1	0	0	1	0	1
Deck	3	1	**3**	1	2	0	0	2	0	1
Drainage	0	4	**5**	0	0	1	0	1	2	0
Footing/Foundation	0	0	**3**	0	0	0	0	1	0	0
Piers	2	1	**4**	1	1	0	0	1	0	1
Wing walls	1	2	**4**	0	1	0	0	1	0	1
Total impact	6	8	**22**	2	5	1	0	7	2	4

The remediation strategies identified in Deliverable 7.1 are assessed for a generalisation of all failure models in Tables Table 8 to Table 12.

Table 8 Remediation Strategies for Bridge Abutments

Abutment				
Mitigation Measures	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Scour protection	5	1	5	2
Upstream debris trap	4	3	5	2
Erosion protection	**4**	**3**	**5**	**3**
Lifting	2	0	5	0
Additional stiffeners	0			
Wind deflection devices	0			
Vibration dampeners	0			

Therefore, the most effective remediation strategy for Bridge abutments is **erosion protection** measures.

Table 9 Remediation Strategies for Bridge Decks

Deck				
Mitigation Measures	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Scour protection	0			
Upstream debris trap	0			
Erosion protection	0			
Lifting	**5**	**1**	**5**	**0**
Additional stiffeners	4	2	3	0
Wind deflection devices	4	2	2	0
Vibration dampeners	3	2	5	0

According to Table 9, the most effective remediation strategy for bridge decks is **'lifting/raising'** the bridge deck.

Table 10 Remediation Strategies for Bridge Footings/Foundations

Footing/Foundation				
Mitigation Measures	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Scour protection	5	1	4	2
Upstream debris trap	4	2	4	2
Erosion protection	**4**	**3**	**4**	**3**
Lifting	2	0	4	0
Additional stiffeners	0			
Wind deflection devices	0			
Vibration dampeners	3	2	4	0

The most effective remediation strategy for footing/foundations is **erosion protection**.

Table 11 Remediation Strategies for Bridge Piers

Piers				
Mitigation Measures	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Scour protection	**5**	**3**	**4**	**2**
Upstream debris trap	5	2	4	2
Erosion protection	**4**	**3**	**4**	**3**
Lifting	2	0	3	0
Additional stiffeners	0			
Wind deflection devices	0			
Vibration dampeners	2	2	4	0

The most effective remediation strategy for bridge piers is **erosion protection and scour protection**.

Table 12 Remediation Strategies for Bridge Wing Walls

Wing walls				
Mitigation Measures	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Scour protection	5	1	4	2
Upstream debris trap	3	2	4	2
Erosion protection	**4**	**3**	**4**	**3**
Lifting	2	0	4	0
Additional stiffening	0			
Wind deflection devices	0			
Vibration dampeners	0			

The most effective remediation strategy for wing walls is **erosion protection** methods.

4 Pavements

4.1 Introduction

The function of a pavement is to dissipate the traffic loads and provide drainage to the roadway. Leading causes of pavement failures as identified in Deliverable 7.1, can be considered of two general types, climatological and due to human factors and include: extreme weather events such as heavy rainfall, windstorms and flooding leading to structural problems when the capacity of drainage systems are exceeded, bleeding or flushing, aging of surface course, rutting, cracking, potholing, spalling, faulting or ravelling, oxidation and collapse due to failure of lower layers.

Several remediation measures were outlined in D7.1. There are three main levels of techniques used to protect pavement, categorised into design, maintenance and rehabilitation. The methods include;

- Ensuring that the drainage system can cope with relevant design storms
- Careful consideration of material used in the construction of the system
- Prevention of moisture ingress
- Restoration of flexibility of the pavement by use of fog seals
- The use of chipseal and re-sheeting to prolong the life of roads
- Micro surfacing, crack/ break and seat, rubblization
- Additives and emulsifiers such as elastomers and plastomers in the asphalt mix

It is noted that the distresses indicated in the previous deliverable, D7.1, have been classified into three subsets according the intensity and importance of the damage, namely;

(a) Superficial damage. This level of damage increases the vulnerability of the lower layers and causes an unsmooth and uncomfortable feeling for the driver. The distresses included in this subset are bleeding or flushing, durability cracking, edge cracking, fatigue cracking, longitudinal cracking, thermal cracking, oxidation, premature aging surface, ravelling and rutting.

(b) Damage in deeper layers. This level implies a further damage, which can affect even the lower layers, resulting in important alteration of the regularity of the pavement. The distresses included in this subset are bumps and sags, faulting, pocking, potholing, pumping, punch out and spalling.

(c) Structural damage. This level of damage is due to the loss of stability of the lower layers causing the collapse of pavements.

4.2 Technical Impact Matrix for Pavements

The effect of weather hazards on the various failure modes for pavements is considered in Table 13.

Table 13 List of Weather Hazards and their Impact on Pavements

Type of pavement distress	Wind-storms	Heavy rainfall	River floods	Thunder-storm gust	Tornado	Hail	Lightening	Snow & snow storms	Freezing rain	Wildfire	Coastal flood	Icing	Snow-loading	Convective windstorms
Superficial damage	0	3	**4**	0	1	2	0	4	1	5	**4**	4	5	0
Damage in deeper layers	0	2	**5**	0	1	1	0	3	1	0	**5**	3	3	0
Structural damage	0	0	**5**	0	0	0	0	0	0	0	**5**	0	0	0
Total Impact	0	5	**14**	0	2	3	0	7	2	5	**14**	7	8	0

The remediation strategies identified in Deliverable 7.1 are assessed for the separate failure models in Tables 14 to 16.

Table 14 Remediation Strategies for Superficial Damage

Superficial Damage. Remediation strategies	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Design Level. Adequate drainage systems	4	1	5	4
Design Level. Materials and compositions adapted to extreme conditions	3	3	4	4
Maintenance Level. Fog seal, cheapseal, micro surfacing, etc.	2	2	2	2
Maintenance Level. Cleaning and repair of drainage systems	**3**	**3**	**4**	**5**
Rehabilitation Level. Structural overlays, milling and filling, crack/break and seat, etc.	0			
Use of chemical technology	3	2	3	3

The most effective remediation strategy for superficial damage is to provide regular **cleaning and repair** of drainage systems.

Table 15 Remediation Strategies for Damage in Deeper Layers

Damage in Deeper Layers. Remediation strategies	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Design Level. Adequate drainage systems	4	1	5	4
Design Level. Materials and compositions adapted to extreme conditions	**4**	**3**	**4**	**4**
Maintenance Level. Fog seal, cheapseal, micro surfacing, etc.	3	2	2	2
Maintenance Level. Cleaning and repair of drainage systems	**3**	**3**	**4**	**5**
Rehabilitation Level. Structural overlays, milling and filling, crack/break and seat, etc.	2	1	1	2
Use of chemical technology	2	2	3	3

The TIM suggests that there are two optimal remediation methods for damage in deeper layers. These methods are to provide regular **cleaning and repair** of drainage systems and **at the design level, to ensure that materials and compositions are adapted to extreme conditions.**

Table 16 Remediation Strategies for Structural Damage

Structural Damage. Remediation strategies	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Design Level. Adequate drainage systems	**5**	**1**	**5**	**5**
Design Level. Materials and compositions adapted to extreme conditions	5	3	4	4
Maintenance Level. Fog seal, cheapseal, micro surfacing, etc.	2	2	2	2
Maintenance Level. Cleaning and repair of drainage systems	4	3	4	5
Rehabilitation Level. Structural overlays, milling and filling, crack/break and seat, etc.	3	1	1	2
Use of chemical technology	0			

The TIM suggests that there are several potential remediation methods for structural damage. However, the most effective remediation strategy for existing assets is to, at the design level, provide **adequate drainage systems**.

5 Cuttings and Embankments

5.1 Introduction

Failures in slopes (either natural or man-made) have a direct impact on road and rail infrastructure. They can disrupt traffic, cause economic losses and can result in casualties and fatalities.

There are a number of different contributors to the occurrence of a landslide such as bedrock and soil properties, slope morphology, relief energy, land use and heavy/ prolonged rainfall. After heavy rainfall, there is a change in hydrostatic pressure acting on the slope surface, this leads to changes in the total stresses and pore stresses in the soil. Other important trigger factors include earthquakes, snow melts, slope toe erosion by rivers or sea waves, thawing of mountain permafrost, volcanic eruption and anthropogenic activities such as excavation, loading and land use changes.

Leading causes of landslides as detailed identified in Deliverable 7.1 are: high antecedent rainfall, and high intensity period rainfall, poor surface drainage, high risk slope geometry and soil material instability.

Several remediation measures were outlined in D7.1 to mitigate the effects of landslides, these include:

- Analysis of the wetting front depth in soil masses
- Monitoring and mapping of landslide events, and prediction of rainfall events
- Surface drainage techniques such as buried drains
- The use of vegetation
- Slope re-grading, reduction of disturbing forces and soil improvements
- Structural inclusions, the use of gabions, geogrids, anchored beams etc.

5.2 Technical Impact Matrix for Cuttings and Embankments

For each type of landslide considered (shallow, deep, flows, rockfalls), different natural hazards considered in WP2 of the RAIN project, have been analysed and ranked (Table 17) depending on their impact (according to the scoring table: see Table 1). Some hazards such as freezing rain or thunderstorms have no impact on triggering landslides whereas heavy rainfall has the strongest impact for triggering landslides.

Table 17 List of Weather Hazards and their Impact on Landslides

Type of landslides	**Wind-storms**	**Heavy rainfall**	**Floods**	**Thunder-storm gust**	**Tornado**	**Hail**	**Lightening**	**Snow and Ice loading**	**Freezing rain**	**Wildfire**
Shallow	0	**5**	1	0	2	0	0	4	0	3
Deep	0	**3**	5	0	2	0	0	2	0	0
Flows	0	**4**	5	0	3	0	0	2	0	0
Rockfalls	1	**5**	1	0	3	0	0	4	3	0
Total impact	1	**17**	12	0	11	0	0	12	0	3

The efficacy of the remediation measures in increasing resilience against the different failures models are given in Table 18 to 21.

Table 18 Remediation Strategies for Shallow Landslides

Shallow landslides remediation strategies	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact**
Barriers	4	1	4	3
Nets	1	2	2	2
Drapes	0			
Wire ropes	0			
Shortcrete	3	1	4	1
Anchors	0			
Drainage	**5**	**4**	**3**	**4**
Monitoring	3	2	3	4
Vegetation	4	5	2	4

Therefore, the most effective remediation strategies for shallow landslides is the provision of engineered **drainage.**

Table 19 Remediation Strategies for Deep Landslides

Deep landslides remediation strategies	Effectiveness	Cost	Human and financial loss	Positive environmental impact*
Barriers	2	1	1	3
Nets	0			
Drapes	0			
Wire ropes	0			
Shortcrete	1	1	1	1
Anchors/piles	**5**	**2**	**5**	**3**
Drainage	2	4	3	4
Monitoring	3	2	4	4
Vegetation	1	5	1	4

The most effective remediation strategy for deep landslides **piles and anchors**.

Table 20 Remediation Strategies for Flows

Flow landslides remediation strategies	Effectiveness	Cost	Human and financial loss	Positive environmental impact*
Barriers	3	1	1	3
Nets	0			
Drapes	0			
Wire ropes	0			
Shortcrete	0			
Anchors	0			
Drainage	**3**	**4**	**3**	**4**
Monitoring	3	2	4	4
Vegetation	1	5	1	4

The most effective remediation strategy for flows is the provision of engineered **drainage**.

Table 21 Remediation Strategies for Rock falls

Rock fall	**Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact***
Barriers	5	1	4	1
Rockfall nets	**4**	**3**	**4**	**3**
Classical nets	3	2	3	3
Drapes	4	2	4	3
Wire ropes	2	2	3	3
Shortcrete	2	1	1	1
Anchors	4	2	4	3
Drainage	1	4	1	4
Monitoring	**4**	**2**	**4**	**4**
Vegetation	0			

The most effective remediation strategies for rock falls are **monitoring** and **rock fall nets**.

6 Rail Tracks

6.1 Introduction

The major components of the railway system are the crossing and switches (C&S), sleepers, ballast, substructure and tracks. Switches and crossings are the devices used to divide single tracks into multiple tracks, which provide movement in straight or divergent directions. The failures that occur in rail are based upon the component, e.g. rail, sleeper, ballast etc. and the nature of the failure, e.g. fatigue cracks, rolling contact fatigue cracks, wear, material deformation and shear failure.

Some of the leading causes of indirect failure as detailed in D7.1 are: freeze- thaw action, flooding leading to washout of ballast, build-up of vegetation waste such as fallen leaves, ice, snow, and excessive heat.

Several remediation measures were outlined in Deliverable 7.1 to mitigate the effects of extreme weather events on rail tracks, these include:

- Pre-stressing or stretching of rail track
- The provision of small gaps between track lengths to allow for thermal expansion
- Inspection of tracks to detect local weaknesses in Winter
- Replenishment of ballast around sleepers, and re-tensioning of welded rails
- At-risk rails are painted white so that they absorb less heat
- Regular measurement of rail temperatures

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6.2 Technical Impact Matrix for Rails Tracks

In Table 22, different natural hazards considered in WP2 of the RAIN project, have been analysed and ranked for rail tracks (including S&C), depending on their impact (according to the scoring table: see Table 1). Some hazards such have no whereas some have a great importance.

Table 22 List of Weather Hazards and their Impact on Rail Tracks and S&C

Type of asset	Windstorms	Heavy rainfall	Floods	Thunderstorm gust	Tornado	Hail	Lightening	Snow and Ice loading	Freezing rain	Wildfire
Rail Tracks (Including Switches and Crossings)	4	3	4	3	3	4	2	4	5	4

Several remediation strategies were considered and are presented in Table 23.

Table 23 Remediation Strategies for Rail Tracks including S&C

Rail tracks (including S&C) remediation strategies	**Technical Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact**
Pre-stressing (Stretching)	5	3	2	3
Track Painting	4	2	2	3
Replenishing of Ballast (on which the tracks lay)	3	3	3	3
“Slab Track”	4	1	3	4
Regular Inspection and Maintenance	4	3	4	4
Remote Distance Monitoring of Tracks	4	2	4	5
Weather Monitoring Systems and EWS	4	1	4	5
Hazard Management	**5**	**2**	**5**	**5**

Therefore, the most effective remediation strategy for rail tracks is **Hazard Management**.

7 Tunnels

7.1 Introduction

Tunnels are very important infrastructure components for modern transport networks. Advances in tunnelling technology has led to longer and deeper tunnels being constructed. Some of the most notable tunnels in the world are The Laedal tunnel in Norway with 24.5km in length and The San Gotardo tunnel in Switzerland with 17km in length. Tunnels are particularly vulnerable to flooding and weather related failures.

The following are some of the leading causes of tunnel failure as detailed in Deliverable 7.1: weather hazards such as flooding from rainfall, oceans, rivers or groundwater, gravity falls, rock mass failures such as spalling, slabbing and major rock bursting, squeezing and swelling, running sand settlement and cratering.

Several remediation measures were outlined in D7.1 to mitigate the effects of extreme weather events on bridges, these include:

- Strengthening waterproofing capacity of structures
- Rigorous maintenance and upgrading of sewer networks
- Temporary overflow storage tanks
- Frequent checks to ensure structures can withstand high water pressures and wind forces in ventilation shafts
- Waterproofing barriers and doors and emergency reserve pumps

7.2 Technical Impact Matrix for Tunnels

It is difficult to determinate the differences in vulnerability caused by natural hazards between the different tunnel’s typologies. Due to this, only Immersed and Non-Immersed tunnels have been selected in this ranking procedure.

For each type of tunnel, the different natural hazards considered in WP2 have been analysed and ranked depending on their impact (see Table 1). Some hazards such as lightning or thunderstorms have no impact on tunnels whereas river and coastal floods have the strongest impact for tunnels. The different possible remediation strategies for each tunnel type are then assessed.

Table 24 List of Weather Hazards Analysis and their Impact on Tunnels

Tunnel type	**Windstorms**	**Heavy rainfall**	**River floods**	**Thunderstorm gust**	**Tornado**	**Hail**	**Lightning**	**Snow & snow storms**	**Freezing rain**	**Wildfire**	**Coastal flood**
Not immersed tunnels	1	4	5	0	1	1	0	3	3	3	**4**
Immersed tunnels	1	3	2	0	1	1	0	3	3	0	**5**
Total Impact	2	7	7	0	2	2	0	6	6	3	**9**

As depicted from the table above, flooding has the most significant influence in tunnels operational vulnerability.

The first typology studied, not immersed tunnels, is primarily affected by river floods. Other important natural hazards are heavy rainfall and coastal floods (for tunnels located inside a coastal influence area). As it was mentioned above, floods are the first problem regarding tunnel infrastructure vulnerability.

The second typology, immersed tunnels, are, due to their location, affected primarily by coastal flood and secondly by heavy rainfall.

Table 25 Remediation Strategies for Immersed Tunnels

Immersed tunnels	**Effectiveness**	**Cost**	**Human & Financial loss**	**Positive Environmental Impact**
Strengthening waterproofing capacity	4	2	2	3
Upgrading of sewers and drainage systems	5	4	4	3
Maintenance of sewers and drainage systems	**4**	**5**	**5**	**4**
Install underground tanks	4	3	4	4
Repair structures to withstand higher water and wind pressure	3	1	3	3
Install porous paving	1	3	4	3
Improve user warning systems	**4**	**4**	**5**	**5**
Install floodgates	5	1	1	3

The most effective remediation strategies for immersed tunnels are **Improving user warning systems**, and M**aintenance of sewers and drainage systems.**

Table 26 Remediation Strategies for non Immersed Tunnels

Non immersed tunnels	**Effectiveness**	**Cost**	**Human & Financial loss**	**Positive Environmental Impact**
Strengthening waterproofing capacity	4	3	2	3
Upgrading of sewers and drainage systems	5	4	3	4
Maintenance of sewers and drainage systems	**4**	**5**	**5**	**4**
Installation of underground tanks	5	4	4	4
Repair structures to withstand higher water and wind pressure	3	2	3	3
Install porous paving	1	3	4	3
Improve on user warning systems	**4**	**4**	**5**	**5**
Install floodgates	4	1	1	3

The most effective remediation strategy for not immersed tunnels are **Improving on user warning systems**, **and Maintenance of sewers and drainage systems**.

8 Electrical and Telecommunications Networks

8.1 Introduction

In terms of electrical power grid infrastructure, power lines are always hit the hardest in extreme weather events. This is not surprising, as lines cover extensive lengths across both urban and country areas, and are quite exposed to weather. The most common type of transmission and distribution line is the overhead line. Underground lines are much less common, except in some cases such as submarine power cables connecting islands. Submarine power lines are almost immune to all weather threats but they are not often used as they are very expensive.

The following are some of the leading causes of electrical and telecommunications network failures as detailed in Deliverable 7.1; wind storms, ice/ wet snow storms, extreme heat, lightning, flash floods, wild fires and sand storms

Several remediation measures were outlined in D7.1 to mitigate the effects of extreme weather events on electrical and telecommunications networks, these include:

- Rights of way maintenance, such as vegetation management
- De-icing and anti-icing measures
- Prevention of line sagging
- Regular tower inspections maintenance

8.2 Technical Impact Matrix for Electricity Sector

The table below lists the impact assessment for each of the weather threats identified, as applied to each of the critical components of the power grid: generators, lines, transformers, breakers, etc.

Table 27 List of Weather Hazards and their Impact on Electric Grids

	Lightning	**Windstorms**	**Ice/snow storms**	**Flash floods**	**Extreme cold**	**Extreme heat**	**Wild fires**	**Sand storms**	**Seasonal drought**
Generators (housed)	**1**	1	1	**5**	5	3	1	1	5
Generators (wind / PV)	**3**	5	5	**3**	1	1	3	5	1
Lines	**5**	5	5	**3**	5	5	3	3	1
Transformers	**5**	5	5	**5**	5	5	5	1	1
Switches/ Breakers	**5**	3	3	**5**	3	1	3	1	1
Relays	**5**	3	3	**3**	1	3	3	1	1
SCADA & telecom	**5**	3	3	**3**	1	3	3	1	1
Voltage control devs	**5**	3	3	**3**	1	1	1	1	1
Total Impact	**34**	27	28	**30**	23	22	22	14	12

The Electricity sector is highly regulated; strict requirements for the reporting of significant events. Many economic studies on the societal costs of power outages, the following are some examples.

- US White House report 2013: Weather-related outages were the leading cause of outages and are estimated to have cost the U.S. economy an inflation-adjusted annual average of $18 to $33 billion (this is 0.13% to 0.25% of the 2012 real GDP)
- Congressional Research Service study 2012: estimated the inflation-adjusted cost of weather-related outages at $25 to $70 billion/yr. (0.18% to 0.52% of the 2012 real GDP)

Other natural threats

Other threats that may have strong impact on Electrical Networks, but not related to weather and therefore not considered here are: earthquakes, tsunamis, and space weather (geomagnetic storms produced by coronal mass ejections from the sun, i.e. solar flares). Solar superstorms in particular have attracted more attention recently, as in 2012 there was a large flare that luckily missed the earth but had the potential to knock out large portions of the grid all around the world. A geomagnetic storm induces currents in the power grid, causing damages via over-voltages or overloads.

8.3 Technical Impact Matrix for Telecommunications

This is a highly deregulated sector; it did not have as strict requirements on reporting incidents until recently (ENISA reports start from 2011). The industry mostly focuses on loss of service (extent and duration). Hyper-convergence with IT makes it hard to assess monetary losses to customers, but for some (“knowledge workers”) it approaches 100% of their work life.

Table 28 List of Weather Hazards and their Impact on Telecommunication Networks

	Lightning	**Windstorms**	**Ice/snow storms**	**Flash floods**	**Extreme cold**	**Extreme heat**	**Wild fires**	**Sand storms**
Outside Plants	5	**5**	**5**	5	1	3	**5**	5
End Offices	3	**3**	**3**	3	1	1	**3**	3
Central Offices	1	**1**	**1**	1	1	1	**1**	1
Aerial lines	3	**5**	**5**	3	1	1	**5**	3
Underground lines	1	**1**	**1**	1	1	1	**1**	1
RF/Sat links	5	**5**	**5**	3	1	3	**5**	5
Base Stations	5	**5**	**5**	5	1	3	**5**	5
*MSC	3	**3**	**3**	3	1	1	**3**	3
*BSC	1	**1**	**1**	1	1	1	**1**	1
Total Impact	27	**29**	**29**	25	9	15	**29**	27

*Where MSC= **Mobile Switching Centre,** BSC= **Base Station Controllers**

Table 29 Remediation Strategies for Electrical and Telecommunications Networks

	Technical Effectiveness	**Cost**	**Human and financial loss**	**Positive environmental impact**
Vegetation management	5	3	2	2
De-icing and anti-icing measures	4	2	3	0
Prevention of line sagging	3	2	3	0
Regular tower inspections maintenance	4	1	4	3

9 Dams

9.1 Introduction

As a result of progress in engineering techniques and the development of new construction materials, dams have been continuously growing in size and elegance, with dams such as The Three Gorges Dam in China, The Akosombo Dam in the Volta River and The Alqueva, La Serena and Alcantara Dams in Europe. Depending on their shape, dams can be classified into six types, gravity, buttress, arch, embankment, arch-gravity and mixed dams. Depending on their materials, dams can be classified into three further types, masonry, concrete and embankment dams such as earth filled and rock filled. According to break, they are classified into another one of two types, instant breaking or partial breaking. There is also a method of classifying dams in terms of the potential impact of the dam's failure:

- Type A; Essential services or urban areas could be globally affected
- Type B; A reduced housing number could be affected
- Type C: Human casualties could happen but only incidentally, moderate damages on materials and environment are expected.

Some of the leading causes of dam failure as detailed in Deliverable 7.1 are; Overtopping of a dam, due to inadequate spillway design, debris blocking spillways, settlement of dam crest, Foundation defects, including settlement and static sliding instability or slope instability, Piping, internal erosion due to seepage, Structural failures due to the materials used in construction, Static sliding, High rainfall and High temperature.

The following are a small number of the remediation measures outlined in Deliverable 7.1 to mitigate the effects of extreme weather events on dams, these include:

- Monitoring of future meteorological conditions and their potential impact
- Correct design to meet the necessary design loads and standards
- Regular and frequent maintenance of valves and joints etc.
- Maintenance and removal of vegetation and waste build up, dredging etc.
- Correct operation of the dam and its components

9.2 Technical Impact Matrix for Dams

For each type of dam (Gravity, Buttress, Arch and Embankment dams), the different natural hazards considered in WP2 have been analysed and ranked depending on their impact (see Table 30). Some hazards such as coastal flood or thunderstorms have no impact on dams whereas heavy rainfall does have a major impact.

Table 30 Natural hazards analysis depending on their impact

Dams	Wind-storms	Heavy rainfall	River floods	Thunderstorm gust	Tornado	Hail	Lightning	Snow & snow storms	Freezing rain	Wildfire	Coastal flood
Gravity, Buttress and Arch Dams	0	**4**	**4**	0	0	1	0	2	1	2	0
Embankment dams	2	**5**	**5**	0	2	1	0	1	2	2	0
Total	2	**9**	**9**	0	2	1	0	1	2	2	0

Heavy rainfall and river floods are one of the natural hazards with more influence in dam structures (mainly in the case of embankment dams) and operational (in all cases) vulnerability. There are two different dam typologies according to their breakage process, erodible and non-erodible dams. Gravity, buttress and arch dams follow a similar breakage process, but embankment dams are more influenced by heavy rainfall and river floods because they are erodible dams. In embankment dams, once a certain amount of water surpasses the dam, the dam begins to lose its structural integrity, and this might end in the infrastructure's collapse.

The different remediation strategies have been ranked for each dam's typology (See Table 31 below) in terms of effectiveness, cost, human and financial loss and environmental impact.

9.2.1 Gravity, Buttress and Arch Dams

An assessment of remediation measures for gravity dams is presented in Table 30.

Table 31 Remediation strategies for Gravity, Buttress and Arch Dams

Non-erodible dams (Gravity, Buttress and Arch dams) remediation strategies	Effectiveness	Cost	Human and financial loss	Positive environmental impact
Increase Dam height to increase freeboard	5	2	1	2
Increase erosion protection measures	0			
Management to reduce sediment inflow	3	4	2	4
Improving maintenance of ancillary infrastructures (Outlet systems, gate maintenance sedimentation control, etc.)	**5**	**4**	**4**	**3**
Improving spillways and outlets capacity	5	3	2	4
Increase capacity of effluent reservoirs	4	1	2	3

Therefore, the most effective remediation strategies for gravity and buttress dams are **Improving maintenance of ancillary infrastructures**.

9.2.2 Embankment Dams

An assessment of remediation measures for embankment dams is presented in Table 30.

Table 32 Remediation strategies for embankment dams

Erodible dams (Embankment dams) remediation strategies	**Effectiveness**	**Cost**	**Human and financial loss**	**Positive environmental impact**
Increase Dam height to increase freeboard	5	2	1	2
Increase erosion protection measures	4	3	3	4
Management to reduce sediment inflow	2	4	3	4
Improving maintenance of ancillary infrastructures (Outlet systems, gate maintenance sedimentation control, etc.)	**5**	**3**	**4**	**4**
Improving spillways and outlets capacity	5	3	2	4
Increase capacity of effluent reservoirs	4	2	2	3

10 Summary and Conclusions

According to the European Commission Report Adapting Infrastructure to climate change (2013) the impact of weather stresses represents 30% to 50% of current road maintenance costs in Europe. Major failure of elements of infrastructure as a result of weather impacts is increasing, this is particularly the case for ageing rail networks. The report “Impacts of Europe’s changing climate – 2008 indicator-based assessment” by the EEA and JCR, identifies the need to limit deterioration effects from adverse weather conditions (e.g. prolonged precipitation, heat stress, freeze-thaw cycle) and damaging consequences in case of extreme events (i.e. storms and floods) as a key factor influencing construction designs.

This report, in conjunction with Deliverable 7.1, considers the effect of climate change on major infrastructure assets in the surface transport and energy domains. By first considering typical effects across a range of infrastructure, a set of likely hazards affecting elements of infrastructure were identified. Whilst some infrastructure elements, e.g. bridges and slopes are affected by multiple weather hazards, others such as tunnels and dams are primarily affected by one hazard.

Remediation measures which increase the resilience of elements are outlined. The methods can be broadly classified as (i) design and construction related (ii) retrofitted solutions and (iii) indirect methods. A methodology for scoring the technical impact of the available remediation measures is presented for a selection of critical infrastructural assets. The TIM ranking system was shown in this report to be a robust method for recommending the optimum remediation methods while considering technical effectiveness, cost, human and financial loss and environmental impact and has the potential to be widely adopted a decision support tool for infrastructural management. The results for each asset type were used as expert judgement data to adjust risk values in the analyses performed in Work Package 5 of the RAIN project.